

18.905-906 – Algebraic Topology

Taught by Haynes Miller, notes by Sanath Devalapurkar

ABSTRACT. 18.905/906 is being taught by Professor Haynes Miller in Fall 2016/Spring 2017 (respectively). I am planning on taking notes throughout the semester. I'll add drawings by putting them on a notepad, scanning them as images, and finally inserting them in the appropriate spots. This means that they might be messy. Any mistakes in these notes are only mine, and not Professor Miller's.

Here are hyperlinks to the notes from each of the semesters.

- (1) The notes for 18.905 start at section 1.
- (2) The notes for 18.906 start at section 39.

CONTENTS

1. Introduction, simplices	2
2. Simplices, more about homology	3
3. Categories, functors, natural transformations	4
4. More about categories, and computing the homology of a star-shaped region	5
5. Homotopy, star-shaped regions	6
6. Homotopy invariance of homology	8
7. Basically a recap of what we did last time	9
8. Relative Homology	11
9. Long exact homology sequence, Excision, and Genealogy	12
10. Excision, and the Eilenberg-Steenrod axioms	15
11. Application of our previous calculation of $H_*(S^n)$ and the “locality principle”	17
12. Mayer-Vietoris and Subdivision	19
13. Locality (almost done!)	20
14. Concluding Locality! and CW-complexes	23
15. CW-complexes and cellular homology	25
16. Homology of CW-complexes	27
17. Missing lemmas, \mathbf{RP}^n again, and even CW-complexes	30
18. Relative attaching maps, \mathbf{RP}^n , Euler characteristic, and homology approximation	32
19. “Euler’s theorem”, and “homology approximation” - CTC Wall. I) Singular homology, II) CW complexes, III) “homological algebra”	34
20. \otimes	36
21. Tensor and Tor	39
22. More about Tor	42
23. Direct Limits	46
24. Universal coefficient theorem (and Hom, adjointness)	47
25. Künneth and Eilenberg-Zilber	49
26. A few more things about coefficients, cohomology	51
27. Cohomology, Ext, cup product	54
28. Universal coefficient theorem, and products in H^*	56
29. Cup product, continued	58

30.	Surfaces and symmetric nondegenerate bilinear forms	60
31.	A plethora of products	62
32.	Cap product and “Čech” cohomology	64
33.	\check{H}^* as a cohomology theory, and the fully relative \cap product	66
34.	\check{H}^* as a cohomology theory	70
35.	Finish off the proof of \check{H}^p excision, topological manifolds, fundamental classes	72
36.	Fundamental class	74
37.	Covering spaces and Poincaré duality	76
38.	Applications	77
39.	Limits, colimits, and adjunctions	80
40.	Compactly generated spaces	82
41.	“Cartesian closed”, Hausdorff, Basepoints	83
42.	Fiber bundles, fibrations, cofibrations	85
43.	Fibrations and cofibrations	87
44.	Homotopy fibers, the Barratt-Puppe sequence	90
45.	Barratt-Puppe sequence, π_*	92
46.	Relative homotopy, π_1 action	95
47.	Action of π_1 , simple spaces, and the Hurewicz theorem	98
48.	Some examples; CW complexes	100
49.	Relative Hurewicz and J. H. C. Whitehead	101
50.	Cellular approximation, cellular homology, obstruction theory	104
51.	... and all the rest	106
52.	Vector bundles, principle bundles	108
53.	Principal bundles, associated bundles	111
54.	I -invariant of Bun_G , and G -CW-complexes	113
55.	Classifying spaces: the Grassmann model	115
56.	Simplicial sets	116
57.	Remember what we have	118
58.	Bundles, classifying spaces, simplicial objects	119
59.	Classifying spaces	121
60.	Why spectral sequences	123
61.	Serre spectral sequence	123

1. Introduction, simplices

Topics to be covered:

- (1) Singular homology
- (2) CW-complexes
- (3) Basics of category theory
- (4) Homological algebra
- (5) The Künneth theorem
- (6) UCT, cohomology
- (7) Cup and cap products, and
- (8) Poincaré duality.

Examples to keep in mind: \mathbf{R}^n . Inside, S^{n-1} being the $(n-1)$ -sphere. This is topologized as a subspace of Euclidean space. Taking the quotient by the equivalence relation $x \simeq -x$ gives \mathbf{RP}^{n-1} , i.e. the space of lines through the origin in \mathbf{R}^{n+1} .

Also, we can look at $V_k(\mathbf{R}^n)$, which is the space of orthonormal k -frames (ordered collection of k orthonormal vectors) in \mathbf{R}^n , called the Stiefel manifold, topologized as a subspace of $(S^{n-1})^k$. The Grassmannian, $\text{Gr}_k(\mathbf{R}^n)$, the space of k -dimensional linear subspaces of \mathbf{R}^n . It's a quotient space of $V_k(\mathbf{R}^n)$, since a k -frame spans a k -dimensional subspace. For example, $\text{Gr}_1(\mathbf{R}^n) = \mathbf{RP}^{n-1}$. These are all *manifolds*.

DEFINITION 1.1. A manifold is a Hausdorff space, locally homeomorphic to \mathbf{R}^n .

All these manifolds are compact except for \mathbf{R}^n . Manifolds exhibit a hidden symmetry, captured by Poincaré duality.

We'll probe general topological spaces through simplices.

DEFINITION 1.2. The standard n -simplex Δ^n is the convex hull of $\{e_0, \dots, e_n\}$ in \mathbf{R}^{n+1} . More explicitly,

$$\Delta^n = \left\{ \sum t_i e_i = 1 : \sum t_i = 1, t_i \geq 0 \right\} \subseteq \mathbf{R}^{n+1}$$

The t_i s are called barycentric coordinates.

Usually we just drop the e_i s and just write “ i ”. There are maps between them, namely inclusions of faces. The map $d^2 : \Delta^1 \rightarrow \Delta^2$ that misses the vertex i (where $0 \leq i \leq 2$) is denoted d^i . They're called “face inclusions”, and are maps $d^i : \Delta^{n-1} \rightarrow \Delta^n$ where $0 \leq i \leq n$; they miss the vertex i .

DEFINITION 1.3. Let X be any topological space. A singular n -simplex in X is a continuous map $\Delta^n \rightarrow X$. Denote by $\text{Sin}_n(X)$ as the collection of all n -simplices of X .

This seems like a “fairly insane” thing to do.

See drawing for a torus. The direction of the simplex is like an orientation given by ordering of the indices of Δ^n . The standard notation is $\sigma : \Delta^n \rightarrow X$.

If $\sigma : \Delta^n \rightarrow X$. Find $(n-1)$ -simplices by looking faces of simplex; get a map $d_i : \text{Sin}_n(X) \rightarrow \text{Sin}_{n-1}(X)$ for $0 \leq i \leq n$ by taking $\sigma \mapsto \sigma \circ d^i =: d_i \sigma$, which is the i th face of σ . This carries a lot of information about the space.

Some simplices are particularly interesting. The issue of when boundaries match up is a key aspect of simplices. If σ is a simplex that goes around the hole in a torus, then $d_1 \sigma = d_0 \sigma$, and this means that the “boundary” is zero. So we want to understand things like $d_0 \sigma - d_1 \sigma$, but this isn't even a simplex anymore; we need to take formal sums and differences. We'll therefore consider the abelian group generated by simplices.

DEFINITION 1.4. The abelian group of singular n -chains in X is the free abelian group generated by n -simplices

$$S_n(X) = \mathbf{Z} \text{Sin}_n(X)$$

Its elements are finite linear combinations, i.e. formal sums of the form $\sum_{i \in \text{finite set}} a_i \sigma_i$ where $a_i \in \mathbf{Z}$. It's a pretty big group. If $n < 0$, say that $S_n(X) = 0$. Now, define a map $\partial : \text{Sin}_n(X) \rightarrow \text{Sin}_{n-1}(X)$ via:

$$\partial \sigma = \sum_{i=0}^n (-1)^i d_i \sigma$$

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We'll extend this to $S_n(X) \rightarrow S_{n-1}(X)$ by additivity.

Cycles are chains whose boundary is zero. These are the interesting chains. A more precise definition is the following:

DEFINITION 1.5. An n -cycle in X is an n -chain c with $\partial c = 0$. Denote $Z_n(X) = \ker(S_n(X) \xrightarrow{\partial} S_{n-1}(X))$.

For example, with the σ on the torus described before, $\partial c = d_0\sigma - d_1\sigma$ and this is zero.

THEOREM 1.6. Any boundary is a cycle, i.e., $B_n(X) := \text{Im}(\partial : S_{n+1}(X) \rightarrow S_n(X)) \subseteq Z_n(X)$.

PROOF. Homework! □

DEFINITION 1.7. The n th singular homology group of X is:

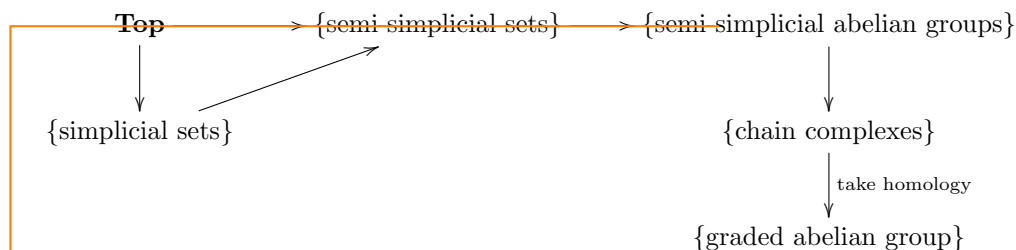
$$H_n(X) = Z_n(X)/B_n(X) = \frac{\ker(\partial : S_n(X) \rightarrow S_{n-1}(X))}{\text{Im}(\partial : S_{n+1}(X) \rightarrow S_n(X))}$$

The kernel is a free abelian group, and so is the image because they're both subgroups of free abelian groups; but the quotient isn't necessarily free abelian. The quotient is finitely generated for all the spaces we are talking about although the kernel and image are uncountably generated.

2. Simplices, more about homology

Recall the standard n -simplex $\Delta^n \subseteq \mathbf{R}^{n+1}$. A singular simplex is a map $\sigma : \Delta^n \rightarrow X$; they are elements of the set $\text{Sin}_n(X)$. For example, $\text{Sin}_0(X)$ consists of points of X . You have a huge collection of maps $d^i : \text{Sin}_n(X) \rightarrow \text{Sin}_{n-1}(X)$ and $s^i : \text{Sin}_n(X) \rightarrow \text{Sin}_{n+1}(X)$, and the collection $\{\text{Sin}_n(X), d^i, s^i\}$ forms a simplicial set. You therefore get a functor **Top** \rightarrow {simplicial sets}. Simplicial sets are really cool, because they're combinatorial models for topological spaces.

Now, you get induced maps on free abelian groups. This produces for each space a semi-simplicial abelian group. Using the d^i 's and s^i 's, you get a boundary map ∂ , and therefore a chain complex because $\partial^2 = 0$ (see homework). We capture this process in a diagram:



If you have a chain complex $\partial : A_n \rightarrow A_{n-1}$, then you have its homology $H_n(A, \partial) = \ker \partial_n / \text{Im } \partial_n$.

Let's practice with simplices. Suppose we have $\sigma : \Delta^1 \rightarrow X$. Construct a map $\phi : \Delta^1 \rightarrow \Delta^1$ via $(t, 1-t) \mapsto (1-t, t)$. This reverses the orientation of σ . Composing σ with ϕ gives another singular simplex $\bar{\sigma}$. It is *not* true that $\bar{\sigma} = -\sigma$ in $S_1(X)$.

Claim: $\bar{\sigma} \equiv -\sigma \pmod{B_1(X) = \text{Im}(\partial)}$, i.e., they are homologous. That is, if $d_0\sigma = d_1\sigma$, so $\sigma \in Z_1(X)$, then $[\bar{\sigma}] = -[\sigma]$ in $H_1(X)$. In other words, $\bar{\sigma} + \sigma$ is a boundary. We have to come up with a 2-simplex in X whose boundary is $\bar{\sigma} + \sigma$.

Let π denote the projection map from $[0, 1, 2]$ to $[0, 1]$. Then, $\partial(\sigma \circ \pi) = \sigma\pi d^0 - \sigma\pi d^1 + \sigma\pi d^2 = \bar{\sigma} - c_{\sigma(0)}^1 + \sigma$ where $c_{\sigma(0)}^1$ is the constant 1-simplex at $\sigma(0)$ (similarly for $c_{\sigma(0)}^n$). The $c_{\sigma(0)}^1$ is an error term. How do we correct this? Consider the constant 2-simplex $c_{\sigma(0)}^2$ at $\sigma(0)$; then the boundary is $c_{\sigma(0)}^1 - c_{\sigma(0)}^1 + c_{\sigma(0)}^1$, which is $c_{\sigma(0)}^1$. So, $\bar{\sigma} + \sigma = \partial(\sigma \circ \pi + c_{\sigma(0)}^2)$.

Let's compute the homologies of \emptyset and $*$. Well, $\text{Sin}_n(\emptyset) = \emptyset$, so $S_*(\emptyset) = 0$. So, $\cdots \rightarrow S_2 \rightarrow S_1 \rightarrow S_0$ is the zero chain complex. This means that $Z_*(\emptyset) = 0$ and similarly for boundaries. The homology in all dimensions is therefore 0.

Now for $*$. Clearly $\text{Sin}_n(*) = *$, and this generates $S_n(*)$, which is thus \mathbf{Z} . The chain complex is $S_0(*) \leftarrow S_1(*) \leftarrow S_2(*) \leftarrow \cdots$. What are the boundary maps? Well, $\partial(c_*^1) = d^0 c_*^1 - d^1 c_*^1 = c_*^0 - c_*^0 = 0$,

$\partial(c_*^2) = d^0 c_*^2 - d^1 c_*^2 + d^2 c_*^2 = c_*^1 - c_*^1 + c_*^1 = c_*^1$, and $\partial(c_*^3) = d^0 c_*^3 - d^1 c_*^3 + d^2 c_*^3 - d^3 c_*^3 = 0$. This means that our chain complex is:

$$\cdots \rightarrow \mathbf{Z} \xrightarrow{0} \mathbf{Z} \xrightarrow{1} \mathbf{Z} \xrightarrow{0} \mathbf{Z}$$

The cycles therefore alternate between 0s and \mathbf{Z} s, namely as $\mathbf{Z}, \mathbf{Z}, 0, \mathbf{Z}, 0, \cdots$. The boundaries are the same as the cycles except for dimension zero, namely as $0, \mathbf{Z}, 0, \mathbf{Z}, 0, \cdots$. This means that $H_0(*) = \mathbf{Z}$ but $H_i(*) = 0$ for $i > 0$.

What do these constructions do? Suppose you have $f : X \rightarrow Y$. You have a map $f_* : \text{Sin}_n(X) \rightarrow \text{Sin}_n(Y)$ induced by composition, namely $\sigma \mapsto f \circ \sigma =: f_*\sigma$. What about face maps; does the following diagram commute?

$$\begin{array}{ccc} \text{Sin}_n(X) & \xrightarrow{f_*} & \text{Sin}_n(Y) \\ \downarrow d_i & & \downarrow d_i \\ \text{Sin}_{n-1}(X) & \xrightarrow{f_*} & \text{Sin}_{n-1}(Y) \end{array}$$

We see that $d_i f_* \sigma = (f_* \sigma) \circ d^i = f \circ \sigma \circ d^i$, and $f_*(d_i \sigma) = f_*(\sigma \circ d^i) = f \circ \sigma \circ d^i$. So the answer is yes! This also holds for the free abelian groups. You therefore get a map of chain complexes.

A chain map $f : C_* \rightarrow D_*$ is a map $f_n : C_n \rightarrow D_n$ such that the following diagram commutes for every n :

$$\begin{array}{ccc} C_n & \xrightarrow{f_n} & D_n \\ \downarrow \text{partial}_C & & \downarrow \partial_D \\ C_{n-1} & \xrightarrow{f_{n-1}} & D_{n-1} \end{array}$$

Does a chain map induce a map in homology $f_* : H_n(C) \rightarrow H_n(D)$? As a preliminary question, do we get a map $Z_n(C) \rightarrow Z_n(D)$? Let $c \in Z_n(C)$, so that $\partial_C c = 0$. Then $\partial_D f_n(c) = f_{n-1} \partial_C c = f_{n-1}(0) = 0$, because f is a chain map. This means that $f_n(c)$ is also an n -cycle, i.e., f gives a map $Z_n(C) \rightarrow Z_n(D)$.

Do we also get a map $B_n(C) \rightarrow B_n(D)$? Let $c \in B_n(C)$, so that there exists $c' \in C_{n+1}$ such that $\partial_C c' = c$. Then $f_n(c) = f_n \partial_C c' = \partial_D f_{n+1}(c')$. Thus $f_n(c)$ is the boundary of $f_{n+1}(c')$, and f gives a map $B_n(C) \rightarrow B_n(D)$.

The two maps $Z_n(C) \rightarrow Z_n(D)$ and $B_n(C) \rightarrow B_n(D)$ give a map on homology. This means that we get a map $f_* : H_n(X) \rightarrow H_n(Y)$, as desired!

3. Categories, functors, natural transformations

Office hours. Hood Chatham's are Mondays, 1:30 - 3:30, in 2-390A. Miller's is Tuesdays, 3:00-5:00 in 2-478.

The collection of all topological spaces forms a category. Similarly with simplicial sets, denoted Set_Δ or $s\text{Set}$. You can take $X \mapsto \text{Sin}_\bullet(X)$, and if $X \rightarrow Y$ is a map of spaces, this induces $\text{Sin}_\bullet(X) \rightarrow \text{Sin}_\bullet(Y)$. This is a functor $\mathbf{Top} \rightarrow s\text{Set}$.

DEFINITION 3.1. A category \mathbf{C} is a class $\text{ob}(\mathbf{C})$ of objects, such that for every two objects, $\mathbf{C}(X, Y)$ is a set (thought of as a set of maps from X to Y); these are called morphisms. These satisfy the properties that for all $X \in \text{ob}(\mathbf{C})$, there exists an element $1_X \in \mathbf{C}(X, X)$ that acts as the identity, and for all $X, Y, Z \in \text{ob}(\mathbf{C})$, there is a composition $\mathbf{C}(X, Y) \times \mathbf{C}(Y, Z) \rightarrow \mathbf{C}(X, Z)$. These in turn satisfy the following properties:

- $1_Y \circ f = f$, and $f \circ 1_X = f$.
- Composition is associative.

EXAMPLE 3.2. The category of sets and functions between sets forms a category. The category of abelian groups and homomorphisms forms a category. Of course, topological spaces and continuous maps. A monoid, which is a category with one object. The simplex category (note that $|[n]| = n + 1$). A poset forms a category; but note that if $x \leq y$ and $y \leq x$, then $x \cong y$, not $x = y$. The latter property holds if the only isomorphisms are identities.

A small category is one such that $\text{ob}(\mathbf{C})$ is a set, not necessarily a class.

DEFINITION 3.3. Let \mathbf{C}, \mathbf{D} be categories. A functor $F : \mathbf{C} \rightarrow \mathbf{D}$ is a function $\text{ob}(\mathbf{C}) \rightarrow \text{ob}(\mathbf{D})$, such that for all $x, y \in \text{ob}(\mathbf{C})$, there is a map $\mathbf{C}(x, y) \rightarrow \mathbf{C}(F(x), F(y))$ that respects composition and the identity.

Let $F, G : \mathbf{C} \rightarrow \mathbf{D}$. A natural transformation $\theta : F \rightarrow G$ is a map $\theta(X) : F(X) \rightarrow G(X)$ for all $X \in \text{ob}(\mathbf{C})$, and a commuting diagram for all $f : X \rightarrow Y$:

$$\begin{array}{ccc} F(X) & \xrightarrow{\theta(X)} & G(X) \\ \downarrow F(f) & & \downarrow G(f) \\ F(Y) & \xrightarrow{\theta(Y)} & G(Y) \end{array}$$

EXAMPLE 3.4. The boundary map $\partial : S_n \rightarrow S_{n-1}$ is a natural transformation. Let G be a group viewed as a one-point category. Any element $F \in \text{Fun}(G, \mathbf{Ab})$ is simply a group action of G on $F(*) = A$, i.e., a representation of G in abelian groups. A natural transformation from $F \rightarrow F'$ is just a G -equivariant map.

4. More about categories, and computing the homology of a star-shaped region

Let $\text{Vect}_{\mathbf{C}}$ be the category of vector spaces and linear transformations. Given a \mathbf{C} -vector space V , you can consider the dual $V^* = \text{Hom}(V, \mathbf{C})$. Is this a functor? If you have a linear transformation $F : V \rightarrow W$, you get a map $F^* : W^* \rightarrow V^*$, so this is like a functor, but isn't strictly functor. This preserves composition and identities. Taking the dual therefore gives a functor $\text{Vect}_{\mathbf{C}}^{\text{op}} \rightarrow \text{Vect}_{\mathbf{C}}$, which is a *contravariant* functor.

DEFINITION 4.1. Given \mathbf{C}, \mathbf{D} . A contravariant functor is a functor from $\mathbf{C}^{\text{op}} \rightarrow \mathbf{D}$ where \mathbf{C}^{op} has the same objects as the category \mathbf{C} but with all morphisms reversed. There's a contravariant functor $\mathbf{C} \rightarrow \mathbf{C}^{\text{op}}$ that is the identity on objects and on morphisms.

Let \mathbf{C} be a category, and let $Y \in \text{ob}(\mathbf{C})$. We get a map $\mathbf{C}^{\text{op}} \rightarrow \text{Set}$ that takes $X \mapsto \mathbf{C}(X, Y)$, and takes a map $X \rightarrow W$ to the map defined by composition $\mathbf{C}(W, Y) \rightarrow \mathbf{C}(X, Y)$. This is called the functor that is represented by Y . It is very important to note that $\mathbf{C}(-, Y)$ is contravariant, but $\mathbf{C}(Y, -)$ is covariant.

Recall that Δ has objects $[0], [1], [2], \dots$ and a functor $\Delta \rightarrow \mathbf{Top}$ that sends $[n] \mapsto \Delta^n$. We get a map $\mathbf{Top}^{\text{op}} \rightarrow \text{Set}$ given by sending $X \mapsto \mathbf{Top}(\Delta^n, X) =: \text{Sin}_n(X)$. The composition gives you a contravariant functor $\Delta^{\text{op}} \rightarrow \text{Set}$, which sends $[n] \mapsto \mathbf{Top}(\Delta^n, X)$. This, along with the description of what happens to the face and degeneracy maps (see psets!) is precisely the singular simplicial set of X . In other words:

PROPOSITION 4.2 (Really a definition...). *Simplicial sets are precisely functors $\Delta^{\text{op}} \rightarrow \text{Set}$, i.e., $s\text{Set} = \mathbf{Fun}(\Delta^{\text{op}}, \text{Set})$. More generally, simplicial objects in a category \mathbf{C} are functors $\Delta^{\text{op}} \rightarrow \mathbf{C}$, i.e., $s\mathbf{C} = \mathbf{Fun}(\Delta^{\text{op}}, \mathbf{C})$.*

(Note that $\mathbf{Fun}(\mathbf{C}, \mathbf{D})$ is the category whose objects are functors and whose morphisms are natural transformations.) Semi-simplicial sets (only face maps, not necessarily degeneracy maps) in a category \mathbf{C} are simply $ss\mathbf{C} = \mathbf{Fun}(\Delta_{inj}^{\text{op}}, \mathbf{C})$ where Δ_{inj} consists of the objects of Δ where the morphisms only consist of the injective maps.

DEFINITION 4.3. Let $f : X \rightarrow Y$ be a morphism in a category \mathbf{C} . Say that f is a *split epimorphism* if there exists $g : Y \rightarrow X$ (often called a section or a splitting) such that $Y \xrightarrow{g} X \xrightarrow{f} Y$ is the identity.

EXAMPLE 4.4. Let $\mathbf{C} = \text{Set}$. If $f : X \rightarrow Y$ is a map of sets, then this says that for every element of Y , there exists some element of X whose image in Y is the original element. This means that f is surjective. Is every surjective map a split epimorphism? This reduces to the axiom of choice because proving that if $y \in Y$, the map $g : Y \rightarrow X$ can be constructed by choosing some $x \in f^{-1}(y)$.

DEFINITION 4.5. Say that $g : Y \rightarrow X$ is a split monomorphism if there is $f : X \rightarrow Y$ such that $f \circ g = 1_Y$.

EXAMPLE 4.6. Let $\mathbf{C} = \text{Set}$. Claim: it's an injection. If $y, y' \in Y$, and $g(y) = g(y')$, we want to show that $y = y'$. Apply f , to get $f(g(y)) = y = f(g(y')) = y'$. If $Y \neq \emptyset$, then every injection $g : Y \rightarrow X$ is a split mono.

EXAMPLE 4.7. An isomorphism is a split epi + split mono.

LEMMA 4.8. *If $f : X \rightarrow Y$ is a split epi or mono in \mathbf{C} , and you have a functor $F : \mathbf{C} \rightarrow \mathbf{D}$, then so is $F(f)$ in \mathbf{D} .*

PROOF. Trivial. \square

EXAMPLE 4.9. Suppose $\mathbf{C} = \mathbf{Ab}$, and you have a split epi $f : A \rightarrow B$. We have a map $g : B \rightarrow A$ so that $fg = 1$. Clearly f must be surjective. Consider the kernel of f , so we have a composition $\ker f \rightarrow A \rightarrow B$. We also have a map $B \rightarrow A$, so we can add, and get $\ker f \oplus B \xrightarrow{[i, g]} A$ where i is the inclusion $\ker f \rightarrow A$. Left for reader: $[i, g]$ is an isomorphism.

If $g : B \rightarrow A$ is a split mono, so there is $f : A \rightarrow B$ so that $fg = 1$. Clearly g is injective, and we get a map $B \rightarrow A \xrightarrow{p} \text{coker}(g)$. We therefore get a map $A \xrightarrow{\begin{pmatrix} p \\ f \end{pmatrix}} \text{coker}(g) \oplus B$. Left to reader again: this is an isomorphism.

We have to get into some topology, since it's on our agenda. Suppose I have a space X . There's always a unique map $X \rightarrow *$, which means categorically that $*$ is trivial. We have an induced map $H_n(X) \rightarrow H_n(*) = \begin{cases} \mathbf{Z} & n = 0 \\ 0 & \text{else} \end{cases}$. Consider the equivalence class (also called the *homology class* of the cycle $\sum a_i x_i$) $[\sum a_i x_i] \in H_0(X)$, where x_i is a point in X . Under the induced map, this goes as: $[\sum a_i x_i] \mapsto [\sum a_i *] = (\sum a_i) [*]$. This is called the augmentation map. This map is a split epi, because we can always choose a point of X and pull an element of \mathbf{Z} back. This motivates the following definition.

DEFINITION 4.10. A pointed space is a pair $(X, *)$, with $*$ $\in X$ called the *basepoint*.

We have an inclusion $* \rightarrow X \rightarrow *$, so we get an induced map $\mathbf{Z} \xrightarrow{\eta} H_*(X) \xrightarrow{\epsilon} \mathbf{Z}$, and the composition is the identity. The map ϵ is the augmentation map we described above. This means, by our above analysis, we see that $H_*(X) \cong \mathbf{Z} \oplus \text{coker } \eta \cong \mathbf{Z} \oplus \ker \epsilon$. The homology $H_*(X, *) = \text{coker } \eta$, and this is called the reduced homology of $(X, *)$. It's isomorphic to $H_*(X)$ in dimensions greater than 0, but differs by a factor of \mathbf{Z} in dimension 0.

We spent up a lot of time on categories, and didn't get to star-shaped regions. We'll pick this up on Friday, but we'll begin a little here.

DEFINITION 4.11. A star-shaped region is a subspace X of \mathbf{R}^n for some n such that $0 \in X$, such that for all $x \in X$, and for all $t \in [0, 1]$, $tx \in X$.

EXAMPLE 4.12. Any convex region containing the origin is star shaped.

THEOREM 4.13. The augmentation map $\epsilon : H_*(X) \rightarrow \mathbf{Z}$ is an isomorphism, i.e., $H_0(X) \cong \mathbf{Z}$ and $H_i(X) \cong 0$ for $i > 0$.

The strategy of proof is that ϵ is induced by sending $X \rightarrow *$. We'll look at the chain map $S_*(x) \rightarrow \mathbf{Z} \rightarrow S_*(X)$. We'll show that this composite induces the same map in homology as the identity map, which means that the identity map factors through \mathbf{Z} , so we're done.

5. Homotopy, star-shaped regions

The idea of homotopy is the central concept of all of algebraic topology, to put it bluntly. We have a functor $H_* : \mathbf{Top} \rightarrow \mathbf{Ab}$, but it's too crude to distinguish between topological spaces. The virtue of this definition is that it's computable, although it can't completely distinguish between two spaces.

DEFINITION 5.1. Let $f_0, f_1 : X \rightarrow Y$ be two maps. A homotopy from f_0 to f_1 is a map $h : X \times I \rightarrow Y$ such that $h(x, 0) = f_0(x)$ and $h(x, 1) = f_1(x)$. We say that f_0 and f_1 are homotopic, and this is written $f_0 \sim f_1$ because this is an equivalence relation on maps (transitivity follows from the gluing lemma).

We denote by $[X, Y]$ the set $\mathbf{Top}(X, Y) / \sim$. On Monday, we'll prove the following result.

THEOREM 5.2. If $f_0 \sim f_1$, then $H_*(f_0) = H_*(f_1)$. In other words, homology cannot distinguish between homotopic things.

Suppose I have two maps $f_0, f_1 : X \rightarrow Y$ and a map $g : Y \rightarrow Z$, with a homotopy $h : f_0 \sim f_1$. Composing h with g gives a homotopy between $g \circ f_0$ and $g \circ f_1$. Precomposing also works. Namely, if $g : W \rightarrow X$ is a

map and $f_0, f_1 : X \rightarrow Y$ are homotopic, then $f_0 g \sim f_1 g$. Does this let us compose homotopy classes? That is, can we complete:

$$\begin{array}{ccc} \mathbf{Top}(Y, Z) \times \mathbf{Top}(X, Y) & \longrightarrow & \mathbf{Top}(X, Z) \\ \downarrow & & \downarrow \\ [Y, Z] \times [X, Y] & \dashrightarrow & [X, Z] \end{array}$$

The answer is yes. If $g_0 \sim g_1 : Y \rightarrow Z$ and $f_0 \sim f_1 : X \rightarrow Y$, then $g_0 f_0 \sim g_0 f_1$, but this is just homotopic to $g_1 f_1$. This therefore gives us a new category, called the homotopy category.

DEFINITION 5.3. The homotopy category of topological spaces is $\mathrm{Ho}(\mathbf{Top})$ whose objects are topological spaces and $\mathrm{Ho}(\mathbf{Top})(X, Y) = [X, Y] = \mathbf{Top}(X, Y) / \sim$.

This is an interesting category because it has *terrible* categorical properties. The theorem that we'll prove on Monday says that the homology functor $H_* : \mathbf{Top} \rightarrow \mathbf{Ab}$ factors as $\mathbf{Top} \rightarrow \mathrm{Ho}(\mathbf{Top}) \rightarrow \mathbf{Ab}$.

DEFINITION 5.4. A map $f : X \rightarrow Y$ is a homotopy equivalence if $[f] \in [X, Y]$ is an isomorphism in $\mathrm{Ho}(\mathbf{Top})$. In other words, there is $g : Y \rightarrow X$ such that $fg \sim 1_Y$ and $gf \sim 1_X$.

EXAMPLE 5.5. Homotopy equivalence doesn't preserve compactness. For example, the inclusion $S^{n-1} \subseteq \mathbf{R}^n - \{0\}$. The homotopy inverse $p : \mathbf{R}^n - \{0\} \rightarrow S^{n-1}$ can be obtained by dividing a (always nonzero!) vector by its length. Clearly $p \circ i = 1_{S^{n-1}}$. We have to find a homotopy $i \circ p \sim 1_{\mathbf{R}^n - \{0\}}$. Namely, we want a map $(\mathbf{R}^n - \{0\}) \times I \rightarrow \mathbf{R}^n - \{0\}$; but this is straightforward, namely, take $(v, t) \mapsto tv + (1-t)\frac{v}{\|v\|}$.

Let's set up the stuff about star-shaped region. The first thing to realize is that the inclusion $\{0\} \rightarrow X$, where X is a star-shaped region, is a homotopy equivalence, precisely like the above example!

DEFINITION 5.6. A space X is contractible if the map $X \rightarrow *$ is a homotopy equivalence.

In other words, the star-shaped region is contractible. The claim is the following.

PROPOSITION 5.7. $H_*(X) \cong \mathbf{Z}$ where X is a star-shaped region.

We want to set up a homotopy in the category of chain complexes.

DEFINITION 5.8. Let C_\bullet, D_\bullet be chain complexes, and $f_0, f_1 : C_\bullet \rightarrow D_\bullet$ be chain maps. A chain homotopy $h : f_0 \sim f_1$ is a collection of homomorphisms $h : C_n \rightarrow D_{n+1}$ such that $\partial h + h\partial = f_1 - f_0$.

It's a really weird relation, but we'll understand why this is a good thing.

$$\begin{array}{ccc} C_{n+2} & \xrightarrow{f_1 - f_0} & D_{n+2} \\ \downarrow \partial & \nearrow h & \downarrow \partial \\ C_{n+1} & \xrightarrow{f_1 - f_0} & D_{n+1} \\ \downarrow \partial & \nearrow h & \downarrow \partial \\ C_n & \xrightarrow{f_1 - f_0} & D_n \end{array}$$

LEMMA 5.9. If $f_0, f_1 : C_\bullet \rightarrow D_\bullet$ are chain homotopic, then $f_{0,*} = f_{1,*} : H(C) \rightarrow H(D)$.

PROOF. This is the same thing as saying that $(f_1 - f_0)_* = 0$. Let $c \in Z_n(C_\bullet)(C)$, so that $\partial c = 0$. Well, $(f_1 - f_0)_* c = (\partial h + h\partial)c = \partial hc + h\partial c = \partial hc$, so it's a boundary. Therefore, $f_{1,*}$ and $f_{0,*}$ have the same homology class (because when you take homology classes, you work modulo boundaries), which means we're done. \square

PROOF. We have the map $S_*(X) \xrightarrow{\epsilon} \mathbf{Z} \xrightarrow{\eta} S_*(X)$ where the latter map sends 1 to the constant map at the origin. The claim is that $\eta\epsilon \sim 1 : S_*(X) \rightarrow S_*(X)$. Let's just mention that $\eta\epsilon(\sum a_i x_i) = (\sum a_i) c_0$ where

c_0 is the zero-simplex that is constant at the origin. We want a homotopy $h : S_q(X) \rightarrow S_{q+1}(X)$, but it suffices to construct $\text{Sin}_q(X) \rightarrow \text{Sin}_{q+1}(X)$. For $\sigma \in \text{Sin}_q(X)$, define $h : \text{Sin}_q(X) \rightarrow \text{Sin}_{q+1}(X)$ as follows:

$$h\sigma(t_0, \dots, t_{q+1}) = (1 - t_0)\sigma\left(\frac{(t_0, \dots, t_{q+1})}{1 - t_0}\right)$$

I give up livetexting the proof; just read Hatcher. □

6. Homotopy invariance of homology

As a side product, we'll construct something called the cross product. Here's the theorem.

THEOREM 6.1. *If $f_0, f_1 : X \rightarrow Y$ and $f_0 \sim f_1$, then $f_{0,*} \sim f_{1,*} : S_*(X) \rightarrow S_*(Y)$.*

COROLLARY 6.2. *With the same hypotheses, then $f_{0,*} = f_{1,*} : H_*(X) \rightarrow H_*(Y)$, because chain homotopic maps induce the same map on homology.*

The proof uses naturality (a lot). We'll produce a chain homotopy from the two inclusions $i_0, i_1 : X \rightarrow X \times I$, and then homotope f_0, f_1 through a map $X \times I \rightarrow Y$. Namely, we'll construct a chain homotopy $h_X : S_n(X) \rightarrow S_{n+1}(X \times I)$ which gives a homotopy $i_{0,*} \sim i_{1,*}$, and this'll be natural in X .

This gives the result we want. We can get a homotopy $h := g \circ h_* : S_n(X) \rightarrow S_{n+1}(X \times I) \rightarrow S_{n+1}(Y)$. Well:

$$\begin{aligned} \partial h + h\partial &= \partial(g_*h_*) + g_*h_*\partial = g_*\partial h_* + g_*h_*\partial = g_*(\partial h_* + h_*\partial) \\ &= g_*(i_{1,*} - i_{0,*}) = g_*i_{1,*} - g_*i_{0,*} = (g \circ i_1)_* - (g \circ i_0)_* = f_{1,*} - f_{0,*} \end{aligned}$$

(The last equality is because h_* is a chain homotopy between $i_{1,*}$ and $i_{0,*}$.) So $h = g_* \circ h_*$ is a chain homotopy. But how do we define $h_* : S_n(X) \rightarrow S_{n+1}(X \times I)$? You want to take $\sigma \mapsto \sigma \times I^n$. More generally, we'll set up a cross product $\times : S_p(X) \times S_q(Y) \rightarrow S_{p+q}(X \times Y)$ that is natural, bilinear, satisfy the Leibniz rule, and are normalized.

Naturality is exactly what you'd expect it to be. If A, B, C are abelian groups, then $A \times B \rightarrow C$ is a bilinear map if $f(a + a', b) = f(a, b) + f(a', b)$ and similarly in the other variable (just substitute the $S_n(X)$ etc here). The Leibniz formula says:

$$\partial(a \times b) = (\partial a) \times b + (-1)^{|a|} a \times \partial b, \quad \text{where } |a| = p \text{ means that } a \in S_p(X).$$

The word normalized means that the following construction is correct. Suppose $q = 0$; then this is a map $S_p(X) \rightarrow S_0(Y) \rightarrow S_p(X \times Y)$, which (it suffices to define a map $\text{Sin}_p(X) \times \text{Sin}_0(Y) \rightarrow S_p(X \times Y)$ because $(\sum_i a_i \sigma_i, \sum_j b_j \tau_j) \mapsto \sum_{i,j} a_i b_j (\sigma_i \times \tau_j)$ by bilinearity) sending:

$$(\sigma, c_y^0) \mapsto \left(\begin{pmatrix} \sigma \\ c_y^p \end{pmatrix} : \Delta^p \rightarrow X \times Y \right)$$

This latter map is just the composition $\Delta^p \xrightarrow{\sigma} X \xrightarrow{\text{inclusion at } y \in Y} X \times Y$. When $p = 0$, we can send:

$$(c_x^0, \tau) \mapsto \left(\begin{pmatrix} c_x^p \\ \tau \end{pmatrix} : \Delta^p \rightarrow X \times Y \right)$$

This latter map is just the composition $\Delta^p \xrightarrow{\tau} Y \xrightarrow{\text{inclusion at } x \in X} X \times Y$. We have to check that this behaves correctly for the boundary map, namely, that Leibniz holds. We have:

$$\partial(\sigma \times c_y^0) = \partial\sigma \times c_y^0$$

and similarly. We're going to use induction to define this for $p+q$; we've only done this for $p+q = 0, 1$. Let's assume it's done for $p+q-1$. First note that there's a universal example of a p -simplex, namely the map $\iota_p : \Delta^p \rightarrow \Delta^p$, because given any p -simplex $\sigma : \Delta^p \rightarrow X$, you get $\sigma = \sigma_*(\iota_p)$ where $\sigma_* : \text{Sin}_p(\Delta^p) \rightarrow \text{Sin}_p(X)$. It suffices to define $\iota_p \times \iota_q \in S_{p+q}(\Delta^p \times \Delta^q)$; you're supposed to think of the product of two simplices as a prism, which isn't a simplex itself - but you can triangulate it and look at it as the formal sum of two simplices. Then $\sigma \times \tau = (\sigma \times \tau)_*(\iota_p \times \iota_q)$ where $(\sigma \times \tau)_* : S_{p+q}(\Delta^p \times \Delta^q) \rightarrow S_{p+q}(X \times Y)$. We need this to satisfy the Leibniz rule, so that:

$$S_{p+q-1}(\Delta^p \times \Delta^q) \ni \partial(\iota_p \times \iota_q) = (\partial\iota_p) \times \iota_q + (-1)^p \iota_p \times \partial\iota_q$$

A necessary condition for $\iota_p \times \iota_q$ to exist is that $\partial((\partial\iota_p) \times \iota_q + (-1)^p \iota_p \times \partial\iota_q) = 0$. Let's compute what this is.

$$\partial((\partial\iota_p) \times \iota_q + (-1)^p \iota_p \times \partial\iota_q) = \partial^2(\iota_p) \times \iota_q + (-1)^{p-1}(\partial\iota_p) \times (\partial\iota_q) + (-1)^p(\partial\iota_p) \times (\partial\iota_q) + (-1)^q \iota_p \times \partial^2\iota_q = 0$$

because $\partial^2 = 0$.

The subspace $\Delta^p \times \Delta^q \subseteq \mathbf{R}^{p+1} \times \mathbf{R}^{q+1}$ is convex, so by translation, it's homeomorphic to a star-shaped region. But we know that $H_{p+q-1}(\Delta^p \times \Delta^q) = 0$ because $p + q > 1$, which means that every cycle is a boundary. In other words, what we checked above is also sufficient! So, choose any element $\iota_p \times \iota_q$ with the right boundary. This means we're done if we check that this choice satisfies naturality, bilinearity, and the Leibniz rule (left to reader). We'll now define $h_X : S_n(X) \rightarrow S_{n+1}(X \times I)$ via $h_X c = c \times \iota$ where $\iota : \Delta^1 \rightarrow I$ is the obvious map. The cross product is in $S_{p+1}(X \times I)$. Let's compute:

$$\partial h_X = \partial(c \times \iota) = \partial c \times \iota + (-1)^{|c|} c \times \partial \iota$$

But now, $\partial \iota = c_1^0 - c_0^0 \in S_0(I)$, which means that this becomes $\partial c \times \iota + (-1)^{|c|}(\iota_{1,*} - \iota_{0,*})$. We'll do a little more next time.

7. Basically a recap of what we did last time

PSet 1 due today. Last time, we showed:

THEOREM 7.1. *There exists a map $S_p(X) \times S_q(Y) \rightarrow S_{p+q}(X \times Y)$ that is:*

- *Natural, in the sense that if $f : X \rightarrow X'$ and $g : Y \rightarrow Y'$, and $a \in S_p(X)$ and $b \in S_p(Y)$ so that $a \times b \in S_{p+q}(X \times Y)$, then $f_*(a) \times g_*(b) = (f \times g)_*(a \times b)$.*
- *Bilinear, in the sense that $(a + a') \times b = (a \times b) + (a' \times b)$, and $a \times (b + b') = a \times b + a \times b'$.*
- *The Leibniz rule is satisfied, i.e., $\partial(a \times b) = (\partial a) \times b + (-1)^{|a|} a \times \partial b$.*
- *Normalized, in the following sense. Let $x \in X$ and $y \in Y$. Write $i_x : Y \rightarrow X \times Y$ sending $y \mapsto (x, y)$, and write $i_y : X \rightarrow X \times Y$ sending $x \mapsto (x, y)$. If $b \in S_q(Y)$, then $c_x^0 \times b = (i_x)_* b \in S_q(X \times Y)$, and if $a \in S_p(X)$, then $a \times c_y^0 = (i_y)_* a \in S_p(X \times Y)$.*

We were a little hasty in the end, so we're going to recall some things.

PROOF SKETCH. There were two steps.

- (1) It's enough to define $\iota_p \times \iota_q \in S_{p+q}(\Delta^p \times \Delta^q)$ where $\iota_n : \Delta^n \rightarrow \Delta^n$ is the identity, because every other simplex is ι_n pushed forward, and the cross product is supposed to be natural.
- (2) Induction on $p + q$. The first thing we use is the Leibniz rule, namely $\partial(\iota_p \times \iota_q) = (\partial\iota_p) \times \iota_q + (-1)^p \iota_p \times \partial\iota_q$. Is this a boundary? A necessary thing for anything to be a boundary is that it's a cycle. But because $\Delta^p \times \Delta^q$ is homeomorphic to a star-shaped region, it's contractible - therefore $H_{p+q-1}(\Delta^p \times \Delta^q) = 0$, a *sufficient* condition for something to be a boundary is that it's a cycle! We showed that $\partial(\iota_p \times \iota_q)$ is a cycle, and therefore a boundary. We just need to choose *some* class $[a]$ in $S_{p+q}(\Delta^p \times \Delta^q)$ such that $\partial([a]) = (\partial\iota_p) \times \iota_q + (-1)^p \iota_p \times \partial\iota_q$, and this works.
 - (a) Naturality is left to the reader.
 - (b) Let's check the Leibniz rule. Let $\sigma : \Delta^p \rightarrow X$ and $\tau : \Delta^q \rightarrow Y$. What's $\partial(\sigma \times \tau)$? We start by asking how we define $\sigma \times \tau$. Well, this is just $\sigma_* \iota_p \times \tau_* \iota_q$. Because of naturality, this is just $(\sigma \times \tau)_*(\iota_p \times \iota_q)$. This means that $\partial(\sigma \times \tau) = \partial((\sigma \times \tau)_*(\iota_p \times \iota_q))$. Now, we can use the naturality of the boundary map to see that this is just $(\sigma \times \tau)_* \partial(\iota_p \times \iota_q)$, which we can expand as:

$$\begin{aligned} (\sigma \times \tau)_* \partial(\iota_p \times \iota_q) &= (\sigma \times \tau)_*((\partial\iota_p) \times \iota_q + (-1)^p \iota_p \times \partial\iota_q) \\ &= \sigma_*(\partial\iota_p) \times \tau_* \iota_q + (-1)^p (\sigma_* \iota_p \times \tau_*(\partial\iota_q)) \\ &= \partial(\sigma_* \iota_p) \times \tau_* \iota_q + (-1)^p (\sigma_* \iota_p \times \partial(\tau_* \iota_q)) \\ &= \partial\sigma \times \tau + (-1)^p \sigma \times \partial\tau \end{aligned}$$

□

A key fact in this whole thing is that $H_{p+q-1}(\Delta^p \times \Delta^q) = 0$. This method of proof, namely of reducing to things that have zero homology (aka acyclic spaces) is called the *method of acyclic models*.

What happens on the level of homology? Let's abstract a little bit. Suppose we have three chain complexes A_\bullet , B_\bullet , and C_\bullet , to be thought of as $S_*(X)$, $S_*(Y)$, and $S_*(X \times Y)$. Suppose we have maps $\times : A_p \times B_q \rightarrow C_{p+q}$ that satisfies bilinearity and the Leibniz formula. What does this induce in homology?

LEMMA 7.2. *This determines a bilinear map $H_p(A) \times H_q(B) \xrightarrow{\times} H_{p+q}(C)$.*

PROOF. Let $[a] \in H_p(A)$ where $a \in Z_p(A)$ such that $\partial a = 0$ (i.e., a is a cycle). Let $[b] \in H_q(B)$ where $b \in Z_q(B)$ such that $\partial b = 0$. We want to define $[a] \times [b] \in H_{p+q}(C)$. We hope that $[a] \times [b] = [a \times b]$. We need to check that $a \times b$ is a cycle; let's check. By Leibniz, $\partial(a \times b) = \partial a \times b + (-1)^p a \times \partial b$. Because a, b are boundaries, this is zero. We still need to check that this thing is well-defined. Let's pick another $[a'] = [a]$ and $[b'] = [b]$. We want $[a \times b] = [a' \times b']$. In other words, we need that $a \times b$ differs from $a' \times b'$ by a boundary. We can write $a' = a + \partial \bar{a}$ and $b' = b + \partial \bar{b}$. What's $a' \times b'$? It's:

$$a' \times b' = (a + \partial \bar{a}) \times (b + \partial \bar{b}) = a \times b + (a \times \partial \bar{b} + (\partial \bar{a}) \times b + (\partial \bar{a}) \times (\partial \bar{b}))$$

But, well, $\partial(a \times \bar{b}) = \partial a \times \bar{b} + (-1)^p a \times \partial \bar{b} = (-1)^p a \times \partial \bar{b}$, and $\partial(\bar{a} \times b) = \partial \bar{a} \times b$, and $\partial(\bar{a} \times \partial \bar{b}) = \partial \bar{a} \times \partial \bar{b}$. This means that $a' \times b' = a \times b + \partial((-1)^{-p}(a \times \bar{b}) + \bar{a} \times b + \bar{a} \times \partial \bar{b})$. They differ by a boundary, so it's well-defined.

The last step is to check bilinearity, which is left to the reader. \square

This gives the following result.

THEOREM 7.3. *There is a map $H_p(X) \times H_q(Y) \rightarrow H_{p+q}(X \times Y)$ that's natural, bilinear, and normalized. This map is also unique (unlike the map $S_p(X) \times S_q(Y) \rightarrow S_{p+q}(X \times Y)$, which isn't unique because we there are uncountably many choices of $\iota_p \times \iota_q$, all differing by a boundary), because the map $\times : S_p(X) \times S_q(Y) \rightarrow S_{p+q}(X \times Y)$ is unique up to chain homotopy!*

Let's go back to homotopy invariance. Recall that if $f_0 \sim f_1 : X \rightarrow Y$, then $f_{0,*} = f_{1,*} : S_*(X) \rightarrow S_*(Y)$. We proved this by showing that this reduces to showing that the two inclusions $i_0, i_1 : X \rightarrow X \times I$ induce the same map on $S_*(X) \rightarrow S_*(X \times I)$. The chain homotopy $h_X : i_{0,*} \sim i_{1,*}$ is defined as follows. Let $c \in S_p(X)$. We need to give an element of $S_{p+1}(X \times I)$, so if $\iota : \Delta^1 \rightarrow I$ is the obvious map, we just define $h_X(c) = (-1)^p c \times \iota$. Let's check that.

Let's compute $\partial h_X c$. This is $\partial((-1)^p c \times \iota) = (-1)^p \partial(c \times \iota)$, which, expanded out, is:

$$\partial((-1)^p c \times \iota) = (-1)^p \partial(c \times \iota) = (-1)^p (\partial c) \times \iota + (-1)^{2p} c \times \partial \iota$$

Well, $\partial \iota = c_1^0 - c_0^0 \in S_0(I)$, so this is equal to $(-1)^p (\partial c) \times \iota + c \times c_1^0 - c \times c_0^0$. But $c \times c_1^0 = (i_1)_* c - (i_0)_* c$. Therefore, this is $(-1)^p (\partial c) \times \iota + (i_1)_* c - (i_0)_* c$. On the other hand, what's $h_X \partial c = (-1)^{p-1} (\partial c) \times \iota$. Let's add them together:

$$\partial h_X c + h_X \partial c = (-1)^p (\partial c) \times \iota + (i_1)_* c - (i_0)_* c + (-1)^{p-1} (\partial c) \times \iota = (i_1)_* c - (i_0)_* c$$

So this is, by definition, a chain homotopy!

I just want to mention that there's an explicit choice of $\iota_p \times \iota_q$. This is called the Eilenberg-Zilber chain. You're highly encouraged to think about this yourself. We're going to consider $\Delta^{p+q} \rightarrow \Delta^p \times \Delta^q$. They're all affine maps, sending vertices to pairs of vertices. We're going to think of an ordered map $\omega : [p+q] \rightarrow [p] \times [q]$. We can complete the diagram to get:

$$\begin{array}{ccc} & & [p] \\ & \nearrow pr_2 \omega & \uparrow pr_2 \\ [p+q] & \xrightarrow{\omega} & [p] \times [q] \\ & \searrow pr_1 \omega & \downarrow pr_1 \\ & & [q] \end{array}$$

We also want ω to be injective (which requires that it takes $(0,0)$ to (p,q)). We can draw out a "staircase" in the $p \times q$ grid, and the area under the staircase defined by ω is denote $A(\omega)$. Define $\iota_p \times \iota_q = \sum (-1)^{A(\omega)} \bar{\omega}$

where $\bar{\omega}$ is the corresponding affine map $\Delta p + q \rightarrow \Delta^p \times \Delta^q$. It's combinatorially annoying to check that this satisfies the conditions of the theorem, but it's a good exercise to check it out. It's in a paper by Eilenberg-Moore.

8. Relative Homology

First, let's recall a little about homology. We showed that homology factors as a functor $\mathbf{Top} \rightarrow \mathbf{hTop} \rightarrow \mathbf{GrAb}$. As a corollary:

COROLLARY 8.1. *If $f : X \rightarrow Y$ is a homotopy equivalence (i.e., an isomorphism in the homotopy category), the induced map on homology $H_*(f) : H_*(X) \rightarrow H_*(Y)$ is an isomorphism. This is the same thing as saying that if $f : X \rightarrow Y$ does not induce an isomorphism on homology, then f can't be a homotopy equivalence. Homology's therefore often used to distinguish spaces.*

EXAMPLE 8.2. If $X \times \mathbf{R}^n \rightarrow X$ is the projection map, this is a homotopy equivalence because \mathbf{R}^n is contractible. Therefore, $H_*(X \times \mathbf{R}^n) \cong H_*(X)$.

8.1. Towards computing homology. Fix a space W , and consider the functor $X \mapsto [W, X]$. This is basically uncomputable - if you could, you'll win a Fields medal! But there's something more that homology has going for it is that it's "local". What do we mean by this? Homology is a bit like a measure:

- (1) If $A \subseteq X$ is a subspace, then $H_*(X)$ is related to $H_*(A) + H_*(X - A)$. Called the lexseq of a pair.
- (2) The homology $H_*(A \cup B)$ is like $H_*(A) + H_*(B) - H_*(A \cap B)$. Called the Mayer-Vietoris sequence.

The thing we use is the notion of exact sequences. Let me tell you about exact sequences.

8.2. Exact sequences. This is a story about abelian groups.

DEFINITION 8.3. Let $A \xrightarrow{i} B \xrightarrow{p} C$ be a sequence of abelian groups and homomorphisms. We say that the sequence is exact (at B) if $\ker p = \text{Im } i$, i.e., $p \circ i = 0$ with no room for error.

EXAMPLE 8.4. If you have a chain complex $\cdots \rightarrow C_{n+1} \rightarrow C_n \rightarrow C_{n-1} \rightarrow \cdots$, it's exact at C_n if the homology $H_n(C)$ in dimension n is zero. So homology is the obstruction to exactness.

EXAMPLE 8.5. $0 \rightarrow A \xrightarrow{i} B$ is exact iff i is injective, and $B \xrightarrow{p} C \rightarrow 0$ is exact iff p is surjective.

There's a beautiful book by Eilenberg and Steenrod, published in 1952, which was the founding of algebraic topology.

EXAMPLE 8.6. If you have a sequence that's exact at every point, it's called a long exact sequence (henceforth called lexseq in these notes). If you have a sequence like $0 \rightarrow A \xrightarrow{i} B \xrightarrow{p} C \rightarrow 0$ that's exact, then this is called a short exact sequence (henceforth called sexseq in these notes). This means that $p \circ i = 0$, i is injective, p is surjective. Also, this sequence factors like:

$$\begin{array}{ccccc}
 & \ker(p) & & & \\
 & \uparrow & \searrow & & \\
 A & \xrightarrow{i} & B & \xrightarrow{p} & C \\
 & & \searrow & \uparrow & \\
 & & & \text{coker}(i) &
 \end{array}$$

So $A \cong \ker p$ and $B \cong \text{coker}(i)$. These things are equivalence to short exactness.

Let's see how this appears in algebraic topology.

DEFINITION 8.7. A pair of spaces is a space X together with subspaces $A \subseteq X$, denoted (X, A) . We have a new category, called \mathbf{Top}_2 where morphisms $(X, A) \rightarrow (Y, B)$ are maps $f : X \rightarrow Y$ that take $A \rightarrow B$. There are two functors $\mathbf{Top} \rightarrow \mathbf{Top}_2$, sending $X \mapsto (X, \emptyset)$ and $X \mapsto (X, X)$. There are also two functors back to \mathbf{Top} , sending $(X, A) \mapsto A$ or $(X, A) \mapsto X$.

How does this behave on the level of chain complexes? If I have a pair (X, A) , I get a map $\text{Sin}_n(A) \rightarrow \text{Sin}_n(X)$ that's clearly injective. Is this a split monomorphism? Yes, unless $A = \emptyset$, because you can choose a point in A and send everything not in A to that point. Let's now apply the free abelian group functor to get $S_n(A) \rightarrow S_n(X)$. Is this a monomorphism? Yes, because monomorphisms are preserved by this functor. This is also split because being a split mono is a categorical property. This is split even when $A = \emptyset$ because then $S_n(\emptyset) = 0$.

DEFINITION 8.8. The relative n -chains is defined as $S_n(X, A) := S_n(X)/S_n(A)$. So we have a sexseq (ses) $0 \rightarrow S_n(A) \rightarrow S_n(X) \rightarrow S_n(X, A) \rightarrow 0$. Is $S_n(X, A)$ free abelian if $S_n(X)$ and $S_n(A)$ are? If you have a ses $0 \rightarrow A \rightarrow B \rightarrow C \rightarrow 0$ such that $A \rightarrow B$ is split, then it's homework to show that $B \cong A \oplus C$. So C must also be free abelian if B and A are; i.e., $S_n(X, A)$ is free abelian.

EXAMPLE 8.9. Consider Δ^n , which contains its boundary $\partial\Delta^n := \bigcup \text{Im } d_i \simeq S^{n-1}$. We have the identity map $\iota_n : \Delta^n \rightarrow \Delta^n$, the universal n -simplex, which is in $\text{Sin}_n(\Delta^n) \subseteq S_n(\Delta^n)$. Its boundary $\partial\iota_n \in S_{n-1}(\Delta^n)$, but it actually lands in $S_{n-1}(\partial\Delta^n)$. So $\partial\iota_n$ is *not* a boundary in $\partial\Delta^n$, as we'll see, but it certainly is a cycle. So it determines a homology class, $[\partial\iota_n]$, which, it turns out, generates $H_{n-1}(\partial\Delta^n) \simeq H_{n-1}(S^{n-1}) \cong \mathbf{Z}$.

I can think of $\iota_n \in S_n(\Delta^n, \partial\Delta^n)$, or rather the class of it mod $S_n(\partial\Delta^n)$. It's a relative chain. Is it a cycle? Let's branch off a bit.

Consider the ses $0 \rightarrow S_n(A) \rightarrow S_n(X) \rightarrow S_n(X, A) \rightarrow 0$. A $c \in S_n(X)$ determines a relative cycle if $\partial c \in S_{n-1}(A)$. I'm sorry, I've messed this up a little bit. There's so much to say here. I'm getting ahead of myself a little bit here. What I meant to say is, let's think of what ∂ does. We have a map of ses:

$$\begin{array}{ccccccccc} 0 & \longrightarrow & S_n(A) & \longrightarrow & S_n(X) & \longrightarrow & S_n(X, A) & \longrightarrow & 0 \\ & & \downarrow & & \downarrow & & \downarrow & & \\ 0 & \longrightarrow & S_{n-1}(A) & \longrightarrow & S_{n-1}(X) & \longrightarrow & S_{n-1}(X, A) & \longrightarrow & 0 \end{array}$$

Does the dotted map exist? We can pull $\bar{c} \in S_n(X, A)$ to some $c \in S_n(X)$, and then define $\partial\bar{c}$ to be the pushforward of ∂c . Is this well-defined? If c, c' both map to \bar{c} , then $c - c' = 0$, so there's some a in $S_n(A)$ that is sent to $c - c'$, and ∂ pushes this forward to say that ∂a maps to $\partial(c - c') = \partial c - \partial c'$. Since we're quotienting out by $S_{n-1}(A)$, this means that the pushforwards of ∂c and $\partial c'$ are the same. I'll leave it to you (although Professor Miller explained this in detail) to show that $\partial^2 = 0$.

Now let's continue. A class $c \in S_n(X)$ gives a relative cycle if and only if $\partial c \in S_{n-1}(A)$ because we want ∂c in $S_n(X, A)$ to be zero. So $\iota_n \in S_n(\Delta^n, \partial\Delta^n)$ is indeed a relative cycle since $\partial\iota_n \in S_{n-1}(\partial\Delta^n)$. Similarly, a class $c \in S_n(X)$ is a relative boundary if and only if there is a $b \in S_{n+1}(X)$ such that $\partial b = c \bmod S_n(A)$, i.e., $\partial b - c \in S_n(A)$. So $\iota_n \in S_n(\Delta^n, \partial\Delta^n)$ isn't a relative boundary. Therefore $H_n(\Delta^n, \partial\Delta^n) \cong \mathbf{Z} = \langle [\iota_n] \rangle$ where $H_n(X, A)$ denotes the relative homology. This stuff takes a little bit of time to get used to.

9. Long exact homology sequence, Excision, and Genealogy

WARNING: I've probably messed up typing some indices. Hopefully not.

9.1. **5-lemma.** Suppose you have two exact sequences of abelian groups.

$$\begin{array}{ccccccccc} A_4 & \xrightarrow{d} & A_3 & \xrightarrow{d} & A_2 & \xrightarrow{d} & A_1 & \xrightarrow{r} & A_0 \\ \downarrow f_4 & & \downarrow f_3 & & \downarrow f_2 & & \downarrow f_1 & & \downarrow f_0 \\ B_4 & \xrightarrow{d} & B_3 & \xrightarrow{d} & B_2 & \xrightarrow{d} & B_1 & \xrightarrow{r} & B_0 \end{array}$$

When can we guarantee that f_2 is an isomorphism? We're going to diagram chase :-(. Just follow your nose.

Let $b_2 \in B_2$. We want to show that there is something in A_2 that can be pushed forward to b_2 , i.e., prove surjectivity of f_2 . We can consider $db_2 \in B_1$. Let's assume that f_1 is surjective. Then there's $a_1 \in A_1$ such that $f_1(a_1) = db_2$. What is da_1 ? Well, $f_0(da_1) = d(f_1(a_1)) = d(db_2) = 0$. So we want f_0 to be injective. Then da_1 is zero, so by exactness of the top sequence, there is some $a_2 \in A_2$ such that $da_2 = a_1$. What is $f_2(a_2)$? What is $d(f_2(a_2))$? By commutativity, $d(f_2(a_2)) = f_1(d(a_2)) = f_1(a_1) = db_2$. Let's consider $b_2 - f_2(a_2)$. This maps to zero under d . So by exactness, there is $b_3 \in B_3$ such that $d(b_3) = b_2 - f_2(a_2)$.

If we assume that f_3 is surjective, then there is $a_3 \in A_3$ such that $f_3(a_3) = b_3$. But now, $d(a_3) \in A_2$, and $f_2(d(a_3)) = d(f_3(a_3)) = b_2 - f_2(a_2)$. But this means that $b_2 = f_2(a_2 + d(a_3))$, which guarantees surjectivity of f_2 . This means that if f_1 is surjective, f_0 is injective, and f_3 is surjective, then f_2 is surjective.

A similar dual process says that f_2 is injective if f_1 is injective, f_3 is injective, and f_4 is surjective. If all of these conditions are satisfied, then f_2 is an isomorphism. This is the content of the five-lemma.

9.2. Relative homology. I guess I didn't really define this. Suppose you have a pair of spaces (X, A) . Then you have an sexseq of chain complexes $0 \rightarrow S_*(A) \rightarrow S_*(X) \rightarrow S_*(X, A) \rightarrow 0$.

DEFINITION 9.1. The relative homology of the pair $H_*(X, A) := H(S_*(X, A))$.

EXAMPLE 9.2. $H_*(X, \emptyset) = H_*(X)$ because $S_*(\emptyset) = 0$. Another case is $H_*(X, X) = 0$ because $S_*(X, X) = S_*(X)/S_*(X) = 0$.

9.3. General study of homologies of sexseqs of chain complexes. Suppose I have three chain complexes $A_\bullet \rightarrow B_\bullet \rightarrow C_\bullet$. By the way, this is an important announcement. Henceforth, differentials in chain complexes will be denoted d , no longer ∂ . For some reason. (It's so much easier for typing as well.) Assume that this is an exact sequence of chain complexes.

Is $H_*(A) \rightarrow H_*(B) \rightarrow H_*(C)$ exact? Let's push this a little further. Suppose I have a sexseq $0 \rightarrow A_\bullet \rightarrow B_\bullet \rightarrow C_\bullet \rightarrow 0$. We can ask the same question as before. Let's write this out more explicitly.

$$\begin{array}{ccccccc}
0 & \longrightarrow & A_{n+1} & \xrightarrow{f} & B_{n+1} & \xrightarrow{g} & C_{n+1} \longrightarrow 0 \\
& & \downarrow d & & \downarrow d & & \downarrow d \\
0 & \longrightarrow & A_n & \xrightarrow{f} & B_n & \xrightarrow{g} & C_n \longrightarrow 0 \\
& & \downarrow d & & \downarrow d & & \downarrow d \\
0 & \longrightarrow & A_{n-1} & \xrightarrow{f} & B_{n-1} & \xrightarrow{g} & C_{n-1} \longrightarrow 0
\end{array}$$

Let $[b] \in H_n(B)$ such that $g([b]) = 0$. It's determined by some $b \in B_n$ such that $d(b) = 0$. If $g([b]) = 0$, then there is some $\bar{c} \in C_{n+1}$ such that $d\bar{c} = gb$. Now, g is surjective, so there is some $\bar{b} \in B_{n+1}$ such that $g(\bar{b}) = \bar{c}$. Then we can consider $d\bar{b} \in B_n$, and $g(d\bar{b}) = d(\bar{c}) \in C_n$. What is $b - d\bar{b}$? This maps to zero in C_n , so by exactness there is some $a \in A_n$ such that $f(a) = b - d\bar{b}$. Is a a cycle? Well, $f(da) = d(fa) = d(b - d\bar{b}) = db - d^2\bar{b} = db$, but we assumed that $db = 0$, so $f(da) = 0$. This means that da is zero because f is an injection by exactness. Therefore a is a cycle. What is $[a] \in H_n(A)$? Well, $f([a]) = [b - d\bar{b}] = [b]$ because $d\bar{b}$ is a cycle. Is the composite $H_n(A) \rightarrow H_n(B) \rightarrow H_n(C)$ zero? Yes, because the composite factors through zero. This proves exactness of $H_n(A) \rightarrow H_n(B) \rightarrow H_n(C)$.

THEOREM 9.3 (lexseq in homology). Let $0 \rightarrow A_\bullet \rightarrow B_\bullet \rightarrow C_\bullet \rightarrow 0$ be a sexseq of chain complexes. Then there is a natural homomorphism $\partial : H_n(C) \rightarrow H_{n-1}(A)$ such that there's lexseq:

$$\begin{array}{ccccc}
& & & \swarrow \partial & \\
H_n(A) & \xrightarrow{\quad} & H_n(B) & \xrightarrow{\quad} & H_n(C) \\
& & \swarrow \partial & & \\
H_{n-1}(A) & \xrightarrow{\quad} & H_{n-1}(B) & \xrightarrow{\quad} & H_{n-1}(C) \\
& & \swarrow \partial & & \\
& & & \swarrow \partial &
\end{array}$$

PROOF. We'll construct ∂ , and leave the rest as an exercise. We have our sexseq:

$$\begin{array}{ccccccc}
0 & \longrightarrow & A_{n+1} & \xrightarrow{f} & B_{n+1} & \xrightarrow{g} & C_{n+1} \longrightarrow 0 \\
& & \downarrow d & & \downarrow d & & \downarrow d \\
0 & \longrightarrow & A_n & \xrightarrow{f} & B_n & \xrightarrow{g} & C_n \longrightarrow 0 \\
& & \downarrow d & & \downarrow d & & \downarrow d \\
0 & \longrightarrow & A_{n-1} & \xrightarrow{f} & B_{n-1} & \xrightarrow{g} & C_{n-1} \longrightarrow 0
\end{array}$$

Let $c \in C_n$ such that $dc = 0$. The map g is surjective, so pick a $b \in B_n$ such that $g(b) = c$. Then consider $db \in B_{n-1}$. But $g(db) = 0 = d(g(b)) = dc$. So by exactness, there is some $a \in A_{n-1}$ such that $f(a) = db$. How many choices are there of picking a ? One, because a is injective. We need to check that a is a cycle. What is $d(a)$? Well, $d^2b = 0$, so da maps to 0 under f . But because f is injective, $da = 0$, i.e., a is a cycle. This means we can define $\partial[c] = [a]$.

