

MATH 526 Notes

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Let X be a topological space with basepoint $x_0 \in X$. We already know two invariants,

- the fundamental group $\pi_1(X, x_0)$, and
- the homology groups $H_n(X)$ for $n \geq 0$, which are abelian groups.

We will look at two more invariants,

- the cohomology groups $H^n(X)$ for $n \geq 0$, and
- the higher homotopy groups $\pi_n(X, x_0)$ for $n \geq 0$.

In particular, $\pi_*(X, x_0)$ is a very good invariant in the following sense:

Theorem 1.1 (Whitehead). If $f : (X, x_0) \rightarrow (Y, y_0)$ is a map of CW-complexes, then f is a homotopy equivalence if and only if $\pi_*(f) : \pi_*(X, x_0) \rightarrow \pi_*(Y, y_0)$ is an isomorphism.

However, π_* is very hard to compute. On the other hand, $H^*(X)$ is relatively easy to compute, but this is not a complete invariant. For instance, $\mathbb{C}P^2$ and $S^2 \vee S^4$ have isomorphic cohomology groups, but they are not equivalent. $H^*(X)$ is closely related to $H_*(X)$, but $H^*(X)$ is a graded ring structure with cup product. It is contravariant in X , where $H_*(X)$ is covariant. The cup product is defined by the composition of induced diagonal map with an external product:

$$H^i(X) \times H^j(X) \xrightarrow{\times} H^{i+j}(X \times X) \xrightarrow{\Delta^*} H^{i+j}(X)$$

Other things we will talk about include:

- Natural transformations $H^i(-) \rightarrow H^j(-)$ encoded by Steenrod operations.
- $H^n(-)$ becomes a representable functor, i.e., $H^n(X) = [X, K(\mathbb{Z}, n)]$, where $K(\mathbb{Z}, n)$ is the Eilenberg-MacLane space, and the bracket indicates the homotopy classes of maps.
- Poincaré duality in $H^*(M)$ for compact manifold M , namely the cup product gives

$$H^i(M) \otimes H^{\dim(M)-i}(M) \xrightarrow{\sim} H^{\dim(M)}(M).$$

- Characteristic classes in $H^*(X)$ associated to vector bundles over X .

Recall for a topological space X , we obtain a collection of (singular) homology groups $H_n(X)$, with $H_*(X) = \bigoplus_{n \geq 0} H_n(X)$. The functoriality of morphisms says that $X \xrightarrow{f} Y \xrightarrow{g} Z$ induces $f_*g_* = (fg)_* : H_*(X) \xrightarrow{f_*} H_*(Y) \xrightarrow{g_*} H_*(Z)$. So

$$H_*(-) : \mathbf{Top} \rightarrow \mathbf{Ab}$$

is a well-defined functor. This factors into

$$\begin{array}{ccc} \mathbf{Top} & \xrightarrow{H_*(-)} & \mathbf{Ab} \\ & \searrow C_*(-) & \nearrow H_*(-) \\ & \mathbf{Ch} & \end{array}$$

Here $C_*(-)$ is usually the singular chain, given by $\partial : C_n(X) \rightarrow C_{n-1}(X)$, where $C_n(X)$ is the free abelian group generated by $\text{Hom}_{\mathbf{Top}}(\Delta^n, X) \cong \bigoplus \mathbb{Z}\sigma$. $\Delta^n \subseteq \mathbb{R}^{n+1}$ is the set of tuples (t_0, \dots, t_n) such that the coordinates sum to 1. The boundary is $\partial\sigma = \sum_{0 \leq i \leq n} (-1)^i \sigma|_{[v_0, \dots, \hat{v}_i, \dots, v_n]}$.

We say $C_*(-)$ is homotopy invariant, i.e., if $f : X \rightarrow Y$ is a homotopy equivalence, then the induced map $C_*(X) \rightarrow C_*(Y)$ on chain complexes is a chain equivalence.

Remark 1.2. $C_*^\Delta(X)$ and $C_*^{\text{CW}}(X)$ are both chain equivalent to $C_*(X)$.

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Here is a list of properties of $C_*(-) : \mathbf{Top} \rightarrow \mathbf{Ch}$:

- Functoriality: given a continuous map $f : X \rightarrow Y$, there is an induced map

$$\begin{aligned} f_* : C_*(X) &\rightarrow C_*(Y) \\ (\sigma : \Delta^n \rightarrow X) &\mapsto (f\sigma : \Delta^n \rightarrow Y) \end{aligned}$$

- Homotopy invariance: given $f, g : X \rightarrow Y$ such that $f \simeq g$, i.e., there is $H : X \times [0, 1] \rightarrow Y$ such that $H|_0 = f$ and $H|_1 = g$, then $f_* \simeq g_*$ as a chain homotopy equivalence, i.e., there exists maps $h_n : C_n(X) \rightarrow C_{n+1}(Y)$ making a diagram

$$\begin{array}{ccccccc} \cdots & \longrightarrow & C_{n+1}(X) & \longrightarrow & C_n(X) & \longrightarrow & C_{n-1}(X) \longrightarrow \cdots \\ & & \searrow h & \downarrow g & \downarrow f & \swarrow h & \downarrow g & \downarrow f \\ \cdots & \longrightarrow & C_{n+1}(Y) & \longrightarrow & C_n(Y) & \longrightarrow & C_{n-1}(Y) \longrightarrow \cdots \end{array}$$

such that $f - g = \partial h + h\partial$. Therefore $f_* = g_* : H_*(X) \rightarrow H_*(Y)$.

Remark 2.1. $f : A_* \rightarrow B_*$ is a chain equivalence if there exists $g : B_* \rightarrow A_*$ and $fg \simeq \text{id}_B$ and $gf \simeq \text{id}_A$, then $f_* : H_*(A_*) \rightarrow H_*(B_*)$ is an isomorphism, i.e., f is a quasi-isomorphism.

Example 2.2. The complexes $A : 0 \rightarrow \mathbb{Z} \xrightarrow{-2} \mathbb{Z} \rightarrow 0$ and $B : 0 \rightarrow 0 \rightarrow \mathbb{Z}/2\mathbb{Z} \rightarrow 0$ gives a quasi-isomorphism $f : A \rightarrow B$ in the canonical way, but this is not a chain equivalence, since the backwards map has to be zero.

- Additivity: $C_*(\coprod_\alpha X_\alpha) \cong \bigoplus_\alpha C_*(X_\alpha)$.
- Excision: given a pair (X, A) with $Z \subseteq A$ such that $\bar{Z} \subseteq \text{int}(A)$, then we have $C_*(X \setminus Z, A \setminus Z) \cong C_*(X, A)$.
- Mayer-Vietoris: given $A, B \subseteq X$, with $X = \text{int}(A) \cup \text{int}(B)$, then we have a short exact sequence

$$0 \longrightarrow C_*(A \cap B) \longrightarrow C_*(A) \oplus C_*(B) \longrightarrow C_*(X) \longrightarrow 0$$

The cochain complex is obtained via inverting the indices and maps δ from a chain complex. This induces a cohomology $H^*(C^*) = \ker(\delta)/\text{im}(\delta)$ as the quotient of cocycles over coboundaries. Now $f : A^* \rightarrow B^*$ is a quasi-isomorphism if $f^* : H^*(A^*) \rightarrow H^*(B^*)$ is an isomorphism. Similarly, one can define the cochain homotopy equivalence.

Example 2.3. If $C_* \in \mathbf{Ch}$, and $k \in \mathbf{Ab}$, then we can form cochain complex $C_k^* := \text{Hom}(C_*, k)$, where $C_k^n = \text{Hom}_{\mathbf{Ab}}(C_n, k) \xrightarrow{\delta} C_k^{n+1}$ by sending $f : C_n \rightarrow k$ to $f\partial : C_{n+1} \rightarrow C_n \rightarrow k$.

- $\text{Hom}(-, k) : \mathbf{Ch} \rightarrow \mathbf{coCh}$ is a functor.
- The functor preserves quasi-isomorphisms between chain complexes of free abelian groups.

Definition 2.4. For $k \in \mathbf{Ab}$, the singular cochains with coefficients in k is

$$\begin{array}{ccc} C^*(-, k) : \mathbf{Top} & \xrightarrow{\quad} & \mathbf{coCh} \\ & \searrow C_*(-) & \nearrow \text{Hom}(-, k) \\ & \mathbf{Ch} & \end{array}$$

The cohomology of X with coefficients in k is defined by $H^*(X; k) = H^*(C^*X, k)$. We have the convention $C^*(X) = C^*(X, \mathbb{Z})$.

Alternatively, we take the opposite categories \mathbf{Top}^* and \mathbf{Ch}^* so that the functors are viewed as covariant.

The corresponding map $\delta : C^n(X; k) \rightarrow C^{n+1}(X; k)$ is given by δf that maps $\sigma \in C_{n+1}(X)$ to $(-1)^{n+1}f(\partial\sigma)$. Although the cochains are in general the dual of chains, the cohomology is not going to be the dual of the homology.

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Recall:

$$\begin{array}{ccccc} & & H^*(-, k) & & \\ & \searrow & \text{arc} & \searrow & \\ \mathbf{Top}^{\text{op}} & \xrightarrow{C_*} & \mathbf{Ch}^{\text{op}} & \xrightarrow{\text{Hom}(-, k)} & \mathbf{coCh} & \xrightarrow{H^*} & \mathbf{GrAb} \end{array}$$

Properties of $H^*(-, k) : \mathbf{Top} \rightarrow \mathbf{GrAb}$:

- Dimension:

Claim 3.1. $H^i(\{*\}, k) = \begin{cases} 0, & i \neq 0 \\ k, & i = 0 \end{cases}$

Proof. Note that each degree of cohomology is given the free abelian group generated by $\text{Hom}(\Delta^n, \{*\})$, but the singleton set is the terminal object in the category of topological spaces, so there is always a unique generator, thus the chain complex is given by \mathbb{Z} 's on each degree $n \geq 0$.

Now the generating map at degree n is $\sigma_n : \Delta^n \rightarrow \{*\}$, and see Homework 1 where we proved the homology. Now looking at $C^*(\{*\}, k)$, we have

$$k \xrightarrow{0} k \xrightarrow{\cong} k \xrightarrow{0} k \longrightarrow \dots$$

and this gives the cohomology. □

- Homotopy: if $f \simeq g : X \rightarrow Y$, then $f^* = g^* : H^*(Y, k) \rightarrow H^*(X, k)$.

Proof. We have $f_* = g_* : C_*X \rightarrow C_*Y$, and then $\text{Hom}(f_*, k) \cong \text{Hom}(g_*, k)$, so $H^*(-)$ is invariant under cochain homotopies. □

- Additivity: $H^*(\coprod_{\alpha} X_{\alpha}, k) \cong \prod_{\alpha} H^*(X_{\alpha}, k)$.

Proof. We know that for chains there is $C_*(\coprod_{\alpha} X_{\alpha}) = \bigoplus_{\alpha} C_*(X_{\alpha})$, so the cochain version says that $C^*(\coprod_{\alpha} X_{\alpha}, k) \cong \text{Hom}(\bigoplus_{\alpha} C_*(X_{\alpha}), k) \cong \prod_{\alpha} \text{Hom}(C_*(X_{\alpha}), k) \cong \prod_{\alpha} C^*(X_{\alpha})$ and $H^* : \mathbf{coCh} \rightarrow \mathbf{GrAb}$ commutes with the product. □

- Exactness: for a pair (X, A) , there is a natural long exact sequence

$$\cdots \longrightarrow H^n(X, A; k) \longrightarrow H^n(X; k) \longrightarrow H^n(A; k) \longrightarrow \cdots$$

Proof. We have a short exact sequence

$$0 \longrightarrow C_*A \longrightarrow C_*X \longrightarrow C_*(X, A) \longrightarrow 0$$

where $C_*A \rightarrow C_*X$ is an inclusion of summands. Therefore, the quotient $C_*(X, A)$ is also a chain complex of free abelian groups. Therefore, taking the cochains also gives a short exact sequence. We then obtain a short exact sequence of cochain complexes

$$0 \longrightarrow C^*(X, A; k) \longrightarrow C^*(X; k) \longrightarrow C^*(A; k) \longrightarrow 0$$

and can then apply cohomology functor. □

- Excision: given a pair (X, A) and Z such that $\bar{Z} \subseteq \text{int}(A)$, we have $H^*(X, A; k) \cong H^*(X \setminus Z, A \setminus Z; k)$.
- Mayer-Vietoris: given $A, B \subseteq X$ such that $\text{int}(A) \cup \text{int}(B) = X$, then we have a natural long exact sequence

$$\cdots \longrightarrow H^n(X; k) \longrightarrow H^n(A; k) \oplus H^n(B; k) \longrightarrow H^n(A \cap B; k) \longrightarrow \cdots$$

Definition 3.2. A functor $E^* : \mathbf{Top}^{\text{op}} \rightarrow \mathbf{GrAb}$ is called a generalized cohomology theory if it satisfies the four middle property (except the dimension property and Mayer-Vietoris).

Remark 3.3. If E^* also satisfies the dimension property, then E^* is naturally isomorphic to the cohomology $H^*(-; k)$. There are also other generalized cohomology theories like K -theory, cobordism, etc.

The Mayer-Vietoris becomes a consequence of the first five properties.

We will now try to use homological algebra to relate $H_*(X) = H_*(CX)$ and $H^*(X; k) = H^*(\text{Hom}(C_*X, k))$.

Definition 3.4. We say $C_*(X; k) \cong C_*(X) \otimes_{\mathbb{Z}} k$ and $H_*(X; k) \cong H_*(C_*X \otimes k)$ gives the singular homology of X with coefficients in k .

Lemma 3.5. $- \otimes k : \mathbf{Ab} \rightarrow \mathbf{Ab}$ is a right exact functor. $\text{Hom}(-, k) : \mathbf{Ab}^{\text{op}} \rightarrow \mathbf{Ab}$ is left exact.

Proof. Exercise. □

Remark 3.6. The covariant hom functor is also left exact.

Remark 3.7. The left adjoint is right exact, the right adjoint is left exact. In particular, we have the hom-tensor adjunction

$$\text{Hom}(A, \text{Hom}(B, C)) \cong \text{Hom}(A \otimes B, C).$$

Note that

$$\text{Hom}(A, \text{Hom}(B, C)) \cong \text{Hom}(A \otimes B, C) \cong \text{Hom}(B \otimes A, C) \cong \text{Hom}(B, \text{Hom}(A, C))$$

Example 3.8. Consider

$$0 \longrightarrow \mathbb{Z} \xrightarrow{\times n} \mathbb{Z} \longrightarrow \mathbb{Z}/n\mathbb{Z} \longrightarrow 0$$

Tensoring with $\mathbb{Z}/n\mathbb{Z}$, we do not have exactness.

Example 3.9.

$$0 \longrightarrow A \longrightarrow A \oplus C \longrightarrow C \longrightarrow 0$$

is always exact after tensoring $- \otimes k$ or applying the hom functor $\text{Hom}(-, k)$.

Definition 3.10. A short exact sequence $0 \rightarrow A \xrightarrow{i} B \xrightarrow{p} C \rightarrow 0$ is split if any of the following equivalence conditions hold:

- (i) p has a section $s : C \rightarrow B$ such that $ps = 1$;
- (ii) i has a retraction $r : B \rightarrow A$ such that $ri = 1$;
- (iii) $B \cong A \oplus C$, i.e.,

$$\begin{array}{ccccccc} 0 & \longrightarrow & A & \xrightarrow{i} & B & \xrightarrow{p} & C \longrightarrow 0 \\ & & \parallel & & \downarrow & & \parallel \\ 0 & \longrightarrow & A & \xrightarrow{i} & A \oplus C & \xrightarrow{p} & C \longrightarrow 0 \end{array}$$

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We will prove that (ii) implies (iii).

Suppose $b \in B$, then $b = (b - irb) + irb$, which is a decomposition of elements in $\ker(r)$ and in $\text{im}(i)$, respectively. Also, $\ker(r) \cap \text{im}(i) = 0$, therefore $B = \ker(r) \oplus \text{im}(i)$. Since i is an inclusion, then $\text{im}(i) \cong A$. Now $p : B \rightarrow C$ factors through the projection onto $\ker(r)$ since $ri = 0$. By restricting p onto $\ker(r)$, we see p is also injective, thereby an isomorphism.

Lemma 4.1. If we have a split exact sequence

$$0 \longrightarrow A \begin{array}{c} \xrightarrow{i} \\ \xleftarrow{r} \end{array} B \begin{array}{c} \xrightarrow{p} \\ \xleftarrow{s} \end{array} C \longrightarrow 0$$

then $- \otimes k$ and $\text{Hom}(-, k)$ preserves the split exactness, i.e.,

$$0 \longrightarrow A \otimes k \longrightarrow B \otimes k \longrightarrow C \otimes k \longrightarrow 0$$

and

$$0 \longrightarrow \text{Hom}(C, k) \longrightarrow \text{Hom}(B, k) \longrightarrow \text{Hom}(A, k) \longrightarrow 0$$

The point is tensors and homs preserve retracts.

Proof. • $(r \otimes \text{id}_k)(i \otimes \text{id}_k) = ri \otimes \text{id}_k = \text{id}_{A \otimes k}$, so $i \otimes \text{id}_k$ is split injective.

- Similarly, $\text{Hom}(i, \text{id})$ is split surjective.

□

Example 4.2. Given a surjection $B \rightarrow C \rightarrow 0$ such that C is free abelian, then there is always a section $s : C \rightarrow B$ making the exact sequence split. (That is, C is projective.) That is, if $0 \rightarrow A \rightarrow B \rightarrow C \rightarrow 0$ is an exact sequence where C is free, then the sequence is split exact.

Definition 4.3. Let $C \in \mathbf{Ab}$. A free resolution of C is a chain complex of free objects

$$\cdots \longrightarrow F_2 \longrightarrow F_1 \longrightarrow F_0 \longrightarrow 0$$

and an augmentation $F_0 \rightarrow C$, so that

$$\cdots \longrightarrow F_2 \longrightarrow F_1 \longrightarrow F_0 \longrightarrow C \longrightarrow 0$$

is acyclic, i.e., exact everywhere.

Example 4.4.

$$0 \longrightarrow \mathbb{Z} \xrightarrow{\times n} \mathbb{Z} \longrightarrow 0$$

is a free resolution of $\mathbb{Z}/n\mathbb{Z}$. So is

$$\cdots \longrightarrow \mathbb{Z} \xrightarrow{\cong} \mathbb{Z} \xrightarrow{0} \mathbb{Z} \xrightarrow{\cong} \mathbb{Z} \xrightarrow{0} \mathbb{Z} \xrightarrow{\times n} \mathbb{Z} \longrightarrow 0$$

and

$$0 \longrightarrow \mathbb{Z} \xrightarrow{\times n} \mathbb{Z} \longrightarrow \mathbb{Z}/n\mathbb{Z} \longrightarrow 0$$

as well as

$$\cdots \longrightarrow \mathbb{Z} \xrightarrow{\cong} \mathbb{Z} \xrightarrow{0} \mathbb{Z} \xrightarrow{\cong} \mathbb{Z} \xrightarrow{0} \mathbb{Z} \oplus \mathbb{Z} \xrightarrow{\text{id} \oplus (\times n)} \mathbb{Z} \oplus \mathbb{Z} \longrightarrow 0$$

Lemma 4.5. Any $C \in \mathbf{Ab}$ admits a free resolution, and moreover, it admits a resolution of length 1; given by

$$0 \longrightarrow F_1 \longrightarrow F_0 \longrightarrow C \longrightarrow 0$$

Proof. Choose a surjection $p : F_0 \rightarrow C$ from a free abelian group F_0 to C . Let $F_1 = \ker(p)$, then F_1 is free, so we are done. \square

Lemma 4.6. Free resolutions are essentially unique, i.e., if $F \rightarrow C$ and $F' \rightarrow C$ are free resolutions, then there is a quasi-isomorphism $F \xrightarrow{\sim} F'$ which commutes with the augmentations to C .

Definition 4.7. Let $C \in \mathbf{Ab}$ and let $F \rightarrow C$ be a free resolution, then we define the torsion groups to be $\mathrm{Tor}_n^{\mathbb{Z}}(C, k) = H_n(F \otimes k)$, and the ext groups to be $\mathrm{Ext}_{\mathbb{Z}}^n(C, k) = H^n(\mathrm{Hom}_{\mathbb{Z}}(F, k))$.

Remark 4.8. • Tor and Ext are independent of the choice of resolutions.

- $\mathrm{Tor}_n^{\mathbb{Z}}$ and $\mathrm{Ext}_{\mathbb{Z}}^n$ are zero for $n > 1$.
- $\mathrm{Tor}_n^{\mathbb{Z}}(C, k) \cong \mathrm{Tor}_n^{\mathbb{Z}}(k, C)$.
- $\mathrm{Tor}_0^{\mathbb{Z}}(C, k) \cong C \otimes k$.
- $\mathrm{Ext}_{\mathbb{Z}}^0(C, k) \cong \mathrm{Hom}(C, k)$.

Example 4.9. • If C is free, then $\mathrm{Tor}_1(C, k) = \mathrm{Ext}^1(C, k) = 0$.

- $\mathrm{Tor}_1(\mathbb{Z}/p\mathbb{Z}, \mathbb{Z}/p\mathbb{Z}) = \mathbb{Z}/p\mathbb{Z}$.
- $\mathrm{Tor}_1(\mathbb{Z}/p\mathbb{Z}, \mathbb{Z}) = 0$.
- $\mathrm{Ext}^1(\mathbb{Z}/p\mathbb{Z}, \mathbb{Z}/p\mathbb{Z}) = \mathbb{Z}/p\mathbb{Z}$.
- $\mathrm{Ext}^1(\mathbb{Z}/p\mathbb{Z}, \mathbb{Z}) = \mathbb{Z}/p\mathbb{Z}$.
- $\mathrm{Ext}^1(\mathbb{Z}, \mathbb{Z}/p\mathbb{Z}) = 0$.

Proof. Look at

$$0 \longrightarrow F_1 = \mathbb{Z} \longrightarrow F_0 = \mathbb{Z} \longrightarrow C = \mathbb{Z}/p\mathbb{Z} \longrightarrow 0$$

then $\mathrm{Tor}_*(\mathbb{Z}/p\mathbb{Z}, k) = H_*(F_1 \otimes k = k \xrightarrow{\times p} F_0 \otimes k = k) = \begin{cases} k[p], * = 0 \\ k/pk, * = 1 \end{cases}$. Here $k[p]$ denotes p -torsion subgroup

of k . Moreover, $\mathrm{Ext}^*(\mathbb{Z}/p\mathbb{Z}, k) = H^*(\mathrm{Hom}(F_1, k) = k \xleftarrow{\times p} \mathrm{Hom}(F_0, k) = k) = \begin{cases} k[p], * = 0 \\ k/pk, * = 1 \end{cases}$. \square

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Recall that cohomology are basically the dual of homology, where the difference originates from the failure of exactness of the hom functor.

Theorem 5.1 (Universal Coefficient Theorem). Let C_* be a chain of free abelian groups and $k \in \mathbf{Ab}$, then there exists a natural short exact sequence

$$0 \longrightarrow \mathrm{Ext}^1(H_{n-1}(C_*), k) \longrightarrow H^n(\mathrm{Hom}(C_*, k)) \xrightarrow{h} \mathrm{Hom}(H_n(C_*), k) \longrightarrow 0$$

that splits in an unnatural sense.

Here we define $h \in \mathrm{Hom}(H^n(\mathrm{Hom}(C_*, k)), \mathrm{Hom}(H_n(C_*), k))$. Note that this hom set is isomorphic to the hom set $\mathrm{Hom}(H^n(\mathrm{Hom}(C_*, k)) \otimes H_n(C_*), k)$ via the tensor-hom adjunction. That is, h is given by a bilinear pairing $H^n(\mathrm{Hom}(C_*, k)) \times H_n(C_*) \rightarrow k$. We use the Kronecker pairing $([f], [x]) \mapsto f(x)$. To see this is well-defined, let $f \in \mathrm{Hom}(C_n, k)$ with $\delta f = 0$, for $x \in C_n$, we have $\partial x = 0$. Now replace x by $x + \partial y$, then $f(x + \partial y) = f(x) = f(\partial y) = f(x) \pm (\delta f)(y) = f(x)$. Also, replace f by $f + \delta(g)$ gives $(f + \delta(g))(x) = f(x) + (\delta g)(x) = f(x) + g(\delta x) = f(x)$.

