SPECTRAL SEQUENCES AND APPLICATIONS

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Contents

0. To readers

0.1. **About this lecture.** It's a lecture note I typed for talks I gave in a seminar about [RB82] during 2022Fall. The goal of this lecture is to introduce applications of spectral sequence, and the most exciting applications are Serre's celebrated theorems about homotopy groups.

This lecture is divided into three parts:

1. In the **first part:** We establish the foundations of spectral sequence in a quick way, and use "zig-zag" to describe the differential maps d_r.
2. In the **second part:** We firstly introduce the spectral sequence we're most concerned about, that is Leray spectral sequence. Holding this spectral sequence, we can compute (de Rham) cohomology groups of a (smooth) manifold, if it can be embedded into a fiber bundle and the cohomology of the other two ones are well known.

   The advantage of cohomology is that it admits a product structure, so we desire to compute cohomology ring structure of a given manifold using Leray spectral sequence. However, in this case, we need to be careful when we're computing cohomology ring structure of total space of a fiber bundle, since there is so-called "multiplicative extension problem", and the most typical example is $S^2 \to \mathbb{CP}^3 \to S^4$.

   In order to consider torsion information of (co)homology groups, we give a quick review about singular (co)homology in different coefficients, establish the spectral sequence for them and then we prove the de Rham theorem using spectral sequence.

   Holding these tools, we give several interesting computations, such as cohomology ring structures of some Lie groups, and path space of spheres.
3. In the **third part:** Firstly we give a quick review of basic homotopy theory, such as homotopy exact sequence, Hurewicz theorem and Bott periodic theorem, and use these tools to compute the homotopy groups of Stiefel manifold under a given dimension.

   The final goal of this part is to compute homotopy groups of sphere and prove Serre's theorems about finitely generated and torsion property of homotopy groups of sphere. The original ideals of Serre to compute homotopy groups of sphere are listed as follows:
   (*a*) Let π_q denote $\pi_q(X)$, where X is a topological space. If we want to compute π_q, just consider homology of $K(\pi_q, n)$, since Hurewicz theorem implies the n-th homology of $K(\pi_q, n)$ is exactly π_q.
   (*b*) If we can fit $K(\pi_q, n)$ into a fiberation, maybe we can use Leray spectral sequence to compute its homology. Luckily, Postnikov approximation will give desired fiberation.

0.2. **Acknowledgement.** Thanks my tutor and friend Chenglong Yu, I can't keep going without his supervision and encouragement. Thanks to everyone who listen to me and discuss with me, especially for Qiliang Luo, Shihao Wang and Yuxuan Li. I learnt quite a lot from them.

Part 1. Spectral Sequences

1. Exact couples

A simple way to construct spectral sequence is through exact couples.

Definition 1.1 (exact couple)**.** An exact couple is an exact sequence of abelian groups of the form

$$\begin{tikzcd} A \arrow[rr, "i"] & & A \arrow[dl, "j"] \\ & B \arrow[ul, "k"] & \end{tikzcd}$$

where i, j and k are group homomorphisms.

From an exact couple, we can define a homomorphism $\mathrm{d} : B \to B$ by $\mathrm{d} = j \circ k$, then $\mathrm{d}^2 = 0$, so the homology group $H(B) = \ker \mathrm{d} / \operatorname{im} \mathrm{d}$ is well-defined.

Furthermore, from this exact couple, we can define a new exact couple, called derived couple,

$$\begin{tikzcd} A' \arrow[rr, "i'"] & & A' \arrow[dl, "j'"] \\ & B' \arrow[ul, "k'"] & \end{tikzcd}$$

by making the following definitions.

1. $A' = i(A)$ and $B' = H(B)$;
2. i' is induced from i, that is $i'(ia) = i(ia)$;
3. For $a' = ia$ for some $a \in A$, then $j'a' = [ja]$. To show j' is well defined, we need to check the following things
   a. ja is a cycle. Indeed, $\mathrm{d}(ja) = jkja = 0$;
   b. The homology class $[ja]$ is independent of the choice of a. Indeed, if $a' = i\overline{a}$ for some other $\overline{a} \in A$. Then $a - \overline{a} = kb$ for some $b \in B$, since $a - \overline{a} \in \ker i = \operatorname{im} k$. Thus
   $$ja - j\overline{a} = jkb = \mathrm{d}b$$
   that is $[ja] = [j\overline{a}]$.
4. k' is induced from k. Let $[b] \in H(B)$, then $\mathrm{d}b = jkb = 0$ implies $kb \in \ker j = \operatorname{im} i$, so there exists $a \in A$ such that $kb = ia$. Define
   $$k'[b] := kb \in i(A) = A'$$
   Note that we also need to check k' is well-defined: take another $b' \in [b]$, that is $b' - b = \mathrm{d}b''$ for some $b'' \in B$. Then
   $$kb' = kb + k\mathrm{d}b'' = kb + kjkb'' = kb$$

As we have already defined these homomorphisms i', j' and k', it suffices to check above diagram is an exact sequence. Let's check step by step:

1. $\operatorname{im} j' = \ker k'$: Take $j'a' \in \operatorname{im} j'$, then $k'j'a' = k'j'(ia) = k'[jia] = kjia = 0$; Conversely , if $[b] \in B'$ such that $k'[b] = kb = 0$, that is $b \in \ker k = \operatorname{im} j$. So there exists $a \in A$ such that $b = ja$, so $[b] = [ja] = j'a'$, where $a' = ia$.
2. $\operatorname{im} k' = \ker i'$: Take $k'[b] = kb \in \operatorname{im} k'$, then $i'kb = ikb = 0$; Conversely , if $ia \in A'$ such that $i'ia = iia = 0$, so there exists $b \in B$ such that $ia = kb$. Furthermore, such b must be a cycle, since $jkb = jia = 0$. So $ia = kb = k'[b]$.
3. $\operatorname{im} i' = \ker j'$: Take $iia \in \operatorname{im} i'$, then $j'(iia) = [jia] = 0$; Conversely , if $ia \in A'$ such that $j'ia = [ja] = [0]$, that is there exists $b \in B$ such that $\mathrm{d}b = jkb = ja$, that is $a - kb \in \ker j = \operatorname{im} i$. So there exists $a' \in A$ such that $a - kb = ia'$. So $a - ia' \in \operatorname{im} k = \ker i$, that is $ia = iia'$. This completes the proof.

2. The Spectral Sequence of a Filtered Complex

In this section we fix a differential graded complex $K = \bigoplus_{k\in\mathbb{Z}} C^k$ with a differential operator $D : C^k \to C^{k+1}$.

Definition 2.1 (filtration)**.** A sequence of subcomplexes

$$K = K_0 \supset K_1 \supset K_2 \supset K_3 \supset \dots$$

is called a filtration on K.

Notation 2.1. We usually extend the filtration to negative indices by defining $K_p = K$ for $p < 0$.

Definition 2.2 (filtered complex)**.** A complex K with a filteration $\{K_p\}_{p\in\mathbb{Z}_{\geq 0}}$ is called a filtered complex and the associated graded complex is defined as

$$GK = \bigoplus_{p=0}^{\infty} K_p/K_{p+1}$$

Consider

$$A = \bigoplus_{p\in\mathbb{Z}} K_p$$

A is again a differential complex with operator D. Define $i : A \to A$ to be the inclusion $K_{p+1} \hookrightarrow K_p$ and define B to be the quotient, then we obtain a short sequence

$$0 \to A \xrightarrow{i} A \xrightarrow{j} B \to 0$$

and it induces a long exact sequence

$$\dots \to H^k(A) \xrightarrow{i_1} H^k(A) \xrightarrow{j_1} H^k(B) \xrightarrow{k_1} H^{k+1}(A) \to \dots$$

In other words, we can write it as an exact couple as follows

$$\begin{tikzcd} A_1 \arrow[rr, "i"] & & A_1 \arrow[dl, "j_1"] \\ & B_1 \arrow[ul, "k_1"] & \end{tikzcd}$$

where $A_1 = H(A), B_1 = H(B)$ and $i = i_1$. We suppress the subcript of i_1 to avoid cumbersome notation later. This exact couple gives rise to a sequence of exact couples:

$$\begin{tikzcd} A_r \arrow[rr, "i"] & & A_r \arrow[dl, "j_r"] \\ & B_r \arrow[ul, "k_r"] & \end{tikzcd}$$

Example 2.1. Let's see a simple example: Consider the filtered complex terminates after K_3, that is

$$\dots = K_{-1} = K_0 \supset K_1 \supset K_2 \supset K_3 \supset 0$$

Then by definition, A_1 is the direct sum of all terms in the following sequence

$$\dots \xleftarrow{\cong} H(K) \xleftarrow{\cong} H(K) \xleftarrow{i} H(K_1) \xleftarrow{i} H(K_2) \xleftarrow{i} H(K_3) \leftarrow 0$$

And by definition of A_2, it equals iA_1, so it's the direct sum of all terms in the following sequence

$$\dots \xleftarrow{\cong} H(K) \xleftarrow{\cong} H(K) \supset iH(K_1) \xleftarrow{i} iH(K_2) \xleftarrow{i} iH(K_3) \leftarrow 0$$

Note that $iH(K_1) \subset H(K)$, and $i : H(K) \to H(K)$ is identity map, thus $iiH(K_1) = iH(K_1)$. So A_3 is the direct sum of all terms in the following sequence

$$\dots \xleftarrow{\cong} H(K) \xleftarrow{\cong} H(K) \supset iH(K_1) \supset iiH(K_2) \xleftarrow{i} iiH(K_3) \leftarrow 0$$

Similarly we have A_4 is the sum of

$$\dots \xleftarrow{\cong} H(K) \xleftarrow{\cong} H(K) \supset iH(K_1) \supset iiH(K_2) \supset iiiH(K_3) \supset 0$$

Since all terms appearing in A_4 is in $H(K)$, then i is identity on A_4. So A's are stationary after A_4 and we define

$$A_4 = A_5 = \dots = A_\infty$$

Furthermore, since $\ker\{i : A_4 \to A_5\} = \operatorname{im} k_4$, thus $k_4 = 0$. Therefore after the fourth stage all the differential of the exact couple are zero, since $\mathrm{d} = jk$. So B's are also stationary, that is

$$B_4 = B_5 = \dots = B_\infty$$

In the exact couple

$$\begin{tikzcd} A_\infty \arrow[rr, "i_\infty"] & & A_\infty \arrow[dl, "j_r"] \\ & B_\infty \arrow[ul, "k_\infty = 0"] & \end{tikzcd}$$

A_∞ is the direct sum of groups

$$\dots \xleftarrow{\cong} H(K) \xleftarrow{\cong} H(K) \supset iH(K_1) \supset iiH(K_2) \supset iiiH(K_3) \supset 0$$

So if we let above sequence be a filteration of $H(K)$, then B_∞ is the associated graded complex of the filtered complex $H(K)$.

Now let's come back to general case. The sequence of subcomplexes

$$\dots = K = K \supset K_1 \supset K_2 \supset K_3 \supset \dots$$

induces a sequence in cohomology

$$\dots \xleftarrow{\cong} H(K) \xleftarrow{\cong} H(K) \xleftarrow{i} H(K_1) \xleftarrow{i} H(K_2) \xleftarrow{i} H(K_3) \leftarrow \dots$$

Note that i are of course no longer inclusions. Let F_p be the image of $H(K_p)$ in $H(K)$. For example, $F_3 = iiiH(K_3)$. There exists a sequence of inclusions

$$H(K) = F_0 \supset F_1 \supset F_2 \supset F_3 \supset \dots$$

making $H(K)$ into a filtered complex. This filtration is called the induced filteration on $H(K)$.

Definition 2.3 (length of filtration)**.** A filtration K_p on the filtered complex K is said to have length l if $K_l \neq 0$ and $K_p = 0$ for $p > l$.

So as we can see from simple example we have computed, if the filtration of K has finite length, then A_r and B_r are stationary and the stationary value B_∞ is the associated graded complex $\bigoplus F_p/F_{p+1}$ of the filtered complex $H(K)$.

It's customary to write E_r for B_r, and there is a differential d_r on E_r such that $H_{\mathrm{d}_r}(E_r) = E_{r+1}$, and that's definition of a spectral sequence.

Definition 2.4 (spectral sequence)**.** A sequence of differential complex $\{E_r, \mathrm{d}_r\}$ in which each E_r is the homology of its predecessor E_r is called a spectral sequence.

Definition 2.5 (convegence of spectral sequence)**.** A spectral sequence $\{E_r, \mathrm{d}_r\}$ is said to converge to some filtered group H, if E_∞ is equal to the associated graded group of H.

Let's summarize what we have done: For a differential complex K and a filteration $\{K_p\}$ of K, if the filtration is finite length, then the spectral sequence we obtained from this filtration will converge to $H(K)$.

However, it's quit strong requirement for a filteration to be finite length. Suppose filtered complex $K = \bigoplus_n K^n$, then a filteration $\{K_p\}$ on K induces a filteration on K^n for each n, that is $K^n_p := K_p \cap K^n$. And we can prove the same result, only asking $\{K^n_p\}$ to be finite length for each n.

Theorem 2.1. Let $K = \bigoplus_n K^n$ be a graded filtered complex with filtration $\{K_p\}$ and let $H^*_D(K)$ be the cohomology of K with filtration given by $\{K_p\}$. Suppose for each n we have $\{K^n_p\}$ is finite length. Then the short exact sequence of complex

$$0 \to \bigoplus K_{p+1} \to \bigoplus K_p \to \bigoplus K_p/K_{p+1} \to 0$$

induces a spectral sequence which converges to $H^*_D(K)$.

Proof. The ideal here is that since it's a convegence between two graded groups, so it suffices to treat the convegence question one dimension at a time, then it's reduced to the ungraded situation.

Fix a number n and consider n-th grade and let $\ell(n)$ be the length of $\{K^n_p\}_{p\in\mathbb{Z}}$, we have the following sequence

$$\ldots \xleftarrow{\cong} H^n(K) \xleftarrow{i} H^n(K_1) \xleftarrow{i} H^n(K_2) \xleftarrow{i} \ldots \xleftarrow{i} H^n(K_{l(n)}) \xleftarrow{i} 0 \xleftarrow{i} \ldots$$

Use F^n_p to denote the image of $H^n(K_p)$ in $H^n(K)$. If $r \geq \ell(n) + 1$, then for all p

$$i^r H^n(K_p) = F^n_p$$

so we have

$$i : i^r H^n(K_{p+1}) \to i^r H^n(K_p)$$

is an inclusion, since both of them are in $H^n(K)$. By definition we have

$$A_r^n = \bigoplus_p i^r H^n(K_p)$$

and i_r sends $i^r H^n(K_{p+1})$ to $i^r H^n(K_p)$. It follows that

$$i_r : A_r^n \to A_r^n$$

is an inclusion thus $k_r : B_r^{n-1} \to A_r^n$ is the zero map. So we have $A_k^n = A_r^n$ and $B_k^{n-1} = B_r^{n-1}$ for all $k \geq r$, that is $A_\infty^n = A_r^n = \bigoplus F_p^n$ and $B_\infty^n = B_r^n = \bigoplus_p F_p^n / F_{p+1}^n$. Thus

$$B_\infty = \bigoplus_n B_\infty^n = \bigoplus_{n,p} F_p^n / F_{p+1}^n = \bigoplus_p F_p / F_{p+1}$$

that is associated graded complex of $H_D^*(K)$, as desired. $\square$

3. The Spectral Sequence of a Double Complex

3.1. **Basic setting.** Now for a double complex $K = \bigoplus_{p,q\geq 0} K^{p,q}$ with differential d and δ, we can make it into a complex, called total complex with differential D by

$$K = \bigoplus_{k=0}^{\infty} C^k$$

where $C^k = \bigoplus_{p+q=k} K^{p,q}$ and $D = \delta + (-1)^p\mathrm{d} = \delta + D''$. There is a natural filtration on K as follows

$$K_p = \bigoplus_{i\geq p, q\geq 0} K^{i,q}$$

The direct sum $A = \bigoplus_{p\geq 0} K_p$ is also a double complex, and we can also make it into a single complex $A = \bigoplus_{k\geq 0} A^k$ by summing the bidegrees.

