

# Stable Homotopy Groups of Spheres [DRAFT]

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# 1 Introduction

- Define homotopy groups
- Freudenthal's suspension theorem: if  $\pi_i(X) = 0$  for  $i \leq k$  (i.e.  $X$  is  $k$ -connected) then the map

$$\begin{aligned} \pi_n(X) &\rightarrow \pi_{n+1}(\Sigma X) \\ [\gamma : S^n \rightarrow X] &\mapsto [\Sigma \gamma : \Sigma S^n = S^{n+1} \rightarrow \Sigma X] \end{aligned}$$

is an isomorphism for  $n \leq 2k$  and surjective for  $n = 2k + 1$

- This implies  $\pi_{n+k}(S^n)$  depends only on  $k$  for  $n \geq k + 2$
- (Obviously be careful with basepoints above)
- Suppose  $X$  is  $k$ -connected. Then, for  $k \geq 0$ ,  $0 = \pi_k(X) \cong \pi_{k+1}(\Sigma X)$ , so whenever a space is  $k$ -connected its suspension is  $k + 1$ -connected.
- As you take suspensions, then, your successive bounds are  $n \leq 2k$ ,  $n + 1 \leq 2k + 2 \implies n \leq 2k + 1$ ,  $n \leq 2k + 2$ , etc ... so the sequence  $\pi_n(X) \rightarrow \pi_{n+1}(\Sigma X) \rightarrow \dots$  will eventually stabilise.
- Thus, if you take the colimit of that direct system, it'll just equal the stable value, with the higher legs just being the inverse isomorphisms.
- [10], Cor 1.9 [not 100% convinced of how this follows, but believing it for now]: if  $X$  is a CW complex of dimension  $d$  and  $Y$  a  $(k - 1)$ -connected space, then the suspension homomorphism  $[X, Y] \rightarrow [\Sigma X, \Sigma Y]$  is bijective if  $d < 2k - 1$  and surjective if  $d = 2k - 1$ .

Miscellaneous facts I might need later:

- Cohomology [possibly only of pointed<sup>1</sup> CW complexes] is representable, and its representing object is the Eilenberg-MacLane space. i.e.  $H^n(-; G) \cong \text{Hom}(-, K(G, n))$ .
- $\mathcal{A}_2$  is generated as an algebra by elements  $Sq^{2^k}$  ([5], Prop 4L.8).
- The map  $\mathcal{A}_2 \rightarrow \tilde{H}^*(K(\mathbb{Z}/2\mathbb{Z}, n); \mathbb{Z}/2\mathbb{Z})$ ,  $Sq^I \mapsto Sq^I(\iota_n)$  is an isomorphism from the degree  $d$  part of  $\mathcal{A}_2$  onto  $H^{n+d}(K(\mathbb{Z}/2\mathbb{Z}, n); \mathbb{Z}/2\mathbb{Z})$  for  $d \geq n$ . In particular, the admissible monomials  $Sq^I$  form an additive basis for  $\mathcal{A}_2$ . Thus,  $\mathcal{A}_2$  is exactly the algebra of all  $\mathbb{Z}/2\mathbb{Z}$  cohomology operations that are stable, commuting with suspension ([6], Cor 5.38).
- “Stable homotopy groups are a homology theory” (whatever that means)
- Hurewicz theorem: for any path-connected space  $X$  and  $n > 0$  there exists a group homomorphism  $h_* : \pi_n(X) \rightarrow H_n(X)$ . For  $n = 1$  this induces an isomorphism  $\pi_1^{\text{ab}}(X) \cong H_1(X)$ . For  $n \geq 2$ , if  $X$  is  $(n - 1)$ -connected then  $\tilde{H}_i(X) = 0$  for all  $i < n$ , and the map  $h_* : \pi_n(X) \rightarrow H_n(X)$  is an isomorphism.

[10], [4], [5]

## 2 The Steenrod algebra

The following is from [5] 4L.

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<sup>1</sup>What's the relevance of the ‘pointedness’ when you're only taking cohomology?? See C.

