

# Mathematical Ghostbusters: Despookifying Spectral Sequences

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# 1 Introduction: Differential Modules and Spectral Sequences

## Definition 1.1.

- (a) A differential module is a pair  $(C, \partial)$ , where  $C$  is a module and  $\partial : C \rightarrow C$  is an endomorphism such that  $\partial^2 = 0$ .
- (b) A morphism  $f : (C, \partial) \rightarrow (C', \partial')$  of differential modules is a morphism  $f : C \rightarrow C'$  that commutes with the differentials, i.e. that satisfies  $\partial'f = f\partial$ .

The condition  $\partial^2 = 0$  is equivalent to saying that the submodule  $B := \text{im } \partial$  of coboundaries is contained in the submodule  $Z := \ker \partial$  of cocycles, and we define the cohomology of  $(C, \partial)$  to be

$$HC = \frac{Z}{B} = \frac{\ker \partial}{\text{im } \partial}.$$

Taking cohomology is functorial: a morphism  $f : (C, \partial) \rightarrow (C', \partial')$  of differential modules induces a map

$$Hf : HC \rightarrow HC'.$$

**Remark 1.2.** Sometimes we will use the notation  $B(\partial) \subset Z(\partial)$  and  $H(C, \partial)$  if we want to emphasize  $\partial$ . Having said this, we will often drop the  $\partial$  and call  $C$  itself the differential module, and also drop all notational embellishment (e.g. primes) on  $\partial$ , using  $\partial$  to refer to the differential of any differential module. Similar notational sleights-of-hand will be made without further comment.

**Theorem 1.3.** A short exact sequence of differential modules

$$0 \rightarrow C' \xrightarrow{i} C \xrightarrow{p} C'' \rightarrow 0$$

induces an exact triangle in cohomology, i.e. there is a morphism  $\delta : HC'' \rightarrow HC'$  that makes the triangle

$$\begin{array}{ccc} & HC & \\ Hi \nearrow & & \searrow Hp \\ HC' & \xleftarrow{\delta} & HC'' \end{array}$$

exact.

*Proof.* Given a class  $[c] \in HC''$ , pick a representative  $c \in C''$  of  $[c]$  and a  $b \in C$  with  $p(b) = c$ . Then  $p(\partial b) = \partial p(b) = \partial c = 0$ , so that  $\partial b \in \ker p = \text{im } i$ , and hence there is an  $a \in C'$  such that  $i(a) = \partial b$ . Then  $i(\partial a) = \partial i(a) = \partial^2 b = 0$ , whence  $a$  is a cocycle and hence  $[a] \in HC'$ . The map  $\delta : HC'' \rightarrow HC'$  takes  $[c] \mapsto [a]$ . It is standard to check that this is well-defined irrespective of the choices made above, and makes the above triangle exact. ■

**Remark 1.4.** Of course, the data of a short exact sequence  $0 \rightarrow C' \rightarrow C \rightarrow C'' \rightarrow 0$  amounts to a submodule  $C' \subset C$  and an identification  $C/C' \rightarrow C''$  of the quotient module with  $C''$ . With this perspective, the map  $\delta$  in the above theorem, called the **connecting homomorphism**, is given by the recipe “pick representative in  $C$  and take  $\partial$ ”—this will be very helpful to keep in mind in what follows.

Now we are ready to define spectral sequences.

**Definition 1.5.** A (cohomological) spectral sequence is a sequence  $E = (E_r, \partial_r)_{r \geq 0}$  of differential modules and given isomorphisms  $H(E_r, \partial_r) \xrightarrow{\sim} E_{r+1}$  for each  $r \geq 0$ .

We leave it to the reader to formulate the notion of a morphism of spectral sequences. The differential modules in the sequence  $E$  are often called the **pages** of the spectral sequence, for reasons that should soon be clear. The essential data of a spectral sequence is contained in the  $E_0$  page and the differentials

$\partial_r$  for  $r \geq 0$ ; we will often use the given isomorphisms to implicitly identify  $H(E_r, \partial_r)$  with  $E_{r+1}$  for each  $r \geq 0$ .