Note that

$$A^k = \bigoplus_p A^k \cap K_p$$

and inclusion $i : A^k \to A^k$ is given by

$$i : A^k \cap K_{p+1} \to A^k \cap K_p$$

This gives an inclusion $i : A \to A$ and the quotient is denoted by B, where B is also a double complex, we can also make it into a single complex $B = \bigoplus_{k\geq 0} B^k$ by summing the bidegrees. We can write this short exact sequence as follows

$$0 \to \bigoplus_{k,p} A^k \cap K_p \to \bigoplus_{k,p} A^k \cap K_p \to \bigoplus_{k,p} B^k \cap (K_p/K_{p+1}) \to 0$$

where the differential of these complexes are listed as follows:

1. A inherits the differential operator $D = \delta + (-1)^p\mathrm{d}$ from K;
2. $B = \bigoplus K_p/K_{p+1}$ also inherits the differential operator D, but D on B is just $(-1)^p\mathrm{d}$, since any element in K_p is mapped into K_{p+1} by δ. Therefore

$$E_1 = H_D(B) = H_{\mathrm{d}}(K)$$

Remark 3.1. From above section, we obtain a spectral sequence which converges $H_D(K)$, since our filtration is finite on each degree n. However, we want to show a more refinement theorem, since in this case our complex comes from a double complex, which has a more subtle structure. In order to do this, we need to compute the explicit formula of d_r.

Notation 3.1. We will denote the class of b in E_r, if it's well-defined, by $[b]_r$.

3.2. **Explicit formula of** d_r**.**

3.2.1. *Case of* d_1. Note that

$$B^k = \bigoplus_p B^k \cap (K_p/K_{p+1})$$

So if we want to compute $k_1 : H^k(B) \to H^{k+1}(A)$, it suffices to compute

$$k_1 : H^k(B) \cap (K_p/K_{p+1}) \to H^{k+1}(A) \cap K_{p+1}$$

for each p.

Remark 3.2 (**characterization of elements in** E_1). Any element $[b]_1 \in H^k(B) \cap (K_p/K_{p+1})$ is $b + K_{p+1} \in B^k \cap (K_p/K_{p+1})$ such that $b \in K^{p,k-p}$ and $\mathrm{d}b = 0$. So you can regard $E_1^{p,q}$ as $H_{\mathrm{d}}^{p,q}(K)$.

Now we fix p and consider

$$\begin{tikzcd}
 & {} & {} & {} & \\
0 \arrow[r] & A^{k+1} \cap K_{p+1} \arrow[u] \arrow[r] & A^{k+1} \cap K_p \arrow[u] \arrow[r] & B^{k+1} \cap K_p/K_{p+1} \arrow[u] \arrow[r] & 0 \\
0 \arrow[r] & A^k \cap K_{p+1} \arrow[u, "D"] \arrow[r] & A^k \cap K_p \arrow[u, "D"] \arrow[r] & B^k \cap K_p/K_{p+1} \arrow[u, "\mathrm{d}"] \arrow[r] & 0 \\
 & {} \arrow[u] & {} \arrow[u] & {} \arrow[u] &
\end{tikzcd}$$

In order to get $k_1[b]_1$, where $[b]_1 \in E_1^{p,k-p}$, we need to chase diagram as follows

1. Choose $b \in A^k \cap K_p$ to represent $[b]_1$[1];
2. $Db = \delta b + (-1)^p \mathrm{d}b = \delta b \in A^{k+1} \cap K_p$, since $\mathrm{d}b = 0$;
3. Take inverse of $\delta b \in A^{k+1} \cap K_p$ under i, we obtain $\delta b \in A^{k+1} \cap K_{p+1}$.

Thus $k_1[b]_1 = [\delta b]_1 \in H^{k+1}(A) \cap K_{p+1}$. By definition of d_1 we can see

$$\begin{aligned} \mathrm{d}_1 : H^k(B) \cap (K_p/K_{p+1}) &\to H^{k+1}(B) \cap (K_{p+1}/K_{p+2}) \\ [b]_1 &\mapsto [\delta b]_1 \end{aligned}$$

By characterization of elements in E_1, we can regard $\mathrm{d}_1[b]_1$ as $\delta b \in K^{p+1,k-p}$ with $\mathrm{d}(\delta b) = 0$, and $[\delta b]_1 = 0 \in E_1$ is equivalent to say there exists $c \in K^{p+1,k-p-1}$ such that $\delta b = -D''c$.

Remark 3.3 (**characterization of elements in** E_2). For an element of $[b]_2 \in E_2$, it can be represented by an element $b \in K$ with a zig-zag of length 2

[1]It's clear the choice isn't unique, any element taking form $b + c$, where $c \in A^k \cap K_{p+1}$ also can represent $b + K_{p+1}$.

$$\begin{tikzcd} 0 & \\ b \arrow[u, "\mathrm{d}"] \arrow[r, "\delta"] & \delta b \\ & c \arrow[u, "D''"] \end{tikzcd}$$

In other words, $E_2 = H_\delta H_{\mathrm{d}}(K)$.

For $[b]_2 \in E_2^{p,q}$, by definition of derived couple, we have

$$\mathrm{d}_2[b]_2 = j_2 k_2 [b]_2 = j_2[k_1[b]_1]_2$$

In order to compute $j_2[k_1[b]_1]_2$, we need to find $a \in K$ such that $k_1[b]_1 = i[a]_1$, then $j_2[k_1[b]_1]_2 = [j_1 a]_2$. Since $k_1[b]_1 \in A^{k+1} \cap K_{p+1}$, we have $a \in A^{k+1} \cap K_{p+2}$.

To find such a we use not b but $b+c$ in $A^k \cap K_p$ to represent $[b]_1$, that's possible since b and $b+c$ have the same image under the projection $K_p \to K_p/K_{p+1}$, since $c \in A^k \cap K_{p+1}$. Then

$$k_1[b]_1 = D(b+c) = \delta b + Dc = \delta b + \delta c + D''c = i(\delta c) \in A^{k+1} \cap K_{p+1}$$

where $\delta c \in A^{k+1} \cap K_{p+2}$. So

$$\mathrm{d}_2[b]_2 = [\delta c]_2$$

Thus differential d_2 is given by the delta of the tail of the zig-zag which extends b. By characterization of E_2, you can regard it as an element in $H_\delta H_{\mathrm{d}}(K)$. Now let's check well-defineness:

1. $\delta c \in H_\delta H_{\mathrm{d}}(K)$: $\delta(\delta c) = 0$ is clear; $\mathrm{d}\delta c = \delta \mathrm{d} c = (-1)^p \delta\delta b = 0$, since $(-1)^p \mathrm{d}c = \delta b$.
2. $\mathrm{d}_2[b]_2$ is independent of the choice of c: Any two possible c and c' differs something lies in $\ker \mathrm{d}$. Assume $c' = c + x$ where $x \in \ker \mathrm{d}$, then it suffices to show $[\delta x]_2 = 0$, and that's tautological.

Remark 3.4 (**characterization of elements in E_3**). For an element of $[b]_3 \in E_3$, it can be represented by an element $b \in K$ with a zig-zag of length 3

$$\begin{tikzcd} 0 & & \\ b \arrow[u, "\mathrm{d}"] \arrow[r, "\delta"] & \delta b & \\ & c_1 \arrow[u, "D''"] \arrow[r, "\delta"] & \delta c_1 \\ & & c_2 \arrow[u, "D''"] \end{tikzcd}$$

Notation 3.2. We say that an element b in K lives to E_r if it represents a cohomology class in E_r, or equivalently, b is a cocycle in $E_1, E_2, \ldots, E_{r-1}$. And we already see there is a zig-zag description for d_1 and d_2.

Remark 3.5 (**characterization of elements in** E_r). Generally, an element $b \in K$ lives to E_r if it can be extended to a zig-zag of length r

$$\begin{tikzcd}
0 & & & \\
b \arrow[u, "\mathrm{d}"] \arrow[r, "\delta"] & \delta b & & \\
& c_1 \arrow[u, "D''"] \arrow[dr, "\cdots"] & & \\
& & c_{r-2} \arrow[r, "\delta"] & \delta c_{r-2} \\
& & & c_{r-1} \arrow[u, "D''"]
\end{tikzcd}$$

The differential d_r on E_r is given by δ of the tail of zig-zag:

$$\mathrm{d}_r[b]_r = [\delta c_{r-1}]_r$$

Thus the bidegrees (p, q) of the double complex persist in the spectral sequence

$$E_r = \bigoplus_{p,q} E_r^{p,q}$$

and d_r shifts the bidegrees by $(r, -r+1)$.

$$d_r : E_r^{p,q} \to E_r^{p+r,q-r+1}$$

The filtration on $H(K)$

$$H(K) = F_0 \supset F_1 \supset F_2 \supset \ldots$$

induces a filteration on each component $H^n(K)$ as follows

$$H^n(K) = (F_0 \underbrace{H^n) \supset (F_1}_{E_\infty^{0,n}} \underbrace{H^n) \supset (F_2}_{E_\infty^{1,n-1}} H^n) \supset \cdots \supset (F_n \underbrace{H^n) \supset 0}_{E_\infty^{n,0}}$$

where $F_i H^n := F_i \cap H^n(K)$. In a summary, we have proven the following refinement:

Theorem 3.1. Given a double complex $K = \bigoplus K^{p,q}$ there is a spectral sequence $\{E_r, \mathrm{d}_r\}$ converging to the total cohomology $H_D(K)$ such that E_r has a bigrading with

$$\mathrm{d}_r : E_r^{p,q} \to E_r^{p+r,q-r+1}$$

and

$$E_1^{p,q} = H_{\mathrm{d}}^{p,q}(K)$$
$$E_2^{p,q} = H_\delta^{p,q} H_{\mathrm{d}}(K)$$

Furthermore, the associated graded complex of the total cohomology is given by

$$GH^n_D(K) = \bigoplus_{p+q=n} E^{p,q}_\infty(K)$$

Remark 3.6. There is another filtration, that is $K_q = \bigoplus_{j\geq q, p\geq 0} K^{p,j}$. This gives a second spectral sequence $\{E'_r, \mathrm{d}'_r\}$ converging to the total cohomology $H_D(K)$, but with

$$\begin{aligned} E'_1 &= H_\delta(K) \\ E'_2 &= H_\mathrm{d} H_\delta(K) \end{aligned}$$

and

$$\mathrm{d}'_r : E'^{p,q}_r \to E'^{p-r+1,q+r}_r$$

Example 3.1 (Revisit generalized Mayer-Vietoris principle)**.** Given a smooth manifold M and an open covering $\mathfrak{U}$ of it, consider double complex $C^*(\mathfrak{U}, \Omega^*)$, then there is only one column in E'_1-page, therefore the E'_2-page degenrates, which implies generalized Mayer-Vietoris principle. Furthermore, if we take good cover, the E_2-page also degenrates, which implies

$$H^*_{dR}(M) \cong H^*(\mathfrak{U}, \mathbb{R})$$

3.3. **Additive extension problem.** Since the dimension is the only invariant of a vector space, the associated graded vector space GV of a filtered vector space V is isomorphic to V itself. In particular, if a double complex K is a vector space, then

$$H^n_D(K) \cong GH^n_D(K) \cong \bigoplus_{p+q=n} E^{p,q}_\infty$$

However, the same thing fails in the realm of abelian groups. For example, consider filtered groups $\mathbb{Z}_2 \oplus \mathbb{Z}_2$ and $\mathbb{Z}_4$, which are filtered by

$$\mathbb{Z}_2 \subset \mathbb{Z}_2 \oplus \mathbb{Z}_2$$

and

$$\mathbb{Z}_2 \subset \mathbb{Z}_4$$

respectively. Thus they have isomorphic associated graded groups, but $\mathbb{Z}_2 \oplus \mathbb{Z}_2$ is not isomorphic to $\mathbb{Z}_4$. In other words, in a short exact sequence of abelian groups

$$0 \to A \to B \to C \to 0$$

A and C do not determine B uniquely. The ambiguity is called the (additive) extension problem.

Proposition 3.1. In a short exact sequence of abelian groups

$$0 \to A \xrightarrow{f} B \xrightarrow{g} C \to 0$$

if C is free, then there exists a homomorphism $s : C \to B$ such that $g \circ s$ is identity on C.

Proof. Since C is free, then it suffices to define a suitable s on the generators $\{c_i\}$ of C and it automatically extends to C linearly. Take c_i and choose any preimage of c_i, denoted by b_i, then s is defined by $c_i \mapsto b_i$. Clearly $s \circ g$ is identity on C, but note that such s is not unique. □

Corollary 3.1. Under the hypothesis of above proposition,
1. The map $(f, s) : A \oplus C \to B$ is an isomorphism;
2. For any abelian group G the induced sequence
$$0 \to \mathrm{Hom}(C, G) \to \mathrm{Hom}(B, G) \to \mathrm{Hom}(A, G) \to 0$$
is exact;
3. For any abelian group G the sequence
$$0 \to A \otimes G \to B \otimes G \to C \otimes G \to 0$$
is exact.

Proof. For (1). Since (f, s) is a group homomorphism, it suffices to check it's both injective and surjective. It's easy to see (f, s) is injective, since f and s are injective; For $b \in B$, if $b \in \operatorname{im} f$, that is $b = f(a)$ for some $a \in A$, then $(a, 0)$ is mapped to b. If $b \notin \operatorname{im} f = \ker g$, then consider $g(b) \in C$. Although $sg(b)$ may not equal to b, we have $sg(b) - b \in \ker g = \operatorname{im} f$, so there exists $a \in A$ such that $f(a) + sg(b) = b$, this completes the proof of surjectivity.

For (2). Since it's known to all $\mathrm{Hom}(-, G)$ is a left exact functor, then it suffices to show $\mathrm{Hom}(B, G) \to \mathrm{Hom}(A, G)$ is surjective. Take any $k : A \to G$, then consider the composition of following maps
$$B \xrightarrow{(f,s)^{-1}} A \oplus C \xrightarrow{p_1} A \xrightarrow{k} G$$
it's a map in $\mathrm{Hom}(B, G)$ such that it extends k.

For (3). Since it's known to all $- \otimes G$ is a right exact functor, then it suffices to show $A \otimes G \to B \otimes G$ is injective, and the proof is quite similar as above. □

Remark 3.7. Accoring to facts in homological algebra, there are the following exact sequences

1.
$$0 \to \mathrm{Hom}(C, G) \to \mathrm{Hom}(B, G) \to \mathrm{Hom}(A, G) \to \mathrm{Ext}(C, G) \to \dots$$
2.
$$0 \to A \otimes G \to B \otimes G \to C \otimes G \to \mathrm{Tor}(A, G) \to \dots$$

If G is an abelian group, then $\mathrm{Ext}(\text{-}, G) = \mathrm{Tor}(\text{-}, G) = 0$, which yields desired results.

Part 2. Applications to cohomology theory

4. Leray spectral sequence

Now let's focus on a special spectral sequence we're concerned about, that is Leray spectral sequence.

4.1. **Basic setting.** Let $\pi : E \to M$ be a fiber bundle with fiber F over a manifold M. Given a good cover $\mathfrak{U}$ of M, $\pi^{-1}\mathfrak{U}$ is a cover on E and we can form the double complex

$$K = C^*(\pi^{-1}\mathfrak{U}, \Omega^*)$$

with E_1-page and E_2-page as follows

$$\begin{aligned} E_1^{p,q} &= H_{\mathrm{d}}^{p,q}(K) = \prod_{\alpha_0 < \cdots < \alpha_p} H^q(\pi^{-1}U_{\alpha_0 \ldots \alpha_p}) = C^p(\mathfrak{U}, \mathscr{H}^q) \\ E_2^{p,q} &= H_\delta^p(\mathfrak{U}, \mathscr{H}^q) \end{aligned}$$

where $\mathscr{H}^q$ is a locally constant presheaf $U \mapsto H^q(\pi^{-1}U)$ on M. Furthermore, if M is simply-connected, then there is no monodromy, which implies $\mathscr{H}^q$ is a constant sheaf $\underbrace{\mathbb{R} \oplus \cdots \oplus \mathbb{R}}_{\dim H^q(F)}$, thus

$$E_2^{p,q} = H^p(M) \otimes H^q(F)$$

By theorem 3.1 we have the spectral sequence of K converges to $H_D^*(K)$, which is equal to $H^*(E)$ by generalized Mayer-Vietoris principle, since $\pi^{-1}\mathfrak{U}$ is a cover of E.