To make sure that this is well-defined, let's make sure that this choice of homology class a didn't depend on the b that we chose. Pick some other b' such that $g(b') = c$. Then there is $a' \in A_{n-1}$ such that $f(a') = db'$. We want $a - a'$ to be a boundary, so that $[a] = [a']$. We want $\bar{a} \in A_n$ such that $d\bar{a} = a - a'$. Well, $g(b - b') = 0$, so by exactness, there is $\bar{a} \in A_n$ such that $f(\bar{a}) = b - b'$. What is $d\bar{a}$? Well, $d\bar{a} = d(b - b') = db - db'$. But $f(a - a') = b - b'$, so because f is injective, $d\bar{a} = a - a'$, i.e., $[a] = [a']$. What else do I have to check? It's an exercise to check that ∂ as defined here is a homomorphism. Also, left as an exercise to check that this doesn't depend on $c \in [c]$, and that ∂ actually makes the exact sequence above exact. \square

9.4. Mathematical Genealogy. I'm not typing in anything here. It's a rather big tree:

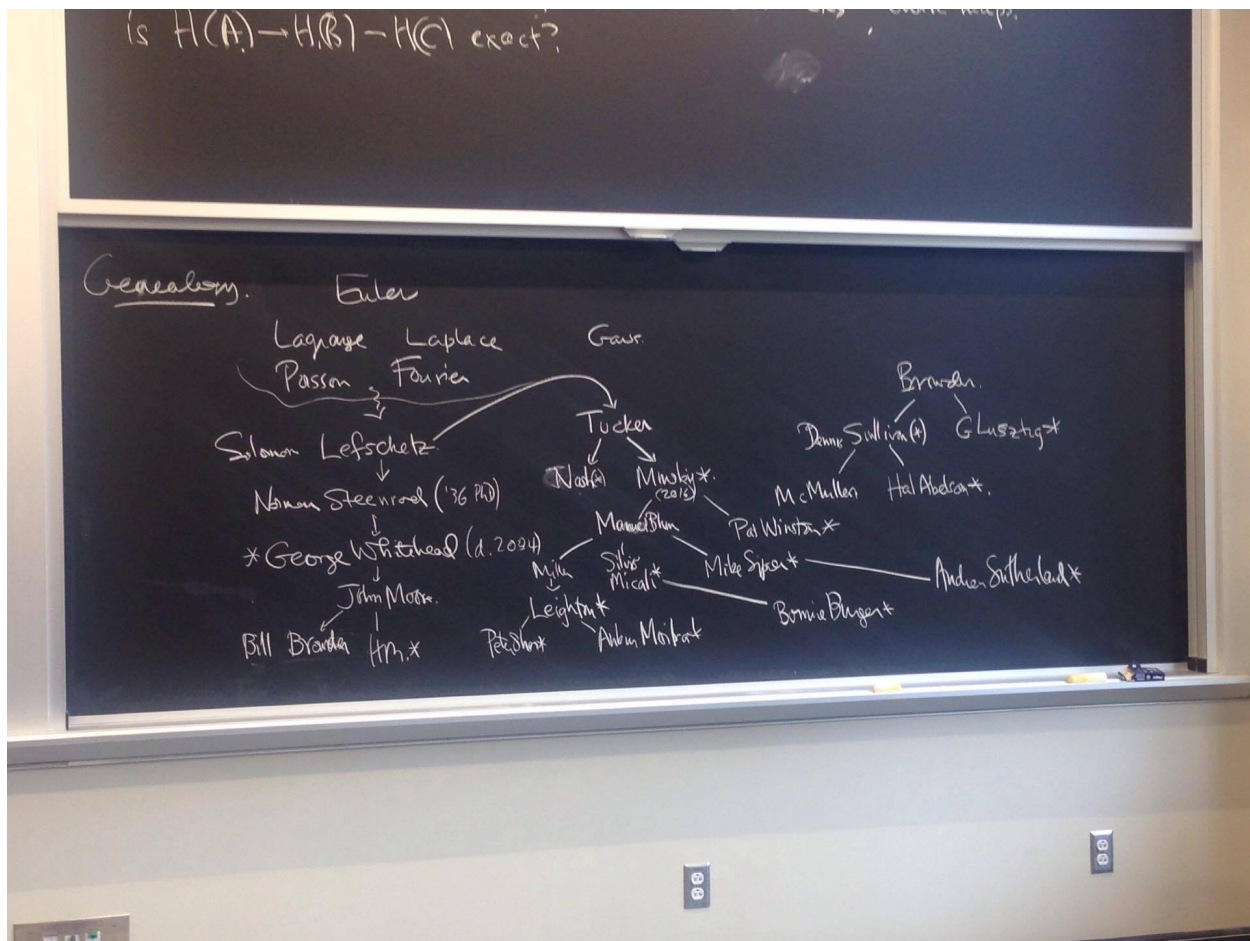


FIGURE 1. Mathematical genealogy, growing from Lefschetz, who was initially a chemist. The asterisks are meant to indicate that someone's at MIT.

10. Excision, and the Eilenberg-Steenrod axioms

We have homotopy invariance and the lexseq of a pair. We claimed that $H_*(X, A)$ “depends only on $X - A$ ”. You have to be careful about this.

DEFINITION 10.1. A triple (X, A, U) where $U \subseteq A \subseteq X$ is *excisive* if $\overline{U} \subseteq \text{Int}(A)$. This is a point-set definition. From an excisive triple you can get a pair $(X - U, A - U) \subseteq (X, A)$, and this is called an excision.

THEOREM 10.2. *An excision induces an isomorphism in homology, i.e., $H_*(X - U, A - U) \cong H_*(X, A)$. We might prove this on Wednesday.*

What are some consequences? We'll compute $H_*(S^n)$ and $H^*(D^n, S^{n-1})$. Here's the result. We'll use the homeomorphisms $D^n \simeq \Delta^n$ and $S^{n-1} \simeq \partial \Delta^n$. Let's write $S^0 = \{0, 1\}$, and $\iota_n : \Delta^n \rightarrow \Delta^n$.

THEOREM 10.3. (1)

$$H_q(S^n) = \begin{cases} \mathbf{Z} = \langle [c_*^0] \rangle & q = 0, n > 0 \\ \mathbf{Z} \oplus \mathbf{Z} = \langle [c_1^0], [\partial \iota_1] \rangle & q = n = 0 \\ \mathbf{Z} = \langle [\partial \iota_{n+1}] \rangle & q = n > 0 \\ 0 & \text{else} \end{cases}$$

(2)

$$H_q(D^n, S^{n-1}) = \begin{cases} \mathbf{Z} = \langle [\iota_n] \rangle & q = n \\ 0 & \text{else} \end{cases}$$

If $n = 0$, then we say that $S^{-1} = \emptyset$. What are the generators of these groups?

PROOF. We'll use the lexseq, homotopy invariance, and excision. We have the lexseq:

$$\begin{array}{ccccc} & & \swarrow \partial & & \\ H_q(S^{n-1}) & \xleftarrow{\quad} & H_q(D^n) & \longrightarrow & H_q(D^n, S^{n-1}) \\ & & \swarrow \partial & & \\ H_{q-1}(S^{n-1}) & \xrightarrow{\quad} & H_{q-1}(D^n) & \longrightarrow & H_{q-1}(D^n, S^{n-1}) \\ & & \swarrow \partial & & \end{array}$$

But we know that D^n is contractible, so $H_q(D^n) = \begin{cases} \mathbf{Z} & q = n \\ 0 & \text{else} \end{cases}$. This means that $\partial : H_q(D^n, S^{n-1}) \cong H_{q-1}(S^{n-1})$ for $q > 1$, but when $q = 1$, we get $0 \rightarrow H_1(D^n, S^{n-1}) \xrightarrow{\partial} H_0(S^{n-1}) \rightarrow H_0(D^n) \rightarrow H_0(D^n, S^{n-1}) \rightarrow 0$.

Let's think about the case $n > 1$. Then $H_0(S^{n-1}) = \mathbf{Z} = \langle [c_*^0] \rangle$, and $H_0(D^n) = \mathbf{Z} = \langle [c_*^0] \rangle$, so you have an isomorphism, which means that $H_0(D^n, S^{n-1}) = 0$ and $H_1(D^n, S^{n-1}) = 0$. Now, let's go to the case $n = 1$. Then $H_0(S^0) = \mathbf{Z} \oplus \mathbf{Z} = \langle [c_*^0], [\partial \iota_1] \rangle$ and $H_0(D^0) = \mathbf{Z}$. But $[\partial \iota_1]$ goes to zero, and $[c_*^0]$ goes to the generator of $\mathbf{Z} = H_0(D^0)$. This means that $H_1(D^1, S^0)$ is generated by $\langle [\iota_1] \rangle \cong \mathbf{Z}$ because the map $H_1(D^n, S^{n-1}) \rightarrow H_0(S^{n-1})$ is the boundary map, so $[\iota_1] \mapsto [\partial \iota_1]$.

Excision will come into play through the following statement.

PROPOSITION 10.4. *If $n > 1, q > 1$, then $H_q(D^n, S^{n-1}) \rightarrow H_q(D^n/S^{n-1}, *) \cong H_q(S^n, *) \cong H_q(S^n)$, because $D^n/S^{n-1} \simeq S^n$. The claim is that this collapse map is an isomorphism.*

This provides the inductive step. Let's assume we've proved the proposition. Then $H_q(D^n, S^{n-1}) \cong H_{q-1}(S^{n-1})$. The proposition says that $H_q(S^n) \cong H_{q-1}(S^{n-1})$. But we also have the boundary map $\partial : H_{q+1}(D^n, S^{n-1}) \cong H_q(S^n)$, i.e., $H_{q+1}(D^n, S^{n-1}) \cong H_q(D^n, S^{n-1})$.

Now I want to prove the proposition.

PROOF OF PROPOSITION. We want to compare $H_q(D^n, S^{n-1})$ and $H_q(D^n/S^{n-1}, *)$. We'll use excision to do this. We have $D^n = \{x \in \mathbf{R}^{n+1} | |x| \leq 1\}$. Let $A = \{x | 1/3 \leq |x| \leq 1\}$ and $U = \{x | 2/3 < |x| \leq 1\}$, and $\{x | |x| = 1\} = S^{n-1} \subseteq U$. We need a preliminary step. $H_q(D^n, S^{n-1}) \rightarrow H_q(D^n, A)$. We claim that this is an isomorphism, but this is true because of the lexseq and the 5-lemma. By excision, $H_q(D^n, A) \cong H_q(D^n - U, A - U)$. We can collapse the $(n-1)$ -sphere, and $(D^n/S^{n-1} - U/S^{n-1}, A/S^{n-1} - U/S^{n-1}) = (D^n - U, A - U)$ because you're collapsing something from something that's already been collapsed! Now, we claim that $H_q(D^n/S^{n-1} - U/S^{n-1}, A/S^{n-1} - U/S^{n-1}) \cong H_q(D^n/S^{n-1}, A/S^{n-1})$, which is true by excision. THE FOLLOWING PART IS MOST DEFINITELY NOT RIGHT¹. But also, $H_q(D^n/S^{n-1}, \text{disk}) = H_q(D^n/S^{n-1}, A/S^{n-1})$. Because the disk is contractible, using the lexseq and the 5-lemma completes the proof of the proposition. □

□

"This really turns me on, because I love homology." Why should you care about homology?

COROLLARY 10.5. *If $m \neq n$, then $S^m \not\cong S^n$ because they have different homology groups.*

COROLLARY 10.6. *If $m \neq n$, then $\mathbf{R}^m \not\cong \mathbf{R}^n$, because they're not homeomorphic.*

¹My own comment: this proof can be finished by noticing that $A \simeq S^{n-1}$ via $\mathbf{v} \mapsto \frac{\mathbf{v}}{\|\mathbf{v}\|}$, and that $D^n/S^{n-1} \simeq S^n$.

PROOF. Let $m, n > 0$. Assume we have a homeomorphism $f : \mathbf{R}^m \rightarrow \mathbf{R}^n$. This restricts to $\mathbf{R}^m - \{0\} \rightarrow \mathbf{R}^n - \{0\}$, but each of these are homotopy equivalent to spheres, but we can't get a homotopy equivalence between two spheres of different dimension by the above corollary. \square

10.1. Eilenberg-Steenrod axioms.

DEFINITION 10.7. A homology theory (on **Top**) is:

- a functor $h_n : \mathbf{Top}_2 \rightarrow \mathbf{Ab}$ for all n . We'll write $h_n(X) = h_n(X, \emptyset)$
- natural transformations $\partial : h_n(X, A) \rightarrow h_{n-1}(A)$.

such that:

- if $f_0, f_1 : (X, A) \rightarrow (Y, B)$ are homotopic, then $f_0, * \simeq f_1, * : h_n(X, A) \rightarrow h_n(Y, B)$.
- an excision induces isomorphisms.
- a lexseq:

$$\cdots \rightarrow h_{q+1}(X, A) \xrightarrow{\partial} h_q(A) \rightarrow h_q(X) \rightarrow h_q(X, A) \xrightarrow{\partial} \cdots$$

- (the dimension axiom): $h_n(*)$ is nonzero only in dimension zero. This is like the parallel postulate.

EXAMPLE 10.8. Ordinary singular homology satisfies these.

THEOREM 10.9 (Brouwer fixed-point theorem). *If $f : D^n \rightarrow D^n$, then there is some point $x \in D^n$ such that $f(x) = x$.*

PROOF. Suppose not. Then you can draw a ray from x to $f(x)$ to the boundary S^{n-1} , intersecting at a point $g(x)$. Left to you to check that g is continuous. If x was on the boundary, then $x = g(x)$. This is inconsistent by our computation because otherwise the identity on $H_{n-1}(S^{n-1})$ would be zero, contradiction! \square

11. Application of our previous calculation of $H_*(S^n)$ and the “locality principle”

THEOREM 11.1. *Let $n \geq 1$. There is a surjective monoid homomorphism $[S^n, S^n] \rightarrow \mathbf{Z}_\times$, where \mathbf{Z}_\times is the multiplicative monoid of \mathbf{Z} . $[S^n, S^n]$ is a monoid under composition. (This is basically the degree...)*

PROOF. Given $f : S^n \rightarrow S^n$, take the homology, which is just a homomorphism $\mathbf{Z} \rightarrow \mathbf{Z}$, all of which are simply multiplication by an integer. The integer by which you're multiplying to get this homomorphism is the integer associated to f .

Construction. If $n = 1$, this is just the winding number. Suppose I've constructed this in dimension $n - 1$. We have:

$$\begin{array}{ccccc} H_{n-1}(S^{n-1}) & \longleftarrow & H_n(D^n, S^{n-1}) & \longrightarrow & H_n(S^n) \\ \downarrow n & & \downarrow & & \downarrow \\ H_{n-1}(S^{n-1}) & \longleftarrow & H_n(D^n, S^{n-1}) & \longrightarrow & H_n(S^n) \end{array}$$

So we're basically suspending $f : S^{n-1} \rightarrow S^{n-1}$. More explicitly, if you have $f : S^{n-1} \rightarrow S^{n-1}$. We can extend to $\bar{f} : D^n \rightarrow D^n$ by sending $tx \mapsto tf(x)$ where tx denotes the ray connecting $x \in S^{n-1}$ to the origin, and we can then quotient out by S^{n-1} to get the map $S^n \rightarrow S^n$ as required. \square

11.1. Addendum to the ES axioms. There's a further axiom, which isn't due to ES, but rather due to Milnor. It's this.

- Suppose I a set. For each $\alpha \in I$ there's have a space $X_\alpha \in \mathbf{Top}$. I can consider $\coprod_\alpha X_\alpha$. There are inclusion maps $X_\alpha \rightarrow \coprod_\alpha X_\alpha$. Then $\bigoplus_\alpha h_n(X_\alpha) \cong h_n(\coprod_\alpha X_\alpha)$.

This is known for ordinary singular homology.

11.2. Homological algebra.

- (1) Suppose $A, B \subseteq C$ are abelian groups. Then $A + C \subseteq C$. You have a sexseq $0 \rightarrow A \cap B \rightarrow A \oplus B \rightarrow A + C \rightarrow 0$ where the map $c \mapsto (c, -c)$ is how the map $A \cap B \rightarrow A \oplus B$ is defined.
- (2) “Fundamental isomorphism for abelian groups” says the following. We have two sexseqs.

$$\begin{array}{ccccccc}
 0 & \longrightarrow & A \cap B & \longrightarrow & B & \longrightarrow & B/A \cap B \longrightarrow 0 \\
 & & \downarrow & & \downarrow & & \downarrow \cong \\
 0 & \longrightarrow & A & \longrightarrow & A + B & \longrightarrow & (A + B)/A \longrightarrow 0
 \end{array}$$

I’m not going to write out the diagram chase that we did.

- (3) “Snake lemma”. Suppose I have²:

$$\begin{array}{ccccccc}
 & & \ker f' & \longrightarrow & \ker f & \longrightarrow & \ker f'' \\
 & & \downarrow & & \downarrow & & \downarrow \\
 0 & \longrightarrow & A' & \longrightarrow & A & \longrightarrow & A'' \longrightarrow 0 \\
 & & \downarrow f' & & \downarrow f & & \downarrow f'' \\
 0 & \longrightarrow & B' & \longrightarrow & B & \longrightarrow & B'' \longrightarrow 0 \\
 & & \downarrow & & \downarrow & & \downarrow \\
 & & \operatorname{coker} f' & \longrightarrow & \operatorname{coker} f & \longrightarrow & \operatorname{coker} f''
 \end{array}$$

Claim is that there’s a map $\ker f'' \rightarrow \operatorname{coker} f$ so that $0 \rightarrow \ker f' \rightarrow \ker f \rightarrow \ker f'' \rightarrow \operatorname{coker} f' \rightarrow \operatorname{coker} f \rightarrow \operatorname{coker} f'' \rightarrow 0$. This is basically the lexseq in homology associated to the sexseqs of the following three chain complexes: $0 \rightarrow A' \rightarrow B' \rightarrow 0$, $0 \rightarrow A \rightarrow B \rightarrow 0$, and $0 \rightarrow A'' \rightarrow B'' \rightarrow 0$. Work this out yourself.

11.3. Locality.

DEFINITION 11.2. The (not necessarily open) cover of a topological space. Won’t write this.

DEFINITION 11.3. Let \mathcal{A} be a cover of X . An n -simplex σ is \mathcal{A} -small if there is $A \in \mathcal{A}$ such that the image of σ is entirely in A .

Notice that if $\sigma : \Delta^n \rightarrow X$ is \mathcal{A} -small, then so is $d^i \sigma$. Let’s denote by $\operatorname{Sin}_n^{\mathcal{A}}(X)$ the set of \mathcal{A} -small n -simplices. This means that we get a map $\operatorname{Sin}_n^{\mathcal{A}}(X) \rightarrow \operatorname{Sin}_{n-1}^{\mathcal{A}}(X)$. Let $S_n^{\mathcal{A}}(X) = \mathbf{Z}[\operatorname{Sin}_n^{\mathcal{A}}(X)]$. Then there’s a subchain complex $S_*^{\mathcal{A}}(X)$.

THEOREM 11.4. *The inclusion $S_*^{\mathcal{A}}(X) \subseteq S_*(X)$ is a chain homotopy equivalence.*

COROLLARY 11.5. *If $H_*^{\mathcal{A}}(X) := H(S_*^{\mathcal{A}}(X))$, then $H_*^{\mathcal{A}}(X) \cong H_*(X)$.*

We’ll do this on Monday.

EXAMPLE 11.6. If $\mathcal{A} = \{A, B\}$, then $\overline{X - B} = X - \operatorname{Int}(B) \subseteq \operatorname{Int}(A)$. Let $X - B = U$. Then $U \subseteq \overline{U} \subseteq \operatorname{Int}(A) \subseteq A \subseteq X$. This is an excision! So $U \subseteq A \subseteq X$ is an excision. But now, $(X - U, A - U) \rightarrow (X, A)$ is an excision, but $(X - U, A - U) = (B, A \cap B)$, so we have $(B, A \cap B) \rightarrow (X, A)$ is an excision. Now, also, $S_*^{\mathcal{A}}(X) = S_*(A) + S_*(B)$. Says he got off track, let me just write things out and explain in a moment.

$$\begin{array}{ccccccc}
 0 & \longrightarrow & S_n(A) \cap S_n(B) = S_n(A \cap B) & \longrightarrow & S_n(B) & \longrightarrow & S_n(B, A \cap B) \longrightarrow 0 \\
 & & \downarrow & & \downarrow & & \downarrow \cong \\
 0 & \longrightarrow & S_n(A) & \longrightarrow & S_n(A) + S_n(B) = S_n^{\mathcal{A}}(X) & \longrightarrow & S_n^{\mathcal{A}}(X)/S_n(A) \longrightarrow 0
 \end{array}$$

But we can consider $S_*(X)/S_*(A) = S_*(X, A)$. By the lexseq + 5 lemma, this thing is isomorphic to $S_n^{\mathcal{A}}(X)/S_n(A)$, so $S_*(B, A \cap B) \cong S_*(X, A)$ in homology. This is precisely the excision theorem. QED.

²“It’s my Turn”, Jill Clayburgh

12. Mayer-Vietoris and Subdivision

(Is it Meyer-Vietoris or Mayer-Vietoris?) Today is the lecture with a lot of formulae.

THEOREM 12.1. *Let \mathcal{A} be a cover of X , so that $X = \bigcup_{A \in \mathcal{A}} \text{Int}(A)$. Then the theorem we're going to prove is this. If $S_*^{\mathcal{A}}(X) = \sum_{A \in \mathcal{A}} S_*(A) \rightarrow S_*(X)$ induces an isomorphism in H_* . (This is a “quasi-isomorphism” of chain complexes.)*

Because this lecture's full of formulas, I'm going to stand around with a piece of paper in my hand.

EXAMPLE 12.2. Let $\mathcal{A} = \{A, B\}$ of X , so that:

$$\begin{array}{ccc} A \cap B & \xrightarrow{j_1} & A \\ \downarrow j_2 & & \downarrow i_1 \\ B & \xrightarrow{i_2} & X \end{array}$$

Then consider the following diagram:

$$\begin{array}{ccccccc} 0 & \longrightarrow & S_*(A \cap B) & \xrightarrow{\begin{pmatrix} j_{1*} \\ -j_{2*} \end{pmatrix}} & S_*(A) \oplus S_*(B) & \longrightarrow & S_*^{\mathcal{A}}(X) \longrightarrow 0 \\ & & \parallel & & \downarrow & & \parallel \\ 0 & \longrightarrow & S_*(A) \cap S_*(B) & \longrightarrow & S_*(A) \oplus S_*(B) & \xrightarrow{(i_{1*}, i_{2*})} & S_*(A) + S_*(B) \longrightarrow 0 \\ & & & & \searrow & & \downarrow \\ & & & & & & S_*(X) \end{array}$$

The map $S_*(A) + S_*(B) \hookrightarrow S_*(X)$ is a quasi-isomorphism, this is what locality says. Take the homology of this to get a lexseq:

$$\begin{array}{ccccc} \cdots & \xrightarrow{\begin{pmatrix} j_{1*} \\ -j_{2*} \end{pmatrix}} & & \xrightarrow{\quad} & H_{n+1}(X) \\ & \swarrow & & \searrow & \\ H_n(A \cap B) & \xrightarrow{\quad} & H_n(A) \oplus H_n(B) & \xrightarrow{(i_{1*}, i_{2*})} & H_n(X) \\ & \swarrow & & \searrow & \\ H_{n-1}(A \cap B) & \xrightarrow{\quad} & H_{n-1}(A) \oplus H_{n-1}(B) & \longrightarrow & \cdots \end{array}$$

Voila, you have Mayer-Vietoris. (I have a different proof of this that I submitted in homework.)

12.1. The cone construction. Let $X \subseteq \mathbf{R}^N$ be a star-shaped region, and let $b \in \mathbf{R}^N$. Then we showed that the augmentation $S_*(X) \xrightarrow{\epsilon} \mathbf{Z}$ is a chain homotopy equivalence. There's another map going backwards $\mathbf{Z} \xrightarrow{\eta_b} S_*(X)$ sending $1 \mapsto c_b^0$. Clearly the composition $\epsilon \circ \eta_b$ is the identity. We want to show that η_b and ϵ are chain homotopy inverses to each other. One direction is easy. The other map $S_*(X) \xrightarrow{\eta_b \epsilon} S_*(X)$ being homotopic to $1_{S_*(X)}$ is a little harder. This means that we want to construct a map $b_* : S_n(X) \rightarrow S_{n+1}(X)$ such that $db_* + b_*d = 1 - \eta_b \epsilon$.

Consider some $\sigma : \Delta^1 \rightarrow X$. Then because X is star shaped, you can send σ to b . This gives a 2-simplex $b_*\sigma$, called the *join*. We'll define this 2-simplex and label it so that the zero vertex is b itself, the 1 vertex is $d_1\sigma$, and the 2 vertex is $d_0\sigma$. Define $b_*\sigma$ as follows (where $(t_0, \dots, t_{n+1}) \in \Delta^{n+1}$):

$$b_*\sigma(t_0, \dots, t_n, t_{n+1}) = t_0b + (1 - t_0)\sigma\left(\frac{t_1, \dots, t_{n+1}}{1 - t_0}\right)$$

When $t_0 = 0$, then you recover exactly $\sigma(t_1, \dots, t_{n+1})$ and when $t_0 = 1$, this is exactly b . (Why can you divide by $1 - t_0 = 0$?) This is a map $b_* : \text{Sin}_n(X) \rightarrow \text{Sin}_{n+1}(X)$, so we can extend linearly to get

$S_n(X) \rightarrow S_{n+1}(X)$, also denoted $b*$. What is $d_i(b * \sigma)$? This is exactly:

$$d_i(b * \sigma) = \begin{cases} \sigma & i = 0 \\ c_b^0 & i = 1, n = 0 \\ b * d_{i-1}\sigma & i > 0, n > 0 \end{cases}$$

The latter thing seems true because in the case when $n = 1$, $d_2(b * \sigma)$ is the cone on $d_1\sigma$. The middle thing is true because when $n = 0$ you can't use the bottom thing (what is the boundary in that case?), and if you draw this out, noting our convention that when $t_0 = 1$ you have $d_1\sigma$ and when $t_0 = 0$ you have b , this automatically yields $d_1(b * \sigma) = b$ if $\sigma : \Delta^0 \rightarrow X$. We can rewrite this as follows. Here $c \in S_n(X)$.

$$d_i(b * c) = \begin{cases} c & i = 0 \\ b * d_0c + \eta_b \epsilon c & i = 1 \\ b * d_{i-1}\sigma & i > 1 \end{cases}$$

Because d_0 of a 0-simplex is defined to be zero. This may seem confusing, but it's just a translation of what we wrote down above. We want to compute that this thing is actually a chain homotopy. Let's compute.

$$\begin{aligned} d(b * c) &= d_0(b * c) - d_1(b * c) + \sum_{i>1} (-1)^i d_i(b * c) \\ &= c - (b * d_0c + \eta_b \epsilon c) + \sum_{i=2}^n (-1)^i b * d_{i-1}c \\ &= c - \eta_b \epsilon c - \sum_{j=0}^{n-1} (-1)^j b * d_jc \\ &= c - \eta_b \epsilon c - b * dc \end{aligned}$$

Here $j = i - 1$. The equality $\sum_{j=0}^{n-1} (-1)^j b * d_jc = b_*dc$ holds because $b*$ is linear (by definition on $S_n(X)$). This means that $b*$ is a chain homotopy, QED. This completes what we've claimed about the star shaped region. We want to use this cone construction to talk about subdivision.

12.2. Subdivide the standard simplex. Let's focus on the standard simplex. This is a nice thing about singular homology. For the 1-simplex, you just cut in half. For the 2-simplex, just look at the subdivision of each face, and look at the barycenter³, and join the barycenter to the 1-simplex between each "half" 1-simplex. We want to formalize this process. Define a natural transformation $\$: S_n(X) \rightarrow S_n(X)$ by defining on standard n -simplex, namely by specifying what $\$(\iota_n)$ is where $\iota_n : \Delta^n \xrightarrow{\text{id}} \Delta^n$, and then extending by naturality (namely $\$(\sigma) = \sigma_*\(ι_n)). Here's the definition. When $n = 0$, define $\$ = \text{id}$, i.e., $\$(\iota_0) = \iota_0$. For $n > 0$, define $\$\iota_n := b_n * \$d\iota_n$ where b_n is the barycenter of Δ^n . This makes a *lot* of sense if you draw out a picture, and it's a very clever definition that captures the geometry we described. Let me tell you what we'll prove about this, most likely on Wednesday.

PROPOSITION 12.3. $\$$ is a chain map $S_*(X) \rightarrow S_*(X)$, i.e., $\$d = d\$$. Also, $\$ \simeq 1$.

Also, class is cancelled on Friday.

13. Locality (almost done!)

THEOREM 13.1. We discovered that $S_*^A(X) \hookrightarrow S_*(X)$ is a subcomplex, and this induced an isomorphism in homology.

We talked about subdivision and the cone construction, the latter of which dealt with a star-shaped region, relative to some point (which we can safely assume is the origin) b . If $\sigma : \Delta^n \rightarrow X$ is a map, then $b * \sigma : S_n(X) \rightarrow S_{n+1}(X)$ where $*$ is the join. We did all of this before. The property that this had is that it's a homotopy between 1 and $\eta_b \epsilon$, i.e., $db * + b * d = 1 - \eta_b \epsilon$. This is called equation (*). Look above for the definition of η_b and ϵ . Hopefully you remember this story.

³The barycenter of the n -simplex is $b_n := \frac{(1, \dots, 1)}{n+1}$.

The subdivision operator $\$: S_*(X) \rightarrow S_*(X)$ for any space X is natural, so it's enough to say what $\$\iota_n$ and $\$\iota_0$ is. Define $\$\iota_0 = \iota_0$, and define $\$\iota_n = b_n * \$ (d\iota_{n-1})$ where b_n is the barycenter of the n -simplex. The standard simplex is star-shaped relative to its barycenter, so by naturality, it suffices to do this for ι_n . The two key properties are the following.

THEOREM 13.2. (1) $\$$ is a chain map.
 (2) There is a chain homotopy $T : \$ \sim 1$.

PROOF. Let's try to prove that it's a chain map. We'll use induction on n . It's enough to show that $d\$\iota_n = \$d\iota_n$, because:

$$d\$\sigma = d\$\sigma_*\iota_n = \sigma_*d\$\iota_n = \sigma_*\$d\iota_n = \$d\sigma_*\iota_n = \$d\sigma$$

We declared $d\$\iota_0 = d\iota_0 = 0$. But also $\$d\iota_0 = \$0 = 0$, so this works.

For $n \geq 1$, we want to compute $d\$\iota_n$. This is:

$$\begin{aligned} d\$\iota_n &= d(b_n * \$d\iota_n) \\ &= (1 - \eta_b \epsilon - b_n * d)(\$d\iota_n) \end{aligned} \quad \text{by } (*)$$

What happens when $n = 1$? Well:

$$\eta_b \epsilon \$d\iota_1 = \eta_b \epsilon \$ (c_1^0 - c_0^0) = \eta_b \epsilon (c_1^0 - c_0^0 - 0) = 0$$

Because ϵ takes sums of coefficients, which is $1 + (-1) = 0$. Let's continue.

$$\begin{aligned} d\$\iota_n &= \dots \\ &= \$d\iota_n - b_n * d\$d\iota_n \\ &= \$d\iota_n - b_n \$d^2\iota_n \\ &= \$d\iota_n \end{aligned} \quad \text{because } d^2 = 0$$

So we're done.

To define the chain homotopy T , we'll just write down a formula and not justify it. We just need to define $T\iota_n$ by naturality. So define:

$$T\iota_n = \begin{cases} 0 & n = 0 \\ b_n * (\$ \iota_n - \iota_n - Td\iota_n) \in S_{n+1}(\Delta^n) & n > 0 \end{cases}$$

This is because $T : S_n(X) \rightarrow S_{n+1}(X)$ such that $dT + Td = \$ - 1$. I'm confused about this, so help me out. Hmm. The term $\$ \iota_n - \iota_n - Td\iota_n$ is an n -chain. We're going to do this by induction. Again, we need to check only on the universal case.

When $n = 0$, $dT\iota_0 + Td\iota_0 = 0 + 0 = 0 = \$\iota_0 - \iota_0$ because $\$\iota_0 = \iota_0$. Now let's induct. For $n \geq 1$, let's start by computing $dT\iota_n$. This is:

$$\begin{aligned} dT\iota_n &= d_n(b_n * (\$ \iota_n - \iota_n - Td\iota_n)) \\ &= (1 - b_n * d)(\$ \iota_n - \iota_n - Td\iota_n) \quad \text{by } (*) \\ &= \$\iota_n - \iota_n - Td\iota_n - b_n * (d\$ \iota_n - d\iota_n - dTd\iota_n) \end{aligned}$$

We can ignore the $\eta_b \epsilon$ part because we're in dimension ≥ 1 . All we want now is that $b_n * (d\$ \iota_n - d\iota_n - dTd\iota_n) = 0$. We can do this via induction, because $T(d\iota_n)$ is in dimension n (or is it $n - 1$?):

$$\begin{aligned} dTd\iota_n &= -Td(d\iota_n) + \$d\iota_n - d\iota_n \\ &= \$d\iota_n - d\iota_n \\ &= d\$ \iota_n - d\iota_n \end{aligned}$$

This means that $d\$ \iota_n - d\iota_n - dTd\iota_n = 0$, so we're done. \square

COROLLARY 13.3. $\$^k \sim 1 : S_*(X) \rightarrow S_*(X)$. I.e., we're iterating subdivision. We want T_k such that $dT_k + T_k d = \$^k - 1$

PROOF. $dT + Td = \$ - 1$. Let's apply $\$$ to this. We get $\$dT + \$Td = \$^2 - \$$. Sum up these two things, so we get $dT + Td + \$dT + \$Td = \$^2 - 1$. But now, $\$d = d\$$, so the left hand side is $dT + d\$T + Td + \$Td = d(\$ + 1)T + (\$ + 1)Td$, i.e., $d(\$ + 1)T + (\$ + 1)Td = \$^2 - 1$. So define $T_2 = (\$ + 1)T$, and continuing, you see that $T_k = (\$^{k-1} + \$^{k-2} + \cdots + 1)T = \left(\sum_{i=0}^{k-1} \$^i\right)T$. \square

PROPOSITION 13.4 (Almost completes the proof of locality). *Let \mathcal{A} be a cover of X . For every chain $c \in S_n(X)$, there is a $k \geq 0$ such that $\$^k c \in S_n^{\mathcal{A}}(X)$. This is the geometric thing we have to prove.*

PROOF. We may assume that $c : \sigma : \Delta^n \rightarrow X$, and this makes sense because you just take the max of the k of the terms of the sum. A great trick is the following: define an open cover \mathcal{U} of Δ^n defined by $\mathcal{U} := \{\sigma^{-1}(\text{Int}(A)) \mid A \in \mathcal{A}\}$. This is a cover, a basic result from topology. Then we use the Lesbegue covering lemma:

LEMMA 13.5 (Lesbegue covering lemma). *We'll pretend this is part of 18.901. Let M be a compact metric space (eg. Δ^n), and let \mathcal{U} be an open cover. Then there is $\epsilon > 0$ such that for all $x \in M$, there is $B_\epsilon(x) \subseteq U$ for some $U \in \mathcal{U}$.*

PROOF. Omitted, may be in 18.901. Or even 18.100B. \square

Let's apply this to the cover we constructed. What we want is that for all $\epsilon > 0$, there is a k such that the diameter of the simplices in $\$^k \iota_n$ is less than ϵ . Let's do that.

QUESTION 13.6. How small are these subdivided simplices in $\$^k \iota_n$?

For example, suppose $\sigma : \Delta^n \rightarrow \Delta^n$ is something in the subdivision. These are all affine simplexes, i.e., it's determined by where the simplices of Δ^n go to in σ . We can write $\sigma = \langle v, \dots, v_n \rangle$. It could be in \mathbf{R}^N if you wanted; maybe it's easier to think of it this way. The barycenter is $\frac{\sum_{i=0}^n v_i}{n+1}$. Let's compute:

$$\begin{aligned} |b - v_i| &= \left| \frac{v_0 + \cdots + v_n - (n+1)v_i}{n+1} \right| \\ &= \left| \frac{(v_0 - v_i) + (v_1 - v_i) + \cdots + (v_n - v_i)}{n+1} \right| \\ &\leq \frac{n}{n+1} \max_{i,j} |v_i - v_j| \\ &= \frac{n}{n+1} \text{diam}(\text{Im } \sigma) \end{aligned}$$

The following lemma completes the proof because there's always a k such that $\left(\frac{n}{n+1}\right)^k < \epsilon$.

LEMMA 13.7. *Let τ be a simplex in $\$^k \sigma$ where σ is an affine simplex. Then $\text{diam}(\tau) \leq \frac{n}{n+1} \text{diam}(\sigma)$.*

PROOF. Let's write $\tau = \langle w_0 = b, \dots, w_n \rangle$ and $\sigma = \langle v_0, \dots, v_n \rangle$. We saw:

$$\begin{aligned} |b - w_i| &\leq \max_i |b - v_i| \\ &\leq \frac{n}{n+1} \text{diam}(\sigma) \end{aligned}$$

For the other cases, well, we use induction:

$$\begin{aligned} |w_i - w_j| &\leq \text{diam}(\text{simplex in } \$d\sigma) \\ &\leq \frac{n-1}{n} \text{diam}(d\sigma) \\ &\leq \frac{n}{n+1} \text{diam}(\sigma) \end{aligned}$$

We're almost there. We'll finish the proof of locality on Friday. \square

\square

14. Concluding Locality! and CW-complexes

Again recall what \mathcal{A} -small covers, etc. are. We want to prove that:

THEOREM 14.1. $S_*^{\mathcal{A}}(X) \hookrightarrow S_*(X)$ is a quasi-isomorphism, i.e., an isomorphism on homology.

We developed the subdivision operator $\$^k : S_*(X) \rightarrow S_*(X)$, and proved that it's a chain map. We showed that $T_k : \$^k \sim 1$.

PROOF OF LOCALITY. We want to prove surjectivity of $H_n(S_*^{\mathcal{A}}(X)) \rightarrow H_n(S_*(X)) = H_n(X)$. Let $c \in Z_n(C_\bullet)(X)$. We want to find an \mathcal{A} -small n -cycle that is homologous to c . There's only one thing to do. Pick k such that $\$^k c$ is \mathcal{A} -small. This is a cycle because $d\$^k c = \$^k dc = 0$ because $\k is a chain map. I want to compare this new cycle with c . Consider the chain homotopy T_k ; then: $dT_k c + T_k dc = \$^k c - c$. But $dc = 0$, so $\$^k c - c = dT_k c$, so they differ by a boundary, and they're homologous.

Now for injectivity. Suppose $c \in S_n^{\mathcal{A}}(X)$ with $dc = 0$. Suppose that $c = db$ for some $b \in S_{n+1}(X)$, not necessarily \mathcal{A} -small. We want c to be a boundary of an \mathcal{A} -small chain. Well:

$$\begin{aligned} dT_k b + T_k db &= \$^k b - b \\ \Rightarrow dT_k b + T_k c &= \$^k b - b \\ \Rightarrow d(dT_k b + T_k c) &= \$^k b - b = dT_k c = d\$^k b - c \\ \Rightarrow c &= d\$^k b - dT_k c = d(\$^k b - T_k c) \end{aligned}$$

Now, $\k is \mathcal{A} -small. Is $T_k c$ also \mathcal{A} -small? I claim that it is. Why? It is enough to show that $T_k \sigma$ is \mathcal{A} -small if σ is. We know that $\sigma = \sigma_* \iota_n$. Because σ is \mathcal{A} -small, we know that $\sigma : \Delta^n \rightarrow X$ is the composition $i_* \bar{\sigma}$ where $\bar{\sigma} : \Delta^n \rightarrow A$ and $i : A \rightarrow X$ is the inclusion for some $A \in \mathcal{A}$. This means that $T_k \sigma = T_k i_* \bar{\sigma} = i_* T_k \bar{\sigma}$, which certainly is \mathcal{A} -small. \square

“Are you happy? You should be very happy, because we’ve finished our first portion of this course. We now have a whole package of homology.”

14.1. CW-complexes. Simplicial complexes are rigid and combinatorial. But manifolds are smooth. In between, you have CW-complexes. (A lot of advertisement for this.) We want to “glue” things. This is the pushout construction. Namely, if you have $i : A \hookrightarrow B$ and $f : A \rightarrow X$, then you define $X \cup_f B$ (or $X \cup_A B$) via:

$$\begin{array}{ccc} A & \xrightarrow{f} & X \\ i \downarrow & & \downarrow \\ B & \longrightarrow & X \cup_f B \end{array}$$

defined by $X \cup_f B = X \sqcup B / \sim$ where $\forall a \in A, f(a) \sim a$. This is X with B attached along f . There are two kinds of equivalence classes, namely elements of $B - A$, because anything not in A is just a singleton. The other is $\{x\} \cup f^{-1}(x)$ for $x \in X$, because anything that's not in $\text{Im } f$ is a singleton, but if something is in $\text{Im } f$, you identify it with its preimage. This is what it is as a set. It has a universal property. Suppose you have another space Y .

$$\begin{array}{ccc} A & \xrightarrow{f} & X \\ i \downarrow & & \downarrow j \\ B & \longrightarrow & X \cup_f B \end{array} \quad \begin{array}{c} \nearrow \bar{j} \\ \searrow \bar{g} \end{array} \quad \begin{array}{c} Y \end{array}$$

such that $\bar{j}f = \bar{g}i$. The topology is right too because that's what the quotient topology does for you. As I wrote before, this is called a *pushout* of the following diagram:

$$\begin{array}{ccc} A & \xrightarrow{f} & X \\ \downarrow i & & \\ B & & \end{array}$$

EXAMPLE 14.2. Let $X = *$. Then you have a pushout:

$$\begin{array}{ccc} A & \xrightarrow{f} & * \\ \downarrow i & & \downarrow \\ B & \longrightarrow & * \cup_f B \end{array}$$

So then $* \cup_f B = B/A$.

EXAMPLE 14.3.

$$\begin{array}{ccc} \emptyset & \xrightarrow{f} & X \\ \downarrow i & & \downarrow \\ B & \longrightarrow & X \cup_f B \end{array}$$

It's then clear that this is exactly $X \sqcup B$.

EXAMPLE 14.4. If both:

$$\begin{array}{ccc} \emptyset & \xrightarrow{f} & * \\ \downarrow i & & \downarrow \\ B & \longrightarrow & * \cup_f B \end{array}$$

So $B/\emptyset = * \sqcup B$. For example, $\emptyset/\emptyset = *$. This is “creation from nothing”. “We won't get into the religious ramifications.”

EXAMPLE 14.5 (Attaching a cell, the most important). Consider:

$$\begin{array}{ccc} S^{n-1} & \xrightarrow{f} & X \\ \downarrow i & & \downarrow \\ D^n & \longrightarrow & X \cup_f D^n \end{array}$$

This is called attaching a “cell”. The D^n is what's called a cell. You're attaching a contractible space. You might want to generalize this a little bit:

$$\begin{array}{ccc} \coprod_{\alpha \in A} S_{\alpha}^{n-1} & \xrightarrow{f} & X \\ \downarrow i & & \downarrow \\ \coprod_{\alpha \in A} D_{\alpha}^n & \longrightarrow & X \cup_f \coprod_{\alpha \in A} D_{\alpha}^n \end{array}$$

What are some examples? When $n = 0$, the declaration is that $S^{-1} = \emptyset$, so this is:

$$\begin{array}{ccc} \emptyset & \xrightarrow{f} & X \\ \downarrow i & & \downarrow \\ \coprod_{\alpha \in A} * & \longrightarrow & X \cup_f \coprod_{\alpha \in A} * \end{array}$$

You're just adding a bunch of points to X . This is a little more interesting. What about:

$$\begin{array}{ccc} S^0 \sqcup S^0 & \xrightarrow{f} & * \\ \downarrow i & & \downarrow \\ D^1 \sqcup D^1 & \longrightarrow & * \cup_f (D^1 \sqcup D^1) \end{array}$$

Then $* \cup_f (D^1 \sqcup D^1)$ is a figure 8, because you have two 1-disks, where you identify the four boundary points together. If we consider $(X, *)$, $(Y, *)$, then $X \vee Y := X \sqcup Y / * \sim *$. So $* \cup_f (D^1 \sqcup D^1) = S^1 \vee S^1$. More interestingly:

$$\begin{array}{ccc} S^1 & \xrightarrow{aba^{-1}b^{-1}} & S^1 \vee S^1 \\ \downarrow i & & \downarrow \\ D^2 & \longrightarrow & (S^1 \vee S^1) \cup_f D^2 \end{array}$$

This is exactly the torus, i.e., $(S^1 \vee S^1) \cup_f D^2 = T^2$.

DEFINITION 14.6. A *CW-complex* is a space X with a sequence of subspaces $\emptyset = X_{-1} \subseteq X_0 \subseteq X_1 \subseteq \dots \subseteq X$ (could be an infinite sequence) such that for all n , there is a pushout diagram like this:

$$\begin{array}{ccc} \coprod_{\alpha \in A_n} S_\alpha^{n-1} & \xrightarrow{f} & X_{n-1} \\ \downarrow i & & \downarrow \\ \coprod_{\alpha \in A_n} D_\alpha^n & \longrightarrow & X_n \end{array}$$

And $X = \bigcup X_n$, topologically (i.e. $A \subseteq X$ is open if and only if $A \cap X_n$ is open for all n). Often, $X_n = \text{Sk}_n(X)$, called the n -skeleton, in honor of Halloween (coming right up!), of X .

EXAMPLE 14.7. The torus is $\emptyset \subseteq T_0^2 \subseteq T_1^2 \subseteq T^2$. Here, $T_0^2 = *$ and $T_1^2 = S^1 \vee S^1$.

DEFINITION 14.8. A CW-complex is *finite-dimensional* if $X_n = X$ for some n . Say that X is of *finite type* if each A_n is finite, i.e., finitely many cell in each dimension. Say that X is *finite* if it's finite-dimensional and of finite type.

In CW, the C is for cell, and the W is for weak, because of the topology on a CW-complex. This definition is due to J. H. C. Whitehead. Some people say that the "CW" comes from his name.

THEOREM 14.9. (1) Any CW-complex is Hausdorff, and it's compact if and only if it's finite.
(2) Any compact smooth manifold admits a CW structure.

PROOF. Not going to do this. □

Note that there could be multiple CW-structures on something.

15. CW-complexes and cellular homology

Recall:

DEFINITION 15.1. A *CW-complex* is a space X with a sequence of subspaces $\emptyset = X_{-1} \subseteq X_0 \subseteq X_1 \subseteq \dots \subseteq X$ (could be an infinite sequence) such that for all n , there is a map $f : \coprod_{\alpha \in A_n} S_\alpha^{n-1} \rightarrow X_{n-1}$ (called the *attaching map*), such that there is a pushout diagram like this:

$$\begin{array}{ccc} \coprod_{\alpha \in A_n} S_\alpha^{n-1} & \xrightarrow{f} & X_{n-1} \\ \downarrow i & & \downarrow \\ \coprod_{\alpha \in A_n} D_\alpha^n & \longrightarrow & X_n \end{array}$$

And $X = \bigcup X_n$, topologically (i.e. $A \subseteq X$ is open if and only if $A \cap X_n$ is open for all n). Often, X_n is written $\text{Sk}_n(X)$, and is called the n -skeleton of X .

REMARK 15.2. This means that if you ignore the topology, i.e., as sets: $X = \coprod_{n \geq 0} (\coprod_{\alpha \in A_n} \text{Int}(D_\alpha^n))$ where $\text{Int}(D^n) = \{x \in D^n : |x| < 1\}$ (the interior of D^n), so that $\text{Int}(D^0) = D^0 = *$. The $\text{Int}(D_\alpha^n)$ are called “open n -cells”. Note that the open n -cells are not generally open in the topology on X .

EXAMPLE 15.3. The n -sphere S^n . Let $\text{Sk}_0(S^n) = * = \text{Sk}_1(S^n) = \dots = \text{Sk}_{n-1}(S^n) \subseteq \text{Sk}_n(S^n) = S^n$. We attach it by using the pushout:

$$\begin{array}{ccc} S^{n-1} & \longrightarrow & * \\ \downarrow & & \downarrow \\ D^n & \longrightarrow & S^n \end{array}$$

Here’s another CW-structure. Let $\text{Sk}_0(S^n) = S^0 = S^n \cap \mathbf{R}^1 \langle \mathbf{e}_1 \rangle$, $\text{Sk}_1(S^n) = S^1 = S^n \cap \mathbf{R}^2 \langle \mathbf{e}_1, \mathbf{e}_2 \rangle$, $\text{Sk}_2(S^n) = S^2 = S^n \cap \mathbf{R}^3 \langle \mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3 \rangle$, etc. until $\text{Sk}_n(S^n) = S^n$. I have to give maps $u, \ell : D^k \rightarrow S^k$ so that you have a pushout:

$$\begin{array}{ccc} D^k & \longrightarrow & S^k \\ \uparrow & & \uparrow \\ S^{k-1} & \xlongequal{\quad} & \text{Sk}_k(S^n) \end{array}$$

Let $u(x) = (x, \sqrt{1 - |x|^2})$ and $\ell(x) = (x, -\sqrt{1 - |x|^2})$ where $x \in D^k$. Clearly u, ℓ take values in S^k .

There’s another definition I have to make.

DEFINITION 15.4. Let X be a CW-complex. A subcomplex of X is a subspace $Y \subseteq X$ such that $\emptyset \subseteq Y \cap X_0 \subseteq Y \cap X_1 \subseteq \dots \subseteq Y \cap X_k \subseteq \dots \subseteq Y$ is a CW-structure on Y .

EXAMPLE 15.5. $X_n \subseteq X$ is a subcomplex of a CW-complex X . It’s not that hard to see why. In particular, $S^0 \subseteq S^1 \subseteq S^2 \subseteq \dots \subseteq \bigcup_{n \geq 1} S^n =: S^\infty$. This of finite type, but isn’t finite-dimensional.

LEMMA 15.6. S^∞ is contractible.

PROOF. S^0 itself is not contractible, but attaching two 1-cells makes this contractible. Similarly, S^1 isn’t contractible, but attaching two 2-cells makes this contractible. This is the idea. You have $S^{k-1} \times I \rightarrow S^k$ by $(x, t) \mapsto u(tx + (1-t)\mathbf{e}_1)$ where u is the map we defined above. Therefore we get a map $S^\infty \times I \rightarrow S^\infty$ that’s a contracting homotopy. \square

EXAMPLE 15.7. Recall $\mathbf{RP}^n = S^n / \sim$ where $x \sim -x$. There’s a map from $S^n \rightarrow \mathbf{RP}^n$ that’s a double cover. Let me propose a CW-decomposition. We have:

$$\begin{array}{ccccccc} \dots \hookrightarrow S^{k-1} \hookrightarrow S^k \longrightarrow \dots \longrightarrow S^n \\ \downarrow \qquad \qquad \downarrow \qquad \qquad \downarrow \\ \dots \hookrightarrow \mathbf{RP}^{k-1} \hookrightarrow \mathbf{RP}^k \longrightarrow \dots \longrightarrow \mathbf{RP}^n \end{array}$$

We claim that this is a CW-decomposition. We have a double cover $S^1 \rightarrow \mathbf{RP}^1 = S^1$. The maps $S^{k-1} \rightarrow \mathbf{RP}^{k-1}$ are not degree 2 maps – they’re different spaces! If we use the double cover $S^{k-1} \rightarrow \mathbf{RP}^{k-1}$, then we claim that there is a pushout:

$$\begin{array}{ccccccc} \mathbf{RP}^{k-1} \hookrightarrow \mathbf{RP}^k \hookrightarrow \dots \hookrightarrow \bigcup_{k \geq 0} \mathbf{RP}^k = \mathbf{RP}^\infty \\ \uparrow \text{double cover} \qquad \uparrow \\ S^{k-1} \longrightarrow D^k \end{array}$$

This is true if you notice that the preimage of any point of \mathbf{RP}^k must be two points, one of which must be in the upper hemisphere, which is a disk, unless both points are on the equatorial sphere.

15.1. Homology of CW-complexes. Consider:

$$\begin{array}{ccccc} A \hookrightarrow & B & \longrightarrow & B/A \\ \downarrow f & \downarrow & & \downarrow \\ X \hookrightarrow & X \cup_f B & \longrightarrow & (X \cup_f B)/X \end{array}$$

By a diagram chase, the dotted arrow exists and is continuous. This is actually a pointed map. You can see that this is a homeomorphism. What if this is part of a CW-structure?

$$\begin{array}{ccccc} \coprod_{\alpha} S^{k-1} \hookrightarrow & \coprod_{\alpha} D_{\alpha}^k & \longrightarrow & \bigvee_{\alpha} S_{\alpha}^k \\ \downarrow f & \downarrow & & \downarrow \\ X_{k-1} \hookrightarrow & X_k \cup_f B & \longrightarrow & X_k/X_{k-1} \end{array}$$

where \bigvee is the wedge product (disjoint union with all basepoints identified). Then $\bigvee_{\alpha} S_{\alpha}^k$ is a bouquet of spheres. So $X_k/X_{k-1} \cong \bigvee_{\alpha} S_{\alpha}^k$. We know the homology of spheres very well by now, so let's exploit this.

LEMMA 15.8. $H_q(X_k, X_{k-1}) \rightarrow H_q(X_k/X_{k-1}, *)$ is an isomorphism.

PROOF. Later. □

But now, we know $H_q(X_k/X_{k-1}, *)$ very well! It's exactly $\tilde{H}_q(\bigvee_{\alpha \in A_k} S_{\alpha}^k) \cong \begin{cases} \mathbf{Z}[A_k] & q = k \\ 0 & q \neq k \end{cases}$. Therefore the relative homology $H_q(X_k, X_{k-1})$ counts the number of k -cells of X .

DEFINITION 15.9. Let $C_k(X) := H_k(X_k, X_{k-1})$. This is the “cellular k -chains” of X .

COROLLARY 15.10. *There's an exact sequence:*

$$\begin{array}{ccccccc} & & & & H_{k+1}(X_k, X_{k-1}) = 0 & & \\ & & & \swarrow & & & \\ H_k(X_{k-1}) & \longrightarrow & H_k(X_k) & \longrightarrow & C_k(X) & & \\ & \nwarrow & & \searrow & & & \\ H_{k-1}(X_{k-1}) & \longrightarrow & H_{k-1}(X_k) & \longrightarrow & H_{k-1}(X_k, X_{k-1}) = 0 & & \end{array}$$

And in other dimensions, $H_q(X_k, X_{k-1}) \cong H_q(X_k)$ for $q \neq k, k-1$. So:

- (1) We have maps $H_q(X_k) \rightarrow H_q(X_{k+1}) \rightarrow \dots$ that are all isomorphisms for $q < k$. (There was a lot of confusion here about what q is greater than or less than). All of these map to $H_q(X)$. There's another lemma that I will defer again:

LEMMA 15.11. *This limit $H_q(X_k) \rightarrow H_q(X_{k+1}) \rightarrow \dots \rightarrow H_q(X)$ is an isomorphism.*

PROOF. Deferred. □

- (2) (There was a bit of confusion at this point, I'm not sure on what exactly.) $H_q(X_0) \rightarrow H_q(X_1) \rightarrow \dots \rightarrow H_q(X_k)$ are all isomorphisms for $q > k$. Agreed? That's not what I wanted to say. I'll continue this on Wednesday. It's not supposed to be confusing.

16. Homology of CW-complexes

LEMMA 16.1. *There are isomorphisms:*

$$H_q(X_n, X_{n-1}) \xrightarrow{\cong} H_q(X_n/X_{n-1}, *) = H_q\left(\bigvee_{\alpha \in A_n} S_{\alpha}^n, *\right) = \begin{cases} 0 & q \neq n \\ \mathbf{Z}[A_n] & q = n \end{cases}$$

Let's talk about "characteristic maps". This is a map $(\coprod D_\alpha^n, \coprod S_\alpha^{n-1}) \rightarrow (X_n, X_{n-1})$. This is like a "relative homeomorphism" (I was drinking water, so this isn't exactly accurate). We have a map $H_q(X_n, X_{n-1}) \rightarrow H_q(X_n/X_{n-1}, *)$, to get a commutative diagram:

$$\begin{array}{ccc} H_q(\coprod D_\alpha^n, \coprod S_\alpha^{n-1}) & \longrightarrow & H_q(\vee S_\alpha^n, *) \\ \downarrow & & \downarrow \\ H_q(X_n, X_{n-1}) & \longrightarrow & H_q(X_n/X_{n-1}, *) \end{array}$$

The right arrow is an isomorphism. The top arrow is an isomorphism. The lemma says that the bottom map is an isomorphism, so that $H_q(\coprod D_\alpha^n, \coprod S_\alpha^{n-1}) \rightarrow H_q(X_n, X_{n-1})$ is an isomorphism. This is called the "cellular n -chains" on X .

Now, fix q . For $q = 0$, there is:

$$\begin{array}{ccccccc} H_1(X_1, X_0) & & H_0(X_1, X_0) = 0 & & H_0(X_2, X_1) = 0 & & \\ \downarrow & & \uparrow & & \uparrow & & \\ H_0(X_0) & \longrightarrow & H_0(X_1) & \longrightarrow & H_0(X_2) & \longrightarrow & \dots \\ & \searrow & \uparrow & \searrow & \searrow & \searrow & \downarrow \\ & & H_1(X_2, X_1) = 0 & & & & H_0(X) \end{array}$$

We know that $H_0(X_1, X_0) = 0$, but $H_1(X_1, X_0)$ is not necessarily 0. This means that $H_0(X_0) \rightarrow H_0(X_1)$ is surjective, and $H_0(X_1) \cong H_0(X_2)$, and so on for higher dimensions. This makes sense because adding higher dimensional cells does not change path components.

Let's try this for $q > 0$. Then you have:

$$\begin{array}{ccccccc} & & H_{q+1}(X_q, X_{q+1}) = 0 & & H_{q+1}(X_{q+1}, X_q) & & \\ & & \downarrow & & \downarrow & & \\ \dots & \longrightarrow & H_q(X_{q-1}) & \longrightarrow & H_q(X_q) & \longrightarrow & H_q(X_{q+1}) \longrightarrow H_q(X_{q+2}) \longrightarrow \dots \\ & & \searrow & & \downarrow & & \downarrow \\ & & & & H_q(X_q, X_{q-1}) & & H_q(X_{q+1}, X_q) = 0 & & H_q(X) \end{array}$$

So the first maps $(H_q(X_0) \rightarrow H_q(X_1) \rightarrow \dots)$ are isomorphisms, the map $H_q(X_{q+1}) \rightarrow H_q(X_q)$ is an injection, and the map $H_q(X_q) \rightarrow H_q(X_{q+1})$ is surjective. But also, $H_q(X_{q+1}) \cong H_q(X_{q+2}) \cong \dots$. But also, $H_q(X_0) \cong 0$, and we have:

COROLLARY 16.2. $H_q(X) = 0$ for $q > \dim X = n$.

LEMMA 16.3. $H_q(X_n) \cong H_q(X)$ for $n > 0$.

I want you to have the following picture in mind. We have a diagram coming from the lexseq in the homology of a pair:

$$\begin{array}{ccccc}
C_{n+1}(X) = H_{n+1}(X_{n+1}, X_n) & & & & 0 = H_{n-1}(X_{n-2}) \\
\downarrow \partial & \searrow d & & & \downarrow \\
H_n(X_n) & \xrightarrow{j} & C_n(X) = H_n(X_n, X_{n-1}) & \xrightarrow{\partial} & H_{n-1}(X_{n-1}) \\
\downarrow & & \searrow d & & \downarrow j \\
H_n(X_{n+1}) & & & & C_{n-1}(X) = H_{n-1}(X_{n-1}, X_{n-2}) \\
\downarrow & & & & \\
0 = H_n(X_{n+1}, X_n) & & & &
\end{array}$$

Now, $\partial \circ j = 0$. So the composite of the diagonals is zero, i.e., $d^2 = 0$, and we have a chain complex! More precisely, we get a chain complex, denoted $C_*(X)$. This is the “cellular chain complex” of X . We should compute the homology of this chain complex. Well, $H_n(C_*(X)) = \ker d / \text{Im } d$. Now, $\ker d = \ker(j \circ \partial)$. But j is injective, so $\ker d = \ker \partial$. Also, $\text{Im } d = \text{Im}(j \circ \partial) = j(\text{Im } \partial)$ because j is injective.

The kernel of ∂ is the image of j by exactness, but j is a monomorphism, so $\ker \partial \cong H_n(X)$. Now, $H_n(C_*(X)) \cong \frac{H_n(X)}{\text{Im}(\partial)}$. This is equal to $H_n(X_{n+1})$, again by exactness. But our lemma shows that $H_n(X_{n+1}) = H_n(X)$. In other words, we’ve proved:

THEOREM 16.4. *If X is a CW-complex, then $H_*(C_*(X)) \cong H_*(X)$. I didn’t use specific attaching maps at all, so this is natural in “skeletal” maps of CW-complexes.*

What is the differential? You have a relative cycle in dimension $(n+1)$, you’re taking its boundary, and then working relative the $(n-1)$ -skeleton. You’ll see this better in the example we’re going to do now, namely projective space.

EXAMPLE 16.5. We’ll try $H_*(\mathbf{RP}^n)$. We have: $\text{sk}_k(\mathbf{RP}^n) = \mathbf{RP}^k$, which are just 1-dimensional subspaces of \mathbf{R}^{k+1} . Think of the inclusion $\mathbf{R}^{k+1} \rightarrow \mathbf{R}^{n+1}$ as the inclusion of the first $(k+1)$ basis vectors. This is a CW-complex because the map $S^{k-1} \rightarrow \mathbf{RP}^{k-1}$ is a double cover, and you have a pushout:

$$\begin{array}{ccc}
S^{k-1} & \longrightarrow & \mathbf{RP}^{k-1} \\
\downarrow & & \downarrow \\
D^k & \longrightarrow & \mathbf{RP}^k
\end{array}$$

The attaching maps are the double cover maps.

The notation is as follows. $\mathbf{RP}^n = \mathbf{RP}^{n-1} \cup_f D^n = \mathbf{RP}^{n-1} \cup_f e^n$. The e^n is the notation for an n -cell. In particular, $\mathbf{RP}^n = e_0 \cup_f e_1 \cup_f \dots \cup_f e_n$. You have:

$$\begin{array}{ccccccc}
0 & \longleftarrow & C_0(\mathbf{RP}^n) & \longleftarrow & C_1(\mathbf{RP}^n) & \longleftarrow \dots \longleftarrow & C_n(\mathbf{RP}^n) & & 0 \\
& & \downarrow & & \downarrow & & \downarrow & & \downarrow \\
& & \mathbf{Z}\langle e^0 \rangle & \xleftarrow{d=0} & \mathbf{Z}\langle e^1 \rangle & \xleftarrow{\quad} & \dots & \xleftarrow{\quad} & \mathbf{Z}\langle e^n \rangle
\end{array}$$

The first differential is zero because we know what $H_0(\mathbf{RP}^n)$ is (it’s \mathbf{Z} !). I have $S^{n-1} \xrightarrow{f} \mathbf{RP}^{n-1} \rightarrow \mathbf{RP}^{n-1}/\mathbf{RP}^{n-2} = S^{n-1}$. Also recall the commutative diagram from before.

$$\begin{array}{ccccc}
H_n(D^n, S^{n-1}) & \xrightarrow{\partial} & H_{n-1}(S^{n-1}) & \longrightarrow & H_{n-1}(S^{n-1}, *) \\
\downarrow \cong & & \downarrow \cong & & \downarrow \cong \\
C_n = H_n(\mathbf{RP}^n, \mathbf{RP}^{n-1}) & \xrightarrow{\partial} & H_{n-1}(\mathbf{RP}^{n-1}) & \longrightarrow & H_{n-1}(\mathbf{RP}^{n-1}, \mathbf{RP}^{n-2}) = C_{n-1}
\end{array}$$

The first map on the top is an isomorphism. The bottom composite is our differential. So the map $H_{n-1}(S^{n-1}) \rightarrow H_{n-1}(S^{n-1}, *)$. Therefore, $S^{n-1} \xrightarrow{\text{double cover}} \mathbf{RP}^{n-1} \xrightarrow{\text{pinching}} S^{n-1}$.

$$\begin{array}{ccccc} S^{n-1} & \xrightarrow{\text{double cover}} & \mathbf{RP}^{n-1} & \xrightarrow{\text{pinching}} & S^{n-1} \\ & \searrow & & \swarrow & \\ & & S^{n-1}/S^{n-2} = S^{n-1} \vee S^{n-1} & & \end{array}$$

One of the maps $S^{n-1} \rightarrow S^{n-1}$ from the wedge is the identity, and the other map is the antipodal map, as can be seen by looking at a picture. If α is the antipodal map, then $S^{n-1} \vee S^{n-1} \rightarrow S^{n-1}$ is $[1, \alpha]$. If σ is a generator of $H_{n-1}(S^{n-1})$, we have $\sigma \mapsto (\sigma, \sigma) \mapsto \sigma + \alpha_*\sigma$. What is the degree of $\alpha_* : H_{n-1}(S^{n-1}) \rightarrow H_{n-1}(S^{n-1})$, so $\deg \alpha = (-1)^n$. Thus the composite, and hence the attaching map, is $(1 + (-1)^n)\sigma$. This means the cellular chain complex is:

$$0 \xleftarrow{0} \mathbf{Z} \xleftarrow{2} \mathbf{Z} \xleftarrow{0} \cdots \xleftarrow{2 \text{ or } 0} \mathbf{Z} \xleftarrow{\quad} 0 \xleftarrow{\quad} 0 \xleftarrow{\quad} \cdots$$

We'll continue next time⁴.

17. Missing lemmas, \mathbf{RP}^n again, and even CW-complexes

LEMMA 17.1. We want to show that $H_*(X_n, X_{n-1}) \cong H_*(X_n/X_{n-1}, *)$. We have the characteristic map $(\coprod_{\alpha} D^n, \coprod_{\alpha} S^{n-1}) \rightarrow (X_n, X_{n-1})$, where the map $\coprod_{\alpha} S^{n-1} \rightarrow X_{n-1}$ is the attaching map.

$$\begin{array}{ccc} H_*(X_n, X_{n-1}) & \longleftarrow & H_*(\coprod_{\alpha} D^n, \coprod_{\alpha} S^{n-1}) \\ \downarrow \cong & & \downarrow \cong, \text{homework} \\ H_*(X_n/X_{n-1}, *) & \xleftarrow{\cong} & H_*(\bigvee_{\alpha} S^n, *) \end{array}$$

For preparation, we will talk about “strong deformation retracts”. For example, $S^{n-1} \hookrightarrow D^n - \{0\}$. You just deform everything back radially.

DEFINITION 17.2. A subspace of a space A inside X is a *strong deformation retract* if there is a homotopy $h : X \times I \rightarrow X$ such that $h(x, 0) = x$, $h(x, 1) \in A$, and $h(a, t) = a$ if $a \in A$.

EXAMPLE 17.3. For example, for the map $S^{n-1} \hookrightarrow D^n - \{0\}$ can be defined as $h(x, t) = (1-t)x + t \frac{x}{\|x\|}$.

A strong deformation retract is a homotopy equivalence, because we can just define the homotopy inverse to be $h(-, 1)$. Then $A \hookrightarrow X \xrightarrow{h(-, 1)} A$ is the identity, and $X \xrightarrow{h(-, 1)} A \hookrightarrow X$ is homotopic to the identity.

EXAMPLE 17.4. The map $\coprod_{\alpha} S_{\alpha}^{n-1} \xrightarrow{\text{Id}} (D_{\alpha}^{n-1} - \{0\})$.

Terminology: if X is a CW-complex with filtration $X_0 \subseteq X_1 \subseteq \cdots \subseteq X$. A choice of characteristic maps is a “cell structure” for X . Note that this isn't specified in the CW-structure.

PROOF OF THE LEMMA. Let X be a CW-complex, with a choice of a cell structure, say with characteristic maps $g_{\alpha} : D_{\alpha}^n \rightarrow X_n$. Let $C_n = \{g_{\alpha}(0) | \alpha \in A_n\}$. We know that $X_{n-1} \hookrightarrow X_n - C_n$. We claim that this is a strong deformation retract. This follows from our observation that $\coprod_{\alpha} S_{\alpha}^{n-1} \xrightarrow{\text{Id}} (D_{\alpha}^{n-1} - \{0\})$ is a strong deformation retract. In particular, $X_{n-1} \hookrightarrow X_n - C_n$ is a homotopy equivalence.

For example, consider the torus. If you look at the fundamental polygon, and remove a hole, you can retract everything back to the boundary.