Lemma 5.2. h is a split surjection.

Proof. Write $C_k^* = \text{Hom}(C_*, k)$. Now $h : \ker(\delta, C_k^n \rightarrow C_k^{n+1}) \rightarrow \text{Hom}(H_n(C_*), k)$ via $h : f \mapsto (x \mapsto f(x))$, then we will construct a section of h via $\varphi \mapsto \tilde{\varphi}$. Let $Z_n = \ker(\partial)$ and $B_n = \text{im}(\partial)$, then $H_n(C_*) = Z_n/B_n$, and the short exact sequence of free abelian groups

$$0 \longrightarrow Z_n \xrightarrow{i} C_n \longrightarrow B_{n-1} \longrightarrow 0$$

and this splits so $C_n \cong Z_n \oplus B_{n-1}$. Given $\varphi : H_n(C_*) \rightarrow k$, we have

$$C_n \xrightarrow{r} Z_n \longrightarrow Z_n/B_n \xrightarrow{\varphi} k$$

where r is the retraction to i , and we define the composition to be $\tilde{\varphi}$. Now the composition

$$C_{n+1} \xrightarrow{\partial} C_n \longrightarrow Z_n \longrightarrow Z_n/B_n \longrightarrow k$$

is still zero since $C_{n+1} \rightarrow Z_n$ is zero, but that means $\delta\tilde{\varphi}$ is also zero. \square

We will now prove the universal coefficient theorem.

Proof. Since h is a split surjection, then we know this extends to a short exact sequence, hence we just need to identify the kernel of h , i.e., to show that $\ker(h) \cong \text{Ext}^1(H_{n-1}(C_*), k)$. Given the split short exact sequence

$$0 \longrightarrow Z_n \xrightarrow{i} C_n \xrightarrow{\partial} B_{n-1} \longrightarrow 0$$

we have a diagram

$$\begin{array}{ccccccc} & & \vdots & & \vdots & & \vdots \\ & & \downarrow 0 & & \downarrow \delta & & \downarrow 0 \\ 0 & \longrightarrow & \text{Hom}(B_{n-1}, k) & \longrightarrow & \text{Hom}(C_n, k) & \longrightarrow & \text{Hom}(Z_n, k) \longrightarrow 0 \\ & & \downarrow 0 & & \downarrow \delta & & \downarrow 0 \\ 0 & \longrightarrow & \text{Hom}(B_n, k) & \longrightarrow & \text{Hom}(C_{n+1}, k) & \longrightarrow & \text{Hom}(Z_{n+1}, k) \longrightarrow 0 \\ & & \downarrow 0 & & \downarrow \delta & & \downarrow 0 \\ & & \vdots & & \vdots & & \vdots \end{array}$$

which is a short exact sequence of complexes. By the snake lemma, we have the long exact sequence of cohomology $\cdots \rightarrow H^n(B_k^{*-1}) \rightarrow H^n(C_k^*) \rightarrow H^n(Z_k^*) \rightarrow H^{n+1}(B_k^{*-1}) \rightarrow \cdots$. We claim that the connecting homomorphism $H^n(Z_k^*) \rightarrow H^{n+1}(B_k^{*-1})$ is $\text{Hom}(B_n \subseteq Z_n, k)$. But $0 \rightarrow B^n \rightarrow Z^n \rightarrow H_n(C_*) \rightarrow 0$ is a free resolution of $H_n(C_*)$ of length 1. Then $H^*(\beta : \text{Hom}(Z_n, k) \rightarrow \text{Hom}(B_n, k)) = \text{Ext}^*(H_n(C_*), k)$ where β has kernel $\text{Hom}(H_n(C_*), k)$ and cokernel $\text{Ext}^1(H_n(C_*), k)$. Therefore, the long exact sequence of cohomology is the splicing (as epi-mono factorization) of

$$0 \longrightarrow \text{coker}(\beta_{n-1}) \longrightarrow H_n(C_k^*) \longrightarrow \ker(\beta_n) \longrightarrow 0$$

and by identification we are done. \square

Corollary 5.3. If $C_* \rightarrow C'_*$ is a quasi-isomorphism, then $\text{Hom}(C'_*, k) \rightarrow \text{Hom}(C_*, k)$ is a quasi-isomorphism.

Corollary 5.4. Let $X \in \mathbf{Top}$ and $A \subseteq X$, then there exists a short exact sequence

$$0 \longrightarrow \text{Ext}^1(H_{n-1}(X, A), k) \longrightarrow H^n(X, A; k) \longrightarrow \text{Hom}(H_n(X, A); k) \longrightarrow 0$$

which is natural in (X, A) . This also splits in (X, A) in an unnatural way.

Theorem 5.5. If C_* is a chain complex of free abelian groups, then there is a short exact sequence

$$0 \longrightarrow H_n(C_*) \otimes k \longrightarrow H_n(C_* \otimes k) \longrightarrow \mathbf{Tor}_1(H_{n-1}(C_*, k) \longrightarrow 0$$

which is natural. It splits unnaturally.

Corollary 5.6. For any pair (X, A) , there is a natural short exact sequence

$$0 \longrightarrow H_n(X, A) \otimes k \longrightarrow H_n(X, A; k) \longrightarrow \mathbf{Tor}_1(H_{n-1}(X, A), k) \longrightarrow 0$$

which splits in an unnatural way.

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Example 6.1. Take $X = \mathbb{C}P^2$, then the Tor and Ext terms go away, so the cohomology is equivalent to the homology.

Example 6.2. Take $X = \mathbb{R}P^2$, the Tor term gives $\mathbf{Tor}_1(\mathbb{Z}/2\mathbb{Z}, k) = k/2 \cong k[2]$, as the 2-torsion of k , i.e., the set of $a \in k$ such that $2a = 0$. Also, $\mathbf{Ext}^1(\mathbb{Z}/2\mathbb{Z}, k) = k/2k$.

Indeed, the Tor is given by the homology on multiplication by 2 map over k via tensor, and the Ext is given by the cohomology on multiplication by 2 map over k via hom.

Tor stands for torsion and Ext stands for extension.

Went on to talk about the limits and colimits.

Remark 6.3. In many abelian categories (and in particular, the category of abelian groups), we find a short exact sequence

$$0 \longleftarrow \operatorname{colim}_I \longleftarrow \bigoplus_{i \geq 0} X_i \longleftarrow \bigoplus_{i \geq 0} X_i \longleftarrow 0$$

and note that taking the dual version in the opposite category, we should obtain a sequence in the covariant sense. However, there is an asymmetry given by

$$0 \longrightarrow \lim_{I^{\text{op}}} X \longrightarrow \prod_{i \geq 0} X_i \longrightarrow \prod_{i \geq 0} X_i \longrightarrow \lim_{I^{\text{op}}}^1 X \longrightarrow 0$$

which is not short anymore. This is called a Milnor sequence.

7 SEPT 6, 2023

The colimit of the empty diagram is the initial object; dually, the limit of the empty diagram is the terminal object.

Definition 7.1. We say $X : I \rightarrow \mathcal{C}$ is a filtered diagram if

- $\text{Ob}(\mathcal{C}) \neq \emptyset$,
- for all $i, j \in I$, there exists $k \in I$ and morphisms $i \rightarrow k$ and $j \rightarrow k$, and
- for parallel morphisms $a, b : i \rightarrow j$ in I , then there exists coequalizers.

Example 7.2. A poset (as a category) P is a directed set if for any $i, j \in P$, there exists $k \in P$ such that $i \leq k$ and $j \leq k$.

For a filtered diagram $X : I \rightarrow \mathbf{Set}$, the colimit $\operatorname{colim}_I X$ exists and is isomorphic to $\coprod_{i \in I} X_i / \sim$, where $x_i \in X_i$ and $x_j \in X_j$ are equivalent if for some $k \in I$, we have $a : i \rightarrow k$ and $b : j \rightarrow k$ and that $a(x_i) = b(x_j)$

For concrete categories, we forget the additional structure to the category of sets, and find the colimits there, and give it the additional structure we want.

Lemma 7.3. If I is a directed set, then

$$0 \longrightarrow \bigoplus_{i \in I} A_i \longrightarrow \bigoplus_{i \in I} A_i \longrightarrow \operatorname{colim}_{i \in I} A_i \longrightarrow 0$$

$$(a_i)_{i \in I} \longrightarrow (a_j - f_{ij}(a_i))$$

where $f_{ij} : i \rightarrow j$.

Example 7.4. The colimit of a sequence given by $A \xrightarrow{\times n} A$ is $A \left[\frac{1}{n} \right]$.

Lemma 7.5. Colimit functor is exact in category of abelian groups.

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- For a sequential diagram

$$\cdots \longrightarrow A_2 \longrightarrow A_1 \longrightarrow A_0$$

the limit of A_i 's is the terminal cone, and in fact is the kernel of

$$\begin{aligned} \prod_{i \geq 0} A_i &\rightarrow \prod_{i \geq 0} A_i \\ (a_i) &\mapsto (a_i - f_{i+1}(a_{i+1}))_i \end{aligned}$$

However, this sequence is not exact, as we discussed before.

Lemma 8.1. Let

$$\begin{array}{ccccccc} 0 & \longrightarrow & A_i & \longrightarrow & B_i & \longrightarrow & C_i \longrightarrow 0 \\ & & \downarrow & & \downarrow & & \downarrow \\ 0 & \longrightarrow & A_{i-1} & \longrightarrow & B_{i-1} & \longrightarrow & C_{i-1} \longrightarrow 0 \end{array}$$

then we have a long exact sequence

$$0 \longrightarrow \lim A_i \longrightarrow \lim B_i \longrightarrow \lim C_i \longrightarrow \lim^1 A_i \longrightarrow \lim^1 B_i \longrightarrow \lim^1(C_1) \longrightarrow 0$$

Proof. Take the products to get

$$\begin{array}{ccccccc} 0 & \longrightarrow & \prod_i A_i & \longrightarrow & \prod_i B_i & \longrightarrow & \prod_i C_i \longrightarrow 0 \\ & & \downarrow & & \downarrow & & \downarrow \\ 0 & \longrightarrow & \prod_i A_{i-1} & \longrightarrow & \prod_i B_{i-1} & \longrightarrow & \prod_i C_{i-1} \longrightarrow 0 \end{array}$$

and now use the snake lemma. □

Example 8.2. The p -adic integers $\mathbb{Z}_p = \lim(\cdots \rightarrow \mathbb{Z}/p^k \rightarrow \mathbb{Z}/p^{k+1} \rightarrow \cdots)$ is a limit.

Theorem 8.3 (Mittag-Leffler Condition). If $\{A_{i+1} \rightarrow A_i\}$ satisfies for each k , there is $i \geq k$ such that $\operatorname{im}(A_i \rightarrow A_k) \rightarrow \operatorname{im}(A_j \rightarrow A_k)$ for all $j \geq i \leq k$, then $\lim^1(A_i) = 0$.

Example 8.4. 1. This is true if all maps are surjections.

2. This is also true if all A_i 's are finite.

Definition 8.5. Recall that a mapping cylinder is $M_f = (X \times s[0, 1] \amalg Y) / ((x, 1) \sim f(x))$, so there is an inclusion $X \hookrightarrow M_f \cong Y$. Now given a sequence with $f_i : X_i \rightarrow X_{i+1}$, then the mapping telescope is

$$T = \text{Tel}(X_*) = \left(\coprod_{n \geq 0} X_n \times [0, 1] \right) / ((n, x, 1) \sim (n+1, f_n(x), 0)),$$

with

$$\begin{aligned} i_n : X_n &\rightarrow T \\ x &\mapsto (n, x_n, 0) \end{aligned}$$

and homotopies $(i_n \circ f_{n-1}) \cong i_{n-1} : X_{n-1} \rightarrow T$. Therefore, the diagrams

$$\begin{array}{ccc} H_*(X_{n-1}) & & \\ \downarrow (f_{n-1})_* & \searrow (i_{n-1})_* & \\ & H_*(T) & \\ \uparrow (i_n)_* & \nearrow & \\ H_*(X_n) & & \end{array}$$

commute. This induces a map $\text{colim}_n(H_*(X_n)) \rightarrow H_*(T)$. We claim that this is an isomorphism.

Proof. Indeed, consider the refinement

$$\begin{aligned} \lambda : T = \coprod_n X_n \times [0, 1] / \sim &\rightarrow \mathbb{R}_{\geq 0} \\ (n, x, t) &\mapsto n + t \end{aligned}$$

Let $T_{\leq a} = \lambda^{-1}([0, a])$ or $T_{< a} = \lambda^{-1}([0, a])$. We observe that $T_{\leq n}$ has a homotopy equivalence via $X_n \hookrightarrow T_{\leq n}$ with a deformation retraction. But $T_{\leq n}$ is also homotopy equivalent to $T_{< n+1}$. The upshot is that it suffices to show that $\text{colim}(H_*(T_{< n})) \rightarrow H_*(T)$ is an isomorphism. \square

Proposition 8.6. Let Y be a space and let \mathcal{A} be a collection of subspaces forming a direct system under inclusion. Assume that $Y = \bigcup_{A \in \mathcal{A}} A$, and for any compact $K \subseteq Y$, $K \subseteq A$ for some $A \in \mathcal{A}$. Then the map $\text{colim}_{A \in \mathcal{A}} C_*(A \rightarrow C_*(Y))$ is an isomorphism, hence induces an isomorphism on the level of homology: $\text{colim}(H_*(A)) \cong H_*(Y)$.

9 SEPT 11, 2023

Recall that $H_*(\text{Tel}(X_n)) \cong \text{colim}_n H_*(X_n)$, with the proof replying on $C_*(\text{Tel}(X_n)) \cong \text{colim}_n C_*(X_n)$.

Example 9.1. $\text{Tel}(S^1 \xrightarrow{p} S^1 \xrightarrow{p} \dots) = T = S^1 \left[\frac{1}{p} \right]$. Correspondingly, we have $\text{colim}(H_0(S^1) \cong \mathbb{Z} \xrightarrow{p*} H_0(S^1) \cong \mathbb{Z} \xrightarrow{p*} \dots) = \mathbb{Z}$, where the induced maps are just identities. Also, $\text{colim}(H_1(S^1) \cong \mathbb{Z} \xrightarrow{p*} H_1(S^1) \cong \mathbb{Z} \xrightarrow{p*} \dots) = \mathbb{Z} \left[\frac{1}{p} \right] \cong H_1(T)$, where the induced maps are multiplications by p .

By the Universal Coefficient theorem, we can calculate the cohomology of T as follows:

$$0 \longrightarrow \text{Ext}^1(H_n^1(S^1 \left[\frac{1}{p} \right]), \mathbb{Z}) \longrightarrow H^n(S^1 \left[\frac{1}{p} \right]) \text{Hom}(H_n(S^1 \left[\frac{1}{p} \right]), \mathbb{Z}) \longrightarrow 0$$

Here

- $H^0 * (S^1 \left[\frac{1}{p} \right]) = \text{Hom}(\mathbb{Z}, \mathbb{Z}) = \mathbb{Z};$
- $H^1(S^1 \left[\frac{1}{p} \right]) \cong \text{Hom}(\mathbb{Z} \left[\frac{1}{p} \right], \mathbb{Z}) = 0$, since the Ext term is 0;

- Higher homologies are zero, so $H^2(S^1 \left[\frac{1}{p} \right]) \cong \text{Ext}(\mathbb{Z} \left[\frac{1}{p} \right], \mathbb{Z}) \cong \mathbb{Z}_p/\mathbb{Z}$, the p -adic integers over \mathbb{Z} .

We are interested in calculating $H^*(\text{Tel})$ in terms of $H^*(X_i)$'s. Note that the chain complex $C_*(\text{Tel}(X_i)) \cong \text{colim}_i(C_*X_i)$, so

$$\begin{aligned} C^*(\text{Tel}(X_i)) &= \text{Hom}(\text{colim}_i(C_*X_i), \mathbb{Z}) \\ &= \lim_i(C^*(X_i)). \end{aligned}$$

Therefore, the question becomes, what is $H^*(\lim_i(C_i^*))$?

Theorem 9.2 (Milnor Exact Sequence). Suppose $\{C_i^*\}$ is an inverse system of cochain complexes, such that for each n , $\{C_i^n\}$ is an inverse system that satisfies Mittag-Leffler condition, i.e., we need $\lim^1_i = 0$, then we have a short exact sequence

$$0 \longrightarrow \lim_i^1(H^{n-1}(C_i^*)) \longrightarrow H^n(\lim_i C_i^*) \longrightarrow \lim_i(H^n(C_i^*)) \longrightarrow 0$$

Proof. We set $B_i^n = \text{im}(\delta : C_i^{n-1} \rightarrow C_i^n)$, and $Z_i^n = \ker(\delta : C_i^n \rightarrow C_i^{n+1})$. With this notation, we have a system of short exact sequences

$$\begin{array}{ccccccc} 0 & \longrightarrow & Z_i^n & \longrightarrow & C_i^n & \xrightarrow{\delta} & B_i^{n+1} \longrightarrow 0 \\ & & \downarrow & & \downarrow & & \downarrow \\ 0 & \longrightarrow & Z_{i-1}^n & \longrightarrow & C_{i-1}^n & \xrightarrow{\delta} & B_{i-1}^{n+1} \longrightarrow 0 \end{array}$$

Therefore we have a long exact sequence

$$0 \longrightarrow \lim_i Z_i^n \longrightarrow \lim_i C_i^n \longrightarrow \lim_i B_i^{n+1} \longrightarrow \lim_i^1 Z_i^n \longrightarrow \lim_i^1 C_i^n \longrightarrow \lim_i^1 B_i^{n+1} \longrightarrow 0$$

By assumption, $\lim_i^1 C_i^n = 0$, so $\lim_i^1 B_i^{n+1} = 0$, and we have the sequence

$$0 \longrightarrow \lim_i Z_i^n \longrightarrow \lim_i C_i^n \longrightarrow \lim_i B_i^{n+1} \longrightarrow \lim_i^1 Z_i^n \longrightarrow 0$$

Denote $C^* = \lim_i C_i^*$, and $Z^n = \ker(C^n \xrightarrow{\delta} C^{n+1})$, and $B^n = \text{im}(C^{n-1} \rightarrow C^n)$. This gives

$$\begin{array}{ccccccc} 0 & \longrightarrow & Z^n & \longrightarrow & C^n & & \lim_i B_i^{n+1} \longrightarrow \lim_i^1 Z_i^n \longrightarrow 0 \\ & & & & \searrow \delta & \nearrow & \\ & & & & B_{n+1} & & \end{array}$$

We know have $0 \subseteq B^{n+1} \subseteq \lim_i B_i^{n+1} \subseteq \lim_i Z_i^{n+1} = Z^{n+1}$, therefore this gives an exact sequence

$$0 \longrightarrow \lim_i B_i^{n+1}/B^{n+1} \longrightarrow Z^{n+1}/B^{n+1} \longrightarrow Z^{n+1}/\lim_i B_i^{n+1} \longrightarrow 0$$

so this is

$$0 \longrightarrow \lim_i^1 Z_i^n \longrightarrow H^{n+1}(C^*) \longrightarrow Z^{n+1}/\lim_i B_i^{n+1} \longrightarrow 0$$

From the canonical exact sequence

$$0 \longrightarrow B_i^n \longrightarrow Z_i^n \longrightarrow H^n(C_i^*) \longrightarrow 0$$

we induce

$$0 \longrightarrow \lim_i B_i^n \longrightarrow Z^n \longrightarrow \lim_i H^n(C_i^n) \longrightarrow \lim_i^1 B_i^n \longrightarrow \lim_I^1 Z_i^n \longrightarrow \lim_i^1 H^n(C_i^*) \longrightarrow 0$$

but we have $\lim_i^1 B_i^n = 0$, so $\lim_i^1 Z_i^n \cong \lim_i^1 H^n(C_i^*)$, therefore we identify $Z^n / \lim_i B_i^{n+1} \cong \lim_i H^{n+1}(C_i^*)$. \square

Corollary 9.3. Let $X \in \mathbf{Top}$ and $X = \bigcup_i X_i$ such that if there is compact $K \subseteq X$, then there exists some i such that $K \subseteq X_i$. If this is the case, then we have a short exact sequence in cohomology given by

$$0 \longrightarrow \lim_i^1 H^{n-1}(X_i) \longrightarrow H^n(X) \longrightarrow \lim_i H^n(X_i) \longrightarrow 0$$

Proof. We have $C_*(X) \cong \text{colim}(C_*(X_i))$, and $C^*(X) \cong \lim C^*(X_i)$.

Claim 9.4. $\lim_i^1 (C^n(X_i)) = 0$ for all n .

Subproof. We want the open cover of X to be a direct system, i.e., nested in some sense, so that we have a telescope and by the Mittag-Leffler condition we win. For instance, if we have telescopes, then $T = \text{Tel}(X_0 \rightarrow X_1 \rightarrow \cdots)$, then $\bigcup_n T_{\leq n}$ gives $T_{\leq 0} \subseteq T_{\leq 1} \subseteq \cdots \subseteq T = \bigcup_i T_{\leq i}$. The point being, now we have $T_{\leq i} \cong X_i$ by deformation retraction, so we have a Milnor exact sequence on the level of cohomology of T , and we are done. \blacksquare

\square

Example 9.5.

$$0 \longrightarrow \lim^1 H^1(S^1) \xrightarrow{\cong} H^2(S^1 \left[\frac{1}{p} \right]) \longrightarrow H^2(S^1) \longrightarrow 0$$

where $\lim^1 H^1(S^1)$ is $\lim^1(\cdots \rightarrow \mathbb{Z} \xrightarrow{p} \mathbb{Z} \rightarrow \cdots) \cong \mathbb{Z}_p / \mathbb{Z}$.

10 SEPT 13, 2023

We now want to define a map on cohomology groups. Let R be a commutative ring, and let $\varphi_i \in C^{n_i}(X, R)$ be with $i = 1, 2$, then we can define the cup product on \smile with

$$\begin{aligned} C^{n_1}(X, R) \times C^{n_2}(X, R) &\rightarrow C^{n_1+n_2}(X, R) \\ (\varphi_1 \smile \varphi_2)(\sigma) &= \varphi_1(\sigma|_{[v_0, \dots, v_{n_1}]}) \varphi_2(\sigma|_{[v_{n_1}, \dots, v_{n_1+n_2}]}) \end{aligned}$$

and we extend it linearly. Note that if $n_1 = 0$, then the map sends σ to $\varphi_1(\sigma|_{v_0})\varphi_2(\sigma)$. Moreover, if $\varphi_1 = e$ is the constant mapping with image 1, then $e \smile \varphi = \varphi = \varphi \smile e$. By associativity, we know $C^*(X, R)$ is a graded ring.

Lemma 10.1. \smile is functorial in X , that is, if $f : X \rightarrow Y$, then $f^* : C^*(Y, R) \rightarrow C^*(X, R)$ is a ring homomorphism.

Lemma 10.2. $\partial(\varphi_1 \smile \varphi_2) = \partial\varphi_1 \smile \varphi_2 + (-1)^{|\varphi_1|} \varphi_1 \smile \partial\varphi_2$.

Corollary 10.3. • If $\varphi_1, \varphi_2 \in Z^*$ are cocycles, then the cup product $\varphi_1 \smile \varphi_2 \in Z^*$.

• If $\varphi_i \in Z^*$, and one is in B^* , then $\varphi_1 \smile \varphi_2 \in B^*$.