Given a spectral sequence  $E$ , each page  $E_r$  for  $r \geq 0$  is a subquotient<sup>1</sup> of  $E_0$ . This is made precise by

**Proposition 1.6.** If  $E$  is a spectral sequence, then there is a chain of submodules

$$0 = B_0 \subset B_1 \subset B_2 \subset \cdots \subset Z_2 \subset Z_1 \subset Z_0 = E_0$$

and, for each  $r \geq 0$ , a surjection  $\pi_r : Z_r \rightarrow E_r$  with kernel  $B_r$ , giving us an identification

$$Z_r/B_r \xrightarrow{\sim} E_r.$$

*Proof.* Take  $B_0 = 0$  and  $Z_0 = E_0$  with  $\pi_0 = \text{id}_{E_0}$ . Inductively, for each  $r \geq 0$ , let

$$B_{r+1} := \pi_r^{-1}B(\partial_r) \subset \pi_r^{-1}Z(\partial_r) =: Z_{r+1} \text{ and } \pi_{r+1} := [\cdot]_{E_{r+1}} \circ \pi_r|_{Z_{r+1}},$$

where  $[\cdot]_{E_{r+1}} : Z(\partial_r) \rightarrow E_{r+1}$  takes classes modulo  $B(\partial_r)$ , using  $H(E_r, \partial_r) \xrightarrow{\sim} E_{r+1}$ . ■

Proposition 1.6 also works in the “other direction”: to give a spectral sequence  $E$ , it also suffices to give a module  $E_0$  with a chain of submodules as in the proposition, and to give the differentials  $\partial_r : Z_r/B_r \rightarrow Z_r/B_r$  for each  $r \geq 0$ .

**Definition 1.7.** Given a spectral sequence  $E$  and submodules  $B_r, Z_r$  for  $r \geq 0$  as in Proposition 1.6, we define

$$B_\infty := \bigcup_{r \geq 0} B_r \subset \bigcap_{r \geq 0} Z_r =: Z_\infty \text{ and } E_\infty := Z_\infty/B_\infty.$$

It is customary to call the module  $E_\infty$ , the “infinite-th” (or the “infinith,” or the “infinity”) page of the spectral sequence  $E$ , and to say that  $E$  **converges** to  $E_\infty$ .

**Remark 1.8.** In a general abelian category, the (co)limits defining  $Z_\infty$  and  $B_\infty$  may not exist, but we don’t need to worry too much about that because: these certainly exist in the category of  $R$ -modules, and, in practice, most spectral sequences we will work with degenerate at some finite stage.

**Remark 1.9.** For each  $r$  with  $1 \leq r \leq \infty$ , we have

$$\begin{aligned} Z_r &= \{x \in E_0 : \partial_q([x]_{E_q}) = 0 \text{ for all } q \text{ with } 1 \leq q \leq r-1\}, \text{ and} \\ B_r &= \{x \in E_0 : \text{there exists } y_q \in E_q \text{ such that } [x]_{E_q} = \partial_q y_q \text{ for all } q \text{ with } 1 \leq q \leq r-1\}. \end{aligned}$$

The conditions defining these sets are somewhat recursive: for each  $q \geq 0$ , we need to have  $\partial_q([x]_{E_q}) = 0$  in order for  $[x]_{E_{q+1}}$  to be defined. For this reason, for each  $0 \leq r \leq \infty$ , I like to call  $Z_r$  the submodule of  $r$ -**deep cocycles** and  $B_r$  the submodule of  $r$ -**deep coboundaries**; this is, of course, not standard terminology.

Often the differential modules we want to work with will either be **graded** or **filtered**. Let’s talk about gradings and filtrations now.

<sup>1</sup>The sub- of quotient-, which is also the quotient- of a sub-.

## 1.1 Gradings

Fix an abelian group  $G$ .