Now, we have:

$$\begin{array}{ccc} H_*(\coprod_{\alpha} D_{\alpha}^n, \coprod_{\alpha} S_{\alpha}^{n-1}) & \longrightarrow & H_*(X_n, X_{n-1}) \\ \downarrow & & \downarrow \\ H_*(\coprod_{\alpha} D_{\alpha}^n, \coprod_{\alpha} (D_{\alpha}^n - \{0\})) & & H_*(X_n, X_n - C_n) \end{array}$$

⁴Why don't we work in $\mathbf{Z}/2\mathbf{Z}$ coefficients? This is so much easier then. :P

The downwards arrows are isomorphisms because of strong deformation retractions, homotopy invariance, lexseq, and the 5-lemma. Recall that if $U \subseteq A \subseteq X$, then $H_*(X - U) \cong H_*(X, A)$ if $\overline{U} \subseteq \text{int}(A)$. Suppose we consider $X_{n-1} \subseteq X_n - C_n \subseteq X_n$. This is an excision because X_{n-1} is already closed, and $X_n - C_n$ is already open. Then excision tells us that $H_*(X_n - X_{n-1}, X_n - X_{n-1} - C_n)$. This means we can extend the diagram as follows.

$$\begin{array}{ccc}
H_* (\coprod_{\alpha} D_{\alpha}^n, \coprod_{\alpha} S_{\alpha}^{n-1}) & \longrightarrow & H_*(X_n, X_{n-1}) \\
\downarrow & & \downarrow \\
H_* (\coprod_{\alpha} D_{\alpha}^n, \coprod_{\alpha} (D_{\alpha}^n - \{0\})) & & H_*(X_n, X_n - C_n) \\
\cong \uparrow & & \cong \uparrow \\
H_* (\coprod_{\alpha} (D_{\alpha}^n - S_{\alpha}^{n-1}), \coprod_{\alpha} (D_{\alpha}^n - S_{\alpha}^{n-1} - \{0\})) & \longrightarrow & H_*(X_n - X_{n-1}, X_n - X_{n-1} - C_n)
\end{array}$$

The left arrow on the second row is the excision from $\coprod_{\alpha} S_{\alpha}^{n-1} \subseteq \coprod_{\alpha} D_{\alpha}^n - \{0\} \subseteq \coprod_{\alpha} D_{\alpha}^n$. The bottom right arrow is an isomorphism because $\coprod_{\alpha} (D_{\alpha}^n - S_{\alpha}^{n-1}), \coprod_{\alpha} (D_{\alpha}^n - S_{\alpha}^{n-1} - \{0\}) \rightarrow (X_n - X_{n-1}, X_n - X_{n-1} - C_n)$ is a homeomorphism, and hence an isomorphism. This concludes the proof of the lemma. \square

Now for the second lemma

LEMMA 17.5. *We have:*

$$\begin{array}{ccccccc}
\cdots & \longrightarrow & H_q(X_{q-1}) & \longrightarrow & H_q(X_q) & \twoheadrightarrow & H_q(X_{q+1}) \xrightarrow{\cong} H_q(X_{q+2}) \xrightarrow{\cong} \cdots \\
& & \parallel & & \downarrow \cong & \searrow & \downarrow \\
& & 0 & & H_n(C_*(X_n)) & & H_n(X) \\
& & & & \parallel & & \uparrow \\
& & & & \ker(C_n(X) \xrightarrow{d} C_{n-1}(X)) & & \\
& & & & \downarrow & & \\
& & & & C_n(X_n) & &
\end{array}$$

So $H_q(X_q)$ is free abelian. The lemma is that $H_n(X_{n+1}) \rightarrow H_n(X)$ is an isomorphism.

For preparation, we'll talk about subcomplexes.

DEFINITION 17.6. Let X be a CW-complex with a cell structure $\{g_{\alpha} : D_{\alpha}^n \rightarrow X_n | \alpha \in A_n\}$. A subcomplex is a subspace $Y \subseteq X$ such that for all n , there are $B_n \subseteq A_n$ such that $Y_n = Y \cap X_n$ is a CW-filtration for Y with characteristic maps $\{g_{\beta} | \beta \in B_n\}$.

EXAMPLE 17.7. $X_n \subseteq X$ is a subcomplex.

PROPOSITION 17.8 (Bredon, p. 196). *Let X be a CW-complex with a chosen cell structure. Let $K \subseteq X$ be compact. Then K sits inside some finite subcomplex.*

REMARK 17.9. For fixed cell structures, unions and intersections of subcomplexes are subcomplexes.

PROOF OF LEMMA 2. Let's do surjectivity. Pick $c \in Z_n(C_{\bullet})(X)$. Well, $c = \sum c_i \sigma_i$ where $\sigma_i : \Delta^n \rightarrow X$. Since Δ^n is compact, $\sigma_i(\Delta^n)$ is compact, and thus $\bigcup \sigma_i(\Delta^n)$ is compact, and hence it lies in a finite subcomplex. Hence it sits in some X_N for some N , possibly very large. Thus $c \in S_n(X_N) \subseteq S_n(X)$. It's still a cycle because it was a cycle before. (This is a stronger result, we've proved that cycles come from cycles). This is more than enough.

Let's do injectivity. Let $c \in Z_n(C_{\bullet})(X_{n+1})$. If i_* denotes the maps $H_n(X_q) \rightarrow H_n(X)$, then $i_*c \in Z_n(C_{\bullet})(X)$. Suppose there was b such that $db = i_*(c)$, so that $i_*(c) = 0$ in $H_n(X)$. Well, $b = \sum b_i \tau_i$ where $\tau_i : \Delta^{n+1} \rightarrow X$. Then $\bigcup \tau_i(\Delta^{n+1})$ is compact, and thus sits inside X_M . So $b \in S_{n+1}(X_M)$, so the equation $db = i_*(c)$ is still true in X_M . So $[c] = 0$ in $H_n(X_M)$. It's not quite what I wanted.

This is good enough, because the maps $H_n(X_{n+1}) \rightarrow H_n(X_{n+2}) \rightarrow \cdots$ are all isomorphisms. \square

We'll talk about real projective space next week.

REMARK 17.10. Suppose X has only even cells. For example, \mathbf{CP}^n , namely complex lines in \mathbf{C}^{n+1} through the origin, or $S^{2n+1}/v \sim \zeta z$ for any $\zeta \in \mathbf{C}$ such that $|\zeta| = 1$. I have a map $S^{2n-1} \rightarrow \mathbf{CP}^{n-1}$. We have:

$$\begin{array}{ccc} S^{2n-1} & \hookrightarrow & D^{2n} \\ \downarrow & & \downarrow \\ \mathbf{CP}^{n-1} & \hookrightarrow & \mathbf{CP}^n \end{array}$$

The same argument that we had before for \mathbf{RP}^n show that the CW structure on \mathbf{CP}^n is $\mathbf{CP}^0 \subseteq \mathbf{CP}^1 \subseteq \dots \subseteq \mathbf{CP}^n$. So $\mathbf{CP}^n = D^0 \cup D^2 \cup \dots \cup D^{2n}$.

Anyway, if you had X only with even cells, then $C_{\text{odd}}(X) = 0$, so $H_n(X) = \begin{cases} C_n(X) & n = 2k \\ 0 & n = 2k + 1 \end{cases}$.

We've shown that:

$$H_k(\mathbf{CP}^n) = \begin{cases} \mathbf{Z} & k = 2n \\ 0 & k = 2n + 1 \end{cases}$$

18. Relative attaching maps, \mathbf{RP}^n , Euler characteristic, and homology approximation

Recall:

$$\begin{array}{ccccccc} H_n(\coprod_{\alpha} D_{\alpha}^n) & \xrightarrow[\cong]{\partial} & H_{n-1}(\coprod_{\alpha} S_{\alpha}^{n-1}) & & H_{n-1}(\coprod_{\beta} D_{\beta}^{n-1}, \coprod_{\beta} S_{\beta}^{n-2}) & \xrightarrow[\cong]{\partial} & \tilde{H}_{n-1}(\bigvee_{\beta} D_{\beta}^{n-1}/S_{\beta}^{n-2}) \\ \text{char. map} \downarrow \cong & & \text{attaching map} \downarrow & & \nearrow \cong & & \downarrow \cong \\ H_n(X_n, X_{n-1}) & \xrightarrow{\partial} & H_{n-1}(X_{n-1}) & \xrightarrow{j} & H_{n-1}(X_{n-1}, X_{n-2}) & \xrightarrow[\cong]{\partial} & \tilde{H}_{n-1}(X_{n-1}/X_{n-2}) \\ \parallel & & & & \parallel & & \\ C_n(X) & \xrightarrow{d} & & & C_{n-1}(X) & & \end{array}$$

This boundary map d is the effect of $H_{n-1}(-)$ to:

$$\begin{array}{ccccc} \coprod_{\alpha} S_{\alpha}^{n-1} & \xrightarrow{f_{n-1}} & X_{n-1} & \longrightarrow & X_{n-1}/X_{n-2} \cong \bigvee_{\beta} D_{\beta}^{n-1}/S_{\beta}^{n-2} \\ & & \downarrow & & \\ & & X_n & & \end{array}$$

The composite in the top row of this diagram is called the “relative attaching map” because you’re working relative to the $(n-2)$ -skeleton.

Before, I coyly said before that there is a monoid homomorphism $\deg : [S^{n-1}, S^{n-1}] \rightarrow \mathbf{Z}_{\times}$ that sends $f \mapsto (H_{n-1}(f) : H_{n-1}(S^{n-1}) \rightarrow H_{n-1}(S^{n-1}))$. I said that this was surjective. This is actually an isomorphism. We won’t prove injectivity here, but we’ll do this in 18.906.

18.1. \mathbf{RP}^m . Recall the CW-structure $\mathbf{RP}^0 \subseteq \mathbf{RP}^1 \subseteq \dots \subseteq \mathbf{RP}^{n-1} \subseteq \mathbf{RP}^n \subseteq \dots \subseteq \mathbf{RP}^m$, where \mathbf{RP}^{n-1} is the collection of lines in \mathbf{R}^n . The attaching map is the double cover $\pi : S^{n-1} \rightarrow \mathbf{RP}^{n-1}$ to get a pushout

$$\begin{array}{ccc} S^{n-1} & \xrightarrow{\text{double cover}} & \mathbf{RP}^{n-1} \\ \downarrow & & \downarrow \\ D^n & \longrightarrow & \mathbf{RP}^n \end{array}$$

The cellular chain complex C_* will look like:

$$0 \longleftarrow C_0 = \mathbf{Z} \longleftarrow C_1 = \mathbf{Z} \longleftarrow \dots \longleftarrow C_{n-1} = \mathbf{Z} \longleftarrow C_n = \mathbf{Z} \longleftarrow \dots \longleftarrow C_m = \mathbf{Z} \longleftarrow 0$$

The first map $C_1 \rightarrow C_0$ is easy because \mathbf{RP}^m is connected. Thus $C_1 \rightarrow C_0$ is the zero map.

The relative attaching maps are: $S^{n-1} \xrightarrow{\pi} \mathbf{RP}^{n-1} \rightarrow \mathbf{RP}^{n-1}/\mathbf{RP}^{n-2} \cong S^{n-1}$. All we have to do is figure out the degree of this map. What happens when I collapse out \mathbf{RP}^{n-2} ? This has the effect of collapsing out by the equator because you are collapsing all those points on the equator of S^{n-1} that go to \mathbf{RP}^{n-1} . So the composition $S^{n-1} \xrightarrow{\pi} \mathbf{RP}^{n-1} \rightarrow \mathbf{RP}^{n-1}/\mathbf{RP}^{n-2} \cong S^{n-1}$ splits as:

$$\begin{array}{ccccc} S^{n-1} & \xrightarrow{\pi} & \mathbf{RP}^{n-1} & \longrightarrow & \mathbf{RP}^{n-1}/\mathbf{RP}^{n-2} \cong S^{n-1} \\ & \searrow \text{pinching} & & \nearrow & \\ & & S^{n-1}/S^{n-2} & \xlongequal{\quad} & S_u^{n-1} \vee S_\ell^{n-1} \end{array}$$

The map $S_u^{n-1} \vee S_\ell^{n-1} \rightarrow S^{n-1}$ sends the top hemisphere to S^{n-1} itself via the identity, so the first factor is a homeomorphism. The lower hemisphere will be sent to S^{n-1} via the antipodal map (called α), which is also a homeomorphism, but I won't draw this in because I don't want to do that here. What does this do in homology? In $(n-1)$ -dimensional homology, we choose a generator σ of $H_{n-1}(S^{n-1})$.

The pinch map sends σ to (σ, σ) . The map from $S_u^{n-1} \vee S_\ell^{n-1}$ to S^{n-1} sends $(\sigma, \sigma) \mapsto \sigma + \alpha_*\sigma$. The degree of α_* is $(-1)^n$, as you saw in homework. The composite in homology for S^{n-1} is multiplication by $1 + (-1)^n$. Thus the differential $d : C_n(X) \rightarrow C_{n-1}(X)$ is multiplication by $1 + (-1)^n$. So the cellular chain complex now looks like, if n is even:

$$0 \longleftarrow C_0 = \mathbf{Z} \xleftarrow{0} C_1 = \mathbf{Z} \xleftarrow{2} C_2 = \mathbf{Z} \xleftarrow{0} \cdots \xleftarrow{0} C_{n-1} = \mathbf{Z} \xleftarrow{2} C_n = \mathbf{Z} \longleftarrow 0$$

and if n is odd:

$$0 \longleftarrow C_0 = \mathbf{Z} \xleftarrow{0} C_1 = \mathbf{Z} \xleftarrow{2} C_2 = \mathbf{Z} \xleftarrow{0} \cdots \xleftarrow{2} C_{n-1} = \mathbf{Z} \xleftarrow{0} C_n = \mathbf{Z} \longleftarrow 0$$

Thus:

$$H_k(\mathbf{RP}^n) = \begin{cases} \mathbf{Z} & k = 0 \text{ and } k = n \text{ odd} \\ \mathbf{Z}/2\mathbf{Z} & k \text{ odd, } 0 < k < n \\ 0 & \text{else} \end{cases}$$

This means that odd-dimensional real projective space is orientable, and even-dimensional real projective is non-orientable.

18.2. Euler char. On Friday, I made the comment that things are simpler if you have (?). Here's a lemma.

LEMMA 18.1. *If X is a CW-complex with only even cells (eg. $\mathbf{CP}^n, \mathbf{HP}^n$), then $H_{\text{odd}}(X) = 0$, and $H_{\text{even}}(X) = C_{\text{even}}(X)$. Actually, I can just write $H_*(X) \cong C_*(X)$. Even homology groups are free abelian groups with rank given by the number of $(2q)$ -cells.*

PROOF. Trivial. □

Here's a result that'll improve this.

THEOREM 18.2 ("Euler" because this is the generalization of the Euler characteristic). *Let X be a finite CW-complex⁵. (We write A_n to index the n -cells.)⁶ Then $\sum_{n=0}^{\infty} (-1)^n \#A_n =: \chi(X)$ = Euler characteristic is independent of the CW-structure on X .*

When n is even, the lemma is much stronger than this. I'm going to prove this theorem. Now I want to give a little reminder about the structure of finitely generated abelian groups.

⁵Some alarm starts ringing. "What are we supposed to do? It's just here to annoy us. It's ringing, but there's nothing to answer. Can we ignore it? (Turns off the light.) Let's just talk over it".

⁶Alarm ends, yay!

18.3. Finitely generated abelian groups. If you have an abelian group A , you have a torsion subgroup $T(A)$, i.e., elements of finite order in A , i.e., $\{a \in A | \exists n \in \mathbf{Z}_{>0}, na = 0\}$. Then $A/T(A)$ is *torsion free*. For a general abelian group, that's all you can say. Assume A is finitely generated. Then $A/T(A)$ is also a finitely generated torsion free abelian group (take the image of the generators of A). This is actually a *free abelian group*, and so it's isomorphic to \mathbf{Z}^r . We say that r is the *rank* of A . It's an invariant of A .

Another fact is the following. Recall that any subgroup of A is finitely generated (nontrivial fact). This means that $T(A)$ is finitely generated. It is true that $T(A) = \mathbf{Z}/n_1 \oplus \mathbf{Z}/n_2 \oplus \cdots \oplus \mathbf{Z}/n_t$ where $n_1|n_2|\cdots|n_t$, where t is well-defined and is “the number of torsion generators”. What this means for us is that $A \cong T(A) \oplus A/T(A) \cong \mathbf{Z}^r \oplus \mathbf{Z}/n_1 \oplus \mathbf{Z}/n_2 \oplus \cdots \oplus \mathbf{Z}/n_t$ where $n_1|n_2|\cdots|n_t$. If $0 \rightarrow A \rightarrow B \rightarrow C \rightarrow 0$ is a sexseq of finitely generated abelian groups, then $\text{rank}(A) + \text{rank}(B) = \text{rank}(C)$.

19. “Euler’s theorem”, and “homology approximation” - CTC Wall. I) Singular homology, II) CW complexes, III) “homological algebra”

THEOREM 19.1 (“Euler”). *Let X be a space which admits the structure of a finite CW complex. The sum $\sum_{h=0}^{\infty} (-1)^k \#(k\text{-cells})$ (generalizes $V - E + F$) is independent of that structure.*

PROOF. Pick a CW-structure. We have $0 \rightarrow C_n \rightarrow \cdots \rightarrow C_2 \rightarrow C_1 \rightarrow C_0 \rightarrow 0$. We also have a sexseq $0 \rightarrow Z_k \rightarrow C_k \rightarrow B_{k-1} \rightarrow 0$, and another one $0 \rightarrow B_k \rightarrow Z_k \rightarrow H_k \rightarrow 0$. Let's use them and facts about rank that I talked about on Monday to compute what this alternating sum is. The Euler sum is the same as:

$$\begin{aligned} \sum_{h=0}^{\infty} (-1)^k \#(k\text{-cells}) &= \sum_{k=0}^{\infty} (-1)^k \text{Rank}(C_k) \\ &= \sum_{k=0}^{\infty} (-1)^k \text{Rank}(Z_k) + \sum_{k=0}^{\infty} (-1)^k \text{Rank}(B_{k-1}) \\ &= \sum_{k=0}^{\infty} (-1)^k (\text{Rank}(H_k) + \text{Rank}(B_k) + \text{Rank}(B_{k-1})) \end{aligned}$$

The terms $\text{Rank } B_k + \text{Rank } B_{k+1}$ telescope because it's an alternating sum, and hence vanish. The sum is $\sum_{k=0}^{\infty} (-1)^k \text{Rank}(H_k)$. But $H_k(X) = H_k^{\text{sing}}(X)$ is an invariant of the space, independent of the CW-structure. \square

Given $H_k(X)$, X a finite type CW-complex, what's a lower bound on the number of k -cells? Let's see. $H_k(X)$ is finitely generated because $C_k(X) \subseteq Z_k(X)$ is, and it surjects onto $H_k(X)$. Thus $H_k(X) = \bigoplus_{i=1}^{t(k)} \mathbf{Z}/n_i(k) \oplus \mathbf{Z}^{r(k)}$ where the $n_1(k)|\cdots|n_{t(k)}(k)$ are the torsion indices.

The minimal chain complex with $H_k = \mathbf{Z}$ and $H_q = 0$ for $q \neq k$ is just the chain complex with 0 everywhere else except for \mathbf{Z} in the k th degree. The minimal chain complex with $H_k = \mathbf{Z}/n\mathbf{Z}$ and $H_q = 0$ for $q \neq k$ is just the chain complex with 0 everywhere else except for $\mathbf{Z} \xrightarrow{n} \mathbf{Z}$ in dimension $k+1$ to k . These things are called elementary chain complexes.

A lower bound on the minimal number of k -cells is $r(k) + t(k) + t(k-1)$ where the last term comes for the “torsion generator in dimension $k-1$ ” (didn't catch that).

THEOREM 19.2 (Wall). *Let X be a simply connected CW-complex of finite type. Then there exists a CW complex Y with $r(k) + t(k) + t(k-1)$ k -cells, for all k , and a homotopy equivalence $Y \rightarrow X$.*

I'm not going to prove this theorem. You can read Wall's theorem. You really can't ask for more. Oh, also here's a theorem.

THEOREM 19.3. *Let X be connected and pointed $* \in X$. Then $\pi_1(X, *) \rightarrow H_1(X, *)$ exists, called the Hurewicz homomorphism, and it factors as $\pi_1(X, *) \rightarrow \pi_1(X, *)^{ab} \rightarrow H_1(X, *)$. The last map is an isomorphism.*

Some examples of Wall's theorem:

EXAMPLE 19.4. We know that S^k has $\tilde{H}_q(X) = \mathbf{Z}$ when $q = k$ and 0 else. Can you construct a space with $\tilde{H}_q(X) = \mathbf{Z}/n\mathbf{Z}$ when $q = k$ and 0 else? We need to construct a space with the elementary chain complex with 0 everywhere else except for $\mathbf{Z} \xrightarrow{n} \mathbf{Z}$ in dimension $k+1$ to k . You need to have one 0-cell, do nothing until you get to dimension k , which is when you add a k -cell, and then use the attaching map $S^k \rightarrow S^k$ of degree n , i.e.:

$$\begin{array}{ccc} S^k & \xrightarrow{\text{degree } n} & S^k \\ \downarrow & & \downarrow \\ D^{k+1} & \longrightarrow & X \end{array}$$

For example, when $k = 1$ and $n = 2$, you have \mathbf{RP}^2 . This is called a “Moore space”.

I brought up doing this in more generality with generators and relations, and Professor Miller built up on that:

EXAMPLE 19.5. For more general abelian groups, you have a free abelian group F_0 sitting in a sexseq $0 \rightarrow F_1 \rightarrow F_0 \rightarrow M \rightarrow 0$ (this is an example of a *resolution of M* , which is what I’m going to start talking about). Then F_1 is also free. Pick some $k > 0$. You get a space whose homology is F_0 , namely $\bigvee_{\alpha} S^k$, and a space whose homology is F_1 , namely $\coprod S^k$. You can construct a map $\coprod S^k \rightarrow \bigvee_{\alpha} S^k$ such that the map $\alpha : F_1 \rightarrow F_0$ is what’s induced on homology. Then you get:

$$\begin{array}{ccc} \coprod S^k & \xrightarrow{\text{gives } \alpha} & \bigvee_{\alpha} S^k \\ \downarrow & & \downarrow \\ \coprod D^{k+1} & \longrightarrow & X \end{array}$$

Such an X is called a Moore space, and has homology M in dimension k and zero everywhere else. You can’t make this into a functor, i.e., this can’t be made into a functor $\mathbf{Ab} \rightarrow \mathbf{Top}$.

19.1. Homological algebra. You can put coefficients into homology. Let M an abelian group. You can talk about homology with coefficients in M . For example, $M = \mathbf{Z}, \mathbf{Q}, \mathbf{Z}/n\mathbf{Z}, \dots$. The $\mathbf{Z}/n\mathbf{Z}$ case when n is prime is pretty important because it’s then a field.

Given X , you get a singular simplicial set $\text{Sin}_*(X)$. Then we took the free abelian group S_* generated by $\text{Sin}_*(X)$. I.e., $S_n = \mathbf{Z}[\text{Sin}_n(X)] = \bigoplus_{\text{Sin}_n(X)} \mathbf{Z}$. But I could replace \mathbf{Z} with anything I wanted, and do the *exact* same construction. I can just as well as put any abelian group here.

Define the “singular chain complex with coefficients in M ” as $S_n(X; M) = \bigoplus_{\text{Sin}_n(X)} M$. There’s a boundary map $d : S_n(X; M) \rightarrow S_{n-1}(X; M)$. Then the homology $H(S_*(X; M)) =: H_*(X; M)$. You can verify all the Eilenberg-Steenrod axioms yourself, except for one, namely the dimension axiom - $H_k(*; M) =$

$$\begin{cases} M & k = 0 \\ 0 & k \neq 0 \end{cases}.$$

If you think about it, you’ll realize that this whole unit in CW-complexes didn’t use anything except for the Eilenberg-Steenrod axioms. This shows, by the way, that if you get some weird homology theory satisfying the Eilenberg-Steenrod axioms you get all the same results as if you used what we constructed before.

As an experiment, let’s compute $H_*(\mathbf{RP}^n; \mathbf{Z}/2\mathbf{Z})$. The cellular chain complex is $0 \rightarrow \mathbf{Z}/2\mathbf{Z} \rightarrow \dots \rightarrow \mathbf{Z}/2\mathbf{Z} \rightarrow \mathbf{Z}/2\mathbf{Z} \rightarrow 0$ where the maps are alternately multiplying by 2 and 0. But in this case, all the maps are 0 because $2 = 0!$ So $H_k(\mathbf{RP}^n; \mathbf{Z}/2\mathbf{Z}) = \begin{cases} \mathbf{Z}/2\mathbf{Z} & 0 \leq k \leq n \\ 0 & \text{else} \end{cases}$. How about $H_*(\mathbf{RP}^n; \mathbf{Q})$? Or $H_*(\mathbf{RP}^n; \mathbf{Z}[\frac{1}{p}])$

where $\mathbf{Z}[\frac{1}{p}] \subseteq \mathbf{Q}$? What about $\mathbf{Z}_{(p)} \subseteq \mathbf{Q}$ where you’ve localized at p ?

Anyway, if I consider $H_*(\mathbf{RP}^n; \mathbf{Z}[\frac{1}{2}])$, then the cellular chain complex simplifies, but in a different way. You have $0 \rightarrow \mathbf{Z}[\frac{1}{2}] \rightarrow \dots \rightarrow \mathbf{Z}[\frac{1}{2}] \rightarrow \mathbf{Z}[\frac{1}{2}] \rightarrow 0$. Multiplication by 2, however, is an isomorphism. So,

$$H_k(\mathbf{RP}^n; \mathbf{Z}[\frac{1}{2}]) = \begin{cases} \mathbf{Z}[\frac{1}{2}] & q = 0, n, q \text{ odd} \\ 0 & \text{else} \end{cases}. \text{ You get a much simpler result. From this point of view, even}$$

projective spaces look like a point, and odd projective spaces look like a sphere!

It's a little awkward to go through this thing. I'd like to understand:

QUESTION 19.6. How is $H_*(X; M)$ related to $H_*(X) = H_*(X; \mathbf{Z})$? This is a reasonable question.

The answer is called the “universal coefficient theorem”. I'll spend a few days developing what we need to talk about this.

I want to talk about tensor products. Let me take a poll. Do you know tensor products? Working with a commutative ring instead of \mathbf{Z} ? Actually, all of these examples $M = \mathbf{Z}, \mathbf{Q}, \mathbf{Z}/n\mathbf{Z}, \mathbf{Z}[\frac{1}{p}] \subseteq \mathbf{Q} \supseteq \mathbf{Z}_{(p)}, \dots$ are rings. The boundary map $d : S_n(X; M) \rightarrow S_{n-1}(X; M)$ is a module homomorphism if $M = R$ is a (*always commutative*) ring.

This means that if R is a commutative ring, then $H_*(X; R)$ is an R -module. If R is a ring and M is an R -module, then $H_*(X; M)$ is an R -module. Just look at what you have here. The $\bigoplus_{\text{Sin}_n(X)} M$ is an R -module, and d is an R -module homomorphism.

I'll admit, this is a little bit scary, because commutative rings are pretty complicated in general. I won't talk about some weirdo rings, though. I'll develop this more on Friday. Let me pass out homework.

20. \otimes

Welcome to algebraic topology! This is family weekend, so welcome. Today'll be more about algebra, and there'll be very little topology, I'm afraid. Today'll be about tensor products. I got your permission to talk about modules over a commutative ring. We're always going to let R be a commutative ring (they're going to be simple; for example, $\mathbf{Q}, \mathbf{F}_p, \mathbf{Z}, \mathbf{Z}/n\mathbf{Z}, \dots$, PIDs).

I want to tell you that the category of R -modules is what's called a “categorical ring”, where the addition corresponds to the direct sum, the zero element is the zero module, 1 is R itself, and multiplication is where you put a circle around a multiplication symbol.

The reason we do this is because of bilinear maps. Let me recall the definition of a bilinear map.

DEFINITION 20.1. If I have M, N, P are R -modules, then a bilinear (or if you want to be annoying, R -bilinear) map is a map $\beta : M \times N \rightarrow P$ such that $\beta(x + x', y) = \beta(x, y) + \beta(x', y)$ and $\beta(x, y + y') = \beta(x, y) + \beta(x, y')$, and such that $\beta(rx, y) = r\beta(x, y)$ and $\beta(x, ry) = r\beta(x, y)$.

EXAMPLE 20.2. $\mathbf{R}^n \times \mathbf{R}^n \rightarrow \mathbf{R}$ given by the dot product is a \mathbf{R} -bilinear map. The cross product $\mathbf{R}^3 \times \mathbf{R}^3 \rightarrow \mathbf{R}$ is \mathbf{R} -bilinear. More generally, if R is a ring then the multiplication $R \times R \rightarrow R$ is R -bilinear, and the multiplication on an R -module M given by $R \times M \rightarrow M$ is R -bilinear. This enters into topology because the map $H_n(X; R) \times H_n(Y; R) \xrightarrow{\times} H_{m+n}(X \times Y; R)$ is R -bilinear.

Wouldn't it be great to reduce stuff about bilinear maps to linear maps? We're going to do this by means of the universal property.

DEFINITION 20.3. Let M, N be R -modules. A *tensor product* of M, N is a R -module P and a bilinear map $M \times N \xrightarrow{\beta_0} P$ such that for every bilinear map $M \times N \xrightarrow{\beta} Q$ there is a unique factorization.

$$\begin{array}{ccc} M \times N & \xrightarrow{\beta_0} & P \\ & \searrow \beta & \downarrow f \\ & & Q \end{array}$$

through an R -module homomorphism f . It's easy to check that $f \circ \beta_0$ is bilinear.

So β_0 is universal bilinear map out of $M \times N$. Instead of β_0 we're going to write $M \times N \xrightarrow{\otimes} P$. This means that $\beta(x, y) = f(x \otimes y)$ in the above diagram. There are lots of things to say about this. When you have something that is defined via a universal property, you first have to check that it exists!

CONSTRUCTION 20.4. I want to construct an R -bilinear map out of $M \times N$. I guess I should say it like this. Let $\beta : M \times N \rightarrow Q$ be any R -bilinear map. This β isn't linear. Maybe we should first extend it to a linear map. Consider $R\langle M \times N \rangle$, the free R -module generated by $M \times N$. Well, β is a map of sets, so there's a unique R -linear homomorphism $\bar{\beta} : R\langle M \times N \rangle \rightarrow Q$. Then I get a factorization:

$$\begin{array}{ccc} M \times N & \xrightarrow{\beta} & Q \\ & \searrow [-] \quad \nearrow \bar{\beta} & \\ & R\langle M \times N \rangle & \end{array}$$

The map $[-]$ isn't bilinear. So we should quotient $R\langle M \times N \rangle$ by a submodule S of relations. More precisely, S is the sub R -module generated by the relations needed to map $[-]$ a R -bilinear map, namely:

- (1) $[(x + x', y)] - [(x, y)] - [(x' - y)]$.
- (2) $[(x, y + y')] - [(x, y)] - [(x, y')]$.
- (3) $[(rx, y)] - r[(x, y)]$.
- (4) $[(x, ry)] - r[(x, y)]$.

for all $x, x' \in M$ and $y, y' \in N$. Now, this map $[-]$ is bilinear - we've quotiented out by all things that made it false! Now the map $R\langle M \times N \rangle \rightarrow Q$ factors through via $R\langle M \times N \rangle \rightarrow R\langle M \times N \rangle/S \xrightarrow{f} Q$ because the map $\bar{\beta}$ is linear, and f is unique because the $\bar{\beta}$ is unique, so there's at most one factorization. We just checked that there was one, so we're done. We'll also write the composition $M \times N \xrightarrow{[-]} R\langle M \times N \rangle \rightarrow R\langle M \times N \rangle/S$ as \otimes .

You're never going to use this construction to compute anything. If you find yourself using this construction, stop and think about what you're doing.

REMARK 20.5. Note that the image of (m, n) in $R\langle M \times N \rangle/S$ generates $R\langle M \times N \rangle/S$ as an R -module. The R -module $R\langle M \times N \rangle/S$ contains elements of the form $x \otimes y$ with $x \in M$ and $y \in N$ because they generate $R\langle M \times N \rangle$, and $R\langle M \times N \rangle/S$ is a quotient of that.

These $x \otimes y$ are called "decomposable tensors". (I've heard them called pure tensors.)

What are the properties of $R\langle M \times N \rangle/S =: P$?

- (1) How many maps are there that make the following diagram commute?

$$\begin{array}{ccc} & & P \\ & \nearrow \otimes & \vdots \\ M \otimes N & & P \\ & \searrow \otimes & \vdots \\ & & P \end{array}$$

By the uniqueness statement, there's only one map, namely the identity!

- (2) Suppose that we have two tensor products of M and N , say P and P' . We have

$$\begin{array}{ccc} & & P \\ & \nearrow \otimes & \uparrow \\ M \otimes N & & b' \\ & \searrow \otimes & \downarrow \\ & & P' \end{array}$$

And b, b' are unique. If you compose b and b' , you'll see that you get the identity of P and P' , depending on how you compose the maps. More precisely, you have:

$$\begin{array}{ccc}
 & & P \\
 & \nearrow \otimes & \downarrow b \\
 M \otimes N & & P' \\
 & \searrow \otimes & \downarrow b' \\
 & & P'
 \end{array}$$

and

$$\begin{array}{ccc}
 & & P' \\
 & \nearrow \otimes & \downarrow b' \\
 M \otimes N & & P \\
 & \searrow \otimes & \downarrow b \\
 & & P'
 \end{array}$$

Thus $bb' = 1$ and $b'b = 1$. So b, b' are isomorphisms, i.e., $P \cong P'$. We say that there is a canonical⁷ isomorphism between any two constructions of a tensor products. The universal property defines the object up to canonical isomorphism. This is a general principle.

We can thus write the tensor product as if it just depended on just M and N . We write $M \otimes N$. A general element is a finite sum $\sum_i x_i \otimes y_i$. To be really honest, we'll write $M \otimes_R N$. If R is understood, we'll omit it. I'll usually forget to add the \otimes_R , and simply write \otimes .

- (3) Functoriality. If I have homomorphisms $M \times N \xrightarrow{f \times g} M' \times N'$. I have:

$$\begin{array}{ccc}
 M \times N & \xrightarrow{\otimes} & M \otimes N \\
 \downarrow f \times g & \searrow & \downarrow \\
 M' \times N' & \xrightarrow{\otimes} & M' \otimes N'
 \end{array}$$

The dotted map exists because the diagonal map is R -bilinear. We write the map $M \otimes N \rightarrow M' \otimes N'$ as $f \otimes g$. We need to check stuff though.

$$\begin{array}{ccc}
 M \times N & \xrightarrow{\otimes} & M \otimes N \\
 \downarrow f \times g & \searrow & \downarrow f \otimes g \\
 M' \times N' & \xrightarrow{\otimes} & M' \otimes N' \\
 \downarrow f' \times g' & \searrow & \downarrow f' \otimes g' \\
 M'' \times N'' & \xrightarrow{\otimes} & M'' \otimes N''
 \end{array}$$

And the composite matches up, i.e., $(f' \otimes g')(f \otimes g) = (f'f) \otimes g'g$.

- (4) I said that this was gonna be a categorical ring, so we need to check this. Well, $R \otimes_R M$ should be isomorphic to M . Let's think about this for a minute. I just need to check the universal property. Suppose I have an R -bilinear map $\beta : R \times M \rightarrow P$. We already have a universal R -bilinear map $\varphi : R \times M \rightarrow M$. I have to construct a universal factorization $f : M \rightarrow P$. Just let $f(x) = \beta(1, x)$. It's R -bilinear. We can check that this diagram commutes now because $f(\varphi(r, x)) = f(rx) = \beta(1, rx) = r\beta(1, x) = \beta(r, x)$. Well, this map $R \times M \rightarrow M$ is surjective, so there's at most one factorization. So we're done. There are other checks that are extremely boring, but they're part of the toolkit.

⁷This means god given, but here it means that it's naturally constructed.

I need to check that $L \otimes (M \otimes N) \cong (L \otimes M) \otimes N$ that's compatible with $L \times (M \times N) \cong (L \times M) \times N$. There's a canonical isomorphism. I don't know how to not say that this is trivial. Also, we need to check that $M \otimes N \cong N \otimes M$. (Just do this yourself. It's really easy.)

- (5) What happens with $M \otimes (\bigoplus_{\alpha \in A} N_\alpha)$? It might be a finite direct sum, or maybe an uncountable collection. How does this relate to $\bigoplus_{\alpha \in A} (M \otimes N_\alpha)$? Let's construct a map $\bigoplus_{\alpha \in A} (M \otimes N_\alpha) \rightarrow$

$M \otimes \left(\bigoplus_{\alpha \in A} N_\alpha \right)$. We just need to define maps $M \otimes N_\alpha \rightarrow M \otimes (\bigoplus_{\alpha \in A} N_\alpha)$ because direct sums are coproducts. Let this map be $1 \otimes \text{in}_\alpha$ where $\text{in}_\alpha : N_\alpha \rightarrow \bigoplus_{\alpha \in A} N_\alpha$. These give you a map $f : \bigoplus_{\alpha \in A} (M \otimes N_\alpha) \rightarrow M \otimes (\bigoplus_{\alpha \in A} N_\alpha)$

What about a map the other way? This is a bit trickier. An element of $M \otimes (\bigoplus_{\alpha \in A} N_\alpha)$ is $x \otimes (y_\alpha)_{\alpha \in A}$, where you note that $y_\alpha = 0$ for all but finitely many $\alpha \in A$. Define $g : M \otimes (\bigoplus_{\alpha \in A} N_\alpha) \rightarrow \bigoplus_{\alpha \in A} (M \otimes N_\alpha)$ via $x \otimes (y_\alpha)_{\alpha \in A} \mapsto (x \otimes y_\alpha)_{\alpha \in A}$. It's up to you to check that these are inverses and that you can extend to a general nondecomposable tensor by linearity.

We have not done any computations yet. I guess I should end with the statement that $S_*(X; M) := S_*(X) \otimes_R M$ if M is an R -module. We'll discuss on Monday the question we raised last time, namely:

QUESTION 20.6. How is $H_*(X; M)$ related to $H_*(X) = H_*(X; \mathbf{Z})$? This is a reasonable question.

21. Tensor and Tor

Office hours are: for Hood, today from 1:30 to 3:30 in 2-390, and for me on Tuesday from 1 to 3 in 2-478. Point-set topology is the hardest part of this course, sorry for messing up the question on this week's pset. I like to emphasize the algebraic part.

21.1. Properties over \otimes_R .

- (6) A ring is precisely specified by a map $R \otimes_{\mathbf{Z}} R \xrightarrow{\mu} R \xleftarrow{\eta} \mathbf{Z}$. You can define a ring purely diagrammatically. Associativity is commutativity of the following diagram:

$$\begin{array}{ccc} R \otimes R \otimes R & \xrightarrow{\mu \otimes 1} & R \otimes R \\ \downarrow 1 \otimes \mu & & \downarrow \mu \\ R \otimes R & \xrightarrow{\mu} & R \end{array}$$

The identity map is commutativity of the following diagram.

$$\begin{array}{ccccc} \mathbf{Z} \otimes R & \xrightarrow{\eta \otimes 1} & R \otimes R & \xleftarrow{1 \otimes \eta} & R \otimes \mathbf{Z} \\ & \searrow \cong & \downarrow \mu & \swarrow \cong & \\ & & R & & \end{array}$$

In fact, an R -module is an abelian group with a map $R \otimes M \xrightarrow{\varphi} M$ such that the following diagram commutes.

$$\begin{array}{ccc} R \otimes R \otimes M & \xrightarrow{\mu \otimes 1} & R \otimes M \\ \downarrow 1 \otimes \eta & & \downarrow \varphi \\ R \otimes M & \xrightarrow{\varphi} & R \end{array}$$

If A is an abelian group, then $R \otimes A$ is an R -module, where the multiplication is: $R \otimes (R \otimes A) \rightarrow (R \otimes R) \otimes A \xrightarrow{\mu \otimes 1} R \otimes A$. If A is an abelian group, then $A \rightarrow R \otimes A$ sending $a \mapsto 1 \otimes a$ is universal for maps from A to an R -module. We say that it's "initial". This means that if M is an R -module,

there is a factorization:

$$\begin{array}{ccc} A & \longrightarrow & R \otimes A \\ \downarrow f & \swarrow & \\ M & & \end{array}$$

Where the map $R \otimes A \rightarrow M$ is an R -module homomorphism and the map $A \rightarrow M$ is an abelian group homomorphism. Why is this true? We have a map $R \otimes A \xrightarrow{1 \otimes f} R \otimes M$, so the multiplication $\varphi : R \otimes M \rightarrow M$ is what we want. I.e., the extension is the composition:

$$\begin{array}{ccc} A & \longrightarrow & R \otimes A \\ \downarrow f & \swarrow \varphi \circ (1 \otimes f) & \downarrow 1 \otimes f \\ M & \xleftarrow{\varphi} & R \otimes M \end{array}$$

EXAMPLE 21.1. What if we let $A = \mathbf{Z}/n\mathbf{Z}$? Then if B is an abelian group (i.e., a \mathbf{Z} -module), $B \otimes \mathbf{Z}/n\mathbf{Z} \cong B/nB$.

- (7) Consider $0 \rightarrow \mathbf{Z} \xrightarrow{2} \mathbf{Z} \rightarrow \mathbf{Z}/2\mathbf{Z} \rightarrow 0$. Let's tensor with $\mathbf{Z}/2\mathbf{Z}$, to get $0 \rightarrow \mathbf{Z}/2\mathbf{Z} \rightarrow \mathbf{Z}/2\mathbf{Z} \rightarrow \mathbf{Z}/2\mathbf{Z} \rightarrow 0$. This cannot be a sexseq! But it's clear that the surjection $\mathbf{Z} \rightarrow \mathbf{Z}/2\mathbf{Z}$ gives an isomorphism $\mathbf{Z}/2\mathbf{Z} \rightarrow \mathbf{Z}/2\mathbf{Z}$, i.e., $0 \rightarrow \mathbf{Z}/2\mathbf{Z} \xrightarrow{0} \mathbf{Z}/2\mathbf{Z} \xrightarrow{\cong} \mathbf{Z}/2\mathbf{Z} \rightarrow 0$. This is one of the major tragedies, that tensoring isn't exact. Exact means preserves exact sequences. The moral is that tensoring isn't generally exact, but preserves cokernels. More precisely:

PROPOSITION 21.2. *The functor $N \otimes M \otimes_R N$ preserves cokernels. What do I mean? This means that this functor is right exact, i.e., if $N' \xrightarrow{i} N \xrightarrow{p} N'' \rightarrow 0$ is exact, then so is $M \otimes_R N' \rightarrow M \otimes_R N \rightarrow M \otimes_R N'' \rightarrow 0$.*

PROOF. We have:

$$\begin{array}{ccccc} M \otimes_R N' & \xrightarrow{1 \otimes i} & M \otimes_R N & \longrightarrow & M \otimes_R N'' \\ & & \downarrow & \searrow \bar{\phi} & \\ & & M \otimes_R N / (\text{Im}(1 \otimes i)) = M \otimes_R N / I & & \end{array}$$

At least we know that the composite $M \otimes_R N' \rightarrow M \otimes_R N \rightarrow M \otimes_R N''$ is zero. But this means that the dotted map exists, because the image I has to be sent to zero. The claim is that $\bar{\phi}$ is an isomorphism. We can construct an inverse to $\bar{\phi}$. It's easy to construct maps *out* of tensor products. This inverse will be a map $M \otimes_R N'' \xrightarrow{q} M \otimes_R N/I$. How do we construct maps out of a tensor product? Consider:

$$\begin{array}{ccc} M \otimes_R N'' & \xrightarrow{\bar{q}} & M \otimes_R N/I \\ \uparrow & \nearrow q & \\ M \times N'' & & \end{array}$$

Where will $x \otimes y$ be sent? Let's pick $\bar{y} \in N$ such that $p\bar{y} = y$. I can do that because I supposed that p was surjective in the first place. Maybe I'm using the axiom of choice. (By the way, if I had a split exact sequence, tensoring will preserve split exact sequences, but not general exact sequences.) Anyway, map $x \otimes y \mapsto x \otimes \bar{y} + I$. That's the only thing I can think of doing, and so we pray and hope that it works. Let's check that this is well-defined first.

We know that \bar{y} is only well-defined up to the image of something from N' . So consider $\bar{y}' = \bar{y} + iz$ for $z \in N'$. These are the only possible lifts. Then we get $x \otimes \bar{y}' = x \otimes (\bar{y} + iz) + x \otimes \bar{y} + x \otimes i(z) = x \otimes \bar{y} + (1 \otimes i)(x \otimes z) \in x \otimes \bar{y} + I$. Luckily, we divided out by I . There's *four* other things I have to check. I have to check that this is linear in each variable. This is just fussing around with the formula. Let's assume we've done that.

Pretty much by construction, \bar{q} is the inverse for \bar{p} . This is because p takes $x \otimes \bar{y} + I$ to $x \otimes y$ because that's what \bar{p} does – it just applies p to the second factor. \square

How about this failure of exactness? What can we do about that? Failure of exactness is bad, so let's try to repair it.

Think of a sexseq of chain complexes (that are bounded below by 0 and are nonnegatively graded) $0 \rightarrow N'_\bullet \rightarrow N_\bullet \rightarrow N''_\bullet \rightarrow 0$. We get an exact sequence $H_0 N' \rightarrow H_0 N \rightarrow H_0 N'' \rightarrow 0$. We already know that this isn't exact on the left because we have a lexseq in homology (because $H_1 N''$ need not be trivial). Let's imagine $M \otimes_R -$ as analogous to H_0 . We already have an example of a functor that is right exact but not left exact (namely H_0), so this isn't unreasonable. I think I'll write down a theorem and finish the proof on Wednesday.

THEOREM 21.3. *There are functors $\text{Tor}_n^R(M, -) : \mathbf{Mod}_R \rightarrow \mathbf{Mod}_R$ for $n \geq 0$, where I have a fixed ring R and a fixed R -module M , and natural transformations sending a sexseq $0 \rightarrow N' \rightarrow N \rightarrow N'' \rightarrow 0$ to $\partial : \text{Tor}_n^R(M, N'') \rightarrow \text{Tor}_{n-1}^R(M, N') \rightarrow \text{Tor}_{n-1}^R(M, N) \rightarrow \text{Tor}_n^R(M, N'')$ such that you get a lexseq:*

$$\begin{array}{ccccccc} \cdots & \longrightarrow & \text{Tor}_n^R(M, N) & \longrightarrow & \text{Tor}_n^R(M, N'') & & \\ & & \searrow & & \swarrow & & \\ & & \text{Tor}_{n-1}^R(M, N') & \longrightarrow & \text{Tor}_{n-1}^R(M, N) & \longrightarrow & \cdots \end{array}$$

such that $\text{Tor}_0^R(M, N) = M \otimes_R N$. Basically, Tor fulfills the same role as homology.

Some properties are as follows.

- $\text{Tor}_q^R(M, N) = 0$ for $q > 1$ if R is a PID.
- $\text{Tor}_q^R(M, F) = 0$ for $q > 0$ if F is a free R -module.

Let's explore what this gives us before we construct it.

EXAMPLE 21.4. Let $R = \mathbf{Z}$, and consider the sexseq $0 \rightarrow \mathbf{Z} \xrightarrow{n} \mathbf{Z} \rightarrow \mathbf{Z}/n\mathbf{Z} \rightarrow 0$. Because \mathbf{Z} is free, you have:

$$\begin{array}{ccccccc} \cdots & \longrightarrow & 0 & \longrightarrow & \text{Tor}_n^{\mathbf{Z}}(C_\bullet)(M, \mathbf{Z}/n\mathbf{Z}) & & \\ & & \searrow & & \swarrow & & \\ & & \text{Tor}_0^{\mathbf{Z}}(M, \mathbf{Z}) = M \otimes \mathbf{Z} & \xrightarrow{\times n} & \text{Tor}_0^{\mathbf{Z}}(M, \mathbf{Z}) = M \otimes \mathbf{Z} & \longrightarrow & \text{Tor}_0^{\mathbf{Z}}(M, \mathbf{Z}/n\mathbf{Z}) = M/nM \longrightarrow 0 \end{array}$$

So $\text{Tor}_1^{\mathbf{Z}}(M, \mathbf{Z}/n\mathbf{Z}) = \ker(M \xrightarrow{n} M)$. This is the n -torsion of M . That's the origin of Tor . This is the key example to keep in mind. He said something like "In general, Tor isn't free, but it is here because \mathbf{Z} is a PID."

Take a general R -module N . You can always take a free module F_0 that surjects onto N , i.e., $F_0 \rightarrow N \rightarrow 0$. For example, you can let F_0 be the free R -module on the underlying set of N . Form a sexseq $0 \rightarrow K_0 \rightarrow F_0 \rightarrow N \rightarrow 0$. You have an exact sequence for $n > 1$:

$$\begin{array}{ccccccc} \cdots & \longrightarrow & 0 & \longrightarrow & \text{Tor}_n^R(M, N) & & \\ & & \searrow & & \swarrow & & \\ & & \text{Tor}_{n-1}^R(M, K_0) & \longrightarrow & 0 & \longrightarrow & \cdots \end{array}$$

So for $n > 1$, $\text{Tor}_n^R(M, N) \rightarrow \text{Tor}_{n-1}^R(M, K_0)$ is an isomorphism. If $n = 1$, then:

$$\begin{array}{ccccccc} \cdots & \longrightarrow & 0 & \longrightarrow & \text{Tor}_1^R(M, N) & & \\ & & \searrow & & \swarrow & & \\ & & M \otimes_R K_0 & \longrightarrow & M \otimes_R F_0 & \longrightarrow & M \otimes_R N \longrightarrow 0 \end{array}$$

The maps between the tensors might be hard to compute, but you can compute this as a kernel.

But I've not constructed the functors yet. I just said to assume that it exists. This was so much fun, taking a free module and surjecting it onto N . What I'm trying to do is:

$$\begin{array}{ccccccc}
 \cdots & \xrightarrow{\quad} & F_2 & \xrightarrow{\quad d \quad} & F_1 & \xrightarrow{\quad d \quad} & F_0 \\
 & \nearrow & \searrow & \nearrow & \searrow & \nearrow & \searrow \\
 & K_2 & & K_1 & & K_0 & & N \\
 & \nearrow & \searrow & \nearrow & \searrow & \nearrow & \searrow \\
 0 & & 0 & & 0 & & 0 & & 0
 \end{array}$$

Where F_{i+1} surjects onto K_i and the F_i are free R -modules. Splicing these exact sequences gives you a exact sequence in the top row. This is what's called a *free resolution* of N . You can actually write this as:

$$\begin{array}{ccccccc}
 \cdots & \longrightarrow & F_2 & \longrightarrow & F_1 & \longrightarrow & F_0 & \longrightarrow & 0 \\
 & & & & & & \downarrow & & \\
 & & & & & & N & &
 \end{array}$$

The F_0 are generators of N , the F_1 are relations, the F_2 are relations between relations, and so on. We say that these are syzygies. The singular term is syzygy.

22. More about Tor

Where is everybody? Looks like nobody wants to hear about Tor. You're the select few.

On Monday I gave "axioms" for Tor, basically by saying that $\text{Tor}_n^R(M, -) : \mathbf{Mod}_R \rightarrow \mathbf{Mod}_R$ is like a homology theory. Today I'm going to show a construction of Tor, and verify the axioms. Or at least the lexseq business. I also tried to show that it's a reasonable idea to study free resolutions, namely:

$$\begin{array}{ccccccc}
 \cdots & \xrightarrow{\quad} & F_2 & \xrightarrow{\quad d \quad} & F_1 & \xrightarrow{\quad d \quad} & F_0 \\
 & \nearrow & \searrow & \nearrow & \searrow & \nearrow & \searrow \\
 & K_2 & & K_1 & & K_0 & & N \\
 & \nearrow & \searrow & \nearrow & \searrow & \nearrow & \searrow \\
 0 & & 0 & & 0 & & 0 & & 0
 \end{array}$$

Where F_{i+1} surjects onto K_i and the F_i are free R -modules. Splicing these exact sequences gives you a exact sequence in the top row, which is a free resolution of N . Of course there are a lot of choices involved, so free resolutions aren't unique. The resolution F_\bullet does *not* include N , and in the following diagram, the top row isn't exact but $\cdots \rightarrow F_0 \rightarrow N \rightarrow 0$ is exact.

$$\begin{array}{ccccccc}
 \cdots & \longrightarrow & F_2 & \longrightarrow & F_1 & \longrightarrow & F_0 & \longrightarrow & 0 \\
 & & & & & & \downarrow \epsilon & & \\
 & & & & & & N & &
 \end{array}$$

Then, note that:

$$H_q(F_\bullet) = \begin{cases} N & q = 0 \\ 0 & q > 0 \end{cases}$$

CONSTRUCTION 22.1. We construct $\text{Tor}_n^R(M, N)$ via $H_n(M \otimes_R F_\bullet)$ where F_\bullet is a free resolution of N .

I have to check that this is well-defined, that it's functorial, and that it satisfies the lexseq. Maybe I should also check what $H_0(M \otimes_R F_\bullet)$ is. I do get $M \otimes_R F_\bullet$, because tensoring with M is right exact, i.e., you have an exact sequence $M \otimes_R F_1 \xrightarrow{p} M \otimes_R F_0 \rightarrow M \otimes_R N \rightarrow 0$, and the zeroth homology is the cokernel of p , which is $M \otimes_R N$.

The check that it's well-defined goes like this. I call this the fundamental theorem of homological algebra.

THEOREM 22.2 (Fundamental theorem of homological algebra). *Let $f : M \rightarrow N$ be an R -module homomorphism. Let $\cdots \rightarrow E_1 \rightarrow E_0 \rightarrow M \rightarrow 0$ be such that each E_n is free, and $\cdots \rightarrow F_1 \rightarrow F_0 \rightarrow N \rightarrow 0$ is exact. The fundamental theorem says that I can lift the map $f : M \rightarrow N$ to a chain map $E_\bullet \rightarrow F_\bullet$ (i.e. they commute with the differentials and the augmentations $\epsilon_N : F_0 \rightarrow N$ and $\epsilon_M : E_0 \rightarrow M$), that is unique up to chain homotopy. I.e., they sit in the following commutative diagram:*

$$\begin{array}{ccccccc} \cdots & \longrightarrow & E_2 & \longrightarrow & E_1 & \longrightarrow & E_0 \xrightarrow{\epsilon_M} M \longrightarrow 0 \\ & & \downarrow f_2 & & \downarrow f_1 & & \downarrow f_0 \\ \cdots & \longrightarrow & F_2 & \longrightarrow & F_1 & \longrightarrow & F_0 \xrightarrow{\epsilon_N} N \longrightarrow 0 \end{array}$$

I'm making a big deal about homological algebra in this course on algebraic topology, because this really is a homotopy-theoretic statement. It's part of the homotopy theory of chain complexes. I just want to mention something.

DEFINITION 22.3. A projective R -module P is something such that there's a lift:

$$\begin{array}{ccc} & & M \\ & \nearrow & \downarrow \\ P & \longrightarrow & N \end{array}$$

Every free module is projective, clearly. Anything that's a direct summand in a projective is also projective. Any projective module is a direct summand of a free module.

EXAMPLE 22.4. Let k be a field. Then $k \times k$ acts on k via $(a, b)c = ac$. This is an example of a projective that isn't free.

REMARK 22.5. This proof uses only that E_n is projective. But if you have a PID, there's no difference between projective and free.

PROOF OF THE FUNDAMENTAL THEOREM OF HOMOLOGICAL ALGEBRA. Let's try to construct f_0 . Consider:

$$\begin{array}{ccccccc} 0 & \longrightarrow & K_0 & \longrightarrow & E_0 & \xrightarrow{\epsilon_M} & M \\ & & \downarrow g_0 & & \downarrow f_0 & & \downarrow f \\ 0 & \longrightarrow & L_0 = \ker(\epsilon_N) & \longrightarrow & F_0 & \xrightarrow{\epsilon_N} & N \longrightarrow 0 \end{array}$$

We know that $E_0 = R\langle S \rangle$. What we do is push forward the generators of E via ϵ_M , push it forward to f , and pull it back via ϵ_N which makes sense because it's surjective. This gives us f_0 . You can restrict it to get g_0 . Now I'm in exactly the same situation.

$$\begin{array}{ccccccc} 0 & \longrightarrow & K_1 & \longrightarrow & E_1 & \xrightarrow{\epsilon_M} & K_0 \\ & & \downarrow g_1 & & \downarrow f_1 & & \downarrow g_0 \\ 0 & \longrightarrow & L_1 & \longrightarrow & F_1 & \longrightarrow & L_0 \longrightarrow 0 \end{array}$$

And g_1 exists. Now we need to prove the chain homotopy claim. Suppose I have $f_\bullet : E_\bullet \rightarrow F_\bullet$ and $f'_\bullet : E_\bullet \rightarrow F_\bullet$. Then $f'_n - f_n$ (which we'll rename ℓ_n) is a chain map lifting $0 : M \rightarrow N$. Let's rename things, so I have:

$$\begin{array}{ccccccc} \cdots & \longrightarrow & E_2 & \longrightarrow & E_1 & \longrightarrow & E_0 \xrightarrow{\epsilon_M} M \longrightarrow 0 \\ & & \downarrow \ell_2 & & \downarrow \ell_1 & & \downarrow \ell_0 \\ \cdots & \longrightarrow & F_2 & \longrightarrow & F_1 & \longrightarrow & F_0 \xrightarrow{\epsilon_N} N \longrightarrow 0 \end{array}$$

We want that $\ell_\bullet \simeq 0$. That is, we want $h : E_n \rightarrow F_{n+1}$ such that $dh + hd = \ell$. To begin with, we consider:

$$\begin{array}{ccc} & E_0 & \\ \swarrow h & \downarrow \ell_0 & \\ F_1 & \xrightarrow{d} & F_0 \end{array}$$

At the beginning, we want $dh = 0$. Well, we consider:

$$\begin{array}{ccccc} & & E_0 & & \\ & \swarrow & \downarrow \ell_0 & \searrow & \\ F_1 & \xrightarrow{\quad} & L_0 & \xrightarrow{\quad} & F_0 \end{array}$$

Because $F_1 \rightarrow L_0$ is a surjection, the lift exists, and we have $dh = \ell_0$. For the next step, we have:

$$\begin{array}{ccccccc} & & E_1 & \xrightarrow{\quad} & E_0 & & \\ & \swarrow & \downarrow \ell_1 & \searrow h & \downarrow \ell_0 & & \\ F_2 & \xrightarrow{\quad} & L_1 & \xrightarrow{\quad} & F_1 & \xrightarrow{d} & F_0 \end{array}$$

So what do I want to do here? Ultimately what I want is that $dh = \ell_1 - hd$. Well, $d(\ell_1 - hd) = d\ell_1 - dh d = d\ell_1 - \ell_0 d = 0$ where the last equality comes because ℓ is a chain map. So now we can use exactness of E_\bullet to define h . Exactly the same process continues. \square

That's it. We're going to use this several times. I'm glad to have mentioned the notion of projectivity, because we'll use it later. Now, apply $M \otimes_R -$ to that resolution (???). Suppose I have $f : N \rightarrow N'$, and get a map $f_\bullet : F_\bullet \rightarrow F'_\bullet$. Apply $M \otimes_R -$ to this, to get a chain map $M \otimes_R F_\bullet \rightarrow M \otimes_R F'_\bullet$ to get a map in homology $H_*(M \otimes_R F_\bullet) \rightarrow H_*(M \otimes_R F'_\bullet)$. How independent is this of the lifting that I chose? Suppose I have two chain maps $1 \otimes f_0, f \otimes f'_0 : M \otimes_R F_\bullet \rightarrow M \otimes_R F'_\bullet$. I can certainly form $1 \otimes h : M \otimes_R F_n \rightarrow M \otimes_R F'_{n+1}$. I know that $dh + hd = f - f'$. When I tensor, I get $1 \otimes (hd + dh) = 1 \otimes (f - f')$. But I want that $(1 \otimes h)(1 \otimes d) + (1 \otimes d)(1 \otimes h) = 1 \otimes f - 1 \otimes f'$. We use a further property of the tensor product:

- (8) If $f, f' : N \rightarrow N'$, then $1 \otimes (f + f') = 1 \otimes f + 1 \otimes f' : M \otimes_R N \rightarrow M \otimes_R N'$, and $1 \otimes (rf) = r(1 \otimes f)$. And $M \otimes_R -$ is an R -linear functor.

There's things called derived functors. In more general cases, you can't use chain complexes, but rather you use simplicial resolutions. There's non-additive homological algebra. Anyway, you check that $1 \otimes f$ and $1 \otimes f'$ are indeed chain homotopic, and so you're done.

I think I've verified that it's well-defined and functorial. What about the lexseq? Now, I start with a sexseq and want to get an lexseq. Suppose I have a sexseq $0 \rightarrow A \rightarrow B \rightarrow C \rightarrow 0$. I should first come up with an sexseq of resolutions. Consider:

$$\begin{array}{ccccccc} 0 & \longrightarrow & A & \longrightarrow & B & \longrightarrow & C \longrightarrow 0 \\ & & \uparrow & & & & \uparrow \\ & & F'_0 & & & & F''_0 \\ & & \uparrow & & & & \uparrow \\ & & F'_1 & & & & F''_1 \\ & & \uparrow & & & & \uparrow \\ & & \vdots & & & & \vdots \end{array}$$

I want to get a free resolution in the middle. The only thing that I can think of doing is constructing:

$$\begin{array}{ccccccc}
0 & \longrightarrow & A & \xrightarrow{i} & B & \longrightarrow & C \longrightarrow 0 \\
& & \uparrow \epsilon_A & & \uparrow \epsilon_B & & \uparrow \epsilon_B \\
0 & \longrightarrow & F'_0 & \longrightarrow & F'_0 \oplus F''_0 & \longrightarrow & F''_0 \longrightarrow 0 \\
& & \uparrow & & \uparrow & & \uparrow \\
& & F'_1 & & & & F''_1 \\
& & \uparrow & & & & \uparrow \\
& & \vdots & & & & \vdots
\end{array}$$

In fact, it's the only choice because you have a free module and the sexseq splits. If I'm going to make this work, this is the only thing I can do. I need the augmentation, though. We can think of ϵ_B as a row vector. The first entry obviously has to be $i\epsilon$. And, well, there's a lift⁸ because F''_0 is a free resolution:

$$\begin{array}{ccccccc}
0 & \longrightarrow & A & \xrightarrow{i} & B & \longrightarrow & C \longrightarrow 0 \\
& & \uparrow \epsilon_A & & \uparrow \epsilon_B & \swarrow \bar{\epsilon} & \uparrow \epsilon_B \\
0 & \longrightarrow & F'_0 & \longrightarrow & F'_0 \oplus F''_0 & \longrightarrow & F''_0 \longrightarrow 0 \\
& & \uparrow & & \uparrow & & \uparrow \\
& & F'_1 & & & & F''_1 \\
& & \uparrow & & & & \uparrow \\
& & \vdots & & & & \vdots
\end{array}$$

So that $\epsilon_B = [i\epsilon, \bar{\epsilon}]$. This is surjective by the Snake lemma. Consider:

$$\begin{array}{ccccccc}
& & 0 & & 0 & & 0 \\
& & \uparrow & & \uparrow & & \uparrow \\
0 & \longrightarrow & A & \xrightarrow{i} & B & \longrightarrow & C \longrightarrow 0 \\
& & \uparrow \epsilon_A & & \uparrow \epsilon_B & \swarrow \bar{\epsilon} & \uparrow \epsilon_B \\
0 & \longrightarrow & F'_0 & \longrightarrow & F'_0 \oplus F''_0 & \longrightarrow & F''_0 \longrightarrow 0 \\
& & \uparrow & & \uparrow & & \uparrow \\
0 & \longrightarrow & K'_0 = \ker \epsilon_A & \longrightarrow & K_0 & \longrightarrow & K''_0 = \ker \epsilon_B \longrightarrow 0 \\
& & \uparrow & & \uparrow & & \uparrow \\
& & 0 & & 0 & & 0
\end{array}$$

The bottom row is exact by the 3×3 -lemma. It's why I gave it to you for homework! Anyway, I now have a sexseq of free resolutions $0 \rightarrow F'_\bullet \rightarrow F_\bullet \rightarrow F''_\bullet \rightarrow 0$. Now I want a sexseq $0 \rightarrow M \otimes_R F'_\bullet \rightarrow M \otimes_R F_\bullet \rightarrow M \otimes_R F''_\bullet \rightarrow 0$, but I don't know this because $M \otimes_R -$ isn't exact. It's why we got into the business in the whole place. But $0 \rightarrow F'_\bullet \rightarrow F_\bullet \rightarrow F''_\bullet \rightarrow 0$ is split. And applying any functor gives a splitting of the sexseq, i.e., $M \otimes_R -$ sends split sexseqs to (split) sexseq. This means that $0 \rightarrow M \otimes_R F'_\bullet \rightarrow M \otimes_R F_\bullet \rightarrow M \otimes_R F''_\bullet \rightarrow 0$ also splits. Thus we're done proving the lexseq in Tor.

The key idea in homological algebra is that free modules are good.

⁸There's some ambiguity here. I have to make a choice. It might seem that the boundary map is made up of the choices, but it *isn't*! I haven't proved that. It still needs to be proved.

23. Direct Limits

Goals are UCT (universal coefficient theorem), which is about $H_*(X; M)$ for varying M , the Künneth theorem (which is about $H_*(X \times Y)$), cohomology, and Poincaré duality.

23.1. Two more things about Tor. If R is a PID, then there's not so much to say about Tor, because any submodule of a free module is free. So that means that any R -module has a free resolution $0 \rightarrow F_1 = \ker(f) \rightarrow F_0 \xrightarrow{f} N \rightarrow 0$. It follows that $\text{Tor}_n^R(M, N) = 0$ for $n > 1$. If you have a field, then tensoring is exact, so $\text{Tor}_0^k(M, N) = 0$ for $n > 0$. That's why it's easy to work with fields. (There's also Prüfer rings, where every module is flat.) By the way, this means that if you have a sexseq $0 \rightarrow A \rightarrow B \rightarrow C \rightarrow 0$, then over a PID R , there's a six-term exact sequence $0 \rightarrow \text{Tor}_1^R(M, A) \rightarrow \text{Tor}_1^R(M, B) \rightarrow \text{Tor}_1^R(M, C) \rightarrow M \otimes_R A \rightarrow M \otimes_R B \rightarrow M \otimes_R C \rightarrow 0$.

EXAMPLE 23.1. I want to give an example when you do have higher Tor. Let k be a field. Let $R = k[e]/(e^2)$. This is sometimes called the “dual numbers”, or the exterior algebra over k . We're going to consider R -modules. Let's construct a projective resolution of k . Hmm. What is an R -module M ? It's just a k -vector space M with an operator d that has action given by multiplication by e , and this satisfies $d^2 = 0$. And this is a chain complex! I guess it's not quite a chain complex because for us chain complexes are graded. So I guess it's an ungraded chain complex. I can consider $H(M; d) := \ker d / \text{Im } d$. Here's an example of an R -module. There's the augmentation $R \rightarrow k$ sending $e \mapsto 0$. This makes k an R -module, where $d = 0$. Let's construct a free resolution of k .

Here we go. We're going to write $k = \bullet (= 1)$ and $R := (1 =) \bullet \xrightarrow{d} \bullet (= e)$. Well, we have $R \rightarrow k$ given by $(\bullet \xrightarrow{d} \bullet) \rightarrow \bullet$. The kernel is not free, so we get $(\bullet \xrightarrow{d} \bullet) \rightarrow (\bullet \xrightarrow{d} \bullet) \rightarrow \bullet$. And this continues, so we get a projective resolution $\cdots \xrightarrow{e} R \xrightarrow{e} R \xrightarrow{e} R \rightarrow k$. What is Tor? Well, $\text{Tor}_*^R(M, k)$ is the homology of the following chain complex $\cdots \xrightarrow{d} M \xrightarrow{d} M \rightarrow 0$. What is that homology? Clearly $\text{Tor}_0^R(M, k) = M \otimes_R k = M/dM = M/eM$. This is often called the module of indecomposables. And, $\text{Tor}_n^R(M, k) = H(M; d)$.

Last comment about Tor is that there's a symmetry there. Of course, $M \otimes_R N \cong N \otimes_R M$. This uses the fact that R is commutative. This leads right on to saying that $\text{Tor}_n^R(M, N) \cong \text{Tor}_n^R(N, M)$. We've been computing Tor by taking a resolution of the second variable. But I could equally have taken a resolution of the first variable. This follows from the fundamental theorem of homological algebra.

23.2. Direct limits. A long time ago, I said what a poset was. Let me tell you a joke about posets. I was at a conference, and Quillen was giving a talk. He was a student of Raoul Bott. Quillen was giving his talk, and he used the term “poset”. This word was invented by Garrett Birkhoff(?). Then Bott objected and said “What is this crazy word?”, and Quillen responded “What are you talking about? Your colleague invented it!”. Anyway, it's not a joke. I guess it's just a piece of MIT and Harvard rivalry.

Anyway, a poset is a small category \mathcal{J} such that $\#\mathcal{J}(i, j) \leq 1$ and isomorphism implies identity. I want to talk about a *directed set*.

DEFINITION 23.2. A poset (\mathcal{J}, \leq) is *directed* if, for every i, j , there exists a k such that $i \leq k$ and $j \leq k$.

EXAMPLE 23.3. For example, the natural numbers $\mathbf{Z}_{\geq 0}$ with equality. Another example: if X is a space and I is the set of open subsets of X . It's directed by saying that $U \leq V$ if $U \subseteq V$. This is because U, U' need not be comparable, but $U, U' \subseteq U \cup U'$. Another example is $\mathbf{Z}_{> 0}$ where $i \leq j$ if $i|j$. This is because $i, j|(ij)$.

DEFINITION 23.4. Let \mathcal{J} be a directed set. An \mathcal{J} -directed diagram in \mathbf{C} is a functor $\mathcal{J} \rightarrow \mathbf{C}$. This means that for every $i \in \mathcal{J}$, there is $X_i \in \mathbf{C}$, and for every $i \leq j$, there's a map $X_i \xrightarrow{f_{ij}} X_j$ (and similarly for composition).

EXAMPLE 23.5. If $\mathcal{J} = (\mathbf{Z}_{\geq 0}, \leq)$, then you get $X_0 \xrightarrow{f_{01}} X_1 \xrightarrow{f_{12}} X_2 \rightarrow \cdots$. This is the most important.