Using these two facts, we know that $\smile : H^{n_1}(X, \mathbb{R}) \times H^{n_2}(X, \mathbb{R}) \rightarrow H^{n_1+n_2}(X, \mathbb{R})$ is an induced map. In particular, if X is connected, then $H^0(X, R) \cong R$, and the cup product becomes the product on R . This has a graded ring structure.

Theorem 10.4. The cohomology cup product satisfies:

1. naturality in X ,

2. $1 \smile \alpha = \alpha = \alpha \smile 1$ for $\alpha \in H^*(X, R)$. This is given by $1 : C_0 X \rightarrow R$ with $\sigma : \Delta^0 \rightarrow X$ sent to 1. Therefore, $1 = [1]$.
3. $\alpha \smile (\beta \smile \gamma) = (\alpha \smile \beta) \smile \gamma$.
4. $\alpha \smile \beta = (-1)^{|\alpha||\beta|} \beta \smile \alpha$.
5. For any pair (X, A) with $i : A \hookrightarrow X$ with $\delta : H^*(A; R) \rightarrow H^{*+1}(X, A; R)$, then for $\alpha \in H^*(A; R)$ and $\beta \in H^*(X; R)$, then $\delta(\alpha \smile i^* \beta) = \delta(\alpha) \smile \beta$, and $\delta(i^* \beta \smile \alpha) = (-1)^{|\beta|} \beta \smile \delta(\alpha)$.

Remark 10.5. The cup product \smile comes from $C^*(X) \otimes C^*(X) \rightarrow C^*(X)$, also regarded as $\text{Hom}(C_* X, R) \otimes \text{Hom}(C_* X, R) \rightarrow \text{Hom}(C_* X, R)$, which is given by the factoring via $\text{Hom}(C_* X \otimes C_* X, R)$. This gives a pairing on $C^* X$ if we have a commutative diagram

$$\begin{array}{ccc} C_* X & \longrightarrow & C_* X \otimes C_* X \\ \downarrow \sigma_n \mapsto 0 & & \downarrow \\ \mathbb{Z} & \xlongequal{\quad} & \mathbb{Z} \otimes \mathbb{Z} \cong \mathbb{Z} \end{array}$$

The map $C_* X \rightarrow C_* X \otimes C_* X$ is called the diagonal approximation. More generally, if we think of X and Y , then we have

$$\begin{array}{ccc} C_*(X \times Y) & \longrightarrow & C_* X \otimes C_* Y \\ \downarrow & & \downarrow \\ \mathbb{Z} & \xlongequal{\quad} & \mathbb{Z} \end{array}$$

In particular, if $X = Y$, then we have a diagonal mapping $X \rightarrow X \times X$, therefore induces $C_* X \rightarrow C_*(X \times X)$.

Definition 10.6. The Alexander-Whitney map is given by

$$AW_{X,Y} : C_*(X \times Y) \rightarrow C_* X \otimes C_* Y$$

where $C_* X \otimes C_* Y$ is given by total complex of degree n , i.e., $\bigoplus_{i+j=n} C_i X \otimes C_j Y$, and differential $\partial(a \otimes b) = \partial a \otimes b + (-1)^{|a|} a \otimes \partial b$.

$$\begin{array}{ccccc} & & X & & \\ & \nearrow \sigma & \uparrow \pi_X & & \\ \Delta^n & \xrightarrow{(\sigma, \tau)} & X \times Y & & \\ & \searrow \tau & \downarrow \pi_Y & & \\ & & Y & & \end{array}$$

The Alexander-Whitney map defines $AW(\sigma, \tau) = \sum_{i+j=n} \sigma|_{[v_0, \dots, v_i]} \otimes \tau|_{[v_i, \dots, v_n]}$. On the level of cochains, the cup product is $\text{Hom}(-, R)$ of composition of Alexander-Whitney map and the induced diagonal mapping.

Similarly, we can define the cochain version, with a pair (X, A) , then

$$\begin{array}{ccc} C_*(X \times Y, A \times Y) & \dashrightarrow & C_*(X, A) \otimes C_* Y \\ \uparrow & & \uparrow \\ C_*(X \times Y) & \xrightarrow{AW_{X \times Y}} & C_* X \otimes C_* Y \\ \uparrow & & \uparrow \\ C_*(A \times Y) & \xrightarrow{AW_{A,Y}} & C_* A \otimes C_* Y \end{array}$$

We now want $(X, A) \times (Y, B) = (X \times Y, A \times Y \cup X \times B)$ to have the suitable mapping. Naturally, we get the Alexander-Whitney map

$$\begin{array}{ccc} C_*(X \times Y)/(C_*(X \times B) + C_*(A \times Y)) & \longrightarrow & C_*(X, A) \otimes C_*(Y, B) \\ \downarrow & \dashrightarrow & \\ C_*(X \times Y)/C_*(A \times Y \cup X \times B) & & \end{array}$$

The summation is not the direct sum but not summation in complex.

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Recall that the Alexander-Whitney map is the natural transformation of functors $\mathbf{Top} \times \mathbf{Top} \rightarrow \mathbf{Ch}$ via $C_*(X \times Y) \rightarrow C_*(X) \rightarrow C_*(Y)$, where

$$AW(\sigma, \tau) = \sum_{i+j=n} \sigma|_{[v_0, \dots, v_i]} \otimes \tau|_{[v_i, \dots, v_n]}$$

for $\sigma, \tau : \Delta^n \rightarrow X \times Y$. We also note that the cross product is defined as the composition

$$\begin{array}{ccc} H^*(\text{Hom}(C_*X, R)) \otimes H^*(\text{Hom}(C_*Y, R)) & \longrightarrow & H^*(\text{Hom}(C_*X \otimes C_*Y, R)) \\ & \searrow \times & \downarrow AW^* \\ & & H^*(\text{Hom}(C_*(X, Y), R)) \end{array}$$

where the horizontal map is induced by homological algebra. The cup product is composed by the diagonal inclusion and the cross product:

$$\begin{array}{ccccc} H^*(X) \otimes H^*(X) & \xrightarrow{\times} & H^*(X \times X) & \xrightarrow{\Delta^*} & H^*(X) \\ & \searrow & & \nearrow & \\ & & & & \end{array}$$

given by

$$(f \smile g)(\sigma) = f(\sigma|_{[v_0, \dots, v_i]}) g(\sigma|_{[v_i, \dots, v_{i+j}]})$$

for $f \in H^i(X)$, $g \in H^j(X)$, $\sigma : \Delta^{i+j} \rightarrow X$.

Remark 11.1. • If X is connected, then $H^0(X, R) = R$.

• The cup product gives the R -module structure on $H^n(X)$.

Example 11.2. Let $X = S^n$, then

$$H^*(X, R) = \begin{cases} R, & * = 0, n \\ 0, & \text{otherwise} \end{cases}$$

This says that the induced multiplication map $R \otimes R \rightarrow R$ on cohomology has the same behavior, i.e., $H^n(S^n; R) \otimes H^n(S^n; R) \rightarrow H^{2n}(S^n, R) = 0$. That is, we have $H^*(S^n; R) \cong R[e_n]/e_n^2$.

For the unit interval $I = [0, 1]$, then

$$\tilde{H}^*(S^1) \cong H^*(I, \partial I) = \begin{cases} \mathbb{Z}, & * = 1 \\ 0, & \text{otherwise} \end{cases}$$

Claim 11.3.

$$H^1(I, \partial I) \otimes H^n(Y) \xrightarrow{\times} H^{n+1}(I \times Y, \partial I \times Y)$$

is an isomorphism for any Y .

Corollary 11.4.

$$H^*(S^1) \otimes H^*(Y) \xrightarrow{\times} H^*(S^1 \times Y)$$

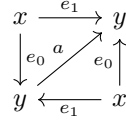
is an isomorphism for any space Y .

Example 11.5. Consider the Moore spaces. For any $m \in \mathbb{Z}$, we have $X_m = S^1 \cup_m e^2$, so we have

$$\begin{array}{ccc} S^1 & \longrightarrow & D^2 \\ m \downarrow & & \downarrow \\ S^1 & \longrightarrow & X_m \end{array}$$

We can give this a cell structure, so for instance $m = 2$, we have $X_m = \mathbb{R}P^2$. For general m , we have the cell structure with vertices x and y , $m+1$ edges a, e_0, \dots, e_m , and m faces C_0, \dots, C_{m-1} , then the boundary map is given by $\partial(a) = 0$, $\partial(e_i) = y - x$, and $\partial(C_i) = a - e_{i+1} + e_i$.

In the case $m = 2$, we have



where the upper triangle is the face C_0 and the bottom triangle is the face C_1 . We look at the chain equivalences

$$\begin{array}{ccccccc} C_0 X_2 & \longleftarrow & C_1 X_2 & \longleftarrow & C_0 X_2 & \longleftarrow & \dots \\ \uparrow & & \uparrow & & \uparrow & & \\ \mathbb{Z}\{x, y\} & \longleftarrow & \mathbb{Z}\{a, e_0, e_1\} & \longleftarrow & \mathbb{Z}\{C_0, C_1\} & \longleftarrow & \dots \end{array}$$

The integral cohomology is just the cohomology of the above chain with respect to the dual basis, then checking the kernel and image, we know $\delta(x^\vee) = -e_0^\vee - e_1^\vee$, $\delta(y^\vee) = e_0^\vee + e_1^\vee$, $\delta(a^\vee) = C_0^\vee + C_1^\vee$, and $\delta(e_0^\vee) = C_0^\vee - C_1^\vee$, $\delta(e_1^\vee) = C_1^\vee - C_0^\vee$, therefore $x^\vee + y^\vee$ generates H^0 . Similarly, we can show that $H^1 = 0$ and $H^2 = \mathbb{Z}/2$.

12 SEPT 18, 2023

We need to prove that $\alpha \smile \beta = (-1)^{|\alpha||\beta|} \beta \smile \alpha$ in $H^*(X; k)$. Define $\rho : \Delta^n \rightarrow \Delta^n$ by sending $[v_0, \dots, v_n]$ to $[v_n, \dots, v_0]$. Using this, we can define a map

$$\begin{aligned} \rho : C_* X &\rightarrow C_* X \\ \sigma &\mapsto (-1)^{\varepsilon_n} \sigma|_{[v_n, \dots, v_0]} \end{aligned}$$

where ε_n is the number of permutations required to permute $(0, \dots, n)$ into $(n, \dots, 0)$. This should just be $\binom{n+1}{2}$.

Exercise 12.1. ρ is a chain map.

This induces $\rho : C^* X \rightarrow C^* X$ with $\rho(\alpha)(\sigma) = (-1)^{\varepsilon_i} \alpha(\sigma)|_{[v_n, \dots, v_0]}$. Therefore,

$$\begin{aligned} \rho(\alpha \smile \beta)(\sigma) &= (-1)^{\varepsilon_n} (\alpha \smile \beta)(\sigma|_{[v_n, \dots, v_0]}) \\ &= (-1)^{\varepsilon_n} \alpha(\sigma|_{[v_n, \dots, v_j]}) \beta(\sigma|_{[v_j, \dots, v_0]}) \\ &= (-1)^{\varepsilon_n} (-1)^{\varepsilon_i} \alpha(\sigma|_{[v_j, \dots, v_n]}) \cdot (-1)^{\varepsilon_j} \rho(\beta)(\sigma|_{[v_0, \dots, v_j]}) \\ &= (-1)^{\varepsilon_n + \varepsilon_i + \varepsilon_j} \rho(\beta) \smile \rho(\alpha)(\sigma). \end{aligned}$$

Claim 12.2. $\varepsilon_i + \varepsilon_j - \varepsilon_{i+n} \equiv ij \pmod{2}$.

In particular, this proves the claim. Moreover, ρ is a chain equivalence.

Proposition 12.3. If $f, g : C_* X \rightarrow C_* X$ are natural transformations of functors $\mathbf{Top} \rightarrow \mathbf{Ch}$, such that f_0 and g_0 are naturally isomorphic (as components of the natural transformations), then f and g are naturally equivalent. Here $f_0, g_0 : \mathbf{Top} \rightarrow \mathbf{Ab}$.

Theorem 12.4. Given a functor $F : \mathcal{C} \rightarrow \mathbf{Ch}$, there is an equivalence of categories $\mathbf{Func}(\mathcal{C}, \mathbf{Ch}) \cong \mathbf{Ch}(\mathbf{Func}(\mathcal{C}, \mathbf{Ab}))$.

To prove the theorem, we introduce acyclic models. Suppose we have a functor $F : \mathcal{C} \rightarrow \mathbf{Ch}$. We regard \mathcal{C} as \mathbf{Top} , or $\mathbf{Top} \times \mathbf{Top}$.

Definition 12.5. A functor $F : \mathcal{C} \rightarrow \mathbf{Ab}$ is called free on models M if

- there exists a set $M \subseteq \mathbf{Ob}(\mathcal{C})$ such that F is naturally isomorphic to the functor defined by the mapping $X \mapsto \bigoplus_{A \in M} \mathbb{Z}\{\mathrm{Hom}_{\mathcal{C}}(A, X)\}$.

Remark 12.6. Note that if $G : \mathcal{C} \rightarrow \mathbf{Set}$ is representable with respect to $A \in \mathcal{C}$, then the composition of the free functor $\mathbf{Set} \rightarrow \mathbf{Ab}$ and $G : \mathcal{C} \rightarrow \mathbf{Set}$ is free on model A .

- A functor $F_* : \mathcal{C} \rightarrow \mathbf{Ch}$ is free on models $\{M_n\}_{n \in \mathbb{Z}}$ if each $F_n : \mathcal{C} \rightarrow \mathbf{Ab}$ is free on M_n .
- Given $M \subseteq \text{Ob}(\mathcal{C})$, a functor $F : \mathcal{C} \rightarrow \mathbf{Ch}$ is M -acyclic in positive degrees if for all $A \in M$, $H_q(F(A)) = 0$ for all $q > 0$.

Example 12.7. $C_* : \mathbf{Top} \rightarrow \mathbf{Ch}$ is acyclic in positive degrees on $\{\Delta^n\}_{n \in \mathbb{Z}}$.

Example 12.8. Consider $\mathbf{Top}^2 \rightarrow \mathbf{Ch}$.

1. If we have $(X, Y) \mapsto C_*(X \times Y)$, then $C_n(- \times -)$ is free on the model $\Delta^n \times \Delta^n$, and $C_*(- \times -)$ is acyclic on $\{\Delta^p \times \Delta^q\}_{p, q \geq 0}$.
2. If we have $(X, Y) \mapsto C_*(X) \otimes C_*(Y)$, then $(C_*(-) \otimes C_*(-))_n$ is free on the models $\{\Delta^p \times \Delta^{n-p}\}_p$, which is acyclic in positive degrees on $\{\Delta^p \times \Delta^q\}$.

13 SEPT 20, 2023

Theorem 13.1 (Acyclic Models). Suppose $F_*, G_* : \mathcal{C} \rightarrow \mathbf{Ch}$ are functors, and assume $F_n = 0 = G_n$ for $n < 0$. Assume

- (a) each $F_n : \mathcal{C} \rightarrow \mathbf{Ab}$ is free on models $M_n \subseteq \text{ob}(\mathcal{C})$, and
- (b) G_* is acyclic in positive degrees on $\bigcup_{n \geq 0} M_n$,

then

1. any natural transformation $H_0 F_* \rightarrow H_0 G_*$ of functors $\mathcal{C} \rightarrow \mathbf{Ab}$ is induced by a natural transformation $F_* \rightarrow G_*$, and
2. if $f, g : F_* \rightarrow G_*$ are natural transformations such that $H_0 f = H_0 g$, then there exists a natural chain homotopy $f \simeq g$, and
3. assume, in addition, that G_* is free on some model N , then if $f : F_* \rightarrow G_*$ is a natural transformation such that $H_0 f : H_0 F_* \rightarrow H_0 G_*$ is a natural isomorphism, then f is a natural chain equivalence.

Claim 13.2. Any natural transformation $C_* X \rightarrow C_* X$ that induces an isomorphism $H_0 X \rightarrow H_0 X$ is a chain equivalence.

Example 13.3. Take $\rho : C_* X \rightarrow C_* X$ that inverts orientation, then ρ induces identity on cohomology, so

$$\alpha \smile \beta = \rho(\alpha \smile \beta) = (-1)^{|\beta| \times |\alpha|} \rho(\beta) \smile \rho(\alpha) = (-1)^{|\beta| \times |\alpha|} \beta \smile \alpha$$

Claim 13.4.

$$AW : C_*(X \times Y) \rightarrow C_*(X) \otimes C_*(Y)$$

is a natural chain equivalence.

Proof. Apply acyclic models. □

Lemma 13.5 (Yoneda). If $G : \mathcal{C} \rightarrow \mathbf{Set}$ is a functor, and let $C \in \text{Ob}(\mathcal{C})$ be a representation of the functor, that is, $F_c(d) = \text{Hom}_{\mathcal{C}}(c, d)$, then there is a natural bijection of sets $\text{Nat}(F_c, G) \cong G(c)$ by $f : F_c \rightarrow G \mapsto f(\text{id}_c)$.

Corollary 13.6. If $F : \mathcal{C} \rightarrow \mathbf{Ab}$ is free on models M , that is, $F(X) = \mathbb{Z} \left\{ \coprod_{A \in M} \text{Hom}_{\mathcal{C}}(A, X) \right\} \cong \bigoplus_{A \in M} \mathbb{Z} \{F_A(X)\}$, which induces

$$F : \mathcal{C} \xrightarrow{\coprod_{A \in M} F_A} \mathbf{Set} \xrightarrow{\text{Free}} \mathbf{Ab}$$

then for any $G : \mathcal{C} \rightarrow \mathbf{Ab}$, then we have a natural isomorphism $\text{Nat}(F, G) \cong \prod_{A \in M} G(A)$ given by $(f : F \rightarrow G) \mapsto (f(\text{id}_A))_{A \in M}$.

We will now prove the acyclic models theorem.

Proof. 1. Take $F_* \rightarrow G_*$, then we are given a natural transformation $\bar{\varphi}_{-1} : H_0 F_* \rightarrow H_0 G_*$ with

$$\begin{array}{ccccccc} 0 & \longleftarrow & H_0 F_* & \longleftarrow & F_0 & \longleftarrow & F_1 & \longleftarrow & \cdots \\ & & \downarrow \bar{\varphi}_{-1} & & & & & & \\ 0 & \longleftarrow & H_0 G_* & \longleftarrow & G_0 & \longleftarrow & G_1 & \longleftarrow & \cdots \end{array}$$

We want to lift $\varphi_0 \in \text{Nat}(F_0, G_0)$, we take a look into the commutative diagram

$$\begin{array}{ccc} \text{Nat}(F_0, G_0) & \xrightarrow{\cong} & \prod_{A \in M_0} G_0(A) \\ \partial_G \downarrow & & \downarrow \\ \text{Nat}(F_0, H_0 G_0) & \xrightarrow{\cong} & \prod_{A \in M_0} H_0 G_0(A) \end{array}$$

so we take $\varphi_{-1} \circ \partial_F \in \prod_{A \in M_0} H_0 G_0(A)$, then lift it to $\varphi_0 \in \prod_{A \in M_0} G_0(A)$, then we obtain $\varphi_0 : F_0 \rightarrow G_0$ as desired.

By construction, $\partial_G \varphi_0 = \varphi_{-1} \partial_F$. Proceeding inductively, we complete the diagram.

2. Now given $f, g : F_* \rightarrow G_*$, with $H_0 f = H_0 g$, we want $f \simeq g$. We want $h_i : F_i \rightarrow G_i$ to be such that $f_i - g_i = h_{i-1} \partial_F + \partial_F h_i$. □

14 SEPT 22, 2023

A complex C_* that is chain equivalent to 0 implies it is acyclic, i.e., $H_q(C_*) = 0$ for all q .

Proposition 14.1. If C_* is a complex of free abelian groups with $C_n = 0$ for $n \ll 0$, then C_* is acyclic if and only if it is chain equivalent to 0.

Proof. We can assume $C_n = 0$ for $n < 0$. Now consider $F : \mathcal{C} = \{*\} \rightarrow \mathbf{Ch}$ where $F(*) = C_*$. Now F is free and acyclic on models $\{*\}$, then the identity and zero map gives the same map on H_0 , and by the acyclic model theorem we are done. □

Example 14.2. If $X \in \mathbf{Top}$, then X is acyclic if $H_* X = \begin{cases} \mathbb{Z}, * = 0 \\ 0, \text{otherwise} \end{cases}$, and so we extend the kernel and get a short exact sequence

$$0 \longrightarrow \tilde{C}_* X \longrightarrow C_* X \twoheadrightarrow C_* \{*\} \longrightarrow 0$$

Note that the last map admits a section with respect to a choice of a point $x_0 \in X$. Therefore, X is acyclic if and only if $\tilde{C}_* X$ is acyclic. Also, $\tilde{C}_* X$ is a complex of free abelian groups, so $\tilde{C}_* X$ being acyclic implies $\tilde{C}_* X$ is chain equivalent to 0. Therefore, $C_* X$ is chain homotopic to zero, as a complex concentrated at degree 0.

For instance, let $X = \Delta^p$ or $\Delta^p \times \Delta^q$.

Corollary 14.3 (Eilenberg-Zilber). For any $X, Y \in \mathbf{Top}$, $C_*(X \times Y) \cong C_* X \otimes C_* Y$.

Claim 14.4. There is an anti-commutative diagram

$$\begin{array}{ccc} H^p(X) \times H^q(Y) & \xrightarrow{\times} & H^{p+q}(X \times Y) \\ s \downarrow \cong & & \downarrow s^* \\ H^q(Y) \times H^p(X) & \xrightarrow[\times]{} & H^{q+p}(Y \times X) \end{array}$$

with $\alpha \times \beta = (-1)^{|\alpha||\beta|} s^*(\beta \times \alpha)$.

This follows from

Lemma 14.5.

$$\begin{array}{ccc} C_*(X \times Y) & \xrightarrow{AW} & C_*(X) \otimes C_*(Y) \\ s_* \downarrow & & \uparrow T \\ C_*(Y \times X) & \xrightarrow{AW} & C_*(Y) \otimes C_*(X) \end{array}$$

where T is a twist map via $T(y \otimes x) = (-1)^{|x||y|}x \otimes y$.

Theorem 14.6 (Kunneth). Let $C_*, D_* \in \mathbf{Ch}$, say C_* is built out of free abelian groups, then

$$0 \longrightarrow \bigoplus_{i+j=n} H_i(C_*) \otimes H_j(D_*) \longrightarrow H_n(C_* \otimes D_*) \longrightarrow \bigoplus_{i+j=n-1} \mathrm{Tor}_1^{\mathbb{Z}}(H_i C_*, H_j D_*) \longrightarrow 0$$

splits unnaturally.

Remark 14.7. $\mathrm{Tor}(M, A) \cong \mathrm{Tor}(A, M)$.

Example 14.8. $\mathrm{Tor}(A, \mathbb{Z}) = 0 = \mathrm{Tor}(\mathbb{Z}, A)$, and $\mathrm{Tor}(\mathbb{Z}/n\mathbb{Z}, \mathbb{Z}/n\mathbb{Z}) = \mathbb{Z}/n\mathbb{Z}$.

15 SEPT 25, 2023

Remark 15.1. Similar results for chain complexes of R -modules for PID R holds. If R is not a PID, then there may be extra terms.

Example 15.2. If C_*, D_* are chain complexes of k -modules for a field k , then $H_*(C_* \otimes_k D_*) \cong H_*(C_*) \otimes_k H_*(D_*)$.

Theorem 15.3 (Kunneth). If $X, Y \in \mathbf{Top}$, there is a short exact sequence

$$0 \longrightarrow \bigoplus_{i+j=n} H_i(X) \otimes H_j(Y) \longrightarrow H_n(X \times Y) \longrightarrow \bigoplus_{i+j=n-1} \mathrm{Tor}(H_i(X), H_j(Y)) \longrightarrow 0$$

which splits unnaturally.