Example 4.1 (orientability and the Euler class of sphere bundle)**.** Let $\pi : E \to M$ be a S^n-bundle over a manifold M and let $\mathfrak{U}$ be a good cover of M. Then the E_2-page of Leray spectral sequence is

$$E_2^{p,q} = H^p(\mathfrak{U}, \mathscr{H}^q(S^n))$$

However, since only n-th and 0-th cohomology of S^n don't vanish, so there are only two non-zero rows in E_2-page, thus $\mathrm{d}_2 = \cdots = \mathrm{d}_{n-1} = 0$, that is

$$E_n = E_2 = H_\delta H_{\mathrm{d}}(K) = H^*(\mathfrak{U}, \mathscr{H}^*(S^n))$$

Let $\sigma \in E_1^{0,n}$ be the local angular forms on the sphere bundle E, it's clear that $\mathrm{d}_1\sigma = 0$ if and only if E is orientable. So if E is orientable, σ lives to E_2, and it lives to E_n.

Up to a sign $\mathrm{d}_n\sigma \in H^{n+1}(\mathfrak{U}, \mathscr{H}^0(S^n)) \cong H^{n+1}(M)$, so whether σ lives to $E_{n+1} = \cdots = E_\infty = H^*(E)$ or not depends on $\mathrm{d}_n\sigma = 0 \in H^{n+1}(M)$ or not, that is there is a global angular form on E if and only if the Euler class $e(E)$ of E vanishes.

Example 4.2 (orientability of simply-connected manifold)**.** Let M be a simply-connected manifold of dimension n and $S(T_M)$ is the S^{n-1}-sphere bundle of its tangent bundle. $H^1(M) = 0$ since M is simply-connected, thus let $\sigma \in E_1^{0,n-1}$ be the local angular forms on $S(T_M)$, we must have $\mathrm{d}_1\sigma = 0$, since $E_2^{1,n-1} = H^1(M) \otimes H^{n-1}(S^{n-1})$, thus $S(T_M)$ is orientable, that is T_M is orientable, which implies M is orientable.

Example 4.3 (The cohomology group of $\mathbb{CP}^2$)**.** Consider Hopf fiberation of $\mathbb{CP}^2$, that is

$$\begin{tikzcd} S^1 \arrow[r] & S^5 \arrow[d] \\ & \mathbb{CP}^2 \end{tikzcd}$$

Since $\mathbb{CP}^2$ is simply-connected, thus

$$E_2^{p,q} = H^p(\mathbb{CP}^2) \otimes H^q(S^1)$$

that is E_2-page looks like

$$\begin{tikzcd} 1 & \mathbb{R} \arrow[drr] & A \arrow[drr] & B \arrow[drr] & C \arrow[drr] & D \arrow[drr] & & \\ 0 & \mathbb{R} & A & B & C & D & 0 & 0 \\ & 0 & 1 & 2 & 3 & 4 & 5 & 6 \end{tikzcd}$$

Since d_3 moves down two steps, then $\mathrm{d}_3 = 0$, similarly for $\mathrm{d}_4 = \cdots = 0$. So the spectral sequence degenerates at the E_3-page, but $E_3 = E_\infty = H^*(S^5)$, that is E_3 page should look like

$$\begin{array}{c|ccccc} 1 & & & & & \mathbb{R} \\ 0 & \mathbb{R} & & & & \\ \hline & 0 & 1 & 2 & 3 & 4 \end{array}$$

which implies

$$0 \to A, \quad \mathbb{R} \to B, \quad A \to C, \quad B \to D, \quad C \to 0$$

are isomorphisms. Thus

$$H^q(\mathbb{CP}^2) = \begin{cases} \mathbb{R} & q = 0, 2, 4 \\ 0 & \text{otherwise} \end{cases}$$

Remark 4.1. By same argument one can compute cohomology group of $\mathbb{CP}^n$.

4.2. **Product structure and multiplicative extension problem.** If a double complex K has a product structure $\cup$, relative to which its differential D is an antiderivation, the same is true of all the groups E_r and their operator d_r, since E_r is the homology of E_{r-1} and d_r is induced from D. With product structures, we have

Theorem 4.1. Let K be a double complex with a product structure relative to which D is an antiderivation. There exists a spectral sequence

$$\{E_r, \mathrm{d}_r : E_r^{p,q} \to E_r^{p+r,q-r+1}\}$$

converging to $H_D(K)$ with the following properties:
1. The E_2-page is $H_\delta H_{\mathrm{d}}(K)$;
2. Each E_r, being the homology of E_{r-1}, inherits a product structure from E_{r-1}. Relative to this product, d_r is an antiderivation.

Example 4.4 (The ring structure of E_2-page of Leray spectral sequence)**.** If we consider Leray spectral sequence to fiber bundle (E, M, F), and equip the double complex $C^*(\pi^{-1}\mathfrak{U}, \Omega^*)$ with the following product structure

$$\begin{aligned} \cup : C^p(\pi^{-1}\mathfrak{U}, \Omega^q) \otimes C^r(\pi^{-1}\mathfrak{U}, \Omega^s) &\to C^{p+r}(\pi^{-1}\mathfrak{U}, \Omega^{q+s}) \\ \omega \otimes \eta &\mapsto \omega \cup \eta \end{aligned}$$

where

$$\omega \cup \eta(\pi^{-1}U_{\alpha_0 \dots \alpha_{p+r}}) := (-1)^{qr} \omega(\pi^{-1}U_{\alpha_0 \dots \alpha_p}) \wedge \eta(\pi^{-1}U_{\alpha_p \dots \alpha_{p+r}})$$

Remark 4.2. Here we need sign $(-1)^{qr}$ to make the differential operator D into an antiderivation with respect to this product, that is[2]

$$D(\omega \cup \eta) = D\omega \cup \eta + (-1)^{\deg \omega} \omega \cup D\eta$$

If M is simply-connected, then E_2-page of Leray spectral sequence is isomorphic to $H^p(M) \otimes H^q(F)$. If we equip $H^p(M) \otimes H^q(F)$ with the following product structure

$$(a \otimes b)(c \otimes d) := (-1)^{\deg b \deg c}(ac \otimes bd)$$

Then $H_\delta^p(\mathfrak{U}, \mathscr{H}^q)$ is isomorphic[3] to $H^p(M) \otimes H^q(F)$ as rings.

Example 4.5 (cohomology ring of $\mathbb{CP}^2$)**.** Consider E_2-page

$$\begin{tikzcd}[column sep=small]
1 & 1 \otimes a \arrow[drr] & & x \otimes a \arrow[drr] & & x^2 \otimes a \\
0 & 1 \otimes 1 & & x \otimes 1 & & x^2 \otimes 1 \\
 & 0 & 1 & 2 & 3 & 4
\end{tikzcd}$$

where two d_2 are isomorphisms. Let a be a generator of $H^1(S^1)$, then

$$\mathrm{d}_2(1 \otimes a) = 1 \otimes x$$

[2]You can directly check this fact by yourself, or refer to Hatcher for a proof.

[3]In fact, it's almost clear from the definition: You can regard an element in $H_\delta^p(\mathfrak{U}, \mathscr{H}^q)$ as two parts, one eats an intersection of $(p+1)$-fold, and the other outputs a q-form, that's how you get this isomorphism.

is a generator of $E_2^{2,0} = H^2(\mathbb{CP}^2) \otimes H^0(S^1)$, where x is a generator of $H^2(\mathbb{CP}^2)$. Then $x \otimes a$ is a generator of

$$E_2^{2,1} = H^2(\mathbb{CP}^2) \otimes H^1(S^1)$$

Thus a generator of $E_2^{4,0} = H^4(\mathbb{CP}^2)$ is given by

$$\begin{aligned} \mathrm{d}_2(x \otimes a) &= \mathrm{d}_2(x \otimes 1) \cdot (1 \otimes a) + (-1)^2 (x \otimes 1) \cdot \mathrm{d}_2(1 \otimes a) \\ &= (1 \otimes x^2) \end{aligned}$$

which implies x^2 is a generator of $H^4(\mathbb{CP}^2)$. So the ring structure of $\mathbb{CP}^2$ is

$$H^*(\mathbb{CP}^2) = \mathbb{R}[x]/(x^3)$$

where $|x| = 2$.

Remark 4.3. The same argument shows $H^*(\mathbb{CP}^n) = \mathbb{R}[x]/(x^{n+1})$, where $|x| = 2$.

In above example, we compute the cohomology ring of $\mathbb{CP}^2$ using fiber bundle $S^1 \to S^5 \to \mathbb{CP}^2$, in which $\mathbb{CP}^2$ is the base space. However, when we want to use spectral sequence to compute cohomology ring of total space of some fiber bundle, we need to be careful, since there is so-called "multiplicative extension problem". To be explicit, there are two product structure on E_∞-page:

1. The one inherited from double complex K;
2. The one induced by fiberation as follows: For elements $\overline{a}, \overline{b}$ belonging to $E_\infty^{p,q} = F^p H^{p+q}/F^{p+1}H^{p+q}$ and $E_\infty^{p',q'} = F^{p'} H^{p'+q'}/F^{p'+1}H^{p'+q'}$ respectively, we set
$$\overline{a} \cup \overline{b} := \overline{a \cup b}$$
in $E_\infty^{p+p',q+q'}$. Here $a \cup b$ makes sense since there is a product structure on $H^*(E)$.

We desire these two product structure are same, since the first one is computable, and the second one is the product structure we want. However, some thing bad may happen, such as the following example:

Example 4.6. Consider the fiber bundle $S^2 \to \mathbb{CP}^3 \to S^4$, the E_2-page of Leray spectral sequence is

2	$\mathbb{R}$				$\mathbb{R}$
1					
0	$\mathbb{R}$				$\mathbb{R}$
	0	1	2	3	4

By dimension reasons it's clear that this spectral sequence E_2 degenrates, that is $E_2 = \cdots = E_\infty$. If we use x to denote the generator of $H^2(S^2)$ and use y to denote the generator of $H^4(S^4)$, it's clear the cohomology ring structure of E_∞-page is $\mathbb{R}[x,y]/(x^2,y^2)$, where $|x|=2, |y|=4$, which is not isomorphic to the cohomology ring structure of $\mathbb{CP}^3$.

Remark 4.4. One can also refer to Example 1.17 in Page29 of [Hat04] for another example.

So the key point is that when does the product structure of E_∞ recover the one on $H^*(E)$. The next theorem gives some special condition under which the product structure of E_∞ recovers the one on $H^*(E)$.

Theorem 4.2. In Leray spectral sequence, if the product structure of total complex of E_∞ is free, then it recovers the product structure of cohomology of total space.

Proof. See Example in Page25 of [McC00]. □

4.3. **Gysin sequence.** In special cases the spectral sequence simplifies to a long exact sequence. One special case is the cohomology of sphere bundle and the resulting sequence is called Gysin sequence.

Let $\pi : E \to M$ be an oriented sphere bundle with fiber S^k. By assumption of orientability, there is no monodromy of locally constant sheaf $\mathscr{H}^k$, thus the E_2-page of Leray spectral sequence is $H^p(M)\otimes H^q(S^k)$. Note that for arbitrary integer $n \geq k$, nothing in $E_2^{n-k,k}$ can be killed, thus there is an exact sequence

$$0 \to E_\infty^{n-k,k} \to E_2^{n-k,k}$$

and it can be extended to the following exact sequence

$$0 \to E_\infty^{n-k,k} \to E_2^{n-k,k} \xrightarrow{\mathrm{d}_{k+1}} E_2^{n+1,0} \to E_\infty^{n+1,0} \to 0$$

since d_{k+1} is the only possible non-trivial map. On the other hand, the filtration on $H^n(E)$ becomes

$$\underbrace{H^n(E) \supset E_\infty^{n,0}}_{E_\infty^{n-k,k}} \supset 0$$

which gives another exact sequence

$$0 \to E_\infty^{n,0} \to H^n(E) \to E_\infty^{n-k,k} \to 0$$

Fit these two exact sequence together one has

$$\cdots \to H^n(E) \to H^{n-k}(M) \to H^{n+1}(M) \to H^{n+1}(E) \to \dots$$

To be explicit, you can find the map $H^{n-k}(M) \to H^{n+1}(M)$ is to wedge the Euler class of E.

4.4. **Other coefficients.** Since the de Rham cohomology is a cohomology theory with real coefficients, it's also necessary to overlook the torsion phenomena. In this section we give a quick review of singular (co)homology, and show that the preceding results on spectral sequences carry over to integer coefficients.

4.4.1. *Review of singular (co)homology.* From now on, we usually use X to denote a topological space.

Definition 4.1 (singular q-simplex)**.** A singular q-simplex in X is a continous map $s : \Delta_q \to X$, where Δ_q is standard q-simplex.

Definition 4.2 (singular q-chain with $\mathbb{Z}$ coefficients)**.** A singular q-chain in X is a finite linear combination with integer coefficients of singular q-simplices.

Notation 4.1. All singular q-chains form an abelian group, denoted by $S_q(X;\mathbb{Z})$.

Definition 4.3 (boundary map)**.** The boundary map ∂ is defined as follows

$$\begin{aligned}\partial_q : S_n(X;\mathbb{Z}) &\to S_{q-1}(X;\mathbb{Z})\\ \sigma &\mapsto \sum_i (-1)^i \sigma|[v_0, \dots, \widehat{v_i}, \dots, v_q]\end{aligned}$$

where we identify $[v_0, \dots, \widehat{v_i}, \dots, v_q]$ with Δ^{q-1}.

Definition 4.4 (singular homology group $\mathbb{Z}$ coefficients)**.** The q-th singular homology group $H_q(X;\mathbb{Z})$ is defined as

$$H_q(X;\mathbb{Z}) := \ker \partial_q / \operatorname{im} \partial_{q+1}$$

Lemma 4.1 (Poincaré lemma)**.** $H_q(\mathbb{R}^n;\mathbb{Z}) = 0$ for all $q > 0$.

Definition 4.5 (singular q-cochain with $\mathbb{Z}$ coefficients)**.** The group of singular q-cochains is defined as

$$S^q(X;\mathbb{Z}) := \operatorname{Hom}(S_q(X;\mathbb{Z}), \mathbb{Z})$$

with coboundary map d_q defined by

$$(\mathrm{d}_q\omega)(c) = \omega(\partial_{q+1}c)$$

where $\omega \in S^q(X), c \in S_q(X)$.

Definition 4.6 (singular cohomology group with $\mathbb{Z}$ coefficients)**.** The q-th singular cohomology group $H^q(X;\mathbb{Z})$ is defined as

$$H^q(X;\mathbb{Z}) := \ker \mathrm{d}_q / \operatorname{im} \mathrm{d}_{q-1}$$

Remark 4.5. Replacing $\mathbb{Z}$ with any arbitrary abelian group G, you can define singular (co)homology group with coefficients G.

Proposition 4.1. Given an open covering of X, the following sequence is exact

$$0 \leftarrow S_q^{\mathfrak{U}}(X;G) \leftarrow \bigoplus_{\alpha_0} S_q(U_{\alpha_0};G) \leftarrow \bigoplus_{\alpha_0<\alpha_1} S_q(U_{\alpha_0\alpha_1};G) \leftarrow \dots$$

where G is an arbitrary abelian group G and $S_q^{\mathfrak{U}}(X,G)$ is the group of $\mathfrak{U}$-small singular q-chain. Furthermore, there is a chain homotopy between $S_q(X;G)$ and $S_q^{\mathfrak{U}}(X;G)$.

Corollary 4.1. Given an open covering of X, the following sequence is exact

$$0 \to S^q_{\mathfrak{U}}(X;G) \to \bigoplus_{\alpha_0} S^q(U_{\alpha_0};G) \to \bigoplus_{\alpha_0<\alpha_1} S^q(U_{\alpha_0\alpha_1};G) \to \dots$$

where G is an arbitrary abelian group G and $S_q^{\mathfrak{U}}(X,G)$ is the group of $\mathfrak{U}$-small singular q-chain.

Theorem 4.3 (de Rham theorem)**.** The singular cohomology with coefficients $\mathbb{R}$ is isomorphic to de Rham cohomology on smooth manifold.

Proof. Consider the double complex $C^*(\mathfrak{U}, S^*(\mathfrak{U};\mathbb{R}))$, we can show Čech cohomology of constant sheaf $\mathbb{R}$ is isomorphic to singular cohomology with coefficients $\mathbb{R}$, and we also know Čech cohomology of constant sheaf $\mathbb{R}$ is isomorphic to de Rham cohomology. □

Remark 4.6. In fact, for a topological space X with good cover is cofinal, we can show Čech cohomology of constant sheaf G is isomorphic to singular cohomology with coefficients G.

Notation 4.2. From now on, unless otherwise specified, we use $H^*(X)$ to denote the $\mathbb{Z}$ coefficients cohomology, and we use $H^*(X;\text{-})$ to specify. For example, $H^*(X;\mathbb{R})$ denotes the $\mathbb{R}$ coefficients singular cohomology, that's also de Rham cohomology.