- There are maps  $Sq^i : H^n(-; \mathbb{Z}/2\mathbb{Z}) \rightarrow H^{n+i}(-; \mathbb{Z}/2\mathbb{Z})$  for each  $i$ , and they satisfy the following properties:
  1.  $Sq_X^i(f^*(\alpha)) = f^*(Sq_Y^i(\alpha))$  for  $f : X \rightarrow Y$  (i.e.  $Sq^i$  is a natural transformation).
  2.  $Sq_X^i(\alpha + \beta) = Sq_X^i(\alpha) + Sq_X^i(\beta)$  (i.e.  $Sq_X^i$  respects the group operation for all  $X$ ).
  3.  $Sq^i(\alpha \smile \beta) = \sum_{0 \leq j \leq i} (Sq^j(\alpha) \smile Sq^{i-j}(\beta))$  (the Cartan formula)
  4.  $Sq^i(\sigma(\alpha)) = \sigma(Sq^i(\alpha))$  where  $\sigma : H^n(X; \mathbb{Z}/2\mathbb{Z}) \rightarrow H^{n+1}(\Sigma X; \mathbb{Z}/2\mathbb{Z})$  is the “suspension isomorphism given by reduced cross product with a generator of  $H^1(S^1; \mathbb{Z}/2\mathbb{Z})$ ”. [see: [5], p219. N.B: I think this “relative cross product” theory is required – you can argue that there is an isomorphism via MV, but this point says that it’s this specific one. Maybe they’re the same, but Hatcher doesn’t say that anywhere and there could be many isomorphisms.]
  5.  $Sq^i(\alpha) = \alpha^2$  if  $i = \deg(\alpha)$  and  $Sq^i(\alpha) = 0$  if  $i > \deg(\alpha)$ .
  6.  $Sq^0 = \text{id}$ .
  7.  $Sq^1$  is the “ $\mathbb{Z}/2\mathbb{Z}$  Bockstein homomorphism  $\beta$  associated with the coefficient sequence  $0 \rightarrow \mathbb{Z}/2\mathbb{Z} \rightarrow \mathbb{Z}/4\mathbb{Z} \rightarrow \mathbb{Z}/2\mathbb{Z} \rightarrow 0$ ”.
- Define  $Sq := Sq^0 + Sq^1 + \dots$ . Then  $Sq(\alpha \smile \beta) = Sq(\alpha) \smile Sq(\beta)$  (since  $(Sq(\alpha \smile \beta))_n = \sum_i Sq^i(\alpha) \smile Sq^{n-i}(\beta) = (Sq(\alpha) \smile Sq(\beta))_n$ ). Thus,  $Sq$  is a ring homomorphism.
- Adem relations:

$$Sq^a Sq^b = \sum_j \binom{b-j-1}{a-2j} Sq^{a+b-j} Sq^j \quad \text{if } a < 2b,$$

where  $\binom{m}{n}$  is zero if  $m$  or  $n$  is negative, or  $m < n$ , and  $\binom{m}{0} = 1$  for  $m \geq 0$ .

- The Steenrod algebra  $\mathcal{A}_2$  is the algebra over  $\mathbb{Z}/2\mathbb{Z}$  that is the quotient of the algebra of polynomials in the noncommuting variables  $Sq^1, Sq^2, \dots$  by the two-sided ideal generated by the Adem relations. Thus, for every space  $X$ ,  $H^*(X; \mathbb{Z}/2\mathbb{Z})$  is a module over  $\mathcal{A}_2$ .
- $\mathcal{A}_2$  is graded, and its elements of degree  $k$  are those that map  $H^n(X; \mathbb{Z}/2\mathbb{Z})$  to  $H^{n+k}(X, \mathbb{Z}/2\mathbb{Z})$  for all  $n$ . [Presumably you’ve fixed a space  $X$  while you’re doing all this?]

[1], [9], [10], [7], [5], [2]

## 3 Spectra may not be your friends, but I can introduce you

### 3.1 Categorical nonsense

- [10]: There is a category  $\mathcal{H}$  of finite [because the corollary wanted f.d. CW complexes] based CW complexes, with  $\text{Hom}(X, Y) =: [X, Y]$  the set of homotopy classes of base-point preserving maps  $X \rightarrow Y$ .
- There is a category  $\mathbf{St}(\mathcal{H})$  of finite[?] based CW complexes, with  $\text{Hom}(X, Y) =: \{X, Y\}$  the set  $\text{colim}_i [\Sigma^i X, \Sigma^i Y]$  [it’s just a colimit of sets, and  $\mathbf{Set}$  is cocomplete, so we should be fine. [10] says it’s a group?] [Also, how do these guys compose?]