### Definition 1.10.

- (a) A  $G$ -graded module is a module  $C$  along with submodules  $C^g \hookrightarrow C$  indexed by  $g \in G$  such that  $C$  is the internal direct sum of the  $C^g$ 's, i.e. the natural map  $\bigoplus_{g \in G} C^g \rightarrow C$  is an isomorphism.
- (b) A morphism  $f : C \rightarrow C'$  of  $G$ -graded modules is a pair  $(f, d)$ , where  $f : C \rightarrow C'$  is a morphism of modules and  $d \in G$  such that for all  $g \in G$ , we have  $f(C^g) \subset (C')^{g+d}$ . The element  $d \in G$  is called the **degree** of  $f$  is denoted by  $\deg f$ .

Now we would like to combine the structures from Definitions 1.1 and 1.10.

### Definition 1.11.

- (a) A  $G$ -graded differential module is a pair  $(C, \partial)$ , where  $C$  is a  $G$ -graded module and  $\partial : C \rightarrow C$  is an endomorphism of  $G$ -graded modules such that  $\partial^2 = 0$ .
- (b) A morphism  $f : (C, \partial) \rightarrow (C', \partial')$  of  $G$ -graded differential modules is a morphism  $f : C \rightarrow C'$  that is both a morphism of differential modules and of  $G$ -graded modules.

The degree  $\deg \partial \in G$  of  $\partial$  is called the **degree** of the  $G$ -graded differential module  $(C, \partial)$ . If  $f : (C, \partial) \rightarrow (C', \partial')$  is a morphism of  $G$ -graded differential modules, then the relation  $\partial' f = f \partial$  implies  $\deg \partial' = \deg \partial$  in all but the most degenerate of cases, and we will assume this equality of degrees to be the case whenever we speak of such morphisms.

**Remark 1.12.** If  $C$  is a  $G$ -graded differential module, then  $Z, B$  and  $HC$  are all  $G$ -graded via

$$B^g := B \cap C^g \subset Z \cap C^g =: Z^g \text{ and } H^g C = Z^g / B^g \hookrightarrow HC$$

for  $g \in G$ . If  $f : C \rightarrow C'$  is a morphism of such modules, then the induced morphism in cohomology  $Hf : HC \rightarrow HC'$  is a morphism of  $G$ -graded modules as well, with  $\deg Hf = \deg f$ . Finally, if  $0 \rightarrow C' \xrightarrow{i} C \xrightarrow{p} C'' \rightarrow 0$  is a short exact sequence of such modules, then the connecting homomorphism  $\delta : HC'' \rightarrow HC'$  is graded of degree

$$\deg \delta = \deg \partial - \deg i - \deg p,$$

as is clear from the proof of Theorem 1.3 (see also Remark 1.4). This amounts to saying that if you “go around” the exact triangle once, then you change the degree by exactly  $\deg \partial$ .

**Example 1.13.** A cochain complex is a differential  $\mathbb{Z}$ -graded module  $C$  of degree  $\deg \partial = 1$ ; such an object is often denoted as  $(C^\bullet, \partial)$ . If  $0 \rightarrow C' \xrightarrow{i} C \xrightarrow{p} C'' \rightarrow 0$  is a short exact sequence of cochain complexes with  $\deg i = \deg p = 0$ , then the exact triangle in cohomology from Theorem 1.3 “unfolds” to give us the usual long exact cohomology sequence

$$\dots \rightarrow H^q C' \xrightarrow{H^q i} H^q C \xrightarrow{H^q p} H^q C'' \xrightarrow{\delta} H^{q+1} C' \rightarrow \dots$$

The notion of a  $G$ -grading can also be defined for spectral sequences.

**Definition 1.14.** A  $G$ -graded spectral sequence is a spectral sequence  $E = (E_r, \partial_r)_{r \geq 0}$  such that each page  $(E_r, \partial_r)$  is a  $G$ -graded differential module and the given isomorphisms  $HE_r \rightarrow E_{r+1}$  are morphisms of  $G$ -graded modules.