EXAMPLE 23.6. Suppose $\mathcal{J} = (\mathbf{Z}_{> 0}, |)$, i.e., the third example above. You can consider $\mathcal{J} \rightarrow \mathbf{Ab}$, say assigning to each i the integers \mathbf{Z} , and $f_{ij} : \mathbf{Z} \xrightarrow{j/i} \mathbf{Z}$. You get the picture.

These directed systems are a little complicated. But there's a simple one, namely the constant one.

EXAMPLE 23.7. Let \mathcal{J} be any directed set. You have a constant functor $c_A : \mathcal{J} \rightarrow \mathbf{C}$ at some $A \in \mathbf{C}$.

Of course, \mathcal{J} -directed systems in \mathbf{C} are functors $\mathcal{J} \rightarrow \mathbf{C}$. They have natural transformations, and those are the morphisms in the category of \mathcal{J} -directed systems. That just means that if I have two directed systems $X, Y : \mathcal{J} \rightarrow \mathbf{C}$, then a map from one to the other is a commuting diagram:

$$\begin{array}{ccc} X_i & \longrightarrow & X_j \\ \downarrow g_i & & \downarrow g_j \\ Y_i & \longrightarrow & Y_j \end{array}$$

for all $i \leq j$.

It'd be great if every directed system was constant, but this isn't true. This leads to direct limits.

DEFINITION 23.8. A direct limit is an object L and a map $X \rightarrow c_L$, which is initial among maps to constant systems. This means that I have some other map $X \rightarrow c_A$, then there's a unique induced map $c_L \rightarrow c_A$ that is induced from a map $L \rightarrow A$. We write $\varinjlim_{i \in \mathcal{J}} X_i = \text{colim}_{i \in \mathcal{J}} X_i$. (My own note: it's also sometimes called an inductive limit.)

This is a universal property. So two different direct limits are canonically isomorphic.

EXAMPLE 23.9. Consider $\mathcal{J} = (\mathbf{Z}_{\geq 0}, \leq)$, then you get $X_0 \xrightarrow{f_{01}} X_1 \xrightarrow{f_{12}} X_2 \rightarrow \cdots$ in \mathbf{Top} . What is the direct limit? It's going to be $\bigcup_i X_i$. But what's the topology? Give it the finest topology so that all of the maps to the union are open. This just means that a subset is open in $\bigcup_i X_i$ if the preimage is open.

EXAMPLE 23.10. Recall our example where we let $\mathcal{J} = (\mathbf{Z}_{>0}, |)$, i.e., the third example above. You can consider $\mathcal{J} \rightarrow \mathbf{Ab}$, say assigning to each i the integers \mathbf{Z} , and $f_{ij} : \mathbf{Z} \xrightarrow{j/i} \mathbf{Z}$. The colimit is \mathbf{Q} , where you send $X_n \rightarrow \mathbf{Q}$ via $1 \mapsto \frac{1}{n}$.

LEMMA 23.11. Let $X : \mathcal{J} \rightarrow \mathbf{Ab}$ (or \mathbf{Mod}_R). A map $f : X \rightarrow c_L$ is the direct limit (we write $f_i : X_i \rightarrow L$) if and only if:

- (1) For every $x \in L$, there exists an i and an $x_i \in X_i$ such that $f_i(x_i) = x$.
- (2) Let $x_i \in X_i$ be such that $f_i(x_i) = 0$ in L . Then there exists some $j \geq i$ such that $f_{ij}(x_i) = 0$ in X_j .

PROOF. Straightforward. □

It generalizes the observation that \mathbf{Q} is the colimit of the diagram we drew above for $\mathcal{J} = (\mathbf{Z}_{>0}, |)$.

COROLLARY 23.12. The direct limit $\varinjlim_I : \text{Fun}(\mathcal{J}, \mathbf{Ab}) \rightarrow \mathbf{Ab}$ is exact. In other words, $X_\bullet \rightarrow Y_\bullet \xrightarrow{p} Z_\bullet$ is an exact sequence of \mathcal{J} -directed systems (at every degree, we get an exact sequence of abelian groups), then $\varinjlim_I X_\bullet \xrightarrow{i} \varinjlim_I Y_\bullet \xrightarrow{p} \varinjlim_I Z_\bullet$.

PROOF. First of all, $X_\bullet \rightarrow Z_\bullet$ is zero. Thus it factors through the constant zero object, so that $\varinjlim_I X_\bullet \rightarrow \varinjlim_I Z_\bullet$ is zero. Let $y \in \varinjlim_I Y_\bullet$, and suppose y maps to 0 in $\varinjlim_I Z_\bullet$. By the first condition, there exists i such that $y = f_i(y_i)$ for some $y_i \in Y_i$. Then $p(y) = f_i p(y_i)$ because p is a map of systems. This is zero. This means that there is $j \geq i$ such that $f_{ij} p(y_i) = 0$. We have an element in Y_j that maps to zero, so there is some x_j that is the preimage of the element in Y_j . So we're done. □

This makes the world a nice place to live.

24. Universal coefficient theorem (and Hom, adjointness)

On Wednesday, we'll talk about the Künneth theorem, and later we'll talk about the Künneth theorem. We've been talking about tensor products of R -modules, but we can do something that's more natural in a way. That's the notion of $\text{Hom}_R(M, N)$, which is the collection of R -linear homomorphisms between R -modules M and N . This is actually itself an R -module. It's an abelian group, first of all, because you can add morphisms. How does $r \in R$ act on $f \in \text{Hom}_R(M, N)$? Just define $(rf)(x) = f \cdot f(x)$. You should check that this does actually define an R -module homomorphism. (This is trivial.) If R isn't commutative I guess there'd be an action of $Z(R)$ on $\text{Hom}_R(M, N)$. In particular, $\text{Hom}_R(M, -) : \mathbf{Mod}_R \rightarrow \mathbf{Mod}_R$.

REMARK 24.1. You're supposed to technically write $\underline{\text{Hom}}_R(M, N)$ to mean $\text{Hom}_R(M, N)$ with the structure of an R -module. But in these notes, I will not do this.

I wanted to bring this up because it relates to tensor products in a beautiful way. Consider $\text{Hom}_R(M \otimes_R N, L)$. This is the collection of R -bilinear maps $M \times N \rightarrow L$. I claim that $\text{Hom}_R(M \otimes_R N, L) \cong \text{Hom}_R(M, \text{Hom}_R(N, L))$. The way this works is the following. Suppose $f : M \otimes_R N \rightarrow L$. Define $\hat{f} : M \rightarrow \text{Hom}_R(N, L)$ via $\hat{f} : m \mapsto (n \mapsto f(m \otimes_R n))$. This is a special case of the notion of an adjoint functor, introduced by Dan Kan, who was actually here at MIT. This is a big part of category theory.

PROPOSITION 24.2. *Let \mathcal{I} be a direct set, and let $M : \mathcal{I} \rightarrow \mathbf{Mod}_R$ be a \mathcal{I} -directed system of R -modules. There is a natural isomorphism $(\varinjlim_{\mathcal{I}} M_i) \otimes_R N \cong \varinjlim_{\mathcal{I}} (M_i \otimes_R N)$. It's very technical but it might be very useful. Maybe in the homework for example ;-)*

PROOF. Consider $\text{Hom}_R((\varinjlim_{\mathcal{I}} M_i) \otimes_R N, L) \cong \text{Hom}_R(\varinjlim_{\mathcal{I}} M_i, \text{Hom}_R(N, L))$. That's cool, because this is the same thing as $\text{Map}_{\text{Fun}(\mathcal{I}, \mathbf{Mod}_R)}(\{M_i\}, c_{\text{Hom}_R(N, L)})$ because $\{M_i\}$ is a \mathcal{I} -directed system. Now, this is the same as $\text{Map}_{\text{Fun}(\mathcal{I}, \mathbf{Mod}_R)}(\{M_i \otimes_R N\}, c_L)$ by the Hom-tensor adjunction. We can unspool this to see that this is $\text{Hom}_R(\varinjlim_{\mathcal{I}} (M_i \otimes_R N), L)$. Now conclude via the Yoneda lemma (which we haven't discussed yet, but I think is a homework problem). Basically this states that $\text{Map}_{\mathbf{C}}(X, -)$ determines X . \square

We'll talk a lot more about Hom and adjunctions, but not today.

Here's the question I want to talk about today. Suppose that I'm given $H_*(X; \mathbf{Z})$. Does it determine $H_*(X; \mathbf{Z}/2\mathbf{Z})$? Consider $\mathbf{RP}^2 \rightarrow S^2$. In homology with coefficients in \mathbf{Z} , in dimension 2, this map must induce 0. But in $\mathbf{Z}/2\mathbf{Z}$ -coefficients, in dimension 2, this map gives an isomorphism. I could have considered reduced homology. This shows that there's not a functorial relationship between $H_*(X; \mathbf{Z})$ and $H_*(X; \mathbf{Z}/2\mathbf{Z})$. So how *do* we go between different coefficients? That's the mystery.

Let R be a commutative ring. Let M be a R -module. I want to think about some chain complex C_\bullet of R -modules. It could be the singular complex of a space, but it doesn't have to be. I'm going to forget to write \otimes_R now; I'll just write \otimes . I can consider $H_n(C_\bullet) \otimes M$, or $H_n(C_\bullet \otimes M)$. The latter thing gives homology with coefficients in M . How can we compare these two? I claim that I can construct a map $\alpha : H_n(C_\bullet) \otimes M \rightarrow H_n(C_\bullet \otimes M)$. Recall the exact sequence $0 \rightarrow B_n \rightarrow Z_n(C_\bullet) \rightarrow H_n \rightarrow 0$ that defines homology. So I get an exact sequence $B_n \otimes M \rightarrow Z_n(C_\bullet) \otimes M \rightarrow H_n(C_\bullet) \otimes M \rightarrow 0$. And there's a surjection $Z_n(C_\bullet)(C \otimes M) \rightarrow H_n(C_\bullet \otimes M)$. I have to tell you where $x \otimes m \in Z_n(C_\bullet) \otimes M$ goes. I'll send it to $x \otimes m \in Z_n(C_\bullet)(C \otimes M)$. I claim that this is a cycle, because $d(x \otimes m) = (dx) \otimes m$. But $x \in \ker d$, so this is zero, and thus $x \otimes m \in Z_n(C_\bullet)(C \otimes M)$. Does it descend to a map in homology? We want to check that $B_n \otimes M \rightarrow Z_n(C_\bullet)(C \otimes M)$ is zero. Suppose $y \in C_{n+1}$. Then $dy \in C_n$. Where does $dy \otimes x$ go? Send it to $d(y \otimes x) \in B_n(C_\bullet \otimes M)$. And this maps to zero.

The problem is that α is not always an isomorphism. But it is if M is free, say $M = R\langle S \rangle$. That's because then $C_\bullet \otimes M \cong \bigoplus_S C_\bullet$. Now there's a little lemma that nobody tells you about, because it's obvious, but here it is anyway:

LEMMA 24.3. *Suppose I have a collection of exact sequences of R -modules $A_i \rightarrow B_i \rightarrow C_i$. Then $\bigoplus A_i \rightarrow \bigoplus B_i \rightarrow \bigoplus C_i$ is short exact, i.e., \bigoplus is an exact functor.*

PROOF. The composition is obviously zero. If $(b_i) \in \bigoplus B_i$ maps to 0, then by exactness, there are a_i that map to b_i , and we assume that if some $b_i = 0$, then $a_i = 0$. \square

This in particular implies that $H(\bigoplus C_i) \cong \bigoplus H(C_i)$.

Consider a free resolution of M . Assume R is a PID, so that M has a free resolution of the form $0 \rightarrow F_1 \rightarrow F_0 \rightarrow M \rightarrow 0$. Thus we get a chain complex $C_\bullet \otimes F_1 \rightarrow C_\bullet \otimes F_0 \rightarrow C_\bullet \otimes M \rightarrow 0$. Now I get a lexseq in Tor, namely $\cdots \rightarrow \text{Tor}_1^R(C_\bullet, M) \rightarrow C_\bullet \otimes F_1 \rightarrow C_\bullet \otimes F_0 \rightarrow C_\bullet \otimes M \rightarrow 0$.

Now I'm going to make a second assumption. Suppose C_n is a free R -module for all n . At least that $\text{Tor}_1^R(C_n, M) = 0$. This shouldn't bother you at all, because the chain complexes that we need satisfy this condition. In particular, we have a sexseq $0 \rightarrow C_\bullet \otimes F_1 \rightarrow C_\bullet \otimes F_0 \rightarrow C_\bullet \otimes M \rightarrow 0$. What happens then? We

get a lexseq. I want to give an unsplined form of this (huge diagram coming up!).

$$\begin{array}{ccc}
0 & \xlongequal{\quad} & 0 \\
\downarrow & & \downarrow \\
\text{coker}(H_n(C_\bullet \otimes F_1) \rightarrow H_n(C_\bullet \otimes F_0)) & \xlongequal{\quad} & H_n(C_\bullet) \otimes M \\
\downarrow & & \downarrow \alpha \\
H_n(C_\bullet \otimes M) & \xlongequal{\quad} & H_n(C_\bullet \otimes M) \\
\downarrow \partial & & \downarrow \partial \\
\ker(H_{n-1}(C_\bullet \otimes F_1) \rightarrow H_{n-1}(C_\bullet \otimes F_0)) & \xlongequal{\quad} & \text{Tor}_1^R(H_{n-1}(C_\bullet), M) \\
\downarrow & & \downarrow \\
0 & \xlongequal{\quad} & 0
\end{array}$$

Because $\ker(H_{n-1}(C_\bullet \otimes F_1) \rightarrow H_{n-1}(C_\bullet \otimes F_0)) = \ker(H_{n-1}(C_\bullet) \otimes F_1 \rightarrow H_{n-1}(C_\bullet) \otimes F_0)$ and $\text{coker}(H_n(C_\bullet) \otimes F_1 \rightarrow H_n(C_\bullet) \otimes F_0) = \text{coker}(H_n(C_\bullet) \otimes F_1 \rightarrow H_n(C_\bullet) \otimes F_0)$. Also, $\ker(H_{n-1}(C_\bullet \otimes F_1) \rightarrow H_{n-1}(C_\bullet \otimes F_0)) = \text{Tor}_1^R(H_{n-1}(C_\bullet), M)$ because of the lexseq $0 \rightarrow \text{Tor}_1^R(H_{n-1}(C_\bullet), M) \rightarrow H_{n-1}(C_\bullet) \otimes F_1 \rightarrow H_{n-1}(C_\bullet) \otimes F_0 \rightarrow H_{n-1}(C_\bullet) \otimes M \rightarrow 0$.

Thus we have a sexseq, which gives the universal coefficient theorem:

THEOREM 24.4 (Universal Coefficient Theorem). *If R is a PID and C_n is free for all n , then there is a natural sexseq of R -modules:*

$$0 \rightarrow H_n(C_\bullet) \otimes M \xrightarrow{\alpha} H_n(C_\bullet \otimes M) \xrightarrow{\partial} \text{Tor}_1^R(H_{n-1}(C_\bullet), M) \rightarrow 0$$

A further fact that we won't prove is that this splits as a sexseq of R -modules, but not naturally.

EXAMPLE 24.5. Consider $H_2(\mathbf{RP}^2; \mathbf{Z}/2\mathbf{Z}) \cong \mathbf{Z}/2\mathbf{Z}$, and we can consider $H_2(\mathbf{RP}^2; \mathbf{Z}) \otimes \mathbf{Z}/2\mathbf{Z} = 0$. So by the UCT, this must come from $\text{Tor}_1^{\mathbf{Z}}(H_1(\mathbf{RP}^2; \mathbf{Z}), \mathbf{Z}/2\mathbf{Z}) \cong \mathbf{Z}/2\mathbf{Z}$. So ∂ is an isomorphism. This explains the mystery that we began with.

REMARK 24.6. Suppose R is not a PID. For example, consider what we worked with before, e.g., $R = k[e]/(e^2)$, and let $M = k$ (so e acts as 0). Consider the chain complex $C_\bullet : \cdots \rightarrow R \xrightarrow{e} R \xrightarrow{e} R \xrightarrow{e} R \rightarrow 0$.

This is actually the free resolution of k that we found before. In particular, $H_n(C_\bullet) = \begin{cases} k & n = 0 \\ 0 & n \neq 0 \end{cases}$. What is

$C_\bullet \otimes_R k$? It's exactly $\cdots \rightarrow k \xrightarrow{0} k \xrightarrow{0} k \xrightarrow{0} k \rightarrow 0$. So $H_n(C_\bullet \otimes_R k) = \begin{cases} k & n > 0 \\ 0 & n \leq 0 \end{cases} = \text{Tor}_n^R(k, k)$. The two

homologies are super different. The excess Tor's are accounted for via spectral sequences, which you'll see when you take 18.906.

The next step is to consider the homology of products.

25. Künneth and Eilenberg-Zilber

We want to compute the homology of a product. Long ago, we constructed a bilinear map $S_p(X) \times S_q(Y) \rightarrow S_{p+q}(X \times Y)$, called the cross product. So we get a linear map $S_p(X) \otimes S_q(Y) \rightarrow S_{p+q}(X \times Y)$, and it satisfies the Leibniz formula, i.e., $d(x \times y) = dx \times y + (-1)^p x \times dy$. The method we used was really another example of the fundamental theorem of homological algebra.

DEFINITION 25.1. Let C_\bullet, D_\bullet be chain complexes that are bounded below (i.e., $C_i = 0$ and $D_i = 0$ for $i \ll 0$; we'll be looking at the case where they're zero if $i < 0$). Define $(C_\bullet \otimes D_\bullet)_n = \bigoplus_{p+q=n} C_p \otimes D_q$. The boundedness says that it's a finite sum. The differential $(C_\bullet \otimes D_\bullet)_n \rightarrow (C_\bullet \otimes D_\bullet)_{n-1}$ sends $C_p \otimes D_q \rightarrow C_{p-1} \otimes D_q \oplus C_p \otimes D_{q-1}$ given by $x \otimes y \mapsto dx \otimes y + (-1)^p x \otimes dy$.

So the cross product is a map of chain complexes $S_*(X) \otimes S_*(Y) \rightarrow S_*(X \times Y)$. The Künneth theorem in dimension zero is really easy, because $\pi_0(X) \times \pi_0(Y) = \pi_0(X \times Y)$.

25.1. Acyclic models. Let \mathbf{C} be a category, and let $F : \mathbf{C} \rightarrow \mathbf{Ab}$ be a functor. Fix a set of object in \mathbf{C} , and let \mathcal{M} be the “models”. If $\mathbf{C} = \mathbf{Top} \times \mathbf{Top}$, then \mathcal{M} is the set of pairs of simplices.

DEFINITION 25.2. We say that F is \mathcal{M} -free if it is a direct sum of the free abelian group of the corepresentable functors, i.e., F is a direct sum of $\mathbf{Z} \text{Hom}_{\mathbf{C}}(M, -)$ where $M \in \mathcal{M}$.

EXAMPLE 25.3. For example, $S_n(X \times Y) = \mathbf{Z} \text{Hom}_{\mathbf{Top}}(\Delta^n \times Y) = \mathbf{Z} \text{Hom}_{\mathbf{Top} \times \mathbf{Top}}((\Delta^n, \Delta^n), (X, Y))$. Another example is that $\bigoplus_{p+q=n} S_p(X) \otimes S_q(Y) = \bigoplus \mathbf{Z} \text{Hom}_{\mathbf{Top}}(\Delta^p, X) \otimes \mathbf{Z} \text{Hom}_{\mathbf{Top}}(\Delta^q, Y) = \bigoplus_{p+q=n} \mathbf{Z} \langle \text{Hom}_{\mathbf{Top}}(\Delta^p, X) \times \text{Hom}_{\mathbf{Top}}(\Delta^q, Y) \rangle = \bigoplus_{p+q=n} \mathbf{Z} \text{Hom}_{\mathbf{Top} \times \mathbf{Top}}((\Delta^p, \Delta^q), (X, Y))$.

DEFINITION 25.4. A natural transformation of functors $\theta : F \rightarrow G$ is a \mathcal{M} -epimorphism if $\theta_M : F(M) \rightarrow G(M)$ is a surjection of abelian groups for every $M \in \mathcal{M}$. Consider a composition of natural transformations of functors $G' \rightarrow G \rightarrow G''$ that is zero. Let K be the objectwise kernel of $G \rightarrow G''$. So there's a factorization $G' \rightarrow K$. Say that the sequence is \mathcal{M} -exact if $G' \rightarrow K$ is a \mathcal{M} -epi.

This means that $G'(M) \rightarrow G(M) \rightarrow G''(M)$ is exact for all $M \in \mathcal{M}$.

EXAMPLE 25.5. We claim that $S_n(X \times Y) \rightarrow S_{n-1}(X \times Y) \rightarrow \cdots \rightarrow S_0(X \times Y) \rightarrow H_0(X \times Y) \rightarrow 0$ is \mathcal{M} -exact, because when I plug in (Δ^p, Δ^q) , I get an exact sequence (it's contractible so all homology groups vanish).

EXAMPLE 25.6. Consider the sequence $\cdots \rightarrow (S_*(X) \otimes S_*(Y))_1 \rightarrow S_0(X) \otimes S_0(Y) \rightarrow H_0(X) \otimes H_0(Y) \rightarrow 0$. Is this \mathcal{M} -exact? We don't know that yet, although it's true in each factor if you plug in a simplex. It turns out that it actually *is* \mathcal{M} -exact, but I'll come back to this in a few minutes.

I've been checking things for our chain complexes that'll come up in the Künneth theorem. Here's the key lemma that makes it all work.

LEMMA 25.7. *Let \mathbf{C} be a category with a set of models \mathcal{M} and let $F, G, G' : \mathbf{C} \rightarrow \mathbf{Ab}$ be functors. Let F be \mathcal{M} -free, and let $G' \rightarrow G$ be a \mathcal{M} -epimorphism. Then there's a lifting:*

$$\begin{array}{ccc} & & G' \\ & \nearrow f & \downarrow \\ F & \xrightarrow{\quad} & G \end{array}$$

PROOF. Clearly we may assume that $F(X) = \mathbf{Z} \text{Hom}_{\mathbf{C}}(M, X)$. Suppose $X = M$. We get:

$$\begin{array}{ccc} & & G'(M) \\ & \nearrow \bar{f}_M & \downarrow \\ \mathbf{Z} \text{Hom}_{\mathbf{C}}(M, M) & \xrightarrow{f_M} & G(M) \end{array}$$

Consider $1_M \in \mathbf{Z} \text{Hom}_{\mathbf{C}}(M, M)$. This maps to $f_M(1_M)$. But because $G' \rightarrow G$ is a \mathcal{M} -epi, there is some c_M that maps to $f_M(1_M)$. This is going to be $\bar{f}_M(1_M)$, i.e., $\bar{f}_M(1_M) := c_M$.

Now we're done by naturality! Because given any $\varphi : M \rightarrow X$, we get a commutative diagram:

$$\begin{array}{ccc} \mathbf{C}(M, X) & \xrightarrow{\bar{f}_X} & G'(X) \\ \downarrow & & \downarrow \\ \mathbf{C}(M, M) & \xrightarrow{\bar{f}_M} & G'(M) \end{array}$$

Now, $1_M \mapsto \varphi$, and so $\bar{f}_X(\varphi) = \varphi_*(c_M)$ by commutativity. Now extend linearly. □

We already knew the following result, but now we can make this formal:

THEOREM 25.8 (Eilenberg-Zilber theorem). *There exists a natural chain map:*

$$\begin{array}{ccc} S_*(X) \otimes S_*(Y) & \xrightarrow{\times} & S_*(X \times Y) \\ \downarrow & & \downarrow \\ H_0(X) \otimes H_0(Y) & \xrightarrow{\cong} & H_0(X \times Y) \end{array}$$

That is unique up to natural chain homotopy (this is part we didn't show before). There's also a map $\alpha : S_(X \times Y) \rightarrow S_*(X) \otimes S_*(Y)$ because $H_0(X) \otimes H_0(Y) \rightarrow H_0(X \times Y)$ is an isomorphism. These two maps α and \times are naturally chain homotopy inverses.*

COROLLARY 25.9. *There is an isomorphism $H(S_*(X) \otimes S_*(Y)) \cong H_*(X \times Y)$.*

We will show the following:

THEOREM 25.10. *Let C_\bullet, D_\bullet be chain complexes, bounded below, where C_n is a free R -module for all n . Then we have a generalization of the universal coefficient theorem. There is a sexseq:*

$$\begin{array}{ccccccc} 0 & \longrightarrow & \bigoplus_{p+q=n} H_p(C) \otimes H_q(D) & \xlongequal{\quad} & (H_*(C) \otimes H_*(D))_n & & \\ & & \swarrow & & \searrow & & \\ H_n(C_\bullet \otimes D_\bullet) & \xleftarrow{\quad} & \bigoplus_{p+q=n-1} \text{Tor}_1^R(H_p(C), H_q(D)) & \longrightarrow & 0 & & \end{array}$$

This is true over any PID, too.

PROOF. This is exactly the same as the proof for the UCT. It's a good idea to work through this on your own. \square

So, by combining this theorem and previous corollary, we get:

THEOREM 25.11 (Künneth theorem). *If R is a PID, there is a natural sexseq (that splits, but not naturally):*

$$\begin{array}{ccccccc} 0 & \longrightarrow & \bigoplus_{p+q=n} H_p(X) \otimes H_q(Y) & \xlongequal{\quad} & (H_*(X) \otimes H_*(Y))_n & & \\ & & \swarrow & & \searrow & & \\ H_n(X \times Y) & \xleftarrow{\quad} & \bigoplus_{p+q=n-1} \text{Tor}_1^R(H_p(X), H_q(Y)) & \longrightarrow & 0 & & \end{array}$$

EXAMPLE 25.12. If $R = k$ is a field, every module is already free, so the Tor term vanishes, and you get a Künneth isomorphism:

$$H_*(X; k) \otimes_k H_*(Y; k) \cong H_*(X \times Y; k)$$

This is rather spectacular. For example, what is $H_*(\mathbf{RP}^2 \times \mathbf{RP}^3; \mathbf{Z}/2\mathbf{Z})$? Well, directly, we see that there is 1 cell in dimensions 0 and 5, 2 cells in dimensions 1 and 4, 3 cells in dimensions 2 and 3. Note the symmetry. This isn't an accident, it's Poincaré duality, which we'll get to soon. By Künneth, it's $H_*(\mathbf{RP}^2; \mathbf{Z}/2\mathbf{Z}) \otimes_{\mathbf{Z}/2\mathbf{Z}} H_*(\mathbf{RP}^3; \mathbf{Z}/2\mathbf{Z})$, i.e.:

$$H_n(\mathbf{RP}^2 \times \mathbf{RP}^3; \mathbf{Z}/2\mathbf{Z}) = \bigoplus_{p+q=n} H_p(\mathbf{RP}^2; \mathbf{Z}/2\mathbf{Z}) \otimes H_q(\mathbf{RP}^3; \mathbf{Z}/2\mathbf{Z}) = \left\{ \text{work it out yourself} \right\}$$

26. A few more things about coefficients, cohomology

Problem Set 5 now due Friday! Recall our example where we let $\mathcal{J} = (\mathbf{Z}_{>0}, |)$. You can consider $\mathcal{J} \rightarrow \mathbf{Ab}$, say assigning to each i the integers \mathbf{Z} , and $f_{ij} : \mathbf{Z} \xrightarrow{j/i} \mathbf{Z}$. The colimit is \mathbf{Q} , where you send $X_n \rightarrow \mathbf{Q}$ via $1 \mapsto \frac{1}{n}$. It's rather natural. But it's not the simplest way to define \mathbf{Q} . You just could have defined $\mathbf{Q} = \varinjlim (\mathbf{Z} \xrightarrow{2} \mathbf{Z} \xrightarrow{3} \mathbf{Z} \xrightarrow{4} \mathbf{Z} \rightarrow \dots)$.

We saw that \varinjlim is exact, that it commutes with tensor products, and that homology commutes with direct limits. So if I had a chain complex C_\bullet of abelian groups, then the process of computing homology involves exact sequences. If I want to compute:

$$H(C_\bullet \otimes \mathbf{Q}) = H(C_\bullet \otimes \varinjlim \mathbf{Z}) = H(\varinjlim (C_\bullet \otimes \mathbf{Z})) = H(\varinjlim C_\bullet) = \varinjlim H(C_\bullet) = H(C_\bullet) \otimes \varinjlim \mathbf{Z} = H(C_\bullet) \otimes \mathbf{Q}$$

Thus $- \otimes \mathbf{Q}$ is exact, i.e., \mathbf{Q} is *flat* over \mathbf{Z} , so $\text{Tor}_1^{\mathbf{Z}}(M, \mathbf{Q}) = 0$. By UCT, this means that $H_*(X) \otimes \mathbf{Q} \simeq H_*(X; \mathbf{Q})$.

DEFINITION 26.1. The n th Betti number of X is defined to be $\beta_n := \dim_{\mathbf{Q}} H_n(X; \mathbf{Q})$.

The Euler characteristic can just as well have been defined as $\chi(X) = \sum_{n=0}^{\infty} (-1)^n \beta_n$.

Oh, let me ask if 11 am works for those of you who are going to take 18.906. OK? It seems like it's too early.

Anyway, every space has a diagonal map $X \xrightarrow{\Delta} X \times X$. This induces a map $H_*(X; R) \rightarrow H_*(X \times X; R)$, where R is a PID. But now, we have a Künneth map $\alpha : H_*(X; R) \otimes_R H_*(X; R) \rightarrow H_*(X \times X; R)$. We can get some kind of comultiplication if α is an isomorphism. And, well, the Künneth theorem says that $\text{Tor}_1^R(H_*(X; R), H_*(X; R)) = 0$ if and only if α is an isomorphism. This condition is satisfied, for example, if each $H_n(X; R)$ is flat over R for all n (for example, free over R). A special case is when R is a field. So you get a comultiplication $\Delta : H_*(X; R) \rightarrow H_*(X; R) \otimes_R H_*(X; R)$ if this condition is satisfied.

This diagonal map has many properties.

DEFINITION 26.2. Let R be a ring. A (graded, bounded below) coalgebra over R is a (graded) R -module M with a multiplication $\Delta : M \rightarrow M \otimes_R M$ and an augmentation map $\varepsilon : M \rightarrow R$ such that all of the following diagrams commute:

$$\begin{array}{ccccc} & & M & & \\ & \swarrow & \downarrow & \searrow & \\ R \otimes_R M & \xleftarrow[\varepsilon \otimes 1]{} & M \otimes_R M & \xrightarrow{1 \otimes \varepsilon} & M \otimes_R R \end{array}$$

Where the diagonal maps are the canonical isomorphisms. And you have coassociativity:

$$\begin{array}{ccc} M & \xrightarrow{\Delta} & M \otimes_R M \\ \downarrow \Delta & & \downarrow \Delta \otimes 1 \\ M \otimes_R M & \xrightarrow{1 \otimes \Delta} & M \otimes_R M \otimes_R M \end{array}$$

And it's cocommutative (he'll just say commutative because there's no need to say "co" if we know we're working with coalgebras, but I want to write it anyway – I'll probably abuse it though) if:

$$\begin{array}{ccc} & M & \\ \swarrow \Delta & & \searrow \Delta \\ M \otimes_R M & \xrightarrow{\tau} & M \otimes_R M \end{array}$$

Where $\tau(x \otimes y) = (-1)^{|x| \cdot |y|} y \otimes x$ is the twisting map.

EXAMPLE 26.3. The Künneth map is coassociative and cocommutative.

Consider:

$$\begin{array}{ccc} S_*(X) \otimes S_*(Y) & \xrightarrow{\tau} & S_*(Y) \otimes S_*(X) \\ \downarrow \times & & \downarrow \times \\ S_*(X \times Y) & \xrightarrow{\tau_*} & S_*(Y \times X) \end{array}$$

Where τ is as defined above on the tensor product and τ is also used to denote the twisting map $X \times Y \rightarrow Y \times X$. And this diagram commutes up to chain homotopy.

COROLLARY 26.4. *Let k be a field. Then $H_*(X; k)$ has the natural structure of a cocommutative graded coalgebraic structure.*

I could just talk about coalgebras. But one of my friends told me that nobody in France knew what coalgebras were. So we're going to talk about cohomology, and get an algebra structure. Some say that cohomology is better because you have algebras, but that's more of a sociological statement than a mathematical one.

SLOGAN 26.5. Cohomology gives algebras. It's a contravariant functor on spaces.

A better reason for looking at cohomology is that there are many geometric constructions that pull back. For example, if I have some covering space $\tilde{X} \rightarrow X$, and I have a map $f : Y \rightarrow X$, I get a pullback covering space $f^*\tilde{X}$. A better example is vector bundles (that we'll talk about in 18.906) – they don't push out, they pullback. This'll give the theory of *characteristic classes*. Another even better reason is that cohomology is the target of the Poincaré duality map.

DEFINITION 26.6. Let N be an abelian group. A singular n -cochain on X with coefficients in N is a function $\text{Sin}_n(X) \rightarrow N$.

If N is an R -module, then I can extend linearly to get a map $S_n(X; R) \rightarrow N$.

NOTATION 26.7. Write $S^n(X; N) := \text{Map}(\text{Sin}_n(X); N) = \text{Hom}_R(S_n(X; R); N)$.

This is going to give me something contravariant, that's for sure. But I want to get a cochain complex $(S^*(X; N), d)$. Cochain means that the differential increases the degree.

I have a map $(-, -) : S^n(X; N) \otimes S_n(X; R) \rightarrow N$ given by evaluation. I want d on $S^*(X; N)$ that makes the map $S^n(X; N) \otimes S_n(X; R) \rightarrow N$ a chain map where we regard N as a chain complex with zeros everywhere except in dimension 0. But the way I've said it doesn't quite make sense because $S^*(X; N)$ isn't a chain complex! So let $S^*(X; N)$ be a chain complex with $S^n(X; N)$ in dimension $(-n)$. But now it's not bounded below. So, to be honest, I should say that we're going to make a decision. If C_\bullet, D_\bullet aren't necessarily bounded below chain complex, then $(C_\bullet \otimes D_\bullet)_n := \bigoplus_{i+j=n} C_i \otimes D_j$.

Let $f \in S^n(X; R)$ and $\sigma \in S_n(X; R)$. This is a chain map if $d(f, \sigma) = 0$. And $d(f, \sigma) = (df, \sigma) + (-1)^{|f|}(f, d\sigma)$. Let me erase this. This doesn't make sense. Scratch that. Let's start over.

Let $f \in S^{n+1}(X; R)$ and $\sigma \in S_n(X; R)$. Then $(df, \sigma) + (-1)^{|f|}(f, d\sigma) = d(f, \sigma) = 0$. So $(df)(\sigma) = (-1)^{|f|+1}f(d\sigma)$. That's what the differential is. This makes $S^*(X; N)$ a cochain complex. So you can consider its homology.

DEFINITION 26.8. The n th cohomology of X with coefficients in N is $H^n(X; N) := H^n(S^*(X; N))$. This is a contravariant functor on **Top**.

If you fix X , I get a covariant functor $H^n(X; -)$ on **Mod** $_R$.

CONSTRUCTION 26.9. I have a chain map $(,) : S^*(X; N) \otimes_R S_*(X; R) \rightarrow N$. I can apply homology to this, to get $\alpha : H^*(X; N) \otimes_R H_*(X; R) \rightarrow H(S^*(X; N) \otimes_R S_*(X; R))$. In particular, you get a natural pairing $(,) : H^*(X; N) \otimes_R H_*(X; R) \xrightarrow{\alpha} H(S^*(X; N) \otimes_R S_*(X; R)) \xrightarrow{(,)} N$. This "evaluation map" is called the Kronecker pairing.

WARNING 26.10. $S^n(X; \mathbf{Z}) = \text{Map}(\text{Sin}_n(X); \mathbf{Z}) = \prod_{\text{Sin}_n(X)} \mathbf{Z}$, which is probably an uncountable product. An awkward fact is that this is never free abelian.

CONSTRUCTION 26.11. If $A \subseteq X$, there is a restriction map $S^n(X; N) \rightarrow S^n(A; N)$. There is an injection $\text{Sin}_n(A) \hookrightarrow \text{Sin}_n(X)$. And as long as A is empty, I can split this. So any function $\text{Sin}_n(A) \rightarrow N$ extends to $\text{Sin}_n(X) \rightarrow N$. This means that $S^n(X; N) \rightarrow S^n(A; N)$ is surjective. You can define the kernel as $S^n(X, A; N)$, which sits in $0 \rightarrow S^n(X, A; N) \rightarrow S^n(X; N) \rightarrow S^n(A; N) \rightarrow 0$. This gives the *relative cochains*.

I can take the homology of this sexseq to get a lexseq:

$$\begin{array}{ccccccc}
& & \cdots & \xleftarrow{\delta} & & & \\
& & & & \delta & & \\
H^1(X, A; N) & \longrightarrow & H^1(X; N) & \longrightarrow & H^1(A) & & \\
& & \delta & & & & \\
H^0(X, A; N) & \longrightarrow & H^0(X; N) & \longrightarrow & H^0(A) & &
\end{array}$$

And $H^0(X; N)$ sits in the cokernel of $\text{Map}(\text{Sin}_0(X), N) \rightarrow \text{Map}(\text{Sin}_1(X), N)$, so that $H^0(X; N) = \text{Map}(\pi_0(X), N)$.

27. Cohomology, Ext, cup product

Let R be a ring, probably a PID. It's often a field, but it could be \mathbf{Z} . Let N be an R -module. Define $S^n(X; N) = \text{Map}(\text{Sin}_n(X), N)$. There's a boundary map $d : S^n(X; N) \rightarrow S^{n+1}(X; N)$ that takes a cochain f to the map df defined by $df(\sigma) = (-1)^{n+1}f(d\sigma)$ where $\sigma \in \text{Sin}_{n+1}(X)$. Now, $d^2 = 0$, so $H^n(X; N) := H^n(S^*(X; N))$. This is a contravariant functor from **Top** to **Ab** and it's covariant in the coefficients.

When $n = 0$, you have $0 \rightarrow S^0(X; N) \xrightarrow{d} S^1(X; N)$. Thus $H^0(X; N) = \ker d$. Well, $S^0(X; N) = \text{Map}(X, N)$, and d sends a 0-cochain f to $\sigma \mapsto \pm f(d\sigma) = \pm(f(\sigma(0)) - f(\sigma(1)))$. So a function is in the kernel of d if its values on the ends of any path is the same. Thus $H^0(X; N) = \text{Map}(\pi_0(X), N)$.

We also talked about the Kronecker pairing. This gave an evaluation $H^n(X; N) \otimes_R H_n(X; R) \rightarrow N$. Taking the adjoint gives a map $H^n(X; N) \xrightarrow{\beta} \text{Hom}_R(H_n(X; R), N)$. We can try to understand cohomology in terms of homology. β 'll often be an isomorphism, but not always.

THEOREM 27.1 (UCT for cohomology). *There is a natural sexseq:*

$$0 \rightarrow \text{Ext}_R^1(H_{n-1}(X; R), N) \rightarrow H^n(X; N) \xrightarrow{\beta} \text{Hom}_R(H_n(X; R), N) \rightarrow 0$$

that splits, but not naturally. This also holds for relative cohomology.

I will tell you what Ext means now. I will prove this on Friday.

The problem that arises is that $\text{Hom}_R(-, N) : \mathbf{Mod}_R \rightarrow \mathbf{Mod}_R$ is not exact. More precisely, it preserves right exact sequences, but not left exact sequences. Consider $M' \xrightarrow{i} M \xrightarrow{p} M'' \rightarrow 0$ an exact sequence of R -modules. This gives a sequence $0 \rightarrow \text{Hom}_R(M'', N) \rightarrow \text{Hom}_R(M, N) \rightarrow \text{Hom}_R(M', N)$. If I have $f : M'' \rightarrow N$, and I compose with p to get a zero map, then is f zero? Well, yes, because p is surjective. Now suppose I have $g : M \rightarrow N$, such that $i \circ g = 0$. So it factors through the cokernel, and you get a unique factorization $M'' \rightarrow N$ (unique because $M \rightarrow M''$ is surjective).

Suppose I have an injection $0 \rightarrow M' \rightarrow M$. Is $\text{Hom}(M, N) \rightarrow \text{Hom}(M', N)$ surjective? If I have some map $M' \rightarrow N$ and $M' \hookrightarrow N$, then does this extend to a map $M \rightarrow N$? No! For example, if you have $1 : \mathbf{Z}/2\mathbf{Z} \rightarrow \mathbf{Z}/2\mathbf{Z}$ and $\mathbf{Z}/2\mathbf{Z} \hookrightarrow \mathbf{Z}/4\mathbf{Z}$, then you can't lift to a map $\mathbf{Z}/4\mathbf{Z} \rightarrow \mathbf{Z}/2\mathbf{Z}$. This works, though, if the sexseq splits.

Homological algebra now comes to the rescue! Pick a free resolution of M given by $\cdots \rightarrow F_2 \rightarrow F_1 \rightarrow M \rightarrow F_0 \rightarrow 0$. If I apply Hom, I get a chain complex $0 \rightarrow \text{Hom}(F_0, N) \rightarrow \text{Hom}(F_1, N) \rightarrow \text{Hom}(F_2, N) \rightarrow \cdots$.

DEFINITION 27.2. Define $\text{Ext}_R^n(M, N) = H^n(\text{Hom}_R(F_\bullet, N))$ as the n -dimensional homology of this chain complex.

REMARK 27.3. If R is a PID, then $\text{Ext}^n = 0$ if $n > 1$. If R is a field, then $\text{Ext}^n = 0$ for $n > 0$. Also, Ext is well-defined and functorial (by the fundamental theorem of homological algebra). Another important point is that $\text{Hom}_R(-, N)$ takes chain homotopies to chain homotopies. This is a pretty important thing, and is something to think about for a minute. This is because if I have $M' \rightarrow M$, I get an induced map $\text{Hom}_R(M', N) \leftarrow \text{Hom}_R(M, N)$, and this is actually an R -module map, and in particular, additive. And this means that the $dh - hd = f_1 - f_0$ is preserved. Lastly, if M is free or projective, then $\text{Ext}^n(M, -) = 0$ for $n > 0$. In addition, $\text{Ext}^0(M, N) = \text{Hom}_R(M, N)$.

Recall the trick that if I have a sexseq $0 \rightarrow A \rightarrow B \rightarrow C \rightarrow 0$, and I have free resolutions $F'_\bullet \rightarrow A$ and $F''_\bullet \rightarrow 0$, I can get a free resolution $F_\bullet \rightarrow B$ to get a sexseq $0 \rightarrow F'_\bullet \rightarrow F_\bullet \rightarrow F''_\bullet \rightarrow 0$. I can now apply $\text{Hom}_R(-, N)$ to get a sexseq of cochain complexes, because this sequence splits in any given degree. Thus, I get a lexseq:

$$\begin{array}{ccccccc}
 & & & & & & 0 \\
 & & & & & \swarrow & \\
 \text{Hom}_R(M'', N) & \longrightarrow & \text{Hom}_R(M, N) & \longrightarrow & \text{Hom}_R(M', N) & & \\
 & & & & \swarrow & & \\
 \text{Ext}_R^1(M'', N) & \longrightarrow & \text{Ext}_R^1(M, N) & \longrightarrow & \text{Ext}_R^1(M', N) & & \\
 & & & & \swarrow & & \\
 \dots & & & & & &
 \end{array}$$

In this sense, Ext is like a cohomology theory for R -modules.

Let us use this to make a calculation.

EXAMPLE 27.4. Let $R = \mathbf{Z}$, and look at the sexseq $0 \rightarrow \mathbf{Z} \xrightarrow{k} \mathbf{Z} \rightarrow \mathbf{Z}/k\mathbf{Z} \rightarrow 0$. Here N is some abelian group. So, our lexseq will look like:

$$\begin{array}{ccccccc}
 & & & & & & 0 \\
 & & & & & \swarrow & \\
 \text{Hom}_R(\mathbf{Z}/k\mathbf{Z}, N) & \longrightarrow & \text{Hom}_R(\mathbf{Z}, N) = N & \longrightarrow & \text{Hom}_R(\mathbf{Z}, N) = N & & \\
 & & & & \swarrow & & \\
 \text{Ext}_R^1(\mathbf{Z}/k\mathbf{Z}, N) & \longrightarrow & 0 & \longrightarrow & 0 & & \\
 & & & & \swarrow & & \\
 \dots & & & & & &
 \end{array}$$

The map $N \rightarrow N$ in this lexseq is multiplication by k . Thus $\text{Hom}(\mathbf{Z}/k\mathbf{Z}, N) = \ker(N \xrightarrow{k} N)$. And, well, $\text{Ext}_{\mathbf{Z}}^1(\mathbf{Z}/k\mathbf{Z}, N) = N/kN$.

Let's get some consequences of cohomology from the UCT. Even independent of that, we get some properties.

27.1. Properties of cohomology.

- (1) It's homotopy invariant. This means that if $f_0 \sim f_1 : (X, A) \rightarrow (Y, B)$, then $H^*(X, A; N) \xleftarrow{f_0^*, f_1^*} H^*(Y, B; N)$ are equal. I can't use the UCT to address this because the UCT only tells you that things are isomorphic (use the 5-lemma). But we did establish a chain homotopy $f_{0,*} \sim f_{1,*} : S_*(X, A) \rightarrow S_*(Y, B)$, and applying Hom still retains this chain homotopy, and hence you get the same map on cohomology.
- (2) Excision. If $U \subseteq A \subseteq X$ such that $\overline{U} \subseteq \text{Int}(A)$, then $H^*(X, A; N) \leftarrow H^*(X - U, A - U; N)$ is an isomorphism. This follows from the UCT (in the relative form, which is also true).

- (3) Mayer-Vietoris sequence. If I have $A, B \subseteq X$ such that their interiors cover X , then I have an lexseq:

$$\begin{array}{ccccccc}
 & & & & & & \cdots \\
 & & & & & \swarrow & \\
 H^n(X; N) & \longrightarrow & H^n(A; N) \oplus H^n(B; N) & \longrightarrow & H^n(A \cap B; N) & & \\
 & & & & \swarrow & & \\
 H^{n+1}(X; N) & \longrightarrow & \cdots & & & &
 \end{array}$$

28. Universal coefficient theorem, and products in H^*

We talked about cohomology $H^*(X, A; N)$, which was contravariant in (X, A) . We can repeat some of the arguments for homology in the cohomological context. We can also relate cohomology to homology. This is the purpose of the universal coefficient theorem for cohomology. I won't actually prove this here, because I've put up notes on the website that covers this.

THEOREM 28.1 (Mixed variance UCT). *Let R be a PID, let N be a R -module, and let C_\bullet be a chain complex of free R -modules. We've decided that $\text{Hom}_R(C_\bullet, N)$ is a cochain complex. I'm always a little confused on how to write the homology of a cochain complex? Should I write H^n or H_n ? Maybe this is a personal problem, and I should keep it personal? We'll just write H^n . (Some ridiculous notation with the n sitting on the line in H was suggested, but this'd be impossible to TeX!)*

Anyway, we had a map $H^n \text{Hom}_R(C_\bullet, N) \rightarrow \text{Hom}_R(H_n(C_\bullet), N)$. The theorem is that this is surjective, which has kernel $\text{Ext}_R^1(H_{n-1}(C_\bullet), N)$. I.e, there is a natural sexseq:

$$0 \rightarrow \text{Ext}_R^1(H_{n-1}(C_\bullet), N) \rightarrow H^n \text{Hom}_R(C_\bullet, N) \rightarrow \text{Hom}_R(H_n(C_\bullet), N) \rightarrow 0$$

that splits, but not naturally.

STRATEGY OF THE PROOF. I have a sexseq $0 \rightarrow Z_n(C_\bullet) \rightarrow C_n \rightarrow C_n/Z_n(C_\bullet) \rightarrow 0$ where $Z_n(C_\bullet) = \ker d_n$ (where C_\bullet is a chain complex). But $C_n/Z_n(C_\bullet) = B_{n-1} \hookrightarrow C_{n-1}$ where $B_n(C_\bullet) = \text{Im } d_{n-1}$ (this last thing probably has wrong indexing). We assumed C_{n-1} is a free R -module, and that R is a PID, so that B_{n-1} is also free. Thus the sexseq $0 \rightarrow Z_n(C_\bullet) \rightarrow C_n \rightarrow B_{n-1} \rightarrow 0$ splits.

Another sexseq that's important is $0 \rightarrow Z_n(C_\bullet)/B_n(C_\bullet) \rightarrow C_n/B_n(C_\bullet) \rightarrow C_n/Z_n(C_\bullet) \rightarrow 0$. If you like, you can think of this as follows:

$$\begin{array}{ccccccc}
 & & 0 & & 0 & & 0 \\
 & & \uparrow & & \uparrow & & \uparrow \\
 0 & \longrightarrow & Z_n(C_\bullet)/B_n(C_\bullet) & \longrightarrow & C_n/B_n(C_\bullet) & \longrightarrow & C_n/Z_n(C_\bullet) \longrightarrow 0 \\
 & & \uparrow & & \uparrow & & \uparrow \\
 0 & \longrightarrow & Z_n(C_\bullet) & \longrightarrow & C_n & \longrightarrow & C_n/Z_n(C_\bullet) \longrightarrow 0 \\
 & & \uparrow & & \uparrow & & \uparrow \\
 0 & \longrightarrow & B_n(C_\bullet) & \longrightarrow & B_n(C_\bullet) & \longrightarrow & 0 \longrightarrow 0 \\
 & & \uparrow & & \uparrow & & \uparrow \\
 & & 0 & & 0 & & 0
 \end{array}$$

Thus $0 \rightarrow Z_n(C_\bullet)/B_n(C_\bullet) \rightarrow C_n/B_n(C_\bullet) \rightarrow C_n/Z_n(C_\bullet) \rightarrow 0$ splits. But $Z_n(C_\bullet)/B_n(C_\bullet) = H_{n-1}$, so this gives: $0 \rightarrow H_{n-1} \rightarrow C_n/B_n(C_\bullet) \rightarrow B_{n-1} \rightarrow 0$.

Now, we have a sexseq $0 \rightarrow B^n \text{Hom}_R(C_\bullet, N) \rightarrow Z^n \text{Hom}_R(C_\bullet, N) \rightarrow H^n \text{Hom}_R(C_\bullet, N) \rightarrow 0$. We want to compare this to $\text{Hom}_R(H_n(C_\bullet), N)$. But, now, $0 \rightarrow H_{n-1} \rightarrow C_n/B_n(C_\bullet) \rightarrow B_{n-1} \rightarrow 0$ splits, so we get a

sexseq $0 \rightarrow \text{Hom}(B_{n-1}, N) \rightarrow \text{Hom}(C_n/B_n(C_\bullet), N) \rightarrow \text{Hom}(H_{n-1}(C_\bullet), N) \rightarrow 0$. Let me write this out:

$$\begin{array}{ccccccc} 0 & \longrightarrow & B^n \text{Hom}_R(C_\bullet, N) & \longrightarrow & Z^n \text{Hom}_R(C_\bullet, N) & \longrightarrow & H^n \text{Hom}_R(C_\bullet, N) \longrightarrow 0 \\ & & \downarrow & & \downarrow & & \downarrow \\ 0 & \longrightarrow & \text{Hom}(B_{n-1}, N) & \longrightarrow & \text{Hom}(C_n/B_n(C_\bullet), N) & \longrightarrow & \text{Hom}(H_{n-1}(C_\bullet), N) \longrightarrow 0 \end{array}$$

An element of $Z^n \text{Hom}_R(C_\bullet, N)$ is a map $f : C_n \rightarrow N$ such that $f \circ d = 0$. So this map f factors as $C_n/B_n(C_\bullet) \rightarrow N$. Thus we have the middle dotted map, and it's actually an isomorphism. You can then check compatibility, to get the left dotted map.

Is the map $H^n \text{Hom}_R(C_\bullet, N) \rightarrow \text{Hom}(H_{n-1}(C_\bullet), N)$ surjective? Well, use the snake lemma. I can then use diagram chasing to see that the map is indeed surjective, with kernel given by the kernel of $B^n \text{Hom}_R(C_\bullet, N) \rightarrow \text{Hom}(B_{n-1}, N)$. And the rest of the proof amounts to showing that this kernel is $\text{Ext}_R^1(H_{n-1}(C_\bullet), N)$. And for splitting we can construct a splitting map, see the notes. \square

REMARK 28.2. Miguel: Why is Ext called Ext?

Miller: It deals with extensions. Let R be a commutative ring, and let M, N be two R -modules. I can think about extensions $0 \rightarrow N \rightarrow L \rightarrow M \rightarrow 0$. Well, for example, I have two extensions $0 \rightarrow \mathbf{Z}/2\mathbf{Z} \rightarrow \mathbf{Z}/2\mathbf{Z} \oplus \mathbf{Z}/2\mathbf{Z} \rightarrow \mathbf{Z}/2\mathbf{Z} \rightarrow 0$, and $0 \rightarrow \mathbf{Z}/2\mathbf{Z} \rightarrow \mathbf{Z}/4\mathbf{Z} \rightarrow \mathbf{Z}/2\mathbf{Z} \rightarrow 0$. Say that two extensions are equivalent if there's a map of sexseqs between them is the identity on N and M . The two extensions above aren't equivalent, for example.

Another definition of $\text{Ext}_R^1(M, N)$ is the set of extensions like this modulo this notion of equivalence. The zero in the group is the split extension.

Also, Ext is contravariant in the first variable, but not in the second variable. If you want to find the Ext groups, you can use an injective resolution of the second variable, or a projective resolution of the first variable. These are what are known as derived functors. Tor is a left derived functor because it uses a projective resolution that goes off to the left, but Ext is a right derived functor because it uses an injective resolution that goes off to the right.

28.1. Products. We'll talk about the cohomology cross product.

CONSTRUCTION 28.3. Define $S^p(X) \otimes S^q(Y) \xrightarrow{\times} S^{p+q}(X \times Y)$ as follows. Let σ be a $(p+q)$ -simplex in $X \times Y$. Let $f \otimes g \in S^p(X) \otimes S^q(Y)$. We'll define $f \times g \in S^{p+q}(X \times Y)$. Then $f : S_p(X) \rightarrow R$ and $g : S_q(Y) \rightarrow R$. I can write $\sigma = \begin{pmatrix} \sigma_1 \\ \sigma_2 \end{pmatrix}$ where $\sigma_1 : \Delta^{p+q} \rightarrow X$ and $\sigma_2 : \Delta^{p+q} \rightarrow Y$. Define:

$$(f \times g)(\sigma) = f(\sigma_1 \circ \alpha_p)g(\sigma_2 \circ \omega_q)$$

where $\alpha_p : \Delta^p \rightarrow \Delta^{p+q}$ takes $k \mapsto k$ where $k \in [p]$. And $\omega_q : \Delta^q \rightarrow \Delta^{p+q}$ sends $\ell \mapsto \ell + p$ where $\ell \in [q]$. It is an extremely (idiotic I think was the word used) construction that I have never gotten used to.

REMARK 28.4. It is *incredibly* stupid.

We get a map on cochains. We need to check that this is a chain map $S^*(X) \otimes S^*(Y) \rightarrow S^*(X \times Y)$. This is your homework! What this means is that you get a map $H^*(S^*(X) \otimes S^*(Y)) \rightarrow H^*(X \times Y)$. I guess I have coefficients in R . I'm not quite done, but I have a map $H^*(X) \otimes H^*(Y) \rightarrow H^*(S^*(X) \otimes S^*(Y))$. The composition $H^*(X) \otimes H^*(Y) \rightarrow H^*(S^*(X) \otimes S^*(Y)) \rightarrow H^*(X \times Y)$ is the cross product.

It's not very easy to do computations with this. It's just hard to deal with. Let me make some points about this construction, though.

DEFINITION 28.5. Now take $X = Y$. Then I get $H^p(X) \otimes H^q(X) \xrightarrow{\times} H^{p+q}(X \times X) \xrightarrow{\Delta^*} H^{p+q}(X)$ where $\Delta : X \rightarrow X \times X$ is the diagonal. This composition is called the cup product. Some people write \smile , and others write \cup . (I'll TeX it as \cup .)

Some properties of the cup product are the following. I claim that $H^0(X) \cong \text{Map}(\pi_0(X), R)$ as rings. This α and ω stuff collapses if $p = q = 0$. There's nothing to do ... they're both the identity maps. So this isomorphism is clear. Also, inside $H^0(X)$, we pick the element that maps to $(c \mapsto 1) \in \text{Map}(\pi_0(X), R)$. This

is the identity for the cup product. This comes out because when $p = 0$ in our above story, then α_0 is just including the 0-simplex, and ω is the identity, so this is completely clear from that description.

PROPOSITION 28.6. *If $f \in S^p(X)$ and $g \in S^q(Y)$ and $h \in S^r(Z)$, then $((f \times g) \times h)(\sigma) = (f \times (g \times h))(\sigma)$ where $\sigma : \Delta^{p+q+r} \rightarrow X \times Y \times Z$.*

PROOF. Well, $((f \times g) \times h)(\sigma) = (f \times g)(\sigma_{12} \circ \alpha_{p+q})h(\sigma_3 \circ \omega_r)$ where $\sigma_{12} : \Delta^{p+q+r} \rightarrow X \times Y$ and $\sigma_3 : \Delta^{p+q+r} \rightarrow Z$. But $(f \times g)(\sigma_{12} \circ \alpha_{p+q}) = f(\sigma_1 \circ \alpha_p)g(\sigma_2 \circ \mu_q)$ where μ_q is the “middle portion” that sends $\ell \mapsto \ell + p$ where $\ell \in [q]$. In other words, $((f \times g) \times h)(\sigma) = f(\sigma_1 \circ \alpha_p)g(\sigma_2 \circ \mu_q)h(\sigma_3 \circ \omega_r)$. I’ve used associativity of the ring. But this thing is exactly the same as $(f \times (g \times h))(\sigma)$, so this is associative. \square

Therefore, $(\alpha \cup \beta) \cup \gamma = \alpha \cup (\beta \cup \gamma)$.

But this product is obviously not commutative. It treats the two maps completely differently. But we have ways of dealing with this. This comes from the story of acyclic models, where I’ll show that $\alpha \cup \beta = (-1)^{|\alpha| \cdot |\beta|} \beta \cup \alpha$. Thus $H^*(X)$ forms a *graded commutative ring*.

29. Cup product, continued

We can construct an explicit map $S^p(X) \otimes S^q(Y) \xrightarrow{\times} S^{p+q}(Y)$ via:

$$(f \times g)(\sigma) = f(\sigma_1 \circ \alpha_p)g(\sigma_2 \circ \omega_q)$$

where $\alpha_p : \Delta^p \rightarrow \Delta^{p+q}$ takes $k \mapsto k$ where $k \in [p]$, and $\omega_q : \Delta^q \rightarrow \Delta^{p+q}$ sends $\ell \mapsto \ell + p$ where $\ell \in [q]$.

I would like to modify this definition a bit, and correct what I said. I think it’s more natural to put a sign so that:

$$(f \times g)(\sigma) = (-1)^{pq} f(\sigma_1 \circ \alpha_p)g(\sigma_2 \circ \omega_q)$$

You’ll see why we’re adding the sign soon. The claim is that \times is a chain map, so we get a map $H(S^p(X) \otimes S^q(Y)) \rightarrow H_{p+q}(X \times Y)$. There is a map $H_p(X) \otimes H_q(Y) \xrightarrow{\mu} H(S^p(X) \otimes S^q(Y))$ defined as follows. Given chain complexes C_\bullet and D_\bullet , define $\mu : H(C_\bullet) \otimes H(D_\bullet) \rightarrow H(C_\bullet \otimes D_\bullet)$. We’ve done this before, but let me just say: $\mu : [x] \otimes [y] \mapsto [x \otimes y]$. For some reason, he said that we’ll not call this μ . But I don’t want to delete the μ so I’ll just leave it there.

We get the cup product as follows. Given $\Delta : X \rightarrow X \times X$, we get $\cup : H_p(X) \otimes H_q(X) \rightarrow H_{p+q}(X \times X) \xrightarrow{\Delta^*} H_{p+q}(X)$. We proved that there was a class $1 \in H_0(X) = \text{Map}(\pi_0(X), R) \ni (\alpha \mapsto 1)$. This acts as a unit for the cup product. Also, the cup product is strictly associative.

DEFINITION 29.1. Let R be a commutative ring. A *graded R -algebra* is a graded R -module $\cdots, A_{-1}, A_0, A_1, A_2, \cdots$ (integer graded sequence) (some people take a direct sum, but I find no reason for doing that) with maps $A_p \otimes_R A_q \rightarrow A_{p+q}$ and a map $R \rightarrow A_0$ (that determines the unit), that makes the following diagram commute.

$$\begin{array}{ccc} A_p \otimes_R (A_q \otimes_R A_r) & \longrightarrow & A_p \otimes_R A_{q+r} \\ \downarrow & & \downarrow \\ (A_{p+q}) \otimes_R A_r & \longrightarrow & A_{p+q+r} \end{array}$$

DEFINITION 29.2. A graded R -algebra A is said to be (graded) commutative if the following diagram commutes:

$$x \otimes y \longmapsto (-1)^{|x| \cdot |y|} y \otimes x$$

$$\begin{array}{ccc} A \otimes A & \xrightarrow{\tau} & A \otimes A \\ & \searrow & \swarrow \\ & A & \end{array}$$

We claim that $H_*(X)$ forms a graded commutative ring under the cup product. This is nontrivial. On the cochain level, this is clearly not graded commutative. We’re going to have to work hard – in fact, so hard that you’re going to do some of it for homework.

We'll do a chain level construction. I say there's a map $\alpha : S_n(X \times Y) \rightarrow \bigoplus_{p+q=n} S_p(X) \otimes S_q(Y)$. First I'll tell you what happens to n -simplices $\sigma : \Delta^n \rightarrow X \times Y$. Let $\sigma_1 : \Delta^n \rightarrow X \times Y \rightarrow X$, and similarly for σ_2 . Define $S_n(X \times Y) \xrightarrow{\alpha} \bigoplus_{p+q=n} S_p(X) \otimes S_q(Y)$ by sending:

$$\sigma \mapsto \sum_{p+q=n} (\sigma_1 \circ \alpha_p) \otimes (\sigma_2 \circ \omega_q)$$

We claim that this is a chain map, and that this induces the cross product on cochains.

REMARK 29.3. This map α is called the Alexander-Whitney map.

If I have two chain complexes, I want to consider a map $\mu : \text{Hom}(C_\bullet, R) \otimes \text{Hom}(D_\bullet, R) \rightarrow \text{Hom}(C_\bullet \otimes D_\bullet, R)$ given by $f \otimes g \mapsto (x \otimes y \mapsto (-1)^{pq} f(x)g(y))$ where $|f| = |x| = p$ and $|g| = |y| = q$. I haven't quite done the right thing here, have I? I have to write:

$$f \otimes g \mapsto \begin{cases} (x \otimes y \mapsto (-1)^{pq} f(x)g(y)) & |x| = |f| = p, |y| = |g| = q \\ 0 & \text{else} \end{cases}$$

You should check that this is a chain map.

Recall that we have: $S^p(X) \otimes S^q(Y) = \text{Hom}(S_p(X), R) \otimes_R \text{Hom}(S_q(Y), R)$. The map μ we constructed just now gives a map $\text{Hom}(S_p(X), R) \otimes_R \text{Hom}(S_q(Y), R) \xrightarrow{\mu} \text{Hom}(S_p(X) \otimes S_q(Y), R) \xrightarrow{\alpha} \text{Hom}(S_{p+q}(X \times Y), R) = S^{p+q}(X \times Y)$. This is exactly the cross product $\times : S^p(X) \otimes S^q(Y) \rightarrow S^{p+q}(X \times Y)$.

Now, α is a natural transformation. Acyclic models comes into play. For homework, you're going to check that the following diagram commutes.

$$\begin{array}{ccc} S_*(X \times Y) & \xrightarrow{T_*} & S_*(Y \times X) \\ \alpha_{X,Y} \downarrow & & \downarrow \alpha_{Y,X} \\ S_*(X) \otimes_R S_*(Y) & \xrightarrow{\tau} & S_*(Y) \otimes_R S_*(X) \end{array}$$

Acyclic models helps us prove things like this.

All of this implies that $H_*(X; R)$ is graded commutative. It's a theorem that you can't find a commutative multiplication. This is where Steenrod operations come from. They're called cohomology operations, and we'll talk more about this in 18.906.

My goal is to compute the cohomology of some space.

PROPOSITION 29.4. $H^*(X) \otimes H^*(Y) \xrightarrow{\times} H^*(X \times Y)$ is a R -algebra homomorphism.

If A and B are graded R -algebras, then $(A \otimes B)_n = \bigoplus_{p+q=n} A_p \otimes B_q$, and $(a \otimes b)(a' \otimes b') = (-1)^{|a'| \cdot |b|} aa' \otimes bb'$. This tensor product is graded commutative if A and B are.

PROOF. I have $\Delta_X : X \rightarrow X \times X$ and $\Delta_Y : Y \rightarrow Y \times Y$. I also have $\Delta_{X \times Y} : X \times Y \rightarrow X \times Y \times X \times Y$, which factors as $(1 \times T \times 1) \circ (\Delta_X \times \Delta_Y)$. Let $\alpha_1, \alpha_2 \in H^*(X)$ and $\beta_1, \beta_2 \in H^*(Y)$. Then $\alpha_1 \times \beta_1, \alpha_2 \times \beta_2 \in H^*(X \times Y)$. I want to calculate what $(\alpha_1 \times \beta_1) \cup (\alpha_2 \times \beta_2)$ is. Let's see:

$$\begin{aligned} (\alpha_1 \times \beta_1) \cup (\alpha_2 \times \beta_2) &= \Delta_{X \times Y}^*(\alpha_1 \times \beta_1 \times \alpha_2 \times \beta_2) \\ &= (\Delta_X \times \Delta_Y)^*(1 \times T \times 1)^*(\alpha_1 \times \beta_1 \times \alpha_2 \times \beta_2) \\ &= (\Delta_X \times \Delta_Y)^*(\alpha_1 \times T^*(\beta_1 \times \alpha_2) \times \beta_2) \\ &= (-1)^{|\alpha_2| \cdot |\beta_1|} (\Delta_X \times \Delta_Y)^*(\alpha_1 \times \alpha_2 \times \beta_1 \times \beta_2) \end{aligned}$$

Now, I have a diagram:

$$\begin{array}{ccc} H^*(X \times Y) & \xleftarrow{\times_{X \times Y}} & H^*(X) \otimes_R H^*(Y) \\ (\Delta_X \times \Delta_Y)^* \uparrow & & \uparrow \Delta_X^* \otimes \Delta_Y^* \\ H^*(X \times X \times Y \times Y) & \xleftarrow{\times_{X \times X, Y}} & H^*(X \times X) \otimes H^*(Y \times Y) \end{array}$$

This diagram commutes because the cross product is natural. This is exactly what commutativity of the diagram means. This means that:

$$\begin{aligned} (\alpha_1 \times \beta_1) \cup (\alpha_2 \times \beta_2) &= (-1)^{|\alpha_2| \cdot |\beta_1|} (\Delta_X \times \Delta_Y)^* (\alpha_1 \times \alpha_2 \times \beta_1 \times \beta_2) \\ &= (-1)^{|\alpha_2| \cdot |\beta_1|} (\alpha_1 \cup \alpha_2) \times (\beta_1 \cup \beta_2) \end{aligned}$$

That's exactly what we wanted. \square

EXAMPLE 29.5. How about $H^*(S^p)$? Let $p > 0$. This is: $H^k(S_p) = \begin{cases} \mathbf{Z} & k = 0, p \\ 0 & \text{else} \end{cases}$. Say that σ_p generates $H^p(S^p)$. We now have $H^*(S^p) \otimes H^*(S^q) \rightarrow H^*(S^p \times S^q)$. From the Kunneth theorem, we know that $H^k(S^p \times S^q) = \begin{cases} \mathbf{Z} & k = 0, p, q, p+q \\ 0 & \text{else} \end{cases}$. This structure $H^*(S^p) \otimes H^*(S^q) \cong \mathbf{Z}[\sigma_p, \sigma_q] / (\sigma_p^2, \sigma_q^2) \cong H^*(S^p \times S^q)$ where $\sigma_p \sigma_q = (-1)^{|p| \cdot |q|} \sigma_q \sigma_p$ where by $\mathbf{Z}[\sigma_p, \sigma_q]$ I mean the free \mathbf{Z} -algebra on σ_p, σ_q . When $p = q = 1$, this gives an exterior algebra.

This is to be contrasted with $X = S^p \vee S^q \vee S^{p+q}$. This has the same homology as the product of two spheres. But in cohomology, the product of the generators must be zero. There is a diagram:

$$\begin{array}{ccc} X & \longrightarrow & S^p \vee S^q \\ \uparrow & & \\ S^p & & \end{array}$$

On cohomology, notice that $\sigma_p \sigma_q = 0$ in $H^*(S^p \vee S^q)$ because there's no $(p+q)$ -dimensional cohomology. Therefore we find that $S^p \vee S^q \vee S^{p+q} \not\cong S^p \times S^q$.