- There is a functor  $\mathcal{H} \rightarrow \mathbf{St}(\mathcal{H})$ . [10] doesn't say what this is but it's presumably the one that is the identity on objects and sends  $[f : X \rightarrow Y] \in [\Sigma^0 X, \Sigma^0 Y]$  to whatever it gets sent to in  $\{X, Y\}$  using the universal property of the colimit. Uniqueness makes it functorial, etc.
- We have a fully faithful functor  $\mathbf{St}(\mathcal{H}) \rightarrow \mathbf{St}(\mathcal{H})$  given by the suspension on objects, and the unique isomorphism  $\{X, Y\} \rightarrow \{\Sigma X, \Sigma Y\}$  on maps (such an isomorphism exists, since both of those things are colimits for  $[\Sigma^i X, \Sigma^i Y]$  - one of the sequences is cut off at the beginning, but it doesn't matter because both reach the stable value (see above discussion and [10] 1.9), aka the colimit).
- It's not an equivalence, because not every object is isomorphic to a suspension (e.g. anything not connected, since suspensions always connected [?])
- We can formally adjoin desuspensions  $\Sigma^{-n} X$  for all  $n$  [does this mean just putting the objects there and defining  $\text{Hom}(Y, \Sigma^{-n} X) := \text{Hom}(\Sigma^n Y, X)$  and  $\text{Hom}(\Sigma^{-n} X, Y) := \text{Hom}(X, \Sigma^n Y)$ ?], but this category does not have weak colimits (i.e. colimits w/o uniqueness property). [why does it not, and why do we even want that?]
- We instead consider formal sequences of desuspensions  $X_0 \rightarrow \Sigma^{-1} X_1 \rightarrow \dots$ , or sequences  $(X_n)$  and maps  $\Sigma X_n \rightarrow X_{n+1}$ , i.e. spectra. [and this fixes the problem?]

## 3.2 Definitions and examples

Below follows [6], Section 5.2.

[Maybe I could also look at [5] p454 onwards?]

DEFINITION 3.2.1. A *spectrum* is a collection of pointed topological spaces  $\{X_n\}_{n \in \mathbb{N}}$ , together with basepoint-preserving maps  $\sigma_n : \Sigma X_n \rightarrow X_{n+1}$ .

EXAMPLE 3.2.2. Let  $X$  be a topological space. The *suspension spectrum* of  $X$ , denoted by  $\Sigma^\infty X$ , has  $X_n = \Sigma^n X$  and  $\sigma_n = \text{id} : \Sigma X_n \rightarrow X_{n+1}$ .

We write  $\mathbb{S} := \Sigma^\infty S^0$ , and call  $\mathbb{S}$  the *sphere spectrum*.

EXAMPLE 3.2.3. The *Eilenberg-MacLane spectrum* has  $X_n$  a CW complex  $K(G, n)$  and  $\sigma_n : \Sigma K(G, n) \rightarrow K(G, n+1)$  is the adjoint of the CW approximation  $K(G, n) \rightarrow \Omega K(G, n+1)$ .

[N.B. the important point of the above is not that it's 'an' EM space rather than 'the' (they're all homotopy equivalent). It's that a) we can definitely construct one that's a CW complex, and b) even though  $\Omega(\text{a CW complex})$  is not necessarily a CW complex, we can make it one via CW approximation.]

DEFINITION 3.2.4. Let  $X = \{X_n\}$  be a spectrum. We define  $\pi_i(X) = \text{colim}_n \pi_{i+n}(X_n)$ , where the map  $\pi_{i+n}(X_n) \rightarrow \pi_{i+n+1}(X_{n+1})$  is given by the composition

$$\pi_{i+n}(X_n) \xrightarrow{\Sigma} \pi_{i+n+1}(\Sigma X_n) \xrightarrow{(\sigma_n)_*} \pi_{i+n+1}(X_{n+1}).$$

EXAMPLE 3.2.5. If  $X$  is a topological space, then  $\pi_i(\Sigma^\infty X) = \pi_i^S(X)$ , the  $i$ th stable homotopy group of  $X$ .