If  $E$  is a  $G$ -graded spectral sequence, setting

$$B_r^g := B_r \cap E_0^g \subset Z_r \cap E_0^g =: Z_r^g$$

for all  $0 \leq r \leq \infty$  and  $g \in G$  gives  $G$ -gradings on the modules  $B_r$  and  $Z_r$  such that the morphisms  $\pi_r : Z_r \rightarrow E_r$  are morphisms of graded  $G$ -modules for all  $r \geq 0$ . We give  $E_\infty$  a  $G$ -grading by defining

$E_\infty^g := [Z_\infty^g]_{E_\infty}$  for all  $g \in G$ , which makes

$$0 \rightarrow B_\infty \rightarrow Z_\infty \rightarrow E_\infty \rightarrow 0$$

a short exact sequence of  $G$ -graded modules. Finally, we invite the reader to define morphisms of  $G$ -graded spectral sequences, and check that they induces morphisms of  $G$ -graded modules on all the  $B_r, Z_r$  and  $E_\infty$ .

## 1.2 Filtrations

### Definition 1.15.

- (a) A (descending or cohomological) filtration  $F$  on a module  $C$  is a sequence  $(F^p C)_{p \in \mathbb{Z}}$  of submodules  $F^p C \subset C$  such that for all  $p \in \mathbb{Z}$  we have  $F^p C \supset F^{p+1} C$ . The filtration is usually denoted by writing

$$F^{-\infty} C := C \supset \dots \supset F^p C \supset F^{p+1} C \supset \dots$$

A filtered module is a pair  $(C, F)$ , where  $C$  is a module and  $F$  a filtration on  $C$ .

- (b) A morphism of filtered modules  $f : C \rightarrow C'$  is a morphism  $f$  respecting the filtrations, i.e. such that for all  $p \in \mathbb{Z}$  we have  $f(F^p C) \subset F^p C'$ .

More generally, we can also define filtrations indexed by totally ordered abelian groups, or morphisms that alter the filtering degree, but we will not need these notions in what follows. Given a filtered module  $C$ , the graded module  $\text{gr } C$  associated to  $C$  is the  $\mathbb{Z}$ -graded module defined by

$$\text{gr } C = \bigoplus_{p \in \mathbb{Z}} \text{gr}^p C \text{ where } \text{gr}^p C = F^p C / F^{p+1} C \text{ for } p \in \mathbb{Z}.$$

A morphism  $F : C \rightarrow C'$  of filtered modules induces a morphism of  $\text{gr } f : \text{gr } C \rightarrow \text{gr } C'$  of the associated graded modules.

Finally, we can combine Definitions 1.1 and 1.15 to arrive at

### Definition 1.16.

- (a) A filtered differential module is a pair  $(C, \partial)$ , where  $C$  is a filtered module and  $\partial : C \rightarrow C$  is an endomorphism of filtered modules such that  $\partial^2 = 0$ .
- (b) A morphism  $f : (C, \partial) \rightarrow (C', \partial')$  of filtered differential modules is a morphism  $f : C \rightarrow C'$  that is both a morphism of differential modules and of filtered modules.

Similarly, one can define filtered spectral sequences, although we will not need this notion either.

**Remark 1.17.** If  $C$  is a filtered differential module, then  $(F^p C, \partial|_{F^p C})$  is a differential module for each  $p \in \mathbb{Z}$ , and the inclusion  $F^p C \hookrightarrow F^q C$  is a morphism of differential modules for each  $p \geq q \geq -\infty$ , yielding maps  $HF^p C \rightarrow HF^q C$ . From this, we get two things:

- (a) The associated graded module  $\text{gr } C$  acquires the structure of a  $\mathbb{Z}$ -graded differential module of degree 0 such that for all  $p \in \mathbb{Z}$  we have

$$H^p \text{gr } C = H(F^p C / F^{p+1} C).$$

- (b) We get filtrations on  $B, Z$  and  $HC$  via

$$F^p B := B \cap F^p C \subset Z \cap F^p C =: F^p Z \text{ and } F^p HC := \text{im}(HF^p C \rightarrow HC)$$

for each  $p \in \mathbb{Z}$ .<sup>2</sup> The graded module associated to  $HC$  is then given by

$$\text{gr}^p HC := \frac{\text{im}(HF^p C \rightarrow HC)}{\text{im}(HF^{p+1} C \rightarrow HC)} \cong \frac{F^p Z}{F^p B + F^{p+1} Z}$$

for  $p \in \mathbb{Z}$ .

We may now ask: given a filtered differential module  $C$ , what is the relationship between the  $\mathbb{Z}$ -graded modules  $H^\bullet \text{gr } C$  and  $\text{gr}^\bullet HC$ ? In general, there need not be a map between them in any direction; however, it seems implausible that they are not related altogether. Let's first examine a special case.

**Example 1.18.** A short exact sequence  $0 \rightarrow C' \rightarrow C \rightarrow C'' \rightarrow 0$  of differential modules induces a two-step filtration

$$C \supset C' \supset 0$$

<sup>2</sup>Note that the maps  $HF^p C \rightarrow HC$  need not be injective in general, and also that  $F^p Z = Z(\partial|_{F^p C})$  and  $F^p B \supset B(\partial|_{F^p C})$ , but the last containment can be proper in general.

on  $C$  via the identifications mentioned in Remark 1.4 (i.e.  $F^p C = C$  for  $p \leq 0$ , and  $F^1 C = C'$ , and  $F^p C = 0$  for  $p \geq 2$ ). In this case, we have in degrees 0 and 1 when read from left to right (check!) that

$$\begin{aligned} \operatorname{gr} C &= C'' && \oplus C', \\ H \operatorname{gr} C &= HC'' && \oplus HC', \text{ and} \\ \operatorname{gr} HC &= \frac{HC}{\operatorname{Im}(HC' \rightarrow HC)} \oplus \operatorname{Im}(HC' \rightarrow HC). \end{aligned}$$

From this chart, the relationship between  $H \operatorname{gr} C$  and  $\operatorname{gr} HC$  becomes clear: Theorem 1.3 gives us a map  $\delta : H^0 \operatorname{gr} C \rightarrow H^1 \operatorname{gr} C$  making  $(H^\bullet \operatorname{gr} C, \delta)$  a cochain complex with cohomology  $\operatorname{gr} HC$ .

In general, at least when the filtration on  $C$  is **bounded** and **exhaustive** (to be defined soon), the correct answer to the above question is that there is a  $\mathbb{Z}$ -graded spectral sequence  $E$  such that

- (a) for each  $r \geq 0$ , we have  $\deg \partial_r = r$  (so, e.g., the  $E_1$  page is cochain complex),
- (b) for  $r = 0$  we have  $E_0 = \operatorname{gr} C$  with induced differentials, so that  $E_1 = H \operatorname{gr} C$ , and
- (c) for  $r = \infty$ , we have an isomorphism  $E_\infty \cong \operatorname{gr} HC$ .

In Example 1.18, this spectral sequence collapsed at the  $E_2$  page, i.e. we had  $E_2 \cong E_\infty$ , and the isomorphism  $E_\infty \cong \operatorname{gr} HC$  was the content of Theorem 1.3. Our next goal is to prove this general result; as we shall see, it is the key to understanding spectral sequences.

## 2 Fundamental Spectral Sequences

### 2.1 Spectral Sequence associated to a Filtered Differential Module

Let  $C$  be a filtered differential module. Our goal is to produce a spectral sequence with  $E_0$  page  $\text{gr } C$  and  $E_\infty$  page  $\text{gr } HC$ . For this, for each pair of integers  $(p, r)$ , let

$$S_r^p := \{x \in F^p C : \partial x \in F^{p+r} C\},$$

which is the collection of elements in  $F^p C$  pushed  $r$  steps deep into the filtration by  $\partial$ .