Proof. Identify $C_*(X \times Y) \cong C_*(X) \otimes C_*(Y)$ and use the previous Kunneth theorem. \square

Remark 15.4. Let $(X, A) \times (Y, B) = (X \times Y, A \times Y \cup X \times B)$, then $H_*(X, A) \cong \tilde{H}_*(X) = \ker(H_*(X) \rightarrow H_*(A)) \cong \mathrm{coker}(H_*(A) \rightarrow H_*(X))$.

Definition 15.5 (Smash Product). We denote $(X, *) \times (Y, *) \cong (X \times Y, C := X \times * \cup * \times Y)$, then $X \wedge Y = X \times Y / C$ is the smash product.

Theorem 15.6 (Kunneth). We have an unnatural short exact sequence

$$0 \longrightarrow \bigoplus_{i+j=n} \tilde{H}_i(X) \otimes \tilde{H}_j(Y) \longrightarrow \tilde{H}_n(X \wedge Y) \longrightarrow \bigoplus_{i+j=n-1} \mathrm{Tor}(\tilde{H}_i(X), \tilde{H}_j(Y)) \longrightarrow 0$$

Example 15.7. Take $X = S^k$, then $S^k \wedge Y = \Sigma^k Y$ with $Y = S^m$, i.e., $S^k \wedge S^m \cong S^{k+m}$. Therefore, $\tilde{H}_n(\Sigma^k Y) \cong \tilde{H}_{n-k}(Y)$ as the suspension isomorphism.

Example 15.8. Let A be an abelian group, then there is a space $M(A, n)$ with the property that $\tilde{H}_*(M(A, n)) = A$ if $*$ is n and is 0 otherwise.

- If $A = \mathbb{Z}$, then $M(A, n) = S^n$;
- $A = \mathbb{Z} \left[\frac{1}{p} \right]$, then $M(A, n)$ is the mapping telescope of $S^n \xrightarrow{p} S^n \rightarrow \cdots$;
- if $A = \mathbb{Z}/k\mathbb{Z}$, then $M(A, n) \cong S^n \cup e^{n+1}$.

Therefore,

$$0 \longrightarrow \tilde{H}_r(Y) \otimes A \longrightarrow \tilde{H}_{n+r}(M(A, n) \wedge Y) \longrightarrow \text{Tor}(A, \tilde{H}_{r-1}(Y)) \longrightarrow 0$$

One can compare this to the universal coefficient theorem for homology, i.e., $\tilde{H}_*(Y \wedge M(A, n)) = \tilde{H}_*(Y, A)$.

Definition 15.9. If A^* and B^* are cochain complexes, with a multiplication structure, then $A^* \otimes B^*$ also has a multiplicative structure by $(a \otimes b)(a' \otimes b') = (-1)^{|a||b|}(aa' \otimes bb')$.

For instance, $H^*X \otimes H^*Y$ is a graded commutative ring.

Proposition 15.10. The cross product $\times : H^*X \otimes H^*Y \rightarrow H^*(X \times Y)$ is a map of graded rings via $(a \times b) \smile (a' \times b') = (-1)^{|a'||b|}(a \smile a') \times (b \smile b')$.

Proof. Consider the diagonal maps $\text{diag}_{X \times Y} : X \times Y \rightarrow X \times Y \times X \times Y$ and $\text{diag}_X \times \text{diag}_Y : X \times Y \rightarrow X \times X \times Y \times Y$, then the left-hand side is just $\text{diag}_{X \times Y}^*(a \times b \times a' \times b')$, and

$$\begin{aligned} (a \smile a') \times (b \smile b') &= \text{diag}_X^*(a \times a') \times \text{diag}_Y^*(b \times b') \\ &= (\text{diag}_X \times \text{diag}_Y)^*(a \times a' \times b \times b') \\ &= (\text{diag}_{X \times Y})^*(1 \times \tau \times 1)^*(a \times a' \times b \times b') \\ &= (\text{diag}_{X \times Y})^*(-1)^{|a'||b|}a \times b \times a' \times b' \end{aligned}$$

where τ swaps $X \times Y$ to $Y \times X$, therefore $1 \times \tau \times 1$ factors $\text{diag}_X \times \text{diag}_Y$ via $\text{diag}_{X \times Y}$. \square

16 SEPT 27, 2023

Theorem 16.1 (Kunneth). Let X and Y be topological spaces such that $H_n(Y)$ is finitely-generated as abelian groups, then we have a short exact sequence

$$0 \longrightarrow \bigoplus_{i+j=n} H^i(X) \otimes H^j(Y) \xrightarrow{\times} H^n(X \times Y) \longrightarrow \bigoplus_{i+j=n+1} \text{Tor}(H^i(X), H^j(Y)) \longrightarrow 0$$

Remark 16.2. 1. One can think of this as

$$0 \longrightarrow H^*(X) \otimes H^*(Y) \xrightarrow{\times} H^*(X \times Y) \longrightarrow \text{Tor}(H^*(X), H^{*+1}(Y)) \longrightarrow 0$$

2. same for coefficients in a PID;

3. If k is a field, then we have a Kunneth isomorphism $H^*(X, k) \otimes_k H^*(Y, k) \cong H^*(X \times Y)$.

Proof. Consider

$$\begin{array}{ccc} C^*(X) \otimes C^*(Y) & \xrightarrow{\quad \quad \quad} & C^*(X \times Y) \\ & \searrow & \nearrow \cong \\ & \text{Hom}(C_*(X) \otimes C_*(Y), \mathbb{Z}) & \text{AW}^* \end{array}$$

note that the first map in the splitting is not an equivalence in general. If $H_n(Y)$ is finitely-generated in each degree, then there is a complex D_* such that each D_n is finitely-generated, and $D_*D \cong C_*Y$, so

$$\begin{array}{ccc} \text{Hom}(C_*X \otimes D_*, \mathbb{Z}) & \xleftarrow{\sim} & \text{Hom}(C_*X \otimes C_*Y, \mathbb{Z}) \\ \uparrow \cong & & \uparrow \text{dashed} \\ C^*X \otimes \text{Hom}(D_*, \mathbb{Z}) & \xleftarrow{\sim} & C^*X \otimes C_*Y \end{array}$$

Note that in this case, the dashed map is an equivalence. By the algebraic Kunneth theorem, we are done. \square

- Example 16.3.** 1. If $X = S^m$, then $\times : H^*(S^m) \otimes H^*(Y) \xrightarrow{\sim} H^*(S^m \times Y)$, so $H^*(S^m \times Y) \cong H^*(Y)[e_m]/e_m^2$.
2. $H^*(\mathbb{R}P^2 \times \mathbb{R}P^2; \mathbb{F}_2) = \mathbb{F}_2[x, y]/(x^3, y^3)$, with $|x| = |y| = 1$.
3. $H^*(\mathbb{C}P^2) = \mathbb{Z}[x]/x^3$, with $|x| = 2$. Note that $\mathbb{C}P^2$ and $S^2 \vee S^4$ have the same cohomology, but different cohomology rings. The first one is obtained by attaching a 3-cell on S^2 by the Hopf map, and the second one is obtained by attaching a 4-cell on S^2 by the trivial map.

Definition 16.4 (Bockstein Operation). Consider a short exact sequence

$$0 \longrightarrow A \longrightarrow B \longrightarrow C \longrightarrow 0$$

of abelian groups, we then have two connecting homomorphisms $H_n(X, C) \rightarrow H_{n-1}(X, A)$ and $H^n(X, C) \rightarrow H^{n+1}(X, A)$. For instance, consider

$$0 \longrightarrow \mathbb{Z}/p\mathbb{Z} \longrightarrow \mathbb{Z}/p^2\mathbb{Z} \longrightarrow \mathbb{Z}/p\mathbb{Z} \longrightarrow 0$$

and therefore we have Bockstein maps $\beta : H_n(X, \mathbb{Z}/p\mathbb{Z}) \rightarrow H_{n-1}(X, \mathbb{Z}/p\mathbb{Z})$ as well as $\beta : H^n(X, \mathbb{Z}/p\mathbb{Z}) \rightarrow H^{n+1}(X, \mathbb{Z}/p\mathbb{Z})$. Consider another sequence

$$0 \longrightarrow \mathbb{Z} \xrightarrow{p} \mathbb{Z} \longrightarrow \mathbb{Z}/p\mathbb{Z} \longrightarrow 0$$

where $\tilde{\beta} : H^n(X; \mathbb{Z}/p\mathbb{Z}) \rightarrow H^{n+1}(X, \mathbb{Z})$. This is also called a Bockstein map. In particular, they agree in the sense that

$$\begin{array}{ccc} H^n(X; \mathbb{Z}/p\mathbb{Z}) & \xrightarrow{\tilde{\beta}} & H^{n+1}(X, \mathbb{Z}) \\ & \searrow \beta & \downarrow \text{mod } p \\ & & H^{n+1}(X, \mathbb{Z}/p\mathbb{Z}) \end{array}$$

Considering

$$\cdots \longrightarrow H^n(X, \mathbb{Z}) \longrightarrow H^n(X, \mathbb{Z}/p\mathbb{Z}) \xrightarrow{\tilde{\beta}} H^{n+1}(X, \mathbb{Z}) \longrightarrow \cdots$$

then $\tilde{\beta}x = 0$ if and only if x lifts to an integral cohomology class.

Proposition 16.5. β is a derivation with respect to \smile and \times , that is, $\beta(x \smile y) = (\beta x) \smile y + (-1)^{|x|} x \smile (\beta y)$, and similarly for \times .

Proof. We will prove this for \smile . Let $x = [f]$ and $y = [g]$ for $f \in C^n(X, \mathbb{Z}/p\mathbb{Z})$ and $g \in C^m(X, \mathbb{Z}/p\mathbb{Z})$ as cocycles. Given

$$0 \longrightarrow \mathbb{Z}/p\mathbb{Z} \longrightarrow \mathbb{Z}/p^2\mathbb{Z} \longrightarrow \mathbb{Z}/p\mathbb{Z} \longrightarrow 0$$

this induces maps on the cochain level with respect to the connecting homomorphisms. Use the fact that $\delta(\tilde{f} \smile \tilde{g}) = \delta\tilde{f} \smile \tilde{g} + (-1)^{|\tilde{f}|} \tilde{f} \smile \delta\tilde{g}$. \square

17 SEPT 29, 2023

Lemma 17.1. $\beta^2 = 0$.

Proof. Identify the cycles as the cochains over the boundaries, then $\beta(x) = \frac{1}{n} \delta(\tilde{x})$ where δ is the connecting map between them, then $\beta^2(x)$ is identified to be $\frac{1}{n^2} \times \delta^2(\tilde{x}) = 0$. \square

Example 17.2. We know $H^*(\mathbb{R}P^\infty; \mathbb{Z}/2\mathbb{Z})$ is just $\mathbb{Z}/2\mathbb{Z}$ for all $* \geq 0$, so this is $\mathbb{Z}/2\mathbb{Z}[x]$. For every n , we know $H^*(\mathbb{R}P^n; \mathbb{Z}/2\mathbb{Z}) = \mathbb{Z}/2\mathbb{Z}[x]/(x^{n+1})$ for $|x| = 1$, with $\beta(x^k) = x^{k+1}$ if k is odd and is zero otherwise.

Motivated by this, we will work on Steenrod operations with coefficients in $\mathbb{Z}/2\mathbb{Z}$, in particular the Steenrod squares. (The Steenrod powers are over $\mathbb{Z}/p\mathbb{Z}$ in general.)

A cohomology operation θ is a natural transformation $H^i(-, A) \rightarrow H^j(-, B)$. We usually want the functors **Top** \rightarrow **Set** to be additive. For instance, the Bockstein map would be.

Definition 17.3. The Steenrod squares are additive cohomology operations $\text{Sq}^i : H^n(X, A; \mathbb{Z}/2\mathbb{Z}) \rightarrow H^{n+i}(X, A; \mathbb{Z}/2\mathbb{Z})$ for $i \geq 0$, satisfying

1. $\text{Sq}^0 = \text{id}$;
2. if $|x| = i$, then $\text{Sq}^i x = x^2$;
3. if $|x| < i$, then $\text{Sq}^i x = 0$;
4. $\text{Sq}^k(x \smile y) = \sum_{k=i+j} \text{Sq}^i x \smile \text{Sq}^j y$. Alternatively, $\text{Sq}^k(x \times y) = \sum_{k=i+j} \text{Sq}^i x \times \text{Sq}^j y$.

Corollary 17.4. 1. $\beta = \text{Sq}^1$;

2. Adem relation: if $0 < a < 2b$, then $\text{Sq}^a \text{Sq}^b = \binom{b-j-1}{a-2j} \sum_{j=0}^{\lfloor \frac{a}{2} \rfloor} \text{Sq}^{a+b-j} \text{Sq}^j$. For example, if $a = b = 1$ and $j = 0$, then $\binom{0}{1} = 0$, so $\text{Sq}^1 \text{Sq}^1 = 0$.

Proposition 17.5. For any (X, A) , the diagram

$$\begin{array}{ccc} H^s(A; \mathbb{Z}/2\mathbb{Z}) & \xrightarrow{\delta} & H^{s+1}(X, A; \mathbb{Z}/2\mathbb{Z}) \\ \downarrow \text{Sq}^i & & \downarrow \text{Sq}^i \\ H^{s+i}(A; \mathbb{Z}/2\mathbb{Z}) & \xrightarrow{\delta} & H^{s+i+1}(X, A; \mathbb{Z}/2\mathbb{Z}) \end{array}$$

commutes.

Proof. For $A \hookrightarrow X$, we have a mapping cylinder $M = X \smile_{A \times \{1\}} (A \times I)$. Then

$$(X, A) \xleftarrow{\sim} (M, A \times I) \xleftarrow{\sim} (M, A \times \{0\}) \longrightarrow (M, A \times \{0\}) \cup X \cup (A \times [0, \frac{1}{2}]) \longleftarrow (A \times I, A \times \partial I)$$

where the last map is the excision. Then

$$\begin{array}{ccccccc} H^s(A) & \xrightarrow{\sim} & H^s(A \times I) & \longrightarrow & H^s(A \times \{0\}) & \ll & H^s(A \times \{0\} \sqcup Z) \xrightarrow{\cong} H^s(A \times \partial I) \\ \delta \downarrow & & \downarrow \delta & & \downarrow \delta & & \downarrow \delta \\ H^{s+1}(X, A) & \xrightarrow{\sim} & H^{s+1}(M, A \times I) & = & H^{s+1}(M, A \times \{0\}) & \longleftarrow & H^{s+1}(M, A \times \{0\} \cup Z) \xrightarrow{\cong} H^{s+1}(A \times I, A \times \partial I) \end{array}$$

□

18 OCT 2, 2023

Let (X, A) be a pair, then we have a commutative diagram

$$\begin{array}{ccc} H^q(A; \mathbb{Z}/2\mathbb{Z}) & \xrightarrow{\delta} & H^{q+1}(X, A) \\ \text{Sq}^i \downarrow & & \downarrow \text{Sq}^i \\ H^{q+i}(A; \mathbb{Z}/2\mathbb{Z}) & \xrightarrow{\delta} & H^{q+i+1}(X, A) \end{array}$$

Corollary 18.1. Sq^i 's are stable operations, i.e.,

$$\begin{array}{ccc} \tilde{H}^*(X; \mathbb{Z}/2\mathbb{Z}) & \xrightarrow{\cong} & \tilde{H}^{*+1}(\Sigma X; \mathbb{Z}/2\mathbb{Z}) \\ \text{Sq}^i \downarrow & & \downarrow \text{Sq}^i \\ \tilde{H}^{*+i}(X; \mathbb{Z}/2\mathbb{Z}) & \xrightarrow{\cong} & \tilde{H}^{*+i+1}(\Sigma X; \mathbb{Z}/2\mathbb{Z}) \end{array}$$

Proof. Take (CX, X) , then $H^*(CX, X) \cong \tilde{H}^*(\Sigma X)$. □

Example 18.2. Let $\eta : S^3 \rightarrow S^2$ be the Hopf map, then $\text{cone}(\eta) = \mathbb{C}P^2 = S^2 \cup_{\eta} e^4$. This extends to

$$\begin{array}{ccc} S^3 & \xrightarrow{\eta} & S^2 \\ \downarrow & & \downarrow \simeq \\ \mathbb{C}^2 \setminus \{0\} & \xrightarrow{[z_1, z_2]} & \mathbb{C}P^1. \end{array}$$

In fact, $H^*(\mathbb{C}P^2; \mathbb{Z}) = \mathbb{Z}[y]/(y^3)$, where $|y| = 2$, so the two structures do not have the same cohomology rings, therefore $\mathbb{C}P^2 \not\cong S^2 \vee S^4$.

Example 18.3. Consider $\Sigma\eta : S^4 \rightarrow S^3$ with $\text{cone } \Sigma(\mathbb{C}P^2)$, and $H^*(\Sigma(\mathbb{C}P^2)) \cong H^*(S^3 \wedge S^5)$ as rings. Therefore $H^*(\mathbb{C}P^2; \mathbb{Z}/2\mathbb{Z}) = \mathbb{Z}/2\mathbb{Z}[y]/(y^3) = \mathbb{Z}/2\mathbb{Z}\{y_0, y_2, y_4\}$. On the other hand, $H^*(\Sigma(\mathbb{C}P^2))$ is $\mathbb{Z}/2\mathbb{Z}\{1, z_3, z_5\}$, where $\text{Sq}^2(z_3) = z_5$ (the Steenrod operation commutes with the suspension), and $\text{Sq}^2(y_2) = y_2^2 = y_4$. By the same argument, $H^*(S^3 \wedge S^5) = \mathbb{Z}/2\mathbb{Z}\{1, w_3, w_5\}$. However, now we see $\text{Sq}^2(w_3) = 0$.

Note that as a ring, we must map generators of degree n to generators of degree n as a ring isomorphism, but in this case, there are no mappings over the topological structure, as we see the transform to the topology structure does not preserve the Steenrod operation.

The punchline being, cohomology is a bad invariant in the sense that non-identical spaces can have the same cohomology. Moreover, if two spaces are homotopy equivalent, then they must have isomorphic cohomology rings. (Therefore, cohomology, cohomology rings, and Steenrod algebras, are all homotopy invariants.) However, even if they have the same cohomology rings (as algebraic structure), they can still have different cohomology modules over the Steenrod algebra, that is, the different topology structure over the Steenrod operation, so non-homotopy equivalent.

Corollary 18.4. $\Sigma^n \eta \neq 0$ for any $n \geq 0$.

Example 18.5. $H^*(\mathbb{R}P^\infty; \mathbb{Z}/2\mathbb{Z}) \cong \mathbb{Z}_2[x]$ for $|x| = 1$, then $\text{Sq}^1(x) = x^2$ as dimension axiom says. More generally, let $x \in H^1(X; \mathbb{Z}/2\mathbb{Z})$, then $\mathbb{Z}/2\mathbb{Z}[x] \rightarrow H^*(X; \mathbb{Z}/2\mathbb{Z})$.

Lemma 18.6. For $x \in H^1(X; \mathbb{Z}/2\mathbb{Z})$, then $\text{Sq}^i(x^k) = \binom{k}{i} x^{k+i}$.

Proof. This is true by induction on k and by the Cartan formula. On the inductive step, we have

$$\begin{aligned} \text{Sq}^i(x^{k+1}) &= \sum_{a+b=i} \text{Sq}^a(x) \text{Sq}^b(x^k) \\ &= x \text{Sq}^i(x^k) + x^2 \text{Sq}^{i-1}(x^k) \\ &= x \binom{k}{i} x^{k+i} + x^2 \binom{k}{i-1} x^{k+i-1} \\ &= \binom{k+1}{i} x^{k+i+1} \end{aligned}$$

since $\text{Sq}^a(x)$ is x if $a = 0$, is x^2 if $a = 1$, and is 0 otherwise. \square

Lemma 18.7. If $y \in H^2(X; \mathbb{Z}/2\mathbb{Z})$ such that $\beta y = \text{Sq}^1(y) = 0$, then $\text{Sq}^{2i}(y^k) = \binom{k}{i} y^{k+i}$, and $\text{Sq}^{2i+1}(y^k) = 0$.

Remark 18.8. Let a and b be 2-adic, then $\binom{a}{b} \equiv \prod_i \binom{a_i}{b_i} \pmod{2}$.

For $x \in H^1(X; \mathbb{Z}/2\mathbb{Z})$, we know $\text{Sq}^i(x^k) = \binom{k}{i} x^{k+i}$, for instance $\text{Sq}^i(x^{2^k})$ is x^{2^k} if $i = 0$, is $x^{2^{k+1}}$ if $i = 2^k$, and is 0 otherwise.

Theorem 18.9. A minimal set of algebraic generators of Steenrod algebra A^* is given by Sq^{2^i} . That is, for any Sq^i where $i \neq 2^k$, it is decomposable as a sum of products of Sq^j 's for $j < i$.

Proof. By Adem relations, for $0 < a < 2b$, then $\binom{b-1}{a} \text{Sq}^{a+b} = \text{Sq}^a \text{Sq}^b = \sum_{j>0} \binom{b-1-j}{a-2j} \text{Sq}^{a+b-j} \text{Sq}^j$.

- If $\binom{b-1}{a} \equiv 1$, then Sq^{a+b} is decomposable.
- If $i \neq 2^k$, then $i = a = b$ where $b = 2^l$ for some l , now $\binom{b-1}{a} \equiv 1 \pmod{2}$.

\square

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$$\begin{array}{ccccc}
 & & \frown & & \\
 C^*(X; \mathbb{F}_2) \otimes C^*(X; \mathbb{F}_2) & \longrightarrow & C^*(X \times X, \mathbb{F}_2) & \longrightarrow & C^*(X; \mathbb{F}_2) \\
 \tau \downarrow & & \searrow & \frown & \\
 C^*(X; \mathbb{F}_2) \otimes C^*(X; \mathbb{F}_2) & & & &
 \end{array}$$

is not (graded) commutative, but it commutes in cohomology, therefore it is up to homotopy. In fact, it commutes up to “coherent homotopy”, i.e., Steenrod operations.

Let k be a commutative ring and G be a finite group. The group ring $k[G]$ is free as module over k , therefore $k[G] \cong \bigoplus_{g_i \in G} k[g_i]$. The multiplication is given by $[g][h] = [gh]$ and extended k -linearly.

Example 19.1. Let $G = \Sigma_2 \langle t \rangle$ be symmetric group on two letters. We write $k[\Sigma_2] = k \cdot 1 \oplus k \cdot t = k[t]/(t^2 - 1)$.

Recall that a k -module with a G -action corresponds to a $k[G]$ -module, where the action is given by

$$\begin{aligned}
 G \times M &\rightarrow M \\
 (g, m) &\mapsto g \cdot m
 \end{aligned}$$

where $1 \cdot m = m$ and $g \cdot (h \cdot m) = (gh) \cdot m$. The invariants/fixed points are $M^G \subseteq M$, i.e., $\{m \mid g \cdot m = m \forall g \in G\}$. Note that this corresponds to $\text{Hom}_{k[G]}(k, M)$. The dual construction is the coinvariants/orbits, as $M \otimes_{k[G]} k \cong M_G = M / \langle m - gm \mid g \in G \rangle$.

In the example of $G = \Sigma_2$, then $M = k[\Sigma_2] = k[t]/(t^2 - 1)$. Then $M^{\Sigma_2} = k$ and $M_{\Sigma_2} = k$.

Moreover, (co)chain complexes of k -modules with G -actions correspond to (co)chain complexes of $k[G]$ -modules. Therefore the construction $(C^*)^G$ and $(C^*)_G$ are well-defined. Therefore, we can build a free $k[G]$ -resolution of k , where P_i is free, i.e., $P_i \cong \bigoplus k[G]$ and such that P_* is an acyclic complex.

Example 19.2. For $k[\Sigma_2]k[t]/(t^2 - 1)$, we have a resolution

$$k \xleftarrow{1-t} k[\Sigma_2] \xleftarrow{1-t} k[\Sigma_2] \xleftarrow{1+t} k[\Sigma_2] \xleftarrow{1-t} k[\Sigma_2] \xleftarrow{\quad} \cdots$$

Let $EG_* \in \mathbf{Ch}_{k[G]}$ be any acyclic free resolution of k . We define

Definition 19.3. The homotopy fixed point is $M^{hG} = \text{Hom}(EG_*, M)$. The homotopy orbit is $M_{hG} = M \otimes_{k[G]} EG_*$.