DEFINITION 3.2.6. A CW spectrum is a spectrum  $X$  consisting of CW complexes  $X_n$  with the maps  $\Sigma X_n \hookrightarrow X_{n+1}$  inclusions of subcomplexes.

[Define cells and dimension of a CW spectrum]

[Insert brief but enlightening observation of the effect of suspension on cells of CW complexes here]

DEFINITION 3.2.7. A spectrum  $X$  is *connective* if its cells have dimensions which are bounded below.

[The above is phrased exactly as in hatcher - presumably he means that there is some absolute bound below which no cell has dimension, rather than a bound dependent on each cell?]

DEFINITION 3.2.8. A CW spectrum is *finite* if it has only finitely many cells, and *of finite type* if it has only finitely many cells in each dimension.

DEFINITION 3.2.9. Let  $X = \{X_n\}$  be a CW spectrum. A *subspectrum* of  $X$  is a sequence of subcomplexes  $\{X'_n \subseteq X_n\}$  satisfying  $\Sigma X'_n \subseteq X'_{n+1}$

DEFINITION 3.2.10. Let  $X = \{X_n\}$  be a CW spectrum, and  $X' = \{X'_n\}$  a subspectrum of  $X$ . Then  $x'$  is *cofinal* if, for each  $n$  and each cell  $e_\alpha^i$  of  $X_n$ , the cell  $\Sigma^k e_\alpha^i$  belongs to  $X'_{n+k}$  for all sufficiently large  $k$ .

### 3.3 Homology and cohomology

[From Hatcher: “the inclusions  $\Sigma X_n \hookrightarrow X_{n+1}$  induce inclusions  $C_*(X_n; G) \hookrightarrow C_*(X_{n+1}; G)$  with a dimension shift to account for the suspension”. Below is my vague explanation of what I understand this to mean.

$C_i(X_n; G)$  is the free abelian group on maps  $\Delta^i \rightarrow X_n$ . I claim  $\Sigma \Delta^i \cong \Delta^{i+1}$ . If this is true, it gives a map

$$\begin{aligned} C_i(X_n; G) &\rightarrow C_{i+1}(\Sigma X_n; G) \\ f &\mapsto \Sigma f. \end{aligned}$$

I claim this is an injection. If this is true, we also have an injection  $C_{i+1}(\Sigma X_n; G) \rightarrow C_{i+1}(X_{n+1}; G)$  induced by the structure map  $\sigma_n$ , so we get an injection  $C_i(X_n; G) \hookrightarrow C_{i+1}(X_{n+1}; G)$ , which indeed has a dimension shift.

Some issues:

- Everything I’ve done above is unreduced and unpointed
- The way it’s phrased, it seems to be that this is a morphism of chain complexes - i.e. these maps commute with the  $\partial$ s. Why would they?

]

[1], [9], [10], [7], [2], [6]

## 4 The Adams spectral sequence

### 4.1 Spectral sequences

Some notes from [10] (or maybe not)

How about some notes from [8], C2:

DEFINITION 4.1.1. A *differential bigraded module*  $E$  over a ring  $R$  is a collection of  $R$ -modules  $\{E^{p,q}\}$ ,  $p, q \in \mathbb{Z}$ , together with a map  $d : E^{p,q} \rightarrow E^{p+s, q-s+1}$  for each  $p, q$  and some fixed  $s \in \mathbb{Z}$ , satisfying  $d^2 = 0$ .

We can take the homology of  $(E, d)$ :

$$H^{p,q}(E^{*,*}, d) = \ker(d : E^{p,q} \rightarrow E^{p+s,q-s+1}) / \operatorname{im}(d : E^{p-s,q+s-1} \rightarrow E^{p,q}).$$

DEFINITION 4.1.2. A *spectral sequence* (of *cohomological type*) is a collection of differential bigraded  $R$ -modules  $\{E_r^{*,*}, d_r\}, r \in \mathbb{N}$ , with the differentials  $d_r$  of bidegree  $(r, 1 - r)$ . These satisfy the further condition that for all  $p, q, r$ ,  $E_{r+1}^{p,q} \cong H^{p,q}(E_r^{*,*}, d_r)$ .

We will sometimes write  $d_r^{p,q}$  for the differential  $d_r : E^{p,q} \rightarrow E^{p+r,q-s+1}$ .