It's very interesting to think about what the attaching map is:

$$\begin{array}{ccc} S^{p+q-1} & \longrightarrow & S^p \vee S^q \\ \downarrow & & \downarrow \\ D^{p+q} & \longrightarrow & S^p \times S^q \end{array}$$

On wednesday we'll have a relaxed talk about surfaces. BTW I might not TeX that.

30. Surfaces and symmetric nondegenerate bilinear forms

Never mind, I decided to TeX this.

30.1. Case of Poincaré duality. Let M be a compact manifold of dimension n (this is the kind of thing most of the world cares about). This whole lecture will be happening with coefficients in \mathbf{F}_2 . There is a cup product pairing $H^p(M) \otimes H^q(M) \rightarrow H^{p+q}(M)$.

THEOREM 30.1. *There exists a unique class $[M] \in H_n(M)$, called the fundamental class, such that there's a pairing $H^p(M) \otimes H^q(M) \xrightarrow{\cup} H^n(M) \xleftarrow{\langle -, [M] \rangle} \mathbf{F}_2$ when $p+q=n$. This pairing is a nonsingular (aka perfect) pairing, i.e., the map $H^p(M) \rightarrow \text{Hom}(H^q(M), \mathbf{F}_2)$ defined by $x \mapsto (y \mapsto \langle x \cup y, [M] \rangle)$ is an isomorphism.*

One thing I should say is that $H_*(M)$ is zero in dimensions above n , and $H_i(M)$ are finitely generated.

COROLLARY 30.2. *From the UCT, it follows that $H^p(M) \xrightarrow{\cong} \text{Hom}(H^q(M), \mathbf{F}_2) = H_q(M)$. The corresponding classes under this association are said to be Poincaré dual to each other.*

REMARK 30.3. This means I get a pairing $H_q(M) \otimes H_q(M) \rightarrow \mathbf{F}_2$ in homology when $p+q=n$. This is called the *intersection pairing*. If you have one p -cycle and one q -cycle, this means that I can make them intersect transversely, i.e., they intersect in points – or not at all. I count the number of points modulo 2, and this is the element in \mathbf{F}_2 .

EXAMPLE 30.4. Let $M = T^2 = S^1 \times S^1$. We know that $H^1(M) = \mathbf{F}_2 \times \mathbf{F}_2 = \langle x, y \rangle$ where $x^2 = 0$ and $y^2 = 0$, and $xy \neq 0$ (this is the generator of $H^2(M)$). In terms of homology, this means that I can pick cycles on the torus so that they intersect on one point. This makes sense. Also, $x^2 = 0 = y^2$ because the second copy of x and y can just be moved so that they don't intersect.

EXAMPLE 30.5 (Especially interesting case). If $n = 2k$, I get a symmetric bilinear form on $H_k(M)$ via $H_k(M) \otimes H_k(M) \rightarrow \mathbf{F}_2$ that is nondegenerate.

30.2. Symmetric bilinear forms. I've really screwed up when TeXing this.

If $W \subseteq V$ is a subspace, then a bilinear form on V gives a bilinear form on W , but this need not be nonsingular even if the bilinear form on V is. Observe though that the induced bilinear form on W is nonsingular if and only if $W \cap W^\perp = 0$. This result should be obvious, but I don't want to say why.

I have a map $V \xrightarrow{\cong} V^*$ by sending $v \mapsto (v' \mapsto v \cdot v')$. Inside V , I have W^\perp , and I have a quotient $V^* \xrightarrow{\text{Res}} W^*$, with kernel $\ker \text{Res}$. I want to claim that $V/W^\perp \cong W^*$. We know that $\dim W + \dim W^\perp = \dim V =: n$. If W is nonsingular, then $V = W \oplus W^\perp$. This is true as vector spaces, but also as quadratic forms.

To see this, pick a basis e_1, \dots, e_k for W . The quadratic form is represented by some matrix $(e_i \cdot e_j)$. It's nonsingular exactly when its determinant is nonzero, i.e., 1. Then I can also pick a basis for W^\perp . Then I have nondegenerate quadratic form on V given by $\begin{pmatrix} (e_i \cdot e_j) & 0 \\ 0 & (\dots) \end{pmatrix}$ where the bottom left thing is that of W^\perp . Since the quadratic form on V has determinant 1, the matrix for W^\perp also has determinant 1, and hence $V = W \oplus W^\perp$ as quadratic forms.

Now:

- (1) Suppose $v \in V$ has $v \cdot v = 1$. Then $V = \langle v \rangle \oplus \langle v \rangle^\perp$. This is an orthogonal splitting into nonsingular forms.
- (2) Assume $v \cdot v = 0$ for all⁹ $v \in V$. Anyway, in our general situation, v might be zero – so pick $v \neq 0$. But the form is nonsingular, so there exists w such that $v \cdot w \neq 0$, i.e., $v \cdot w = 1$. Then $\langle v, w \rangle$ is a 2-dimensional subspace sitting inside V , so it splits off. Thus we get a hyperbolic form $\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$ (or something like this). (Example: torus)

Thus we conclude:

PROPOSITION 30.6. *Any nonsingular symmetric bilinear form on a finite dimensional vector space over \mathbf{F}_2 is isomorphic to:*

$$\begin{pmatrix} \begin{pmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{pmatrix} & 0 \\ 0 & \begin{pmatrix} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} & \\ & \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \end{pmatrix} \end{pmatrix} \text{ where the bottom left thing has some number}$$

of the hyperbolic $\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$.

Let **Bil** be the set of nonsingular symmetric bilinear forms that are finite dimensional over \mathbf{F}_2 modulo isomorphisms. I've just given a classification of these things. This is a commutative monoid under \oplus . This **Bil** is {nonsingular matrices}/similarity where similarity means $M \sim N$ if $N = AMA^T$ for some nonsingular A .

CLAIM 30.7.

$$\begin{pmatrix} & 1 \\ 1 & \\ & 1 \end{pmatrix} \sim \begin{pmatrix} 1 & \\ & 1 \\ & & 1 \end{pmatrix}$$

⁹Your intuition about dot products isn't very useful here, for example the torus. This is because the matrix for the quadratic form on the torus is $\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$. Also, $(x+y) \cdot (x+y) = 0$. This means that every cycle on the torus can be moved to have no self-intersection, at least modulo 2.

This is the same thing as saying that $\begin{pmatrix} & 1 \\ 1 & \\ & 1 \end{pmatrix} = AA^T$ for some nonsingular A .

PROOF. Let $A = \begin{pmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \\ 0 & 1 & 1 \end{pmatrix}$. □

So, **Bil** is the commutative monoid generated by (1) , $\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$ with relation $\begin{pmatrix} & 1 \\ 1 & \\ & 1 \end{pmatrix} \sim \begin{pmatrix} 1 & \\ & 1 & \\ & & 1 \end{pmatrix}$.

30.3. Connected surfaces. Let's go back to topology. Let $n = 2$, $k = 1$ (so that $2k = n$). Then you get an intersection pairing on $H_1(M)$. Suppose I consider \mathbf{RP}^2 . We know that $H_1(\mathbf{RP}^2) = \mathbf{F}_2$. This must be that "(1)"-form. This says that anytime you have a cycle on a projective plane, there's nothing I can do to remove its self intersections. This is also seen on a Mobius band that I will not draw because I don't know how to draw fundamental polygons in LaTeX. But this can be seen by looking at the projection from the Mobius band to the circle.

We also had the notion of connected sums. Let's compute the homology of $\Sigma_1 \# \Sigma_2$ using Mayer-Vietoris, like you did in the exercise. You get $H_2(\Sigma_1 \# \Sigma_2) \rightarrow H_1(S^1) \rightarrow H_1(\Sigma_1 - D^2) \oplus H_1(\Sigma_2 - D^2) \rightarrow H_1(\Sigma_1 \# \Sigma_2)$. When you pierce a surface, it collapses down into its 1-skeleton, so $H_2(\Sigma_1 - D^2) \oplus H_2(\Sigma_2 - D^2) \cong 0$. Let's restrict ourselves to connected surfaces. The map $H_1(S^1) \rightarrow H_1(\Sigma_1 - D^2) \oplus H_1(\Sigma_2 - D^2)$ is the zero map when you think of it as a boundary. Actually, that argument needs to use something, because we know that with integer coefficients, this isn't right – you need to find an oriented chain in that case – but this orientation issue goes away in \mathbf{F}_2 because there's no issues with \pm . And actually, the map $H_1(\Sigma_1 \# \Sigma_2) \rightarrow H_0(S^1)$ is zero as well, so $H_1(\Sigma_1 - D^2) \oplus H_1(\Sigma_2 - D^2) \cong H_1(\Sigma_1) \oplus H_1(\Sigma_2) \cong H_1(\Sigma_1 \# \Sigma_2)$ that respect the intersection pairing.

Let **Surf** be the commutative monoid of connected compact surfaces modulo homeomorphism. What we've proved is that there's a map **Surf** \rightarrow **Bil** that takes connected sums to direct sums of orthogonal bilinear forms. And this map is an isomorphism. I.e.:

THEOREM 30.8. *There is an isomorphism of commutative monoids **Surf** \rightarrow **Bil**.*

This is a little strange. What is our claim $\begin{pmatrix} & 1 \\ 1 & \\ & 1 \end{pmatrix} \sim \begin{pmatrix} 1 & \\ & 1 & \\ & & 1 \end{pmatrix}$ saying in this context? It's saying that $T^2 \# \mathbf{RP}^2 \cong (\mathbf{RP}^2)^{\#3}$.

CLAIM 30.9. If Σ is nonoriented, then $\Sigma \# T^2 \cong \Sigma \# K$ (where K is the Klein bottle $\mathbf{RP}^2 \# \mathbf{RP}^2$).

If it's nonoriented, then a Mobius strip M sits into Σ . Uh I guess you're dragging your attachment of the torus along M ?

There's more to be said about this. You can think of quadratic forms if you're working over the reals or something. You can't do this modulo 2. Under the story we talked about, the oriented surfaces are the ones where the dot product is always zero. A better thing to ask over \mathbf{F}_2 are quadratic forms such that $q(x + y) = q(x) + q(y) + x \cdot y$. This leads to the Kervaire invariant, etc.

Happy Thanksgiving! See you on Monday.

31. A plethora of products

REMARK 31.1. Please note that these notes might be absolute bullshit, because I came back today from my flight at 8 am.

Recall that we have the Kronecker pairing $\langle, \rangle : H^p(X) \otimes H_p(X) \rightarrow R$, which obviously isn't natural because H^p is contravariant while homology isn't.

Consider the following. Given $f : X \rightarrow Y$, and $b \in H^p(Y)$ and $x \in H_p(X)$, how does $\langle f^*b, x \rangle$ relate to $\langle b, f_*x \rangle$?

CLAIM 31.2.

$$\langle f^*b, x \rangle = \langle b, f_*x \rangle$$

PROOF. Easy! I find it useful to write out diagrams of where things are. We're gonna work on the chain model.

$$\begin{array}{ccc} \mathrm{Hom}(S_p(X), R) \otimes S_p(X) & \xrightarrow{\langle \cdot, \cdot \rangle} & R \\ f^* \otimes 1 \uparrow & & \uparrow \langle \cdot, \cdot \rangle \\ \mathrm{Hom}(S_p(Y), R) \otimes S_p(X) & \xrightarrow{1 \otimes f_*} & \mathrm{Hom}(S_p(Y), R) \otimes S_p(Y) \end{array}$$

The top line is what gives the Kronecker pairing. Note that f^* means contravariant and f_* means covariant. This diagram commuting is the statement we want to prove. Let's see. Suppose $[\beta] = b$ and $[\xi] = x$. Then from the bottom left, going to the right and then the top is $\beta \otimes \xi \mapsto \beta \otimes f_*(\xi) \mapsto \beta(f_*\xi)$. The other way is $\beta \otimes \xi \mapsto f^*(\beta) \otimes \xi = (\beta \circ f) \otimes \xi \mapsto (\beta \circ f)(\xi)$. This is exactly $\beta(f_*\xi)$, because, oh, that's just how composition works. \square

There's another product around. We called this μ I think, where $\mu : H(C_\bullet) \otimes H(D_\bullet) \rightarrow H(C_\bullet \otimes D_\bullet)$ given by $[c] \otimes [d] \mapsto [c \otimes d]$. I'm secretly using this in the above proof.

We also have the cross product(s!) $\times : H_p(X) \otimes H_q(Y) \rightarrow H_{p+q}(X \times Y)$ and $\times : H^p(X) \otimes H^q(Y) \rightarrow H^{p+q}(X \times Y)$. You should think of this as fishy because both maps are in the same direction – but this is OK because we're using different things to make these constructions. Still, they're related:

THEOREM 31.3. *Let $a \in H^p(X), b \in H^q(Y), x \in H_p(X), y \in H_q(Y)$. Then:*

$$\langle a \times b, x \times y \rangle = (-1)^{|x| \cdot |b|} \langle a, x \rangle \langle b, y \rangle$$

This isn't just idle – although idle things are a great thing to do!

PROOF. Say $[\alpha] = a, [\beta] = b, [\xi] = x, [\eta] = y$. Then recall that $\langle a \times b, x \times y \rangle$ comes from $(\alpha \times \beta)(\sigma) = (-1)^{pq} \alpha(\sigma_1 \circ \alpha_p) \beta(\sigma_2 \circ \omega_q)$ where $\sigma : \Delta^{p+q} \rightarrow X \times Y$. There's two uses of the symbol α , and there'll be a third one in a minute, but they'll all have subscripts, so I hope you'll forgive me.

Recall also the $((p, q)$ th component of the) Alexander-Whitney map $\alpha_{X,Y} : S_{p+q}(X \times Y) \rightarrow S_p(X) \otimes S_q(Y)$. We have a big diagram:

$$\begin{array}{ccc} S_p(X) \otimes S_q(Y) & \xrightarrow{\times} & S_{p+q}(X \times Y) \\ & \searrow 1 \sim & \downarrow \alpha_{X,Y} \quad \searrow \alpha \cdot \beta \\ & & S_p(X) \otimes S_q(Y) \xrightarrow{\alpha \cdot \beta} R \end{array}$$

Where $\alpha \cdot \beta : (\xi \otimes \eta) \mapsto (-1)^{pq} \alpha(\xi) \cdot \beta(\eta)$. Now, the diagonal arrow $S_p(X) \otimes S_q(Y) \rightarrow S_p(X) \otimes S_q(Y)$ is unique up to chain homotopy, and is homotopic to the identity – this is what the method of acyclic models tells me. (See the statement of the Eilenberg-Zilber theorem above.)

Thus we find that $\alpha_{X,Y}(\xi \times \eta) = \xi \otimes \eta + (dh + hd)(\xi \otimes \eta)$ for some chain homotopy h . I think we're really down now, because ξ and η are both cycles, and hence d will kill them (wait it seems like it only kills η ??). So $\alpha_{X,Y}(\xi \times \eta) = \xi \otimes \eta$. Now, $\alpha \cdot \beta$ is a cocycle (check!). When I apply α it kills the dh factor (what??), therefore $(\alpha \cdot \beta)\alpha_{X,Y}(\xi \times \eta) = (\alpha \cdot \beta)(\xi \otimes \eta)$. \square

All because of the magic of acyclic models.

Let's now try to prove a Kunneth theorem for H^* . Let $R = k$ be a field (eg \mathbf{F}_p, \mathbf{Q}) that's our coefficient. Then we have $H_*(X) \otimes_k H_*(Y) \cong H_*(X \times Y)$. Also, this map $H^p(X) \otimes H^q(Y) \rightarrow k$ has an adjoint $H^p(X) \rightarrow \mathrm{Hom}_k(H_q(Y), k) =: H_p(Y)^\vee$, which is an isomorphism because Ext vanishes over a field.

THEOREM 31.4. *Let k be a field. Assume that $H_p(X)$ is finite-dimensional for all p . Then $H^*(X) \otimes H^*(Y) \cong H^*(X \times Y)$.*

PROOF. We have:

$$\begin{array}{ccc}
H^*(X) \otimes H^*(Y) & \xrightarrow{\times} & H^*(X \times Y) \\
\downarrow \cong & & \downarrow \cong \\
H_*(X) \otimes H_*(Y)^\vee & & H_*(X \times Y)^\vee \\
\downarrow \zeta & \swarrow \cong & \\
(H_*(X) \otimes H_*(Y))^\vee & &
\end{array}$$

Where $\zeta : \alpha \otimes \beta \mapsto (x \otimes y \mapsto \pm \alpha(x)\beta(y))$. The theorem we proved above implies that this diagram commutes.

In general, I might have two (graded) vector spaces U, V , and consider $U^\vee \otimes V^\vee \rightarrow (U \otimes V)^\vee$ by the above formula. Well, $(U \otimes V)^\vee = \text{Hom}_k(U \otimes V, k) = \text{Hom}_k(U, V^\vee)$. Thus I get a map $U^\vee \otimes V^\vee \rightarrow \text{Hom}_k(U, V^\vee)$. This map is an isomorphism when U or V is finite dimensional. I also have $\hat{\alpha} : U^\vee \otimes W \rightarrow \text{Hom}(U, W)$ via $\alpha \otimes w \mapsto (u \mapsto \alpha(u)w)$. And that's the map we have in mind. The image of $\hat{\alpha}$ consists of finite rank homomorphisms because a general tensor is a finite sum. This is therefore an isomorphism if U or W is finite dimensional.

This shows that the map ζ above is an isomorphism if $H_*(X)$ or $H_*(Y)$ is finite-dimensional. We're done by commutativity. \square

We saw before that \times is an algebra map! So this is an isomorphism of algebras.

There are more products around. There is a map $H^p(Y) \otimes H^q(X, A) \rightarrow H^{p+q}(Y \times X, Y \times A)$. Constructing this is on your homework. You can see how this comes about. This comes from the map on the chain level, and it comes from looking at the cochains, and you're going to get a map (???). Anyway. Suppose $Y = X$. Then I get $\cup : H^*(X) \otimes H^*(X, A) \rightarrow H^*(X \times X, X \times A) \xrightarrow{\Delta^*} H^*(X, A)$ where $\Delta : (X, A) \rightarrow (X \times X, X \times A)$. This “relative cup product” makes $H^*(X, A)$ into a graded module over $H^*(X)$. This is *not* a ring – it doesn't have a unit, for example – but it is a module. Also the lexseq is a sequence of $H^*(X)$ -modules. I'm just making statements here.

I want to introduce you to *one more* product, which we'll talk more about, and forms the foundation of Poincaré duality. This is the cap product. What can I do with $S^p(X) \otimes S^n(X)$? Well, I get big map:

$$S^p(X) \otimes S_n(X) \xrightarrow{1 \times (\alpha_X, X \circ \Delta_*)} S^p(X) \otimes S_p(X) \otimes S_{n-p}(X) \xrightarrow{\langle -, - \rangle \otimes 1} S_{n-p}(X)$$

This composite participates in a chain map. This induces a map in homology $\cap : H^p(X) \otimes H_n(X) \rightarrow H_{n-p}(X)$ that comes from μ . This is a pretty interesting map.

LEMMA 31.5. $(\alpha \cup \beta) \cap x = \alpha \cap (\beta \cap x)$ and $1 \cap x = x$.

PROOF. Easy to check from the definition. \square

This makes $H_*(X)$ into a module over $H^*(X)$. These are not hard things to check. There's a lot of structure, and the fact that $H^*(X)$ forms an algebra is a good thing. Notice how the dimensions work. People made a mistake before, and they should have indexed cohomology with negative numbers, so that $\cap : H^p(X) \otimes H_n(X) \rightarrow H_{n-p}(X)$ makes sense. A cochain complex with positive grading is the same as a chain complex with negative grading.

There's also slant products (two of them!). Maybe we won't talk about them. We will check a few things about cap products, and then we'll go into Poincaré duality. We can prove nice theorems then.

32. Cap product and “Čech” cohomology

Let R be a commutative ring with coefficients. The cap product is a map $\cap : H^p(X) \otimes H_n(X) \rightarrow H_q(X)$ where $p + q = n$. This comes from a chain level map $S^p(X) \otimes S_n(X) \xrightarrow{1 \otimes \alpha} S^p(X) \otimes S_p(X) \otimes S_q(X) \xrightarrow{\langle -, - \rangle \otimes 1} R \otimes S_q(X) \cong S_q(X)$. Using our explicit formula for α , we can write:

$$\cap : \beta \otimes \sigma \mapsto \beta \otimes (\sigma \circ \alpha_p) \otimes (\sigma \circ \omega_q) \mapsto (\beta(\sigma \circ \alpha_p)) \cdot (\sigma \circ \omega_q)$$

There's many things to say:

- (1) $H_*(X)$ is a module for $H^*(X)$.

- (2) The only reasonable thing to ask for in terms of naturality is the following. Suppose $f : X \rightarrow Y$, and let $b \in H^p(Y)$ and $x \in H_n(X)$. We then have $f_*(f^*(b) \cap x) = b \cap f_*(x)$, where $f^*(b) \cap x \in H_q(X)$ and $b \cap f_*(x) \in H_n(X)$. This is called a projection formula. To see this, let $[\beta] = b$. Then:

$$\begin{aligned} f_*(f^*(\beta) \cap \sigma) &= f_*((f^*(\beta)(\sigma \circ \alpha_p)) \cdot (\sigma \circ \omega_q)) \\ &= f_*(\beta(f \circ \sigma \circ \alpha_p) \cdot (\sigma \circ \omega)) \\ &= \beta(f \circ \sigma \circ \alpha_p) \cdot f_*(\sigma \circ \omega_q) \\ &= \beta(f \circ \sigma \circ \alpha_p) \cdot (f \circ \sigma \circ \omega_q) \\ &= \beta \cap f_*(\sigma) \end{aligned}$$

So we're done.

- (3) There's a relation between the cap and Kronecker product. Any space has an augmentation $\varepsilon : X \rightarrow *$, so I get $\varepsilon_* : H_*(X) \rightarrow R$. Maybe we should compute $\varepsilon_*(\beta \cap \sigma)$. I will get zero unless $p = n$ and $q = 0$. What does our formula say? This just says that $\varepsilon_*(b \cap x) = \varepsilon_*(\beta(\sigma) \cdot c_{\sigma(n)}^0) = \beta(\sigma) \varepsilon_*(c_{\sigma(n)}^0) = \beta(\sigma) = \langle \beta, \sigma \rangle$ because ε_* counts the number of points, i.e., it's 1. Hence $\varepsilon_*(b \cap x) = \langle b, x \rangle$.
- (4) What is $\langle a \cup b, x \rangle$? This is $\varepsilon_*((a \cup b) \cap x) = \varepsilon_*(a \cap (b \cap x))$ by an assertion in the previous lecture (namely that $(\alpha \cup \beta) \cap x = \alpha \cap (\beta \cap x)$ and $1 \cap x = x$), which becomes $\langle a, b \cap x \rangle$. In other words, $\langle a \cup b, x \rangle = \langle a, b \cap x \rangle$. So the cup product is adjoint to the cap product.

32.1. Relative \cap . There's a lot of structure, but we want more. We want to now try to understand the relative cap product. Suppose $A \subseteq X$ is a subspace. We have:

$$\begin{array}{ccccc} 0 & & & & 0 \\ \downarrow & & & & \downarrow \\ S^p(X) \otimes S_n(A) & \xrightarrow{i^* \otimes 1} & S^p(A) \otimes S_n(A) & \xrightarrow{\cap} & S_q(A) \\ \downarrow 1 \otimes i_* & & & & \downarrow \\ S^p(X) \otimes S_n(X) & \xrightarrow{\cap} & & & S_q(X) \\ \downarrow & & & & \downarrow \\ S^p(X) \otimes S_n(X, A) & \dashrightarrow & & & S_q(X, A) \\ \downarrow & & & & \downarrow \\ 0 & & & & 0 \end{array}$$

The left sequence is exact because $0 \rightarrow S_n(A) \rightarrow S_n(X) \rightarrow S_n(X, A) \rightarrow 0$ splits and tensoring with $S^p(X)$ still leaves it exact. We have to check that this diagram commutes.

Let $\beta \otimes \sigma \in S^p(X) \otimes S_n(A)$. We then get:

$$\beta \otimes \sigma \xrightarrow{i^* \otimes 1} i^* \beta \otimes \sigma \rightarrow i^*(\beta) \cap \sigma \xrightarrow{i_*} i_*(i^*(\beta) \cap \sigma)$$

And:

$$\beta \otimes \sigma \xrightarrow{1 \otimes i_*} \beta \otimes i_* \sigma \rightarrow \beta \cap i_*(\sigma)$$

So they're equal by the projection formula. Hence you get $\cap : H^p(X) \otimes H_n(X, A) \rightarrow H_q(X, A)$ that makes $H_*(X, A)$ a $H^*(X)$ -module.

32.2. A different perspective on excision. Recall what excision is. We know that $H_*(X - U, A - U) \cong H_*(X, A)$. There's another perspective on this. Suppose $K \subseteq U \subseteq X$ such that $\overline{K} \subseteq \text{Int}(U)$. To simplify things, suppose K is closed and U is open. Let $A = X - K \supseteq X - U = V$. Then excision says that $H_*(X - V, A - V) = H_*(X - (X - U), (X - K) - (X - U)) \cong H_*(X, A) = H_*(X, X - K)$. There's a simpler expression: $H_*(X - (X - U), (X - K) - (X - U)) = H_*(U, U - K)$, so $H_*(U, U - K) \cong H_*(X, X - K)$, i.e., it depends only on an open neighborhood of K . A question that we now have is: how does this depend on $H_*(K)$? $H^*(K)$? This is really what Poincaré duality wants to understand.

EXAMPLE 32.1. We'll eventually be talking, for example, about $X = S^3$ and $K = \text{knot}$.

We want to understand $H_*(X, X - K)$ better. We have a cap product $H^p(X) \otimes H_n(X, X - K) \rightarrow H_q(X, X - K)$. We just decided that $H_n(X, X - K) \cong H_n(U, U - K)$, and so I have the cap product $H^p(U) \otimes H_n(U, U - K) \rightarrow H_q(U, U - K)$. Hence I get the cap product map like $H^p(U) \otimes H_n(X, X - K) \rightarrow H_q(X, X - K)$. But this seems to depend upon a choice of U . What if I make U smaller?

LEMMA 32.2. *Let $U \supseteq V \supseteq K$. Then:*

$$\begin{array}{ccc} H^p(U) \otimes H_n(X, X - K) & & \\ \downarrow i^* \otimes 1 & \searrow \cap & \\ & & H_q(X, X - K) \\ & \nearrow \cap & \\ H^p(V) \otimes H_n(X, X - K) & & \end{array}$$

PROOF. Hint: use projection formula again. □

Let \mathcal{U}_K be the set of open neighborhoods of K in X . This is a poset (actually a directed set because you can take intersections), under reverse-inclusion as the ordering. This lemma says that $H^p : \mathcal{U}_K \rightarrow \mathbf{Ab}$.

DEFINITION 32.3. $\check{H}^p(K) := \varinjlim_{U \in \mathcal{U}_K} H^p(U)$.

This is bad notation because it depends on the way K is sitting in X .

You therefore get $\check{H}^p(K) \otimes H_n(X, X - K) \xrightarrow{\cap} H_q(X, X - K)$. This is the best you can do. It's the natural structure that this relative homology has, i.e., $H_*(X, X - K)$ is a module over $\check{H}^*(K)$.

Sometimes, $\check{H}^*(K)$ will just be $H^*(K)$. Suppose $K \subseteq X$ satisfies the condition (called the “regularity” condition) that for every open $U \supseteq K$, there exists an open V such that $U \supseteq V \supseteq K$ such that $K \rightarrow V$ is a homotopy equivalence (or actually just a homology isomorphism). (for example, a smooth knot in S^3) Then:

LEMMA 32.4. *Suppose \mathcal{J} is a directed set (nonempty). Let $F : \mathcal{J} \rightarrow \mathbf{Ab}$, and suppose I have a natural transformation $\theta : F \rightarrow c_A$ (for example, a map from F to its direct limit). This expresses A as $\varinjlim_{\mathcal{J}} F$ provided that for all i , there is $j \geq i$ such that $F(i) \rightarrow A$ factors through $F(j) \rightarrow A$, which should be an isomorphism, i.e.:*

$$\begin{array}{ccc} F(i) & \xrightarrow{\quad} & A \\ & \searrow & \nearrow \cong \\ & F(j) & \end{array}$$

PROOF. Given $a \in A$, it has to come from somewhere to be a direct limit. This is obviously true. Also, for any i and $a_i \in F(i)$ such that $a_i \mapsto 0$, then there exists $j \geq i$ such that $a_i \mapsto 0 \in F(j)$. This is also obvious. □

REMARK 32.5. This is a really strong condition by the way. It is a really stupid way.

This works in the case that K is regular in X . Thus, under this condition, $\check{H}^p(K) \cong H^p(K)$. One other comment is that more generally, if X is an Euclidean neighborhood retract (a retract of a neighborhood in some \mathbf{R}^n), and K is locally compact, then $\check{H}^p(K)$ depends only on K , and it is isomorphic to Čech cohomology (which is a different type of cohomology theory).

33. \check{H}^* as a cohomology theory, and the fully relative \cap product

pset 6 is now due December 7. If you read any book about Poincaré duality, there'll be an incomprehensible smear of stuff about cap products. I want to give you a cleaner explanation. The motivation is that it's the main step in the proof of Poincaré duality.

Let X be any space, and let $K \subseteq X$ be a closed subspace. We'll write $\check{H}^p(K) = \varinjlim_{U \in \mathcal{U}_K} H^p(U)$ (and call it the Čech cohomology – but there's a different definition, although in certain cases they are isomorphic). We should write down a relative version of this as well. Suppose $L \subseteq K$ be closed. Define $\check{H}^p(K, L) = \varinjlim_{(U, V) \in \mathcal{U}_{K, L}} H^p(U, V)$ where $K \supseteq L$ and $K \subseteq U$, and $L \subseteq V$ such that $V \subseteq U$. Here $\mathcal{U}_{K, L}$ is the directed set:

$$\mathcal{U}_{K, L} \text{ is the set of } \begin{array}{ccc} K & \longleftarrow & L \\ \downarrow & & \downarrow \\ U & \longleftarrow & V \end{array}$$

such that U and V are open.

THEOREM 33.1. *There is a lexseq:*

$$\cdots \rightarrow \check{H}^p(K, L) \rightarrow \check{H}^p(K) \rightarrow \check{H}^p(L) \xrightarrow{\delta} \check{H}^{p+1}(K, L) \rightarrow \cdots$$

All the maps in the lexseq are mysterious.

Also, excision holds:

THEOREM 33.2 (Excision). *Suppose $A, B \subseteq X$ are closed. Then $\check{H}^p(A \cup B, A) \cong \check{H}^p(B, A \cap B)$. This is a form of excision that doesn't hold for ordinary cohomology.*

So Čech cohomology is better suited for talking about closed sets.

We defined $\cap : \check{H}^p(K) \otimes H_n(X, X - K) \rightarrow H_q(X, X - K)$, such that $p + q = n$. Fix $x_K \in H_n(X, X - K)$. Then capping with x_K gives a map $\cap x_K : \check{H}^p(K) \rightarrow H_q(X, X - K)$.

Now, if $K \supseteq L$, then $X - K \subseteq X - L$, so I get $H_n(X, X - K) \xrightarrow{i_*} H_n(X, X - L)$. Then $x_K \mapsto x_L$. We can now extend our lexseq:

$$\begin{array}{ccccccc} \cdots & \longrightarrow & \check{H}^p(K, L) & \longrightarrow & \check{H}^p(K) & \longrightarrow & \check{H}^p(L) \xrightarrow{\delta} \check{H}^{p+1}(K, L) \longrightarrow \cdots \\ & & & & \downarrow -\cap x_K & & \downarrow -\cap x_L \\ & & H_q(X - L, X - K) & \longrightarrow & H_q(X, X - K) & \longrightarrow & H_q(X, X - L) \xrightarrow{\partial} H_{q-1}(X - L, X - K) \longrightarrow \cdots \end{array}$$

Where the bottom thing comes from the lexseq of the triple (see exercise 9 on your pset) $X - K \subseteq X - L \subseteq X$ (I think). Then we can extend our theorem on the lexseq:

THEOREM 33.3. *There is a lexseq and a ladder:*

$$\begin{array}{ccccccc} \cdots & \longrightarrow & \check{H}^p(K, L) & \longrightarrow & \check{H}^p(K) & \longrightarrow & \check{H}^p(L) \xrightarrow{\delta} \check{H}^{p+1}(K, L) \longrightarrow \cdots \\ & & \downarrow -\cap x_K & & \downarrow -\cap x_K & & \downarrow -\cap x_L \\ \cdots & \longrightarrow & H_q(X - L, X - K) & \longrightarrow & H_q(X, X - K) & \longrightarrow & H_q(X, X - L) \xrightarrow{\partial} H_{q-1}(X - L, X - K) \longrightarrow \cdots \end{array}$$

What I have to do is define a cap product of the following form (bottom row):

$$\begin{array}{ccc} \check{H}^p(K) \otimes H_n(X, X - K) & \xrightarrow{\cap} & H_q(X, X - K) \\ \uparrow & & \\ \check{H}^p(K, L) \otimes H_n(X, X - K) & \xrightarrow{\cap} & H_q(X - L, X - K) \end{array}$$

(where $p + q = n$)

I want to define this fully relative cap product $\check{H}^p(K, L) \otimes H_n(X, X - K) \rightarrow H_q(X - L, X - K)$. We'll use this in the inductive proof of (some) important theorem.

Our map $\check{H}^p(K) \otimes H_n(X, X - K) \rightarrow H_q(X, X - K)$ came from $S^p(U) \otimes S_n(U, U - K) \rightarrow S_q(U, U - K)$ where $U \supseteq K$, defined via $\beta \otimes \sigma \mapsto \beta(\sigma \circ \alpha_p) \cdot (\sigma \circ \omega_q)$. I'm hoping to get:

$$\begin{array}{ccc} S^p(U) \otimes S_n(U, U - K) & \longrightarrow & S_q(U, U - K) \\ \uparrow & & \uparrow \\ S^p(U, V) \otimes S_n(U - L)/S_n(U - K) & \longrightarrow & S_q(U - L)/S_q(U - K) \end{array}$$

where again we have inclusions (U, V open and K, L closed):

$$\begin{array}{ccc} K & \longleftarrow & L \\ \downarrow & & \downarrow \\ U & \longleftarrow & V \end{array}$$

The bottom map $S^p(U, V) \otimes S_n(U - L)/S_n(U - K) \rightarrow S_q(U - L)/S_q(U - K)$ makes sense. We can evaluate a cochain that kills everything on V . This means that we can add in $S_n(V)$ to get $S^p(U, V) \otimes (S_n(U - L) + S_n(V))/S_n(U - K) \rightarrow S_q(U - L)/S_q(U - K)$ by sending $\beta \otimes \tau \mapsto 0$ where $\tau : \Delta^n \rightarrow V$. This means that the diagram:

$$\begin{array}{ccc} S^p(U) \otimes S_n(U, U - K) & \longrightarrow & S_q(U, U - K) \\ \uparrow & & \uparrow \\ S^p(U, V) \otimes (S_n(U - L) + S_n(V))/S_n(U - K) & \longrightarrow & S_q(U - L)/S_q(U - K) \end{array}$$

commutes. It's not that far off from where we want to go.

Now, $(U - L) \cup V = U$. I have this covering of U by two open sets. In $S_n(U - L) + S_n(V)$ we're taking the sum of n -chains. We have a map $S_*(U - L) + S_*(V) \rightarrow S_*(U)$. We have already worked through this – the locality principle! This tells us that $S_*(U - L) + S_*(V) \rightarrow S_*(U)$ is a homotopy equivalence. Hence we can extend our diagram:

$$\begin{array}{ccc} S^p(U) \otimes S_n(U, U - K) & \longrightarrow & S_q(U, U - K) \\ \uparrow & & \uparrow \\ S^p(U, V) \otimes (S_n(U - L) + S_n(V))/S_n(U - K) & \longrightarrow & S_q(U - L)/S_q(U - K) \\ \downarrow \simeq & & \\ S^p(U, V) \otimes S_n(U)/S_n(U - K) & & \end{array}$$

We want the homology of $S_n(U)/S_n(U - K)$ to approximate $H_n(X, X - K)$.

CLAIM 33.4. There is an isomorphism $H_n(S_*(U)/S_*(U - K)) = H_n(U, U - K) \rightarrow H_n(X, X - K)$.

PROOF. This is exactly excision! Remember our recasting of excision in the previous lecture. \square

This means that what we've constructed really *is* what we want! We now have our large lexseq:

$$\begin{array}{ccccccc} \cdots & \longrightarrow & \check{H}^p(K, L) & \longrightarrow & \check{H}^p(K) & \longrightarrow & \check{H}^p(L) \xrightarrow{\delta} \check{H}^{p+1}(K, L) \longrightarrow \cdots \\ & & \downarrow -\cap x_K & & \downarrow -\cap x_K & & \downarrow -\cap x_L \\ \cdots & \longrightarrow & H_q(X - L, X - K) & \longrightarrow & H_q(X, X - K) & \longrightarrow & H_q(X, X - L) \xrightarrow{\partial} H_{q-1}(X - L, X - K) \longrightarrow \cdots \\ & & \uparrow \cong, \text{ five-lemma} & & \uparrow \cong, \text{ locality} & & \uparrow \cong, \text{ locality} \\ \cdots & \longrightarrow & H_q(U - L, U - K) & \longrightarrow & H_q(U, U - K) & \longrightarrow & H_q(U, U - L) \longrightarrow \cdots \end{array}$$

As desired.

The diagram:

$$\begin{array}{ccc} \check{H}^p(L) & \xrightarrow{\delta} & \check{H}^{p+q}(K, L) \\ \downarrow -\cap x_L & & \downarrow -\cap x_K \\ H_q(X, X-L) & \xrightarrow{\partial} & H_{q-1}(X-L, X-K) \end{array}$$

says that:

$$(\delta b) \cap x_k = \partial(b \cap x_L)$$

It's rather wonderful! You have a decreasing sequence below and an increasing one above.

I want to reformulate all of this in a more useful fashion, from Mayer-Vietoris. We had two different proofs, one from locality, and another one that we'll remind you of:

$$\begin{array}{ccccccc} \cdots & \longrightarrow & A_n & \longrightarrow & B_n & \longrightarrow & C_n \longrightarrow A_{n-1} \longrightarrow \cdots \\ & & \downarrow & & \downarrow \cong & & \downarrow \\ \cdots & \longrightarrow & A'_n & \longrightarrow & B'_n & \longrightarrow & C'_n \longrightarrow A'_{n-1} \longrightarrow \cdots \end{array}$$

then you get a lexseq:

$$\cdots \rightarrow C_{n+1} \rightarrow C'_{n+1} \oplus A_n \rightarrow A'_n \xrightarrow{\partial} C_n \rightarrow \cdots$$

You can use this to prove Mayer-Vietoris – I will do this in a special case. (This is exactly what I did in a homework assignment¹⁰!) We have a ladder of lexseqs:

$$\begin{array}{ccccccc} \cdots & \longrightarrow & H_q(X, X-A \cup B) & \longrightarrow & H_q(X, X-A) & \longrightarrow & H_{q-1}(X-A, X-A \cup B) \longrightarrow \cdots \\ & & \downarrow & & \downarrow & & \downarrow \cong, \text{ excision} \\ \cdots & \longrightarrow & H_q(X, X-B) & \longrightarrow & H_q(X, X-A \cap B) & \longrightarrow & H_{q-1}(X-A \cap B, X-B) \longrightarrow \cdots \end{array}$$

This means that (using the lexseq of the ladder) you have a lexseq:

$$\cdots \rightarrow H_q(X, X-A \cup B) \rightarrow H_q(X, X-A) \oplus H_q(X, X-B) \rightarrow H_q(X, X-A \cap B) \rightarrow H_{q-1}(X, X-A \cup B) \rightarrow \cdots$$

This can be used to give a lexseq for Čech cohomology:

$$\cdots \rightarrow \check{H}^p(A \cup B) \rightarrow \check{H}^p(A) \oplus \check{H}^p(B) \rightarrow \check{H}^p(A \cap B) \rightarrow \check{H}^{p+q}(A \cup B) \rightarrow \cdots$$

so that we're going to get a commutative Mayer-Vietoris ladder:

THEOREM 33.5. *There's a "Mayer-Vietoris" ladder:*

$$\begin{array}{ccccccc} \rightarrow \check{H}^p(A \cup B) & \longrightarrow & \check{H}^p(A) \oplus \check{H}^p(B) & \longrightarrow & \check{H}^p(A \cap B) & \longrightarrow & \check{H}^{p+q}(A \cup B) \longrightarrow \cdots \\ \downarrow -\cap x_{A \cup B} & & \downarrow (-\cap x_A) \oplus (-\cap x_B) & & \downarrow & & \downarrow \\ \rightarrow H_q(X, X-A \cup B) & \longrightarrow & H_q(X, X-A) \oplus H_q(X, X-B) & \longrightarrow & H_q(X, X-A \cap B) & \longrightarrow & H_{q-1}(X, X-A \cup B) \longrightarrow \cdots \end{array}$$

¹⁰Suppose $A \subseteq X$ is a subspace of X . Then there is a lexseq in reduced homology $\cdots \rightarrow \tilde{H}_n(A) \rightarrow \tilde{H}_n(X) \rightarrow H_n(X, A) \rightarrow \tilde{H}_{n-1}(A) \rightarrow \cdots$ that can be obtained by using the lexseq in homology of the sexseq $0 \rightarrow \tilde{S}_*(A) \rightarrow \tilde{S}_*(X) \rightarrow S_*(X, A) \rightarrow 0$. Now suppose $X = A \cup B$. Consider the ladder:

$$\begin{array}{ccccccc} \cdots \rightarrow H_{n+1}(A, A \cap B) & \rightarrow & \tilde{H}_n(A \cap B) & \rightarrow & \tilde{H}_n(A) & \rightarrow & H_n(A, A \cap B) \rightarrow \cdots \\ \downarrow & & \downarrow & & \downarrow & & \downarrow \\ \cdots \rightarrow H_{n+1}(X, B) & \rightarrow & \tilde{H}_n(B) & \rightarrow & \tilde{H}_n(X) & \rightarrow & H_n(X, B) \rightarrow \cdots \end{array}$$

The first and fourth maps as shown are isomorphisms because of excision. The lexseq from the ladder (see above) therefore yields the Mayer-Vietoris sequence $\cdots \rightarrow \tilde{H}_n(A \cap B) \rightarrow \tilde{H}_n(B) \oplus \tilde{H}_n(A) \rightarrow \tilde{H}_n(X) \rightarrow \tilde{H}_{n-1}(A \cap B) \rightarrow \cdots$.

where I have four cohomology classes $x_{A \cup B}, x_A, x_B, x_{A \cap B}$ that commute in:

$$\begin{array}{ccc}
 & H_n(X, X - A) & \\
 \nearrow & & \searrow \\
 H_n(X, X - A \cap B) & & H_n(X, X - A \cap B) \\
 \searrow & & \nearrow \\
 & H_n(X, X - B) &
 \end{array}$$

This is the most complicated blackboard for the rest of the course. Also xymatrix is not compiling properly because the diagram is too big!

34. \check{H}^* as a cohomology theory

Office hours: today, Hood in 4-390 from 1:30 to 3:30 and Miller in 4-478 from 1-3 on Tuesday. Note that pset 6 is due Wednesday. Also, Wednesday we'll have a lightning review of π_1 and covering spaces.

We're coming to the end of the course, and there are going to be oral exams. I have some questions that I'd like to ask you. They won't be super advanced, detailed questions – they'll be basic things. I'll post a list of examples of questions. I won't select questions from that list, that's cruel and isn't the point. The oral will be 40 minutes. It'll be fun – better than a written exam. It's much better than grading a written exam!

PLEASE DRAW A PICTURE WHEN READING THIS IF YOU DIDN'T COME TO CLASS!

34.1. \check{H}^* versus H^* . Let's come up with an example that distinguishes \check{H}^* and H^* . This is a famous example – the topologist's sine curve. The topologist's sine curve is defined as follows. Consider the graph of $\sin(\pi/x)$ where $0 < x \leq 1$, where we draw a continuous curve from $(0, -1)$ to $(1, 0)$. This is a counterexample for a lot of things, you've probably seen it in 18.901.

What is H_* of the topologist sine curve? Use Mayer-Vietoris! I can choose the bottom half to be some connected portion of the continuous curve from $(0, -1)$ to $(1, 0)$, and the top half to be the rest of the space that intersects the bottom half (in two spots). The top is the union of two path components, each contractible.

To see this, suppose I have $\sigma : I \rightarrow \text{top}$ such that $\sigma(0) = (0, b)$ for some $-3/2 < b \leq 1$ (the $-3/2$ is arbitrary, just choose something ≤ 0). If $b < 1$, pick $\epsilon > 0$ such that if we write $\sigma = (\sigma_1, \sigma_2)$, then $\sigma_2(t) < 1$ for all $t \in [0, \epsilon)$, where we use continuity. Then $\sigma|_{[0, \epsilon)}$ can't be on the sine curve. If $b = 1$, pick $\epsilon > 0$ such that $\sigma_2(t) > -1$ for all $t \in [0, \epsilon)$. Similarly, it can't be on the sine curve.

Thus, H_1 is simple: it fits into $0 \rightarrow H_1(X) \rightarrow H_0(\text{top} \cap \text{bottom}) \rightarrow H_0(\text{top}) \oplus H_0(\text{top}) \rightarrow H_0(X) \rightarrow 0$. This is basically $0 \rightarrow H_1(X) \xrightarrow{\partial} \mathbf{Z} \oplus \mathbf{Z} \hookrightarrow \mathbf{Z} \oplus \mathbf{Z} \oplus \mathbf{Z} \rightarrow \mathbf{Z} \rightarrow 0$, so $\partial = 0$. This means that $H_*(X) \cong H_*(*)$ and this implies that $H^*(X) \cong H^*(*)$.

How about \check{H}^* ? Let $X \subset U$ be an open neighborhood. The interval is contained in some ϵ -neighborhood that's contained in U . This implies that there exists a neighborhood $X \subseteq V \subseteq U$ such that $V \sim S^1$. Therefore, $\varinjlim_{U \in \mathcal{U}_X} H^*(U) \cong H^*(S^1)$ by “cofinality”. So \check{H}^* and H^* differ.

34.2. Cofinality. Let \mathcal{J} be a directed set. Let $A : \mathcal{J} \rightarrow \mathbf{Ab}$ be a functor. If I have a functor $f : \mathcal{K} \rightarrow \mathcal{J}$, then I get $Af : \mathcal{K} \rightarrow \mathbf{Ab}$, i.e., $(Af)_j = A_{f(j)}$.

I can form $\varinjlim_{\mathcal{K}} Af$ and $\varinjlim_I A$. I claim you have a map $\varinjlim_{\mathcal{K}} Af \rightarrow \varinjlim_I A$. All I have to do is the following:

$$\begin{array}{ccc}
 \varinjlim_{\mathcal{K}} Af & \longrightarrow & \varinjlim_I A \\
 \uparrow \text{in}_j & & \\
 A_{f(j)} & &
 \end{array}$$

So I have to give you maps $A_{f(j)} \rightarrow \varinjlim_I A$ for various j . I know what to do, because I have $\text{in}_{f(j)} : A_{f(j)} \rightarrow \varinjlim_I A$. Are they compatible when I change j ? Suppose I have $j' \leq j$. Then I get a map $f(j') \rightarrow f(j)$, so I

have a map $A_{f(j')} \rightarrow A_{f(j)}$, and thus the maps are compatible. Hence I get:

$$\begin{array}{ccc} \varinjlim_J Af & \longrightarrow & \varinjlim_I A \\ \uparrow \text{in}_j & \nearrow \text{in}_{f(j)} & \\ (Af)_j = A_{f(j)} & & \end{array}$$

EXAMPLE 34.1. Suppose $K \supseteq L$ be closed, then I get a map $\check{H}^*(K) \rightarrow \check{H}^*(L)$. Is this a homomorphism? Well, $\check{H}^*(K) = \varinjlim_{U \in \mathcal{U}_K} H^*(U)$ and $\check{H}^*(L) = \varinjlim_{V \in \mathcal{U}_L} H^*(V)$. This is an example of a \mathcal{J} and \mathcal{K} that I care about. Well, $\mathcal{U}_K \subseteq \mathcal{U}_L$, and thus I get a map $\check{H}^*(K) \rightarrow \check{H}^*(L)$, which is what I wanted.

I can do something for relative cohomology. Suppose:

$$\begin{array}{ccc} K & \longleftarrow & L \\ \downarrow & & \downarrow \\ K' & \longleftarrow & L' \end{array}$$

I get a homomorphism $\check{H}^*(K, L) \rightarrow \check{H}^*(K', L')$ because I have $\mathcal{U}_{K,L} \rightarrow \mathcal{U}_{K',L'}$.

This isn't exactly what we need:

QUESTION 34.2. When does $f : \mathcal{K} \rightarrow \mathcal{J}$ induce an isomorphism $\varinjlim_J Af \rightarrow \varinjlim_I A$?

This is a lot like taking a sequence and a subsequence and asking when they have the same limit. There's a cofinality condition in analysis, that has a similar expression here.

DEFINITION 34.3. $f : \mathcal{K} \rightarrow \mathcal{J}$ is cofinal if for all $i \in \mathcal{J}$, there exists $j \in \mathcal{K}$ such that $i \leq f(j)$.

EXAMPLE 34.4. If f is surjective.

LEMMA 34.5. If f is cofinal, then $\varinjlim_J Af \rightarrow \varinjlim_I A$ is an isomorphism.

PROOF. Check that $\{A_{f(j)} \rightarrow \varinjlim_I A\}$ satisfies the necessary and sufficient conditions:

- (1) For all $a \in \varinjlim_I A$, there exists j and $a_j \in A_{f(j)}$ such that $a_j \mapsto a$. We know that there exists some i and $a_i \in A$ such that $a_i \mapsto a$. Pick j such that $f(j) \geq i$, so we get a map $a_i \rightarrow a_{f(j)}$, and by compatibility, we get $a_{f(j)} \mapsto a$.
- (2) The other condition is also just as easy.

□

This is a very convenient condition.

EXAMPLE 34.6. I had a perverse way of constructing \mathbf{Q} by using the divisibility directed system. A much simpler (linear!) directed system is $\mathbf{Z} \xrightarrow{2} \mathbf{Z} \xrightarrow{3} \mathbf{Z} \xrightarrow{4} \mathbf{Z} \rightarrow \dots$. This has the same colimit as the divisibility directed system because $n|n!$, so we have a cofinal map between directed systems.

How about the direct limits in the Čech cohomology case?

EXAMPLE 34.7. Do I have a map $\check{H}^*(K, L) \rightarrow \check{H}^*(K)$? Suppose:

$$\begin{array}{ccc} K & \longleftarrow & L \\ \downarrow & & \downarrow \\ U & \longleftarrow & V \end{array}$$

Then $\check{H}^p(K, L) = \varinjlim_{(U,V) \in \mathcal{U}_{K,L}} H^p(U, V)$ and $\check{H}^p(K) = \varinjlim_{U \in \mathcal{U}_K} H^p(U)$. I have a map of directed sets $\mathcal{U}_{K,L} \rightarrow \mathcal{U}_K$ by sending $(U, V) \mapsto U$. I didn't have to use cofinality. I want a long exact sequence, though, and I'm going to do this by saying that it's a directed limit of a long exact sequence. I'm going to have to have all of these various Čech cohomologies as being the directed limit over the *same* indexing set.

I'd really like to say that $\check{H}^p(K) = \varinjlim_{U \in \mathcal{U}_K} H^p(U) \cong \varinjlim_{(U,V) \in \mathcal{U}_{K,L}} H^p(U)$. Thus I need to show that $\mathcal{U}_{K,L} \rightarrow \mathcal{U}_K$ where $(U, V) \mapsto U$ is cofinal. This is easy, because if $U \in \mathcal{U}_K$, just pick (U, U) , i.e., $\mathcal{U}_{K,L} \rightarrow \mathcal{U}_K$

is cofinal. How about $\mathcal{U}_{K,L} \rightarrow \mathcal{U}_L$ by $(U, V) \mapsto V$; is it cofinal? Yes! For $V \in \mathcal{U}_L$, pick (X, V) ! This means that $\cdots \check{H}^{p-1}(L) \rightarrow \check{H}^p(K, L) \rightarrow \check{H}^p(K) \rightarrow \check{H}^p(L) \rightarrow \check{H}^{p+1}(K, L)$ is $\varinjlim_{\mathcal{U}_{K,L}} (\cdots \rightarrow H^p(U, V) \rightarrow \cdots)$, and hence exact.

How about excision? I need this to get to Mayer-Veitoris!

LEMMA 34.8. *Assume X is normal and A, B are closed subsets. Then $\check{H}^p(A \cup B, B) \rightarrow \check{H}^p(A, A \cap B)$ is an isomorphism.*

PROOF. Well, $\check{H}^p(A \cup B, B)$ is \varinjlim over $\mathcal{U}_{A \cup B, B}$ and $\check{H}^p(A, A \cap B)$ is \varinjlim over $\mathcal{U}_{A, A \cap B}$. Let $W \supseteq A$ and $Y \supseteq B$ are neighborhoods. I claim that $\mathcal{U}_A \times \mathcal{U}_B \rightarrow \mathcal{U}_{A \cup B, B}$ sending $(W, Y) \mapsto (W \cup Y, Y)$ and $\mathcal{U}_A \times \mathcal{U}_B \rightarrow \mathcal{U}_{A, A \cap B}$ sending $(W, Y) \mapsto (W, W \cap Y)$ are cofinal.

If I give you $(U, V) \in \mathcal{U}_{A \cup B, B}$, define $(W, V) \in \mathcal{U}_A \times \mathcal{U}_B$ where $W = U$ and $Y = V$, so $\mathcal{U}_A \times \mathcal{U}_B \rightarrow \mathcal{U}_{A \cup B, B}$ is surjective, hence cofinal. The latter is trickier. Let $U \supseteq A$ and $V \supseteq A \cap B$. Here's where normality comes into play. Separate $B - V$ from A . Let $T \supseteq B - V$. Shit. *Shit!*

Maybe I'll leave this to you. I'll put this on the board on Wednesday. Anyway, I'll use normality to show that $\mathcal{U}_A \times \mathcal{U}_B \rightarrow \mathcal{U}_{A, A \cap B}$ is cofinal, and thus this verifies excision – so you actually have excision. \square

35. Finish off the proof of \check{H}^p excision, topological manifolds, fundamental classes

35.1. The end of the proof. Let's finish off the proof from last time. Suppose A, B are closed in normal X . Excision for \check{H}^p :

$$\begin{array}{ccc}
 \varinjlim_{(W,Y) \in \mathcal{U}_A \times \mathcal{U}_B} H^p(W \cup Y, Y) & \xrightarrow{\cong, \text{ordinary excision}} & \varinjlim_{(W,Y) \in \mathcal{U}_A \times \mathcal{U}_B} H^p(W, W \cap Y) \\
 \downarrow \cong, \text{cofinality/surjectivity} & & \downarrow \cong, \text{cofinality, see below} \\
 \varinjlim_{(U,V) \in \mathcal{U}_{A \cup B, B}} H^p(U, V) & \xrightarrow{\quad \quad \quad} & \varinjlim_{(U,V) \in \mathcal{U}_{A, A \cap B}} H^p(U, V) \\
 \parallel & & \parallel \\
 \check{H}^p(A \cup B, B) & \xrightarrow{\quad \quad \quad} & \check{H}^p(A, A \cap B)
 \end{array}$$

$\mathcal{U}_A \times \mathcal{U}_B \rightarrow \mathcal{U}_{A, A \cap B}$ is cofinal since: start with $(U, V) \supseteq (A, A \cap B)$. Using normality, separate $B \cap (X - V) \subseteq T$ and $A \subseteq S$. Take $W = U \cap S$ and $Y = V \cup T$. Then $A \subseteq W \subseteq U$ and $A \cap B \subseteq W \cap Y = S \cap V \subseteq V$.

This means that \check{H}^p satisfies excision, hence Mayer-Vietoris. Let's put this in the drawer for now.

35.2. Topological manifolds + Poincaré duality. yayyyyyyyyyyyyy finally

35.2.1. Fundamental class and orientation local system.

DEFINITION 35.1. A *topological manifold* is a Hausdorff space M such that for every $x \in M$, there exists a neighborhood $U \ni x$ that is homeomorphic to some Euclidean space \mathbf{R}^n . It's called an n -manifold if all U are homeomorphic to \mathbf{R}^n for the *same* n .

EXAMPLE 35.2. \mathbf{R}^n , duh. \emptyset is an n -manifold for every n . The sphere S^n . The Grassmannian $\text{Gr}_k(\mathbf{R}^n)$, introduced in the beginning of the course. I don't know exactly what the dimension of this is, but you can figure it out. Also, $V_k(\mathbf{R}^n)$, and surfaces.

These things are the most interesting things to look at.

WARNING 35.3. We assume the following.

- (1) There exists a countable basis.
- (2) There exists a good cover, i.e., all nonempty intersections are Euclidean as well (always true for differentiable manifolds because you can take geodesic neighborhoods, and in particular for the manifolds we listed above).

This is the context in which duality works.

DEFINITION 35.4. Let X be any space, and let $a \in X$. The local homology of X at a is the homology $H_*(X, X - a)$. We're always working over a commutative ring.

For example, $H_q(\mathbf{R}^n, \mathbf{R}^n - 0) = \begin{cases} \text{free of rank 1} & q = n \\ 0 & q \neq n \end{cases}$. This means that local homology is picking out

the characteristic feature of Euclidean space. Therefore we also have $H_q(M, M - a) = \begin{cases} \text{free of rank 1} & q = n \\ 0 & q \neq n \end{cases}$ for n -manifolds.

NOTATION 35.5. Let $j_a : (M, \emptyset) \rightarrow (M, M - a)$ be the inclusion.

DEFINITION 35.6. A fundamental class for M (an n -manifold) is $[M] \in H_n(M)$ such that for every $a \in M$, the image of $[M]$ under $j_{a,*} : H_n(M) \rightarrow H_n(M, M - a)$ is a generator of $H_n(M, M - a)$.

This is somehow trying to say that this class $[M]$ covers the whole manifold.

EXAMPLE 35.7. When does a space have a fundamental class?

	\mathbf{R}^2	\mathbf{RP}^2	T^2
$R = \mathbf{Z}$	no!	no!	yes! you did this for homework
$R = \mathbf{Z}/2\mathbf{Z}$	no!	yes!	yes!

Something about orientability and compactness seem to be involved.

What do we have?

DEFINITION 35.8. $o_M = \coprod_{a \in M} H_n(M, M - a)$ as a set. This has a map $p : o_M \rightarrow M$.

CONSTRUCTION 35.9. This can be topologized in Euclidean neighborhoods. Let $U \cong \mathbf{R}^n$ be an Euclidean neighborhood of a . I can always arrange so that a corresponds to 0. We have the open disk sitting inside the closed disk: $\widetilde{D}^n \subseteq D^n \subseteq \mathbf{R}^n$ that corresponds to some open $V \subseteq \overline{V} \subseteq U$. Let $x \in V$. I have a diagram:

$$\begin{array}{ccccc}
 H_n(M, M - \overline{V}) & \xleftarrow[\text{excision of } M - U]{\cong} & H_n(U, U - \overline{V}) & = & H_n(\mathbf{R}^n, \mathbf{R}^n - D^n) \\
 \downarrow & & \downarrow \cong & & \downarrow \cong, \text{ homotopy equivalence} \\
 H_n(M, M - x) & \longleftarrow & H_n(U, U - x) & = & H_n(\mathbf{R}^n, \mathbf{R}^n - 0)
 \end{array}$$

Hence $H_n(M, M - \overline{V}) \cong H_n(M, M - x)$. Thus I can collect points in o_M together when they come from the same class in $H_n(M, M - \overline{V})$, so they form “sheets”.

I have a map $V \times H_n(M, M - \overline{V}) \rightarrow o_M|_V = p^{-1}(V)$ by sending $(x, c) \mapsto (j_x)_*(c) \in H_n(M, M - x)$, and this map is bijective (that’s what comes from excision). This LHS has a nice topology by letting $H_n(M, M - \overline{V})$ be discrete. I’m topologizing o_M as the weakest topology these generate.

“Have I been sufficiently obscure enough? This is not supposed to be a complicated point”. This $o_M \rightarrow M$ is called the *orientation local system*, and is a covering space.

DEFINITION 35.10. A continuous map $p : E \rightarrow B$ is a covering space if:

- (1) $p^{-1}(b)$ is discrete for all $b \in B$.
- (2) For every b there’s a neighborhood V and a map $p^{-1}(V) \rightarrow p^{-1}(b)$ such that $p^{-1}(V) \xrightarrow{\cong} V \times p^{-1}(b)$ is a homeomorphism.

That’s exactly the way we topologized o_M . There’s more structure though because $H_n(M, M - \overline{V})$ is an R -module!

DEFINITION 35.11. A local system (of R -modules) $p : E \rightarrow B$ is a covering space together with structure maps $E \times_B E := \{(e, e') | pe = pe'\} \xrightarrow{+} E$ and $z : B \rightarrow E$ such that:

$$\begin{array}{ccccc}
 E \times_B E & \xrightarrow{+} & E & \longleftarrow & R \times E \\
 & \searrow & \nearrow z & & \\
 & & B & = & B
 \end{array}$$

making $p^{-1}(b)$ a R -module.

We have $H_n(M) \xrightarrow{j_x} H_n(M, M - x)$, which gives a *section* of o_M . If I have a covering space $p : E \rightarrow B$, a section is a continuous map $s : B \rightarrow E$ such that $ps = 1_B$. Write $\Gamma(E)$ to be the set of sections. If E is a local system, this is an R -module. Hence $H_n(M) \xrightarrow{j_x} H_n(M, M - x)$ gives a map $j : H_n(M) \rightarrow \Gamma(o_M)$. This is pretty cool because it's telling you about this high-dimensional homology of M into something “discrete”.

THEOREM 35.12. *If M is compact then $j : H_n(M) \rightarrow \Gamma(o_M)$ is an isomorphism, and $H_q(M) = 0$ for $q > n$.*

This is case of Poincaré duality actually because $\Gamma(o_M)$ is somewhat like zero-dimensional cohomology. If this is trivial, like it is for a torus, so if the manifold is connected, then $\Gamma(o_M)$ is just R .

36. Fundamental class

Note that if M is a compact manifold, then $H_q(M; R) = 0$ for $q \gg 0$, and if R is a PID, then for all q , $H_q(M; R)$ is finitely-generated. This follows from:

CLAIM 36.1. Suppose X admits an open cover $\{U_i\}_{i=1}^n$ such that all intersections are either empty or contractible (this is what you get for a good cover on a manifold). Then $H_q(X; R) = 0$ for $q \geq n$, and if R is a PID, then for all q , $H_q(X; R)$ is finitely-generated.

PROOF. Induct. Certainly true for $n = 1$. Let $Y = \bigcup_{i=1}^{n-1} U_i$, then this statement is true by induction – and similarly for $Y \cap U_n$. Now use Mayer-Vietoris. You have $\cdots \rightarrow H_q(Y \cap U_n) \rightarrow H_q(Y) \oplus H_q(U_n) \rightarrow H_q(X) \rightarrow H_{q-1}(Y \cap U_n) \rightarrow \cdots$. When $q = n - 1$, $H_q(Y \cap U_n)$ could be nonzero, and so you might get something nontrivial(???). Also, you'll get a sexseq by unsplicing the lexseq: $0 \rightarrow H_q(Y) \oplus H_q(U_n)/\text{something} \rightarrow H_q(X) \rightarrow \text{submodule of } H_{q-1}(Y \cap U_n) \rightarrow 0$, where you use R being a PID to conclude that submodule of $H_{q-1}(Y \cap U_n)$ is finitely generated. \square

Let M be an n -manifold. We had a map $j : H_n(M) \rightarrow \Gamma(M; o_M)$. Here $\Gamma(M; o_M)$ is the collection of compatible elements of $H_n(M, M - x)$ for $x \in M$. This map $j : H_n(M) \rightarrow \Gamma(M; o_M)$ sends $c \mapsto (x \mapsto j_x c)$ where $j_x : H_n(M, \emptyset) \rightarrow H_n(M, M - x)$. I want to make two refinements.

You can't expect j to be surjective, except maybe when M is compact. Here's why. Let $c \in Z_n(M)$. It's a sum of simplices, and each simplex is compact, and so the union of the images is compact, and hence there's a compact subset $K \subseteq M$ such that $c \in Z_n(K)$. Now if I take $x \notin K$, then the map $H_n(K) \rightarrow H_n(M)$ splits as $H_n(K) \rightarrow H_n(M - x) \rightarrow H_n(M)$. In the relative homology, $H_n(M, M - x)$, the map $H_n(K) \rightarrow H_n(M) \rightarrow H_n(M, M - x)$ sends c to zero.

DEFINITION 36.2. Let σ be a section of $p : E \rightarrow B$ (local system). Then the support of σ is defined as $\text{supp}(\sigma) = \{x \in B \mid \sigma(x) \neq 0\}$. The collection of all sections with compact support is $\Gamma_c(B; E)$, and it's a submodule of $\Gamma(B; E)$.

The first refinement is that $j : H_n(M) \rightarrow \Gamma(M; o_M)$ lands in $\Gamma_c(M; o_M)$, because homology is compactly supported.

The second refinement seems a little artificial but is part of the inductive process. Let $A \subseteq M$ be closed. Then you have a restriction map $H_n(M, M - A) \xrightarrow{j_x} H_n(M, M - x)$ for $x \in A$. Thus you get a map $j : H_n(M, M - A) \rightarrow \Gamma_c(A; o_M|_A)$, the latter of which we'll just denote $\Gamma_c(A; o_M)$.

THEOREM 36.3. *The map $j : H_n(M, M - A) \rightarrow \Gamma_c(A; o_M|_A)$ is an isomorphism and $H_q(M, M - A) = 0$ for $q > n$. (If $A = M$ then $j : H_n(M) \rightarrow \Gamma_c(M; o_M)$ is an isomorphism.)*

PROOF. For $X = \mathbf{R}^n$ and $A = D^n$. Well, $o_{\mathbf{R}^n} = \mathbf{R}^n \times H_n(\mathbf{R}^n, \mathbf{R}^n - 0)$ is trivial (i.e., a product projection), so $\Gamma(D^n; o_{\mathbf{R}^n}) = \text{Hom}_{\mathbf{Top}}(D^n, H_n(\mathbf{R}^n, \mathbf{R}^n - 0))$ where $H_n(\mathbf{R}^n, \mathbf{R}^n - 0)$ is discrete, and this is therefore just a map from π_0 into this, and thus $\Gamma(D^n; o_{\mathbf{R}^n}) = R$ (your coefficient). But also, $H_n(\mathbf{R}^n, \mathbf{R}^n - D^n) \cong R$, so you have that j gives $H_n(\mathbf{R}^n, \mathbf{R}^n - D^n) \rightarrow \Gamma_c(D^n; o_{\mathbf{R}^n}|_{D^n})$.

Say that this is true for $A, B, A \cap B$ – we'll prove this for $A \cup B$. Obviously, use Mayer-Vietoris. I have a restriction $\Gamma_c(A \cup B; o_M) \rightarrow \Gamma_c(A; o_M) \oplus \Gamma_c(B; o_M)$ that sits in an exact sequence $0 \rightarrow \Gamma_c(A \cup B; o_M) \xrightarrow{\text{inclusion, determined by } A, B} \Gamma_c(A; o_M) \oplus \Gamma_c(B; o_M) \rightarrow \Gamma_c(A \cap B; o_M)$. This is a gluing lemma. We also

have a relative Mayer-Vietoris $H_n(M, M - A \cup B) \rightarrow H_n(M, M - A) \oplus H_n(M, M - B) \rightarrow H_n(M, M - A \cap B)$, so we have:

$$\begin{array}{ccccccc}
0 & \longrightarrow & \Gamma_c(A \cup B; o_M) & \xrightarrow{\text{inclusion } A, B \rightarrow A \cup B} & \Gamma_c(A; o_M) \oplus \Gamma_c(B; o_M) & \longrightarrow & \Gamma_c(A \cap B; o_M) \\
& & \uparrow & & \uparrow j_* \cong & & \uparrow j_* \cong \\
H_{n+1}(M, M - A \cap B) = 0 & \twoheadrightarrow & H_n(M, M - A \cup B) & \twoheadrightarrow & H_n(M, M - A) \oplus H_n(M, M - B) & \twoheadrightarrow & H_n(M, M - A \cap B)
\end{array}$$

This is a “local-to-global” argument. “I don’t feel like going through the point-set topology – the rest of the proof is just annoyance.” See Bredon’s book for the conclusion of the proof. \square

COROLLARY 36.4. $j : H_n(M) \rightarrow \Gamma_c(M; o_M)$ is an isomorphism.

DEFINITION 36.5. An R -orientation for M is a section σ of $\Gamma(M; o_M^\times)$ where o_M^\times is the covering space of M given by the generators (as R -modules) of the fibers of o_M .

If M is compact, then $j : H_n(M) \rightarrow \Gamma(M; o_M)$, and you get $[M] \leftrightarrow \sigma$. When does that exist?