Note that $\text{Hom}_{k[G]}(A, B) = \text{Hom}_k(A, B)^G$ with the action $(g \cdot f)(a) = g \cdot f(g^{-1} \cdot a)$. Also, if $M = k[G]$, then $M_{hG} = EG_*$.

Example 19.4. There is a Σ_2 -action on $C^*(X; \mathbb{F}_2) \otimes C^*(X; \mathbb{F}_2)$, given by $t \cdot (x \otimes y) = \tau(x \otimes y) = y \otimes x$. More generally, we have a Σ_2 -action on $V^* \otimes V^*$.

We will now denote $D_2(V^*) = (V^* \otimes V^*)_{h\Sigma} = (V^* \otimes V^*) \otimes_{\mathbb{F}_2[\Sigma_2]} E\Sigma_2$. More generally, we can write $D_n(V^*) = ((V^*)^{\otimes n})_{h\Sigma_n}$. If we have a (associative) multiplication $m : V^* \otimes V^* \rightarrow V^*$, then m is commutative if and only if

$$\begin{array}{ccc}
 V^* \otimes V^* & \xrightarrow{m} & V^* \\
 \searrow & & \nearrow \\
 & (V^* \otimes V^*)_{\Sigma_2} &
 \end{array}$$

commutes.

We say m is symmetric if we can factor through $D_2(V^*)$, that is, commutative up to homotopy. Moreover, we can ask for multiplications $m_n : D_n(V^*) \rightarrow V^*$.

Proposition 19.5. There is a natural map of $\mathbb{Z}[\Sigma_2]$ -chain complexes $C_*(X) \otimes E\Sigma_2 \rightarrow C_*(X) \otimes C_*(X)$ where Σ_2 acts by the twisting τ on $C_*(X) \otimes C_*(X)$, such that

$$\begin{array}{ccc} C_*(X) \otimes E\Sigma_2 & \longrightarrow & C_*(X) \otimes C_*(X) \\ \downarrow & \nearrow AW_X & \\ C_*(X) & & \end{array}$$

commutes up to homotopy.

Proof. Acyclic models for functors $F, G : \mathbf{Top} \rightarrow \mathbf{Ch}_{\mathbb{Z}[\Sigma_2]}$ then $F(X) = C_*(X) \otimes E\Sigma_2$ is free over models, and $G(X) = C_*(X) \otimes C_*(X)$ are acyclic on those models, all with respect to $\mathbb{Z}[\Sigma_2]$. Extending this into tensoring with $E\Sigma_2$ makes sure this is free and acyclic, and we can apply the theorem. \square

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Recall there is a Σ_n -action on $V^{\otimes n}$, so we have a commutative diagram

$$\begin{array}{ccc} V \otimes V & \xrightarrow{m} & V \\ & \searrow & \nearrow \\ & (V \otimes V)_{\Sigma_2} & \end{array}$$

Proposition 20.1. There is a natural map of $\mathbb{Z}[\Sigma_2]$ -cochain complexes $C_*(X) \otimes E\Sigma_2 \rightarrow C_*X \otimes C_*X$ which refines the Alexander-Whitney map.

Example 20.2. Consider the free resolution $EG_* \rightarrow \mathbb{Z}$. For instance, we have

$$\mathbb{Z}[\Sigma_2] \xrightarrow{1+T} \mathbb{Z}[\Sigma_2] \xrightarrow{1-T} \mathbb{Z}[\Sigma_2] \longrightarrow \mathbb{Z}$$

and therefore $\mathrm{Hom}_{\mathbb{Z}}(\mathbb{Z}[G], \mathbb{Z}) \cong \mathbb{Z}[G]$ as G -modules. This implies $\mathrm{Hom}_{\mathbb{Z}}(EG_*, \mathbb{Z}) \cong EG_*$ gives $\mathbb{Z} \rightarrow EG_*$.

Proof. Apply acyclic models for functors $\mathbf{Top} \rightarrow \mathbf{Ch}_{\mathbb{Z}[\Sigma_2]}$. \square

Proposition 20.3. There is a symmetric multiplication

$$\begin{array}{ccc} D_2(C^*X) = (C^*(X) \otimes C^*(X) \otimes E\Sigma_2)_{\Sigma_2} & \xrightarrow{m_2} & C^*(X) \\ \uparrow & \nearrow \smile & \\ C^*(X) \otimes C^*(X) & & \end{array}$$

that commutes up to homotopy.

Proof.

$$\begin{array}{ccc} C^*(X) \otimes C^*(X) & \longrightarrow & \mathrm{Hom}(C_*(X) \otimes C_*(X), \mathbb{Z}) \\ \smile \downarrow & & \downarrow \\ \mathrm{Hom}(C_*(X), \mathbb{Z}) & \longleftarrow & \mathrm{Hom}(C_*(X) \otimes E\Sigma_2, \mathbb{Z}) \cong \mathrm{Hom}(E\Sigma_2, C^*(X)) \end{array}$$

The map $C^*(X) \otimes C^*(X) \rightarrow \mathrm{Hom}(E\Sigma_2, C^*(X))$ is equivalent to $C^*(X) \otimes C^*(X) \otimes E\Sigma_2 \rightarrow C^*(X)$ where $C^*(X)$ has the trivial action, and $C^*(X) \otimes C^*(X) \otimes E\Sigma_2$ has action T given by $T(x \otimes y \otimes a) = (y \otimes x \otimes Ta)$. This makes the map Σ_2 -equivariant. Take $(-)\Sigma_2$, we get $D_2(C^*(X)) \rightarrow C^*(X)$. \square

Remark 20.4. Let A_* be a chain complex. Then $A_* \otimes E\Sigma_2$ is the same as having A_* tensoring $\cdots \rightarrow \mathbb{Z}[\Sigma_2] \xrightarrow{1+T} \mathbb{Z}[\Sigma_2] \xrightarrow{1-T} \mathbb{Z}[\Sigma_2]$ in non-negative degrees, so $(A_* \otimes E\Sigma_2)_n \cong (A_n \otimes \mathbb{Z}[\Sigma_2]) \oplus (A_{n-1} \otimes \mathbb{Z}[\Sigma_2]) \oplus \cdots \oplus (A_0 \otimes \mathbb{Z}[\Sigma_2])$.

What does an equivariant chain map out of $A_* \otimes E\Sigma_2$ look like? Note that $\mathrm{Hom}_{\Sigma_2}(A \otimes \mathbb{Z}[\Sigma_2], B) = \mathrm{Hom}(A, B)$, i.e., there is an adjunction between \mathbf{Mod}_R and $\mathbf{Mod}_{R[G]}$, as $- \otimes R[G] \dashv U$, where U is forgetful.

To give a chain map of $\mathbb{F}_2[\Sigma_2]$ -complexes $C_*(X; \mathbb{F}_2) \otimes E\Sigma_2 \rightarrow C_*(X; \mathbb{F}_2) \otimes C_*(X; \mathbb{F}_2)$, we want a collection of maps $\{d_j : C_*(X) \rightarrow C_*(X) \otimes C_*(X)\}$ such that d_j is a chain map of degree $-j$ such that $(1+T)d_{j-1} = \partial d_j + d_j \partial$, and $d_0 = AW$.

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Let $A_* = C_*X \otimes E\Sigma_2$ and $B_* = C_*X \otimes C_*X$. Therefore, there is an Σ_2 -equivalence between $A_* \otimes E\Sigma_2$ and B_* such that the diagram

$$\begin{array}{ccc} A_* \otimes E\Sigma_2 & \xrightarrow{\simeq} & B_* \\ \downarrow & \nearrow_{AX} & \\ C_*X & & \end{array}$$

Let $E\Sigma_2$ be $\mathbb{F}_2[\Sigma_2] \xleftarrow{1+T} \mathbb{F}_2[\Sigma_2] \xleftarrow{1+T} \cdots$, then $(A_* \otimes E\Sigma_2)_n$ is just a direct sum $\bigoplus_{i=0}^n A_i \otimes \mathbb{F}_2[\Sigma_2]$ such that $f_* : (A_* \otimes E\Sigma_2)_n \rightarrow (B_*)_n$ corresponds to $f_n : \bigoplus_{i=0}^n A_i \otimes \mathbb{F}_2[\Sigma_2] \rightarrow B_n$, which corresponds to $f_n^{n-i} : A_i \rightarrow B_i$ for $0 \leq i \leq n$.

Lemma 21.1. Let B_* be a Σ_2 -equivalence of chain complexes, given a map $\varphi : A_* \rightarrow B_*$, to give an extension of φ to a map

$$\begin{array}{ccc} A_* \otimes E\Sigma_2 & \xrightarrow{f} & B_* \\ & \nearrow_{\varphi} & \\ A_* & & \end{array}$$

is equivalent to giving a collection of $f^j : A_* \rightarrow B_{*+j}$ such that $f^0 = \varphi$, and $(1+T)f^{j-1} = \partial_B f^j + f^j \partial_A$.

Therefore, all of this gives a degree j map $f^j C_*X \rightarrow C_*X \otimes C_*X$. On cochains, we have

$$\begin{array}{ccc} C^*X \otimes C^*X & \longrightarrow & \text{Hom}(C_*X \otimes C_*X, \mathbb{F}_2) \\ & \searrow_{h^j} & \downarrow_{\text{Hom}(f^j, \mathbb{F}_2)} \\ & & C^*X \end{array}$$

where h^j has degree $-j$. Alternatively, we can write $h^j(\alpha \otimes \beta) = \alpha \smile_j \beta$.

Therefore, h^j 's satisfy $h^j(1 + \tau) = h^{j+1}\delta + \delta h^{j+1}$.

Remark 21.2. • $h^{j+1}(\delta a \otimes \delta a) = \delta h^{j+1}(a \otimes \delta a) + \delta h^j(a \otimes a)$.

• $h^j((a+b) \otimes (a+b)) = h^j(a \otimes a) + h^j(b \otimes b) + h^{j+1}\delta(a \otimes b) + \delta h^{j+1}(a \otimes b)$.

Theorem 21.3. The map h^{q-n} induces a natural homomorphism $\text{Sq}^n : H^q(X) \rightarrow H^{q+n}(X)$ by $\text{Sq}^n([a]) = [h^{q-n}(a \otimes a)]$.

Proposition 21.4. If $a \in H^q(X)$, then $\text{Sq}^q(a) = a^2$, and if $n > q$, then $\text{Sq}^n(a) = 0$.

Theorem 21.5. The operations Sq^n are independent of the choice of a chain map $C_*X \otimes E\Sigma_2 \rightarrow C_*X \otimes C_*X$.

Recall if V^* is cochain complex, then $D_2(V^*) = (V \otimes V \otimes E\Sigma_2)/\Sigma_2$. The enhanced AW map gave us a symmetric multiplication from $m_2 : D_2(C^*X) \rightarrow C^*(X)$ to $H^*(D_2C^*X) \rightarrow H^*X$.

We should study $H^*(D_2\mathbb{F}_2[n])$. So given θ in this cohomology, and $x \in H^*V$, we get $\theta(x) \in H^*V$ by $m_2 \circ D_2x \circ \theta : \mathbb{F}_2[m] \rightarrow V$.

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We saw that the enhanced AW map

$$\begin{array}{ccc} C_*X \otimes E\Sigma_2 & \xrightarrow{\Sigma_2 \simeq} & C_*X \otimes C_*X \\ \uparrow & \nearrow_{AW} & \\ C_*X & & \end{array}$$

and this gives rise to a symmetric multiplication $m_2 : D_2(C^*X) \cong (C^*X \otimes C^*X \otimes E\Sigma_2)_{\Sigma_2} \rightarrow C^*X$. Here $E\Sigma_2 = (\cdots \xrightarrow{1+T} \mathbb{F}_2[\Sigma_2] \xrightarrow{1+T} \mathbb{F}_2[\Sigma_2])$ is a chain complex in non-negative degree, i.e., cochain complex in non-positive degree. On cohomology, m_2 gives $H^*(D_2C^*X) \rightarrow H^*X$, and to get an operation on $H^*(X)$, we need natural transformations $H^k(X) \rightarrow H^m(D_2C^*X)$. We observe that if V^* is a cochain complex, then $H^n(V^*) = \text{Hom}_{\text{coCh}}(\mathbb{F}_2[n], V^*) / \sim$, quotient by chain homotopy.

Proposition 22.1. Natural transformations $H^n(V^*) \rightarrow H^m(D_2V^*)$ are in correspondence with elements of $H^m(D_2\mathbb{F}_2[n])$.

Proof. Given $\theta \in H^m(D_2\mathbb{F}_2[n])$ represented by $\theta : \mathbb{F}_2[m] \rightarrow D_2\mathbb{F}_2[n]$, let $x \in H^n(V^*)$, then x is represented by $x : \mathbb{F}_2 + 2[n] \rightarrow V^*$. Apply D_2 to get $D_2x : D_2\mathbb{F}_2[n] \rightarrow D_2V^*$, by precomposing with θ , we get $\mathbb{F}_2[m] \rightarrow D_2V^*$.

For the converse, given $\varphi : H^n(-) \rightarrow H^m(D_2-)$, let $x \in H^n(V^*)$, $x : \mathbb{F}_2[n] \rightarrow V^*$, so

$$\begin{array}{ccc} H^n(\mathbb{F}_2[n]) & \xrightarrow{\varphi} & H^m(D_2\mathbb{F}_2[n]) \\ \downarrow & & \downarrow \\ H^n(V^*) & \xrightarrow{\varphi} & H^m(D_2V^*) \end{array}$$

this traces a generator in \mathbb{F}_2 to $x \in H^n(V^*)$ and to $\theta \in H^m(D_2\mathbb{F}_2[n])$. \square

Therefore, to compute the cohomology of $H^*(D_2\mathbb{F}_2[n])$, note that $\mathbb{F}_2[n] \otimes_{\mathbb{F}_2} \mathbb{F}_2[n] \cong \mathbb{F}_2[2n]$, so $D_2\mathbb{F}_2[n] = (\mathbb{F}_2[2n] \otimes E\Sigma_2)_{\Sigma_2}$, but note that $\mathbb{F}_2[2n]$ now has a trivial action, so this is just $\mathbb{F}_2[2n] \otimes (E\Sigma_2/\Sigma_2)$, where $E\Sigma_2/\Sigma_2$ is the cochain complex in non-positive degrees

$$\cdots \longrightarrow \mathbb{F}_2 \xrightarrow{\times 2} \mathbb{F}_2 \xrightarrow{\times 2} \mathbb{F}_2 \longrightarrow 0 \longrightarrow \cdots$$

but over \mathbb{F}_2 they are just zero. Therefore, tensoring $\mathbb{F}_2[2n]$ with this complex is just identifying the degree 0 in the complex by the twisting, i.e., as degree $2n$, so the thing we want is

$$H^m(D_2\mathbb{F}_2[n]) = \begin{cases} \mathbb{F}_2, & m \leq 2n \\ 0, & \text{otherwise} \end{cases}$$

This means the natural transformations $\text{Nat}(H^n(-) \rightarrow H^m(D_2-))$ is just \mathbb{F}_2 if $m \leq 2n$ and is 0 otherwise. Relabel $i = m - n$, and denote $\overline{\text{Sq}}^i$ to be the non-zero transformation $H^n(-) \rightarrow H^{n+i}(D_2-)$. If V^* has a symmetric multiplication, then we get $\text{Sq}^i : H^n(V^*) \xrightarrow{\overline{\text{Sq}}^i} H^{n+i}(D_2V^*) \xrightarrow{m^*} H^{n+i}(V^*)$.

Example 22.2. 1. $V^* = C^*X$;

2. Suppose $X \in \mathbf{Top}$ has a homotopy commutative multiplication $X \times X \rightarrow X$, i.e., X is an H -space, for instance consider S^1, S^3, S^7 , or BG where G is abelian, then $C_*(X)$, as a cochain complex in non-positive degrees, has a symmetric multiplication.

Proposition 22.3. If V^* has a symmetric multiplication, then for $x \in H^n(V^*)$, $\text{Sq}^n(x) = x^2$.

Proof. Note that Sq^n corresponds to the generator of $H^{2n}(D_2\mathbb{F}_2[n])$, which is $i_n \otimes i_n$, where i_n is the generator of $H^n(\mathbb{F}_2[n])$. Therefore $\overline{\text{Sq}}^n(x) = [x \otimes x] \in H^{2n}(D_2V^*)$. \square

Proposition 22.4. $\overline{\text{Sq}}^i$ are additive, i.e., given $v, v' \in H^n(V^*)$, then $\overline{\text{Sq}}^i(v + v') = \overline{\text{Sq}}^i(v) + \overline{\text{Sq}}^i(v') \in H^{n+i}(D_2V^*)$.

Proof. Let $v : \mathbb{F}_2[n] \rightarrow V^*$ and $v' : \mathbb{F}_2[n] \rightarrow V^*$, then $v + v' : \mathbb{F}_2[n] \oplus \mathbb{F}_2[n] \rightarrow V^* \oplus V^* \rightarrow V^*$, so it suffices to show additivity on the direct sum. Let $W = \mathbb{F}_2[n] \oplus \mathbb{F}_2[n]$, then it suffices to show that the diagram

$$\begin{array}{ccc} H^n(W) & \xrightarrow{\overline{\text{Sq}}^i} & H^{n+i}(D_2W) \\ \downarrow & & \downarrow \\ H^n(\mathbb{F}_2[n]) \oplus H^n(\mathbb{F}_2[n]) & \xrightarrow{(\overline{\text{Sq}}^i, \overline{\text{Sq}}^i)} & H^{n+i}(D_2\mathbb{F}_2[n]) \oplus H^{n+i}(D_2\mathbb{F}_2[n]) \end{array}$$

commutes. The vertical mappings are given by $D_2(A \oplus B) \cong D_2(A) \oplus D_2(B) \oplus \cdots$ and one can check this componentwise. \square

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We want to have Sq^i commutes with suspension. Note that there is a correspondence between suspension and shift as $(V^*[k])^m = V^{m-k}$ and $V^*[k] = V^* \otimes_{\mathbb{F}_2} \mathbb{F}_2[k]$.

Proposition 23.1. The diagram

$$\begin{array}{ccc} H^*(V^*[1]) & \xrightarrow[\sigma]{\cong} & H^{*-1}(V^*) \\ \overline{Sq}^i \downarrow & & \downarrow \overline{Sq}^i \\ H^{*+i}(D_2(V^*[1])) & \longrightarrow & H^{*+i-1}(D_2V^*) \cong H^{*+i}((D_2V^*)[1]) \end{array}$$

where the map $H^{*+i}(D_2(V^*[1])) \rightarrow H^{*+i-1}(D_2V^*) \cong H^{*+i}((D_2V^*)[1])$ is $H^{*+i}(D_2(V[1]) \rightarrow (D_2V)[1])$, where $D_2(V[1])$ is $(V[1] \otimes V[1] \otimes E\Sigma_2)/\Sigma_2 \cong (V \otimes V \otimes E\Sigma_2[2])/\Sigma_2$, therefore the map becomes $(V \otimes V \otimes E\Sigma_2[2])/\Sigma_2 \rightarrow (V \otimes V \otimes E\Sigma_2[1])/\Sigma_2$, i.e., induced by $E\Sigma_2[2] \rightarrow E\Sigma_2[1]$, as a sort of inclusion.

Corollary 23.2. Steenrod operations on \mathbb{F}_2 commutes with suspensions.

We now want $\text{Sq}^0 = \text{id}$ on $H^*(X; \mathbb{F}_2)$.

Example 23.3. $\tilde{H}^*(S^n)$ is $\mathbb{F}_2\{e_n\}$ if $* = n$, and is 0 otherwise. Therefore, $\text{Sq}^i = 0$ for $i \neq 0$.

To understand Sq^0 , use suspension isomorphism to reduce to $n = 0$. We have $\text{Sq}^0\{e_0\} = e_0$ by $\text{Sq}^i(x_i) = x_i^2$, therefore $\text{Sq}^0 = \text{id}$ on $H^*(S^n)$.

Proposition 23.4. Suppose X is equivalent to a CW complex, then $\text{Sq}^0 = \text{id}$ on $H^*(X)$, and $\text{Sq}^i = 0$ for $i < 0$.

Proof. Note that this is true for S^n . Now consider the good pair $(X, X^{(n)})$ with n -skeleton $X^{(n)}$. We trace the diagram

$$\cdots \longrightarrow H^n(X, X^{(n)}) \longrightarrow H^n(X) \hookrightarrow H^n(X^{(n)}) \longrightarrow \cdots$$

and note that $H^n(X, X^{(n)})$ is 0 because there are no cells of dimension at most n . Here $i : X^{(n)} \rightarrow X$ induces the inclusion map.

Theorem 23.5 (Hopf's Classification Theorem). If Y is a CW-complex with all of its cells in dimension at most n , then $H^n(Y, \mathbb{Z}) \cong [Y, S^n]$ where $[Y, S^n]$ is the homotopy classes of maps $Y \rightarrow S^n$. That is, for $\gamma \in H^n(Y, \mathbb{Z})$ corresponds to a map $f_\gamma : Y \rightarrow S^n$ (we can pullback f_γ back to $\gamma = f_\gamma^*(e_n)$).

If we send $\gamma \in H^n(X)$ to $i^*\gamma \in H^n(X^{(n)})$, then since we have $i^*\gamma = f^*(e_n)$, we have $i^*\text{Sq}^0(\gamma) = \text{Sq}^0(i^*\gamma) = \text{Sq}^0(f^*(e_n)) = f^*(\text{Sq}^0(e_n)) = f^*(e_n) = i^*\gamma$. \square

Theorem 23.6 (Cartan Formula). Let $V^*, W^* \in \mathbf{coCh}$, then for $x \in H^n(V^*)$, $y \in H^m(W^*)$, we have

$$f\overline{Sq}^k(x \otimes y) = \sum_{i+j=k} \overline{Sq}^i(x) \otimes \overline{Sq}^j(y) \in H^{n+m+k}(D_2V^* \otimes D_2W)$$

where

$$\begin{array}{ccc} D_2(V \otimes W) = (V \otimes W \otimes V \otimes W \otimes E\Sigma_2)_{\Sigma_2} & \xrightarrow{\quad\quad\quad} & D_2V \otimes D_2W = (V \otimes V \otimes E\Sigma_2)_{\Sigma_2} \\ & \searrow & \nearrow \\ & (V \otimes W \otimes V \otimes W \otimes E\Sigma_2 \otimes E\Sigma_2)_{\Sigma_2 \times \Sigma_2} & \end{array}$$

To define this, note that there is a diagonal map $\Sigma_2 \rightarrow \Sigma_2 \times \Sigma_2$, sending a projective resolution $E\Sigma_2$ to the tensor product over itself, which gives the resolution $E\Sigma_2 \otimes E\Sigma_2 \cong E(\Sigma_2 \times \Sigma_2)$.

Proof. Consider $x : \mathbb{F}_2[n] \rightarrow V^*$ and $y : \mathbb{F}_2[m] \rightarrow W^*$, wwe assume $V = \mathbb{F}_2[n]$ and $W = \mathbb{F}_2[m]$, then $\overline{Sq}^i x \in H^{n+i}(D_2\mathbb{F}_2[n])$ is the generator, and so

$$f : D_2(\mathbb{F}_2[n] \otimes \mathbb{F}_2[m]) \cong \mathbb{F}_2[n+m] \rightarrow D_2\mathbb{F}_2[n] \otimes D_2\mathbb{F}_2[m]$$

on cohomology, we have $f(e_k^{n+m}) = \sum_{i+j=k} e_i^n \otimes e_j^m$. \square

24 OCT 16, 2023

Let M be a topological manifold, then every $m \in M$ has an open neighborhood U such that $U \cong \mathbb{R}^n$. Examples include \mathbb{R}^n and $S^n \subseteq \mathbb{R}^{n+1}$. We say M is closed if M is compact, i.e., $\partial M = \emptyset$.