Consider the term  $E_2^{*,*}$ . Define

$$Z_2^{p,q} := \ker d_2^{p,q} \quad \text{and} \quad B_2^{p,q} := \operatorname{im} d_2^{p-2,q+1}.$$

The condition  $d^2 = 0$  implies that  $B_2^{p,q} \subseteq Z_2^{p,q} \subseteq E_2^{p,q}$ , and by definition we have  $E_3^{p,q} \cong \overline{B}_3^{p,q} / B_2^{p,q}$ .

Now, write

$$Z_3^{p,q} := \ker d_3^{p,q} \quad \text{and} \quad B_3^{p,q} := \operatorname{im} d_3^{p-3,q+2}.$$

Since  $Z_3^{p,q} \subseteq E_3^{p,q}$ , it can be written as  $\overline{Z}_3^{p,q} / B_2^{p,q}$  for some  $\overline{Z}_3^{p,q} \subseteq Z_2^{p,q}$ . Similarly,  $B_3^{p,q} \cong \overline{B}_3^{p,q} / B_2^{p,q}$  for some  $\overline{B}_3^{p,q} \subseteq Z_2^{p,q}$ . Thus,

$$E_4^{p,q} \cong Z_3^{p,q} / B_3^{p,q} \cong \frac{\overline{Z}_3^{p,q} / B_2^{p,q}}{\overline{B}_3^{p,q} / B_2^{p,q}} \cong \overline{Z}_3^{p,q} / \overline{B}_3^{p,q}.$$

Iterating this process, we present the spectral sequence as an infinite tower of submodules of  $E_2^{p,q}$ :

$$B_2^{p,q} \subseteq \overline{B}_3^{p,q} \subseteq \cdots \subseteq \overline{B}_n^{p,q} \subseteq \cdots \subseteq \overline{Z}_n^{p,q} \subseteq \cdots \subseteq \overline{Z}_3^{p,q} \subseteq Z_2^{p,q} \subseteq E_2^{p,q},$$

with the property that  $E_{n+1}^{p,q} \cong \overline{Z}_n^{p,q} / \overline{B}_n^{p,q}$ . The differential  $d_{n+1}^{p,q}$  can be taken as a map  $\overline{Z}_n^{p,q} / \overline{B}_n^{p,q} \rightarrow \overline{Z}_n^{p,q} / \overline{B}_n^{p,q}$  with kernel  $\overline{Z}_{n+1}^{p,q} / \overline{B}_n^{p,q}$  and image  $\overline{B}_{n+1}^{p,q}$ . The short exact sequence induced by  $d_{n+1}$ ,

$$0 \rightarrow \overline{Z}_{n+1}^{p,q} / \overline{B}_n^{p,q} \rightarrow \overline{Z}_n^{p,q} / \overline{B}_n^{p,q} \xrightarrow{d_{n+1}^{p,q}} \overline{B}_{n+1}^{p,q} / \overline{B}_n^{p,q} \rightarrow 0,$$

gives rise to isomorphisms  $\overline{Z}_n^{p,q} / \overline{Z}_{n+1}^{p,q} \cong \overline{B}_{n+1}^{p,q} / \overline{B}_n^{p,q}$  for all  $n$ . Conversely, a tower of submodules of  $E_2$ , together with a set of isomorphisms, gives rise to a spectral sequence.

DEFINITION 4.1.3. An element of  $E_2^{p,q}$  *survives to the  $r$ th stage* if lies in  $\overline{Z}_r^{p,q}$ , having been in the kernel of the previous  $r - 2$  differentials, and is *bounded by the  $r$ th stage* if it lies in  $\overline{B}_r^{p,q}$ . The bigraded module  $E_r^{*,*}$  is called the  $E_r$ -*term* of the spectral sequence.

We define

$$Z_\infty^{p,q} := \bigcap_n \overline{Z}_n^{p,q}, \quad B_\infty^{p,q} := \bigcup_n \overline{B}_n^{p,q}.$$

From the tower of inclusions, we see that  $B_\infty^{p,q} \subseteq Z_\infty^{p,q}$ , so we define  $E_\infty^{p,q} := Z_\infty^{p,q} / B_\infty^{p,q}$ .

DEFINITION 4.1.4. A spectral sequence *collapses at the  $N$ th term* if the differentials  $d_r^{p,q} = 0$  for  $r \geq N$ .