Theorem 4.4 (Leray spectral sequence for singular cohomology with coefficients in a communicative ring A)**.** Let $\pi : E \to X$ be a fiber bundle with fiber F over a topological space X and $\mathfrak{U}$ an open covering of X. There is a spectral sequence converging to $H^*(E;A)$ with E_2-term

$$E_2^{p,q} = H^p(\mathfrak{U}, \mathscr{H}^q(F;A))$$

Each E_r in the spectral sequence can be given a product structure relative to which the differential d_r is an antiderivation. If X is simply-connected and has a good cover, then

$$E_2^{p,q} = H^p(X, H^q(F;A))$$

Furthermore, if $H^*(F;A)$ is a finitely generated free A-module, then

$$E_2 = H^*(X;A) \otimes H^*(F;A)$$

as algebras over A.

Remark 4.7. Of course there is Leray spectral sequence for singular homology with coefficients, just reverse arrows in above case, here we omit the statement of it.

5. Cohomology of some Lie groups

A basic fact in differential geometry is that if G is a Lie group and H is a closed subgroup of G, then there exists the following fiberation

$$\begin{tikzcd} H \arrow[r] & G \arrow[d] \\ & G/H \end{tikzcd}$$

If we're familiar with G/H and H, then above fiberation is a good way to compute cohomology ring of G. In fact, we always use the view of group action to give an explicit description of G/H.

5.1. Cohomology rings of $\mathrm{U}(n)$ and $\mathrm{SU}(n)$.

Note that $\mathrm{U}(n)$ acts on S^{2n-1} with stablizer $\mathrm{U}(n-1)$, that is $\mathrm{U}(n)/\mathrm{U}(n-1) = S^{2n-1}$, thus we have the following fiberation:

$$\begin{tikzcd} \mathrm{U}(n-1) \arrow[r] & \mathrm{U}(n) \arrow[d] \\ & S^{2n-1} \end{tikzcd}$$

The same fiberation still holds if we replace $\mathrm{U}(n)$ by $\mathrm{SU}(n)$.

Proposition 5.1. The cohomology ring of $\mathrm{U}(n)$ is $\Lambda[x_1, \dots, x_{2n-1}]$, where $|x_i| = i, 1 \leq i \leq 2n-1$.

Proof. Note that $\mathrm{U}(1) = S^1$, thus cohomology ring of $\mathrm{U}(1)$ is $\Lambda[x_1]$, where $|x_1| = 1$. Apply Leray spectral sequence fiberation

$$\begin{tikzcd} \mathrm{U}(n-1) \arrow[r] & \mathrm{U}(n) \arrow[d] \\ & S^{2n-1} \end{tikzcd}$$

we have E_2-page has only two columns, that is $p = 0$ and $p = 2n-1$. Furthermore by induction we have cohomology ring of $\mathrm{U}(n-1)$ is $\Lambda[x_1, \dots, x_{2n-3}]$, where $|x_i| = i, 1 \leq i \leq 2n-3$. Although there may toooo many non-zero rows of E_2-page, but it suffices to check d_2 on those generators, that is the ones on $p = 0, q = 0, 1, 3, \dots, 2n-3$.

By dimension reasons, it's clear this spectral sequence degenerates at E_2-page, which implies cohomology group structure of $\mathrm{U}(n)$ is clear. If we choose a generator of $E_2^{2n-1,0}$, denoted by x_{2n-1}, then we can write the generator of $E_2^{2n-1,i}$ through product $E_2^{0,i} \times E_2^{2n-1,0} \to E_2^{2n-1,i}$. This show cohomology ring of $\mathrm{U}(n)$ is exactly $\Lambda[x_1, \dots, x_{2n-1}]$. $\square$

Remark 5.1. Note that here we can compute the cohomology ring structure of total space $\mathrm{U}(n)$, since $\Lambda[x_1, \dots, x_{2n-1}]$ is free as algebras.

Proposition 5.2. The cohomology ring of $\mathrm{SU}(n)$ is $\Lambda[x_3, \dots, x_{2n-1}]$, where $n \geq 2, |x_i| = i, 1 \leq i \leq 2n-1$.

Proof. Note that $\mathrm{SU}(2) = S^3$, thus cohomology ring of $\mathrm{SU}(2)$ is $\Lambda[x_3]$, where $|x_3| = 3$. Apply Leray spectral sequence fiberation

$$\begin{tikzcd} \mathrm{SU}(n-1) \arrow[r] & \mathrm{SU}(n) \arrow[d] \\ & S^{2n-1} \end{tikzcd}$$

The same argument shows the desired result. □

5.2. **Cohomology group of** $\mathrm{SO}(4)$**.** In this section we need to following fact.

Proposition 5.2.1. For a compact orientable manifold M, the integral $\int_M e(TM)$ is equal to the Euler number of it, that is $\sum(-1)^q H^q(M)$.

Example 5.1 (The cohomology ring of the unit tangent bundle of a sphere)**.** The unit tangent bundle $S(T_{S^2})$ to the S^2 is a fiber bundle with fiber S^1, that is

$$\begin{tikzcd} S^1 \arrow[r] & S(T_{S^{n-1}}) \arrow[d] \\ & S^2 \end{tikzcd}$$

If we consider $\mathbb{Z}_2$ coefficients, then the E_2-page of the Leray spectral sequence is $E_2^{p,q} = H^p(S^2) \otimes H^q(S^1)$, that is

$$\begin{array}{c|ccc} 1 & \mathbb{Z}_2 & & \mathbb{Z}_2 \\ 0 & \mathbb{Z}_2 & & \mathbb{Z}_2 \\ \hline & 0 & 1 & 2 \end{array}$$

In order to compute E_3, it suffices to compute above $\mathrm{d}_2 : E_2^{0,1} \to E_2^{2,0}$, and we know it defines the Euler class of $S(T_{S^2})$. By Proposition 5.2.1, we have Euler class of $S(T_{S^2})$ is twice the generator of $H^2(S^2)$, then d_2 is zero, which implies this spectral sequence E_2 degenrates. Thus the cohomology group

$$H^q(S(T_{S^2})) = \begin{cases} \mathbb{Z}_2, & q = 0,1,2,3 \\ 0, & \text{otherwise} \end{cases}$$

Remark 5.2. Here are two ways to think $S(T_{S^2})$:

1. A point in $S(T_{S^2})$ is specified by a unit vector in $\mathbb{R}^3$ and another unit vector orthogonal to it, which can be completed to a unique orthnormal basis with positive determinant. Therefore $S(T_{S^2}) \cong \mathrm{SO}(3)$
2. $\mathrm{SO}(3)$ is the group of all rotations about the origin in $\mathbb{R}^3$, and each rotation is determined by its axis and an angle $-\pi \leq \theta \leq \pi$. In this way $\mathrm{SO}(3)$ is parametrized by the solid 3-ball D^3 of raduis π in $\mathbb{R}^3$.

Furthermore, antipodal points are glued together, since rotating through the angle $-\pi$ is the same as through π. Therefore $S(T_{S^2}) \cong \mathrm{SO}(3)$.

Remark 5.3. Furthermore, since we can regard $S(T_{S^2})$ as $\mathbb{RP}^3$, it's clear above spectral sequence has multiplicative extension problem, since the ring structure of E_∞-page is $\Lambda_{\mathbb{Z}_2}[x_1, x_2]$, where $|x_1| = 1, |x_2| = 2$(The reason is the same as Example 4.6). However, the cohomology ring $H^*(\mathbb{RP}^3, \mathbb{Z}_2) = \mathbb{Z}_2[x]/(x^4)$, where $|x| = 1$.

Example 5.2 (The cohomology group of SO(4))**.** The $\mathrm{SO}(n)$ acts on S^{n-1} transitively with stablizer $\mathrm{SO}(n-1)$, therefore $\mathrm{SO}(n)/\mathrm{SO}(n-1) = S^{n-1}$. Thus we can use Leray spectral sequence to fiber bundle $\mathrm{SO}(3) \to \mathrm{SO}(4) \to S^3$. The E_2-page is

$$
\begin{array}{c|ccccc}
3 & \mathbb{Z} & & & & \mathbb{Z} \\
2 & \mathbb{Z}_2 & & & & \mathbb{Z}_2 \\
1 & & & & & \\
0 & \mathbb{Z} & & & & \mathbb{Z} \\
\hline
 & 0 & 1 & 2 & 3 & 4
\end{array}
$$

It's easy to see $\mathrm{d}_2 = \mathrm{d}_3 = \cdots = 0$, which implies the cohomology group of SO(4) is

$$
H^q(\mathrm{SO}(4)) = \begin{cases} \mathbb{Z} & q = 0, 6 \\ \mathbb{Z}_2 & q = 2, 5 \\ \mathbb{Z} \oplus \mathbb{Z} & q = 3 \\ 0 & \text{otherwise} \end{cases}
$$

since there is no additive extension problem.

Example 5.3. Consider a manifold

$$
W := \mathrm{SU}(3)/\mathrm{SO}(3)
$$

where SO(3) is embedded as a closed subgroup of SU(3). Now we're going to compute its $\mathbb{Z}_2$ coefficients cohomology ring. It's clear that W is simply-connected, thus by Poincaré duality one has

$$
H^1(W) = H^4(W) = 0, \quad H^2(W) = H^3(W)
$$

Note that there is a fiber bundle $\mathrm{SO}(3) \to \mathrm{SU}(3) \to W$. Since SO(3) is diffeomorphic to $\mathbb{RP}^3$, with the cohomology ring $\mathbb{Z}_2[x]/(x^4)$ and the cohomology ring of SU(3) is $\Lambda[x_3, x_5]$, where $|x_i| = i$, the E_2-page looks like

$$
\begin{tikzcd}
3 & \mathbb{Z}_2 & & A & A & & B \\
2 & \mathbb{Z}_2 \arrow[rrd] & & A & A & & B \\
1 & \mathbb{Z}_2 \arrow[rrd] & & A & A \arrow[rrd] & & B \\
0 & \mathbb{Z}_2 & & A & A & & B \\
& 0 & 1 & 2 & 3 & 4 & 5
\end{tikzcd}
$$

where $A = H^2(W) = H^3(W), B = H^5(W)$. In E_2-page, we have the following observations:

1. $\mathrm{d}_2 : E_2^{0,1} \to E_2^{2,0}$ is isomorphism. Indeed, if this d_2 isn't injective, then the kernel of it will live into E_∞-page, that is $E_\infty^{0,1} \neq 0$, a contradiction to $H^1(\mathrm{SU}(3)) = 0$. The same argument shows cokernel of it is also trivial.
2. $\mathrm{d}_2 : E_2^{3,1} \to E_2^{5,0}$ is an isomorphism by the same argument as above.

Now let's consider the cohomology ring structure of W.

1. Since $\mathrm{d}_2 : E_2^{0,1} \to E_2^{2,0}$ is an isomorphism, then we can use $x_2 \otimes 1$ to denote $\mathrm{d}_2(1 \otimes a)$, then x_2 is a generator of $H^2(W)$;
2. Let x_3 be a generator of $H^3(W)$, since $\mathrm{d}_2 : E_2^{3,1} \to E_2^{5,0}$ is an isomorphism, and $x_3 \otimes a$ is a generator of $E_2^{3,1}$, then

$$
\begin{aligned}
\mathrm{d}_2(x_3 \otimes a) &= \mathrm{d}_2(x_3 \otimes 1) \cdot (1 \otimes a) + (-1)^3 (x_3 \otimes 1) \cdot \mathrm{d}_2(1 \otimes a) \\
&= -(x_3 x_2 \otimes 1) \\
&= (x_2 x_3 \otimes 1)
\end{aligned}
$$

which implies $x_2 x_3$ is a generator of $H^5(W)$.

All in all, the cohomology ring of W is $\Lambda[x_2, x_3]$.

6. Path fiberation

Recall that for a fiber bundle (E, X, F), where E, X, F are topological spaces and X admits a good cover, then the E_2-page of Leray's spectral sequence is

$$E_2^{p,q} = H^p(\mathfrak{U}, \mathscr{H}^q(F))$$

where $\mathscr{H}^q(F)$ is a locally constant sheaf. Now suppose $\pi : E \to X$ is just a map, not necessarily locally trivial, we can still obtain a spectral sequence with E_2-page $H^p(\mathfrak{U}, \mathscr{H}^q(F))$ which converges to $H_D(E)$ as long as $\pi : E \to X$ has the property that

Property 6.1. $H^q(\pi^{-1}U) \cong H^q(F)$ for some fixed F and for all contractible open subset U.

An important example is path fiberation.

6.1. Basic setting.

Let X be a topological space with a base point $*$ and $[0, 1]$ the unit interval with base point 0. The path space of X is defined to be the space $P(X)$ consisting of all the paths in X with initial point $*$, that is

$$P(X) := \{\text{maps } \mu : [0, 1] \to X \mid \mu(0) = *\}$$

The path space $P(X)$ is equipped with compact open topology, that is a topology basis consists of all base-point preserving maps $\mu : [0, 1] \to X$ such that $\mu(K) \subset U$ for a fixed compact set K in $[0, 1]$ and a fixed open set U in X.

There is a natural projection $\pi : P(X) \to X$, defined by $\pi(\mu) = \mu(1)$. Now we claim $\pi : P(X) \to X$ has property 6.1. Indeed, for arbitrary contractible open set U containing p, there is a natural inclusion

$$i : \pi^{-1}(p) \to \pi^{-1}(U)$$

Since U is contractible, then we can get a map

$$\phi : \pi^{-1}(U) \to \pi^{-1}(p)$$

It's clear $i \circ \phi = \mathrm{id}$, and $\phi \circ i$ is homotopic to id, which implies $\pi^{-1}(U)$ has the same homotopy type as $\pi^{-1}(p)$. Furthermore, if p and q are in the same path component of X, then a fixed path from p to q gives a homotopy equivalence $\pi^{-1}(p) \cong \pi^{-1}(q)$. Thus all fibers have the homotopy type of $\pi^{-1}(*)$, which is loop space ΩX of X. To be explicit,

$$\Omega X = \{\mu : [0, 1] \to X \mid \mu(0) = \mu(1) = *\}$$

Thus $\pi : P(X) \to X$ has the property 6.1, that is $H^q(\pi^{-1}U) \cong H^*(\Omega X)$. Furthermore, path space PX is always contractible, since we always can shrink every path to its initial point.

Proposition 6.1. Let $\pi : E \to X$ be a path fiberation. If X is simply-connected and E is path-connected, then the fibers are path-connected.

Proof. Trivially the $E_2^{0,0}$ term survives to E_∞, hence

$$E_2^{0,0} = E_\infty^{0,0} = H^0(E) = \mathbb{Z}$$

since E is path-connected. On the other hand,

$$E_2^{0,0} = H^0(X, H^0(F)) = H^0(F)$$

which implies F is path-connected. □

In fact there is a more general class of maps satisfying property 6.1, which is called fiberation. To be explicit, a map $\pi : E \to X$ is called a fiberation if it satisfies the following property:

Property 6.2 (covering homotopy property)**.** Given a map $f : Y \to E$ from any topological space Y into E and a homotopy $\overline{f}_t$ of $\overline{f} = \pi \circ f$, there is a homotopy f_t of f such that $\pi \circ f_t = \overline{f}_t$.

$$\begin{tikzcd} Y \arrow[r, "f"] \arrow[d] & E \arrow[d, "\pi"] \\ Y \times I \arrow[r, "\overline{f}_t"] \arrow[ur, dashed, "f_t"] & X \end{tikzcd}$$

Proposition 6.2. For fiberations we have the following properties:

1. Any two fibers of a fiberation over an arcwise-connected space have the same homotopy type;
2. For every contractible open set U, the inverse image $\pi^{-1}U$ has the homotopy type of the fiber F_a, where a is any point in U.

Proof. Here we only explain some key ideas of proof of (1), which will be used in later.

1. A path γ from a to b may be regarded as a homotopy of the point a;
2. Let $\overline{g} : F_a \times I \to X$ be given by $(y, t) \mapsto \gamma(t)$, then covering homotopy property implies there exists a map $g : F_a \times I \to E$ that covers $\overline{g}$. Furthermore, $g_1 := g|_{F_a \times \{1\}}$ is a map from F_a to F_b, since $\gamma(1) = b$. Thus a path from a to b induces a map from F_a to the fiber F_b.
3. The **key point** is that homotopic paths from a to b in X induces homotopic maps from F_a to F_b.
4. If (3) holds, given $a, b \in X$ and a path γ from a to b, let $u : F_a \to F_b$ be a map induced by γ and $v : F_a \to F_b$ a map induced by γ^{-1}. Since $\gamma^{-1} \circ \gamma^{-1}$ is homotopic to the constant map to a, the composition $v \circ u$ is homotopic to identity on F_a, which implies F_a and F_b have the same homotopy type.