We use the following notation: let A be a subset of X , we write $(X | A) = (X, X \setminus A)$. For $A \subseteq B \subseteq X$, we write $j_A^B : (X | B) \hookrightarrow (X | A)$, so this induces $H^*(X | A) \rightarrow H^*(X | B)$. In particular, if $B = X$, then $H^*(X | A) \rightarrow H^*(X)$.

Example 24.1. Let $x \in U \subseteq M$, then $H_i(M | x) \cong H_i(U | x)$ by excision on $M \setminus U$, which is then isomorphic to $H_i(\mathbb{R}^n | 0) = \begin{cases} \mathbb{Z}, & i = n \\ 0, & i \neq n \end{cases}$.

Definition 24.2 (Orientation). An orientation of M at a point $x \in M$ is a choice of a generator of $H_n(M | x) \cong \mathbb{Z}$. Note that there are exactly two generators of \mathbb{Z} , so the set of orientations of M at x is $\text{Or}(M | x) \subseteq H_n(M | x)$, with two elements.

More generally, let R be a commutative ring, an R -orientation is just a generator of $H_n(M | x; R) \cong R$ as an R -module. Then $\text{Or}(M | x; R) \cong R^\times$, the units of R .

Example 24.3. Let $R = \mathbb{F}_2$, then the set of orientation is a singleton.

Let $\pi : \text{Or}(M) = \coprod_{x \in M} \text{Or}(M | x) \rightarrow M$ be the natural projection, with $\pi^{-1}(x) = \text{Or}(M | x)$. We will topologize this map. Also, we have $\pi : M_{\mathbb{Z}} = \coprod_{x \in M} H_n(M | x) \rightarrow M$ where $\text{Or}(M) \subseteq M_{\mathbb{Z}}$.

Definition 24.4. We say $U \subseteq M$ is a small Euclidean neighborhood if there is $U \subseteq V$ where V is open and there is a homeomorphism $\varphi : V \cong \mathbb{R}^n$ such that $U = \varphi^{-1}(\text{int}(D^n))$.

Example 24.5. $S^n \setminus \{*\} \subseteq S^n$ is not a small Euclidean neighborhood.

Remark 24.6. If $U \subseteq M$ is a small Euclidean neighborhood, then $\bar{U} \cong D^n$ is contained in some Euclidean neighborhood of M . Therefore, the small Euclidean neighborhoods form a basis for the topology on M .

Lemma 24.7. Let $x \in U \subseteq M$ be a small Euclidean neighborhood of $x \in M$, then we have an isomorphism $j_x^U : H_n(M | U) \cong H_n(M | x)$.

Proof. Choose $V \supseteq U$, then $\varphi : V \rightarrow \mathbb{R}^n$ is an isomorphism, so $U = \varphi^{-1}(\text{int}(D^n))$, and $\varphi^{-1}(x) = 0$. We have

$$\begin{array}{ccccc} (M | U) & \xleftarrow{H_* \cong} & (V | U) & \xrightarrow{\cong} & (\mathbb{R}^n | \text{int}(D^n)) \\ \downarrow & & \downarrow & & \downarrow \cong \\ (M | x) & \xleftarrow{H_* \cong} & (V | x) & \xrightarrow{\cong} & (\mathbb{R}^n | 0) \end{array}$$

so all maps are H_* -isomorphisms. □

For a small Euclidean neighborhood $U \subseteq M$ and any $\alpha \in H_n(M | U)$ with any $x \in U$ gives $j_x^U(\alpha) \in H_n(M | x)$.

Definition 24.8. Define $U_\alpha = \{j_x^U(\alpha) | x \in U\} \subseteq M_{\mathbb{Z}} = \coprod_{x \in M} H_n(M | x)$, then $U_\alpha \subseteq \pi^{-1}(U)$.

Claim 24.9. $\{U_\alpha\}$ is a basis of a topology on $M_{\mathbb{Z}}$.

Proof. • Each point of $M_{\mathbb{Z}}$ is in some U_α ;

- If $(x, \alpha_x) \in U'_{\alpha'} \cap U''_{\alpha''}$, then $j_x^{U'}(\alpha') = \alpha_x = j_x^{U''}(\alpha'')$. Let $V \ni x$ be a small Euclidean neighborhood in $U' \cap U''$, and let $\beta = (j_x^V)^{-1}(\alpha_x)$, then $\beta = j_V^{U'}(\alpha') = j_V^{U''}(\alpha'')$.

□

Proposition 24.10. $\pi : M_{\mathbb{Z}} \rightarrow M$ is a covering with fiber \mathbb{Z} .

Proof. For a small Euclidean neighborhood $U \subseteq M$, we have

$$\begin{array}{ccc} \pi^{-1}(U) & \xleftarrow{\cong} & U \times H_n(M | U) \\ \pi \downarrow & \swarrow \text{proj} & \\ U & & \end{array}$$

where the isomorphism sends $(x, \alpha) \mapsto j_x^U(\alpha)$. □

This gives $\text{Or}(M) \subseteq M$ a subspace topology, so $\pi : \text{Or}(M) \rightarrow M$ is a 2-fold covering map.

Definition 24.11. An orientation of M is a section $s : M \rightarrow \text{Or}(M)$ of π . (We say M is orientable if such a section exists.)

Example 24.12. A section $M \rightarrow M_{\mathbb{Z}}$ amounts to giving $\alpha_x \in H_n(M | x)$ which varies in a continuous way.

25 OCT 18, 2023

Lemma 25.1. Suppose M is connected, then M is orientable if and only if $\text{Or}(M) = M \coprod M$, and M is not orientable if and only if $\text{Or}(M)$ is connected, that is, for all $x \in M$, there exists a continuous path between (x, α) to $(x, -\alpha)$ where α is a generator; that path obstructs the existence of a section.

Remark 25.2. If M is orientable, the same argument says that $M_{\mathbb{Z}} \rightarrow M$ gives a splitting $M_{\mathbb{Z}} \cong \coprod_{k \in \mathbb{Z}} M = M \times \mathbb{Z}$. If M is not orientable, we have $M_{\mathbb{Z}} \cong M \coprod \coprod_{m \geq 1} \text{Or}(M)$.

Example 25.3. Let M be the Möbius band, i.e., as $S^1 \times \mathbb{R} / \sim$ where $(x, y) \sim (-x, -y)$, then $M \rightarrow S^1$ corresponds to a 2-fold covering space $\text{Or}(M) \cong S^1 \times \mathbb{R}$ to the choice of $(x, y) \sim (-x, -y)$.

Example 25.4. Suppose $M = \mathbb{R}P^2 \cong S^2/x \sim -x$, then there is a mapping $S^2 = \text{Or}(\mathbb{R}P^2) \rightarrow M = \mathbb{R}P^2$.

Remark 25.5. For any M , $\text{Or}(M)$ is an orientable manifold.

We know $\text{Or}(M, x; R)$ is the set of generators of $H_n(M | x; R)$, then for $\pi : M_R \rightarrow M$ we have preimage $\pi^{-1}(x) = H_n(M | x; R) \cong H_n(M | x) \otimes R$. Therefore $\text{Or}(M; R) \subseteq M_R$ is just $\pi^{-1} \cong R^\times$. Hence, $\text{Or}(M; \mathbb{Z}/2\mathbb{Z}) = M$. Therefore, $M_{\mathbb{Z}/2\mathbb{Z}} \cong M \coprod M$, so R -orientations of M correspond to sections of $\text{Or}(M; R) \rightarrow M$.

Let $\Gamma(M, M_R)$ be the set of continuous sections of $\pi : M_R \rightarrow M$, then this is an R -module. This gives a mapping

$$\begin{aligned} H_n(M; R) &\rightarrow \Gamma(M, M_R) \\ \alpha &\mapsto s_\alpha(x) = j_x^M(\alpha) \in H_n(M | x; R). \end{aligned}$$

More generally, if $A \subseteq M$, then the sections $\Gamma(A, M_R)$ is the set of sections $s : A \rightarrow M_R$ such that the diagram

$$\begin{array}{ccc} & & M_R \\ & \nearrow s & \downarrow \\ A & \hookrightarrow & M \end{array}$$

commutes. Then we have

$$H_n(M | A; R) \rightarrow \Gamma(A, M_R)$$

with the same formula, restricting elements to A . This corresponds to $(M, M \setminus A) \rightarrow (M, M \setminus \{x\})$ where $x \in A$.

Theorem 25.6 (Orientation). Assuming $A \subseteq M$ is compact, then the map

$$f_A : H_n(M | A; R) \rightarrow \Gamma(A, M_R)$$

is an isomorphism.

Corollary 25.7. if M is a compact n -manifold, then

$$H_n(M; R) = \begin{cases} R, & M \text{ orientable, i.e., } M_R \cong \coprod_R M \\ R[2], & M \text{ not orientable} \end{cases}$$

where $R[2]$ means the 2-torsion in r , i.e., $r = -r$.

Remark 25.8. Fiberwise, we have

$$\begin{aligned} M_{\mathbb{Z}} &\rightarrow M_R \\ k &\mapsto k \otimes 1. \end{aligned}$$

In particular, given $r \in R$,

$$\begin{array}{ccc} H_n(M | A) & \longrightarrow & H_n(M | A, R) \\ \parallel & & \\ H_n(M | A) \otimes \mathbb{Z} & \xrightarrow{\text{id} \otimes r} & H_n(M | A) \otimes R \end{array}$$

Therefore this defines $r : M_{\mathbb{Z}} \rightarrow M_R$. If M is orientable, then $M_{\mathbb{Z}} \cong \coprod_{\mathbb{Z}} M$, and if M is not orientable, then $M_{\mathbb{Z}} = M \coprod \coprod_{\mathbb{Z}} \text{Or}(M)$. In particular, if $2r \neq 0$, then $r(\text{Or}(M)) \simeq \text{Or}(M)$; if $2r = 0$, then $r : \text{Or}(M) \xrightarrow{\pi} M \hookrightarrow M_R$.

26 OCT 23, 2023

Recall that if M is an n -dimensional manifold, $M_{\mathbb{Z}} = \coprod_{x \in M} H_n(M | x) \cong \coprod_{x \in M} \mathbb{Z} \rightarrow M$. Note that $M_{\mathbb{Z}} \supseteq \text{Or}(M)$.

Recall that if $U \subseteq M$ is a small Euclidean neighborhood, then for $x \in U$, we have $j_x^U : H_n(M | U) \cong H_n(M | x)$. We can topologize $M_{\mathbb{Z}}$ by $U_{\alpha} = \{j_x^U(\alpha) \mid x \in U\}$ open subsets which form a basis for a topology on $M_{\mathbb{Z}}$.

Proposition 26.1. $\pi : M_{\mathbb{Z}} \rightarrow M$ is a covering.

Proof Idea. If U is a small Euclidean neighborhood, then

$$\begin{array}{ccc} \pi^{-1}(U) & \xrightarrow{j_x^U(\alpha) \leftarrow (x, \alpha)} & U \times H_n(M | U) \cong U \times \mathbb{Z} \\ \downarrow & \swarrow & \\ U & & \end{array}$$

Therefore M is orientable, i.e., there exists a section $s : M \rightarrow \text{Or}(M)$ if and only if $\text{Or}(M) \cong M \coprod M$. Similarly, M being connected but not orientable if and only if $\text{Or}(M)$ is connected. \square

We have $M_R \cong \coprod_{x \in M} H_n(M | x; R)$. For any closed subset $A \subseteq M$, we know $\Gamma(A, M_R)$, the sections $A \rightarrow M_R$ of

$$\begin{array}{ccc} & & M_R \\ & \nearrow & \downarrow \\ A & \hookrightarrow & M \end{array}$$

contains $\Gamma_c(A, M_R)$, the sections with compact support, i.e.,

$$\begin{aligned} s : A &\rightarrow M_R \\ a &\mapsto (a, \alpha(a) \in H_n(M | a; R)) \end{aligned}$$

where $\alpha(a) = 0$ outside of a compact subset of A .

This induces a map

$$\begin{aligned} J_A : H_n(M | A; R) &\rightarrow \Gamma(A, M_R) \\ \alpha &\mapsto J_A(\alpha)(x) = j_x^A(\alpha) \in H_n(M | x). \end{aligned}$$

Claim 26.2. $\text{im}(J_A) \subseteq \Gamma_c(A, M_R)$.

Proof. Let α be represented by $a \in C_n(M; R)$, then a is a finite sum of $\lambda_i \sigma_i$'s where $\sigma_i : \Delta^n \rightarrow M$ and $\lambda_i \in R$. Therefore a is a chain on a compact subset of M , i.e., compact subset $B = \bigcup_i \text{im}(\sigma_i)$. If $x \notin B$, then we need $J_A(\alpha)(x) = (x, 0)$, i.e., $j_x^A(\alpha) = 0$. Since $x \notin B$, then $B \subseteq M \setminus \{x\}$, thus $\alpha \mapsto 0$ in $H_n(M \setminus \{x\}; R)$. \square

Theorem 26.3 (Orientation). Let M be an n -manifold, and let $A \subseteq M$ be closed, then

1. $H_i(M \setminus A; R) = 0$ for $i > n$.
2. $J_A : H_n(M \setminus A; R) \xrightarrow{\cong} \Gamma_c(A, M_R)$.

Remark 26.4. Compare this to the fact that $H_n(M \setminus U; R) \times U \cong \pi^{-1}(M)$ for all small Euclidean neighborhood U , so $\Gamma(U, M_R) \cong H_n(M \setminus U; R)$.

Lemma 26.5. If $A, B \subseteq M$ are closed, and Theorem 26.3 holds for $A, B, A \cap B$, then it also holds for $A \cup B$.

Proof. By commutative diagrams, we have

$$\begin{array}{ccccccc} 0 & \longrightarrow & H_n(M \setminus A \cup B) & \longrightarrow & H_n(M \setminus A) \oplus H_n(M \setminus B) & \longrightarrow & H_n(M \setminus A \cap B) \longrightarrow \cdots \\ & & \downarrow J_{A \cup B} & & \downarrow J_A \oplus J_B \cong & & \downarrow \cong \\ 0 & \longrightarrow & \Gamma_c(A \cup B) & \longrightarrow & \Gamma_c(A) \oplus \Gamma_c(B) & \longrightarrow & \Gamma_c(A \cap B) \longrightarrow \cdots \end{array}$$

(since $H_{n+1}(M \setminus A \cap B) = 0$) and apply five lemma. \square

Proposition 26.6. Let $A_1 \supseteq A_2 \supseteq \cdots$ be a decreasing sequence of compact subsets of M and $A = \bigcap_{i \geq 1} A_i$; if the theorem holds for each of the A_i 's, then it holds for A .

Proof. Consider $(M \setminus A_1) \subseteq (M \setminus A_2) \subseteq \cdots$ and we get a commutative diagram

$$\begin{array}{ccc} \text{colim}_i H_n(M \setminus A_i) & \xrightarrow{\cong} & H_n(M \setminus A) \\ \cong \downarrow & & \downarrow \\ \text{colim}_i \Gamma_c(A_i) & \xrightarrow{\cong} & \Gamma_c(A) \end{array}$$

\square

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Recall that $J_A(\alpha)(x) = j_x^A(\alpha) \in H_n(M \setminus \{x\})$. One can show that $J_A(\alpha)$ has compact support and $J_A(\alpha)$ is continuous.

To see that it is continuous, let $a \in C_n(M; R)$ for $[a] = \alpha$ and $\sum \lambda_i \sigma_i \partial a \in C_n(M \setminus A; R)$, where $\sigma_i : \Delta^n \rightarrow M \setminus A$. Let $B = \bigcup \text{im}(\sigma_i) \subseteq M \setminus A$ as a union of compact sets. Let $x \in A$, then it has a small Euclidean neighborhood U such that $B \subseteq M \setminus \bar{U}$, then $\partial a \in C_n(M \setminus \bar{U})$, therefore $\beta = [a] \in H_n(M \setminus \bar{U})$. The map $U \rightarrow \pi^{-1}(U) \cong U \times H_n(M \setminus U)$ sends x to (x, β) , this implies continuity.

We will now prove the Orientation theorem through the following steps:

1. for $M = \mathbb{R}^n$, A compact and convex;
2. for $M = \mathbb{R}^n$, A is a finite union of compact and convex;
3. for $M = \mathbb{R}^n$, A compact;
4. for any M , A a finite union of compact subsets contained in the Euclidean neighborhood;
5. for any M , A compact;
6. for any M , A closed.

To prove the first part, we rescale and translate the area, so we can assume $A \subseteq D^n \subseteq \mathbb{R}^n = M$. Then $S^{n-1} = \partial D^{n-1} \subseteq \mathbb{R}^n \setminus A$ via $\frac{x}{\|x\|} \leftrightarrow x$.

$$\begin{array}{ccc} H_n(\mathbb{R}^n \mid 0) \cong H_n(\mathbb{R}^n \mid D^n) & \xrightarrow{\cong} & H_n(\mathbb{R}^n \mid A) \\ J_{D^n} \downarrow \cong & & \downarrow J_A \\ \Gamma_c(D^n, M_R) & \xrightarrow{\cong} & \Gamma_c(A, M_R) \end{array}$$

where $\pi^{-1}(D^n) \cong D^n \times R$ gives J_{D^n} , therefore J_A is an isomorphism as well.

To prove the second part, consider [Lemma 26.5](#) and

Lemma 27.1. Let $A_1 \supseteq A_2 \supseteq \dots$ be a decreasing sequence of compact subsets of X (Hausdorff). If U is open and contains $A = \bigcap_{i \geq 1} A_i$, then $A_i \subseteq U$ for some i .

Proof. Since A is compact, and $\bigcap_{i \geq 1} (A_i \setminus (A_i \cap U)) = \emptyset$, then we have a sequence

$$A_1 \setminus (A_1 \cap U) \supseteq A_2 \setminus (A_2 \cap U) \supseteq \dots$$

and therefore $A_i \subseteq U$. □

Proposition 27.2. Let $A_1 \supseteq A_2 \supseteq \dots$ be a decreasing sequence of compact subsets of M such that the orientation theorem holds for each A_i , then it holds for $A = \bigcap A_i$.

Proof. Recall $(M \mid A) = \bigcup (M \mid A_i)$, so we have

$$\begin{array}{ccc} \operatorname{colim}_i H_n(M \mid A_i) & \xrightarrow{\cong} & H_n(M \mid A) \\ \operatorname{colim} J_{A_i} \downarrow \cong & & \downarrow J_A \\ \operatorname{colim} \Gamma_c(A_i, M_R) & \xrightarrow{\cong} & \Gamma_c(A, M_R) \end{array}$$

To see the bottom map is an isomorphism, let $s \in \Gamma_c(A, M_R)$, cover A by finitely many small Euclidean neighborhoods. Suppose their union is U , then s extends to U as well (uniquely). By lemma, we have $A_i \subseteq U$, so s is in the image from $\Gamma_c(A_i)$, so the map is onto. Injectivity follows from a similar argument. □

This means the first step of the proof implies the second step of the proof.

Let A be compact and $M = \mathbb{R}^n$, set the closed balls $B_{\frac{1}{j}}(x)$ over x , then $A \subseteq \bigcup_{x \in C_j} B_{\frac{1}{j}}(x)$ where $C_j \subseteq A$ are finite subsets. Let $A_k = \bigcap_{i=1}^k \left(\bigcup B_{\frac{1}{j}}(x) \right)$, then we can build A using finite union of compact subsets A_k 's.

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Recall that we have proved the first three steps of the theorem. Now let M be arbitrary and let $A = \bigcup_{i=1}^r A_i$ where $A_i \subseteq U_i \cong \mathbb{R}^n$ for Euclidean neighborhoods U_i 's of A_i 's. To do this, we need excision to show that this holds for $\operatorname{Or}(M, A_i)$, then recall that if the statement holds for $\operatorname{Or}(M, A)$, $\operatorname{Or}(M, B)$, $\operatorname{Or}(A \cap B)$, then $\operatorname{Or}(A \cup B)$. This proves step 4. To prove step 5, we want to show this for arbitrary M and compact $A \subseteq M$. This is the same proof as step 3 (from step 2), based on our result of step 4. This uses [Proposition 27.2](#). Finally, to prove step 6, we need to show A being compact implies A being closed, which is proven in Bredon.

Corollary 28.1. Let M be a compact manifold, then $H_n(M; R) \cong \Gamma(M; M_R) \cong \begin{cases} R, & M \text{ orientable} \\ R[2], & M \text{ not orientable} \end{cases}$.

Definition 28.2. Let X be a topological space and R be a commutative rings, any (co)chain or (co)homology is denoted with R -coefficients. There is a pairing $\frown: C^p(X) \otimes C_n(X) \rightarrow C_{n-p}(X)$ for $f \in C^p(X)$ and $C \in C_n(X)$, defined by

$$C_n(X) \xrightarrow{\text{diag}_*} C_n(X \times X) \xrightarrow{AW} \bigoplus_{i+j=n} C_i(X) \otimes C_j(X) \xrightarrow{\pi} C_{n-p}(X) \otimes C_p(X) \xrightarrow{\text{id} \otimes f} C_{n-p}(X) \cong C_{n-p}(X) \otimes_R R$$

This sends $c \in C_n(X)$ to a class $f \frown c \in C_{n-p}(X)$.

Explicitly, let $C = \sigma$ for $\sigma: \Delta^n \rightarrow X$, then

$$\begin{aligned} f \frown \sigma &= (1 \otimes f)(AW \circ \text{diag} \circ \sigma) \\ &= (1 \otimes f)\left(\sum \sigma|_{[v_0, \dots, v_i]} \otimes \sigma|_{[v_i, \dots, v_n]}\right) \\ &= (-1)^{(n-p)p} f(\sigma|_{[v_{n-p}, \dots, v_n]}) \sigma|_{[v_0, \dots, v_{n-p}]} \end{aligned}$$

where $f(\sigma|_{[v_{n-p}, \dots, v_n]})$ gives a Kronecker pairing

$$\begin{aligned} \langle -, - \rangle: C^p(X) \otimes C_p(X) &\rightarrow R \\ \langle f, \sigma \rangle &\mapsto f(\sigma) \end{aligned}$$

Lemma 28.3. For $C \in C_n$, $f \in C^p$, and $g \in C^{n-p}$, we have $\langle f \smile g, C \rangle = \langle f, g \frown c \rangle$.

Proof. Check explicitly for $C = \sigma$. □

Lemma 28.4. $\partial(f \frown C) = \delta f \frown C + (-1)^{|f|} f \frown \partial C$.