From the short exact sequence

$$0 \rightarrow \overline{Z}_r^{p,q} / \overline{B}_{r-1}^{p,q} \rightarrow \overline{Z}_{r-1}^{p,q} / \overline{B}_{r-1}^{p,q} \xrightarrow{d_r^{p,q}} \overline{B}_r^{p,q} / \overline{B}_{r-1}^{p,q} \rightarrow 0,$$

the condition  $d_r^{p,q} = 0$  forces  $\overline{Z}_r^{p,q} = \overline{Z}_{r-1}^{p,q}$  and  $\overline{B}_r^{p,q} = \overline{B}_{r-1}^{p,q}$ . The tower of submodules becomes

$$B_2^{p,q} \subseteq \overline{B}_3^{p,q} \subseteq \cdots \subseteq \overline{B}_{N-1}^{p,q} = B_N^{p,q} = \cdots = B_\infty^{p,q} \subseteq Z_\infty^{p,q} = \cdots = \overline{Z}_N^{p,q} = \overline{Z}_{N-1}^{p,q} \subseteq \cdots \subseteq \overline{Z}_3^{p,q} \subseteq Z_2^{p,q} \subseteq E_2^{p,q}.$$

Thus,  $E_\infty^{p,q} = E_N^{p,q}$ .

## 4.2 Exact couples

(Following [8], C2)

DEFINITION 4.2.1. Let  $D, E$  be  $R$ -modules, and let  $i : D \rightarrow D$ ,  $j : D \rightarrow E$ ,  $k : E \rightarrow D$  be module homomorphisms. We call  $\mathcal{C} = \{D, E, i, j, k\}$  an *exact couple* if the diagram below is exact.

$$\begin{array}{ccc} D & \xrightarrow{i} & D \\ & \nwarrow k \quad \nearrow j & \\ & E & \end{array}$$

Let  $d := jk$ , and define the following:

$$\begin{aligned} E' &:= H(E, d) = \ker d / \operatorname{im} d \\ D' &:= i(D) = \ker j \\ i' &:= i|_{i(D)} : D' \rightarrow D' \\ j' &:= i(x) \mapsto j(x) + dE : D' \rightarrow E' \\ k' &:= (e + dE) \mapsto k(e) : E' \rightarrow D' \end{aligned}$$

We call  $\mathcal{C}' = \{D', E', i', j', k'\}$  the *derived couple* of  $\mathcal{C}$ .

PROPOSITION 4.2.2 ([8], Prop 2.7). If  $\mathcal{C} = \{D, E, i, j, k\}$  is an exact couple, then  $\mathcal{C}'$  is also an exact couple.

THEOREM 4.2.3 ([8], Thm 2.8). Suppose  $D^{*,*} = \{D^{p,q}\}$  and  $E^{*,*} = \{E^{p,q}\}$  are bigraded modules equipped with homomorphisms  $i$  of bidegree  $(-1, 1)$ ,  $j$  of bidegree  $(0, 0)$ , and  $k$  of bidegree  $(1, 0)$ , such that  $\{D^{*,*}, E^{*,*}, i, j, k\}$  is an exact couple. Then these data determine a spectral sequence  $\{E_r, d_r\}$  for  $r \in \mathbb{Z}_+$  of cohomological type, with  $E_r = (E^{*,*})^{(r-1)}$ , the  $(r-1)$ st derived module of  $E^{*,*}$  and  $d_r = j^{(r)} \circ k^{(r)}$ .

A bigraded exact couple may be displayed in the following diagram, known as a *staircase diagram*:

$$\begin{array}{ccccccc} & & \vdots & & \vdots & & \\ & & \downarrow i & & \downarrow i & & \\ \dots & \xrightarrow{k} & D^{p+2,q-1} & \xrightarrow{j} & E^{p+2,q-1} & \xrightarrow{k} & D^{p+3,q-1} \xrightarrow{j} \dots \\ & & \downarrow i & & \downarrow i & & \\ \dots & \xrightarrow{k} & D^{p+1,q} & \xrightarrow{j} & E^{p+1,q} & \xrightarrow{k} & D^{p+2,q} \xrightarrow{j} \dots \\ & & \downarrow i & & \downarrow i & & \\ \dots & \xrightarrow{k} & D^{p,q+1} & \xrightarrow{j} & E^{p,q+1} & \xrightarrow{k} & D^{p+1,q+1} \xrightarrow{j} \dots \\ & & \downarrow i & & \downarrow i & & \\ & & \vdots & & \vdots & & \end{array}$$

## 4.3 The Adams spectral sequence

Things I need before I can set it up (according to Hatcher [6]):

Let  $X$  be a CW spectrum of finite type.