□

Remark 6.1. In fact, we can slightly change the proof to see if $\overline{f}_t, \overline{g}_t : Y \times I \to X$ are two homotopic homotopies, then their lifts $f_t, g_t : Y \times I \to E$ are also homotopic.

6.2. **The cohomology ring of ΩS^n.**

6.2.1. *The cohomology group structure.* In this section, we compute the integer cohomology groups of the loop space $\Omega S^n, n \geq 2$.

Example 6.1 (The cohomology group of ΩS^2)**.** Since S^2 is simply-connected, thus the spectral sequence of the path fiberation

$$\begin{tikzcd} \Omega S^2 \arrow[r] & PS^2 \arrow[d] \\ & S^2 \end{tikzcd}$$

has E_2-page $H^p(S^2, H^q(\Omega S^2)) = H^p(S^2) \otimes H^q(\Omega S^2)$, thus only two non-zero columns at $p = 0, 2$. By dimensional reason, $\mathrm{d}_3 = \mathrm{d}_4 = \cdots = 0$, thus $E_3 = E_\infty$. Furthermore, since PS^2 is contractible, we have all non-zero d_2 are isomorphisms. Thus $\mathrm{d}_2 : E_2^{0,1} \to E_2^{2,0}$ is an isomorphism, that is $H^1(\Omega S^2) = \mathbb{Z}$, but then

$$E_2^{2,1} = H^2(S^2) \otimes H^1(\Omega S^2) = \mathbb{Z}$$

by the same reason $E_2^{0,2} = \mathbb{Z}$. Step by step we find $H^q(\Omega S^2) = \mathbb{Z}$ in every dimension q.

Example 6.2 (The cohomology group of ΩS^3)**.** Since S^3 is simply-connected, thus the spectral sequence of the path fiberation

$$\begin{tikzcd} \Omega S^3 \arrow[r] & PS^3 \arrow[d] \\ & S^3 \end{tikzcd}$$

has E_2-page $H^p(S^3, H^q(\Omega S^3)) = H^p(S^3) \otimes H^q(\Omega S^3)$, thus only two non-zero columns at $p = 0, 3$. By dimensional reason, $\mathrm{d}_2 = \mathrm{d}_4 = \cdots = 0$, thus $E_3 = E_\infty$. Furthermore, since PS^3 is contractible, we have all non-zero d_3 are isomorphisms. Thus $\mathrm{d}_3 : E_2^{0,2} \to E_2^{3,0}$ is an isomorphism, that is $H^2(\Omega S^3) = \mathbb{Z}$, but then

$$E_2^{3,2} = H^3(S^3) \otimes H^2(\Omega S^3) = \mathbb{Z}$$

by the same reason $E_2^{0,4} = \mathbb{Z}$. Step by step we find $H^q(\Omega S^2) = \mathbb{Z}$ in every even dimension q.

Example 6.3. In general

$$H^q(\Omega S^n) = \begin{cases} \mathbb{Z}, & q = n-1, 2(n-1), \ldots \\ 0, & \text{otherwise} \end{cases}$$

6.2.2. *The cohomology ring structure.* In this section, we compute the cohomology rings of the loop space $\Omega S^n, n \geq 2$.

Example 6.4 (The cohomology ring of ΩS^2)**.** Let u be a generator of $E_2^{2,0} = H^2(S^2)$ and x a generator of $H^1(\Omega S^2)$ such that $\mathrm{d}_2(1 \otimes x) = u \otimes 1$, then

$u \otimes x$ is a generator of $H^2(S^2) \otimes H^1(\Omega S^2)$. Direct computation shows

$$\begin{aligned} \mathrm{d}_2(1 \otimes x^2) &= \mathrm{d}_2(1 \otimes x) \cdot (1 \otimes x) - (1 \otimes x) \cdot \mathrm{d}_2(1 \otimes x) \\ &= (u \otimes 1) \cdot (1 \otimes x) - (1 \otimes x) \cdot (u \otimes 1) \\ &= u \otimes x - u \otimes x \\ &= 0 \end{aligned}$$

which implies $x^2 = 0$, since d_2 is an isomorphism. Let e be a generator of $H^2(\Omega S^2)$ such that $\mathrm{d}_2(1 \otimes e) = u \otimes x$ and $u \otimes e \in H^2(S^2) \otimes H^2(\Omega S^2)$, then

$$\begin{aligned} \mathrm{d}_2(1 \otimes ex) &= \mathrm{d}_2(1 \otimes e) \cdot (1 \otimes x) + (1 \otimes e) \cdot \mathrm{d}_2(1 \otimes x) \\ &= (u \otimes x) \cdot (1 \otimes x) + (1 \otimes e) \cdot (u \otimes 1) \\ &= u \otimes e \end{aligned}$$

implies ex is a generator of $H^3(\Omega S^2)$, since d_2 is an isomorphism. Similar computations shows

$$\begin{aligned} \mathrm{d}_2(1 \otimes \frac{e^2}{2}) &= \frac{1}{2}\mathrm{d}_2(1 \otimes e) \cdot (1 \otimes e) + \frac{1}{2}(1 \otimes e) \cdot \mathrm{d}_2(1 \otimes e) \\ &= \frac{1}{2}(u \otimes x) \cdot (1 \otimes e) + \frac{1}{2}(1 \otimes e) \cdot (u \otimes x) \\ &= (u \otimes ex) \\ \mathrm{d}_2(1 \otimes \frac{e^2 x}{2}) &= \frac{1}{2}\mathrm{d}_2(1 \otimes e^2) \cdot (1 \otimes x) + \frac{1}{2}(1 \otimes e^2) \cdot \mathrm{d}_2(1 \otimes x) \\ &= (u \otimes ex) \cdot (1 \otimes x) + \frac{1}{2}(1 \otimes e^2)(u \otimes 1) \\ &= (u \otimes \frac{e^2}{2}) \end{aligned}$$

which implies $\frac{e^2}{2}$ is a generator of $H^4(\Omega S^2)$ and $\frac{e^2 x}{2}$ is a generator of $H^2(\Omega S^2)$. By induction we can show $\frac{e^k}{k!}$ is a generator of $H^{2k}(\Omega S^2)$ and $\frac{e^k x}{k!}$ is a generator of $H^{2k+1}(\Omega S^2)$.

The divided polynomial algebra $Z_\gamma(e)$ with generator e is the $\mathbb{Z}$-algebra with additive basis $\{1, e, e^2/2!, e^3/3!, \dots\}$, then

$$H^*(\Omega S^2) = \Lambda[x_1] \otimes Z_\gamma(e)$$

where $|x_1| = 1, |e| = 2$.

Remark 6.2. By the same argument one can show for n is even

$$H^*(\Omega S^n) = \Lambda[x_{n-1}] \otimes Z_\gamma(e)$$

where $|x_{n-1}| = n - 1, |e| = 2(n - 1)$.

Example 6.5 (The cohomology ring of ΩS^3)**.** Let u be a generator of $E_2^{3,0} = H^3(S^3)$ and e a generator of $H^2(\Omega S^3)$ such that $\mathrm{d}_2(1 \otimes e) = u \otimes 1$, then $u \otimes e$ is a generator of $H^3(S^3) \otimes H^2(\Omega S^3)$. The same computation as above case shows $\frac{e^2}{2}$ is a generator of $H^2(\Omega S^3)$, and by induction one has $\frac{e^k}{k!}$ is a $H^{2k}(\Omega S^3)$, which implies

$$H^*(\Omega S^3) = Z_\gamma(e)$$

where $|e| = 2$.

Remark 6.3. By the same argument one can show for n is odd

$$H^*(\Omega S^n) = Z_\gamma(e)$$

where $|e| = n - 1$.

Part 3. Applications to homotopy theory

7. Review of homotopy theory

7.1. **First properties.** Let X be a topological space with base point $*$.

Definition 7.1 (q-th homotopy group)**.** For $q \geq 1$, the q-th homotopy group $\pi_q(X)$ of X is defined to be the homotopy classes of maps from q-cube I^q to X which send the faces $\dot{I}^q$ of I^q to the base point of X.

Remark 7.1. Equivalently, $\pi_q(X), q \geq 1$ may be regarded as the homotopy classes of base-point preserving maps from S^q to X.

Remark 7.2. $\pi_0(X)$ is defined to be the set of all path components of X, and for a manifold the path components are the same as the connected components. Although $\pi_0(X)$ is in general not a group, if G is a Lie group then $\pi_0(G)$ is a group.

Proposition 7.1. Basic properties:
1. $\pi_q(X \times Y) = \pi_q(X) \times \pi_q(Y)$;
2. $\pi_q(X)$ is abelian if $q \geq 1$;
3. If $\widetilde{X}$ is the universal covering of X, then $\pi_q(X) = \pi_q(\widetilde{X})$ for $q \geq 2$.
4. $\pi_{q-1}(\Omega X) = \pi_q(X)$ for $q \geq 2$.

Proof. For (4). Elements of $\pi_2(X)$ are given by maps of I^2 to X, which can be viewed as a map from I to ΩX, therefore $\pi_2(X) = \pi_1(\Omega X)$. The general case is similar. □

Example 7.1. The homotopy groups of S^1 is

$$\pi_q(S^1) = \begin{cases} \mathbb{Z}, & q = 1 \\ 0, & q > 1 \end{cases}$$

Theorem 7.1 (long exact sequence of homotopy)**.** Let $\pi : E \to X$ be a base-point preserving fiberation with fiber F, then there is an exact sequence of homotopy groups as follows

$$\cdots \to \pi_q(F) \xrightarrow{i_*} \pi_q(E) \xrightarrow{\pi_*} \pi_q(X) \xrightarrow{\partial} \pi_{q-1}(F) \to \cdots \to \pi_0(E) \to \pi_0(X) \to 0$$

Remark 7.3. Here we only gives the descriptions of these homomorphisms, readers may refer to other standard textbooks for exactness.

The maps i_*, π_* are induced by the inclusion $i : F \to E$ and projection $\pi : E \to X$ respectively, where we regard F as the fiber over the base-point $*$ of B. To describe ∂ we use the covering homotopy property of fiberation. A map $\alpha : I^q \to B$ representing an element of $\pi_q(X)$ can be regarded as a homotopy of $\alpha|_{I^{q-1}}$ in X. Note that $\alpha|_{I^{q-1}} : (t_1, \ldots, t_{q-1}, 0) \to * \in X$, then we take constant map $* : I^{q-1} \to E$ from I^{q-1} to the base-point of F as the map that covers $\alpha|_{I^{q-1}}$. By the covering homotopy property, there is a homotopy $\overline{\alpha} : I^q \to E$ which covers α such that $\overline{\alpha}_{I^{q-1}} = *$. Then $\partial[\alpha]$ is the homotopy class of the map $\overline{\alpha} : (t_1, \ldots, t_{q-1}, 1) \to F$. And the well-defineness follows from Remark 6.1.

7.2. **Hurewicz theorem.**

Theorem 7.2 (Hurewicz theorem)**.** Let X be a path-connected space, then $H_1(X)$ is the abelianization of $\pi_1(X)$.

Remark 7.4. So simply-connected space X must have $H_1(X)=0$; Converse statement is not true, although it's quite difficult to give a simple example. For example, you can take an arbitrary perfect group[4] G (For example, $G=A_5$), then the space $K(G,1)$, which will be defined later is what you want. However, in general you don't know what does it look like.

Theorem 7.3 (Hurewicz theorem)**.** Let X be a simply-connected path-connected CW complex. Then the first non-trivial homotopy group and homology group occur in the same dimension and are equal.

Proof. Let n denote the first dimension such that $\pi_n(X)\neq 0$, now let's prove by induction on n. Firstly consider the case $n=2$. The E_2-page of homology spectral sequence of the path fiberation is

$$\begin{tikzcd} 1 & H_1(\Omega X) & & \\ 0 & \mathbb{Z} & 0 & H_2(X) \arrow[ull] \\ & 0 & 1 & 2 \end{tikzcd}$$

Thus $\pi_2(X)=\pi_1(\Omega X)=H_1(\Omega X)=H_2(X)$.

Now let n be any positive integer ≥ 3, then in this case ΩX has the following properties:

1. It's a CW complex[5];
2. It's simply-connected, since $\pi_1(\Omega X)=\pi_2(X)=0$;
3. The dimension of the first non-trivial homotopy group of ΩX is $n-1$, since $\pi_{q-1}(\Omega X)=\pi_q(X), q\geq 2$.

Then we can apply induction hypothesis to ΩX, one has

$$H_q(\Omega X)=\begin{cases}0, & q<n-1\\ \pi_{n-1}(\Omega X)=\pi_n(X), & q=n-1\end{cases}$$

On the other hand, the E_2-page still implies $H_{q-1}(\Omega X)=H_q(X)$ for $2\leq q\leq n$. Then

$$H_q(X)=\begin{cases}0, & 1\leq q<n\\ H_{n-1}(\Omega X)=\pi_n(X), & q=n\end{cases}$$

□

[4] A group G such that its abelianization is trivial is called perfect group.

[5] Not a trivial fact, it's a theorem proved by Milnor: The loop space of a CW complex is still a CW complex.

Remark 7.5. Note that if we want to use Leray spectral sequence, X should admit a good cover. Fortunately, every CW complex admits a good cover.

Example 7.2. It follows from Hurewicz theorem that

$$\pi_q(S^n) = \begin{cases} 0, & q < n \\ \mathbb{Z}, & q = n \end{cases}$$

7.3. **Bott periodic theorem.**

Example 7.3 (stable homotopy groups of $\mathrm{U}(n)$)**.** Consider the following fiberation

$$\begin{array}{ccc} \mathrm{U}(n-1) & \longrightarrow & \mathrm{U}(n) \\ & & \big\downarrow \\ & & S^{2n-1} \end{array}$$

Then homotopy exact sequence implies

$$\cdots \to \pi_{q+1}(S^{2n-1}) \to \pi_q(\mathrm{U}(n-1)) \to \pi_q(\mathrm{U}(n)) \to \pi_q(S^{2n-1}) \to \dots$$

Then for $q < 2n-2$, one has

$$\pi_q(\mathrm{U}(n-1)) = \pi_q(\mathrm{U}(n))$$

these mutally isomorphic groups are called q-th **stable homotopy groups** of the unitary group. They're denoted briefly by $\pi_q(\mathrm{U})$.

Remark 7.6. However, how to compute these stable homotopy groups? Bott has the following theorem:

Theorem 7.4 (Bott periodic theorem)**.** For $q \geq 1$,

$$\pi_{q-1}(\mathrm{U}) \cong \pi_{q+1}(\mathrm{U})$$

From this theorem, it suffices to compute $\pi_0(\mathrm{U})$ and $\pi_1(\mathrm{U})$, and it's quite clear:

$$\pi_0(\mathrm{U}) = \pi_0(\mathrm{U}(1)) = 0$$
$$\pi_1(\mathrm{U}) = \pi_1(\mathrm{U}(1)) = \mathbb{Z}$$

Example 7.4 (stable homotopy groups of $\mathrm{SU}(n)$)**.** For the same reason we have for $q < 2n$,

$$\pi_q(\mathrm{SU}(n-1)) = \pi_q(\mathrm{SU}(n))$$

and we also have q-th stable homotopy groups of the special unitary group, denoted by $\pi_q(\mathrm{SU})$. From the following fiberation

$$\begin{array}{ccc} \mathrm{SU}(n) & \longrightarrow & \mathrm{U}(n) \\ & & \big\downarrow{\scriptstyle \det} \\ & & S^1 \end{array}$$

we can conclude

$$\pi_q(\mathrm{U}(n)) = \begin{cases} \pi_q(\mathrm{SU}(n)), & q \geq 2 \\ \pi_1(\mathrm{SU}(n)) \oplus \mathbb{Z}, & q = 1 \end{cases}$$

for arbitrary $n \geq 1$. In particular, we have the isomorphisms between stable homotopy groups.