Corollary 28.5. We have

$$\begin{aligned} \frown: H^p(X) \otimes H_n(X) &\rightarrow H_{n-p}(X) \\ [f] \frown [c] &\mapsto [f \frown C] \end{aligned}$$

that is natural, i.e., for $\varphi: X \rightarrow Y$, we have

$$\varphi_*(\varphi^*([f]) \frown [c]) = [f] \frown \varphi_*[c].$$

Proof of Lemma. Let $C \in C_n$ and $f \in C^p$, then we have a diagram

$$\begin{array}{ccc} C_n \otimes C_p & \xrightarrow{\text{id} \otimes f} & C_n \\ \partial \otimes 1 \downarrow & & \downarrow \partial \\ C_{n-1} \otimes C_p & \xrightarrow{\text{id} \otimes f} & C_{n-1} \end{array}$$

that commutes up to multiplication of $(-1)^p$. Therefore

$$\partial(\text{id} \otimes f)(c_n \otimes c_p) = \partial(C_n \otimes f(c_p)) = (-1)^{pn} f(c_p) \partial c_n$$

and so

$$\begin{aligned} (\text{id} \otimes f)(\partial \otimes \text{id})(c_n \otimes c_p) &= (1 \otimes f)(\partial c_n \otimes c_p) \\ &= (-1)^{(n-1)p} \partial c_n \otimes f(c_p) \\ &\quad + (-1)^{(n-1)p} f(c_p) \partial c_n. \end{aligned}$$

This gives

$$\begin{aligned} \partial(f \frown c) &= \partial((1 \otimes f)(AW \circ \text{diag} \circ c)) \\ &= (-1)^p (1 \otimes f)(\partial \otimes 1)(AW \circ \text{diag} \circ c) \\ &= (-1)^p ((1 \otimes f) \text{diag}(\partial c) + (-1)^p (1 + \delta f) \text{diag}(c)). \end{aligned}$$

□

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Remark 29.1. 1. $(f \smile g) \frown c = f \smile g \frown c$,2. $1 \frown c = c$,3. for any $\alpha \in H^*X$ and $\beta \in H^*Y$, and $a \in H_*X$ and $b \in H_*Y$, then $(\alpha \times \beta) \frown (a \times b) = (-1)^{|\beta||a|}(\alpha \frown a) \times (\beta \frown b)$, where $a \times b$ is given by the inverse of Alexander-Whitney map, i.e.,

$$\begin{aligned} C_*X \otimes C_*Y &\rightarrow C_*(X \times Y) \\ a \otimes b &\mapsto a \times b. \end{aligned}$$

4. Relative version for open/good pairs:

$$\frown : H^p(X, A) \otimes H_n(X, A \smile B) \rightarrow H_{n-p}(X, B).$$

Definition 29.2. Let M be an n -manifold, then a fundamental class for M is $[M] \in H_n(M, R)$ such that for any $x \in M$, $j_x^M[M] \in H_n(M \mid x; R) \cong R$ is an R -module generator.**Remark 29.3.** If $[M]$ is a fundamental class, then we have a continuous section

$$\begin{aligned} s : M &\rightarrow \text{Or}(M, R) \subseteq M_R \\ x &\mapsto [M]_x. \end{aligned}$$

Therefore M is orientable. By the orientation theorem, if M is a closed (compact) manifold, then $H_n(M; R) \cong \Gamma(M; M_R)$. If so, and suppose M is connected, then $H_n(M; R) \cong R$, therefore we get a fundamental class $[M]$.**Theorem 29.4** (Poincaré Duality). Let M be a compact, closed, and oriented (i.e., orientable and choosing a continuous section of $\text{Or}(M; R)$, which is therefore equivalent to choosing a fundamental class $[M]$) n -manifold, with a fundamental class $[M]$, then

$$- \frown [M] : H^p(M; R) \xrightarrow{\cong} H_{n-p}(M; R)$$

is an isomorphism for all p .**Definition 29.5.** Denote $C^p = \text{Hom}(C_p, R)$, then we say $f \in C^p(M)$ is supported on $K \subseteq M$ if for all $\sigma : \Delta^p \rightarrow M \setminus K$, we have $f(\sigma) = 0$, i.e., $f \in C^p(M, M \setminus K)$, since on the level of cochains there is the exact sequence

$$0 \longrightarrow C^p(M, M \setminus K) \longrightarrow C^p(M) \longrightarrow C^p(M \setminus K) \longrightarrow 0$$

We say f is compactly supported if it is supported on some compact $K \subseteq M$.**Definition 29.6.** Denote $C_c^p(M; R) = \text{colim}_{\text{compact } K} C^p(M, M \setminus K) := \bigcup_{\text{compact } K \subseteq M} C^p(M, M \setminus K) \subseteq C^p(M)$. This is a subcomplex of $C^*(M)$. We denote $H_c^*(M; R) = H^*(C_c^*(M; R))$ to be the cohomology of this complex.**Remark 29.7.** If $\{K_\alpha\}$ is a collection of compact subsets of M such that any compact $K \subseteq K_\alpha$ for some α , then

$$C_c^*(M) \cong \text{colim}_{K_\alpha} C^*(M, M \setminus K_\alpha),$$

and so $H_c^*(M) \cong \text{colim}_{K_\alpha} H^*(M, M \setminus K_\alpha)$.**Example 29.8.** Let $M = \mathbb{R}^n$, then $H_c^*(\mathbb{R}^n) \cong \text{colim}_i H^i(\mathbb{R}^n, \mathbb{R}^n \setminus B_i(0)) \cong \text{colim}_i H^*(\mathbb{R}^n, \mathbb{R}^n \setminus \{0\}) \cong \tilde{H}^*(S^{n-1})$, where $B_i(0)$ is the ball centered at 0 with radius i .**Example 29.9.** If M is compact, then this is just the ordinary cohomology, i.e., the statement is true vacuously.**Remark 29.10.** If $f : X \rightarrow Y$ is a continuous map, we do not have an induced map on H_c^* . However,

1. if f is proper, i.e., the preimage of a compact set is compact, then this gives a map $f^* : H_c^*(Y) \rightarrow H_c^*(X)$;
2. if $i : U \hookrightarrow X$ is an inclusion of an open subset where X is Hausdorff, then we get $i_! : H_c^*(U) \rightarrow H_c^*(X)$ as extension by zero, and $H_c^*(U) = \text{colim}_{K \subseteq U} H^*(U, U \setminus K) \cong \text{colim}_{K \subseteq U} H^*(X, X \setminus K)$ by excision $\overline{X \setminus U} \subseteq K \setminus K = \text{int}(X \setminus K)$. This induces a map $i_! : \text{colim}_{K \subseteq U} H^*(X, X \setminus K) \rightarrow \text{colim}_{L \subseteq X} H^*(X, X \setminus L)$ from the colimit. Note that if $j : V \hookrightarrow U$ and $i : U \hookrightarrow X$ are open inclusions, then $(i \circ j)_! = i_! \circ j_!$.

30 Nov 3, 2023

Proposition 30.1. Suppose $X = U \cup V$, then we have Mayer-Vietoris sequence

$$\cdots \longrightarrow H_c^p(U \cap V) \longrightarrow H_c^p(U) \oplus H_c^p(V) \longrightarrow H_c^p(X) \longrightarrow H_c^{p+1}(U \cap V) \longrightarrow \cdots$$

Proof. Let $K \subseteq U$ and $L \subseteq V$ be compact subsets, then we have an exact sequence

$$\cdots \longrightarrow H^p(X, X \setminus (K \cap L)) \longrightarrow H^p(X, X \setminus K) \oplus H^p(X, X \setminus L) \longrightarrow H^p(X, X \setminus (K \cup L)) \longrightarrow \cdots$$

Let $\mathcal{K}_U \times \mathcal{K}_V = \{(K, L) \mid \text{compact } K \subseteq U, \text{ compact } L \subseteq V\}$ as a directed system, take $\text{colim}_{\mathcal{K}_U \times \mathcal{K}_V} (*)$ and we get an exact sequence

$$\cdots \rightarrow \text{colim } H^*(X, X \setminus (K \cap L)) \rightarrow \text{colim } H^*(X, X \setminus K) \oplus H^*(X, X \setminus L) \rightarrow \text{colim } H^*(X, X \setminus (K \cup L)) \rightarrow \cdots$$

by taking the colimits over $\mathcal{K}_U \times \mathcal{K}_V$. Now colimits distribute over direct sum, so the middle term is just

$$\text{colim}_{\mathcal{K}_U} H^*(X, X \setminus K) \oplus \text{colim}_{\mathcal{K}_V} H^*(X, X \setminus L)$$

Definition 30.2. A map of directed systems $\varphi : \mathcal{D} \rightarrow \mathcal{C}$ is final if for all $C \in \mathcal{C}$, there exists $D \in \mathcal{D}$ such that $C \leq \varphi(D)$, e.g., φ is surjective.

Therefore if $\varphi : \mathcal{D} \rightarrow \mathcal{C}$ is final, then $\text{colim}_{\mathcal{D}} F \circ \varphi \cong \text{colim}_{\mathcal{C}} F$ for any diagram $F : \mathcal{C} \rightarrow \mathcal{A}$.

Remark 30.3. This gives, for example, $\varphi_U : \mathcal{K}_U \times \mathcal{K}_V \rightarrow \mathcal{K}_U$, $\varphi_V : \mathcal{K}_U \times \mathcal{K}_V \rightarrow \mathcal{K}_V$, $\varphi_{U \cap V} : \mathcal{K}_U \times \mathcal{K}_V \xrightarrow{\sim} \mathcal{K}_{U \cap V}$, and finally $\varphi_{U \cup V} : \mathcal{K}_U \times \mathcal{K}_V \xrightarrow{\sim} \mathcal{K}_{U \cup V}$ is surjective. Suppose K is compact in $U \cup V$, then $K = (K \cap U) \cup (K \cap V)$ where $K \setminus (K \cap U)$ and $K \setminus (K \cap V)$ are contained in a disjoint union of open neighborhoods (by some separation axioms). Therefore, there exists open $W \subseteq U$ such that $K \setminus (K \cap U) \subseteq W \subseteq \bar{W} \subseteq K \cap V$, now let $K_V = \bar{W}$ and $K_U = K \setminus W$, then $K_V \cup K_U = K$ as a union of compact subset of U and compact subset of V .

Finally, we look at the Mayer-Vietoris for pairs, given by

$$\begin{array}{ccccccc} 0 & \longrightarrow & C_*(A) & \longrightarrow & C_*(X) & \longrightarrow & C_*(X, A) \longrightarrow 0 \\ & & \uparrow & & \parallel & & \uparrow \\ 0 & \longrightarrow & C_*(A) & \longrightarrow & C_*(X) & \longrightarrow & C_*(X, A) \longrightarrow 0 \end{array}$$

then this gives the complex

$$\begin{array}{ccccccc} & & 0 & & 0 & & 0 \\ & & \downarrow & & \downarrow & & \downarrow \\ 0 & \longrightarrow & C_*(A \cap B) & \longrightarrow & C_*(A) \oplus C_*(B) & \longrightarrow & C_*(A \cup B) \longrightarrow 0 \\ & & \downarrow & & \downarrow & & \downarrow \\ 0 & \longrightarrow & C_*(X) & \longrightarrow & C_*(X) \oplus C_*(X) & \longrightarrow & C_*(X) \longrightarrow 0 \\ & & \downarrow & & \downarrow & & \downarrow \\ 0 & \longrightarrow & C_*(X, A \cap B) & \longrightarrow & C_*(X, A) \oplus C_*(X, B) & \longrightarrow & C_*(X, A \cup B) \longrightarrow 0 \\ & & \downarrow & & \downarrow & & \downarrow \\ & & 0 & & 0 & & 0 \end{array}$$

□

Let M be an n -manifold that is R -oriented, i.e., $s : M \rightarrow M_R$ is a section or gives a fundamental class.

Definition 30.4. Let $A \subseteq M$ be compact, then a fundamental class along A is $[M]_A \in H_n(M \mid A, R)$, such that $j_x^A([M]_A) \in H_n(M \mid x) \cong R$ is a generator of R -module structure, i.e., a local orientation at x .

Let $A \subseteq B$ be two compact subsets of M , with $i : (M | B) \hookrightarrow (M | A)$ and $i_* : H_n(M | B) \rightarrow H_n(M | A)$, then $i_*([M]_B)$ is a fundamental class along A . Therefore, we have a commutative diagram

$$\begin{array}{ccc} H^p(M | A) & & \\ i_* \downarrow & \searrow -\cap [M]_A & \\ H^p(M | B) & \xrightarrow{-\cap [M]_B} & H_{n-p}(M) \end{array}$$

recalling that $\cap : H^p(X, Z) \otimes H_n(X, Z \cup W) \rightarrow H_{n-p}(X, W)$, so taking $W = \emptyset$ gives $\cap : H^p(X, Z) \otimes H_n(X, Z) \rightarrow H_{n-p}(X, \emptyset)$. Take the colimits over compact subsets of M , then we have a duality map

$$D_M : H_c^p(M) \rightarrow H_{n-p}(M).$$

31 Nov 6 & 8, 2023

Lemma 31.1. If $i : U \subseteq M$ open, the the square

$$\begin{array}{ccc} H_c^p(U) & \xrightarrow{D_U} & H_{n-p}(U) \\ i_! \downarrow & & \downarrow i_* \\ H_c^p(M) & \xrightarrow{D_M} & H_{n-p}(M) \end{array}$$

commutes.

Proof. Recall that $i_!$ is given by the composition

$$H_c^p(U) \cong \operatorname{colim}_{\text{compact } K \subseteq U} H^p(U | K) \cong \operatorname{colim}_{\text{compact } K \subseteq U} H^p(M | K) \rightarrow \operatorname{colim}_{\text{compact } L \subseteq M} H^p(M | L) = H_c^p(M).$$

So it suffices to show that for each compact subset $K \subseteq U$, we have a commutative diagram

$$\begin{array}{ccc} H^p(U | K) & \xrightarrow{-\cap [U]_K} & H_{n-p}(U) \\ i_* \uparrow & & \downarrow i_* \\ H^p(M | K) & \xrightarrow{-\cap [M]_K} & H_{n-p}(M) \end{array}$$

where $i_* : H^p(M | K) \rightarrow H^p(U | K)$ is an isomorphism by excision, induced from $U \hookrightarrow M$ and $(U, U \setminus K) \hookrightarrow (M, M \setminus K)$. The notation $[M]_K = i_*[U]_K$ is the induced fundamental class. The diagram commutes because $i_*(u^* \alpha \cap [U]_K) = \alpha \cap i_*[U]_K$. \square

Lemma 31.2. Let $M = U \cup V$ where $U, V \subseteq M$ are open subsets, then we have a commutative diagram

$$\begin{array}{ccccccc} \cdots & \longrightarrow & H_c^p(U \cap V) & \longrightarrow & H_c^p(U) \oplus H_c^p(V) & \longrightarrow & H_c^p(M) \longrightarrow H_c^{p+1}(U \cap V) \longrightarrow \cdots \\ & & \downarrow D_{U \cap V} & & \downarrow D_U \oplus D_V & & \downarrow D_M \\ \cdots & \longrightarrow & H_{n-p}(U \cap V) & \longrightarrow & H_{n-p}(U) \oplus H_{n-p}(V) & \longrightarrow & H_{n-p}(M) \longrightarrow H_{n-p-1}(U \cap V) \longrightarrow \cdots \end{array}$$

Proof. By the previous lemma, the first two squares commute, and we just need to show that the last square commutes as well. Recall that for $K \subseteq U$ and $L \subseteq V$ compact, we have

$$H_c^p(M) \cong \operatorname{colim}(H^p(M | K \cup L) \rightarrow H_c^{p+1}(U \cap V) = \operatorname{colim}(H^{p+1}(U \cap V | K \cap L)) = H^{p+1}(M | K \cap L).$$

Recall $(M | K \cup L) = (M | K) \cap (M | L) =: X \cap Y$, therefore we define δ^{KL} with

$$\begin{array}{ccc} H^p(M | K \cup L) = H^p(X \cap Y) & \xrightarrow{\delta^{KL}} & H^{p+1}(M | K \cap L) = H^{p+1}(X \cup Y) \cong H^{p+1}(U \cap V, (U \cap V) \setminus (K \cap L)) \\ -\cap [M]_{K \cup L} \downarrow & & \downarrow -\cap [U \cap V]_{K \cap L} \\ H_{n-p}(M) & \xrightarrow{\quad \partial \quad} & H_{n-p-1}(U \cap V) \end{array}$$

and we want to show that the diagram commutes. Take $[f] \in H^p(X \cap Y)$, then it has a representative $f \in C^p(X \cap Y)$. Consider the sequence

$$\begin{array}{c}
 0 \\
 \uparrow \\
 C^p(X \cap Y) \\
 \uparrow \\
 C^p(X) \oplus C^p(Y) \xrightarrow{\delta} C^{p+1}(X) \oplus C^{p+1}(Y) \\
 \uparrow \\
 C^p(X \cup Y) \\
 \uparrow \\
 0
 \end{array}$$

We lift f to $\tilde{f} = f_X = f_Y \in C^p(X) \oplus C^p(Y)$, therefore we have $\delta^{KL}([f]) = [\delta f_X] - [\delta f_Y]$. Since the image lands in zero over short exact sequence, we have another lifting.

Suppose we have $[z] \in H_{n-p}(M)$, then $\partial([z]) = [\partial z_U] - [\partial z_V]$ where z_U and z_V are liftings. We take the short exact sequence

$$0 \longrightarrow C_{n-p}(U \cap V) \longrightarrow C_{n-p}(U) \oplus C_{n-p}(V) \longrightarrow C_{n-p}(U \cup V) \longrightarrow 0$$

as we lift $z \in C_{n-p}(U \cup V)$ to $z_U \oplus z_V$ in $C_{n-p}(U) \oplus C_{n-p}(V)$. Let $[\alpha] = [M]_{K \cup L}$, then $\alpha \in C_n(M, M \setminus (K \cup L))$ and use barycentric subdivision and divide the simplex into smaller ones. We take $\alpha = \alpha_{U \setminus V} + \alpha_{U \cap V} + \alpha_{V \setminus K}$ for $\alpha_* \in C_n(*)$. This gives $\partial(\alpha_{U \cap V}) \in C_n((U \cap V) \setminus (K \cap L))$, then $\alpha_{U \cap V}$ is a cycle in $C_n(U \cap V \mid K \cap L)$. Similarly, we have $\alpha_{U \setminus L} + \alpha_{U \cap V}$ as a cycle in $C_n(U \mid K)$, and $\alpha_{V \setminus K} + \alpha_{U \cap V}$ is a cycle in $C_n(V \mid L)$. The claim is that $\alpha_{U \cap V}$ represents $[U \cap V]_{K \cap L}$, $\alpha_{U \setminus L} + \alpha_{U \cap V}$ represents $[U]_K$, and $\alpha_{V \setminus K} + \alpha_{U \cap V}$ represents $[V]_L$. It suffices to check that the diagram

$$\begin{array}{ccc}
 C^p(M \mid K \cup L) & \xrightarrow{\delta^{MV}} & C^{p+1}(M \mid K \cap L) \\
 \downarrow -\cap \alpha & & \downarrow -\cap \alpha_{U \cap V} \\
 C_{n-p}(M) & \longrightarrow & C_{n-p-1}(U \cap V)
 \end{array}$$

□

32 Nov 10, 2023

Theorem 32.1 (Poincaré Duality). Let M be an R -oriented n -manifold, then the duality map

$$D_M : H_c^p(M; R) \rightarrow H_{n-p}(M; R)$$

is an isomorphism for all p .

Proof. Let \mathcal{C} be the set of R -oriented n -manifolds M for which D_M is an isomorphism, then \mathcal{C} satisfies

- (a) \mathcal{C} is closed under homeomorphisms;
- (b) if $M = U \cup V$ where $U, V \hookrightarrow M$ open, and $U, V \in \mathcal{C}$, then $M \in \mathcal{C}$. This follows from the Mayer-Vietoris compatibility;
- (c) if M is a union of a nested sequence of open submanifolds $U_1 \subseteq U_2 \subseteq \cdots \subseteq \cdots M = \bigcup U_i = \text{colim}(U_i)$, and each $U_i \in \mathcal{C}$, then $M \in \mathcal{C}$.

$$\begin{array}{ccc}
 \text{colim}_i H_c^p(U_i) & \xrightarrow{\text{colim}(D_{U_i})} & \text{colim}_i H_{n-p}(U_i) \\
 \cong \downarrow & & \downarrow \cong \\
 H_c^p(M) & \xrightarrow{D_M} & H_{n-p}(M)
 \end{array}$$

Step 1: $\mathbb{R}^n \in \mathcal{C}$. Consider

$$H^p(\mathbb{R}^n) = \operatorname{colim}_{K \subseteq \mathbb{R}^n} H^p(\mathbb{R}^n | K) \cong \operatorname{colim}_r H^p(\mathbb{R}^n | B_r(0)) \cong H^p(\mathbb{R}^n | 0) \cong \tilde{H}^p(S^n)$$

It suffices to check that after doing the cap product, we have $-\smile [\mathbb{R}^n \setminus 0]$ sending this to $H_{n-p}(\mathbb{R}^n)$, hence this is zero unless $p = n$ which is an isomorphism using Kronecker product.

Step 2: by (a), any $U \cong \mathbb{R}^n$ is in \mathcal{C} .

Step 3: if $M \subseteq \mathbb{R}^n$ is open, then M is the countable union of open subsets $U_\alpha \cong \mathbb{R}^n$ such that finite intersections of U_α 's are also isomorphic to \mathbb{R}^n . We write $M_k = \bigcup_{i=1}^k U_i$, then M is the colimit of M_k 's as a nested sequence of open subsets, therefore $M_k \in \mathcal{C}$ by (b), then by (c) we have $M \in \mathcal{C}$.

Step 4: let I_M be the set of open subsets $U \subseteq M$ such that D_U is an isomorphism. This is a non-empty poset, so by Zorn's lemma, for any totally ordered $J \subseteq I_M$ we have a colimit over J contained in I by property (c). Therefore, there exists a maximal element in I_M , that is a maximal open neighborhood $U_{\max} \subseteq M$, such that $D_{U_{\max}}$ is an isomorphism. If $U \subsetneq M$, let $x \in M \setminus U_{\max}$, then take $W \ni x$ as a Euclidean neighborhood of x , then $W \in I_M$, so $U_{\max} \cap W \in I_M$, so by Mayer-Vietoris, we have $U_{\max} \cup W \in I_M$, which is a contradiction, so $U_{\max} = M$. \square

Corollary 32.2. $H^*(\mathbb{R}P^n; \mathbb{F}_2) \cong \mathbb{F}_2[x]/x^{n+1}$ for $|x| = 1$.

Proof. We proceed by induction. For $n = 1$, we have $\mathbb{R}P^1 = S^1$ so this is obvious. Suppose this is true for $n - 1$, we look at the inclusion $j : \mathbb{R}P^{n-1} \hookrightarrow \mathbb{R}P^n$, then the pullback $j^* : H^q(\mathbb{R}P^n) \rightarrow H^q(\mathbb{R}P^{n-1})$. This is an isomorphism for $q \leq n - 1$. It is enough to check that $x^n \in H^n(\mathbb{R}P^n)$ is a generator of the group. We know

$$\begin{aligned} H^p(\mathbb{R}P^n) &\rightarrow H_{n-p}(\mathbb{R}P^n) \\ x \smile [\mathbb{R}P^n] &\mapsto gm \in H_{n-1}(\mathbb{R}P^n) \cong H_{n-1}(\mathbb{R}P^{n-1}) \end{aligned}$$

is an isomorphism, given that $H^n(\mathbb{R}P^n, \mathbb{R}P^{n-1}) \cong H^n(\mathbb{R}P^n)$, therefore the mapping above is sent to $[\mathbb{R}P^{n-1}]$. Therefore, $x^n \smile [\mathbb{R}P^n]$ is a generator of $H_0(\mathbb{R}P^n)$, but that is just $(x^{n-1} \smile x) \smile [\mathbb{R}P^n] = x^{n-1} \smile (x \smile [\mathbb{R}P^n]) = x^{n-1} \smile [\mathbb{R}P^{n-1}]$, which is a generator. \square

33 Nov 13, 2023

Example 33.1. Let M be compact, then $H^p(M, R) \cong H_c^p(M; R) \cong H_{n-p}(M; R)$.

Remark 33.2. Let M be a compact manifold, then M is equivalent to a finite triangulation of CW complexes, so $H_i(M)$ is finitely-generated for all i .

Definition 33.3. We define the Euler characteristic to be $\chi(M) = \sum_{k \geq 0} (-1)^k \operatorname{rank}(H_k(M)) = \sum_{k \geq 0} (-1)^k \operatorname{rank}_{\mathbb{Q}}(H_k(M; \mathbb{Q})) = \sum_{k \geq 0} (-1)^k \operatorname{rank}_{\mathbb{F}_p}(H_k(M; \mathbb{F}_p))$.

Theorem 33.4. If M is a compact manifold of odd dimension, then $\chi(M) = 0$.