- Def:  $H^*(X)$ .
- Def: A wedge of spectra.
- Fact:  $H^*(X)$  is finitely generated.
- Fact:  $H^*(X)$  is an  $\mathcal{A}$ -module. [We know that's true for a topological space]
- Fact: We can pick generators  $\alpha_i$  for  $H^*(X)$  as an  $\mathcal{A}$ -module such that there are at most finitely many in each  $H^n(X)$ .
- Fact: There  $\alpha_i$  determine a map  $X \rightarrow K_0$ , where  $K_0$  is a wedge of EM spectra, and  $K_0$  has finite type.
- Fact: We can replace that map with an inclusion.
- Def: A quotient of (connective) spectra.
- Fact: A quotient of connective spectra of finite type is again a connective spectrum of finite type.
- Prop: [6], 5.46.
- Def: The functor  $\pi_t^Y(Z) = [\Sigma^t Y, Z]$  for a finite spectrum  $Y$ .
- Def: A cofibration. [see : [5], p398.]
- Fact: If  $Y$  is a finite spectrum and  $Z$  is a connective spectrum of finite type, then  $\pi_t^Y(Z)$  is finitely generated.
- Fact: I can do this. I have all the necessary skills to pull this off.
- Fact: I'm going to stop listing things I need to do and start actually doing them.

[8], [1], [9], [2], [6], [10], [3]

## 5 Calculating stable homotopy groups

$\text{Ext}_A^s(\mathbb{F}_2, \mathbb{F}_2)_t$

[1], [9], [10]

## 6 Methods of resolving ambiguities

[1], [9]

## A Algebra

### A.1 Free resolutions

DEFINITION 1.1.1. Let  $M, N$  be modules over a ring  $R$ . A *resolution*  $F$  of  $M$  is an exact sequence

$$\cdots \rightarrow F_2 \rightarrow F_1 \rightarrow F_0 \rightarrow M \rightarrow 0.$$

If in addition each  $F_i$  is a free  $R$ -module, then the resolution is called *free*.



Given a free resolution as above, applying  $\text{Hom}_R(-, N)$  gives us a chain complex

$$\cdots \leftarrow \text{Hom}_R(F_2, N) \leftarrow \text{Hom}_R(F_1, N) \leftarrow \text{Hom}_R(F_0, N) \leftarrow \text{Hom}_R(M, N) \leftarrow 0.$$

Dropping the term  $\text{Hom}_R(M, N)$  [why?] we get the sequence

$$\cdots \leftarrow \text{Hom}_R(F_2, N) \leftarrow \text{Hom}_R(F_1, N) \leftarrow \text{Hom}_R(F_0, N) \leftarrow 0,$$

and we define  $\text{Ext}_R^n(M, N)$  to be the  $n$ th homology group of this chain complex.

[these do not depend on the choice of free resolution of  $M$ ]

## B Topology

All from [5] unless otherwise stated.

### B.1 Suspension

DEFINITION 2.1.1. Let  $X$  be a topological space. The *suspension*  $SX$  is the space  $(X \times I)/\sim$ , where  $(x, 0) \sim (x', 0)$  and  $(x, 1) \sim (x', 1)$  for all  $x, x' \in X$ .

DEFINITION 2.1.2. Let  $X$  be a pointed topological space. The *reduced suspension*  $\Sigma X$  is the space  $SX/\sim$ , where  $[x_0, i] \sim [x_0, i']$  for all  $i, i' \in I$ .

- Loops; the adjunction  $\Sigma \dashv \Omega$ , where  $\Omega$  is the loop functor.

[5], p395:

REMARK 2.1.3. It follows that  $\pi_{n+1}(X) \cong \pi_n(\Omega X)$ . In particular,  $\Omega K(G, n)$  is a  $K(G, n-1)$ .