Over \mathbf{Z} : $o_M^\times \rightarrow M$ is a double cover of M (over every element you have two possible elements given by the two possible orientations (± 1)). If M is an n -manifold and $f : N \rightarrow M$ is a covering space, then N is also locally Euclidean. I have the orientation local system to get a pullback local system:

$$\begin{array}{ccc}
f^*o_M = N \times_M o_M & \longrightarrow & o_M \\
\downarrow & & \downarrow \\
N & \longrightarrow & M
\end{array}$$

Because $N \rightarrow M$ is a covering space, the fibers of f^*o_M are the same as the fibers of o_N , so actually, $f^*o_M \cong o_N$. For example, suppose $N = o_M^\times$. What happens if I consider:

$$\begin{array}{ccc}
o_N = N \times_M N & \longrightarrow & N \\
\downarrow & & \downarrow \\
N & \longrightarrow & M
\end{array}$$

But now, I have the identity $N \rightarrow N$ that sits compatibly as:

$$\begin{array}{ccc}
N & \xrightarrow{\text{id}} & N \\
\downarrow \text{id} & & \downarrow \\
N & \longrightarrow & M
\end{array}$$

And hence you get $N \rightarrow o_M^\times$, which is a section of $o_M^\times \rightarrow N$. The conclusion is that $N = o_M^\times$ is canonically oriented (even if M is not oriented!). If M is oriented, then the local system is trivial and you have the trivial double cover.

The overarching conclusion is: if M is an n -manifold, then:

- (1) $H_q(M) = 0$ for $q > n$.
- (2) If M is compact, then $H_n(M) \xrightarrow{\cong} \Gamma(M, o_M)$.
- (3) If M is connected and compact, then:
 - (a) if M is oriented with respect to R , then $H_n(M) \cong \Gamma(M, o_M) \cong R$.
 - (b) (I have no idea what was happening here, we didn’t reach to a conclusion for a while.) if M is not orientable, then o_M^\times is nontrivial. If o_M^\times has a section, then it’s trivial (and so is o_M) because if it has a section $\sigma : M \rightarrow o_M^\times$, define $M \times R^\times \xrightarrow{\cong} o_M^\times$ by sending $(x, r) \mapsto r\sigma(x) \in o_M^\times$ (and the same thing $M \times R \xrightarrow{\cong} o_M$ for the orientation local system itself). I don’t see an argument to conclude that if M is nonorientable, then there aren’t any section of o_M . In particular, if $R = \mathbf{Z}$, then $H_n(M; \mathbf{Z}) = 0$. I’m going to leave this as a statement without proof, unless any of you can help me.

If a section $\sigma(x) = 0$ for some x , then $\sigma = 0$.

REMARK 36.6. Prof. Miller talked with me about this after class. If I recall correctly, one way to think about this is as follows. If you have a local system $p : E \rightarrow B$, this can be viewed as a representation of $\pi_1(B) \rightarrow R^\times$, and the $\Gamma(B; E) = (E_x)^{\pi_1(B)}$ where $\pi_1(B)$ acts on the fibers by multiplication. Thus $(E_x)^{\pi_1(B)} = R^{\pi_1(B)}$. If $R = \mathbf{Z}$, then $R^\times = \{\pm 1\}$, so $R^{\pi_1(B)} = \{r | ar = r, a \in \pi_1(B)\}$, so that $\mathbf{Z}^{\pi_1(B)} = 0$. Hence there are no sections of o_M , as desired. For a ring R , $o_{M,R} = o_{M,\mathbf{Z}} \otimes R$. Something else for $\mathbf{Z}/2\mathbf{Z}$. A higher homotopy theoretic perspective is that if you have a fibration $E \rightarrow B$, then $E = PB \times_{\Omega B} F$ where F is the fiber of the fibration, so that $\Gamma(B; E) = \text{Map}_{\Omega B}(PB, F) = F^{h\Omega B}$. In the case of a covering space you recover what you have above since $\pi_0(\Omega B) = \pi_1(B)$.

37. Covering spaces and Poincaré duality

Miller's office hours are tomorrow, from 1-3 in 2-478. The first half of this lecture was just explaining the remark above by using less technology.

On the website, there are notes on $\pi_1(X, *)$. I'm assuming people have seen this thing. Assume X is path-connected, and let $* \in X$. There's another technical assumption: semi-locally simply connected (SLSC), which means that for every $b \in X$ and neighborhood $b \in U$, there exists a smaller neighborhood $b \in V \subseteq U$ such that $\pi_1(V, b) \rightarrow \pi_1(X, b)$ is trivial. This is a very very weak condition.

THEOREM 37.1. *Let X be a path-connected, SLSC space with $* \in X$. Then there is an equivalence of categories between covering spaces over X and sets with an action of $\pi_1(X, *)$. The way this functor goes is by sending $p : E \rightarrow X$ to $p^{-1}(*)$, which has an action of $\pi_1(X, *)$ in the obvious way by path-lifting.*

EXAMPLE 37.2 (Stupidest possible case). Suppose $\text{id} : X \rightarrow X$ is sent to $*$ with the trivial action. This is the terminal covering space over X .

We've been interested in $\Gamma(E; X)$, which is the same thing as $\text{Map}_X(X \rightarrow X, E \rightarrow X) \cong \text{Map}_{\pi_1(X)}(*, E_*) = (E_*)^{\pi_1(B)}$, the fixed points of the action. We also thought about the case of E being a local system of R -modules, and the same functor gives an equivalence between local systems of R -modules and $R[\pi_1(X)]$ -modules, i.e., representations of $\pi_1(X)$.

Recall that o_M is the orientation local system, but now *over* \mathbf{Z} . Thus, over a general ring, $o_{M,R} = o_M \otimes R$. We were thinking about what happens with a closed path-connected SLSC subset $* \in A \subseteq M$ of an n -manifold M , and then considering $\Gamma(A, o_M \otimes R)$, which we now see to be $(o_M \otimes R)^{\pi_1(A,*)}$. How many options do we have here?

That is to say, this local system o_M is the same thing as the free abelian group $H_n(M, M - *)$ with an action of $\pi_1(X, *)$. There aren't many options for this action. In other words, this is a homomorphism $\pi_1(M, *) \rightarrow \text{Aut}(H_n(M, M - *))$. I haven't chosen a generator for $H_n(M, M - *)$, and there's only two automorphisms, i.e., we get a homomorphism $w_1 : \pi_1(M, *) \rightarrow \mathbf{Z}/2\mathbf{Z}$. This homomorphism is called the "first Stiefel-Whitney class". 18.906 will describe all the Stiefel-Whitney classes. With R -coefficients, I get a map $\pi_1(M, *) \rightarrow \text{Aut}(H_n(M, M - *; R)) \cong R^\times$. This is a natural construction, so this homomorphism $\pi_1(M, *) \rightarrow R^\times$ factors through $\pi_1(M, *) \rightarrow \mathbf{Z}/2\mathbf{Z}$. This lets us get a good handle on what the sections are: $\Gamma(A; o_M \otimes R) = H_n(M, M - *; R)^{\pi_1(X,*)}$, but our analysis shows that:

$$\begin{aligned} \Gamma(A; o_M \otimes R) &= H_n(M, M - *; R)^{\pi_1(X,*)} \\ &= \begin{cases} H_n(M, M - *; R) \cong R & \text{if } w_1 = 1, \text{ well-defined up to sign; the orientable case} \\ \ker(R \xrightarrow{2} R) & \text{if } w_1 \neq 1, \text{ and this is a canonical identification} \end{cases} \end{aligned}$$

where we get the latter thing because then $a = -a$, i.e., $2a = 0$. In particular, if $R = \mathbf{Z}/2\mathbf{Z}$, since $\text{Aut}_{\mathbf{Z}/2\mathbf{Z}}(\mathbf{Z}/2\mathbf{Z}) = 1$, you always have a unique orientation. If $R = \mathbf{Z}/p\mathbf{Z}, \mathbf{Z}, \mathbf{Q}$, then $\ker(R \xrightarrow{2} R) = 0$.

We had a general theorem:

THEOREM 37.3. $H_n(M, M - A; R) \xrightarrow{j, \cong} \Gamma_c(A; o_M \otimes R)$ and $H_q(M, M - A; R) = 0$ for $q > n$.

COROLLARY 37.4. *If M is connected and $A = M$, and if M is not compact, then $H_n(M; R) = 0$. If M is compact, then the work we just did shows that $H_n(M; R) = \begin{cases} R & \text{oriented} \\ \ker(R \xrightarrow{2} R) & \text{nonorientable} \end{cases}$.*

37.1. Poincare duality, finally. Assume M is R -oriented. Let $K \subseteq M$ be compact. Then $H_n(M, M - K) \xrightarrow{\cong} \Gamma(K; o_M \otimes R)$. Picking an orientation picks an isomorphism $\Gamma(K; o_M \otimes R) \cong R$. This gives some $[M]_K$, which is called the fundamental class along K . If $K = M$, then $[M]_M =: [M] \in H_n(M; R)$.

Suppose $K \subseteq L$ are compact subsets. We now combine all of our results above:

THEOREM 37.5 (Fully relative Poincare duality). *If $p + q = n$, then $\check{H}^p(K, L; R) \xrightarrow{\cap[M]_K} H_q(M - L, M - K; R)$ is an isomorphism.*

PROOF. “It’s, like, not hard at this point.” One thing we did was set up an LES for \check{H} of a pair, which implies that we may assume that $L = \emptyset$. We want to prove that $\check{H}^p(K; R) \xrightarrow{\cap[M]_K} H_q(M, M - K; R)$ is an isomorphism. Now there’s a standard local-to-global process.

In the local case, if $M = \mathbf{R}^n$ and $K = D^n$, then this is saying that $\check{H}^p(D^n; R) \cong H^p(D^n; R) \xrightarrow{\cap[\mathbf{R}^n]_{D^n}} H_q(\mathbf{R}^n, \mathbf{R}^n - D^n; R)$ where the first isomorphism comes from analysis we did earlier about Čech and ordinary cohomology coinciding. If $p \neq 0$, then both sides are zero. When $p = 0$, we are asking that $H^0(D^n; R) \xrightarrow{\cap[\mathbf{R}^n]_{D^n}} H_n(\mathbf{R}^n, \mathbf{R}^n - D^n; R)$. They’re both equal to R , and we are just capping along $[\mathbf{R}^n]_{D^n}$, because we found that $1 \cap [\mathbf{R}^n]_{D^n} = [\mathbf{R}^n]_{D^n}$, as desired.

We carefully set up the Mayer-Vietoris sequence ladder (Theorem 33.5) that allows us to put this all together. “We’re not going to go through the details because there’s point set topology that I don’t like there.” Note that normality is not needed for K, L compact because compact sets in hausdorff spaces can always be separated, normal or not. I just reversed the order in which things are usually taught in books. \square

We have time for one beginning application.

COROLLARY 37.6 (Relative Poincare duality). *Suppose $K = M$ and M is compact and R -oriented. Then $\check{H}^p(M, L; R) \xrightarrow{\cap[M]} H_{n-p}(M - L, R)$ is an isomorphism.*

COROLLARY 37.7 (Poincare duality, corollary of corollary). *Let M be compact and R -oriented, then $H^p(M; R) \xrightarrow{\cap[M]} H_{n-p}(M; R)$ is an isomorphism.*

PROOF. Follows from the above corollary since $\check{H}^p(M; R)$ is literally equal to $H^p(M; R)$ \square

That’s the most beautiful form of all. If you do have an L , you have this ladder, where all vertical maps are isomorphisms:

$$\begin{array}{ccccccc} \cdots & \longrightarrow & \check{H}^p(M, L) & \longrightarrow & \check{H}^p(M) & \longrightarrow & \check{H}^p(L) \xrightarrow{\delta} \check{H}^{p+1}(M, L) \longrightarrow \cdots \\ & & \downarrow -\cap[M] & & \downarrow -\cap[M] & & \downarrow -\cap[M] \\ \cdots & \longrightarrow & H_q(L) & \longrightarrow & H_q(M) & \longrightarrow & H_q(M, M - L) \xrightarrow{\partial} H_{q-1}(L) \longrightarrow \cdots \end{array}$$

This is a consistency statement for Poincare duality. On Wednesday, we’ll specialize even further, and prove the Jordan curve theorem as well as study the cohomology rings of things we haven’t worked through before.

38. Applications

Please check exam schedule! Also, a sample exam is posted. This is the payoff day. All this stuff about Poincare duality has got to be good for something. Recall:

THEOREM 38.1 (Fully relative duality). *Let M be a R -oriented n -manifold. Let $L \subseteq K \subseteq M$ be compact (M need not be compact). Then $[M]_K \in H_n(M, M - K)$, and capping gives an isomorphism:*

$$\check{H}^p(K, L; R) \xrightarrow{\cap[M]_K, \cong} H_{n-p}(M - L, M - K; R)$$

Today we’ll think about the case $L = \emptyset$, so this is saying:

$$\check{H}^p(K; R) \xrightarrow{\cap[M]_K, \cong} H_{n-p}(M, M - K; R)$$

COROLLARY 38.2. $\check{H}^q(K; R) = 0$ for $q > n$.

We can contrast this with singular (co)homology. Here's an example:

EXAMPLE 38.3 (Barratt-Milnor). A two-dimensional version K of the Hawaiian earring, i.e., nested spheres all tangent to a point whose radii are going to zero. What they proved is that $H_q(K; \mathbf{Q})$ is uncountable for every $q > 1$. But if you look at the Čech cohomology, stuff vanishes.

That's nice.

How about an even more special subcase? Suppose $M = \mathbf{R}^n$. The result is called Alexander duality. This says:

THEOREM 38.4 (Alexander duality). *If $\emptyset \neq K \subseteq \mathbf{R}^n$ be compact. Then $\check{H}^{n-q}(K; R) \xrightarrow{\cong} \check{H}_{q-1}(\mathbf{R}^n - K; R)$*

PROOF. We have the LES of a pair, which gives an isomorphism $\partial : H_q(\mathbf{R}^n, \mathbf{R}^n - K; R) \xrightarrow{\cong} \check{H}_{q-1}(\mathbf{R}^n - K; R)$, so the composition $\partial \circ (- \cap [M]_K)$ is an isomorphism by Poincare duality. \square

For most purposes, this is the most useful duality theorem.

EXAMPLE 38.5 (Jordan curve theorem). $q = 1$ and $R = \mathbf{Z}$. Then this is saying that $\check{H}^{n-1}(K) \xrightarrow{\cong} \check{H}_0(\mathbf{R}^n - K)$. But $\check{H}_0(\mathbf{R}^n - K)$ is free on $\#\pi_0(\mathbf{R}^n - K) - 1$ generators. If $n = 2$, for example, and $K \cong S^1$, then $\check{H}^{n-1}(K) = H^{n-1}(K) \cong H^{n-1}(S^1)$, so $H^1(S^1) \cong \check{H}_0(\mathbf{R}^2 - K)$. Hence there are *two* components in the complement of K . This could also be the topologist's sine curve as well. This is the Jordan curve theorem.

Consider the UCT, which states that there's a sexseq $0 \rightarrow \text{Ext}_{\mathbf{Z}}^1(H_{q-1}(X), \mathbf{Z}) \rightarrow H^q(X) \rightarrow \text{Hom}(H_q(X), \mathbf{Z}) \rightarrow 0$ that splits, but not naturally. First, note that $\text{Hom}(H_q(X), \mathbf{Z})$ is always torsion-free. If I assume that $H_{q-1}(X)$ is finitely generated, then $\text{Ext}_{\mathbf{Z}}^1(H_{q-1}(X), \mathbf{Z})$ is a finite abelian group, but in particular it's torsion.

The UCT is making the decomposition of $H^q(X)$ into its torsion-free and torsion parts. I can divide by torsion, so that $H^q(X)/\text{tors} \cong \text{Hom}(H_q(X)/\text{tors}, \mathbf{Z})$. But there's also an isomorphism $\text{Hom}(H_q(X)/\text{tors}, \mathbf{Z}) \rightarrow \text{Hom}(H_q(X), \mathbf{Z})$ because \mathbf{Z} is torsion-free. Therefore I get an isomorphism $\alpha : H^q(X)/\text{tors} \rightarrow \text{Hom}(H_q(X)/\text{tors}, \mathbf{Z})$. I.e.:

$$\begin{array}{ccccccc} 0 & \longrightarrow & \text{Ext}_{\mathbf{Z}}^1(H_{q-1}(X), \mathbf{Z}) & \longrightarrow & H^q(X) & \longrightarrow & \text{Hom}(H_q(X), \mathbf{Z}) \longrightarrow 0 \\ & & & & \downarrow & \nearrow \cong & \uparrow \cong \\ & & & & H^q(X)/\text{tors} & \xrightarrow{\alpha} & \text{Hom}(H_q(X)/\text{tors}, \mathbf{Z}) \end{array}$$

Or I could say it like this: the Kronecker pairing can be quotiented by torsion, and you get an induced map $H^q(X)/\text{tors} \otimes H_q(X)/\text{tors} \rightarrow \mathbf{Z}$ is a perfect pairing, which means that the adjoint map $H^q(X)/\text{tors} \xrightarrow{\cong} \text{Hom}(H_q(X)/\text{tors}, \mathbf{Z})$. Let's combine this with Poincare duality.

Let $X = M$ be a compact oriented n -manifold. Then $H^{n-q}(X) \xrightarrow{- \cap [M], \cong} H_q(M)$, and so we get a perfect pairing $H^q(X)/\text{tors} \otimes H^{n-q}(X)/\text{tors} \rightarrow \mathbf{Z}$. And what is that pairing? It's the cup product! We have:

$$\begin{array}{ccc} H^q(M) \otimes H^{n-q}(M) & \longrightarrow & \mathbf{Z} \\ \downarrow 1 \otimes (- \cap [M]) & \nearrow \langle \cdot, \cdot \rangle & \\ H^q(M) \otimes H_q(M) & & \end{array}$$

And, well:

$$\langle a, b \cap [M] \rangle = \langle a \cup b, [M] \rangle$$

Thus the map $H^q(M) \otimes H^{n-q}(M) \rightarrow \mathbf{Z}$ is $a \otimes b \mapsto \langle a \cup b, [M] \rangle$, and it's a perfect pairing. This is a purely cohomological version, and is the most useful statement.

EXAMPLE 38.6. Suppose $M = \mathbf{CP}^2 = D^0 \cup D^2 \cup D^4$, and its homology is $\mathbf{Z} \oplus \mathbf{Z} \oplus \mathbf{Z}$, and so its cohomology is the same. Let $a \in H^2(\mathbf{CP}^2)$. Then we have $H^2(\mathbf{CP}^2) \otimes H^2(\mathbf{CP}^2) \rightarrow \mathbf{Z}$, and so $a \cup a$ is a generator of $H^4(\mathbf{CP}^2)$, and hence specifies an orientation for \mathbf{CP}^2 . The conclusion is that $H^*(\mathbf{CP}^2) = \mathbf{Z}[a]/(a^3)$ where $|a| = 2$.

How about \mathbf{CP}^3 ? It just adds a 6-cell, so its homology is $\mathbf{Z}0\mathbf{Z}0\mathbf{Z}0\mathbf{Z}$, and so its cohomology is the same. But then $a^3 = a \cup a \cup a$ is a generator of $H^6(\mathbf{CP}^3)$, and etc. Thus in general, we have:

$$H^*(\mathbf{CP}^n) = \mathbf{Z}[a]/(a^{n+1})$$

These things are finite CW-complexes, so you find:

$$(1) \quad H^*(\mathbf{CP}^\infty) = \mathbf{Z}[a]$$

EXAMPLE 38.7. Suppose I look at maps $f : S^m \rightarrow S^n$. One of the most interesting things is that there are lots of non null-homotopic maps $S^m \rightarrow S^n$ if $m > 2$. For example, $\eta : S^3 \rightarrow S^2$ that's the attaching map for the 4-cell in \mathbf{CP}^2 . This is called the Hopf fibration. It's essential. Why is it nullhomotopic? If η was null homotopic, then $\mathbf{CP}^2 \simeq S^2 \wedge S^4$. That's compatible with the cohomology in each dimension, but not into the cohomology ring! There's a map $S^2 \wedge S^4 \rightarrow S^2$ that collapses S^4 , and the generator in $H^*(S^2)$ has $a^2 = 0$, so $a^2 = 0$ in $H^*(S^2 \wedge S^4)$. But this is not compatible with our computation that $H^*(\mathbf{CP}^2) = \mathbf{Z}[a]/(a^3)$ where $|a| = 2$.

With coefficients in a field k , then the torsion is zero, so you find that if M is compact k -oriented, then if the characteristic of $k = 2$, there's no condition for M to be oriented, and if the characteristic of k is not 2, then M is \mathbf{Z} -oriented. Thus we get that $H^q(M; k) \otimes_k H^{n-q}(M; k) \rightarrow k$ is a perfect pairing.

EXAMPLE 38.8. Exactly the same argument as for complex projective space shows that:

$$H^*(\mathbf{RP}^n; \mathbf{F}_2) = \mathbf{F}_2[a]/(a^{n+1})$$

where $|a| = 1$. So:

$$(2) \quad H^*(\mathbf{RP}^\infty; \mathbf{F}_2) = \mathbf{F}_2[a]$$

where $|a| = 1$.

I'll end with the following application.

THEOREM 38.9. Suppose $f : \mathbf{R}^{m+1} \supseteq S^m \rightarrow S^n \subseteq \mathbf{R}^{n+1}$ that is equivariant with respect to the antipodal action, i.e., $f(-x) = -f(x)$. Then $m \leq n$.

So there are no equivariant maps from $S^m \rightarrow S^n$ if $m > n$!

PROOF. Suppose I have a map like that: the map on spheres induces a map $\bar{f} : \mathbf{RP}^m \rightarrow \mathbf{RP}^n$. We claim that $H_1(\bar{f})$ is an isomorphism. Let $\pi : S^n \rightarrow \mathbf{RP}^n$ denote the map. Let $\sigma : I \rightarrow S^m$ be defined via $\sigma(0) = v$ and $\sigma(1) = -v$. So this gives a 1-cycle $\sigma : I \rightarrow S^m \rightarrow \mathbf{RP}^m$, and $H_1(\mathbf{RP}^n) = [\pi\sigma]$ is generated by this thing. When I map this thing to \mathbf{RP}^n , we send $\pi\sigma$ to a generator. What we've actually proved, therefore, is that $H_1(\mathbf{RP}^m) \cong H_1(\mathbf{RP}^n)$. This is also true with mod 2 coefficients, i.e., $H_1(\bar{f}, \mathbf{F}_2) \neq 0$.

That means that $H^1(\bar{f}; \mathbf{F}_2) \neq 0$ by UCT. But what is this? This is a map $H^1(f; \mathbf{F}_2) : H^*(\mathbf{RP}^n; \mathbf{F}_2) \rightarrow H^*(\mathbf{RP}^m; \mathbf{F}_2)$, i.e., a map $\mathbf{F}_2[a]/(a^{n+1}) \rightarrow \mathbf{F}_2[a] \rightarrow (a^{m+1})$. Thus $a \mapsto a$. There's not a lot of ways to do this if $m > n$. Thus what we've shown that $m \leq n$. \square

This is the Borsuk-Ulam theorem from the '20s, I think. This is an example of how you can use the cohomology ring structure for projective space.

Please check the website for details about your finals. I will ask you to sign a form, to make sure that you don't share the questions or that you haven't heard the questions beforehand. I have a fixed set of questions that'll guide the conversation.

39. Limits, colimits, and adjunctions

Hi! This is 18.906. I'm glad to see familiar faces, and new faces. Let me introduce the course. It's a pset based course, with 6 psets. The first one is due Feb 22. It's due every two weeks, so I can't formulate all problems right at the beginning of the two weeks. I'll try to have the psets done a week before the psets are due. So the first couple problems are up for this pset. You'll be glad to hear that there's no final. I don't think I'll do it again, not this term.

I'll have office hours every week, but I don't know when yet. Hood's the grader and he'll have office hours. There's a course website which can be easily found. What's the course about? Really homotopy theory. 905 was homology and cohomology. Here's the table of contents.

- (1) General homotopy theory (category theory). Because it started in algtop, I have the right to talk about it here. Homotopy groups, lexseqs, obstruction theory.
- (2) Bundles. The theme of the course is using bundles to understand spaces. Brown representability, classifying spaces.
- (3) Spectral sequences(!!!) The story is that it was invented as a piece of algtop. But in the last 60 years it's become a general mathematical tool.
- (4) Homotopy-theoretic applications. How to relate homotopy and homology (Hurewicz, whitehead, and local versions like mod C).
- (5) Characteristic classes (Thom, Euler, Chern, Steifel-Whitney class), where applications to geometry come in.
- (6) Time permitting, there's a beautiful story that comes out (on cobordism, etc).

Any questions? I try to correspond problems in the psets and lectures.

39.1. Category theory. I'm interested in "construction". In 905, I began by talking about category theory. I just won't introduce basic concepts again. Suppose \mathcal{I} is a small category (a set of objects), and \mathbf{C} another category.

DEFINITION 39.1. Let $X : \mathcal{I} \rightarrow \mathbf{C}$. A cone under X is a natural transformation from X to a constant functor. So for every $f : i \rightarrow j$ in \mathcal{I} , the diagram should commute:

$$\begin{array}{ccc} X_i & & \\ \downarrow f_* & \searrow f_i & \\ X_j & \xrightarrow{f_j} & Y \end{array}$$

A *colimit* of X is an initial cone under X . So, for all (Y, f_i) , there exists a unique $h : L \rightarrow Y$ such that $h \circ g_i = f_i$.

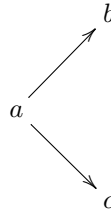
For example, we can let $\mathcal{I} = \mathbf{N}$ made a category via its natural poset structure. For example, if $\mathbf{C} = \mathbf{Ab}$, then you can consider $\mathbf{Z} \xrightarrow{2} \mathbf{Z} \xrightarrow{3} \mathbf{Z} \rightarrow \dots$. The colimit of this is \mathbf{Q} , where the maps are:

$$\begin{array}{ccccc} \mathbf{Z} & \xrightarrow{2} & \mathbf{Z} & \xrightarrow{3} & \mathbf{Z} & \xrightarrow{4} & \dots \\ & \searrow 1 & \downarrow 1/2 & \swarrow 1/3! & & & \\ & & \mathbf{Q} & & & & \end{array}$$

It looks pretty initial, doesn't it?

For example, if $\mathcal{I} = G$ and $\mathbf{C} = \mathbf{Top}$, then this is just a group action on a topological space. The colimit of this functor is the orbit space, i.e., X/G (technically this is $G \backslash X$ because G acts on the left).

How about the following \mathcal{J} :



and $\mathbf{C} = \mathbf{Top}$. The cone of this is the pushout $B \cup_A C := B \sqcup C / \sim$ where $f(a) \sim g(a)$ for all $a \in A$! Basically, you're gluing B and C along A . For example, attaching cells to CW-complexes. If the category is groups, then the pushout is Instead of the disjoint union, you take the free product, and then quotient out to get something known as the *amalgamated free product*.

If you had the following \mathcal{J} :

$$a \rightrightarrows b$$

The colimit of this in any category is what's called the *coequalizer*.

Similarly, if \mathcal{J} is a discrete category (only a set, with identity maps). The colimit is the coproduct. If the category is sets, or spaces, this is the disjoint union. If the category is abelian groups, then one option would be the product. But this only works if \mathcal{J} is finite. A better thing is to take the (possibly infinite) direct sum.

REMARK 39.2. Analogously, you can consider *cones over X* . While Miller defined this in class, I'll leave it you, beloved reader, to figure out this definition. It's really just a cone in the opposite category. Like the notion of a colimit, we get a limit as a terminal object in cones over X . I encourage you to consider limits in the examples above. For example, in the second example above, the limit of a group action is the fixed point set!

So products are limits, for example. Think about this yourself, because I want to talk about one more thing, namely adjoint functors.

39.2. Adjoint functors. This is a very useful concept. We have an example, already. Let $\mathbf{C}^{\mathcal{J}} = \text{Fun}(\mathcal{J}, \mathbf{C})$. We've been working in this category! Ok, so what we have is a functor $\mathbf{C} \rightarrow \mathbf{C}^{\mathcal{J}}$, given by the constant functor. We also have a functor $\mathbf{C}^{\mathcal{J}} \rightarrow \mathbf{C}$ given by the colimit. This may not exist in general, but in our examples above, they always exist. What's the rule this colimit plays? Well:

$$\mathbf{C}(\text{colim}_{i \in \mathcal{J}} X_i, Y) = \mathbf{C}^{\mathcal{J}}(X, \text{const}_Y)$$

where $X : \mathcal{J} \rightarrow \mathbf{C}$. This is reminiscent of the adjunction operator in linear algebra. So this is an example of an adjoint functor. In fact, also:

$$\mathbf{C}(W, \lim_{i \in \mathcal{J}} X_i) = \mathbf{C}^{\mathcal{J}}(\text{const}_W, X)$$

Another adjunction where the constant functor (yes, two "functor"s!) appears on the left!

DEFINITION 39.3 (Invented by Dan Kan, late, of this department). Let \mathbf{C}, \mathbf{D} be categories. Let $F : \mathbf{C} \rightarrow \mathbf{D}$ and $G : \mathbf{D} \rightarrow \mathbf{C}$. An *adjunction* between F and G is an isomorphism:

$$\mathbf{D}(FX, Y) = \mathbf{C}(X, GY)$$

which is natural in X and Y . We say that F is a left adjoint of G and G is a right adjoint of F . People typically write left adjoints on the top.

For example, there's a forgetful functor $\text{Grp} \rightarrow \text{Set}$. Any set determines a group. Hmm. What is this? Set maps $X \rightarrow u\Gamma$ should be the same as group maps $FX \rightarrow \Gamma$ where Γ is a group and F is our mysterious left adjoint. u is the forgetful functor. So FX is the free group! This is literally the definition of the free group.

DEFINITION 39.4. \mathbf{C} is *cocomplete* if all colimits exist. It's *complete* if all limits exist.

Obviously I'm talking about small (co)limits. If a functor has both left and right adjoints, it's super nice! We'll reconvene on Friday.

40. Compactly generated spaces

A lot of the course is going to be about loop spaces, and mapping spaces. Standard topology doesn't do very well with mapping spaces. So we are going to narrate the story of compactly generated spaces. One of the good things is that you have a *Cartesian-closed category*.

The first thing I want to talk about is the Yoneda lemma. We will start to do some topology pretty soon. OK, so I was proposing the notion of a colimit of a functor. It was defined in terms of maps out of the colimit. More precisely:

$$\mathbf{C}(\operatorname{colim}_{j \in \mathcal{J}} X_j, Y) = \mathbf{C}^{\mathcal{J}}(X_{\bullet}, \operatorname{const}_Y)$$

They're naturally isomorphic, and that's all you can ask for in this life. How well-defined is this object, if it exists? Whether it exists is a question of how cocomplete your category is. The question of uniqueness is more general. Let's think about that for a minute. The Yoneda lemma – sometimes “you-need-a-lemma” (!) – is:

THEOREM 40.1 (Yoneda lemma). *Consider the functor $\mathbf{C}(X, -) : \mathbf{C} \rightarrow \mathbf{Set}$. Suppose $G : \mathbf{C} \rightarrow \mathbf{Set}$ is another functor. It turns out that:*

$$\operatorname{nt}(\mathbf{C}(X, -), G) \simeq G(X)$$

PROOF. Let $x \in G(X)$. We then define a natural transformation that sends $f : X \rightarrow Y$ to $f_*(x) \in G(Y)$. On the other hand, suppose $\theta : \mathbf{C}(X, -) \rightarrow G$. Send θ to $\theta_X(1_X)$. These two are so natural and beautiful that you expect that they're inverses, right? And they are. \square

OK, so in particular if $G = \mathbf{C}(Y, -)$ – these are called *corepresentable* functors – then $\operatorname{nt}(\mathbf{C}(X, -), \mathbf{C}(Y, -)) \simeq \mathbf{C}(Y, X)$. What this means is that if you look at natural isomorphisms $\mathbf{C}(X, -) \rightarrow \mathbf{C}(Y, -)$, that's the same as isomorphisms $Y \rightarrow X$. This means that if you have a corepresentable functor, the object that represents is unique¹¹.

40.1. CGHW spaces. Some constructions commute for “categorical reasons”. Here's the example to keep in mind. Let $X \in \mathbf{Top}$. Then $X \times \lim_{j \in \mathcal{J}} Y_j \simeq \lim_{j \in \mathcal{J}} (X \times Y_j)$. Why? This is easily proven because both the limit and the product are defined by what maps into them are. In contrast, $X \times \operatorname{colim}_{j \in \mathcal{J}} Y_j$ is not $\operatorname{colim}_{j \in \mathcal{J}} (X \times Y_j)$ in general. Very sad :- (An example of this failure is a quotient map $Y \rightarrow Z$. Then $X \times Y \rightarrow X \times Z$, is this a quotient map? It's not true in general. It's a very sad state of affairs.

THEOREM 40.2 (Whitehead). *It is if X is a compact Hausdorff space.*

I want to repair that problem. Why were we talking about colimits? Here's an observation. Suppose $X \rightarrow Y$ is a quotient map; then a map $Y \rightarrow Z$ is continuous iff the composite $X \rightarrow Y \rightarrow Z$ is continuous. A quotient map *is* a coequalizer. What I'm saying is, I can find two maps to X such that Y is a coequalizer of X . What space are we mapping into X ? Well, suppose $Z = X/\sim$. If we considered:

$$X \times_Z X \xrightarrow[\pi_2]{\pi_1} X \longrightarrow Z$$

The term here is “regular epimorphism”.

REMARK 40.3. OK, the statement about limits and products is wrong. Think about what happens when \mathcal{J} is a discrete category. We will fix this on Monday.

We don't want to just restrict ourselves to compact Hausdorff spaces. So we look at topologies detected by maps from compact Hausdorff spaces.

DEFINITION 40.4. Let X be a space. A subspace $F \subseteq X$ is called *compactly closed* if for any map $k : K \rightarrow X$ from compact Hausdorff K , then $k^{-1}(F) \subseteq K$ is closed.

If F is closed, then it's clearly compactly closed. But there might be non-closed compactly closed sets.

DEFINITION 40.5. X is a k -space if compactly closed implies closed.

¹¹at least up to isomorphism

The k comes from “kompact” and/or Kelly, an early topologist who considered this stuff.

Let X be any space. It can be k -ified to some space denoted kX . You just enlarge the topology so that it includes the compactly closed sets. This is a topology, bigger than the original one. So the identity $kX \rightarrow X$ is continuous.

REMARK 40.6. X is a k -space iff it has the property that a map $X \rightarrow Y$ is continuous iff for any compact Hausdorff K and map $k : K \rightarrow X$, the composite $K \rightarrow X \rightarrow Y$ is continuous.

EXAMPLE 40.7. Compact Hausdorff spaces are k -spaces. First countable (so metric spaces) and CW-complexes are also k -spaces.

Define $k\mathbf{Top}$ to be the category of k -spaces. There’s an inclusion $i : k\mathbf{Top} \hookrightarrow \mathbf{Top}$. Now k -ification gives a functor $\mathbf{Top} \rightarrow k\mathbf{Top}$. This has the property that:

$$k\mathbf{Top}(X, kY) = \mathbf{Top}(iX, Y)$$

Here’s an adjunction! This means that $k(iX \times iY) = X \times^{k\mathbf{Top}} Y$ where X and Y are k -spaces. It’s true that $kiX \simeq X$.

The takeaway is that $k\mathbf{Top}$ has good categorical properties inherited from \mathbf{Top} , i.e. it’s complete and cocomplete. I want to now talk about mapping spaces, which shows that $k\mathbf{Top}$ is even better!

40.2. Mapping spaces. Let X and Y be spaces. There’s the compact-open topology on $\mathbf{Top}(X, Y)$. For k -spaces, I want to make a slight modification. In particular, if X and Y are k -spaces, define a topology on $k\mathbf{Top}(X, Y)$ generated by: $W(k : K \rightarrow X, \text{open } U \subseteq Y) = \{f : X \rightarrow Y : f(k(K)) \subseteq U\}$. We write Y^X for the k -ification of this space.

- PROPOSITION 40.8. (1) $(k\mathbf{Top})^{op} \times k\mathbf{Top} \rightarrow k\mathbf{Top}$ given by $(X, Y) \mapsto Y^X$ is a functor of both variables.
 (2) $e : X \times Z^X \rightarrow Z$ given by $(x, f) \mapsto f(x)$ and $i : Y \rightarrow (X \times Y)^X$ given by $y \mapsto (x \mapsto (x, y))$ are continuous.

PROOF. Look online – there are references on the webpage. □

I’m not where I wanted to be at this moment in time. Ok, here’s a result of this proposition. Consider $k\mathbf{Top}(X \times Y, Z)$ where the product is the product in k -spaces. What is $k\mathbf{Top}(Y, Z^X)$? I want to say that:

$$k\mathbf{Top}(X \times Y, Z) \simeq k\mathbf{Top}(Y, Z^X)$$

defined by $(f : X \times Y \rightarrow Z) \mapsto (Y \xrightarrow{i} (X \times Y)^X \rightarrow Z^X)$ in one direction, and by $(f : Y \rightarrow Z^X) \mapsto (X \times Y \rightarrow X \times Z^X \xrightarrow{e} Z)$. They’re so natural that they have to be inverses to one another. Let me close with a definition.

DEFINITION 40.9. A category \mathbf{C} with finite products is Cartesian closed if for any X , the functor $X \times - : \mathbf{C} \rightarrow \mathbf{C}$ has a right adjoint.

So $k\mathbf{Top}$ is Cartesian closed, but \mathbf{Top} isn’t. On Monday, I’ll justify why this is important.

41. “Cartesian closed”, Hausdorff, Basepoints

Pset 1 is up, and there’s now a number 4. My office hours are Tuesday from 12 to 1:30 in 2-478.

Remember that I wrote something that’s obviously wrong; let $Y : \mathcal{J} \rightarrow \mathbf{C}$. I claimed that $\lim_{\mathcal{J}}(X \times Y_i) \simeq X \times \lim_{\mathcal{J}} Y_i$. This isn’t right because if \mathcal{J} is a discrete category, this doesn’t make sense. One way to fix this is implemented in problem 4. Another way is, let $X : \mathcal{J} \rightarrow \mathbf{C}$. Then I can take $\lim_{\mathcal{J}}(X_i \times Y_i)$, and this is $\lim_{\mathcal{J}} X_i \times \lim_{\mathcal{J}} Y_i$. This is part of a more general picture involving a Frobenii theorem. You can find out more from MacLane’s book or something.

I want to catch up with something that I had to say before but I didn’t. That’s the relationship between (co)limits and adjoint functors. Namely, left adjoints respect colimits and right adjoints respect limits. There’s something called the adjoint functor theorem. For example, $Y \times - : \mathbf{Top} \rightarrow \mathbf{Top}$. One kind of colimit is the pushout $X/A = X \cup_A *$. But $Y \times X \cup_{Y \times A} * \simeq (Y \times X)/(Y \times A)$. But this isn’t the same as $Y \times (X/A)$! There is a bijective map $Y \times X/Y \times A \rightarrow Y \times (X/A)$, but it’s not a homeomorphism in general. The reason this fails is because $Y \times -$ is *not* a left adjoint!

But it is a left adjoint when working with compactly generated spaces (i.e., k -spaces)¹²! Recall that this means that $k\mathbf{Top}$ is Cartesian closed. We're gonna make a lot of use of the space $Z^X := k(k\mathbf{Top}(X, Z))$. You'll check that $(X, Z) \mapsto Z^X$ is a functor. Another thing is that $Z^{X \times Y} \simeq (Z^X)^Y$ and $(Y \times Z)^X \simeq Y^X \times Z^X$. There's a composition map $Y^X \times Z^Y \rightarrow Z^X$.

When the ancients came up with the definition of a topology, they were good axioms – but these are better! Sometimes, you want even more, e.g., points being closed. There's a further refinement of k -spaces.

41.1. “Hausdorff”.

DEFINITION 41.1. A space is “weakly Hausdorff” if the image of every map $K \rightarrow X$ from a compact Hausdorff space K is closed.

Another way to say this is that the map itself is closed. Clearly Hausdorff implies weakly Hausdorff. Another thing this means is that every point in X is closed (eg $K = *$).

PROPOSITION 41.2. *Let X be a k -space.*

- (1) *X is weakly Hausdorff iff $\Delta : X \rightarrow X \times^k X$ is closed. In algebraic geometry such a condition is called separated.*
- (2) *Let $R \subseteq X \times X$ be an equivalence relation. If R is closed, then X/R is weakly Hausdorff.*

DEFINITION 41.3. A space is compactly generated if it's a weakly Hausdorff k -space. The category of such spaces is called **CG**.

We have a pair of adjoint functors $(i, k) : \mathbf{Top} \rightarrow k\mathbf{Top}$. It's possible to define a functor $k\mathbf{Top} \rightarrow \mathbf{CG}$ given by $X \mapsto X / \bigcap \text{all closed equivalence relations}$. It is easy to check that if Z is weakly Hausdorff, then Z^X is weakly Hausdorff (where X is a k -space). What this implies is that **CG** is also Cartesian closed!

I'm getting a little tired of point set stuff. Let's start talking about homotopy and all that stuff today for a bit. You know what a homotopy is. I will not worry about point-set topology anymore. So when I say **Top**, I probably mean **CG**. A homotopy between $f, g : X \rightarrow Y$ is a map $h : I \times X \rightarrow Y$ such that the following diagram commutes:

$$\begin{array}{ccc}
 X & & \\
 & \searrow f & \\
 & I \times X & \xrightarrow{h} Y \\
 & \nearrow i_1 & \\
 X & & \\
 & \nearrow i_0 & \\
 & I \times X & \xrightarrow{g} Y
 \end{array}$$

We write $f \sim g$. We define $[X, Y] = \mathbf{Top}(X, Y) / \sim$. Well, a map $I \times X \rightarrow Y$ is the same as a map $X \rightarrow Y^I$ but also $I \rightarrow Y^X$. The latter is my favorite! It's a path of maps from f to g . So $[X, Y] = \pi_0 Y^X$.

To talk about higher homotopy groups and induct etc. we need to talk about basepoints.

41.2. Basepoints. A pointed space is $(X, *)$ with $* \in X$. This gives a category \mathbf{Top}_* where the morphisms respect the basepoint. This has products because $(X, *) \times (Y, *) = (X \times Y, (*, *))$. How about coproducts? It has coproducts as well. This is the wedge product, defined as $X \sqcup Y / *_X \sim *_Y =: X \vee Y$. This is **\vee**, not **\wedge**. Is this category also Cartesian closed?

Define the space of pointed maps $Z_*^X \subseteq Z^X$ topologized as a subspace. Does the functor $Z \mapsto Z_*^X$ have a left adjoint? Well $\mathbf{Top}(W, Z_*^X) = \mathbf{Top}(X \times W, Z)$. What about $\mathbf{Top}(W, Z_*^X)$? This is $\{f : X \times W \rightarrow Z : f(*, w) = * \forall w \in W\}$. That's not quite what I wanted either! Thus $\mathbf{Top}_*(W, Z_*^X) = \{f : X \times W \rightarrow Z : f(*, w) = * = f(x, *) \forall x \in X, w \in W\}$. These send both “axes” to the basepoint. Thus, $\mathbf{Top}_*(W, Z_*^X) = \mathbf{Top}_*(X \wedge W, Z)$ where $X \wedge W = X \times W / X \vee W$ because $X \vee W$ are the “axes”.

So \mathbf{Top}_* is not Cartesian closed, but admits something called the smash product¹³. What properties would you like? Here's a good property: $(X \wedge Y) \wedge Z$ and $X \wedge (Y \wedge Z)$ are bijective in pointed spaces. If you work in $k\mathbf{Top}$ or **CG**, then they are homeomorphic! It also has a unit.

¹²Compactly generated spaces are weakly Hausdorff k -spaces, what Professor Miller said here was incorrect.

¹³Remark by Sanath: this is like the tensor product.

Oh yeah, some more things about basepoints! So there's a canonical forgetful functor $i : \mathbf{Top}_* \rightarrow \mathbf{Top}$. Let's see. If I have $\mathbf{Top}(X, iY) = \mathbf{Top}_*(?, Y)$? This is $X_+ = X \sqcup *$. Thus we have a left adjoint $(-)_+$. It is clear that $(X \sqcup Y)_* = X_+ \vee Y_+$. The unit for the smash product is $*_+ = S^0$.

On Friday I'll talk about fibrations and fiber bundles.

42. Fiber bundles, fibrations, cofibrations

My office hours are Tuesday, 12 - 1:30 and Hood's are Tuesday, 12(next week). It'll probably be Mondays in the future, at 12 as well. Next Monday is a holiday, and next Tuesday is a Monday. Oh, pset 1 is due on Wednesday.

Today's gonna be about fiber bundles and fibrations and possibly cofibrations as well. This is proper homotopy theory. You have probably seen fiber bundles before. Do you like the yellow chalk? I think it looks good.

DEFINITION 42.1 (Fiber bundles). A fiber (or fibre, if you're British) bundle is a map (of compactly generated spaces, *always* – although every space in nature is already a weakly Hausdorff k -space; it's not a big deal!) $p : E \rightarrow B$ such that for every $b \in B$, there exists an open $U \subseteq B$ such that $b \in U$, and a map $p^{-1}(U) \rightarrow p^{-1}(b)$ such that $p^{-1}(U) \rightarrow U \times p^{-1}(b)$ is a homeomorphism.

So the preimage over every point looks like a product. So it's locally trivial in the base. Of course, there's an alternate way to say this. Equivalently, there is an open cover \mathcal{U} (called the *trivializing cover*) of B such that for every $U \in \mathcal{U}$, there is a space F and a homeomorphism $p^{-1}(U) \simeq U \times F$ that's compatible with the projections down to U .

REMARK 42.2. We say that E is the total space, B is a base space, p is a projection, and F (which can vary) – actually I'll write $p^{-1}(b)$ – is called the fiber over b .

EXAMPLE 42.3. You know of many examples. A covering space $E \rightarrow B$ is a fiber bundle with discrete fibers. Thus fiber bundles generalize covering spaces to more interesting cases.

EXAMPLE 42.4. The Hopf fibration. It's a fiber bundle. We have $S^3 \subseteq \mathbf{C}^2$. And, well, we can consider the map $S^3 \rightarrow \mathbf{CP}^1$ that sends a vector through the complex line through v . Now, $\mathbf{CP}^1 \simeq S^2$. So you have a non-nullhomotopic map $S^3 \rightarrow S^2$. Here's a picture of this. (I cannot livetex this)

The Hopf fibration is a map between smooth manifolds. This is a great way to construct fibrations.

THEOREM 42.5 (Ehresmann). Suppose E and B are smooth manifolds, and let $p : E \rightarrow B$ be a smooth (i.e., C^∞) map. Then p is a fiber bundle if:

- (1) It's a submersion (so $dp : T_e E \rightarrow T_{p(e)} B$ is a surjection)
- (2) p is proper, so preimages of compact sets are compact.

For example, I can look at the complement of a closed set in S^3 , and then the restriction of p won't be a fiber again.

The whole course is about fiber bundles, namely about its cohomological and homotopical structure.

DEFINITION 42.6 (See Peter May's *Concise Course*). Let X be a space. Say that an open cover \mathcal{U} is *numerable* if there exists a subordinate partition of unity, i.e., for each $U \in \mathcal{U}$ we're given $f_U : X \rightarrow [0, 1] = I$ such that $f^{-1}((0, 1]) = U$ and any $x \in X$ belongs to only finitely many $U \in \mathcal{U}$.

Say that X is paracompact if any open cover admits a numerable refinement.

EXAMPLE 42.7. CW-complexes are paracompact.

The numerable definition is technical, but you're really just restricting the class of coverings you're looking at.

DEFINITION 42.8. A fiber bundle is “numerable” if it admits a numerable trivializing cover.

Fiber bundles are still too narrow. So I will now tell you what a fibration is.

DEFINITION 42.9. A map $p : E \rightarrow B$ is called a *Hurewicz fibration* (I'll just say fibration) if it satisfies the homotopy lifting property (HLP). That says this. Suppose I have a homotopy $h : I \times W \rightarrow B$. Then there exists a lift:

$$\begin{array}{ccc} W & \xrightarrow{f} & E \\ \text{in}_0 \downarrow & \nearrow \bar{h} & \downarrow p \\ I \times W & \xrightarrow{h} & B \end{array}$$

Where the outer diagram commutes. It doesn't need to be a unique lift!

This is an extremely alarming definition. This has to be checked for all spaces and all maps and all homotopies! So it took an act of genius to construct something like this. The idea of doing something like this goes back to Serre back in about 1950. It solved a problem (of defining what a fibration was).

But it's not impossible to check! Let me tell you some stuff. Hurewicz was a faculty member here, one of the first algebraic topologists here. I'm going to try to reformulate this diagram here a little bit. Let me try to adjoint the I . Then I have:

$$\begin{array}{ccc} E & \xrightarrow{p} & B \\ f \uparrow & & \uparrow \text{ev}_0 \\ W & \xrightarrow{\hat{h}} & B^I \end{array}$$

This is just the adjoint of our diagram. Now, a diagram like this is the same as a map $W \rightarrow B^I \times_B E$ (the pullback is the set of paths and points (ω, e) such that $\omega(0) = p(e)$). But now, if our dotted map exists, we'd have a lifted homotopy $\hat{\bar{h}} : W \rightarrow E^I$. We have a map $\tilde{p} : E^I \rightarrow B^I \times_B E$ given by $\omega \mapsto (p\omega, \omega(0))$. Clearly $p\omega(0) = p\omega(0)$, so this lands in $B^I \times_B E$.

Thus the existence of \hat{h} is the same as a lift:

$$\begin{array}{ccc} & & E^I \\ & \nearrow \hat{\bar{h}} & \downarrow \tilde{p} \\ W & \longrightarrow & B^I \times_B E \end{array}$$

Obviously the universal example is $B^I \times_B E$. If p is a fibration, then I can make the lift in the following diagram, and if I can lift for any W , I can obviously construct the lift in the following diagram:

$$\begin{array}{ccc} & & E^I \\ & \nearrow \lambda & \downarrow \tilde{p} \\ B^I \times_B E & \xrightarrow{1} & B^I \times_B E \end{array}$$

We say λ is a *lifting function*. Well, if $\omega(0) = p(e)$, then $\lambda(\omega : I \rightarrow B, e \in E) : I \rightarrow E$. And in particular, $p \circ \lambda(\omega, e) = \omega$ and $\lambda(\omega, e)(0) = e$. So λ starts with a path ω in B , and some point over the starting point, and produces a path in E which lives over ω . In other words, it's a path lifting. The key thing is that it's a continuous way to lift. So you *can* check the HLP in certain cases.

THEOREM 42.10 (Dold). *Let $p : E \rightarrow B$ be a map. Assume there's a numerable cover of B , say \mathcal{U} , such that for every $U \in \mathcal{U}$, the restriction $p|_{p^{-1}(U)} : p^{-1}U \rightarrow U$ is a fibration. (It's locally a fibration over the base). Then p itself is a fibration.*

Check for yourself that at least a product projection $\text{pr}_1 : B \times F \rightarrow B$ is a product fibration (e.g. using the universal property or something). So in particular, *every numerable fiber bundle is a fibration*. I.e., numerable fiber bundles satisfy the homotopy lifting property. We'll see why this is such a good thing next week. Questions?

43. Fibrations and cofibrations

Recall that fibrations are maps $p : E \rightarrow B$ such that for every W there is a lift:

$$\begin{array}{ccc} W & \longrightarrow & E \\ in_0 \downarrow & \nearrow & \downarrow p \\ W \times I & \longrightarrow & B \end{array}$$

Here is a rather simple result to show.

- PROPOSITION 43.1. (1) *Fibrations are closed under pullbacks. In other words, if $p : E \rightarrow B$ is a fibration and $X \rightarrow B$ is any map, then the induced map $E \times_B X \rightarrow X$ is a fibration.*
(2) *Fibrations are closed under exponentiation and products. In other words, if $p : E \rightarrow B$ is a fibration, then $E^A \rightarrow B^A$ is another fibration.*
(3) *Fibrations are closed under composition.*

43.1. Comparing fibers over different points in B . OK, let's consider a path $\omega : I \rightarrow B$ with $\omega(0) = a$ and $\omega(1) = b$. Let F_a be the fiber over a . Then we want to have a map $F_a \rightarrow F_b$, because of our considerations on liftings of paths. How do we get such a map?

Consider the diagram:

$$\begin{array}{ccc} F_a & \longrightarrow & E \\ in_0 \downarrow & \nearrow h & \downarrow p \\ I \times F_a & \xrightarrow{pr_1} & B \xrightarrow{\omega} B \end{array}$$

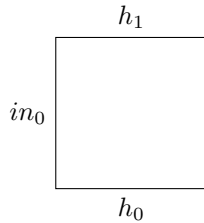
Does this diagram commute? Yes, because $\omega(0) = a$. Thus, by the homotopy lifting property, the dotted arrow exists. Now, if $x \in F_a$, then $h(1, x) \in F_b$ and $h(0, x) = x$. Thus we get a map $f : F_a \rightarrow F_b$ where $f(x) = h(1, x)$.

Great! Now the question we can ask is: how unique is f ? Namely, if we have two homotopic paths ω_0, ω_1 with $\omega_0(0) = \omega_1(0) = a$ and $\omega_0(1) = \omega_1(1) = b$, with a given homotopy $g : I \times I \rightarrow B$, how do f_0 and f_1 relate?

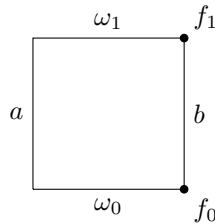
We have a diagram of the form:

$$\begin{array}{ccc} ((\partial I \times I) \cup (I \times 0)) \times F_a & \longrightarrow & E \\ in_0 \downarrow & \nearrow & \downarrow p \\ I \times I \times F_a & \xrightarrow{pr_1} & I \times I \xrightarrow{g} B \end{array}$$

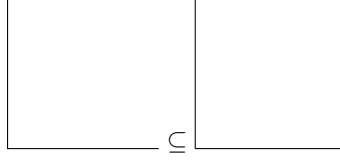
Think of the space $(\partial I \times I) \cup (I \times 0)$ as follows:



and $I \times I$ looks like:



Does the dotted map exist? Clearly this is crying out for us to use the homotopy lifting property. But what should our space W be? Well the following pair:



is homotopy equivalent to $(0 \subseteq I) \times I$. Hence in our diagram we now have:

$$\begin{array}{ccccc}
 I \times F_a & \longrightarrow & (\partial I \times I) \cup (I \times 0) \times F_a & \longrightarrow & E \\
 & & \downarrow in_0 & \nearrow & \downarrow p \\
 I \times I \times F_a & \xrightarrow{\simeq} & I \times I \times F_a & \xrightarrow{pr_1} & I \times I \xrightarrow{g} B
 \end{array}$$

This whole diagram commutes; letting $W = I \times F_a$ thus gives us the desired lift. Restricting to the right side of the C-shaped region (which the HLP says can be completed to a square) gives a homotopy $f_0 \simeq f_1$. Thus liftings of homotopic paths are unique up to homotopy. How do we express this functorially?

43.2. Fundamental groupoid.

DEFINITION 43.2. Given a space X , the fundamental groupoid is a category (in fact, groupoid) denoted $\Pi_1(X)$, whose objects are points of X and maps are homotopy classes of paths in X . Composition of compatible σ and ω is the path:

$$(\sigma \cdot \omega)(t) = \begin{cases} \omega(2t) & 0 \leq t \leq 1/2 \\ \sigma(2t - 1) & 1/2 \leq t \leq 1 \end{cases}$$

What we've therefore showed is:

PROPOSITION 43.3. Any fibration $p : E \rightarrow B$ gives a functor $\Pi_1(B) \rightarrow \mathbf{Top}$.

This is the beginning of a beautiful story involving fibrations. If you're interested, look up "Grothendieck construction".

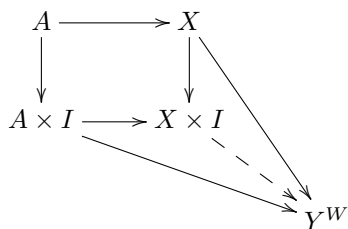
43.3. Cofibrations. Let's turn to a different question. Let $i : A \rightarrow X$. When is $Y^X \rightarrow Y^A$ a fibration? Well, we want a lifting:

$$\begin{array}{ccc}
 W & \longrightarrow & Y^X \\
 in_0 \downarrow & \nearrow & \downarrow \\
 I \times W & \longrightarrow & Y^A
 \end{array}$$

This can be adjointed over to get:

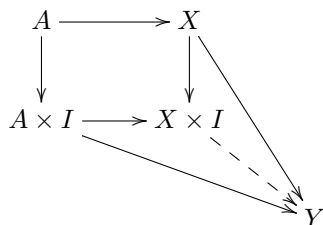
$$\begin{array}{ccc}
 A \times W & \xrightarrow{i \times 1} & X \times W \\
 1 \times in_0 \downarrow & & \downarrow \\
 A \times W \times I & \longrightarrow & X \times I \times W \\
 & \searrow & \nearrow \\
 & & Y
 \end{array}$$

Adjointing over again:

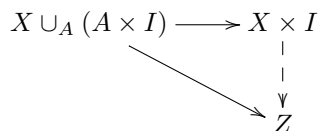


This motivates the following definition of something that's *dual* to the notion of fibration:

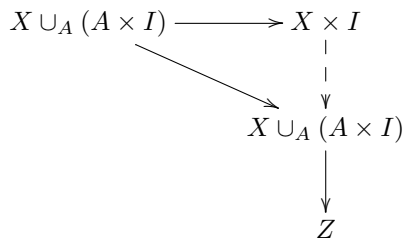
DEFINITION 43.4. $i : A \rightarrow X$ is a *cofibration* if it satisfies the *homotopy extension property*, i.e. for all solid arrow diagrams, the following diagram commutes for any Y :



The universal example is the pushout $X \cup_A (A \times I)$. So, equivalently, we're asking for the existence of a dotted arrow:



for any Z . But this is equivalent to the existence of a dotted arrow in the following diagram:



This is in turn equivalent to asking that $X \cup_A (A \times I)$ is a retract of $X \times I$.

EXAMPLE 43.5. $S^{n-1} \hookrightarrow D^n$ is a cofibration.



FIGURE 2. Drawing by John Ni.

In particular, $\{0, 1\} \hookrightarrow I$ is a cofibration.

44. Homotopy fibers, the Barratt-Puppe sequence

Yesterday, I showed this:

PROPOSITION 44.1. *If $A \rightarrow X$ is a cofibration, then for any Y , the map $Y^X \rightarrow Y^A$ is a fibration.*

We did this by reverse-engineering.

EXAMPLE 44.2. $S^{n-1} \hookrightarrow D^n$ is a cofibration.

Let me point out properties of cofibrations.

- It's closed under cobase change. What this means is if I have a cofibration $A \rightarrow X$ and any $A \rightarrow B$, then $B \rightarrow X \cup_A B$ is a cofibration.
- It's closed under finite products. This is surprising.
- It's closed under composition.
- Any cofibration is a closed inclusion. This is not so obvious, so check out May's book.

By the way, the dual statement would be something like: $p : E \rightarrow B$ a quotient map? No! Fibrations don't have to be surjective at all. It is surjective on path components though, because of the path-lifting stuff. But, for example, $\emptyset \rightarrow B$ is a fibration.

Another fact on fibrations is that $X \rightarrow *$ is a fibration, because the dotted map can be taken to the map $(t, w) \mapsto f(w)$:

$$\begin{array}{ccc} W & \xrightarrow{f} & X \\ \downarrow & \nearrow & \downarrow \\ I \times W & \longrightarrow & * \end{array}$$

Model category folks get excited about this, because this says that all objects in the model structure on topological spaces is fibrant.

DEFINITION 44.3. Now, the inclusion $* \hookrightarrow X$ is not always a cofibration (see your pset!), but if it is, say that $*$ is a nondegenerate basepoint in X .

Eg if $*$ has a neighborhood that contracts to $*$ then $* \hookrightarrow X$ is a cofibration. If $*$ is a nondegenerate basepoint, then $X^A \xrightarrow{ev} X$ is a fibration where A is pointed. The fiber is the space of pointed maps $A \rightarrow X$.

Because $S^{n-1} \hookrightarrow D^n$ is a cofibration, we find that $\{0, 1\} \hookrightarrow I$ is a cofibration. This means that the map $Y^I \rightarrow Y \times Y$ given by $\omega \mapsto (\omega(0), \omega(1))$ is a fibration. This gets into the story of path spaces.

44.1. "Fibrant replacements". Don't worry about the title of this section. If you've seen model categories, this'll make sense.

THEOREM 44.4. *Any map is \simeq to a fibration. What does this mean? This means that for any map $f : X \rightarrow Y$ we can find a space $T(f)$ such that:*

$$\begin{array}{ccc} X & & T(f) \\ f \downarrow & \searrow \simeq & \downarrow p \\ & & Y \end{array}$$

where p is a fibration and $X \xrightarrow{\simeq} T(f)$ is a homotopy equivalence.

PROOF. Consider the map $Y^I \xrightarrow{\begin{pmatrix} ev_0 \\ ev_1 \end{pmatrix}} Y \times Y$. Define $T(f)$ as the pullback:

$$\begin{array}{ccc} T(f) & \longrightarrow & Y^I \\ \downarrow & & \downarrow \begin{pmatrix} ev_0 \\ ev_1 \end{pmatrix} \\ X \times Y & \xrightarrow{f \times 1} & Y \times Y \end{array}$$

In other words, $T(f) = \{(x, \omega) \in X \times Y^I \mid f(x) = \omega(0)\}$. Let's start checking the conditions. First of all, the map $Y^I \rightarrow Y \times Y$ is a fibration. So $T(f) \rightarrow X \times Y$ is a fibration. Since $X \times Y \rightarrow Y$ is a fibration, we can consider the composite $T(f) \rightarrow X \times Y \rightarrow Y$, which is now a fibration. On elements, $T(f) \rightarrow Y$ sends $(x, \omega) \rightarrow \omega(1)$.

To get a map $X \rightarrow T(f)$, I need to give maps $X \rightarrow X \times Y$ and $X \rightarrow Y^I$ that have compatible images in

$Y \times Y$. Define $X \rightarrow X \times Y$ as $X \xrightarrow{\begin{pmatrix} 1 \\ f \end{pmatrix}} X \times Y$, and define $X \rightarrow Y^I$ as the map sending x to the constant loop at $f(x)$. Clearly both composite $X \rightarrow X \times Y \rightarrow Y \times Y$ and $X \rightarrow Y^I \rightarrow Y \times Y$ are the same, so we have a map $X \rightarrow T(f)$.

Is it true that the composite $X \rightarrow T(f) \xrightarrow{p} Y$ is our original map? Yes! So we only have to check that $X \rightarrow T(f)$ is a homotopy equivalence. Let me begin by constructing a homotopy inverse. I.e., a map $T(f) \rightarrow X$. We can define a map $T(f) \rightarrow X$ via $T(f) \rightarrow X \times Y \xrightarrow{pr_1} X$. Clearly the composite $X \rightarrow T(f) \rightarrow X \times Y \rightarrow X$ is the identity. This means we need to study $T(f) \rightarrow X \rightarrow T(f)$. This composite sends $(x, \omega) \mapsto x \mapsto (x, c_{f(x)})$ where $c_{f(x)}$ is the constant path at x . I need a homotopy between this map and the identity on $T(f)$.

This is what I call the spaghetti move. We know that there's no constraint on $\omega(1)$, so I can just suck it back in to get the constant loop. I guess I can define $\omega_s(t) = \omega(st)$. At $s = 1$ I have ω and when $s = 0$ I have $c_{f(x)} = c_{\omega(0)}$. Thus, define $I \times T(f) \rightarrow T(f)$ via $(s, (x, \omega)) \mapsto (x, \omega_s)$.

If you want to work through the diagram, this is how it looks.

$$\begin{array}{ccccc}
 X & & & & \\
 & \searrow^{x \mapsto c_{f(x)}} & & & \\
 & & T(f) & \xrightarrow{\quad} & Y^I \\
 & \searrow^{\begin{pmatrix} 1 \\ f \end{pmatrix}} & \downarrow & & \downarrow \begin{pmatrix} ev_0 \\ ev_1 \end{pmatrix} \\
 X & \xleftarrow{pr_1} & X \times Y & \xrightarrow{\quad} & Y \times Y \\
 & & \downarrow pr_2 & & \\
 & & Y & &
 \end{array}$$

□

Here's a really stupid example.

EXAMPLE 44.5 (Path-loop fibration). Suppose $X = *$. What is $T(f)$? Well it's just paths $\omega(0)$ in Y such that $\omega(0) = *$. I.e., $T(f) = Y_*^I$. This is also called the path space of Y , denoted $P(Y, *)$. It's contractible by the spaghetti move. What is its fiber? The map $PY \rightarrow Y$ sends $\omega \mapsto \omega(1)$. So the fiber is the points that begin at $*$ and end at $*$. The fiber of $PY \rightarrow Y$ is denoted ΩY , which is the space of loops at $*$. This is called the path loop fibration.

44.2. Homotopy fibers over $*$. The ordinary fiber is the pullback

$$\begin{array}{ccc}
 f^{-1}(*) & \longrightarrow & X \\
 \downarrow & & \downarrow f \\
 * & \longrightarrow & Y
 \end{array}$$

DEFINITION 44.6 (Homotopy fiber). The homotopy fiber is the pullback:

$$\begin{array}{ccccc}
 F(f, *) & \longrightarrow & T(f) & \longrightarrow & X \\
 \downarrow & & \downarrow p & \nearrow f & \\
 * & \longrightarrow & Y & &
 \end{array}$$

As a set it's $F(f, *) = \{(x, \omega) \in X \times Y^I \mid f(x) = \omega(0), \omega(1) = *\}$. The ordinary fiber and the homotopy fiber are definitely not generally the same. If $W \rightarrow X \rightarrow Y$ is nullhomotopic, then it factors through $F(f, *)$, i.e., the composite factors as $W \rightarrow F(f, *) \rightarrow X \rightarrow Y$.

PROPOSITION 44.7. *Suppose $p : X \rightarrow Y$ is a fibration. Let $*$ $\in Y$. Then $p^{-1}(*) \rightarrow F(p, *)$ is a homotopy equivalence.*

I'm not going to prove that, but you will for homework.

A different way to construct the homotopy fiber is to replace $f : X \rightarrow Y$ by a fibration. But what if I replace $*$ $\rightarrow Y$ by a fibration? Namely, we now have:

$$\begin{array}{ccccc} ?? & \longrightarrow & P(Y, *) & \xrightarrow{\simeq} & * \\ \downarrow & & & \swarrow & \\ X & \longrightarrow & Y & & \end{array}$$

This space $??$ consists of $(x, \omega) \in X \times Y^I$ such that $\omega(0) = *$ and $\omega(1) = f(x)$. Now, $F(f, *) = \{(x, \omega) : \omega(0) = f(x), \omega(1) = *\}$. So $??$ is homeomorphic to $F(f, *)$ by reversing directions of paths. There's two ways you can produce a homotopy fiber, and all of these are homeomorphic. You could also replace both of these maps f and $*$ $\rightarrow Y$ by a fibration, and you'll get something that's also homeomorphic. Note that when I say $F(f, *)$, I'll mean $??$.

Here's what you'll prove for homework.

THEOREM 44.8. *Suppose you have two fibrations p and p' such that the following diagram commutes, where f is a homotopy equivalence.*

$$\begin{array}{ccc} E & \xrightarrow{p} & E' \\ & \searrow p & \downarrow p' \\ & & B \end{array}$$

Then f is a fiber homotopy equivalence. That means that it's a homotopy equivalence in $\mathbf{Top}_{/B}$. What this means is that there is a map $g : E' \rightarrow E$ over B compatible with the fibrations and homotopies $I \times E \rightarrow E$ over B and $I \times E' \rightarrow E'$ over B . I.e., the following three diagrams commute:

$$\begin{array}{ccc} E' & \xrightarrow{g} & E \\ & \searrow p' & \downarrow p \\ & & B \end{array}$$

and

$$\begin{array}{ccc} I \times E & \xrightarrow{1 \sim gf} & E \\ & \searrow & \downarrow p \\ & & B \end{array}$$

and

$$\begin{array}{ccc} I \times E' & \xrightarrow{1 \sim fg} & E' \\ & \searrow & \downarrow p' \\ & & B \end{array}$$

So we find that for all b , $p^{-1}(b) \xrightarrow{\simeq} (p')^{-1}(b)$. So in particular, the fiber $F(f, *)$, i.e., the homotopy fiber, of $T(f) \rightarrow B$ and the fiber $f^{-1}(*)$ of $f : E \rightarrow B$ are homotopy equivalent if f is a fibration.

45. Barratt-Puppe sequence, π_*

Hood's office hours are from 12 to 1:30 on Mondays in 2-390. Mine are from 4-5 on Tuesday in 2-478. Hood's graded the homework already.

45.1. Fiber sequences. Recall we have a pullback diagram:

$$\begin{array}{ccccc}
 & & F(f, *) & \longrightarrow & PY \\
 & \nearrow & \downarrow p & & \downarrow p \searrow \simeq \\
 f^{-1}(*) & \longrightarrow & X & \xrightarrow{f} & Y \longleftarrow *
 \end{array}$$

The homotopy fiber $F(f, *)$ thus has elements $\{(x, \sigma) \in X \times PY \mid f(x) = \sigma(1)\}$. We also have the ordinary fiber $f^{-1}(*)$. If f is a fibration, the canonical map $f^{-1}(*) \rightarrow F(f, *)$ sending $x \mapsto (x, c_{f(x)})$ is a homotopy equivalence.