Example 7.5 (stable homotopy groups of $\mathrm{O}(n)$)**.** Consider the following fiberation

$$\begin{tikzcd} \mathrm{O}(n-1) \arrow[r] & \mathrm{O}(n) \arrow[d] \\ & S^{n-1} \end{tikzcd}$$

Then homotopy exact sequence implies

$$\cdots \to \pi_{q+1}(S^{n-1}) \to \pi_q(\mathrm{O}(n-1)) \to \pi_q(\mathrm{O}(n)) \to \pi_q(S^{n-1}) \to \dots$$

Then for $q < n-2$, one has

$$\pi_q(\mathrm{O}(n-1)) = \pi_q(\mathrm{O}(n))$$

and we can define q-th stable homotopy groups of special orthogonal groups, defined by $\pi_q(\mathrm{O})$. Similarly we also have the following theorem:

Theorem 7.5 (Bott periodic theorem)**.** For $q \geq 0$,

$$\pi_q(\mathrm{O}) \cong \pi_{q+8}(\mathrm{O})$$

7.4. **Some homotopy groups of Stiefel manifold.**

Definition 7.2 (real Stiefel manifold)**.** The real Stiefel manifold $V_k(\mathbb{R}^{n+k})$ is the set of all orthonormal k-frames in $\mathbb{R}^{n+k}$.

Example 7.6. $\mathrm{SO}(n) = V_{n-1}(\mathbb{R}^n)$.

Example 7.7. $S^n = V_1(\mathbb{R}^{n+1})$.

Lemma 7.1. For $1 \leq k \leq n$, $V_k(\mathbb{R}^{n+k})$ is $(n-1)$-connected, and

$$\pi_n(V_2(\mathbb{R}^{n+2})) = \begin{cases} \mathbb{Z}, & n \text{ is odd} \\ \mathbb{Z}/2\mathbb{Z}, & n \text{ is even} \end{cases}$$

Proof. Apply homotopy exact sequence to the following fiberation

$$\begin{tikzcd} V_{k-1}(\mathbb{R}^{n+k-1}) \arrow[r] & V_k(\mathbb{R}^{n+k}) \arrow[d] \\ & S^{n+k-1} \end{tikzcd}$$

Then if $q < n+k-2$, one has

$$\pi_q(V_k(\mathbb{R}^{n+k})) = \pi_q(V_{k-1}(\mathbb{R}^{n+k-1}))$$

In particular if $q < n$, one has

$$\pi_q(V_k(\mathbb{R}^{n+k})) = \pi_q(V_{k-1}(\mathbb{R}^{n+k-1})) = \cdots = \pi_q(V_1(\mathbb{R}^{n+1})) = \pi_q(S^n) = 0$$

7.5. **Hopf invariant.**

7.5.1. *History.* In general, it's tough to compute $\pi_q(S^n)$ for $n \geq 2, q > n$. So the first non-trivial case is $\pi_3(S^2)$. Consider Hopf fiberation

$$\begin{tikzcd} S^1 \arrow[r] & S^3 \arrow[d] \\ & \mathbb{CP}^1 = S^2 \end{tikzcd}$$

Then the exact sequence of homotopy groups implies

$$\cdots \to \pi_q(S^1) \to \pi_q(S^3) \to \pi_q(S^2) \to \pi_{q-1}(S^1) \to \dots$$

Use the fact that $\pi_q(S^1) = 0, q > 1$ one has

$$\pi_q(S^3) = \pi_q(S^2)$$

for $q > 1$. In particular one has $\pi_3(S^2) = \mathbb{Z}$. $\square$

In history $\pi_3(S^2)$ was first computed by Hopf in 1931 using a linking number argument which associates to each homotopy class of maps from S^3 to S^2 an integer now called the Hopf invariant. We first give an account of the Hopf invariant in the dual language of differential forms and then in terms of the linking number.

7.5.2. *The differential forms definition.*

Definition 7.3 (Hopf invariant)**.** Let $f : S^{2n-1} \to S^n$ be a smooth map and let α be a generator of $H^n_{dR}(S^n)$, then Hopf invariant of f is defined as

$$H(f) = \int_{S^{2n-1}} \omega \wedge \mathrm{d}\omega$$

where $f^*\alpha = \mathrm{d}\omega$.

Proposition 7.2. Properties of Hopf invariant:
1. The definition of Hopf invariant is independent of the choice of ω;
2. For odd n the Hopf invariant is 0;
3. Homotopic maps have the same Hopf invariant.

Proof. For (1). Let ω' be another $(n-1)$-form on S^{2n-1} such that $f^*\alpha = \mathrm{d}\omega'$. Then

$$\begin{aligned}\int_{S^{2n-1}} \omega \wedge \mathrm{d}\omega - \int_{S^{2n-1}} \omega' \wedge \mathrm{d}\omega' &= \int_{S^{2n-1}} (\omega - \omega') \wedge \mathrm{d}\omega \\ &= \pm \int_{S^{2n-1}} \mathrm{d}((\omega - \omega') \wedge \omega) \\ &= 0\end{aligned}$$

For (2). If n is odd, then ω is even-dimensional, thus

$$\omega \wedge \mathrm{d}\omega = \frac{1}{2}\mathrm{d}(\omega \wedge \omega)$$

For (3). From (2) we may assume n is even. Let $F : S^{2n-1} \times I \to S^n$ be a homotopy between $f_0, f_1 : S^{2n-1} \to S^n$. We use i_0 to denote the inclusion $i_0 : S^{2n-1} \to S_0 = S^{2n-1} \times \{0\} \subset S^{2n-1} \times I$ and similar for i_1. Then

$$F \circ i_0 = f_0$$
$$F \circ i_1 = f_1$$

Let α be a generator of $H^n_{dR}(S^n)$, then $F^*\alpha = \mathrm{d}\omega$ for some $(n-1)$-form ω on $S^{2n-1} \times I$. Define $i_0^*\omega = \omega_0$ and $i_1^*\omega = \omega_1$, then

$$f_0^*\alpha = (F \circ i_0)^* = i_0^* \circ F^*\alpha = \omega_0$$
$$f_1^*\alpha = (F \circ i_1)^* = i_1^* \circ F^*\alpha = \omega_1$$

Then

$$\begin{aligned}
H(f_1) - H(f_2) &= \int_{S^{2n-1}} \omega_1 \wedge \mathrm{d}\omega_1 - \int_{S^{2n-1}} \omega_0 \wedge \mathrm{d}\omega_0 \\
&= \int_{S^{2n-1}} i_1^*(\omega \wedge \mathrm{d}\omega) - \int_{S^{2n-1}} i_0^*(\omega \wedge \mathrm{d}\omega) \\
&= \int_{S_1} - \int_{S_0} \omega \wedge \mathrm{d}\omega \\
&= \int_{S^{2n-1}} \mathrm{d}(\omega \wedge \mathrm{d}\omega) \\
&= \int_{S^{2n-1} \times I} F^*(\alpha \wedge \alpha) \\
&= 0
\end{aligned}$$

□

Thus Hopf invariant gives the following map

$$H : \pi_{2n-1}(S^n) \to \mathbb{R}$$

Furthermore, it gives a group homomorphism. Indeed, for two smooth maps $f, g : S^{2n-1} \to S^n$, it suffices to show

$$(fg)^*(\alpha) =$$

where α be a generator of $H^n_{dR}(S^n)$ and $\mathrm{d}\omega_f = f^*\alpha, \mathrm{d}\omega_g = g^*\alpha$. Then

$$H(fg) = \int_{S^{2n-1}}$$

7.5.3. *The intersection-theory definition.*

8. Applications to homotopy theory

8.1. Eilenberg-MacLane spaces.

Definition 8.1 (Eilenberg-MacLane space)**.** Let G be a group, a path-connected space X is called an Eilenberg-MacLane space $K(G,n)$, if

$$\pi_q(X) = \begin{cases} G, & q = n \\ 0, & \text{otherwise} \end{cases}$$

Remark 8.1. For any group G and $n \geq 1$, in the category of CW complexes $K(G,n)$ exists and is unique up to homotopy equivalence.

Example 8.1. S^1 is $K(\mathbb{Z},1)$ according to Example 7.1.

Example 8.2. If F is a free group, then $K(F,1)$ is a connected graph.

Corollary 8.1. Any subgroup of a free group is still a free group.

Example 8.3. For a group G with generators $a_1, b_1, \dots, a_g, b_g$ and a single relations

$$a_1 b_1 a_1^{-1} b_1^{-1} \dots a_g b_g a_g^{-1} b_g^{-1} = 1$$

Then the Riemann surface with genus g is $K(G,1)$, according to the following theorem.

Theorem 8.1 (uniformization theorem)**.** Every simply-connected Riemann surface is biholomorphic to

1. S^2;
2. $\mathbb{C}$;
3. the unit disk Δ in $\mathbb{C}$.

For compact Riemann surfaces,

1. those with universal cover Δ are precisely the surfaces of genus greater than 1;
2. those with universal cover $\mathbb{C}$ are the Riemann surfaces of genus 1, namely the complex tori or elliptic curves;
3. those with universal cover S^2 are those of genus zero, namely the Riemann sphere itself.

Proposition 8.1. Basic properties:

1. $\Omega K(G,n) = K(G,n-1)$;
2. $K(G \times H, n) = K(G,n) \times K(H,n)$.

8.2. The telescoping construction.

In this section we introduce a technique for constructing certain Eilenberg-MacLane space, which is called telescoping construction.

Example 8.4 (The infinite real projective space)**.** Note that we have the following natural inclusions

$$\{\text{point}\} \hookrightarrow \dots \overset{i}{\hookrightarrow} \mathbb{RP}^n \overset{i}{\hookrightarrow} \mathbb{RP}^{n+1} \hookrightarrow \dots$$

Then we define the infinite real projective space $\mathbb{RP}^\infty$ as

$$\mathbb{RP}^\infty := \bigcup_n \mathbb{RP}^n$$

Since $S^n \to \mathbb{RP}^n$ is a double cover, thus $\pi_q(\mathbb{RP}^n) = 0$ for $1 < q < n$ and $\pi_1(\mathbb{RP}^n) = \mathbb{Z}_2$. We claim $\mathbb{RP}^\infty$ is exactly $K(\mathbb{Z}_2, 1)$.

1. For arbitrary $q > 1, f \in \pi_q(\mathbb{RP}^\infty)$, that is a map $f : S^q \to \mathbb{RP}^\infty$. Since S^q is compact, then there exists a sufficiently large N such that $f(S^q) \subset \mathbb{RP}^N$, and $\pi_q(\mathbb{RP}^N) = 0$ implies f is null-homotopic;
2. Similarly we can construct infinite sphere S^∞, which is double cover of $\mathbb{RP}^\infty$, and by the same argument we have S^∞ is contractible. Then homotopy exact sequence of fiberation implies $\pi_1(\mathbb{RP}^\infty) = \mathbb{Z}_2$.

Example 8.5 (The infinite complex projective space)**.** Note that we have the following natural inclusions

$$\{\text{point}\} \hookrightarrow \cdots \hookrightarrow \mathbb{CP}^n \hookrightarrow \mathbb{CP}^{n+1} \hookrightarrow \dots$$

Then we define the infinite complex projective space $\mathbb{CP}^\infty$ as

$$\mathbb{CP}^\infty := \bigcup_n \mathbb{CP}^n$$

Similarly we have the following fiberation

$$\begin{tikzcd}
S^1 \arrow[r] & S^\infty \arrow[d] \\
 & \mathbb{CP}^\infty
\end{tikzcd}$$

By the same argument you can see $\mathbb{CP}^\infty = K(\mathbb{Z}, 2)$.

Proposition 8.2. The cohomology ring of $\mathbb{CP}^\infty$ is $\mathbb{Z}[x]$, where $|x| = 2$.

Proof. Note that $\mathbb{CP}^\infty$ is simply-connected, then the E_2-page of Leray spectral sequence is

$$\begin{tikzcd}
1 & \mathbb{Z} \arrow[drr] & 0 \arrow[drr] & A & B \\
0 & \mathbb{Z} & 0 & A & B \\
 & 0 & 1 & 2 & 3
\end{tikzcd}$$

and these d_2 are isomorphisms, which implies the cohomology group of $\mathbb{CP}^\infty$ is

$$H^q(\mathbb{CP}^\infty) = \begin{cases} \mathbb{Z}, & q \text{ is even} \\ 0, & \text{otherwise} \end{cases}$$

To see its ring structure, we rewrite E_2-page as follows:

$$\begin{tikzcd} 1 & 1\otimes u \arrow[drr] & & x\otimes u \arrow[drr] & & x^2\otimes u \\ 0 & 1\otimes 1 & & x\otimes 1 & & x^2\otimes 1 \\ & 0 & 1 & 2 & 3 & 4 \end{tikzcd}$$

Take a generator u of $H^1(S^1)$ and use $x \otimes 1$ to denote $\mathrm{d}_2(1 \otimes u)$, then x is a generator of $H^2(\mathbb{CP}^\infty)$. Then

$$\begin{aligned} \mathrm{d}_2(x \otimes u) &= \mathrm{d}_2(x \otimes 1) \cdot (1 \otimes u) + (-1)^2 (x \otimes 1) \cdot \mathrm{d}_2(1 \otimes u) \\ &= (x^2 \otimes 1) \end{aligned}$$

implies x^2 is a generator of $H^4(\mathbb{CP}^\infty)$. By induction you can see its cohomology ring is $\mathbb{Z}[x]$, where $|x| = 2$. □

Example 8.6 (The infinite lens spaces)**.** Since S^1 acts freely on S^{2m+1}, so does any subgroup of S^1. Consider $\mathbb{Z}_n$-action on S^{2m+1} as follows

$$\begin{aligned} \mathbb{Z}_n \times S^{2m+1} &\to S^{2m+1} \\ (e^{\frac{2\pi i}{n}}, (z_0, \ldots, z_m)) &\to (e^{\frac{2\pi i}{n}} z_0, \ldots, e^{\frac{2\pi i}{n}} z_m) \end{aligned}$$

The quotient space of S^{2m+1} by action of $\mathbb{Z}_n$ is called lens space $L(m, n)$. Apply telescoping construction we can define infinite lens space $L(\infty, n)$, and there is a fiberation

$$\begin{tikzcd} \mathbb{Z}_n \arrow[r] & S^\infty \arrow[d] \\ & L(\infty, n) \end{tikzcd}$$

By the same argument one can show $L(\infty, n)$ is $K(\mathbb{Z}_n, 1)$.

Remark 8.2. In particular, $L(\infty, 2)$ is exactly $\mathbb{RP}^\infty$.

In order to show the cohomology of $L(m, n)$, the fiberation $\mathbb{Z}_n \to S^{2m+1} \to L(m, n)$ makes no sense, since $L(m, n)$ is not simply-connected. Instead, note that the free action of S^1 on S^{2m+1} descends to an action on $L(m, n)$:

$$(z_0, \ldots, z_m) \mapsto (\lambda z_0, \ldots, \lambda z_m)$$

since S^1 is an abelian Lie group. Furthermore, the quotient of this descend action is still $\mathbb{CP}^m$, so there is a fiberation

$$\begin{tikzcd} S^1 \arrow[r] & L(m, n) \arrow[d] \\ & \mathbb{CP}^m \end{tikzcd}$$

and the E_2-page of Leray spectral sequence to this fiberation is

$$\begin{tikzcd}
1 & 1\otimes u \arrow[drr] & & x\otimes u \arrow[drr] & & x^2\otimes u \\
0 & 1\otimes 1 & & x\otimes 1 & & x^2\otimes 1 \\
 & 0 & 1 & 2 & 3 & 4
\end{tikzcd}$$

Let u be a generator of $H^1(S^1)$ and x a generator of $H^2(\mathbb{CP}^m)$, it suffices to compute what does $\mathrm{d}_2 : E_2^{0,1} \to E_2^{2,0}$ look like, since $x^n \otimes a$ generates $E_2^{2n,1}$. However, since $\pi_1(L(m,n)) = \mathbb{Z}_n$, then Hurewicz theorem implies $H_1(L(m,n)) = \mathbb{Z}_n$, so universal coefficients theorem implies

$$\begin{aligned}
H^1(L(m,n)) &= \mathrm{Hom}(H_1(L(m,n)),\mathbb{Z}) \oplus \mathrm{Ext}(H_0(X),\mathbb{Z}) = 0 \\
H^2(L(m,n)) &= \mathrm{Hom}(H_2(L(m,n)),\mathbb{Z}) \oplus \mathrm{Ext}(H_1(X),\mathbb{Z}) = \text{free part} \oplus \mathbb{Z}_n
\end{aligned}$$

So we have d_2 is multiplication by n, and cohomology group of $L(m,n)$:

$$H^q(L(m,n)) = \begin{cases} \mathbb{Z}, & q = 0, 2m+1 \\ \mathbb{Z}_n, & q = 2,4,\dots,2m \\ 0, & \text{otherwise} \end{cases}$$

If we consider the following fiberation

$$\begin{tikzcd}
S^1 \arrow[r] & K(\mathbb{Z}_n,1) \arrow[d] \\
 & \mathbb{CP}^\infty
\end{tikzcd}$$

Then the same computation shows the cohomology groups of $K(\mathbb{Z}_n,1)$ is

$$H^q(K(\mathbb{Z}_n,1)) = \begin{cases} \mathbb{Z}, & q = 0 \\ \mathbb{Z}_n, & q \text{ is even}, q \neq 0 \\ 0, & \text{otherwise} \end{cases}$$

However, if we consider $\mathbb{Q}$ coefficients, then mutiply by n is an isomorphism of $\mathbb{Q}$, which implies

$$H^q(K(\mathbb{Z}_n,1);\mathbb{Q}) = \begin{cases} \mathbb{Q}, & k = 0 \\ 0, & \text{otherwise} \end{cases}$$

Furthermore, we can use path fiberation of $K(\mathbb{Z}_n,1)$ to conclude

$$H^q(K(\mathbb{Z}_n,m);\mathbb{Q}) = \begin{cases} \mathbb{Q}, & q = 0 \\ 0, & \text{otherwise} \end{cases}$$

holds for all $m \in \mathbb{Z}_{>0}$. Therefore, by the structure of finitely generated abelian groups, the rational cohomology of $K(G,m)$ is trivial for a finitely generated torsion abelian group.