- [5] 2.1 Ex 20 and 2.2 Ex 32:  $\tilde{H}_n(X) \cong \tilde{H}_{n+1}(SX)$ , where  $S$  is the (non-reduced) suspension. (MV?)
- Hatcher also says on p219 that  $\tilde{H}^n(X; R) \cong \tilde{H}^{n+k}(\Sigma^k X; R)$ , where  $\Sigma$  is reduced suspension.

### B.2 Other basic constructions

DEFINITION 2.2.1. Let  $(X, x_0), (Y, y_0)$  be pointed topological spaces, and consider their product  $X \times Y$ . The subspaces  $X \times \{y_0\} \cong X$  and  $\{x_0\} \times Y \cong Y$  intersect at exactly one point,  $(x_0, y_0)$ , and so can be identified with the wedge  $X \vee Y$ . We thus define the *smash product*  $X \wedge Y := (X \times Y)/(X \vee Y)$ , with the canonical basepoint  $(x_0, y_0)$ .

EXAMPLE 2.2.2. We have  $S^n \wedge S^m \cong S^{n+m}$ . [is this obvious?]

REMARK 2.2.3. Note that  $\Sigma X \cong X \wedge S^1$ .

REMARK 2.2.4. Observe that  $X \wedge (Y \wedge Z) \cong (X \wedge Y) \wedge Z$ . Combining this with the remarks above, we see that  $\Sigma^k X = X \wedge S^k$ .

- ‘Reduced mapping cylinder’?
- Mapping cones?

- The Eilenberg-MacLane space is  $K(G, n)$ , and it has the property that

$$\pi_i(K(G, n)) = \begin{cases} G & i = n, \\ 0 & i \neq n. \end{cases}$$

They're unique up to weak homotopy equivalence (i.e. if you have another one  $X$ , there's a map between them which descends to an isomorphism on homotopy groups)

### B.3 Cell complexes

- The product of cell complexes is a cell complex (maybe only if one of them is finite?)
- The smash product of (pointed?) cell complexes is a cell complex (maybe only if one is finite?) [[5] says “the smash product  $X \wedge Y$  is a cell complex if  $X$  and  $Y$  are cell complexes with  $x_0$  and  $y_0$  0-cells, assuming that we give  $X \times Y$  the cell-complex topology rather than the product topology in cases where these two topologies differ”.]
- Cellular maps
- Quotient of a CW complex by a subcomplex is a CW complex, where the quotient map is cellular
- The reduced suspension of a pointed cell complex is a pointed cell complex.
- CW pairs?
- For a CW complex  $X$ ,  $SX \simeq \Sigma X$ .

DEFINITION 2.3.1. Let  $X$  is a topological space. A *CW approximation* to  $X$  is a CW complex  $Z$  equipped with a weak homotopy equivalence  $f : Z \rightarrow X$ .

THEOREM 2.3.2 ([5], Prop 4.13). Every space  $X$  has a CW approximation  $f : Z \rightarrow X$ .

- In particular,  $\Omega K(G, n)$  has a CW approximation  $Z \rightarrow \Omega K(G, n)$ , and since  $\Omega K(G, n)$  is a  $K(G, n-1)$ , so is  $Z$ .

## C Notes to self

### C.1 Vague problems and Questions

- Is ‘pointed’ (co)homology just reduced (co)homology? I’ve noticed ‘pointed things’ ( $\Sigma, \Omega, \wedge, \dots$ ) seem to happen to/in reduced (co)homology, and ‘unpointed things’ ( $S, \times, \dots$ ) happen to/in normal (co)homology. I want to do pointed things.

### C.2 To do/other notes

- READ IF YOUR CALCULATIONS AREN'T WORKING: You are working modulo 2!!!
- Be consistent with either cell complex or CW complex (eventually)

## References

- [1] J. F. Adams. *Stable Homotopy and Generalised Homology*. TExromancers, 2022.
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- [3] R. R. Bruner. *An Adams Spectral Sequence Primer*. 2009. URL: <http://www.rrb.wayne.edu/papers/adams.pdf> (visited on 08/02/2025).
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- [10] John Rognes. *The Adams Spectral Sequence*. 2012. URL: <https://www.mn.uio.no/math/personer/vit/rognes/papers/notes.050612.pdf> (visited on 08/02/2025).