REMARK 45.1. Consider a pointed map¹⁴ $f : X \rightarrow Y$, i.e., $f(*) = *$. Then I'll write Ff for $F(f, *)$.

Ok, what's the fiber of $p : Ff \rightarrow X$? The fiber over the basepoint in X is precisely the space of loops in Y ! I.e., $p^{-1}(*)_X = \Omega Y$, which is the space of loops in Y based at $*_Y$. Note that this is also the homotopy fiber because p is a fibration (fibrations are closed under pullbacks). So the diagram we now have is:

$$\begin{array}{ccccc}
 \Omega Y = p^{-1}(*) & & & & \\
 \downarrow & & & & \\
 & & F(f, *) & \longrightarrow & PY \\
 & \nearrow & \downarrow p & & \downarrow p \searrow \simeq \\
 f^{-1}(*) & \longrightarrow & X & \xrightarrow{f} & Y \longleftarrow *
 \end{array}$$

The composite $Ff \rightarrow X \rightarrow Y$ sends $(x, \omega) \mapsto f(x)$. This is a pointed map, but not equal to the constant map. What does this even mean? Like, what is the basepoint we're choosing for Ff ? Well, choose the basepoint to be the image of the basepoint in $f^{-1}(*)$ under $f^{-1}(*) \hookrightarrow Ff$.

We also have a (pointed!) homotopy between $Ff \rightarrow X \rightarrow Y$ and the constant map, eg via $h : Ff \times I \rightarrow Y$ defined by $h(t, (x, \omega)) = \omega(t)$. We say that the composite is *nullhomotopic*. In fact, suppose $W \rightarrow X \rightarrow Y$ is nullhomotopic, with a chosen nullhomotopy – this is the same as a map $W \rightarrow Ff$. This is a question on your homework.

Let's write $[W, X]_* = \pi_0(X_*^W)$, i.e., the pointed homotopy classes of maps $W \rightarrow X$. This is a pointed set, whose basepoint is the constant map. Ok, I can consider $[W, Ff]_* \rightarrow [W, X]_* \rightarrow [W, Y]_*$. This composite is nullhomotopic. But I want to say that this sequence is exact. What that means is here (because we just have pointed sets). So the preimage of the basepoint in $[W, Y]_*$ equals the image of $[W, Ff]_* \rightarrow [W, X]_*$. This is exactly what I said before, about nullhomotopies $W \rightarrow X \rightarrow Y$ as maps $W \rightarrow Ff$. We say that $Ff \rightarrow X \xrightarrow{f} Y$ is a *fiber sequence*.

45.2. Iterating fiber sequences. I have $Ff \xrightarrow{p} X \xrightarrow{f} Y$. The strict fiber is ΩY , but the homotopy fiber is Fp . These are homotopy equivalent because p is a fibration. Denote the map $i : \Omega Y \rightarrow Ff$. This sits inside:

$$\begin{array}{ccccccc}
 \cdots & \longrightarrow & Fp_3 & \longrightarrow & Fp_2 & \longrightarrow & Fp_1 \xrightarrow{p_2} Ff \xrightarrow{p_1} X \xrightarrow{f} Y \\
 & & \uparrow \simeq & \nearrow i(p_2) & \uparrow \simeq & \nearrow i(p_1) & \uparrow \simeq \nearrow i(p_0) \\
 & & \Omega Fp_0 & \dashrightarrow & \Omega X & \dashrightarrow & \Omega Y
 \end{array}$$

All the p_i s are fibrations (think about why). The dotted maps seem to be missing; I can fill them in up to homotopy, and there's one map I can think of putting there: $\Omega X \xrightarrow{\Omega f} \Omega Y$. But *that's the wrong map*! The right map is $\Omega X \xrightarrow{\overline{\Omega f}} \Omega Y$ (see below for explanation). Here's a lemma.

¹⁴Some people say “based maps”, but it sounds like chemistry ... or evil, so I can't bring myself to say it

LEMMA 45.2. *The following diagram commutes to homotopy:*

$$\begin{array}{ccc} & & Fp \\ & \nearrow i(p) & \uparrow \\ \Omega X & \xrightarrow{\overline{\Omega f}} & \Omega Y \end{array}$$

where $\overline{\Omega f}$ is the diagonal in:

$$\begin{array}{ccc} \Omega X & \xrightarrow{-} & \Omega X \\ \Omega f \downarrow & \searrow \Omega f & \downarrow \Omega f \\ \Omega Y & \xrightarrow{-} & \Omega Y \end{array}$$

where $- : \Omega X \rightarrow \Omega X$ sends $\omega \mapsto \overline{\omega}$.

PROOF. There is a beautiful proof of this. But it's in pictures, and I can't type it. The main point is that the proof wouldn't work unless you moved backwards. See this image:

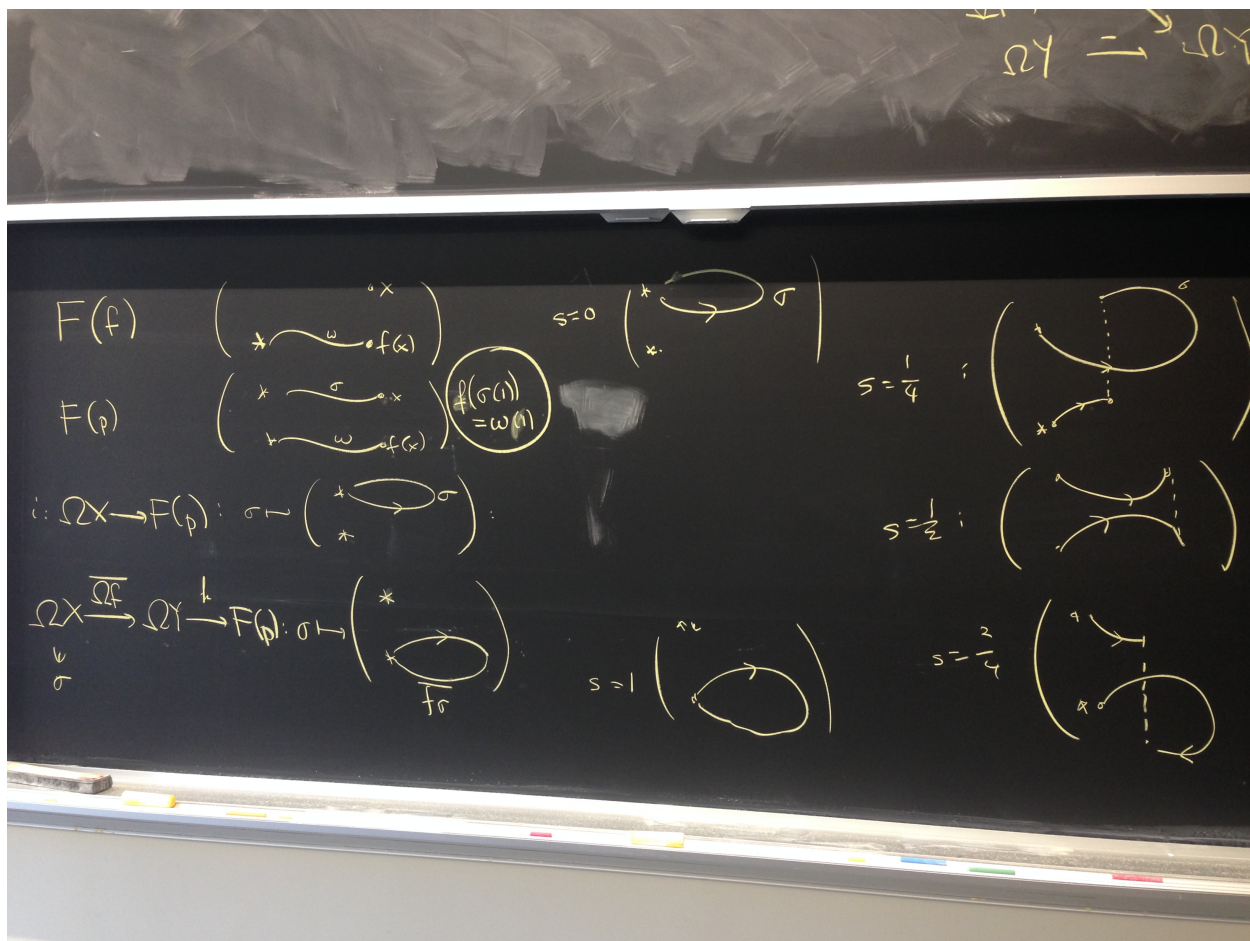


FIGURE 3. A proof of this lemma.

□

LEMMA 45.3. The following diagram commutes:

$$\begin{array}{ccc}
 & F(\overline{\Omega p_0}) & \\
 i(\Omega p_0) \nearrow & \parallel & \searrow \\
 \Omega^2 Y & & \Omega X \\
 \overline{\Omega i(p_0)} \searrow & \Omega F p_0 & \nearrow \overline{\Omega p_1}
 \end{array}$$

What is the map $F\overline{\Omega p_0} \rightarrow \Omega X$? We spent some time figuring this out. But you can now apply $[W, -]_*$ to the following diagram to get a long exact sequence:

$$\begin{array}{ccccccc}
 \cdots & \longrightarrow & Fp_4 & \longrightarrow & Fp_3 & \longrightarrow & Fp_2 \longrightarrow Fp_1 \xrightarrow{p_2} Ff \xrightarrow{p_1} X \xrightarrow{f} Y \\
 & & \uparrow \simeq & & \uparrow \simeq & \nearrow i(p_2) & \uparrow \simeq \nearrow i(p_1) \uparrow \simeq \nearrow i(p_0) \\
 \cdots & \longrightarrow & \Omega Fp_1 & \xrightarrow{\overline{\Omega p_2}} & \Omega Fp_0 & \xrightarrow{\overline{\Omega p}} & \Omega X \xrightarrow{\overline{\Omega f}} \Omega Y \\
 \uparrow \simeq & & \uparrow \simeq & \nearrow \overline{\Omega i(p_0)} & & & \\
 \Omega^2 X & \xrightarrow{\Omega f} & \Omega Y & & & &
 \end{array}$$

For example, $S^0 = \{\pm 1\}$. We get terms like $\pi_0(\Omega^n X)$, because $[S^0, X] = \pi_0 X$. What is $\pi_0(\Omega^n X)$? This is $[S^0, \Omega^n X]_*$. Is it clear to you that this is $[S^n, X]_*$?

Ok, well, $\Omega^2 X = (\Omega X)^{S^1}$. Because $(S^1)^{\wedge n} = S^n$. So we find that $(\Omega X)^{S^1} = (X_*^{S^1})_*^{S^1} = X_*^{S^1 \wedge S^1} = X_*^{S^2}$.

Well, ΩX is a homotopy group by concatenation. It's a group, but where the axioms hold up to homotopy. It's a group in the homotopy category. Therefore, $\pi_0 \Omega X$ is a group! It's exactly $\pi_1 X$, which you know to be a group. And then, there's this other thing that happens.

You can think of $\pi_n(X) = [S^n, X]_*$ as $[(D^n, S^{n-1}), (X, *)] = [(I^n, \partial I^n), (X, *)]$. If I take $n = 2$, for example, how do I take the product of $\alpha, \beta \in \pi_2(X)$? You just literally put them together (when you think of $\pi_2(X) = [(I^2, \partial I^2), (X, *)]$). You can play this game; up to homotopy, you can shrink α and β to make them as small I want, and then reverse their position and expand them again¹⁵. Thus $\pi_2(X)$ is an abelian group.

Thus, when you apply π_0 to our sequence $\cdots \rightarrow \Omega^2 X \rightarrow \Omega^2 Y \rightarrow \Omega Fp_0 \rightarrow \Omega X \rightarrow \Omega Y \rightarrow Fp_0 \rightarrow \Omega X \rightarrow \Omega Y$, you get an exact sequence (of groups when the homotopy groups are > 0 , and of pointed sets when you have π_0):

$$\cdots \rightarrow \pi_2 X \rightarrow \pi_2 Y \rightarrow \pi_1 Ff \rightarrow \pi_1 X \rightarrow \pi_1 Y \rightarrow \pi_0 Ff \rightarrow \pi_0 X \rightarrow \pi_0 Y$$

46. Relative homotopy, π_1 action

Pset 2 has question 8; there's still one more to go. Hood has office hours today 12 – 1 in 2-390, and I have office hours today tomorrow 4-5 in 2-478.

46.1. Spheres and homotopy groups. Let's talk about spheres, first of all. The n -sphere is $S^n = I^n / \partial I^n$. Agreed? It's a standard choice. By the way, $S^1 = I/0 \sim 1$. What about S^0 ? This is $*/\emptyset = *_+$. This is the usual way to think of the zero sphere. The point that you just added is the basepoint.

We have this looping thing going on; we know that ΩX (I'm always working in \mathbf{Top}_* these days) is $X_*^{S^1}$. Thus the adjunction says that $\mathbf{Top}_*(W, \Omega X) = \mathbf{Top}_*(S^1 \wedge W, X)$.

DEFINITION 46.1. The *reduced suspension* ΣW is $S^1 \wedge W$.

If I have $A \subseteq X$, then $X/A \wedge Y/B = (X \times Y) / ((A \times Y) \cup_{A \times B} (X \times B))$. Thus $\Sigma X = S^1 \wedge X$ is $I \times X / (\partial I \times X \cup I \times *)$. I collapse the top and bottom of a cylinder to a point, and also the line along a basepoint gets collapsed.

¹⁵This probably makes no sense without a picture

Similarly, $\Sigma^n X$ is the left adjoint of the n -fold loop space. Hence $\Sigma^n X = (S^1)^{\wedge n} \wedge X$. What is $S^1 \wedge S^n$? This is $I/\partial I \wedge I^n \wedge \partial I^n = (I \times I^n)/(\partial I \times I^n \cup I \times \partial I^n)$. This denominator is exactly ∂I^{n+1} ; hence $S^1 \wedge S^n \simeq S^{1+n}$. In fact, $S^k \wedge S^n \simeq S^{k+n}$.

DEFINITION 46.2. The n th homotopy group of X is $\pi_n X = \pi_0(\Omega^n X)$.

This is $[S^0, \Omega^n X]_* = [S^n, X]_* = [(I^n, \partial I^n), (X, *)]$.

46.2. The homotopy category. We have the *homotopy category of spaces* $\mathbf{Ho}(\mathbf{Top})$ whose objects are spaces and whose mapping spaces are π_0 of mapping spaces. I have to check that if $f_0, f_1 : X \rightarrow Y$ and $g : Y \rightarrow Z$, then $gf_0 \simeq gf_1$. Of course, it is, just by composing with g . Similarly $f_0 h \simeq f_1 h$. This guarantees that you can define composition of maps in $\mathbf{Ho}(\mathbf{Top})$. I can also think about $\mathbf{Ho}(\mathbf{Top}_*)$, with pointed homotopies. A lot of what we've been doing has been taking place in $\mathbf{Ho}(\mathbf{Top}_*)$.

Fix W . We need to check that $X \mapsto X_*^W$ is a homotopy functor. It defines a functor $\mathbf{Top}_* \rightarrow \mathbf{Top}_*$. Namely, I want to complete:

$$\begin{array}{ccc} \mathbf{Top}_* & \xrightarrow{X \mapsto X_*^W} & \mathbf{Top}_* \\ \downarrow & & \downarrow \\ \mathbf{Ho}(\mathbf{Top}_*) & \dashrightarrow & \mathbf{Ho}(\mathbf{Top}_*) \end{array}$$

So I'd better check that if I have a homotopy $f_0 \sim f_1 : X \rightarrow Y$. Is that a map $I \wedge X \rightarrow Y$? This really tells you that there's a nullhomotopy if the basepoint of I is one of the endpoints. I really want to consider $I \times X/I \times *$. Aha, but this is just $I_+ \wedge X$. So a homotopy $f_0 \sim f_1 : X \rightarrow Y$ is a map $I_+ \wedge X \rightarrow Y$.

Suppose I have a homotopy like this; then I get $(I_+ \wedge X)^W \rightarrow Y_*^W$. I wanted $I_+ \wedge X_*^W \rightarrow Y_*^W$, so that's not quite what I wanted. I can get this if I can construct a map $I_+ \wedge X_*^W \rightarrow (I_+ \wedge X)_*^W$. In fact, I want to construct $A \wedge X_*^W \rightarrow (A \wedge X)_*^W$. One thing I can do is $A \wedge X_*^W \rightarrow A_*^W \wedge X_*^W$ by sending $a \mapsto c_a$, and then the exponential law gives a homotopy $A_*^W \wedge X_*^W \rightarrow (A \wedge X)_*^W$. This gives me a map $I_+ \wedge X_*^W \rightarrow (I_+ \wedge X)_*^W \rightarrow Y_*^W$ making $X \mapsto X_*^W$ a homotopy functor. In particular, Ω^n is a homotopy functor.

Let's continue with this homotopical localization of things.

DEFINITION 46.3. A fiber sequence in $\mathbf{Ho}(\mathbf{Top}_*)$ is a composite $X \rightarrow Y \rightarrow Z$ that is isomorphic in $\mathbf{Ho}(\mathbf{Top}_*)$ to some $Ff \xrightarrow{p} E \xrightarrow{f} B$. Namely we want some (possibly zig-zag of) maps that are homotopy equivalences:

$$\begin{array}{ccccc} X & \longrightarrow & Y & \longrightarrow & Z \\ \downarrow & & \downarrow & & \downarrow \\ Ff & \xrightarrow{p} & E & \xrightarrow{f} & B \end{array}$$

We've seen examples in our elaborate story. Recall our diagram:

$$\begin{array}{ccccccccccc} \cdots & \longrightarrow & Fp_4 & \longrightarrow & Fp_3 & \longrightarrow & Fp_2 & \longrightarrow & Fp_1 & \xrightarrow{p_2} & Ff & \xrightarrow{p_1} & X & \xrightarrow{f} & Y \\ & & \uparrow \simeq & & \uparrow \simeq & \nearrow i(p_2) & \uparrow \simeq & \nearrow i(p_1) & \uparrow \simeq & \nearrow i(p_0) & & & & \\ \cdots & \longrightarrow & \Omega Fp_1 & \xrightarrow{\Omega p_2} & \Omega Fp_0 & \xrightarrow{\Omega p} & \Omega X & \xrightarrow{\Omega f} & \Omega Y & & & & & \\ \uparrow \simeq & & \uparrow \simeq & \nearrow \Omega i(p_0) & & & & & & & & & & \\ \Omega^2 X & \xrightarrow{\Omega f} & \Omega Y & & & & & & & & & & & \end{array}$$

So look, $Ff \rightarrow X \rightarrow Y$ is a fiber sequence. And $\Omega Y \rightarrow F \xrightarrow{p} X$ is another fiber sequence because it's isomorphic to $Fp \rightarrow F \rightarrow X$ in $\mathbf{Ho}(\mathbf{Top}_*)$. I also have $\Omega X \xrightarrow{\Omega f} \Omega Y \rightarrow F$ is another fiber sequence. This means that $\Omega X \xrightarrow{\Omega f} \Omega Y \rightarrow F$ is another fiber sequence because these two fiber sequences differ by an automorphism of ΩX because in general, if $A' \xrightarrow{\sim} A$ and $A \rightarrow B \rightarrow C$ is a fiber sequence, so is $A' \xrightarrow{\sim} A \rightarrow B \rightarrow C$.

I can apply Ω again, so I get $\Omega F \xrightarrow{\Omega p} \Omega X \xrightarrow{\Omega f} \Omega Y$. I claim this is a fiber sequence, because this is a loop of a fiber sequence, and taking loops takes fiber sequences to fiber sequences. This is called the *Barratt-Puppe sequence*. I carefully explained that this makes some sense, because it firstly makes sense to ask that Ω is a homotopy functor. I haven't said this yet. So in particular:

- (1) Ω takes fiber sequences to fiber sequences.
- (2) $\Omega Ff \simeq F\Omega f$. Check this!

You can now *loop back* to get $\Omega^2 Y \xrightarrow{\Omega i} \Omega F \xrightarrow{\Omega p} \Omega X$. This is an unstable version of a triangulated category. It wants to be a triangulated category, but it isn't.

REMARK 46.4. If $f : X \rightarrow Y$, I can form Ff . I might have a homotopy commuting diagram like:

$$\begin{array}{ccccccc} \Omega Y & \longrightarrow & Ff & \longrightarrow & X & \xrightarrow{f} & Y \\ \Omega g \downarrow & & \downarrow & & \downarrow h & & \downarrow g \\ \Omega Y' & \longrightarrow & Ff' & \longrightarrow & X' & \xrightarrow{f'} & Y' \end{array}$$

The dotted map exists, but *this map depends on the homotopy* $f'h \simeq gf$. That's an important subtlety.

46.3. Lexseq of a fiber sequence. Applying $\pi_0 = [S^0, -]_*$ to the Barratt-Puppe sequence gives a lexseq:

$$\begin{array}{ccccc} & & \cdots & \longrightarrow & \pi_2 Y \\ & \swarrow & & & \searrow \\ \pi_1 F & \longrightarrow & \pi_1 X & \longrightarrow & \pi_1 Y \\ & \swarrow & & & \searrow \\ \pi_0 F & \longrightarrow & \pi_0 X & \longrightarrow & \pi_1 X \end{array}$$

of pointed sets. But this is even better, because ΩX is a group object in $\text{Ho}(\mathbf{Top}_*)$.

REMARK 46.5. $\text{Ho}(\mathbf{Top})$ and $\text{Ho}(\mathbf{Top}_*)$ has products and coproducts, but very few other limits or colimits. So as a category, it is *horrible*.

I showed you an argument that $\Omega^2 X$ is an *abelian* group object, i.e., multiplication is commutative up to homotopy. Thus π_1 is a group and π_k is an abelian group for $k \geq 2$; hence in our diagram above, all maps (except on π_0) are group homomorphisms!

What if $X \rightarrow Y$ is the inclusion $i : A \hookrightarrow X$ of a subspace? Then $Fi = \{(a, \omega) \in A \times X_*^I \mid \omega(1) = a\}$. This is just the collection of all paths that begin at $*$ in A and ends in A .

DEFINITION 46.6. $\pi_n(X, A, *) = \pi_n(X, A)$ is $\pi_{n-1}Fi = [(I^n, \partial I^n, (\partial I^n \times I) \cup (I^{n-1} \times 0)), (X, A, *)]$.

Inside I^n is ∂I^n , and also including in it is $\partial I^n \times I \cup I^{n-1} \times 0$. Then you can check that $\pi_{n-1}Fi = [(I^n, \partial I^n, (\partial I^n \times I) \cup (I^{n-1} \times 0)), (X, A, *)]$. In this case, you have a lexseq:

$$\begin{array}{ccccc} & & \cdots & \longrightarrow & \pi_2(X, a) \\ & \swarrow & & & \searrow \\ \pi_1 A & \longrightarrow & \pi_1 X & \longrightarrow & \pi_1(X, A) \\ & \swarrow & & & \searrow \\ \pi_0 A & \longrightarrow & \pi_0 X & \longrightarrow & \end{array}$$

47. Action of π_1 , simple spaces, and the Hurewicz theorem

Recall that $\pi_n(X, A, *) = [(I^n, \partial I^n, \partial I^{n-1} \times I \cup I^{n-1} \times 0), (X, A, *)]$. You have a lexseq of the form:

$$\begin{array}{ccccc} & & \cdots & \longrightarrow & \pi_2(X, a) \\ & \swarrow & & & \searrow \\ \pi_1 A & \longrightarrow & \pi_1 X & \longrightarrow & \pi_1(X, A) \\ & \swarrow & & & \searrow \\ \pi_0 A & \longrightarrow & \pi_0 X & \longrightarrow & \end{array}$$

This looks very similar to the lexseq for homology. How does this actually relate?

LEMMA 47.1 (Excision). *If $A \subseteq X$ is a cofibration, then there is an isomorphism $H_*(X, A) \xrightarrow{\cong} \tilde{H}_*(X/A)$. Under this hypothesis, $X/A \simeq$ Mapping cone of $i : A \rightarrow X$. The mapping cone is the dual to the homotopy fiber, i.e., the homotopy quotient, which is defined by the pushout:*

$$\begin{array}{ccc} A & \xrightarrow{i} & X \\ \downarrow in_1 & & \downarrow \\ CA & \longrightarrow & X \cup_A CA \end{array}$$

where CA is the cone on A defined as $CA = A \times I/A \times 0$ (this is a contractible space).

This is dual to saying that $Ff \simeq f^{-1}(*)$ if f is a fibration.

But $\pi_*(X, A)$ is definitely not $\pi_*(X/A)$! For example, $S^1 \rightarrow D^2 \rightarrow S^2$ is a cofibration sequence, but $\pi_* S^1$ is just \mathbf{Z} in dimension 1. We don't know the homotopy groups of S^2 , though. In fact:

THEOREM 47.2 (Now). *If X is a simply connected finite complex, and $X \not\simeq *$, then we do not know $\pi_*(X)$. And we'll probably never be able to know them.*

These groups *are* computable (a theorem by Edgar Brown), but it's super-exponential. This is discouraging. We'll never know what, eg., $\pi_{10000}(S^2)$ is.

Anyway, I said there was $\partial : \pi_n(X, A, *) \rightarrow \pi_{n-1}(A, *)$. How does this look? Well you just look at the restriction of $I^n \rightarrow X$ to $1 \times I^{n-1} \rightarrow A$. And the composite $\pi_n(X, A, *) \xrightarrow{\partial} \pi_{n-1}(A, *) \rightarrow \pi_{n-1}(X, *)$ is trivial by definition!

47.1. π_1 -action. There's a little more structure about this sequence. That's the following thing: $\pi_1(X)$ acts on $\pi_n(X)$ from the left by group homomorphisms. There was a picture, but I didn't understand it. Let me write this out (as I understand it). Suppose $x, y \in X$, and let $\omega : I \rightarrow X$ with $\omega(0) = x$ and $\omega(1) = y$. Then we have a map $f_\omega : \pi_n(X, x) \rightarrow \pi_n(X, y)$, so $\pi_1(X, *)$ acts on $\pi_n(X, *)$.

When $n = 1$, $\pi_1(X)$ acts by conjugation. In fact, $\pi_1(A)$ acts on $\pi_n(X, A, *)$ as well. It then follows that all maps in the lexseq are equivariant for this action of $\pi_1(A)$. We also have the Peiffer identity:

PROPOSITION 47.3 (Peiffer identity). *let $\alpha, \beta \in \pi_2(X, A)$. Then $(\partial\alpha) \cdot \beta = \alpha\beta\alpha^{-1}$.*

For example, if $j : \pi_2(X) \rightarrow \pi_2(X, A)$, and $\alpha = j(\gamma)$, $\partial\alpha = 1$: $\text{Im}(k) \subseteq \text{coker } \pi_2(X, A)$. (I did not follow this)

DEFINITION 47.4. X is simply connected if it's path connected and $\pi_1(X, *) = 1$.

Sometimes you have nontrivial π_1 , and so:

DEFINITION 47.5. X is *simple* if it is path-connected and $\pi_1(X)$ acts trivially on $\pi_n(X)$ for $n \geq 1$.

(In particular, $\pi_1(X)$ is abelian.) What does being simple do for you?

- Being simple is independent of the choice of basepoint. If $\omega : x \rightarrow x'$, then $\omega_\# : \pi_n(X, x) \rightarrow \pi_n(X, x')$ is a group isomorphism. I have $\pi_1(X, x)$ acting on $\pi_n(X, x)$ and $\pi_1(X, x')$ acting on $\pi_n(X, x')$. These actions are compatible, and if $\pi_1(X, x)$ acts trivially then so does $\pi_1(X, x')$.

- Say X is path-connected. Then there's a map $\pi_n(X, *) \rightarrow [S^n, X]$. It's pretty obvious that this map is surjective because I can always choose a basepoint in X as the image of a basepoint in S^n . Thus you'd expect a factorization:

$$\begin{array}{ccc} \pi_n(X, *) & \xrightarrow{\quad} & [S^n, X] \\ & \searrow & \uparrow \cong, \text{homework} \\ & & \pi_1(X, *) \setminus \pi_n(X, *) \end{array}$$

If X is simple, then $\pi_1(X, *) \setminus \pi_n(X, *)$ is trivial, and so $\pi_n(X, *) \cong [S^n, X]$ that's independent of the basepoint. I.e., these groups are canonically the same, i.e., two paths $\omega, \omega' : x \rightarrow y$ give the same map $\omega_{\sharp} = \omega'_{\sharp} : \pi_n(X, x) \rightarrow \pi_n(X, y)$.

47.2. Hurewicz theorem. I talked about homotopy, and I talked about homology. Now it's time to compare the two. This is the story of the Hurewicz theorem. You should think of homology of being computable, while homotopy is a big mystery.

DEFINITION 47.6. The Hurewicz map is a map $h : \pi_n(X, *) \rightarrow H_n(X)$, where X is a path connected space. How does this map go? An element in $\pi_n(X, *)$ is represented by $\alpha : S^n \rightarrow X$. Pick a generator $\sigma : H_n(S^n)$; then $\alpha_*(\sigma) \in H_n(X)$.

This is a homomorphism, as I'll show in a bit.

What happens when $n = 0$? What map $\pi_0(X) \rightarrow H_0(X)$ do we have? A point is like a 0-cycle, and that's the map! In fact, we have an isomorphism $H_0(X) \simeq \mathbf{Z}[\pi_0(X)]$. This is an example of the Hurewicz theorem.

How about $n = 1$? Now, we have $h : \pi_1(X, *) \rightarrow H_1(X)$. This factors as $\pi_1(X, *) \rightarrow \pi_1(X, *)^{ab} \rightarrow H_1(X)$. And the Hurewicz theorem says that $\pi_1(X, *)^{ab} \xrightarrow{\cong} H_1(X)$. I'm not going to prove this; it's not very hard but it's annoying. It's pretty clear why it's true: for example, it's onto. 1-cycles just look like a bunch of circles, so just concatenate loops from the basepoint to these 1-cycles.

Let me show you that the Hurewicz map is a homomorphism. Before that, here's the Hurewicz theorem.

THEOREM 47.7 (Hurewicz). Suppose $\pi_i(X) = 0$ for $i < n$ where $n \geq 2$. Then $\pi_n(X) \xrightarrow{\cong} H_n(X)$.

We can't compute homotopy in general, but we can at least make a start.

OK, why is h a homomorphism? Let $\alpha, \beta : S^n \rightarrow X$ be pointed maps. What is the product in $\pi_n(X)$? It's just the composite:

$$\alpha\beta : S^n \xrightarrow{\delta, \text{pinching along the equator}} S^n \vee S^n \xrightarrow{\beta \vee \alpha} X \vee X \xrightarrow{\nabla, \text{the fold map}} X$$

where $\nabla : X \vee X \rightarrow X$ is defined by:

$$\begin{array}{ccc} X & & \\ \downarrow & \searrow 1 & \\ X \vee X & \xrightarrow{\nabla} & X \\ \uparrow & \nearrow 1 & \\ X & & \end{array}$$

We have two inclusions in_1, in_2 of S^n to $S^n \vee S^n$. Now, we have:

$$\sigma \mapsto in_{1*}\sigma + in_{2*}\sigma \mapsto in_{1*}h(\alpha) + in_{2*}h(\beta) \mapsto h(\alpha) + h(\beta)$$

As desired. It's possible to give an elementary proof of Hurewicz's theorem. But I'll prove this as a consequence of the Serre spectral sequence, which gives a more general theorem. It'll be an inductive proof that'll use Poincaré's result.

One more thing to say is that $\pi_i(S^n) = 0$ if $i < n$. I won't prove this, but it's also kind of obvious, isn't it? By Hurewicz, it follows that $\pi_n(S^n) \simeq H_n(S^n) \simeq \mathbf{Z}$. We actually have one more example: $\pi_3(S^2) \simeq \mathbf{Z}$ generated by the Hopf fibration $S^3 \rightarrow S^2$. It's not obvious that this isn't nullhomotopic, but it's true. But now, for example, I can suspend η (the Hopf fibration) and get $\eta \circ \Sigma\eta$. We thought for a long time that there were the only things we could compute in π_*S^n ; but this is not true! It's a lot more chaotic.

48. Some examples; CW complexes

48.1. Examples.

- (1) Let $E \rightarrow B$ be a covering space with E and B connected. The fibers are discrete, so they don't have any higher homotopy. There's only π_0 . The lexseq says that $\pi_n(E) \rightarrow \pi_n(B)$ is an isomorphism for $n > 1$, and $\pi_1(E) \hookrightarrow \pi_1(B)$, and the subgroup $\pi_1(E)$ classifies the covering space. In general, we know that ΩB acts on the homotopy fiber F . Because F here is discrete, this action factors through $\pi_0(\Omega B) \simeq \pi_1(B)$.

In particular, $\pi_q(S^n) \simeq \pi_q(\mathbf{RP}^n)$ for $q > 1$. Of course, $\pi_1(\mathbf{RP}^n) \simeq \mathbf{Z}/2\mathbf{Z}$. This creates a ton of homology in \mathbf{RP}^n that's not present in the homology of S^n . Here's a piece of language.

DEFINITION 48.1. A space is n -connected if $\pi_i(X) = 0$ for $i \leq n$.

This is not a nonsense definition, although it seems like we need to pick a basepoint – but 0-connected means path connected, so we're good. For instance, 1-connected means simply connected.

Suppose $E \rightarrow B$ is a covering space where E is n -connected. Then $\pi_1(B)$ determines the homology $H_i(B)$ in dimensions $i < n$. In particular, $H_i(B) = H_i(\pi_1(B))$, which is the group homology. This is due to Heinz Hopf.

- (2) What's a nontrivial action of π_1 on higher homotopy? For example, π_1 acting on π_2 . Consider the space $S^1 \vee S^2$. What does the universal cover E look like? This just \mathbf{R} , where at every integer point I put a 2-sphere S^2 . The universal cover is simply connected, so Hurewicz says that $\pi_2(E) \simeq H_2(E)$. Up to homotopy type, I can collapse the line to a point, so I get a countable bouquet of 2-spheres. Thus $\pi_2(E) \simeq H_2(E) = \bigoplus_{\mathbf{Z}}^{\infty} \mathbf{Z}$. But I can say more!

There's an action of $\pi_1(S^1 \vee S^2)$ on E . Certainly $\pi_1(S^1 \vee S^2) = \mathbf{Z}$. There's an induced action on E . All the action does is shift the 2-spheres on the integer points of \mathbf{R} (on E) to the right by 1. Thus $\bigoplus_{\mathbf{Z}}^{\infty} \mathbf{Z} = \mathbf{Z}[\pi_1(B)]$ as a $\mathbf{Z}[\pi_1(B)]$ -module (i.e., as a $\mathbf{Z}[\mathbf{Z}]$ -module). That's actually the same action of $\pi_1(E)$ on $\pi_2(E)$. This tells something horrifying. $S^1 \vee S^2$ is a very simple 3-complex, but its homotopy is huge.

- (3) $\pi_*(X) = ?$. Recall our Hopf fibration $S^1 \rightarrow S^3 \rightarrow S^2$. This gives a lexseq on homotopy groups. Thus I get $\pi_i(S^3) \xrightarrow{\simeq} \pi_i(S^2)$ for $i > 2$ given by $\alpha \mapsto \eta\alpha$. Of course, $\pi_2(S^2) = \mathbf{Z}$. The higher homotopy groups of S^2 are exactly the same as the higher homotopy groups of S^3 ! In particular, $\pi_3(S^3) = \mathbf{Z}$ by Hurewicz, so $\pi_3(S^2) \simeq \mathbf{Z}$ generated by η . There are some low-dimensional calculations that you can make like this.

Here's another way of thinking of the Hopf fibration. Think of $S^3 = SU(2)$. Then there's the subgroup of $\begin{pmatrix} \lambda & \\ & \lambda^{-1} \end{pmatrix}$, which is S^1 . This acts on S^3 by translation, and the orbit space is S^2 .

We'll show later that $\pi_{4n-1}(S^{2n}) \otimes \mathbf{Q} \simeq \mathbf{Q}$. Other than $\pi_n(S^n)$, a theorem of Serre says that these are the only non-torsion homotopy groups of spheres.

48.2. Bringing you up-to-speed on CW-complexes. I want to study a fairly rich example of CW-complexes.

DEFINITION 48.2. A *relative* CW-complex is a pair (X, A) together with a filtration $A = X_{-1} \subseteq X_0 \subseteq X_1 \subseteq \cdots \subseteq X$, such that for all n , I can build X_n as the pushout:

$$\begin{array}{ccc} \coprod_{\alpha \in \Sigma_n} S^{n-1} & \longrightarrow & \coprod_{\alpha \in \Sigma_n} D^n \\ \text{attaching maps} \downarrow & & \downarrow \text{characteristic maps} \\ X_{n-1} & \longrightarrow & X_n \end{array}$$

(X_n is called the n -skeleton), and $X = \varinjlim X_n$.

If $A = \emptyset$, it's not relative anymore – it's just a CW-complex. (Here $S^{-1} = \emptyset$.) Often, X will be a CW-complex, and A will be a subcomplex.

- (1) If A is Hausdorff, then so is X . Actually, last semester I discovered a proof of this in Hatcher.

- (2) $A = \emptyset$: then X is compactly generated. This is one of the reasons I wanted to define compactly generated spaces.
- (3) If X and Y are both CW-complexes. Then define $(X \times^k Y)_n = \bigcup_{i+j=n} X_i \times Y_j$. This gives a CW-structure on the product $X \times^k Y$.
- (4) Any closed smooth manifold admits a CW-structure.

The fun example is \mathbf{CP}^n .

EXAMPLE 48.3. \mathbf{CP}^n is a CW-complex, with skeleta $\mathbf{CP}^0 \subseteq \mathbf{CP}^1 \subseteq \dots \subseteq \mathbf{CP}^n$. The assertion is that there's a pushout diagram:

$$\begin{array}{ccc} \coprod S^{2n-1} & \longrightarrow & \coprod D^{2n} \\ \downarrow & & \downarrow \\ \mathbf{CP}^{n-1} & \longrightarrow & \mathbf{CP}^n \end{array}$$

Any complex line through the origin meets the hemisphere defined by $\begin{pmatrix} z_0 \\ \vdots \\ z_n \end{pmatrix}$ with $\|z\| = 1$ and $\Im(z_n) = 0$ and $\Re(z_n) \geq 0$. It meets this hemisphere (which is D^{2n}) at one point, unless it's on the equator, in which case we find that the pushout diagram is really:

$$\begin{array}{ccc} S^{2n-1} & \longrightarrow & D^{2n} \\ \downarrow & & \downarrow \\ \mathbf{CP}^{n-1} & \longrightarrow & \mathbf{CP}^n \end{array}$$

I want to give you a more complicated example that's fun and that will come up later.

EXAMPLE 48.4 (Grassmannians). Let $V = \mathbf{R}^n$ or \mathbf{C}^n or \mathbb{H}^n . Let's suppose $V = \mathbf{R}^n$ for now. Then $\text{Gr}_k(\mathbf{R}^n)$ is the collection of k -dimensional subspaces of \mathbf{R}^n . One way to do this is by giving a $k \times n$ rank k matrix. Here's some linear algebra.

The span of rows of A is the row space V_A . This is the span of the rows of the reduced echelon form of A . An entry is a *pivot* if its leftmost nonzero is in its row. A column is *pivotal* if it contains a pivot. Any matrix is reduced echelon if the i th pivotal column is e_i .

For instance, $\text{Gr}_2(\mathbf{R}^4)$ is as a set the disjoint union of:

$$\begin{pmatrix} 1 & & & \\ & 1 & & \\ & & 1 & \\ & & & 1 \end{pmatrix}, \begin{pmatrix} 1 & * & & \\ & 1 & & \\ & & 1 & \\ & & & 1 \end{pmatrix}, \begin{pmatrix} 1 & * & * & \\ & 1 & & \\ & & 1 & \\ & & & 1 \end{pmatrix}, \begin{pmatrix} 1 & * & & \\ & 1 & * & \\ & & 1 & \\ & & & 1 \end{pmatrix}, \begin{pmatrix} 1 & * & * & \\ & 1 & * & \\ & & 1 & \\ & & & 1 \end{pmatrix}, \begin{pmatrix} 1 & * & * & \\ & 1 & * & \\ & & 1 & \\ & & & 1 \end{pmatrix}$$

So, define:

DEFINITION 48.5. $\text{sk}_j \text{Gr}_k(\mathbf{R}^n)$ is $\{V : \text{row ech rep with } \leq j \text{ free entries}\}$.

The claim is that it's a CW-structure. See Milnor-Stasheff. They don't know it in 18.06, but they're constructing a CW-structure for the Grassmannian.

The complex Grassmannian has cells in only even dimensions. We now know what the homology of the Grassmannian is, so we actually find Poincare duality if we count the number of cells in this case. (This is visible, for instance, in $\text{Gr}_2(\mathbf{R}^4)$). By the way, the top-dimensional cell tells us that $\dim \text{Gr}_k(\mathbf{R}^n) = k(n-k)$.

49. Relative Hurewicz and J. H. C. Whitehead

I find what I'm talking about today very confusing, because there's this number, this n . I'm going to essentially read from my notes, because I'll get confused otherwise.

DEFINITION 49.1. Let $n \geq 0$. Say that X is $(n-1)$ -connected if for all $0 \leq k \leq n$, and any $f : S^{k-1} \rightarrow X$ extends:

$$\begin{array}{ccc} S^{k-1} & \longrightarrow & X \\ \downarrow & \nearrow & \\ D^k & & \end{array}$$

Let's see what happens in low dimensions. When $n = 0$, we know that $S^{-1} = \emptyset$, and $D^0 = *$. Saying that you're (-1) -connected is just saying that you're nonempty. If $n = 1$, then this is saying that you're path connected, i.e., 0-connected iff path connected. You can check that this is exactly the same as what we said before, using homotopy groups.

DEFINITION 49.2. Let $n \geq 0$. Say that (X, A) is n -connected if for all $0 \leq k \leq n$, there's a lift:

$$\begin{array}{ccc} (D^k, S^{k-1}) & \xrightarrow{f} & (X, A) \\ \downarrow & \nearrow & \\ (A, A) & & \end{array}$$

up to homotopy. In other words, you can homotope f to a map with image in A , without moving $f|_{S^{k-1}}$.

What does this mean for small values? When $n = 0$, we find that 0-connected means that A meets every path component of X .

Equivalently, we can state:

DEFINITION 49.3. (X, A) is n -connected if:

- $n = 0$: then $\pi_0(A) \rightarrow \pi_0(X)$ surjects.
- $n > 0$: then $\pi_0(A) \xrightarrow{\cong} \pi_0(X)$, and for all $a \in A$, $\pi_k(X, A, a) = 0$ for $1 \leq k \leq n$. Equivalently, $\pi_0(A) \xrightarrow{\cong} \pi_0(X)$ and $\pi_k(A, a) \rightarrow \pi_k(X, A)$ is an isomorphism for $1 \leq k < n$ and is onto for $k = n$.

So " $\pi_0(X, A) = 0$ " makes sense, because it means $\pi_0(A) \rightarrow \pi_0(X)$ surjects. I can't define $\pi_0(X, A)$, but you should think of it this way.

Let's try to write down what the relative Hurewicz theorem might be.

49.1. Relative Hurewicz. Assume that $\pi_0(A) = * = \pi_0(X)$, and pick $a \in A$, which I won't bother about any more. We have:

$$\begin{array}{ccccccccccc} \cdots & \longrightarrow & \pi_2(X, A) & \longrightarrow & \pi_1(A) & \longrightarrow & \pi_1(X) & \longrightarrow & \pi_1(X, A) & \longrightarrow & \pi_0(A) & \longrightarrow & \pi_0(X) \\ & & \downarrow h & & \downarrow h & & \downarrow h & & \downarrow h & & \downarrow h & & \downarrow h \\ \cdots & \longrightarrow & H_2(X, A) & \longrightarrow & H_1(A) & \longrightarrow & H_1(X) & \longrightarrow & H_1(X, A) & \longrightarrow & H_0(A) & \longrightarrow & H_0(X) & \longrightarrow & H_0(X, A) \end{array}$$

How do we define the relative Hurewicz map? Let $\alpha \in \pi_n(X, A)$; then $\alpha : (D^n, S^{n-1}) \rightarrow (X, A)$. So we pick a generator in $\mathbf{Z} \in H_n(D^n, S^{n-1})$, and send it to something in $H_n(X, A)$ under the induced $\alpha^* : H_n(D^n, S^{n-1}) \rightarrow H_n(X, A)$.

Because $H_n(X, A)$ is abelian, we find that $\pi_1(A)$ acts trivially on $H_n(X, A)$, i.e., $h(\omega(\alpha)) = h(\alpha)$. Thus the relative Hurewicz map factors through $\pi_n^\dagger(X, A)$, which is $\pi_n(X, A)$ quotiented out by the normal subgroup generated by $(\omega\alpha)\alpha^{-1}$ where $\omega \in \pi_1(A)$ and $\alpha \in \pi_n(X, A)$. Thus you get a map $\pi_n^\dagger(X, A) \rightarrow H_n(X, A)$, that's more likely to be an isomorphism.

THEOREM 49.4 (Relative Hurewicz). Let $n \geq 1$. Assume (X, A) is n -connected. Then $H_k(X, A) = 0$ for $0 \leq k \leq n$, and $\pi_{n+1}^\dagger(X, A) \rightarrow H_{n+1}(X, A)$ is an isomorphism.

PROOF. I won't prove this now; with any luck, we'll come back and prove this once we have the Serre spectral sequence in our toolkit. \square

This is an extremely useful result. Now, that's it! That's all I wanted to say about the relative Hurewicz theorem. Let's apply this to get surprising results.

49.2. J. H. C. Whitehead theorems. He was an interesting character. He raised pigs. He's interested in a continuous map $f : X \rightarrow Y$, and when that's an isomorphism in homology or homotopy, and relate them.

DEFINITION 49.5. Let $f : X \rightarrow Y$ and $n \geq 0$. Say that f is an n -equivalence (some would say n -connected, but I won't say that here) if for every $* \in Y$, the homotopy fiber $F(f, *)$ is $(n - 1)$ -connected.

A 0-equivalence means that $\pi_0(X)$ surjects onto $\pi_0(Y)$. For $n > 0$, this is saying that $\pi_0(X) \xrightarrow{\cong} \pi_0(Y)$, and for every $* \in X$:

$$\pi_k(X, *) \rightarrow \pi_k(Y, f(*)) \text{ is } \begin{cases} \text{iso} & 1 \leq k < n \\ \text{epi, i.e., onto} & k = n \end{cases}$$

Would you like me to tell you about how to replace a map by a cofibration? Never mind – this is the first problem! So, using the “mapping cylinder”, we can always assume $f : X \hookrightarrow Y$, and then $f : X \rightarrow Y$ is an n -equivalence iff (Y, X) is n -connected.

THEOREM 49.6 (J. H. C. Whitehead 1). *Suppose $n \geq 0$, and $f : X \rightarrow Y$ is n -connected. Then:*

$$H_k(X) \rightarrow H_k(Y) \text{ is } \begin{cases} \text{iso} & 1 \leq k < n \\ \text{epi, i.e., onto} & k = n \end{cases}$$

PROOF. When $n = 0$, because $\pi_0(X) \rightarrow \pi_0(Y)$ is surjective, $H_0(X) \simeq \mathbf{Z}[\pi_0(X)] \rightarrow \mathbf{Z}[\pi_0(Y)] \simeq H_0(Y)$ is surjective. The relative Hurewicz theorem gives the rest. Note that the relative Hurewicz dealt with $\pi_n^\dagger(X, A)$, but $\pi_n(X, A) \rightarrow \pi_n^\dagger(X, A)$ is surjective. \square

Let me call out what happens when $n = \infty$.

DEFINITION 49.7. f is a *weak equivalence* (or an ∞ -equivalence, to make it sound more impressive) if it's an n -equivalence for all n , i.e., it's a π_* -isomorphism.

Putting everything together, we obtain:

COROLLARY 49.8. *A weak equivalence induces an isomorphism in integral homology.*

Let's try to go in the other direction.

If $H_0(X) \rightarrow H_0(Y)$ surjects, then $\pi_0(X) \rightarrow \pi_0(Y)$ surjects also. Good start! Assume X and Y path connected. Suppose $H_1(X)$ surjects onto $H_1(Y)$. I'd like to know that $\pi_1(X) \rightarrow \pi_1(Y)$ surjects. It's hard to know this, though, because $H_1(X)$ is the abelianization. Let's give up and assume that $\pi_1(X) \rightarrow \pi_1(Y)$ is surjective.

Assume $\pi_1(X)$ surjects onto $\pi_1(Y)$. Assume $H_2(X) \rightarrow H_2(Y)$ surjects, and $H_1(X) \xrightarrow{\cong} H_1(Y)$ surjects. We know that $H_2(Y, X) = 0$. On the level of the Hurewicz maps, I still don't know what to do because I only know about π_2^\dagger . What to do? Let's assume that $\pi_1(X)$ is trivial. That's a pretty radical assumption. It'd be enough to ask that $\pi_1(X)$ acts trivially on $\pi_2(Y, X)$. That's *technically* what you want to assume. That's basically impossible to check. Anyway, if $\pi_1(X) = 0$, then $\pi_1(Y) = 0$. So $\pi_2(Y, X)$ is trivial, and we can go up the ladder.

THEOREM 49.9 (J. H. C. Whitehead 2). *Let $n \geq 2$. Assume that $\pi_1(X) = 0 = \pi_1(Y)$, and I have $f : X \rightarrow Y$ such that:*

$$H_k(X) \rightarrow H_k(Y) \text{ is } \begin{cases} \text{iso} & 1 \leq k < n \\ \text{epi, i.e., onto} & k = n \end{cases}$$

then f is an n -equivalence.

COROLLARY 49.10. *Let X and Y be simply-connected. If f induces an isomorphism in homology, then it's a weak equivalence.*

That's an *incredibly* useful theorem, because we can actually compute homology! Let's complete this with a further theorem we'll prove on Wednesday.

THEOREM 49.11. *If Y is a CW-complex, a weak equivalence $f : X \rightarrow Y$ is in fact a homotopy equivalence!*

50. Cellular approximation, cellular homology, obstruction theory

pset 3 is up in part. Today I'm going to tell you how to think about CW-complexes and work with them, and I won't give a lot of details. Some good sources are lecture notes by Davis-Kirk, and a beautiful book by Glen Bredon, as well as Hatcher.

50.1. Cellular approximation.

THEOREM 50.1. *Let X and Y be CW-complexes and $A \subseteq X$ a subcomplex. Let $f : X \rightarrow Y$ be a continuous map, and that $f|_A$ is skeletal¹⁶, i.e., $f(\Sigma_n) \subseteq Y_n$. It might not take cells in A to cells in Y , but it takes n -skeleta to n -skeleta. Then f is homotopic to some other $f' : X \rightarrow Y$ relative to A with f' skeletal on all of X .*

This is kind of amazing.

LEMMA 50.2 (Key lemma). *Any $(D^n, S^{n-1}) \rightarrow (Y, Y_{n-1})$ compresses through:*

$$\begin{array}{ccc} (D^n, S^{n-1}) & \longrightarrow & (Y, Y_{n-1}) \\ & \searrow \text{dashed} & \uparrow \\ & & (Y_n, Y_{n-1}) \end{array}$$

“PROOF.” I take this as obvious, but here's something. Since D^n is compact, we know that $f(D^n)$ must lie in some finite subcomplex K of Y . Now the map $D^n \rightarrow K$ might hit some top-dimensional cell $e^m \subseteq K$, which doesn't have anything attached to it, so I can poke a hole in it (namely the approximate this so that you miss a point) and it contracts onto a lower-dimensional cell. Iterating this process gives the desired result. \square

Let's see why the theorem is true based on this lemma.

“PROOF” OF THE CELLULAR APPROXIMATION THEOREM. I'm going to make this homotopy $f \simeq f'$ one cell at a time. I might as well replace A by whatever I've extended the homotopy to. So I have a single cell attachment $A \rightarrow A \cup D^m$. We have:

$$\begin{array}{ccc} A & \longrightarrow & A \cup D^m \\ \text{skeletal} \downarrow & \nearrow & \\ Y & & \end{array} \quad \begin{array}{l} \text{may not be skeletal} \\ \text{may not be skeletal} \end{array}$$

Now we're to use the compression lemma to get $A \cup D^m \rightarrow Y_m$. I'm not satisfied, because I have to do something about the rest of X . Here's a wonderful fact: the inclusion of a subcomplex is a cofibration. Thus we can extend this to a map from X , and iterate to get what we want.

Why's the wonderful fact true? We have a cofibration $S^{n-1} \rightarrow D^n$, so any coproduct of these is a cofibration, and the pushout of a cofibration is a cofibration. \square

COROLLARY 50.3 (Homework). *The pair (X, X_n) is n -connected.*

50.2. Cellular homology. Let (X, A) be a relative CW-complex with $A \subseteq X_{n-1} \subseteq X_n \subseteq \cdots \subseteq X$. We showed last fall that $H_*(X_n, X_{n-1}) \simeq \tilde{H}_*(X_n/X_{n-1})$. More generally, if $B \rightarrow Y$ is a cofibration, then $H_*(Y, B) \simeq \tilde{H}_*(Y/B)$. You can find a precise proof in Bredon, page 433. Anyway, $X_n/X_{n-1} = \bigvee_{\alpha \in \Sigma_n} S^n_\alpha$, so that $H_*(X_n, X_{n-1}) \simeq \mathbf{Z}[\Sigma_n] = C_n(X, A)$. The composite $S^{n-1} \rightarrow X_{n-1} \rightarrow X_{n-1}/X_{n-2}$ is called a relative attaching map.

There's a boundary map $d : C_n = H_n(X_n, X_{n-1}) \xrightarrow{\partial} H_{n-1}(X_{n-1}) \rightarrow H_{n-1}(X_{n-1}, X_{n-2}) = C_{n-1}$. You can check that $d^2 = 0$. The beautiful theorem is that $H_n(X, A) \simeq H_n(C_*(X, A))$. We showed this last fall, but not for relative CW-complexes. Cellular approximation tells us that you can compute the effect of maps on homology.

I could do the same thing of course for cohomology, to get $C^n(X, A; \pi) = \text{Hom}(C_n(X, A), \pi) = \text{Map}(\Sigma_n, \pi)$. Here π is any abelian group. I use π because it's gonna be a homotopy group in just a minute.

¹⁶Some people would say cellular.

50.3. Obstruction theory. The question is: can we extend:

$$\begin{array}{ccc} & X & \\ \uparrow & \searrow & \\ A & \xrightarrow{f} & Y \end{array}$$

We can work out the lower level obstructions

$$\begin{array}{ccccc} A & \hookrightarrow & X_0 & \hookrightarrow & X_1 \\ \downarrow & & \swarrow & \searrow & \\ \emptyset \neq Y & & & & \end{array}$$

for instance if two points in X_0 get connected in X_1 we've to check that they're connected in Y .

For $n \geq 2$, we can form the diagram:

$$\begin{array}{ccccc} \coprod_{\alpha \in \Sigma_n} S_{\alpha}^{n-1} & \xrightarrow{f} & X_{n-1} & \xrightarrow{g} & Y \\ \downarrow & & \downarrow & \searrow & \\ \coprod_{\Sigma_n} D_{\alpha}^n & \longrightarrow & X_n & & \end{array}$$

If the composite $S_{\alpha}^{n-1} \rightarrow X_{n-1} \rightarrow Y$ is nullhomotopic, the extension exists.

We find that $g \circ f_{\alpha} \in [S^{n-1}, Y]$. Let's assume that Y is simple (it's path connected and the action of π_1 is trivial, so all homotopy groups are abelian). Then $[S^{n-1}, Y] = \pi_{n-1}(Y)$. I've given you a map $\Sigma_n \xrightarrow{\theta} \pi_{n-1}(Y)$, which is now a cochain in $C^n(X, A; \pi_{n-1}(Y))$, and it has the property that $\theta = 0$ if and only if g extends to $X_n \rightarrow Y$.

PROPOSITION 50.4. θ is a cocycle, called the “obstruction cocycle”.

PROOF. θ gives a map $H_n(X_n, X_{n-1}) \rightarrow \pi_{n-1}(Y)$, and I want to see that this composite $H_{n+1}(X_{n+1}, X_n) \xrightarrow{\partial} H_n(X_n) \rightarrow H_n(X_n, X_{n-1}) \xrightarrow{\theta} \pi_{n-1}(Y)$ is zero. OK, we know that $\pi_n(X_n, X_{n-1}) \rightarrow H_n(X_n, X_{n-1})$ is surjective. This relative homotopy group holds the characteristic maps, doesn't it? So picking a representative back there is no problem; now I have the lexseq of a pair, which gives:

$$\begin{array}{ccc} \pi_{n+1}(X_{n+1}, X_n) & \twoheadrightarrow & H_{n+1}(X_{n+1}, X_n) \\ \downarrow & & \downarrow \partial \\ \pi_n(X_n) & \longrightarrow & H_n(X_n) \\ \downarrow & & \downarrow \\ \pi_n(X_n, X_{n-1}) & \twoheadrightarrow & H_n(X_n, X_{n-1}) \\ \downarrow \partial & & \downarrow \theta \\ \pi_{n-1}(X_{n-1}) & \xrightarrow{g_*} & \pi_{n-1}(Y) \end{array}$$

This diagram commutes, so θ is indeed a cocycle. □

THEOREM 50.5. Let (X, A) be a CW-complex and Y a simple space. Suppose I have $g : X_{n-1} \rightarrow Y$. Then $g|_{X_{n-2}}$ extends to X_n iff $[\theta(g)] \in H^n(X, A; \pi_{n-1}(Y))$ is zero.

This is a dream come true because it's a cohomological condition for extensions!

COROLLARY 50.6. If $H^n(X, A; \pi_{n-1}(Y)) = 0$ for all $n > 2$, then any:

$$\begin{array}{ccc} A & \longrightarrow & Y \\ \downarrow & \nearrow & \\ X & & \end{array}$$

extends up to homotopy (and thus strictly because $A \rightarrow X$ is a cofibration).

EXAMPLE 50.7. If $X = CA$, does every map $A \rightarrow Y$ factor through the cone? The condition is that $H^n(CA, A; \pi_{n-1}(Y)) \simeq \tilde{H}^{n-1}(A; \pi_{n-1}(Y)) = 0$.

It doesn't make it any easier to compute what the homotopy groups of Y are, but often times you can obtain some information.

REMARK 50.8. Fix a prime p . Later we'll see (I hope) that Y is simply connected (maybe even simple?), and suppose that $\tilde{H}_*(Y; \mathbf{Z}_{(p)}) = 0$ (i.e., no \mathbf{Z} -summands and no \mathbf{Z}/p^k -summands). Then $\pi_*(Y) \otimes \mathbf{Z}_{(p)} = 0$ too. So if $H_*(A; \mathbf{Z}/\ell\mathbf{Z}) = 0$ for $\ell \neq p$, then $[A, Y] \simeq *$.

51. ... and all the rest

I'm going to state a few corollaries of the obstruction theory stuff. Davis-Kirk is a great book, and so is Hatcher – but although it seems to be a chatty book, the proofs are very very dense.

THEOREM 51.1 (Obstruction theory). *Let (X, A) be a relative CW-complex, and Y a simple space. The map $[X, Y] \rightarrow [A, Y]$ is:*

- (1) *is onto if $H^n(X, A; \pi_{n-1}(Y)) = 0$ for all $n \geq 2$.*
- (2) *is one-to-one if $H^n(X, A; \pi_n(Y)) = 0$ for all $n \geq 1$.*

I think (1) implies (2), because suppose I have $g_0, g_1 : X \rightarrow Y$ and a homotopy $h : g_0|_A \simeq g_1|_A$. Let's apply (1) to $(X \times I, A \times I \cup X \times \partial I)$. Because A is a relative CW-complex, $A \hookrightarrow X$ is a cofibration, as is $A \times I \cup X \times \partial I \rightarrow X \times I$. Thus $H^n(X \times I, A \times I \cup X \times \partial I; \pi) \simeq \tilde{H}^n(X \times I / (A \times I \cup X \times \partial I); \pi) = H^n(\Sigma X / A; \pi) \simeq \tilde{H}^{n-1}(X / A; \pi)$.

More precisely, if I have $X_{n-1} \rightarrow Y$, we get $\theta \in Z^n(X, A; \pi_{n-1}(Y))$, constructed by looking at the attaching map f_α of some $\alpha \in \Sigma_n$, to define $\theta(g)$ via $\theta(g)(\alpha) = [g \circ f_\alpha]$. This captures the obstruction to extending g over α . We found that $d\theta = 0$.

PROPOSITION 51.2. *Suppose $g : X_{n-1} \rightarrow Y$. Then $g|_{X_{n-2}}$ extends to $X_n \rightarrow Y$ iff $[\theta(g)] = 0$ in $H^n(X, A; \pi_{n-1}(Y))$.*

Here are some consequences.

- (1) This is called *CW approximation*.

THEOREM 51.3. *Any space admits a weak equivalence from a CW-complex.*

If you're willing to work up to weak equivalences, then CW-complexes are everything.

- (2) If W is a CW-complex and $f : X \rightarrow Y$ is a weak equivalence, then $[W, X] \xrightarrow{\simeq} [W, Y]$. This is actually an if and only if statement.

COROLLARY 51.4. *If X and Y are CW-complexes, then a weak equivalence $f : X \rightarrow Y$ is a homotopy equivalence.*

- (3) Let X be path connected. Then there's a space $X_{\leq n}$ and a map $X \rightarrow X_{\leq n}$ such that $\pi_i(X_{\geq n}) = 0$ for $i > n$, and $\pi_i(X) \xrightarrow{\simeq} \pi_i(X_{\leq n})$ for $i \leq n$. The pair $(X, X_{\leq n})$ is essentially unique up to homotopy. This space $X_{\leq n}$ is called a *Postnikov section*.

Suppose A is some abelian group. Then there is a space $M(A, n)$ with homology given by:

$$\tilde{H}_i(M(A, n)) = \begin{cases} A & i = n \\ 0 & i \neq n \end{cases}$$

We made this by looking at a free resolution $0 \rightarrow F_1 \rightarrow F_0 \rightarrow A \rightarrow 0$ of A . Well, $\bigvee S^n \rightarrow \bigvee S^n$ realizes the first two maps, and then cone this off to get $M(A, n)$.

Suppose I apply this “truncation” construction to this example; namely, let’s look at $M(A, n)_{\leq n}$. What is the n -dimensional homotopy of $M(A, n)$? Well, by Hurewicz:

$$\pi_i(M(A, n)) = \begin{cases} 0 & i < n \\ A & i = n \\ ?? & i > n \end{cases}$$

Thus when we truncate, we obtain:

$$\pi_i(M(A, n)_{\leq n}) = \begin{cases} A & i = n \\ 0 & i \neq n \end{cases}$$

This is a “designer homotopy type”. This space $M(A, n)_{\leq n}$ is called an *Eilenberg-MacLane space*.

When $n = 1$, π_1 doesn’t have to be abelian. But you can still construct $K(G, 1)$. This is called the classifying space of G . Next week, I’ll talk a bit about classifying spaces. You know examples of this; for instance, if Σ is a closed surface not S^2 or \mathbf{R}^2 , then $\Sigma \simeq K(\pi_1(\Sigma), 1)$. Another example is that $S^1 \simeq K(\mathbf{Z}, 1)$.

Also, $K(\mathbf{Z}, 2) \simeq \mathbf{CP}^\infty$. Why’s that? We have a fiber sequence $S^1 \rightarrow S^{2n+1} \rightarrow \mathbf{CP}^n$. So the lexseq in homotopy tells us that the homotopy groups of \mathbf{CP}^n are the same as the homotopy groups of S^1 until S^{2n+1} starts to interfere. But as n grows, namely, if we take the limit, there’s a fibration $S^1 \rightarrow S^\infty \rightarrow \mathbf{CP}^\infty$. But S^∞ is weakly contractible (it has no nonzero homotopy groups), which proves the result. Another example is $K(\mathbf{Z}/2\mathbf{Z}, 1)$, which is \mathbf{RP}^∞ .

$K(A, n)$ is automatically a simple space. Thus if $k > 0$, then $[S^k, K(A, n)] = \pi_k(K(A, n)) = H^n(S^k, A)$. So in fact:

THEOREM 51.5 (Brown representability). *If X is a CW-complex, then $[X, K(A, n)] = H^n(X; A)$.*

I won’t prove this, but they aren’t that hard to prove. This puts a different perspective on what cohomology is. We have it captured completely on $K(A, n)$. For instance, any one-dimensional cohomology class determines a map to a circle.

If X is a CW-complex, then $X_{\leq n}$ is a CW-complex also. If it isn’t, use cellular approximation and then kill homotopy groups. OK, so let X be path connected. Then $X_{\leq 1} = K(\pi_1(X), 1)$. I can then form a tower, which commutes (by uniqueness):

$$\begin{array}{ccc} & \vdots & \longleftarrow \dots \\ & \downarrow & \\ & X_{\leq 3} & \longleftarrow K(\pi_3(X), 3) \\ & \downarrow & \\ & X_{\leq 2} & \longleftarrow K(\pi_2(X), 2) \\ & \downarrow & \\ X & \longrightarrow & X_{\leq 1} = K(\pi_1(X), 1) \end{array}$$

Where $K(\pi_n(X), n) \rightarrow X_{\leq n} \rightarrow X_{\leq n-1}$ is a fiber sequence. This is called a *Postnikov tower*.

Aha, but now I can also do the following.

$$\begin{array}{ccccccc}
& \cdots & \longrightarrow & \cdots & \xlongequal{\quad} & \vdots & \longleftarrow \cdots \\
& \downarrow & & & & \downarrow & \\
X_{>3} & \longrightarrow & X & \xlongequal{\quad} & X_{\leq 3} & \longleftarrow & K(\pi_3(X), 3) \\
\downarrow & & & & \downarrow & & \\
X_{>2} & \longrightarrow & X & \xlongequal{\quad} & X_{\leq 2} & \longleftarrow & K(\pi_2(X), 2) \\
\downarrow & & & & \downarrow & & \\
X_{>1} & \longrightarrow & X & \xlongequal{\quad} & X_{\leq 1} & \xlongequal{\quad} & K(\pi_1(X), 1) \\
\downarrow & & & & \downarrow & & \\
X & \xlongequal{\quad} & X & \longrightarrow & * & &
\end{array}$$

Where $X_{>n} \rightarrow X \rightarrow X_{\leq n}$ is a fiber sequence. See, $X_{>1}$ is the universal cover of X . I now have a tower that maps into X . The left hand tower is called the *Whitehead tower*, named for George Whitehead.

I can take the fiber of $X_{>1} \rightarrow X$, and I get $K(\pi_1(X), 0)$. We can continue this to get:

$$\begin{array}{ccccccc}
& \cdots & \longrightarrow & \cdots & \longrightarrow & \cdots & \longrightarrow \vdots \longleftarrow \cdots \\
& & & \downarrow & & \parallel & \downarrow \\
K(\pi_3(X), 2) & \longrightarrow & X_{>3} & \longrightarrow & X & \longrightarrow & X_{\leq 3} \longleftarrow K(\pi_3(X), 3) \\
& & \downarrow & & \parallel & & \downarrow \\
K(\pi_2(X), 1) & \longrightarrow & X_{>2} & \longrightarrow & X & \longrightarrow & X_{\leq 2} \longleftarrow K(\pi_2(X), 2) \\
& & \downarrow & & \parallel & & \downarrow \\
K(\pi_1(X), 0) & \longrightarrow & X_{>1} & \longrightarrow & X & \longrightarrow & X_{\leq 1} \xlongequal{\quad} K(\pi_1(X), 1) \\
& & \downarrow & & \parallel & & \downarrow \\
& & X & \xlongequal{\quad} & X & \longrightarrow & *
\end{array}$$

By the fiber sequence $\Omega X \rightarrow PX \rightarrow X$ with $PX \simeq *$, we find that $\Omega K(\pi, n) \simeq K(\pi, n-1)$. Note that these Eilenberg-MacLane spaces are unique up to homotopy.

I've laid out the rest of this basic homotopy theory story, and the proofs from a cellular point of view are annoying, but they're not difficult. It's kind of implicit, though, so you can't really use attaching cells to compute, say the cohomology of Eilenberg-MacLane spaces. That's a harder problem.

These constructions go back to the 50's, and they had voluminous computations in low dimensions. One day in 1950, they got a postcard from Serre, who said, "here's a computation you might be interested in: $H^{23}(K(\mathbf{Z}, 14)) = \dots$ ". Of course, Serre and Cartan had a different approach, that was much more effective. They observed that the fact $\Omega K(\pi, n) \simeq K(\pi, n-1)$ wasn't perceived to be useful by Eilenberg and MacLane. They didn't think about fiber sequences. Serre and Cartan did this by means of a spectral sequence. We'll do that later in the course.