Proof. If M is \mathbb{F}_2 -orientable, then by Poincaré duality we have $H_{n-p}(M; \mathbb{F}_2) \cong H^p(M, \mathbb{F}_2)$, then by universal coefficient theorem this is isomorphic to $\operatorname{Hom}_{\mathbb{F}_2}(H_p(M; \mathbb{F}_2), \mathbb{F}_2)$. The Euler characteristic is given by $\chi(M) = \sum_{k=0}^{\frac{n-1}{2}} (-1)^k \dim(H_k) + (-1) \cdot \dim(H_{n-k})$. Note that the two terms are negatives of each other, so they all cancel, thus $\chi(M) = 0$. \square

If M is compact and R -orientable, then we can restate Poincaré duality as

$$\begin{array}{ccc} H^p(M; R) \otimes H^{n-p}(M; R) & \longrightarrow & R \\ & \searrow \smile & \uparrow -\smile [M] \\ & & H^n(M; R) \end{array}$$

gives a graded symmetric pairing. In the case if R is a field, then this is a non-degenerate pairing, i.e., $H^p(M; R) \cong \operatorname{Hom}_R(H^{n-p}(M; R), R)$.

Corollary 33.5. If F is a field, M is a compact F -orientable $(4n+2)$ -dimensional manifold, then $\dim_F(H^{2n+1}(M; F))$ is even.

Proof. The non-degenerate pairing $H^{2n+1}(M) \otimes H^{2n+1}(M) \rightarrow F$ is a non-singular, skew-symmetric form, then by a classification result we know it must be of even dimensional. \square

Remark 33.6. If $\dim(M) = 4n$, $H^{2n}(M)$ has a non-singular symmetric bilinear form classified by the signature invariant.

Definition 33.7. A manifold with boundary is a Hausdorff space M such that for all $x \in M$ has a neighborhood which is either homeomorphic to \mathbb{R}^n or to \mathbb{R}_+^n , the half space $\{(a_i) \mid a_n \geq 0\}$, then the boundary is $\partial M = \{x \in M \mid x \text{ does not have a neighborhood } \cong \mathbb{R}^n\}$, then this is an $(n-1)$ -dimensional manifold.

Example 33.8. $\partial \mathbb{R}_+^n \cong \mathbb{R}^{n-1}$.

Let $M = \mathbb{D}^n$ be a closed n -ball, then $\partial M = S^{n-1}$.

Definition 33.9. M is orientable if $M \setminus \partial M$ is.

We say ∂M has a collar neighborhood if there exists an open neighborhood $\partial M \subseteq U \subseteq M$ homeomorphic to $\partial M \times [0, 1)$. Note that any compact manifold with boundary has a collar neighborhood.

Theorem 33.10 (Poincaré-Lefschetz Duality). For any such manifold M , i.e., compact with boundary, we have an isomorphism

$$- \cap [M] : H^p(M, \partial M) \rightarrow H_{n-p}(M).$$

The fundamental class is given by $H_n(M, \partial M) \cong H_n(M, \partial M \times [0, 1)) \cong H_n(M \setminus \partial M, \partial M \times (0, 1))$ by excision. Therefore this sends fundamental classes to fundamental classes over the cap product.

Corollary 33.11. If M is a compact odd-dimensional manifold, then $\chi(M) = \frac{1}{2}\chi(\partial M)$.

Corollary 33.12. $\mathbb{R}P^{2n}$ or $\mathbb{C}P^{2n}$ are not the boundary of some compact manifolds, since the Euler characteristic is odd.

34 Nov 15, 2023

Definition 34.1. Let B be a topological space, a real/complex vector bundle over B is a continuous map $p : E \rightarrow B$ packaged into data $\xi = (E, B, p)$, where E is called the total space and B is called the base space, such that for all $b \in B$, the fibre $p^{-1}(b) = E_b$ is a real/complex vector space. Furthermore, each $b \in B$ has an open neighborhood U such that the diagram

$$\begin{array}{ccc} p^{-1}(U) & \xleftarrow[\cong]{\varphi} & U \times \mathbb{F}^n \\ p \downarrow & \swarrow \pi & \\ U & & \end{array}$$

for field $F = \mathbb{R}$ or \mathbb{C} and projection π , and φ induces a linear isomorphism $\mathbb{F}^n \rightarrow E_b$ for each $b \in U$, then

$$\begin{aligned} \text{rank}(\xi) : B &\rightarrow \mathbb{N} \\ b &\mapsto \dim(E_b) \end{aligned}$$

is a locally constant function. An isomorphism of vector bundles over B $f : \xi \cong \eta$ is a homeomorphism $f : E(\xi) \cong E(\eta)$ inducing linear isomorphism on fibres.

Example 34.2. Consider $\mathbb{R}P^n \cong \{\ell \subseteq \mathbb{R}^{n+1}\}$ to be lines ℓ through 0 in \mathbb{R}^{n+1} . The canonical line bundle over $\mathbb{R}P^n$ is the set of pairs (ℓ, v) for ℓ above and basepoint $v \in \ell$. This is the set of 1-dimensional vector bundle, the tautological vector bundle γ .

Definition 34.3. A vector bundle is trivial if it is of the form $\mathbb{F}^n \times B \rightarrow B$.

Lemma 34.4. Let ξ, η be vector bundles over B , and let $f : E(\xi) \rightarrow E(\eta)$ be a continuous map on total spaces, i.e.,

$$\begin{array}{ccc} E(\xi) & \xrightarrow{f} & E(\eta) \\ & \searrow & \swarrow \\ & B & \end{array}$$

Suppose we know $f_b : E(\xi)_b \rightarrow E(\eta)_b$ is a linear isomorphism. then f is an isomorphism.

Theorem 34.5. An n -plane bundle is trivial if and only if it has n fibrewise linearly independent nowhere vanishing sections, i.e., there exists $s_1, \dots, s_n : B \rightarrow E$ linearly independent such that $s(b) \in E_b \cong \mathbb{R}^n$ is non-zero for all b .

Proof. Suppose $s_1, \dots, s_n : B \rightarrow E$ are linearly independent nowhere vanishing sections of $p : E \rightarrow B$, then define

$$\begin{array}{ccc} B \times \mathbb{R}^n & \xrightarrow{f} & E \\ & \searrow & \swarrow \\ & B & \end{array}$$

such that $f(b, x_1, \dots, x_n) = x_1 s_1(b) + \dots + x_n s_n(b) \in E_b$. s_i being continuous implies f to be continuous, and being nowhere vanishing sections indicates f is fibrewise a linear isomorphism. Therefore f is an isomorphism of vector bundles. \square

Example 34.6. Let M be a manifold and TM be the tangent bundle. We say a vector bundle is trivializable if it is isomorphic to a trivial bundle. Note that for a manifold, the tangent bundle TM is trivializable if and only if M is parallelizable. This happens on spheres S^n for $n = 0, 1, 3, 7$.

Example 34.7. Let $\text{Gr}_n(\mathbb{R}^q)$ be the n -Grassmanian, as the space of n -planes through the origin in \mathbb{R}^q . It has a universal/tautological n -plane bundle $E(\gamma_q^n)$ as the set of pairs (V, v) for $V \in \text{Gr}_n(\mathbb{R}^q)$ and $v \in V$. The topology on the Grassmannian is the quotient topology from the real space.

There are a few common constructions of vector bundles:

1. Restrictions to subspaces: given a vector bundle $p : E \rightarrow B$ and a subspace $U \subseteq B$, the restriction $p^{-1}(U) \rightarrow U$ is a vector bundle as well.
2. Pullback bundle: given vector bundle $p : E \rightarrow B$ as ξ and $f : B' \rightarrow B$, then there is a pullback bundle $f^*(\xi) : f^*(E) \rightarrow B'$ with base space B' and total space $f^*(E) = E(f^*\xi) = B' \times_B E$.

$$\begin{array}{ccc} f^*(E) & \longrightarrow & E \\ \downarrow & & \downarrow \\ B' & \xrightarrow{f} & B \end{array}$$

3. Cartesian product of bundles: for $\xi_i : E_i \rightarrow B_i$ where $i = 1, 2$, the product bundle $\xi_1 \times \xi_2 : E_1 \times E_2 \rightarrow B_1 \times B_2$. For instance, for manifolds M_1, M_2 , we have $T(M_1 \times M_2) \cong T(M_1) \oplus T(M_2)$.
4. Whitney sum: given ξ_1, ξ_2 vector bundles on B , we have $\xi_1 \oplus \xi_2 = \text{diag}_B^*(\xi_1 \times \xi_2)$, induced by $\text{diag}_B : B \rightarrow B \times B$ and fibres are $E(\xi_1 \oplus \xi_2)_b = E(\xi_1)_b \oplus E(\xi_2)_b$.

Definition 34.8. Let ξ, η be vector bundles over B , then we say ξ is a subbundle of η if the diagram

$$\begin{array}{ccc} E(\xi) & \hookrightarrow & E(\eta) \\ & \searrow & \swarrow \\ & B & \end{array}$$

commutes, and on fibres it is an inclusion of vector spaces.

Lemma 34.9. If $\xi_1, \xi_2 \subseteq \eta$ are submodules such that $E(\xi_1)_b \oplus E(\xi_2)_b \cong E(\eta)_b$ for each $b \in B$, then $\eta \cong \xi_1 \oplus \xi_2$.

Proof. One can check that the assignment

$$\begin{aligned} E(\xi_1) \oplus E(\xi_2) &\rightarrow E(\eta) \\ (b, e_1) \oplus (b, e_2) &\mapsto (b, e_1 + e_2) \end{aligned}$$

commutes over B , i.e.,

$$\begin{array}{ccc} E(\xi_1) \oplus E(\xi_2) & \xrightarrow{\quad} & E(\eta) \\ & \searrow \quad \swarrow & \\ & B & \end{array}$$

□

Example 34.10. If $M \subseteq \mathbb{R}^n$ is a manifold, then the trivial n -bundle is a direct sum of TM and the normal bundle of M .

Recall that if V is an inner product space, i.e., with symmetric bilinear and positive definite form, then it is equivalent to say it has a Euclidean norm.

Definition 34.11. A Euclidean vector bundle is a real vector bundle ξ on B with a continuous function $E(\xi) \rightarrow \mathbb{R}$ which restricted to each fiber is a Euclidean norm.

Example 34.12. The norm sends the trivial bundle $\varepsilon_B^n = (\mathbb{R}^n \times B \rightarrow B)$ with (x_1, \dots, x_n, b) to $\sqrt{x_1^2 + \dots + x_n^2}$ via the norm.

Therefore, by restriction, any subbundle of a Euclidean bundle inherits a Euclidean structure.

Definition 34.13. If ξ is Euclidean, and $\eta \subseteq \xi$ is a subbundle, then the orthogonal complement η^\perp is a vector bundle defined by $E(\eta^\perp) = \bigcup_b E(\eta)_b^\perp$.

Proposition 34.14. Suppose $\eta \subseteq \xi$ is a subbundle of a Euclidean bundle, then $\xi = \eta \oplus \eta^\perp$.

For any tangent bundle TM , there exists some n and some normal bundle such that the direct sum of the tangent bundle and the normal bundle is a trivial n -bundle.

Definition 34.15. We say η is stably trivial if there exists $N \geq 0$ such that $\eta \oplus \varepsilon^N \cong \varepsilon^{N+\text{rank}(\eta)}$, where ε^n is the trivial n -bundle.

Example 34.16. $S^{n-1} \subseteq \mathbb{R}^n$ has trivial normal bundle, that is, $TS^{n-1} \oplus \varepsilon^1 \cong \varepsilon^n$.

We say η and ξ are stably equivalent as vector bundles if $\xi \oplus \varepsilon^{N_1} \cong \eta \oplus \varepsilon^{N_2}$.

One can construct tensor products and homs of vector bundles as well.

Definition 34.17. The Stiefel-Whitney classes satisfies the following axioms. Given a vector bundle $\xi : E \rightarrow B$ with rank n ,

1. the cohomology class $w_i(\xi) \in H^i(B(\xi), \mathbb{Z}/2\mathbb{Z})$ for each $i \geq 0$, such that $w_0(\xi) = 1 \in H^0(B, \mathbb{Z}/2\mathbb{Z}) = \mathbb{Z}/2\mathbb{Z}$, and $w_i(\xi) = 0$ for $i > n$;
2. naturality: given mapping $f : B' \rightarrow B$ and vector bundle ξ on B , then the pullback $f^*(w_i(\xi)) = w_i(f^*\xi)$;
3. Whitney sum/product formula: for η, ξ on B , then $w_k(\xi \oplus \eta) = \sum_{i+j=k} w_i(\xi)w_j(\eta)$. Note that if we define the total Stiefel-Whitney class to be $w(\xi) = \sum w_i(\xi) \in H^*(B(\xi))$, then $w(\xi \oplus \eta) = w(\xi)w(\eta)$;
4. non-degeneracy: for tautological line bundle γ , we have $w_1(\gamma_1^1) \neq 0 \in H^1(\mathbb{R}P^1; \mathbb{Z}/2\mathbb{Z})$.

Remark 34.18. If $\eta \cong \xi$ then $w_i(\eta) = w_i(\xi)$.

For $i > 0$, we have $w_i(\varepsilon_B^n) = 0$, since it is the pullback of

$$\begin{array}{ccc} \varepsilon_B^* & \xrightarrow{\quad} & \mathbb{R}^n \\ \downarrow & & \downarrow \\ B & \xrightarrow{\quad} & * \end{array}$$

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Remark 35.1. On $\mathbb{R}P^n$, we have γ_n^1 that satisfies $w(\gamma_n^1) = 1+x \in H^*(\mathbb{R}P^n)$ and $E(\gamma_n^1) = \{([a : -a], ta), t \in \mathbb{R}\}$ where $\gamma_n^1 \subseteq \xi^{n+1}$ lies in the trivial bundle. The orthogonal bundle is given by $E((\xi_n^1)^\perp) = \{([a : -a], v), v \perp a\}$, such that $\gamma_n^1 \oplus (\gamma_n^1)^\perp \cong \xi^{n+1}$. Therefore $w(\gamma_n^1)w((\gamma_n^1)^\perp) = 1 \in \mathbb{Z}/2\mathbb{Z}[x]/x^{n+1} \cong H^*(\mathbb{R}P^n)$, and $w((\gamma_n^1)^\perp) = 1+x+\dots+x^n$.

The tangent bundle $\tau_{\mathbb{R}P^n}$ is exactly $\text{Hom}(\gamma_n^1, (\gamma_n^1)^\perp)$.

Corollary 35.2. $\tau_{\mathbb{R}P^n} \oplus \xi^1 \cong (\gamma_n^1)^{\oplus(n+1)}$.

Proof. $\xi^1 \cong \text{Hom}(\xi_n^1, \xi_n^1)$ where the identity map is just a nowhere vanishing section, then $\tau_{\mathbb{R}P^n} \oplus \xi^1 \cong \text{Hom}(\gamma_n^1, (\gamma_n^1)^\perp \oplus \gamma_n^1 \cong \xi^{n+1}) \cong \text{Hom}(\gamma_n^1, \varepsilon^1)^{\oplus(n+1)}$, which is just $(\gamma_n^1)^{\oplus(n+1)}$ since γ_n^1 is Euclidean. In particular, $w(\tau_{\mathbb{R}P^n} \oplus \varepsilon^1) \cong (w(\gamma_n^1))^{n+1} = (1+x)^{n+1}$. \square

Corollary 35.3. $w(\tau_{\mathbb{R}P^n}) = 1$ if and only if $n = 2^k - 1$.

Proof. Indeed, this requires $\binom{n+1}{r} \equiv 0 \pmod{2}$ via the 2-adic expansion. \square

Remark 35.4. $w(\tau_{\mathbb{R}P^2}) = (1+x)^3 = 1+x+x^2$ and $w(\tau_{\mathbb{R}P^3}) = (1+x)^4 = 1$.

Definition 35.5. An orientation of a n -dimensional real vector space V is an equivalence class of ordered bases $B = (v_1, \dots, v_n)$ where $B \sim B' = (v'_1, \dots, v'_n)$ if the transition matrix $T_{B,B'}$ has positive determinant.

Remark 35.6. This gives a choice of generator of $H_n(V, V \setminus \{0\}) \cong \mathbb{Z}$.

Definition 35.7. An orientation of a real n -dimensional vector bundle ξ/B is an assignment of an orientation for each fiber E_b for $b \in B$ such that for each $b \in B$, there is a neighborhood $U \subseteq B$ and linear independent sections $s_1, \dots, s_n : U \rightarrow p^{-1}(U)$ over $p : E \rightarrow B$, such that for all $x \in U$ we have $(s_1(x), \dots, s_n(x))$ equivalent to the prescribed orientation at x .

Therefore, for each $b \in B$, we get a “preferred” generator $\tau_{E_b} \in H_n(E_b, E_b \setminus \{0\})$ and for each $b \in B$, there is a neighborhood $U \ni b$ such that there is a class $\tau_{E_U} \in H_n(p^{-1}(U), p^{-1}(U) \setminus \{\text{zero-sections}\})$ restricting to τ_{E_b} for $b \in U$.

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Let $\xi = (E \xrightarrow{p} B)$, then $H^*(E_b, |0) \cong \begin{cases} \mathbb{Z}, * = n \\ 0, \text{otherwise} \end{cases}$. Note that the zero section s_0 gives $s_0(B) \cong B$.

Theorem 36.1 (Thom Isomorphism). Let ξ be a n -bundle, then there is a unique $\tau_E \in H^n(E, E \setminus B; \mathbb{Z}/2\mathbb{Z})$, where B is the zero section of p , such that the restriction $\tau_E|_{E_b} \in H^n(E_b, E_b \setminus \{0\}; \mathbb{Z}/2\mathbb{Z})$ is the generator.

If ξ is an oriented n -bundle, then the same thing can be said for coefficients in \mathbb{Z} .

Further, $H^k(E) \xrightarrow{\sim \tau_E} H^{k+n}(E, E \setminus B)$ is an isomorphism for all $k \in \mathbb{Z}$. Note that $p^* : H^*(B) \rightarrow H^*(E)$ is an isomorphism! In particular, $H^*(E, E \setminus B) = 0$ for $* < n$.

Proof. We will prove this for $\mathbb{Z}/2\mathbb{Z}$ coefficients.

Case 1: suppose ξ is trivial, so $(E, E \setminus B) \cong (B \times \mathbb{R}^n, B \times (\mathbb{R}^n \setminus \{0\}))$. Note that $e^1 \in H^1(\mathbb{R}, \mathbb{R} \setminus \{0\})$ is the generator, then $e^n = e^1 \times \dots \times e^1 \in H^n(\mathbb{R}^n, \mathbb{R}^n \setminus \{0\})$ is the generator. In fact,

$$\begin{aligned} H^k(B) &\rightarrow H^{k+n}(B \times \mathbb{R}^n, B \times (\mathbb{R}^n \setminus \{0\})) \\ \alpha &\mapsto \alpha \times e^n \end{aligned}$$

is an isomorphism. For $\tau_{\mathbb{R}^n \times B}$, we have $1 \times e^n \in H^n(B \times \mathbb{R}^n, B \times (\mathbb{R}^n \setminus \{0\}))$ works to satisfy the theorem. To check the second part, we have

$$\begin{aligned} H^k(B) &\xrightarrow[p^*]{\cong} H^k(B \times \mathbb{R}^n) \xrightarrow{\sim \tau} H^{k+n}(B \times \mathbb{R}^n, B \times (\mathbb{R}^n \setminus \{0\})) \\ \alpha &\longmapsto \alpha \times 1 = p^*(\alpha) \longmapsto (\alpha \times 1) \smile (1 \times e^n) = (\alpha \smile 1) \times (1 \smile e^n) = \alpha \times e^n \end{aligned}$$

which is an isomorphism due to the fact above. In particular, this part works integrally also with any coefficient.

Case 2: now suppose $B = U \cup V$, and that the theorem holds for $\xi|_U$, $\xi|_V$, and $\xi|_{U \cap V}$, then we will prove that this works for $\xi|_B$. Let $E_0 = E \setminus B$. By Mayer-Vietoris, we have

$$\cdots \rightarrow H^{n-1}(E|_{U \cap V}, E_0|_{U \cap V}) \rightarrow H^n(E, E_0) \rightarrow H^n(E|_U, E_0|_U) \oplus H^n(E|_V, E_0|_V) \rightarrow H^n(E|_{U \cup V}, E_0|_{U \cup V}) \rightarrow \cdots$$

By assumption, $H^{n-1}(E|_{U \cap V}, E_0|_{U \cap V}) = 0$, and take $\tau_U \oplus \tau_V$ in $H^n(E|_U, E_0|_U) \oplus H^n(E|_V, E_0|_V)$, then both components restrict to $\tau_{U \cap V}$ by uniqueness. Therefore, $(\tau_U, \tau_V) \mapsto 0$, the difference of two images. The kernel is now $H^n(E, E_0)$, therefore there exists a unique lift τ living in $H^n(E, E_0)$. This shows that the first part of the theorem holds for B and τ . Now consider

$$\begin{array}{ccccccc} \cdots \rightarrow H^{n+k-1}(E|_{U \cap V}, E_0|_{U \cap V}) & \rightarrow & H^n(E, E_0) & \rightarrow & H^{n+k}(E|_U, E_0|_U) \oplus H^{n+k}(E|_V, E_0|_V) & \rightarrow & H^{n+k}(E|_{U \cap V}, E_0|_{U \cap V}) \rightarrow \cdots \\ & \cong \uparrow & & & \cong \uparrow & & \uparrow \\ \cdots & \longrightarrow & H^{k-1}(U \cap V) & \longrightarrow & H^k(B) & \longrightarrow & H^k(U) \oplus H^k(V) \longrightarrow \cdots \end{array}$$

then by the five lemma this proves part 2 of the theorem.

Case 3: now suppose $B = \bigcup_{i=1}^r U_i$, and the theorem holds for $\xi|_{U_i}$, and their intersections, then by induction from the Case 2, the theorem holds for $\xi|_B$.

Up to here, the theorem holds for any ξ on compact base, and holds for any coefficients for oriented bundles, since the uniqueness requires orientability.

General case: consider $\tilde{B} = \text{colim}_{C \subseteq B} C$ for C compact subsets of B . Note that $\text{colim}_{C \subseteq B} H_*(C) \cong H_*(\tilde{B}) \cong H_*(B)$, then $H^*(B, \mathbb{Z}/2\mathbb{Z}) \cong \text{Hom}_{\mathbb{Z}/2\mathbb{Z}}(H_*(B, \mathbb{Z}/2\mathbb{Z}), \mathbb{Z}/2\mathbb{Z}) = \lim_{C \subseteq B} H^*(C, \mathbb{Z}/2\mathbb{Z})$. This isomorphism holds for any coefficient, and we can interpret $H_*(B, \mathbb{Z}/2\mathbb{Z})$ to be the colimit of $H_*(C, \mathbb{Z}/2\mathbb{Z})$ over compact subsets. Similarly, we have $H^*(E, E_0) \cong \lim_{C \subseteq B} H^*(p^{-1}(C), p^{-1}(C)_0)$. Therefore, we have an isomorphism $H^*(B, \mathbb{Z}/2\mathbb{Z}) \cong \text{Hom}_{\mathbb{Z}/2\mathbb{Z}}(H_*(B, \mathbb{Z}/2\mathbb{Z}), \mathbb{Z}/2\mathbb{Z}) = \lim_{C \subseteq B} H^*(C, \mathbb{Z}/2\mathbb{Z}) \xrightarrow{\lim(p^*(-) \circ \tau_C)} \lim_{C \subseteq B} H^{*+n}(p^{-1}(C), p^{-1}(C)_0) \cong H^{*+n}(E, E_0)$.

This proves the theorem for non-oriented spaces.

For the oriented case, e.g., over \mathbb{Z} , observe the following fact: if $C_* \rightarrow D_*$ is a map of (co)chain complexes (of free abelian groups) such that for any field k , we have $H^*(\text{Hom}(D_*, k)) \rightarrow H^*(\text{Hom}(C_*, k))$ to be given from a quasi-isomorphism, then $H^*(\text{Hom}(D_*, R)) \rightarrow H^*(\text{Hom}(C_*, R))$ for any ring R is given by a quasi-isomorphism as well. \square