8.3. **Some results about cohomology ring of $K(\mathbb{Z},3)$.** Since $\pi_q(S^3)=0$ for $q<3$ and $\pi_3(S^3)=\mathbb{Z}$, it's natural to ask whether S^3 is $K(\mathbb{Z},3)$ or not. Since we know $\Omega K(\mathbb{Z},3)=K(\mathbb{Z},2)=\mathbb{CP}^\infty$ and we have the following path fiberation

$$\begin{tikzcd}
K(\mathbb{Z},2) \arrow[r] & PK(\mathbb{Z},3) \arrow[d] \\
 & K(\mathbb{Z},3)
\end{tikzcd}$$

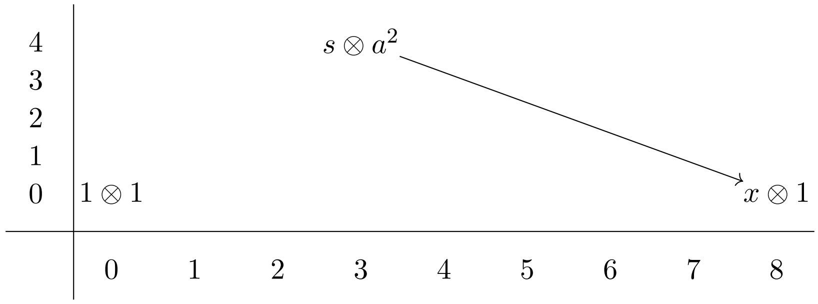
Then we can use Leray spectral sequence to compute cohomology ring of $K(\mathbb{Z},3)$. By dimensional reason, it's clear E_2-page equals to E_3-page, which looks like

$$\begin{tikzcd}[row sep=small, column sep=small]
8 & 1\otimes a^4 \arrow[ddrrr] & & & & & & & & & \\
7 & & & & & & & & & & \\
6 & 1\otimes a^3 \arrow[ddrrr] & & & s\otimes a^3 \arrow[ddrrr] & & & & & & \\
5 & & & & & & & & & & \\
4 & 1\otimes a^2 \arrow[ddrrr] & & & s\otimes a^2 \arrow[ddrrr] & & & s^2\otimes a^2 & & & \\
3 & & & & & & & & & & \\
2 & 1\otimes a \arrow[ddrrr] & & & s\otimes a \arrow[ddrrr] & & & s^2\otimes a \arrow[ddrrr] & & & \\
1 & & & & & & & & & & \\
0 & 1\otimes 1 & & & s\otimes 1 & & & s^2\otimes 1 & & & s^3\otimes 1 \\
 & 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9
\end{tikzcd}$$

where a is the generator of $H^2(\mathbb{CP}^\infty)$. We have the following observations:

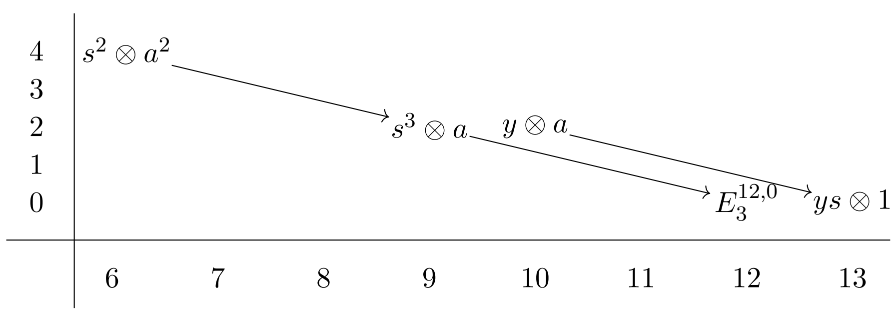
1. It's clear $\mathrm{d}_3: E_3^{0,2}\to E_3^{3,0}$ is an isomorphism, and we use $s\otimes 1$ to denote $\mathrm{d}_3(1\otimes a)$, then s is a generator of $H^3(K(\mathbb{Z},3))$.
2. $H^4(K(\mathbb{Z},3))=0$, otherwise non-zero element in $E_3^{4,0}$ will live to E_∞-page, since nothing can kill it; The same argument shows $H^5(K(\mathbb{Z},3))=0$.
3. Note that $s\otimes a$ is a generator of $E_3^{3,2}$, $s\otimes a^2$ is a generator of $E_3^{3,4}$ and $s\otimes a^3$ is a generator of $E_3^{3,6}$, then by antiderivation property of d_3, we can see
   (a) $\mathrm{d}_3: E_3^{0,4}\to E_3^{3,2}$ is multiplication by 2;
   (b) $\mathrm{d}_3: E_3^{0,6}\to E_3^{3,4}$ is multiplication by 3;
   (c) $\mathrm{d}_3: E_3^{0,8}\to E_3^{3,6}$ is multiplication by 4.
4. $\mathrm{d}_3: E_3^{3,2}\to E_3^{6,0}$ can't be zero map, otherwise $E_\infty^{3,2}=\operatorname{coker}\{\mathrm{d}_3: E_3^{0,4}\to E_3^{3,2}\}=\mathbb{Z}_2$, a contradiction. Furthermore, it's also a surjective, otherwise $E_\infty^{6,0}=\operatorname{coker}\{\mathrm{d}_3: E_3^{3,2}\to E_3^{6,0}\}\neq 0$, also a contradiction. Combine these two facts together one has $E_3^{6,0}=\mathbb{Z}_2$ is generated by $s^2\otimes 1$, that is s^2 is a generator of $H^6(K(\mathbb{Z},3))$.
5. Since $2s^2=0$, then $\mathrm{d}_3: E_3^{3,4}\to E_3^{6,2}=0$. Thus $E_4^{3,4}=\mathbb{Z}_3$, and there is no maps mapping into $E_4^{3,4}$. So the only possible element to kill it is

elements in $E_5^{8,0}$, which implies $H^8(K(\mathbb{Z},3))=\mathbb{Z}_3$, we use x to denote its generator. This process is shown in the following E_5-page.



6. $\mathrm{d}_3: E_3^{6,2}\to E_3^{9,0}$ is an isomorphism, and the reason is the same as (4), which implies s^3 is a generator of $H^9(K(\mathbb{Z},3))$.
7. Since $2s^2=0$, $\mathrm{d}_3: E_3^{3,6}\to E_3^{6,4}$ is a surjective, with kernel $2(s\otimes a^3)$, which implies $E_4^{3,6}=\mathbb{Z}_2$. Note that only the following two maps may kill this non-zero element.
   (*a*) $\mathrm{d}_5: E_5^{3,6}\to E_5^{8,2}$;
   (*b*) $\mathrm{d}_7: E_7^{3,6}\to E_7^{10,0}$.
   Now let's consider case (a), this will happen if and only if $\mathrm{d}_3: E_3^{8,2}\to E_3^{11,0}$ is a zero map, that is $E_5^{8,2}=\mathbb{Z}_3\neq 0$. However, any group homomorphism from $\mathbb{Z}_2$ to $\mathbb{Z}_3$ must be trivial. So case (a) won't kill this $\mathbb{Z}_2$. Furthermore, it can't happen, otherwise $E_\infty^{8,2}\neq 0$. So
   I We must have $\mathrm{d}_7: E_7^{3,6}\to E_7^{10,0}$ is an isomorphism, which implies $H^{10}(K(\mathbb{Z},3))=\mathbb{Z}_2$, and we use y to denote this generator;
   II By the way we conclude $\mathrm{d}_3: E_3^{8,2}\to E_3^{11,0}$ is an isomorphism, which implies xs is a generator of $H^{11}(K(\mathbb{Z},3))$.

Now let's forget some old information and concentrate on something unknown to draw a new picture of E_3-page as follows:



7. Since $2s^2=0$, $\mathrm{d}_3: E_3^{6,4}\to E_3^{9,2}$ is zero map. So $\mathrm{d}_3: E_3^{9,2}\to E_3^{12,0}$ is an injective, which implies there is a $s^4\otimes 1\in E_3^{12,0}$. However, $\mathrm{d}_3: E_3^{9,2}\to E_3^{12,0}$ isn't a surjective, since we also need $\mathrm{d}_9: E_9^{3,8}\to E_9^{12,0}$ to kill $E_9^{3,8}=\mathbb{Z}_5$, which implies $H^{12}(K(\mathbb{Z},3))=\mathbb{Z}_2\oplus\mathbb{Z}^5$, one of the generators is s^4, and the other one we use z to denote it.

8. Finally one can check $d_3 : E_3^{10,2} \to E_3^{13,0}$ is an isomorphism, which implies $H^{13}(K(\mathbb{Z},3))$ is generated by ys.

In summary the first few cohomology groups of $K(\mathbb{Z},3)$ are

q	0	1	2	3	4	5	6	7	8	9	10	11	12	13
$H^q(K(\mathbb{Z},3))$	$\mathbb{Z}$	0	0	$\mathbb{Z}$	0	0	$\mathbb{Z}_2$	0	$\mathbb{Z}_3$	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}_3$	$\mathbb{Z}_2 \oplus \mathbb{Z}_5$	$\mathbb{Z}_2$
generators	1			s			s^2		x	s^3	y	xs	s^4, z	ys

There is a bad news, that is you can't figure out what is $H^{14}(K(\mathbb{Z},3))$ using above method, we do need additional information. However, the situation can be vastly simplified by taking coefficients in $\mathbb{Q}$ rather than $\mathbb{Z}$. In this case we have

Proposition 8.3.

$$H^*(K(\mathbb{Z},n);\mathbb{Q}) = \begin{cases} \mathbb{Q}[x], & n \text{ is even} \\ \Lambda_{\mathbb{Q}}[x], & n \text{ is odd} \end{cases}$$

where $|x| = n$.

Proof. Let's prove by induction on n via the following path fiberation

$$\begin{tikzcd} K(\mathbb{Z},n-1) \arrow[r] & PK(\mathbb{Z},n) \arrow[d] \\ & K(\mathbb{Z},n) \end{tikzcd}$$

1. For $n = 2$, we have already shown $H^*(K(\mathbb{Z},2);\mathbb{Q}) = \mathbb{Q}[x]$, where $|x| = 2$;
2. For $n = 3$, we just need to replace $\mathbb{Z}$ with $\mathbb{Q}$ in above computation, and note that multiplication by i is an isomorphism of $\mathbb{Q}$. Then one can argue inductively that $E_3^{p,0}$ must be zero for $p > 3$, otherwise the first non-zero one will live to E_∞-page, since it can't be killed by any differential.

Then induction process is a routine. □

Remark 8.3. More generally, this holds also when $\mathbb{Q}$ is replaced by any non-zero subgroup of $\mathbb{Q}$. See Proposition 1.20 in Page31 of [Hat04].

8.4. **Basic tricks of the trade.** In homotopy theory, every map $f : A \to B$ from a space A to a path-connected space B may be viewed as

1. An inclusion;
2. A fiberation.

8.4.1. *Inclusion.* Consider the mapping cylinder of f as follows:

$$M_f := (A \times I) \cup B/(a,1) \sim f(a)$$

It's clear that M_f has the same homotopy type as B and A is included in M_f.

8.4.2. *Fiberation.* Without lose of generality we may assume f is an inclusion. Define L to be the space of all paths in B with initial point in A. By shrinking every path to its initial point, we get a homotopy equivalence $L \simeq A$. On the other hand, by projecting every path to its endpoint, we get the following fiberation

$$\begin{tikzcd} \Omega_*^A \arrow[r] & L \simeq A \arrow[d] \\ & B \end{tikzcd}$$

whose fiber is Ω_*^A, the space of all paths from a point $*$ in B to A. So up to homotopy equivalence, $f : A \to B$ is a fiberation.

8.5. **Postnikov approximation.** Let X be a CW complex with homotopy groups $\pi_q(X) = \pi_q$. Although X has the same homotopy groups as the product space $\prod K(\pi_q, q)$, in general it will not have the same homotopy type. However, up to homotopy every CW complex can be thought of as a "twisted product" of Eilenberg-MacLane spaces in the following sense.

Proposition 8.4 (Postnikov approximation)**.** Every CW complex can be approximated by a twisted product of Eilenberg-MacLane spaces; More precisely, for each n, there is a sequence of fiberations $Y_q \to Y_{q-1}$ with the $K(\pi_q, q)$'s as fibers and commuting maps $X \to Y_q$

$$\begin{tikzcd} K(\pi_1, 1) = Y_1 & Y_2 \arrow[l, "K(\pi_2,2)"'] & \dots \arrow[l] & Y_n \arrow[l] \\ & & & X \arrow[ulll] \arrow[ull] \arrow[u] \end{tikzcd}$$

such that the map $X \to Y_q$ induces an isomorphism of homotopy groups in dimensions $\leq q$. Such a sequence of fiberations is called Postnikov tower of X.

Remark 8.4. Firstly let's explain a procedure for killing the homotopy groups of X above a given dimension. For example, to construct $K(\pi_1, 1)$ we kill off the homotopy groups of X in dimensions ≥ 2.

If $\alpha : S^2 \to X$ represents a non-trivial element in $\pi_2(X)$, we attach a 3-cell to X via α as follows:

$$X \cup_\alpha e^3 = X \coprod e^3 / x \sim \alpha(x), \quad x \in S^2$$

This procedure doesn't change the fundamental group of the space, since attaching a n-cell to X could kill an element of $\pi_{n-1}(X)$, but doesn't affect the homotopy of X in dimensions $\leq n-2$. So for each generator of $\pi_2(X)$ we attach a 3-cell to X as above. In this way we create a new space X_1 with the same fundamental group as X but with no π_2. Iterating this procedure we can kill all higher homotopy groups. This gives Y_1.

Proof. To construct Y_n we kill off all homotopy groups of X in dimensions $\geq n+1$ by attaching cells. Then

$$\pi_q(Y_n) = \begin{cases} 0, & q \geq n+1 \\ \pi_q, & q = 1, 2, \dots, n \end{cases}$$

Having constructed Y_n, the space Y_{n-1} is obtained from Y_n by killing the homotopy of Y_n dimension n. Then we have the following inclusions

$$X \subset Y_n \subset Y_{n-1} \subset \cdots \subset Y_1$$

and we can regard it as fiberations. The fiber of $Y_q \to Y_{q-1}$ follows from homotopy exact sequence. □

8.6. **Computation of $\pi_4(S^3)$.** The computation pf $\pi_4 = \pi_4(S^3)$ is based on the fact that the homotopy group π_4 appears as the first non-trivial homology group of $K(\pi_4, 4)$. If we can fit this Eilenberg-MacLane space into some fiberation, then its homology may be derived from Leray spectral sequence. Such fiberation is obtained from Postnikov approximation.