52. Vector bundles, principle bundles

I was late because there was a fire at my dorm. From what I gather, a point is a map from the terminal object; this is also known as the cross section. A vector space over B is a space $E \rightarrow B$ over B with the

following structures:

$$\begin{array}{ccccc} E \times_B E & \xrightarrow{\mu} & E & \xleftarrow{\text{zero}} & B \\ \downarrow & \swarrow & \nearrow & \nearrow & \\ & B & & & \end{array}$$

And an inverse:

$$\begin{array}{ccc} E & \xrightarrow{\chi} & E \\ \downarrow & \nearrow & \\ & B & \end{array}$$

And an action of \mathbf{R} :

$$\begin{array}{ccccc} \mathbf{R} \times E & \xlongequal{\quad} & (B \times \mathbf{R}) \times_B E & \longrightarrow & E \\ & \searrow p \circ pr_2 & \downarrow & \nearrow p & \\ & & B & & \end{array}$$

Because \mathbf{R} is a field, we know that $p^{-1}(b)$ is a \mathbf{R} -vector space over $b \in B$.

A stupid example is the projection $B \times V \rightarrow B$ where V is a (always finite-dimensional) vector space.

EXAMPLE 52.1. The map $\mathbf{R} \times \mathbf{R} \xrightarrow{(s,t) \mapsto (s,st)} \mathbf{R} \times \mathbf{R}$ over \mathbf{R} (with projection onto the first factor) is an isomorphism on all fibers, but is zero everywhere else. Taking the kernel only has 0 everywhere except for over $0 \in \mathbf{R}$. I guess you can call this the “skyscraper” vector bundle over B .

There’s a subject called sheaf theory to accomodate examples like this. Anyway, there’s only so far you can go with this “vector space” over B . So we can refine this:

DEFINITION 52.2. A *vector bundle* over B is a vector space over B that is locally trivial. (We’ll always assume numerable as well, and that the fiber dimensions are always finite.)

If $p : E \rightarrow B$ is a vector bundle, then E is called the *total space*, p is called the projection, and B is called a base space. We denote ξ or ζ or something for a vector bundle, and we write $E(\xi) \rightarrow B(\xi)$ for the actual map.

EXAMPLE 52.3. (1) The trivial bundle $B \times \mathbf{R}^n \rightarrow B$. We denote this by $n\epsilon$. That’s a pretty stupid example.

(2) The most interesting possible example come from the Grassmannians $\text{Gr}_K(\mathbf{R}^n)$, $\text{Gr}_k(\mathbf{C}^n)$, and $\text{Gr}_k(\mathbb{H}^n)$. Over this Grassmannian is the *tautological bundle* γ . This is a sub-bundle of $n\epsilon$. (I’ll just define it for $\text{Gr}_K(\mathbf{R}^n)$, you can do it for the others.) The total space of γ is defined as:

$$E(\gamma) = \{(V, x) \in \text{Gr}_k(\mathbf{R}^n) \times \mathbf{R}^n : x \in V\}$$

This maps down to the Grassmannian via $(V, x) \mapsto V$. I’ll leave it to you to determine why this is locally trivial.

EXAMPLE 52.4. When $k = 1$, we have $\text{Gr}_1(\mathbf{R}^n) = \mathbf{RP}^{n-1}$. Then γ is one-dimensional, and it’s called a line bundle. It’s the canonical line bundle over \mathbf{RP}^{n-1} .

(3) M is a smooth manifold, then τ_M is the tangent bundle $TM \rightarrow M$ over M . This is a super important and useful vector bundle. I’ll give some examples in a minute. Let’s do one example right now! S^{n-1} for example; I can identify $TS^{n-1} = \{(x, v) \in S^{n-1} \times \mathbf{R}^n : v \cdot x = 0\}$.

52.1. Constructions. You can’t take kernels of maps of vector bundles, but just about anything you can do for vector spaces you can do for bundles.

- (1) You can take pullbacks: if $p' : E' \rightarrow B'$, then the leftmost map in the diagram below is a vector bundle also.

$$\begin{array}{ccc} E & \longrightarrow & E' \\ \downarrow & & \downarrow p' \\ B & \xrightarrow{f} & B' \end{array}$$

For instance, if $B = *$, you're just looking at the fiber over that point. If ξ is the bundle $E' \rightarrow B'$, we denote $E \rightarrow B$ as $f^*\xi$.

- (2) If $p : E \rightarrow B$ and $p' : E' \rightarrow B'$, then I can take the product $E \times E' \xrightarrow{p \times p'} B \times B'$.
 (3) If I take $B = B'$, I can take the pullback:

$$\begin{array}{ccc} E \oplus E' & \longrightarrow & E \times E' \\ \downarrow & & \downarrow \\ B & \xrightarrow{\Delta} & B \times B \end{array}$$

This $E \oplus E'$ thing is called the *Whitney sum*. For instance, $n\epsilon = \epsilon \oplus \cdots \oplus \epsilon$.

- (4) If $E, E' \rightarrow B$, I can form another vector bundle $E \otimes_{\mathbf{R}} E' \rightarrow B$ (fiberwise tensor product). I can also take the fiberwise Hom to get $\text{Hom}_{\mathbf{R}}(E, E') \rightarrow B$.

EXAMPLE 52.5. We know that there's the tautologous bundle γ over \mathbf{RP}^{n-1} , denoted $L \rightarrow \mathbf{RP}^{n-1}$. This is the canonical line bundle. That's one bundle I have, but I also have the tangent bundle $T(\mathbf{RP}^{n-1}) \rightarrow \mathbf{RP}^{n-1}$, denoted τ . What's the relationship between these things? The map from $S^{n-1} \rightarrow \mathbf{RP}^{n-1}$ is a covering map, so locally it's a diffeomorphism. Thus I can identify the map on the tangent spaces as an isomorphism.

It looks like $T_{\pm x}\mathbf{RP}^{n-1} = \{(x, v) \in S^{n-1} \times \mathbf{R}^n : x \cdot v = 0\} / (x, v) \sim -(x, v)$. I'm saying that $TR\mathbf{P}^{n-1} = L^\perp$. Do you buy that? I don't. Because look, a point in L^\perp is a point in that orthogonal complement, because I can't tell if I take v or $-v$. That isn't what L^\perp is!

Instead, what I think is that $TR\mathbf{P}^{n-1} = \text{Hom}(L, L^\perp)$. This is because a tangent line to a point is given by a map from a line through $x \rightarrow -x$ to some nearby line, also through the origin. The closer I am to the origin, the less I have to move along the tangent line to get to the nearby line, and the farther I am from the origin, the more I have to move to get to the nearby line. Thus we find:

$$\boxed{TR\mathbf{P}^{n-1} = \text{Hom}(L, L^\perp)}$$

52.2. Metrics. A *metric* on a vector bundle is a continuous choice of inner products on fibers.

LEMMA 52.6. *Any vector bundle admits a metric.*

Why is this true? If g, g' are both inner products on V , then $tg + (1 - t)g'$ is another. The space of metrics forms a real affine space.

PROOF. Pick a trivializing open cover, and a subordinate partition of unity. So $\phi_U : U \rightarrow [0, 1]$ so that the preimage of the complement of 0 is U , and they're locally finite, and they sum to 1. Over each one of these trivial pieces, pick a g_U on $E|_U$. Using the principle mentioned above, just take $\sum_U \phi_U g_U =: g$. \square

The word vector bundle occurs all over mathematics, but you can't pick metrics in, e.g., algebraic geometry.

COROLLARY 52.7. *If $0 \rightarrow E' \rightarrow E \rightarrow E'' \rightarrow 0$ is an exact sequence of vector bundles (over the same base), then it splits.*

This is because I can pick a metric for E , and then look at $E'^\perp \subseteq E \rightarrow E''$, which is an isomorphism; the dimensions are the same. Thus $E \cong E' \oplus E'^\perp \cong E' \oplus E''$. Note that this splitting isn't natural!

53. Principal bundles, associated bundles

Since Tuesday didn't exist, I'll have office hours on Thursday from 4 to 5 in 2-478.

DEFINITION 53.1. Suppose $E, E' \rightarrow B$ are vector bundles over B . An *isomorphism* is a map $\alpha : E \rightarrow E'$ over b that's a linear isomorphism on each fiber.

This implies it's invertible.

NOTATION 53.2. Denote by $\text{Vect}(B)$ the set of isomorphism classes of vector bundles over B .

Why's that a set? I'll let you think about that.

Suppose $\xi \downarrow B$. If $f : B' \rightarrow B$, taking the pullback gives a vector bundle denoted $f^*\xi$. This operation descends to a map $f^* : \text{Vect}(B) \rightarrow \text{Vect}(B')$. This operation certainly is functorial, and we get $\text{Vect} : \mathbf{Top}^{op} \rightarrow \mathbf{Set}$.

WARNING 53.3. In order to say anything meaningful about vector bundles, you've to assume that the vector bundles are numerable. If B is paracompact (eg a CW-complex), this is automatic.

We'd like to understand this functor Vect .

THEOREM 53.4. Vect is I -invariant (here $I = \Delta^1$), i.e. the projection $X \times I \rightarrow X$ induces an isomorphism $\text{Vect}(X) \rightarrow \text{Vect}(X \times I)$.

This is a basic theorem, and we'll prove this. Let me point out a corollary of this.

COROLLARY 53.5. Vect is a homotopy functor.

PROOF. Suppose $f, g : B \rightarrow B'$ with $f \simeq g$. Then I have $H : B' \times I \rightarrow B$. If $\xi \downarrow B$, I'd like to see that $f_0^*\xi \simeq f_1^*\xi$. This is far from obvious. Well, we have:

$$\begin{array}{ccc} B' \times I & \longrightarrow & B \\ \text{pr} \downarrow & & \\ B' & & \end{array}$$

The left map is an isomorphism under Vect . Suppose $\eta \downarrow B$ such that $\text{pr}^*\eta \simeq f^*\xi$. For any $t \in I$, we know that:

$$f_t^*\xi \simeq \text{in}_t^* f^*\xi \simeq \text{in}_t^* \text{pr}^*\eta \simeq (\text{pr} \circ \text{in}_t)^*\eta \simeq \eta$$

where $\text{in}_t : B' \rightarrow B' \times I$ sends $x \mapsto (x, t)$. That's the proof. \square

OK, note that $\text{Vect}(X) \rightarrow \text{Vect}(X \times I)$ being injective is obvious. I'll prove surjectivity on Friday. I'll prove something more general, in fact.

53.1. Principal bundles. There's a famous video of J.-P. Serre talking about mathematics. He says you have to know the difference between “principle” and “principal”. He contemplated “bundles of principles” (like politics, or society, or something).

DEFINITION 53.6. Let G be a topological group¹⁷. A *principal G -bundle* is a right action of G on P such that:

- G acts freely.
- The orbit projection $P \rightarrow P/G$ is a fiber bundle.

EXAMPLE 53.7. Suppose G is discrete. The fibers are discrete, so the condition that $P \rightarrow P/G$ is a fiber bundle is that it's a covering projection, i.e., the action is “properly discontinuous”. As a special case, suppose X is a space with universal cover $\tilde{X} \downarrow X$. Then $\pi_1(X)$ acts freely on \tilde{X} , and $\tilde{X} \downarrow X$ is the orbit projection. So this is a principal bundle; for instance, $S^{n-1} \downarrow \mathbf{RP}^{n-1}$ is a principal $\mathbf{Z}/2\mathbf{Z}$ -bundle. The Hopf fibration $S^{2n-1} \downarrow \mathbf{CP}^{n-1}$ is a principle S^1 -bundle.

¹⁷Really, I only care about discrete groups and Lie groups.

So this is *not* an unfamiliar object.

By looking at the universal cover, we can classify covering spaces of X . Remember how that goes: let F be a set with left $\pi_1(X)$ -action. Then you have the dotted map, which is the desired covering space:

$$\begin{array}{ccc} \tilde{X} \times F & \longrightarrow & \tilde{X} \times F / \sim \\ \downarrow p \circ pr_1 & \swarrow q & \\ X & & \end{array}$$

where $(y, gz) \sim (yg, z)$ where $y \in \tilde{X}$, $z \in F$, and $g \in \pi_1(X)$.

Fix $y_0 \in \tilde{X}$ over $*$ in X , I claim that $F \xrightarrow{\sim} q^{-1}(*)$ via $z \mapsto (y_0, z)$. I'll let you check that that's a bijection – that's supposed to be clear.

THEOREM 53.8 (Covering spaces). *There's an equivalence of categories:*

$$\{\text{Left } \pi_1(X)\text{-sets}\} \xrightarrow{\sim} \{\text{Covering spaces of } X\}$$

with inverse functor given by taking the fiber over the basepoint and lifting a loop in X to get a map from the fiber to itself.

How about a more general picture?

CONSTRUCTION 53.9. If $P \downarrow B$ is a principal G -bundle, and F is a left G -space, we get a new fiber bundle via:

$$\begin{array}{ccc} P \times F & \longrightarrow & P \times F / \sim \\ \downarrow & \swarrow q & \\ B & & \end{array}$$

This gives a new fiber bundle with fiber F , for the following reason. Let $x \in B$, and let $y \in P$ over x . We get $F \xrightarrow{\sim} q^{-1}(*)$ via $z \mapsto [y, z]$. Define $q^{-1}(*) \rightarrow F$ via $[y', z'] \mapsto gz'$ where $y' = yg$ for some unique g . You can check that these two maps are inverse homeomorphisms. This is called an “associated bundle”, and it's denoted $P \times_G F$.

Let $\xi \downarrow B$ be an n -plane bundle (all the fiber dimensions are the same, say n). We can construct a principal $\text{GL}_n(\mathbf{R})$ -bundle $P(\xi)$. Define $P(\xi)_b = \text{set of bases for } E(\xi)_b = \text{Iso}(\mathbf{R}^n, E(\xi)_b)$. What's the topology? Well, $P(B \times \mathbf{R}^n) = B \times \text{Iso}(\mathbf{R}^n, \mathbf{R}^n)$, topologically, where $\text{Iso}(\mathbf{R}^n, \mathbf{R}^n) = \text{GL}_n(\mathbf{R})$ is given the usual topology as a subspace of \mathbf{R}^{n^2} . There's an obvious right action of $\text{GL}_n(\mathbf{R})$ on $P(\xi) \downarrow B$, given by precomposition. Obviously the action is free, and it's simply transitive, so you actually have a *principal action* of $\text{GL}_n(\mathbf{R})$ on $P(\xi)$. This is called the *principalization* of ξ .

Look at the associated bundle with fiber $F = \mathbf{R}^n$, where $\text{GL}_n(\mathbf{R})$ acts on \mathbf{R}^n from the left, as it usually does. So I can form $P(\xi) \times_{\text{GL}_n(\mathbf{R})} \mathbf{R}^n$. Because this is a linear action, it's a vector bundle, and $P(\xi) \times_{\text{GL}_n(\mathbf{R})} \mathbf{R}^n \simeq E(\xi)$.

Fix a topological group G . Define $\text{Bun}_G(B)$ as the set of isomorphism classes of G -bundles over B . An isomorphism is a G -equivariant homeomorphism over the base. We've established that there's a natural isomorphism of functors:

$$\text{Bun}_{\text{GL}_n(\mathbf{R})}(B) \simeq \text{Vect}(B)$$

The I -invariance theorem will follow immediately from:

THEOREM 53.10. Bun_G is I -invariant.

There's a lot more that I wanted to say, but let me say one additional thing.

Principal bundles allow a description of geometric structures on ξ . By that I mean: suppose for instance that I have a metric on ξ . Then instead of all ordered bases, I can look at all ordered orthonormal bases in each fiber. This gives the *frame bundle* $\text{Fr}(B) = \text{ordered orthonormal bases of } E(\xi)_b$, i.e., isometric isomorphisms $\mathbf{R}^n \rightarrow E(\xi)_b$. Again, I have an action of the orthogonal group on $\text{Fr}(B)$, so you have a principal $O(n)$ -bundle. More examples: consistent orientations give an $SO(n)$ -bundle. Trivializations give principal bundles as well. This is called “reduction of the structure group”.

54. I -invariant of Bun_G , and G -CW-complexes

Everybody happy with principal bundles now? Let G be a topological group. Then $\text{Bun}_G : \mathbf{Top}^{op} \rightarrow \text{Set}$. I want to show that this is I -invariant, i.e., given $X \xrightarrow{pr} X \times I$, we have $\text{Bun}_G(X) \xrightarrow{\sim} \text{Bun}_G(X \times I)$. This map is injective, for sure, because the composite $X \xrightarrow{in_0} X \times I \xrightarrow{pr} X$ gives you a splitting $\text{Bun}_G(X) \xrightarrow{pr_*} \text{Bun}_G(X \times I) \xrightarrow{in_0^*} \text{Bun}_G(X)$ whose composite is the identity.

Suppose I have principal G -bundles $P \rightarrow X$ and $Q \rightarrow Y$, with a map $f : X \rightarrow Y$. Then I want to think about maps $P \rightarrow f^*Q$ over X . Equivalently, I want to think of G -equivariant dotted maps that make the following diagram commute.

$$\begin{array}{ccc} P & \xrightarrow{g} & Q \\ \downarrow & & \downarrow \\ X & \xrightarrow{f} & Y \end{array}$$

Suppose I have $P \rightarrow X \times I$; then we get $in_0^*P \rightarrow X$. This has to be what you get when you —. All we have to do is construct a map $P \rightarrow in_0^*P$ like in the diagram above.

We'll do this for X a CW-complex. I'll refer you to Husemoller for a different argument — he does the general case.

54.1. G -CW-complexes. What's a " G -cell"? The answer is $D^n \times H \backslash G$, for closed subgroups $H < G$. The space $H \backslash G$ is a right G -space. It's an orbit. The boundary of $D^n \times H \backslash G$ is just $\partial D^n \times H \backslash G$. We can build up G -CW-complexes exactly as we build up CW-complexes.

DEFINITION 54.1. A G -CW-complex is a (right) G -space X with a filtration $0 = X_{-1} \subseteq X_0 \subseteq \cdots \subseteq X$ such that for all n , there exists a pushout square:

$$\begin{array}{ccc} \coprod \partial D_\alpha^n \times H_\alpha \backslash G & \longrightarrow & \coprod D_\alpha^n \times H_\alpha \backslash G \\ \downarrow & & \downarrow \\ X_{n-1} & \longrightarrow & X_n \end{array}$$

and X has the direct limit topology.

So a CW-complex is a G -CW-complex for the trivial group G .

THEOREM 54.2. *If G is a compact Lie group and M a compact smooth G -manifold. Then M admits a G -CW-structure.*

This is a hard theorem. Note that if G acts principally¹⁸ on P , then every G -CW-structure on P is "free", i.e., $H_\alpha = 0$.

- (1) If X is a G -CW-complex, then X/G inherits a CW-structure where $(X/G)_n = X_n/G$.
- (2) If $P \rightarrow X$ is principal, then a CW-structure on X lifts to a G -CW-structure on P .

This equivariant stuff is very popular these days.

54.2. Proof of I -invariance. First thing to notice is that if $X \simeq *$, then any principal G -bundle over X is trivial, i.e., $P \simeq X \times G$ as a G -bundle. That iso isn't unique. How do we prove this? This is a case of the general theorem. Here's the thing to notice. If $P \downarrow X$ has a section, then it's trivial. That's worth contemplating. Why is that? Suppose I have a section $s : X \rightarrow P$. This P has an action of the group on it, so I can extend this to $X \times G \rightarrow P$ via $(x, g) \mapsto gs(x)$. This is a map of G -bundles over X , so it's an isomorphism. So, to show the general result, we have to construct a section. Let's take any map $X \rightarrow P$. Say the constant map! Then the following diagram commutes up to homotopy, and hence there's an *actual*

¹⁸The action that you have when you say you have a principal G -bundle.

section of $P \rightarrow X$, as desired.

$$\begin{array}{ccc} & & P \\ & \nearrow \text{const} & \downarrow \\ X & \longrightarrow & X \end{array}$$

OK, for the general case, let's assume X is a CW-complex. For notational convenience, let's write $Y = X \times I$. Filter Y by subcomplexes: define $Y_0 = X \times 0$. In general, define $Y_n = X \times 0 \cup X_{n-1} \times I$. Thus, I can construct Y_n out of Y_{n-1} via a pushout:

$$\begin{array}{ccc} \coprod_{\alpha \in \Sigma_{n-1}} (\partial D_\alpha^{n-1} \times I \cup D_\alpha^{n-1} \times 0) & \longrightarrow & \coprod_{\alpha} (D_\alpha^{n-1} \times I) \\ \downarrow \coprod_{\alpha \in \Sigma_{n-1}} f_\alpha \times 1_I \cup \phi_\alpha \times 0 & & \downarrow \\ Y_{n-1} & \longrightarrow & Y_n \end{array}$$

where the maps f_α and ψ_α are defined as:

$$\begin{array}{ccc} \partial D_\alpha^{n-1} & \xrightarrow{f_\alpha} & X_{n-2} \\ \downarrow & & \downarrow \\ D_\alpha^{n-1} & \xrightarrow{\phi_\alpha} & X_{n-1} \end{array}$$

Remember I have $P \xrightarrow{p} Y = X \times I$. Define $P_n = p^{-1}(Y_n)$. We can build P_n from P_{n-1} in a similar way:

$$\begin{array}{ccc} \coprod_{\alpha} (\partial D_\alpha^{n-1} \times I \cup D_\alpha^{n-1} \times 0) \times G & \longrightarrow & \coprod_{\alpha} (D_\alpha^{n-1} \times I) \times G \\ \downarrow & & \downarrow \\ P_{n-1} & \longrightarrow & P_n \end{array}$$

This makes sense since $D_\alpha^n \times I$ is a contractible space, and same thing for the other factor. Note that this isn't *quite* a G -CW-structure. Remember that what I'm trying to do is fill in a dotted map:

$$\begin{array}{ccc} P & \longrightarrow & P_0 \\ \downarrow & & \downarrow \\ Y & \xrightarrow{pr} & P_0 \end{array}$$

I'm constructing this inductively— we have $P_{n-1} \rightarrow P_0$. So I want to define $\coprod_{\alpha} (D_\alpha^{n-1} \times I) \times G \rightarrow P_0$ that's equivariant. That's the same thing as a map $\coprod_{\alpha} (D_\alpha^{n-1} \times I) \rightarrow P_0$ that's compatible with the map from $\coprod_{\alpha} (\partial D_\alpha^{n-1} \times I \cup D_\alpha^{n-1} \times 0)$. Namely, I want to fill in:

$$(3) \quad \begin{array}{ccc} \coprod_{\alpha} (\partial D_\alpha^{n-1} \times I \cup D_\alpha^{n-1} \times 0) & \longrightarrow & \coprod_{\alpha} (D_\alpha^{n-1} \times I) \\ \downarrow & & \downarrow \\ \coprod_{\alpha} (\partial D_\alpha^{n-1} \times I \cup D_\alpha^{n-1} \times 0) \times G & \longrightarrow & \coprod_{\alpha} (D_\alpha^{n-1} \times I) \times G \\ \downarrow & & \downarrow \\ P_{n-1} & \longrightarrow & P_n \end{array}$$

induction

$$\begin{array}{ccc} & & P_0 \\ & \searrow & \downarrow \\ & & X \end{array}$$

Now, I know that $(D^{n-1} \times I, \partial D^{n-1} \times I \cup D^{n-1} \times 0) \simeq (D^{n-1} \times I, D^{n-1} \times 0)$. So what I have is:

$$\begin{array}{ccc} D^{n-1} \times 0 & \xrightarrow{\text{induction}} & P_0 \\ \downarrow & \nearrow & \downarrow \\ D^{n-1} \times I & \xrightarrow{\phi \circ pr} & X \end{array}$$

So the dotted map exists, since $P_0 \rightarrow X$ is a fibration!

OK, so note that I haven't checked that the outer diagram in Equation 3 commutes, because otherwise we wouldn't get $P_n \rightarrow P_0$.

EXERCISE 54.3. Check my question above.

Turns out this is easy, because you have a factorization:

$$\begin{array}{ccccc} D^{n-1} \times 0 & \longrightarrow & P_{n-1} & \xrightarrow{\text{induction}} & P_0 \\ \downarrow & & \nearrow & & \downarrow \\ D^{n-1} \times I & \xrightarrow{\phi \circ pr} & & & X \end{array}$$

Oh my god, look what time it is! Oh well, at least we got the proof done.

55. Classifying spaces: the Grassmann model

Office hours: Hood from 12 in 2-390, and me from 4-5 on Tuesday in 2-478.

I want to talk about classifying spaces for principal bundles and for vector bundles. I'm going to do this in two ways, one via the Grassmann model and via simplicial methods.

LEMMA 55.1. *Over a compact Hausdorff space, any n -plane bundle embeds in a trivial bundle.*

PROOF. Let \mathcal{U} be a trivializing open cover; since it's compact, we might as well assume that it's finite with k elements. There's no numerability issue, so there's a subordinate partition of unity ϕ_i . My bundle is $E \rightarrow X$. By trivialization, there is a fiberwise isomorphism $p^{-1}(U_i) \xrightarrow{f_i} \mathbf{R}^n$. Note that a map to a trivial bundle is the same thing as a bundle map:

$$\begin{array}{ccc} E & \longrightarrow & \mathbf{R}^? \\ \downarrow & & \downarrow \\ B & \longrightarrow & * \end{array}$$

Define $E \rightarrow (\mathbf{R}^n)^k$ via $e \mapsto (\phi_i(p(e))f_i(e))_{i=1, \dots, k}$. This is a fiberwise linear embedding, generally called a "Gauss map". You have to observe that this thing has no kernel on every fiber, so this is an embedding. \square

COROLLARY 55.2. *Over a compact Hausdorff space, any n -plane bundle has a complement (i.e. a ξ^\perp such that $\xi \oplus \xi^\perp = \text{trivial}$), because the trivial bundle has a metric on it, so I just choose the orthogonal complement of the embedding.*

Another way to say this is that if X is compact Hausdorff (henceforth called CHS) with an n -plane bundle ξ , I've constructed a map $f : X \rightarrow \text{Gr}_n(\mathbf{R}^{kn})$; this is exactly the Gauss map. It has the property that I can take the pullback $f^*\gamma^n$ of the tautologous bundle over $\text{Gr}_n(\mathbf{R}^{kn})$, then I get back ξ . I don't have control over k , but in fact I can just consider γ^n over $\text{Gr}_n(\mathbf{R}^\infty)$, topologized as the union of $\text{Gr}_n(\mathbf{R}^m)$, where $\mathbf{R}^\infty = \bigoplus \mathbf{R}$. This is a CW-complex of finite type (i.e. finitely many cells in each dimension)! Note that $\text{Gr}_n(\mathbf{R}^m)$ are not the m -skeleta of $\text{Gr}_n(\mathbf{R}^\infty)$. It's more universal – any n -plane bundle ξ over X can be obtained as the pull back $f^*\gamma^n$ for the Gauss map $f : X \rightarrow \text{Gr}_n(\mathbf{R}^{kn}) \rightarrow \text{Gr}_n(\mathbf{R}^\infty)$.

LEMMA 55.3. *Any (numerable) n -plane bundle is pulled back from $\gamma^n \downarrow \text{Gr}_n(\mathbf{R}^\infty)$.*

This is a little bit tricky, since the covering can be wildly uncountable. To show this, let's use:

LEMMA 55.4. *Let \mathcal{U} be a numerable cover of X . Then there's another numerable cover \mathcal{U}' such that:*

- (1) *the number of open sets in \mathcal{U}' is countable.*
- (2) *Each element of \mathcal{U}' is a disjoint union of elements of \mathcal{U} .*

If \mathcal{U} is a trivializing cover, then \mathcal{U}' is also a trivializing cover.

PROOF. If you don't want to work it out you can refer to Husemoller's book, p.28. I'll put a link on the website. \square

I think that basically proves Lemma 55.3. Don't be deceived! Beware that you can't necessarily expect a complementary bundle.

THEOREM 55.5. *The map $[X, \text{Gr}_n(\mathbf{R}^\infty)] \rightarrow \text{Vect}_n(X)$ via $[f] \mapsto [f^*\gamma^n]$ is bijective, where $[f]$ is the homotopy class and $[f^*\gamma^n]$ is the iso class.*

That's why $\text{Gr}_n(\mathbf{R}^\infty)$ is called the *classifying space* for n -plane bundles.

This is a very explicit geometric description of classifying spaces. There's an abstract way to produce a classifying space for principal G -bundles, which we'll talk about on Wednesday. This is the special case of $\text{GL}_n(\mathbf{R})$.

PROOF. I've already shown surjectivity; we need to show injectivity. Suppose $f_0, f_1 : X \rightarrow \text{Gr}_n(\mathbf{R}^\infty)$ such that $f_0^*\gamma^n \simeq f_1^*\gamma^n$ over X . I'd like to see that $f_0 \simeq f_1$. I might as well identify $f_0^*\gamma^n$ and $f_1^*\gamma^n$ with each other; call it $\xi : E \downarrow X$. What do I have?

Giving f_i is the same thing as giving a map $g_i : E \rightarrow \mathbf{R}^\infty$ that's a fiberwise linear embedding. The g is for Gauss. This homotopy $f_0 \simeq f_1$ is created by saying that we have a homotopy from g_0 to g_1 through Gauss maps, i.e., through other fiberwise linear embeddings. I'm going to do this without any reference from where g_0 came from. I'm saying that *any two* Gauss maps are homotopic through Gauss maps – that's what I'm claiming! I mean, from this given vector bundle E . This is very far from true if I didn't have a \mathbf{R}^∞ on the RHS there.

In fact, let's try for an affine homotopy. Think about $tg_0 + (1-t)g_1$ for $0 \leq t \leq 1$. Now, wouldn't it be great if that works? I guess it can't. We need that for all t , if $tg_0(v) + (1-t)g_1(v) = 0 \in \mathbf{R}^\infty$, then $v = 0$ (where $v \in E$). I.e., on each fiber, this map is injective, i.e., has zero kernel. Of course, I can't guarantee that just from g_0 and g_1 are injective! So we fail.

We should use the fact that this is an infinite-dimensional Euclidean space. I'll give you two linear isometries:

$$\begin{array}{ccc} & \mathbf{R}^\infty = \langle e_0, e_1, \dots \rangle & \\ \swarrow \alpha \quad e_i \mapsto e_{2i} & & \searrow \beta \quad e_i \mapsto e_{2i+1} \\ \mathbf{R}^\infty & & \mathbf{R}^\infty \end{array}$$

We have four Gauss maps: g_0 , $\alpha \circ g_0$, $\beta \circ g_1$, and g_1 . I claim that each of these are homotopic, i.e., $g_0 \simeq \alpha \circ g_0 \simeq \beta \circ g_1 \simeq g_1$ via affine homotopies through Gauss maps.

Shall we do just one case of that? I'll do the middle case. In the middle case, you'll never have cancelation.

Let's try $g_0 \simeq \alpha \circ g_0$. Suppose t, v are such that $tg_0(v) + (1-t)\alpha g_0(v) = 0$. What's the argument I'll make here? So $\alpha g_0(v)$ has only even coordinates. So I might as well suppose that $0 < t < 1$. Anyway, since $\alpha g_0(v)$ has only even coordinates, $g_0(v)$ itself must have only even coordinates. But then that means that the nonzero coordinates only for $0 \pmod 4$. But this equation says that $g_0(v) \neq 0$ only for $i \equiv 0 \pmod 4$. So I repeat this and find that the coordinates are zero for powers of two. \square

Maybe that's all I want to say today. I'll just stop today unless people have questions.

56. Simplicial sets

pset 3 is now due Friday, corrected on Wednesday.

Simplicial sets arose first in algebraic topology, and now they're everywhere. Really I should be saying "simplicial things", or actually simplicial objects. Folks in 905 know about this, because I forced you through this in the beginning of the course.

56.1. Review. $[n]$ is the set $\{0, 1, \dots, n\}$ as a totally ordered set. I define a category $\Delta = \{[n] : n \geq 0\}$ with morphisms order preserving maps. We can define a functor $\Delta : \Delta \rightarrow \mathbf{Top}$ defined via $[n] \mapsto \Delta^n$ which is the convex hull of $\{e_0, \dots, e_n\} \subseteq \mathbf{R}^{n+1}$. This is extremely familiar from simplicial homology. I have the vertices of these things indexed by elements of $[n]$, so I just extend as an affine map. Namely, $\phi : [m] \rightarrow [n]$ gives $\phi : \Delta^m \rightarrow \Delta^n$, an affine extension. Sometimes Δ^n is called the standard simplex.

The next thing we did was to take some space X and think about the set of singular n -simplices $\mathbf{Top}(\Delta^n, X)$, which gives a contravariant functor $\Delta^{op} \rightarrow \mathbf{Set}$ via $[n] \mapsto \mathbf{Top}(\Delta^n, X)$. This gives the singular simplicial set \mathbf{Sin} .

DEFINITION 56.1. Let \mathbf{C} be a category. Denote by $s\mathbf{C}$ the category of simplicial objects in \mathbf{C} , i.e., the category $\mathbf{Fun}(\Delta^{op}, \mathbf{C})$. Typically we write $X_n = X([n])$, called the n -simplices.

Expanding this out, for all $n \geq 0$, there is $X_n \in \mathbf{C}$ and maps given by the following. There are maps $d^i : [n] \rightarrow [n+1]$ given by omitting i (called coface maps) and codegeneracy maps $s^i : [n] \rightarrow [n-1]$ that's the surjection which repeats i . Any order-preserving map can be written as the composite of these maps, and there are famous relations that these things satisfy. They generate the category Δ . Hence they give maps $d_i : X_{n+1} \rightarrow X_n$ and $s_i : X_{n-1} \rightarrow X_n$. These are the face and degeneracy maps. They're called that for a good reason, because in $\mathbf{Sin}(X)$, the face map $d_i \sigma = \sigma \circ d^i$, i.e., the simplex composed with the inclusion of a face.

EXAMPLE 56.2. Suppose \mathbf{C} is a small category, for instance, a group. Notice that $[n]$ is a small category, with:

$$[n](i, j) = \begin{cases} \{\leq\} & \text{if } i \leq j \\ \emptyset & \text{else} \end{cases}$$

So, I'm entitled to think about $\mathbf{Fun}([n], \mathbf{C})$. I thus have a simplicial set $N\mathbf{C}$ whose n -simplices are $(N\mathbf{C})_n = \mathbf{Fun}([n], \mathbf{C})$. This is called the *nerve* of \mathbf{C} . Interestingly enough N defines a functor $\mathbf{Cat} \rightarrow \mathbf{Set}$. Thus an n -simplex in the nerve is $(n+1)$ -objects in \mathbf{C} (possibly with repetitions) and a chain of n composable morphisms. The face maps in the nerve are truncating (at the end) or composing. The degeneracy maps just compose with the identity at that vertex.

For example, $(NG)_n = G^n$ where G is a group regarded as a category.

56.2. Realization. We went from spaces to simplicial sets. There's a way to go back. This was thanks to Milnor. Lucky guy to be able to spell out this construction.

Suppose I have a simplicial set X . I'll define $|X|$ as follows:

$$|X| = \left(\prod_{n \geq 0} \Delta^n \times X_n \right) / \sim$$

where \sim is defined as:

$$\Delta^m \times X_m \ni (v, \phi^* x) \sim (\phi_* v, x) \in \Delta^n \times X$$

for all $v \in \Delta^m$ and $x \in X_n$, where $\phi : [m] \rightarrow [n]$. Let's spell this out a little bit.

EXAMPLE 56.3. Let's look at $\phi^* = d_i : X_{n+1} \rightarrow X_n$ and $\phi_* = d^i : \Delta^n \rightarrow \Delta^{n+1}$. The equivalence relation is then saying that if I have $(v, d_i x) \in \Delta^n \times X_n$, that's supposed to be equivalent to $(d^i v, x) \in \Delta^{n+1} \times X_{n+1}$. So it's saying: I have the copy of Δ^{n+1} indexed by $x \in X_{n+1}$, and I have a copy of Δ^n indexed by $d_i x$. I'm taking the n -simplex indexed by $d_i x$ and identifying it with the i th face of the $(n+1)$ -simplex indexed by x . It's sticking together simplices as dictated by the simplicial structure on X .

There's a similar picture for the degeneracies s^i . For this, \sim is saying that every element of the form $(v, s_i x)$ is already represented by a simplex of lower dimension. Maybe we should do an example of this.

EXAMPLE 56.4. Pick an $n \geq 0$. I'll look at $\Delta(-, [n])$. This is a simplicial set. It's like the most canonical simplicial set of all. Let's call $\Delta(-, [n])$ the "simplicial n -simplex", sorry about that. This is denoted Δ^n . What's $|\Delta^n|$? This is gonna be:

$$|\Delta^n| = \coprod_{\text{nondegenerate } k\text{-simplices in } \Delta^n} \Delta^k / \sim$$

What are these nondegenerate k -simplices in Δ^n ? These are exactly injective order preserving maps $[k] \rightarrow [n]$. And then these are going to glue them together.

Suppose $n = 3$; what are the injective maps $[k] \rightarrow [n]$? First $k \leq 3$. I have the identity. Injective maps $[2] \rightarrow [3]$ just omit one vertex, so I can put in a face. There are four of them. We can do the same thing with 1-simplices. Those are the edges, and same thing for 0-simplices.

What I've tried to prove is that $|\Delta^n| \simeq \Delta^n$. I've also tried to show that $|X|$ is naturally a CW-complex, with $\text{sk}_n |X| = \left(\coprod_{k \leq n} \Delta^k \times X_k \right) / \sim$. These face maps give you the attaching maps. This is a very combinatorial way to produce CW-complexes.

Now, we have two functors going back and forth between spaces and simplicial sets? Do they form an adjoint pair? Actually this is one of the motivating examples of the theory of adjoint pairs. Namely, I have:

$$|-| : s\text{Set} \rightleftarrows \mathbf{Top} : \text{Sin}$$

Let X be a space. We have a map $\Delta^n \times \text{Sin}_n(X) \rightarrow X$ given by $(v, \sigma) \mapsto \sigma(v)$. This is a continuous map. This equivalence relation defining $|\text{Sin}(X)|$ says that the map factors as:

$$\begin{array}{ccc} & |\text{Sin}(X)| & \xrightarrow{\quad} X \\ \uparrow & \nearrow & \\ \coprod \Delta^n \times \text{Sin}_n(X) & & \end{array}$$

This is the counit of the adjunction.

Suppose $K \in s\text{Set}$. I want to define $K \rightarrow \text{Sin}|K|$. If I have $x \in K_n$, I want to send it to $\Delta^n \rightarrow |K|$ defined via $v \mapsto [(v, x)]$.

This is the beginning of a long story in semi-classical homotopy theory which says that you can take any homotopy theoretic question and reformulate it in simplicial sets. For instance, you can define homotopy groups in simplicial sets. If you don't like point-set topology, you can work in simplicial sets, and many people prefer that.

The final thing to say for what happens next is this. If I have a category \mathbf{C} , its realization $|\mathbf{NC}|$ is a CW-complex, called the *classifying space* of \mathbf{C} . That's one thing to say. The other thing to leave you with is this. This construction of realization – exactly the same formula makes sense more generally, even if I was considering simplicial *spaces*. When I take the product, I really mean the product of spaces (in compactly generated spaces).

57. Remember what we have

We spent the first 25 minutes discussing one of the problems in the pset.

A great reference for simplicial sets is Goerss-Jardine, but it's about 500 pages long. Another reference is Weibel's homological algebra. And also May's simplicial objects book.

Remember that $\Delta \ni [n]$ for $n \geq 0$ where $[n] = \{0, \dots, n\}$. A simplicial object is a functor $X : \Delta^{op} \rightarrow \mathbf{C}$. Remember that:

$$|X| = \coprod_{n \geq 0} \Delta^n \times X_n / \sim$$

Remember that $s^i : [n] \rightarrow [n+1]$ repeats i . Part of this relation \sim is that $(v, s_i x) \sim (s^i v, x)$. That means that $x \in X_{n-1}$ and $v \in \Delta^n$. This tells us that $\text{Im}(s_i : X_{n-1} \rightarrow X_n)$ indexes cells that lie in the $(n-1)$ -skeleton $\text{sk}_{n-1} |X| = \coprod_{k \leq n-1} \Delta^k \times X_k / \sim$.

This gives two functors

$$|-| : s\text{Set} \rightleftarrows \mathbf{Top} : \text{Sin}$$

and I defined the unit and counit last time.

THEOREM 57.1 (Milnor). *The map $|\text{Sin}(X)| \rightarrow X$ is a weak equivalence.*

This is a functorial CW-approximation, but it's rather large. It's not at all minimal. It's some uncountable CW-complex.

THEOREM 57.2 (You did this). *There is a homeomorphism $|X \times Y| \xrightarrow{\sim} |X| \times |Y|$ (product in k -spaces). The product of two simplicial sets is defined as $(X \times Y)_n := X_n \times Y_n$.*

Let **Cat** be the category of small categories and functors. The nerve gives a functor:

$$\mathbf{Cat} \xrightarrow{N} \mathbf{sSet}$$

DEFINITION 57.3. In **Cat**, define $C \times D$ as the category whose objects are pairs of object of C and D and morphisms are pairs of morphisms.

Then $N(\mathbf{C} \times \mathbf{D}) = N\mathbf{C} \times N\mathbf{D}$. This is pretty clear. Then, I defined $B\mathbf{C} := |N\mathbf{C}|$.

THEOREM 57.4. *The natural map $B(\mathbf{C} \times \mathbf{D}) \xrightarrow{\sim} B\mathbf{C} \times B\mathbf{D}$ is a homeomorphism.*

I remember trying to explain to you that there's a simplicial simplex $\Delta^n = \Delta(-, [n])$, and trying to convince you that $|\Delta^n| = \Delta^n$.

Here's another observation about **Cat**: it's Cartesian closed. There's that word again. I mean, it's got products, and it's got "function objects" as well. If I have $\mathbf{D}^{\mathbf{C}}$, this is a category, and it's the category of functors $\text{Fun}(\mathbf{C}, \mathbf{D})$ and natural transformations. I leave it to you to verify that this is really the right adjoint of the product.

For instance, here's a category: $[1]$. A functor $[1] \rightarrow \mathbf{C}$ is just an arrow in \mathbf{C} . So, a functor $[1] \rightarrow \mathbf{D}^{\mathbf{C}}$ is a natural transformation between two functors f_0 and f_1 . This is the same thing as a functor $\mathbf{C} \times [1] \rightarrow \mathbf{D}$, and in the product category $\mathbf{C} \times [1]$ is a pair of objects of \mathbf{C} and a map between them. So, we're good.

Now, $B([1] \times \mathbf{C}) \simeq B[1] \times B\mathbf{C} \rightarrow B\mathbf{D}$. But $B[1] = \Delta^1$. In other words, this is a homotopy of maps $Bf_0, Bf_1 : B\mathbf{C} \rightarrow B\mathbf{D}$!

LEMMA 57.5. *A natural transformation $\theta : f_0 \rightarrow f_1$ where $f_0, f_1 : \mathbf{C} \rightarrow \mathbf{D}$ induces a homotopy $Bf_0 \sim Bf_1 : B\mathbf{C} \rightarrow B\mathbf{D}$.*

There's something interesting about this. This notion of a homotopy is *reversible*, but that's not at all true about natural transformations. One of the conclusions is, therefore, that B forgets the "polarity" in **Cat**.

For example, suppose $L \dashv R$ where $L : \mathbf{C} \rightarrow \mathbf{D}$; then we have a unit $1_{\mathbf{C}} \rightarrow RL$ and a counit $LR \rightarrow 1_{\mathbf{D}}$. When I apply classifying spaces, I get induced maps $B\mathbf{C} \rightarrow B\mathbf{D}$ and $B\mathbf{D} \rightarrow B\mathbf{C}$. Thus, B of the unit and counit are homotopy equivalences that are inverse up to homotopy. So if you have two categories that are related by any adjoint pair, then they're homotopy equivalence.

Here's another example. We have the category $[0]$. What is an adjoint pair $L \dashv R$ where $L : [0] \rightarrow \mathbf{D}$? Well L determines an object $*$ of \mathbf{D} . But the composition $LR(d) \rightarrow d$. But L of anything is just $*$. So this is a unique morphism $* \rightarrow X$. It's unique since $\mathbf{D}(*, X) = \mathbf{C}(0, 0) = 0$. An adjoint pair like that therefore specifies an initial object of \mathbf{D} .

The same way, if I had $L \dashv R$ where $L : \mathbf{D} \rightarrow [0]$, we get a terminal object of \mathbf{D} . But look, if \mathbf{D} is any category with a terminal (or initial) object, then $B\mathbf{D}$ is contractible!

Oh my god, look what time it is! I was just getting warmed up.

58. Bundles, classifying spaces, simplicial objects

pset 4 is complete; it's due April 12.

I learned this attitude towards classifying spaces from Segal. An article is on the website.

A bizarre thing we tried to do was look at the category of categories. Among these are groups. We took the nerve of a category, and got a simplicial set. Then we took the geometric realization. All in all, we have:

$$\begin{array}{ccc} \mathbf{Cat} & \xrightarrow{\text{nerve}} & \mathbf{sSet} \\ \uparrow B & & \downarrow |-| \\ \mathbf{Gp} & & \mathbf{Top} \end{array}$$

BG for a group G is called the classifying space, although it isn't clear what it's classifying at this point.

Another example of a category is given by $[n]$. The classifying space of $[n]$ is canonically isomorphic to Δ^n , as we observed. You will discover for homework that B takes products to products. This leads to the

fact that the classifying space construction sends natural transformations to homotopies. This is a sort of 2-categorical thing.

LEMMA 58.1. *Let G be a group, and $g \in G$. Let $c_g : G \rightarrow G$ via $x \mapsto gxg^{-1}$. This gives a self map $Bc_g : BG \rightarrow BG$. This map is homotopic to the identity.*

PROOF. The homomorphism c_g is a functor from G to itself. The claim is that there is a natural transformation from the identity to that functor. What is this natural transformation, call it $\theta : 1 \rightarrow c_g$? It sends the only object to the only object. Define $* \rightarrow *$ via $* \xrightarrow{g} *$. We then need the following diagram to commute, which it obviously does:

$$\begin{array}{ccc} * & \xrightarrow{g} & * \\ 1 \downarrow & & \downarrow g x g^{-1} \\ * & \xrightarrow{g} & * \end{array}$$

This is one of my favorite proofs. □

Groups are born to act. Let's let G act on some set X . More generally, define an action of a category \mathbf{C} as a functor $\mathbf{C} \xrightarrow{X} \text{Set}$.

DEFINITION 58.2. The “translation” category $X\mathbf{C}$ has $\text{ob}(X\mathbf{C}) = \coprod_{c \in \mathbf{C}} X_c$, and morphisms defined via $X\mathbf{C}(x \in X_c, y \in X_d) = \{f : c \rightarrow d : f_*(x) = y\}$.

There is a projection $X\mathbf{C} \rightarrow \mathbf{C}$. This is a special case of the Grothendieck construction.

EXAMPLE 58.3. Suppose G acts on itself by left translation. Let \tilde{G} for this G -set. Then $\tilde{G}G$ has objects as G , and maps $x \rightarrow y$ are elements yx^{-1} . This category is “unicursal”. There's exactly one map from one object to another object. Every object is therefore initial and terminal, so the classifying space of this category is trivial! I.e., $B(\tilde{G}G) \simeq *$. This is denoted EG . It comes equipped with a map down to BG , because we have a map $\tilde{G}G \rightarrow G$.

You could also have G acting by right translation. The right and left action commute with each other, by associativity. Thus the right action is equivariant with respect to the left action. Consequently, we get a right action of G on EG .

Here's the claim: this action is a principal action, and the orbit projection is $EG \rightarrow BG$. I've produced a topologically interesting thing. Note that EG is a CW-complex – the classifying space is always a CW-complex!

Let's think about $N(\tilde{G}G)_n$. An element is a chain of composable morphisms – it's actually just a sequence of $n + 1$ elements in the group. I.e., $N(\tilde{G}G)_n = G^{n+1}$. The right action of the group on this is the diagonal action.

LEMMA 58.4. *This is a free action. More precisely, if G is a group and X is a G -set, and if $X \times^\Delta G$ has the diagonal G -action and $X \times G$ has G acting on the second factor by right translation, then $X \times^\Delta G \simeq X \times G$ as G -sets.*

The word for this is “shearing”.

PROOF. Define $X \times^\Delta G \mapsto X \times G$ via $(x, g) \mapsto (xg^{-1}, g)$. It's clearly bijective. Is this equivariant? Well, $(x, g) \cdot h = (xh, gh)$, while $(xg^{-1}, g) \cdot h = (xg^{-1}, gh)$. The element (xh, gh) is sent to $(xh(gh)^{-1}, gh)$, and so we're done.

For good measure, define $X \times G \rightarrow X \times^\Delta G$ via $(x, g) \mapsto (xg, g)$. □

Isn't that cool?

OK, so G acts freely on $N(\tilde{G}G)_n$. So a nonidentity group element is always going to send a simplex to another simplex. I.e., G acts freely on EG .

What's the orbit space? If I take that diagonal G -action, when I divide by G , according to the shear isomorphism, I'm just canceling out one copy of G . I.e., $N(\tilde{G}G)/G \simeq G^n \simeq (NG)_n$. Of course, you still have to check degeneracies and face maps to see if they work out. But they do, and the realization is BG .

Everything I said here works just as well if we were to consider functors $X : \mathbf{C} \rightarrow \mathbf{Top}$ instead of $X : \mathbf{C} \rightarrow \mathbf{Set}$. I want to study G when it's a topological group, like Lie groups. Define \tilde{G} to be a category in \mathbf{Top} . What do I mean by this? Let \mathbf{C} be a category, with objects \mathbf{C}_0 and morphisms \mathbf{C}_1 . Then we have maps $\mathbf{C}_1 \times_{\mathbf{C}_0} \mathbf{C}_1 \xrightarrow{\text{compose}} \mathbf{C}_1$ and two maps (source and target) $\mathbf{C}_1 \rightarrow \mathbf{C}_0$, and the identity $\mathbf{C}_0 \rightarrow \mathbf{C}_1$. You can give the exact same data in any category with pullbacks.

An example is a topological group – that's a category in \mathbf{Top} . So, if a topological group acts on a space X , then we have XG , which is a category in \mathbf{Top} . Then $(XG)_0 = X$ as a space, and $(XG)_1 = G \times X$ as a space.

Well, I could go on. The nerve of a topological category gives me a simplicial space. In general, you'll have $(N\mathbf{C})_n = \mathbf{C}_1 \times_{\mathbf{C}_0} \mathbf{C}_1 \times \cdots \times_{\mathbf{C}_0} \mathbf{C}_1$. The geometric realization works exactly the same way, so you get a topological space when you realize a simplicial space.

You need to put some mild topological conditions on the group for the theorem we proved above to be true. Again, we have \tilde{G} with G acting on it. Again, we let $EG = B\tilde{G}$.

THEOREM 58.5. *EG is contractible, and G acts from the right principally (at least if G is a Lie group – more generally, absolute neighborhood retract)¹⁹, with orbit projection $EG \rightarrow BG$.*

59. Classifying spaces

Let \mathcal{U} be a cover of X . Let $\check{\mathcal{C}}\mathcal{U}$ denote the ... Let $p : P \rightarrow X$ be a principal G -bundle. Say that \mathcal{U} trivializes P if there are homeomorphisms $p^{-1}(U) \xrightarrow{\sim} U \times G$ over U . Equivalently, it's a trivialization of the pullback bundle ϵ^*P :

$$\begin{array}{ccc} \epsilon^*P & \longrightarrow & P \\ \downarrow & & \downarrow \\ \coprod_{U \in \mathcal{U}} U & \xrightarrow{\epsilon} & X \end{array}$$

This is the same thing as a functor $\check{\mathcal{C}}(\mathcal{U}) \xrightarrow{\gamma} G$. On classifying spaces, we therefore get a map $X \xleftarrow{\cong} \check{\mathcal{C}}(\mathcal{U}) \xrightarrow{\gamma} BG$, with the left map given by ϵ . How unique is θ ?

Suppose I have two principal G -bundles over X :

$$\begin{array}{ccc} P & \xrightarrow{\cong} & Q \\ & \searrow & \downarrow \\ & & X \end{array}$$

Let me put this off for a minute.

We want to vary the open cover. Say that \mathcal{V} refines \mathcal{U} if for any $V \in \mathcal{U}$, there exists $U \in \mathcal{U}$ such that $V \subseteq U$. A *refinement* is a function $p : \mathcal{V} \rightarrow \mathcal{U}$ such that $V \subseteq p(V)$. A refinement defines a map $\coprod_{V \in \mathcal{V}} V \rightarrow \coprod_{U \in \mathcal{U}} U$, also denoted ρ . Both cover X . So I get a map $\check{\mathcal{C}}(\mathcal{V}) \rightarrow \check{\mathcal{C}}(\mathcal{U})$ that covers cX (constant with only identity morphisms) that commutes strictly. When I take classifying spaces, I get a diagram:

$$\begin{array}{ccc} B\check{\mathcal{C}}(\mathcal{V}) & \longrightarrow & B\check{\mathcal{C}}(\mathcal{U}) \\ & \searrow & \downarrow \\ & & X \end{array}$$

Suppose t trivialization of P for \mathcal{U} . Well, I have a functor $B\check{\mathcal{C}}(\mathcal{U}) \rightarrow BG$, so I get a trivialization s for \mathcal{V} . This is a map $s_V : p^{-1}(V) \rightarrow V \times G$ that works as:

$$\begin{array}{ccc} p^{-1}(V) & \xrightarrow{p} & V \times G \\ \downarrow & & \downarrow \\ p^{-1}(\rho(V)) & \xrightarrow{t_{\rho(V)}} & \rho(V) \times G \end{array}$$

¹⁹If you want to work with the p -adics or something, there's a different construction you have to use.

Just by construction, we have a larger commutative diagram:

$$\begin{array}{ccccc} B\check{C}(\mathcal{V}) & \xRightarrow{\quad} & B\check{C}(\mathcal{U}) & \xRightarrow{\quad} & BG \\ & \searrow & \downarrow & & \\ & & X & & \end{array}$$

Suppose I have trivializations \mathcal{U}, t of P and \mathcal{V}, s of Q . Let \mathcal{W} be a common refinement. I have a diagram:

$$\begin{array}{ccc} & \check{C}(\mathcal{U}) & \\ \nearrow & \gamma_P^{\mathcal{W}} & \searrow \gamma_P^{\mathcal{U}} \\ \check{C}(\mathcal{W}) & \xRightarrow{\quad} & G \\ \searrow & \gamma_Q^{\mathcal{W}} & \nearrow \gamma_Q^{\mathcal{V}} \\ & \check{C}(\mathcal{V}) & \end{array}$$

I claim that there is a natural transformation $\beta : \gamma_P^{\mathcal{W}} \rightarrow \gamma_Q^{\mathcal{W}}$. Then, the two maps $\theta_P, \theta_Q : B\check{C}(\mathcal{W}) \simeq X \rightarrow BG$ are homotopic.

OK, so what is β ? It assigns to each object in $\check{C}(\mathcal{W})$ some x_W . At this point I didn't follow what was being said.

Ta-da! This completes the story that G -bundles are represented by BG . Let's see some examples then.

59.1. Two general principles. Let G be some topological group. Here is a summary of what we have done. I constructed EG , which is contractible with G acting freely on the right. There is an orbit projection $EG \rightarrow BG$, and it's a principal G -bundle provided G is, like, a Lie group. For instance a discrete group. And, it's universal, so that $\text{Bun}_G(X) \xleftarrow{\simeq} [X, BG]$ given by $f \mapsto [f^*EG]$.

Suppose G acts on E , say from the left. Then let E^{op} be E as a space, but with G acting on the left. So $g \cdot e = e \cdot g^{-1}$. I claim that we then have a fiber bundle:

$$E \rightarrow EG \times_G E \rightarrow BG$$

Note that I have to choose a point in EG to get a map $E \rightarrow EG \times_G E$.

I could collapse EG to a point instead, and I have a map $G \backslash E$. The fiber of the map $EG \times_G E \rightarrow G \backslash E$, and the fiber over G_x is BG_x , where $G_x = \{g : gx = x\}$.

What I want to say is that if G acts principally on E , then $E \rightarrow E/G$ is a principal G -bundle. We have a fiber bundle $EG \rightarrow EG \times_G E \rightarrow G \backslash E$. Since EG is contractible, then $EG \times_G E$ is weakly equivalent to $G \backslash E$. If $E \simeq *$, then p is also a weak equivalence. Thus $BG \simeq G \backslash E$. So if you come up with another principal action on a contractible space, then BG is weakly equivalent to $G \backslash E$. The construction with simplicial sets was a very concrete way of constructing BG , but you could have chosen any principal action on a contractible space.

Here's the second comment. Suppose X is a pointed path connected. Remember that X has a path space $PX = X_*^I$. This is contractible by the spaghetti move. The map $PX \rightarrow X$ is a fibration, with fiber ΩX .

For instance, suppose $X = BG$. Then, I have:

$$\begin{array}{ccc} G & \xrightarrow{\quad} & \Omega BG \\ & & \downarrow \\ EG_* & \xrightarrow{\quad} & PBG \simeq * \\ & \searrow & \swarrow \\ & BG & \end{array}$$

A nullhomotopy of $EG \rightarrow BG$ (it is nullhomotopic) is exactly a lift into the path space, so I have the map $EG \rightarrow PBG$ in the diagram above. As EG and PBG are both contractible, we find that ΩBG is weakly

equivalent to G . This weak equivalence is a H -map (it commutes up to homotopy with the multiplication on both sides).

REMARK 59.1 (Milnor). If X is a countable CW-complex, then ΩX is homotopy equivalent to a CW-complex. It's not a CW-complex (any space is weakly equivalent to a CW-complex, but these are homotopy equivalent to a CW-complex).

REMARK 59.2 (another Milnor remark). ΩX is weakly equivalent to a topological group $G X$ such that $B G X \simeq X$.

59.2. Examples. I want to say that $B U(n) \simeq \text{Gr}_n(\mathbf{C}^\infty)$. The reason is:

$$\begin{array}{ccc} U(n) & & U(n) \\ \downarrow & & \downarrow \\ E U(n) & \xrightarrow{\simeq} & V_n(\mathbf{C}^\infty) \simeq * \\ \downarrow & & \downarrow \\ B U(n) & \xrightarrow{\simeq} & \text{Gr}_n(\mathbf{C}^\infty) \end{array}$$

Here $V_n(\mathbf{C}^\infty)$ is the contractible space of complex n -frames in \mathbf{C}^∞ . It's the same as isometric embeddings of \mathbf{C}^n into \mathbf{C}^∞ . $U(n)$ acts by precomposition.

Let G be a compact Lie group (eg finite).

THEOREM 59.3 (Peter-Weyl). *There exists an embedding $G \hookrightarrow U(n)$ for some n .*

Thus, G acts principally on $V_n(\mathbf{C}^\infty)$, since $U(n)$ does. Thus $V_n(\mathbf{C}^\infty)/G$ is a model for $B G$!

For instance, what about Σ_n , acting on n -points? I can imitate that linear model like this. Let $\text{Conf}_n(\mathbf{R}^k)$ denote embeddings of $\{1, \dots, n\} \rightarrow \mathbf{R}^k$ (ordered distinct n -tuples). These things are definitely not contractible. The low-dimensional homotopy groups are zero, though. So, $\text{Conf}_n(\mathbf{R}^\infty) \simeq *$. The symmetric group obviously acts freely on this (same as principally for finite groups). Thus, $B \Sigma_n$ is th space of unordered configurations of n distinct points in \mathbf{R}^∞ . But, you know, any group acts freely on itself, and it embeds into a symmetric group. So, like above, if G is finite, a model for $B G$ is $\text{Conf}_n(\mathbf{R}^\infty)/G$.

One more thing. If A is a topological abelian group, then $\mu : A \times A \rightarrow A$ is a homomorphism. So, I get a map $B A \times B A \rightarrow B A$ which is another abelian group structure. We know what it is! $B A = K(A, 1)$. Its universal cover is contractible (it's $E A$). I have a topological abelian group model for $K(A, 1)$. Well, $B^2 A$ sits in a fibration $B A \rightarrow E B A \simeq * \rightarrow B^2 A$. So the homotopy groups of $B^2 A$ are the same as that of $B A$, but shifted. Doing this multiple times gives us a model:

$$B^n A = K(A, n)$$

It's one of the coolest things to do with the classifying space construction.

60. Why spectral sequences

61. Serre spectral sequence

Spectral sequences are one of these things for which anybody who is anybody must suffer through. Once you've done that, it's like linear algebra. You stop thinking so much about the "inner workings" later. Today will be the surface story, and we'll get into the innards later.

On Monday I was talking about the example of a filtered space. That gives rise to a filtered complex. That's a chain complex C , with an increasing sequence $F_* C$ of subchain complexes.

We saw various things: we've got

$$\begin{array}{ccccc} F_{s-1} C & \longrightarrow & F_s C & \longrightarrow & F_{s+1} C \\ & & \downarrow & & \downarrow \\ & & \text{gr}_s C & & \text{gr}_{s+1} C \end{array}$$

We then let $E_{st}^0 = \text{gr}_s C_{s+t}$, and we have a differential $d^0 : E_{st}^0 \rightarrow E_{s,t-1}^0$. We can go even further: I'll define $E_{st}^1 = H_{s,t}(E_{s,t}^0, d^0)$.

$$\begin{array}{ccccc} HF_{s-1} & \longrightarrow & HF_s & \longrightarrow & HF_{s+1} \\ & & \downarrow & & \\ E_{s-1,*}^1 & \xleftarrow{d^1} & E_{s,t}^1 & & \end{array}$$

We saw this already in cellular chains, where the E^1 were the cellular chains. Now, $d^1 : E_{s,t}^1 \rightarrow E_{s-1,t}^1$ since the differentials decrease total degree by 1. I could draw out the spectral sequence like this:

$$\begin{array}{ccc} * & \xleftarrow{d^2} & * \\ & \nwarrow d^1 & \downarrow d^0 \\ & * & * \end{array}$$

the vertical thing is t , called the complementary degree, and the horizontal indexing is the filtration degree s .

THEOREM 61.1. *Let F_*C be a filtered complex. There exists natural:*

- (1) *for any $r \geq 0$, a bigraded group $(E_{s,t}^r)_{s \geq 0, t \in \mathbf{Z}}$.*
- (2) *for any $r \geq 0$, a differential $d^r : E_{s,t}^r \rightarrow E_{s-r,t+r-1}^r$.*
- (3) $H_{s,t}(E_{*,*}^r, d^r) = E_{s,t}^{r+1}$.

*and (E^0, d^0) and (E^1, d^1) are as above. Then under certain hypotheses (see below) (F_*C is bounded below), there is an isomorphism:*

$$E_{s,t}^\infty \simeq \text{gr}_s H_{s+t}(C)$$

See below for what E^∞ means.

It's supposed to help us compute the homology of the thing we started with. This is called a *homology spectral sequence*.

There's a filtration $F_s H_n(C) := \text{Im}(H_n(F_s C) \rightarrow H_n(C))$. What the spectral sequence will tell you is information about the associated graded. This isn't so bad if you're over, like, vector spaces.

Let's assume that the filtration F_*C is bounded below (so $F_{-1}C = 0$). Then $E_{s,t}^0 = F_s C_{s+t} / F_{s-1} C_{s+t} = 0$ for $s < 0$. It's a "right half plane" spectral sequence. Thus, in our example, the differentials from the group at (s, t) must have $d^{s+1} = 0$. This tells us that there's a surjection $E_{s,t}^{s+1} \rightarrow E_{s,t}^{s+2}$. And that continues: we get surjections all the way, and take the direct limit of $E_{s,t}^r$, which is defined to be $E_{s,t}^\infty$.

OK, so for our theorem, we have the following picture of $E_{*,*}^\infty$:

$$\text{gr}_0 H_n(C) \simeq E_{0,n}^\infty$$

$$\text{gr}_1 H_n(C) \simeq E_{1,n-1}^\infty$$

$$\text{gr}_2 H_n(C) \simeq E_{2,n-2}^\infty$$

\ddots

Note that $\text{gr}_0 H_n(C) = F_0 H_n(C) = \text{Im}(H_n(F_0 C) \rightarrow H_n(C))$.

Maybe you still don't get the homology of n (like if F_* is 0). But if F_*C is exhaustive, then $F_* H_* C$ is also exhaustive (I said this on Monday). With this assumption, then we get all the associated graded pieces.

COROLLARY 61.2. Let $C \xrightarrow{f} D$ be a map of filtered complexes. Assume that the filtration on C and D are bounded below and exhaustive. Assume also that $E^r(f)$ is an isomorphism for some r . Then $f_* : H(C) \rightarrow H(D)$ is an isomorphism.

You're completely recovering the homology of C in this sense.

PROOF. $E^r(f)$ is an isomorphism, and it's also a chain map (it's compatible with the differential d^r). Thus $E^{r+1}(f)$ is an isomorphism. And so on. Thus, $E_{s,t}^\infty(f)$ is an isomorphism for all s, t . Thus the associated graded map $\text{gr}_s(f_*) : \text{gr}_s H_*(C) \rightarrow \text{gr}_s H_*(D)$ is an isomorphism. I have a short exact sequence:

$$0 \rightarrow F_0 H_* \rightarrow F_1 H_* \rightarrow \text{gr}_1 H_* \rightarrow 0$$

We have an isomorphism on the left and right nontrivial groups, so by the five lemma and induction, $F_s f_*$ is an isomorphism. The filtration was exhaustive, so f_* is an isomorphism. \square

This is convergence following Eilenberg-Moore.

Wow, OK. Let's talk about the Serre spectral sequence.

61.1. Serre spectral sequence. I'll give two constructions. I have a fibration $E \xrightarrow{p} B$, with B a CW-complex. I can define a filtration on E by taking preimages. So, I get a filtration $F_s S_*(E) = \text{Im}(S_*(p^{-1} \text{sk}_s(B)) \rightarrow S_*(E))$. I'll let $E_s = p^{-1} \text{sk}_s(B)$. This is bounded below and exhaustive. And that's the Serre spectral sequence. The low terms might depend on the CW-structure, but higher terms won't.

Let's think about how you build E_{s-1} . You have a pushout:

$$\begin{array}{ccc} E_{s-1} & \longrightarrow & E_s \\ \downarrow & & \downarrow \\ B_{s-1} & \longrightarrow & B_s \\ \uparrow & & \uparrow \\ \coprod_{\alpha \in \Sigma_s} S_\alpha^{s-1} & \longrightarrow & \coprod_{\alpha \in \Sigma_s} D_\alpha^s \end{array}$$

I can pullback E_s via:

$$\begin{array}{ccc} \coprod_{\alpha \in \Sigma_s} D_\alpha^s \times F_\alpha & \longrightarrow & E_s \\ \downarrow & & \downarrow \\ \coprod_{\alpha \in \Sigma_s} D_\alpha^s & \longrightarrow & B_s \end{array}$$

where F_α is p^{-1} of the center of α cell. In particular, I have a pushout:

$$\begin{array}{ccc} E_{s-1} & \longrightarrow & E_s \\ \uparrow & & \uparrow \\ \coprod_{\alpha \in \Sigma_s} S_\alpha^{s-1} \times F_\alpha & \longrightarrow & \coprod_{\alpha \in \Sigma_s} D_\alpha^s \times F_\alpha \end{array}$$

This fits inside a cube that I didn't have time to TeX . Now, we know that $E_{s,t}^1 = H_{s+t}(E_s, E_{s-1})$. The same argument shows that $E_{s,t}^1 = \bigoplus_{\alpha \in \Sigma_s} H_{s+t}(D_\alpha^s \times F_\alpha, S_\alpha^{s-1} \times F_\alpha)$. I can write this differently as $\bigoplus_{\alpha \in \Sigma_s} H_{s+1}((D_\alpha^s, S_\alpha^{s-1}) \times F_\alpha)$, which is, by Kunneth, exactly $\bigoplus_{\alpha \in \Sigma_s} H_t(F_\alpha)$. I guess I can write this as " $C_s(B; H_t(F_\alpha))$ ". There's some things wrong with writing it like that.

I mean, suppose B isn't connected. Then the F_α could have completely different homotopy types. That symbol $C_s(B; H_t(F_\alpha))$ doesn't make any sense then. Even if you're path-connected, there's still no canonical way to identify the fiber over one point to the fiber over another point. What you get is that $H_t(p^{-1}(-)) : \Pi_1(B) \rightarrow \mathbf{Ab}$. This is the same thing as a "local coefficient system" on B . So, the right thing to say is:

$$E_{s,t}^2 = H_s(B; \underline{H_t(\text{fiber})})$$

Pick a basepoint in B , and build the universal cover $\tilde{B} \rightarrow B$, with an action of $\pi_1(B, *)$. Look at $S_*(\tilde{B})$. There is an action of $\pi_1(B, *)$ on this chain complex. So $S_*(\tilde{B})$ is a chain complex of right modules over $\mathbf{Z}[\pi_1(B)]$. If B is connected, then giving a local coefficient system on B is the same thing as giving an action of $\pi_1(B)$ on $H_t(p^{-1}(*))$. This is now a left action. You know what you want to do then:

$$S_*(B; \underline{H_t(p^{-1}(*))}) = S_*(\tilde{B}) \otimes_{\mathbf{Z}[\pi_1(B)]} H_t(p^{-1}(*))$$

The homology of this chain complex is the E^2 -page. On Friday, I'll try to show you some applications of this.

We'll always be in the case where that local system is trivially (eg if π_1 acts trivially, like if B is simply connected).