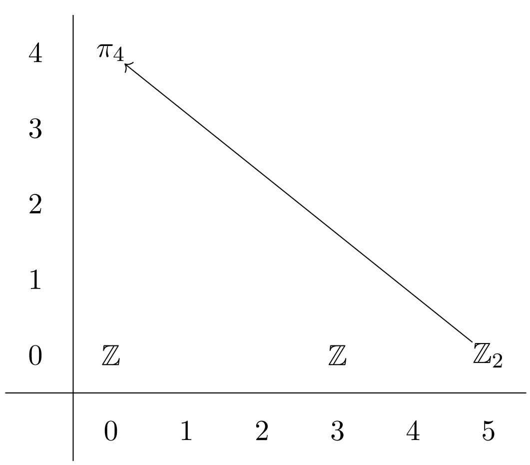
Let Y_4 be a space whose homotopy agrees with S^3 up to and including dimension 4 and vanishes in higher dimension. To get such space it suffices to kill off all homotopy groups of S^3 in dimensions ≥ 5 by attaching cells, that is

$$Y_4 = S^3 \cup e^6 \cup \dots$$

Thus Postnikov approximation gives the following fiberation

$$\begin{tikzcd} K(\pi_4, 4) \arrow[r] & Y_4 \arrow[d] \\ & Y_3 \end{tikzcd}$$

But by definition Y_3 is $K(\mathbb{Z}, 3)$, since it's space with the same homotopy groups with S^3 up to and including dimension 3 and vanishes in higher dimension. The E_5-page of spectral sequence is



By basic facts about attaching cells, we know $H_4(Y_4) = H_5(Y_4) = 0$, thus the arrow shown must be an isomorphism, which implies $\pi_4(S^3) = \mathbb{Z}_2$.

Corollary 8.2 (Serre)**.** For $n \geq 3$,

$$\pi_{n+1}(S^n) = \mathbb{Z}_2$$

Proof. Follows from $\pi_4(S^3) = \mathbb{Z}_2$ and suspension theorem. $\square$

9. Serre's celebrated theorems

In this section we mainly refer to [Hil04] and [BM08].

9.1. The Whitehead tower. The Whitehead tower is a sequence of fiberations, dual to Postnikov approximation in a certain sense, which generalizes the universal covering of a space. To be explicit, the idea of Whitehead tower is to kill at each stage all the homotopy groups below a given dimension.

Up to homotopy the universal covering of a space X may be constructed as follows: If we use π_q to denote $\pi_q(X)$, by attaching cells to X we can kill all π_q for $q \geq 2$. Let $Y = X \cup e^3 \cup \dots$ be the space so obtained, then Y is a $K(\pi_1, 1)$ containing X as a subspace. Consider the space Ω_*^X of all paths in Y from a base point $*$ to X, the endpoint map $\Omega_*^X \to X$ is a fiberation with fiber $\Omega Y = K(\pi_1, 0)$. Then apply homotopy exact sequence to

$$\begin{tikzcd} K(\pi_1,0) \arrow[r] & \Omega_*^X \arrow[d] \\ & X \end{tikzcd}$$

one has

$$\dots \to \pi_1(K(\pi_1,0)) \to \pi_1(\Omega_*^X) \to \pi_1(X) \to \pi_0(K(\pi_1,0)) \to 0$$

which implies $\pi_1(\Omega_*^X) = 0$, and

$$\dots \to \pi_q(K(\pi_1,0)) \to \pi_q(\Omega_*^X) \to \pi_q(X) \to \pi_{q-1}(K(\pi_1,0)) \to \dots$$

implies $\pi_q(\Omega_*^X) = \pi_q(X)$ when $q \geq 2$.

Now let's repeat this process to obtain a sequence of fiberations

$$\begin{tikzcd} & \vdots \arrow[d] \\ K(\pi_n, n-1) \arrow[r] & X_n \arrow[d] \\ & X_{n-1} \arrow[d] \\ & \vdots \arrow[d] \\ K(\pi_1,0) \arrow[r] & X_1 \arrow[d] \\ & X \end{tikzcd}$$

such that

1. X_n is n-connected;
2. above dimension n the homotopy groups of X_n and X agree;
3. the fiber of $X_n \to X_{n-1}$ is $K(\pi_n, n-1)$.

This is called Whitehead tower of X. To construct X_n from X_{n-1}, we first kill all $\pi_q(X_{n-1}), q \geq n+1$ by attaching cells. This gives

$$K(\pi_n, n) = X_{n-1} \cup e^{n+2} \cup \dots$$

Next let $X_n = \Omega_*^{X_{n-1}}$ be the space of all paths in $K(\pi_n, n)$ from a base point $*$ to X_{n-1}. The endpoint map gives the following fiberation

$$\begin{tikzcd} K(\pi_n, n-1) \arrow[r] & X_n \arrow[d] \\ & X_{n-1} \end{tikzcd}$$

The homotopy exact sequence implies

$$\dots \to \pi_q(K(\pi_n, n-1)) \to \pi_q(X_n) \to \pi_q(X_{n-1}) \to \pi_{q-1}(K(\pi_n, n-1)) \to \dots$$

then if $q \neq n, n-1$, one has $\pi_q(X_n) = \pi_q(X_{n-1})$, and

$$0 \to \pi_n(X_n) \to \pi_n(X_{n-1}) \xrightarrow{\partial} \pi_{n-1}(K(\pi_n, n-1)) \to \pi_{n-1}(X_n) \to 0$$

Now it suffices to show that $\partial : \pi_n(X_{n-1}) \to \pi_{n-1}(K(\pi_n, n-1))$ is an isomorphism. Note that inclusion

$$X_{n-1} \subset K(\pi_n, n) = X_{n-1} \cup e^{n+2} \cup \dots$$

gives an isomorphism

$$\pi_n(X_{n-1}) \cong \pi_n(K(\pi_n, n))$$

By Remark 7.3 implies ∂ is exactly how $\pi_n(K(\pi_n, n))$ was identified with $\pi_{n-1}(\Omega K(\pi_n, n))$.

9.2. **Serre class.**

Definition 9.1 (Serre class)**.** The Serre class $\mathscr{C}$ is a non-empty family of abelian groups such that the following Axioms hold:

I If $0 \to A' \to A \to A'' \to 0$ is a short exact sequence of abelian groups, then $A \in \mathscr{C}$ if and only if $A', A'' \in \mathscr{C}$;
II If $A, B \in \mathscr{C}$, then $A \otimes B, \mathrm{Tor}(A, B) \in \mathscr{C}$;
III If $A \in \mathscr{C}$, then $H_k(K(A, 1)) \in \mathscr{C}$ for every $k > 0$.

Example 9.1. The family consist of just the zero group is a Serre class.

Example 9.2. The class of finitely generated abelian groups is a Serre class.

Example 9.3. The class of finite abelian groups is a Serre class.

Example 9.4. The class of torsion abelian groups is a Serre class.

Example 9.5. The class of abelian P-groups, where P is a family of primes.

We now give our first example of a deep Serre result. Here we only need to use the first two Axioms.

Theorem 9.1. Let $\pi : E \to X$ be a fiberation with fiber F, X is simply-connected. Then if the homology groups of any two of E, X, F, in positive dimensions, belong to $\mathscr{C}$, so do the homology groups, in positive dimensions, of the third.

Proof. Let's prove case by case:

1. Suppose the homology groups, in positive dimensions, of X and F belong to $\mathscr{C}$, then by Axiom (I), (II) and universal coefficient theorem one has
$$E_2^{p,q} \in \mathscr{C}$$
where $(p,q) \neq (0,0)$. Then Axiom (I) and finite convegence implies that
$$E_\infty^{p,q} \in \mathscr{C}$$
Now consider the following filtration of $H_n(E)$
$$H_n(E) = F_0 \cap H_n(E) \supset \cdots \supset F_n \cap H_n(E) \supset 0$$
It's clear $0 \in \mathscr{C}$, and $F_p \cap H_n(E)/F_{p+1} \cap H_n(E) = E_\infty^{p,n-p}$, by induction one can show $H_n(E) \in \mathscr{C}$.
2. Suppose the homology groups, in positive dimensions, of E and F belong to $\mathscr{C}$, and prove that those of X also belong to $\mathscr{C}$. If not, let m be the lowest dimension such that $H_m(X) \notin \mathscr{C}$, then $m \geq 2$, since X is simply-connected. As before $E_\infty^{p,q} \in \mathscr{C}, (p,q) \neq (0,0), p < m$. Thus by Axiom (I), one has
$$E_r^{p,q} \in \mathscr{C}, \quad (p,q) \neq (0,0), p < m$$
where $r \geq 2$. On the other hand, $E_2^{m,0} = H_m(X) \notin \mathscr{C}$. Now consider
$$\mathrm{d}_2 : E_2^{m,0} \to E_2^{m-2,1}$$
Then
   (*a*) $E_3^{m,0} = \ker \mathrm{d}_2$, since there is maps mapping into $E_2^{m,0}$.
   (*b*) $\operatorname{im} \mathrm{d}_2$ is a subgroup of $E_2^{m-2,1}$, which implies $\operatorname{im} \mathrm{d}_2 \in \mathscr{C}$ by Axiom (I). Again by Axiom (I), one has $E_3^{m,0} \notin \mathscr{C}$.

   Now consider
$$\mathrm{d}_3 : E_3^{m,0} \to E_3^{m-3,2}$$
The same argument shows $E_4^{m,0} \notin \mathscr{C}$. Repeat this process one has $E_\infty^{m,0} \notin \mathscr{C}$, a contradiction to $H_m(E) \in \mathscr{C}$.
3. The proof for the remaining case is the same as above. Readers are advised to refer to [Hil04] for a more detail proof.

□

We now exploit above Theorem 9.1 to prove a fundamental result about simply-connected spaces.

Theorem 9.2. Let X be a simply-connected space and $\mathscr{C}$ a Serre class of abelian groups. Then the homology groups $H_k(X) \in \mathscr{C}$ for $k \geq 1$ if and only if the homotopy groups $\pi_k(X) \in \mathscr{C}$ for $k \geq 1$.

Firstly we prove a lemma which makes essential use of Axiom (III) of Serre class.

Lemma 9.1. If $A \in \mathscr{C}$, where $\mathscr{C}$ is a Serre class, then $H_k(K(A,n)) \in \mathscr{C}$ for $n, k \geq 1$.

Proof. By Axiom (III) one has $H_k(K(A,1)) \in \mathscr{C}$, and by Theorem 9.1 and fiberation

$$\begin{tikzcd} K(A,n-1) \arrow[r] & PK(A,n) \arrow[d] \\ & K(A,n) \end{tikzcd}$$

one can conclude $H_k(K(A,n)) \in \mathscr{C}, n, k \geq 1$. $\square$

Proof of Theorem 9.2. Here we only prove if homology groups $H_k(X) \in \mathscr{C}$ for $k \geq 1$, then homotopy groups $\pi_k(X) \in \mathscr{C}$ for $k \geq 1$. Consider the Whitehead tower of X, and it begins from X_2, since X is simply-connected, that is

$$\begin{tikzcd} K(\pi_2,1) \arrow[r] & X_2 \arrow[d] \\ & X \end{tikzcd}$$

Hurewicz theorem implies $\pi_2 = H_2(X)$, thus homology groups of $K(\pi_2,1)$ in positive dimensions in $\mathscr{C}$, then those of X_2 are also in $\mathscr{C}$ by Theorem 9.1. However X_2 is 2-connected, and $\pi_3(X_2) = \pi_3$, then Hurewicz theorem implies $\pi_3 \in \mathscr{C}$. Now consider

$$\begin{tikzcd} K(\pi_3,2) \arrow[r] & X_3 \arrow[d] \\ & X_2 \end{tikzcd}$$

The same argument shows homology groups of X_3 in positive dimensions in $\mathscr{C}$, and thus $\pi_4 \in \mathscr{C}$. By induction one can show all $\pi_k \in \mathscr{C}, k \geq 1$. $\square$

Corollary 9.1 (Serre)**.** All homotopy groups of S^n are finitely generated.

9.3. **Serre's torsion theorem.**

Theorem 9.3 (Serre)**.** The homotopy groups of an odd sphere are torsion except in dimension n; thoes of an even sphere are torsion except in dimensions n and $2n-1$.

Proof. The essential facts to be used in the proof are the followings:

(a) In the Whitehead tower of any space X, $\pi_{q+1}(X) = \pi_{q+1}(X_q) = H_{q+1}(X_q)$, thus
$$\pi_{q+1}(X) \otimes \mathbb{Q} = H_{q+1}(X_q; \mathbb{Q})$$

(*b*) The rational cohomology ring of $K(\pi, n)$ is trivial for a torsion finitely generated abelian group π, and is free on one generator of dimension n for $\pi = \mathbb{Z}$.

Since S^n is $(n-1)$-connected and $\pi_n(S^n) = \mathbb{Z}$, then Whitehead tower begins with

$$\begin{tikzcd} K(\mathbb{Z}, n-1) \arrow[r] & X_n \arrow[d] \\ & S^n \end{tikzcd}$$

For convenience we use π_q to denote $\pi_q(S^n)$.

1. If n is odd, and we assume $n \geq 3$. The rational cohomology of $K(\mathbb{Z}, n-1)$ is a polynomial algebra on one generator of dimension $n-1$ and the E_2-page of above fiberation is

$$\begin{tikzcd} 2(n-1) & \mathbb{Q} \arrow[dr] & \mathbb{Q} \\ n-1 & \mathbb{Q} \arrow[dr] & \mathbb{Q} \\ & \mathbb{Q} & \mathbb{Q} \\ & & n \end{tikzcd}$$

   The bottom arrow is an isomorphism since $H_{n-1}(X_n; \mathbb{Q}) = 0$, which implies $H^{n-1}(X_n; \mathbb{Q}) = 0$; the other arrows are all isomorphisms by the product structure. From this we can see X_n has trivial rational cohomology, hence trivial rational homology. By (*a*) one can conclude π_{n+1} is torsion. Now consider

$$\begin{tikzcd} K(\pi_{n+1}, n) \arrow[r] & X_{n+1} \arrow[d] \\ & X_n \end{tikzcd}$$

   Since both X_n and $K(\pi_{n+1}, n)$ have trivial rational cohomology, so does X_{n+1}, thus X_{n+1} has trivial rational homology, and by the same reason one has π_{n+2} is torsion. By induction one has $q \geq n+1$, π_q is torsion.
2. If n is even, then rational cohomology of $K(\mathbb{Z}, n-1)$ is an exterior algebra and the E_2-page of homology spectral sequence is

$$\begin{tikzcd}
n-1 & \mathbb{Q} & \mathbb{Q} \\
& \mathbb{Q} & \mathbb{Q} \arrow[ul] \\
& & n
\end{tikzcd}$$

The arrow shown is an isomorphism, since X_n is n-connected, so

$$H_k(X_n;\mathbb{Q}) = \begin{cases} \mathbb{Q}, & k = 0, 2n-1 \\ 0, & \text{otherwise} \end{cases}$$

I Suppose $n > 2$, then $n+1 < 2n-1$. By (a), one has $\pi_{n+1} = H_{n+1}(X_n)$ is torsion since $H_{n+1}(X_n;\mathbb{Q}) = 0$. Thus $H_*(K(\pi_{n+1}, n);\mathbb{Q})$ is trivial, from the following fiberation

$$\begin{tikzcd}
K(\pi_{n+1}, n) \arrow[r] & X_{n+1} \arrow[d] \\
& X_n
\end{tikzcd}$$

one can conclude X_{n+1} has the same rational homology as X_n, which implies π_{n+2} is also torsion. This argument still holds, untill X_{2n-2} has the same rational homology as X_{2n-3}(which relys on π_{2n-2} is torsion). Thus $H_{2n-1}(X_{2n-2};\mathbb{Q}) = H_{2n-1}(X_n;\mathbb{Q}) = \mathbb{Q}$, which implies π_{2n-1} is not torsion[6].

II Now suppose $n \geq 2$, by (b) one has the rational cohomology ring $H^*(K(\pi_{2n-1}, 2n-2);\mathbb{Q})$ is a polynomial algebra on one generator, so the E_2-page of fiberation $K(\pi_{2n-1}, 2n-2) \to X_{2n-1} \to X_{2n-2}$ is

$$\begin{tikzcd}
4n-4 & \mathbb{Q} & \mathbb{Q} \\
2n-2 & \mathbb{Q} & \mathbb{Q} \arrow[ul] \\
& \mathbb{Q} & \mathbb{Q} \arrow[ul] \\
& & 2n-1
\end{tikzcd}$$

Since $H_{2n-1}(X_{2n-1}) = 0$, then arrow shown must all be isomorphisms. It follows the rational cohomology of X_q are trivial except 0 dimension for all $q \geq 2n-1$. In particular, one has

$$\pi_{q+1} \otimes \mathbb{Q} \cong H_{q+1}(X_q;\mathbb{Q}) = 0$$

which implies π_q is torsion for $q > 2n-1$.

$\square$

[6]In fact, π_{2n-1} has one infinite cyclic generator and possibly some torsion generators.

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