**Remark 2.1.** It follows from the definition that

- (a) for each  $p \in \mathbb{Z}$ , we have  $S_r^p \supset F^{p+r} C$  for all  $r \geq 0$  and  $S_r^p = F^p C$  for all  $r \leq 0$ .
- (b) for each  $p, r \in \mathbb{Z}$ , we have  $S_r^p \cap F^{p+1} C = S_{r-1}^{p+1}$ , and
- (c) for each  $p, r, s \in \mathbb{Z}$ , we have  $\partial S_r^p \subset S_s^{p+r}$ .

The idea is that for each  $r \geq 0$ , the submodule  $S_r^p$  behaves like the submodule of  $r$ -deep cycles, and its image  $\partial S_r^p \subset S_{r+1}^{p+r}$  behaves like the submodule of  $(r+1)$ -deep coboundaries. To make this precise, consider for each  $p \in \mathbb{Z}$  and  $r \geq 0$  the submodules of  $\text{gr}^p C$  defined by

$$B_r^p := \frac{\partial S_{r-1}^{p-r+1} + F^{p+1} C}{F^{p+1} C} \subset \frac{S_r^p + F^{p+1} C}{F^{p+1} C} =: Z_r^p,$$

from which we have for each  $p \in \mathbb{Z}$  that

$$0 = B_0^p \subset B_1^p \subset B_2^p \subset \cdots \subset Z_2^p \subset Z_1^p \subset Z_0^p = \text{gr}^p C.$$

For each  $p \in \mathbb{Z}$  and  $r \geq 0$ , let

$$E_r^p := \frac{Z_r^p}{B_r^p} \cong \frac{S_r^p + F^{p+1} C}{\partial S_{r-1}^{p-r+1} + F^{p+1} C} \cong \frac{S_r^p}{\partial S_{r-1}^{p-r+1} + S_{r-1}^{p+1}},$$

where in the last isomorphism we are using Remark 2.1(b), and define the map  $\partial_r^p : E_r^p \rightarrow E_r^{p+r}$  by the diagram

$$\begin{array}{ccccccc} 0 & \longrightarrow & \partial S_{r-1}^{p-r+1} + S_{r-1}^{p+1} & \longrightarrow & S_r^p & \longrightarrow & E_r^p \longrightarrow 0 \\ & & \downarrow \partial & & \downarrow \partial & & \downarrow \partial_r^p \\ 0 & \longrightarrow & \partial S_{r-1}^{p+1} + S_{r-1}^{p+r+1} & \longrightarrow & S_r^{p+r} & \longrightarrow & E_r^{p+r} \longrightarrow 0, \end{array}$$

where the rows are short exact; in English,  $\partial_r^p$  is given by the recipe “pick representative in  $S_r^p$ , take  $\partial$ , and then take the class”. Let  $\pi_r^p : Z_r^p \rightarrow E_r^p$  be the canonical surjection. Then it follows immediately for each  $r \geq 0$  that  $\partial_r^2 = 0$  and for each  $p \in \mathbb{Z}$  that

$$B_{r+1}^p = (\pi_r^p)^{-1} B(\partial_r^p) \text{ and } Z_{r+1}^p = (\pi_r^p)^{-1} Z(\partial_r^p),$$

giving us a  $\mathbb{Z}$ -graded spectral sequence  $E$  satisfying  $\deg \partial_r = r$  for each  $r \geq 0$ . This is the required spectral sequence, and this is what allows us to relate  $H^\bullet \text{gr } C$  and  $\text{gr}^\bullet HC$ . Precisely, we have



**Theorem 2.2 (The Fundamental Theorem of Spectral Sequences).** If  $C$  is a filtered differential module, then there is a  $\mathbb{Z}$ -graded spectral sequence  $E = (E_r^\bullet, \partial_r)_{r \geq 0}$ , natural in  $C$ , such that

- (a) for each  $r \geq 0$ , we have  $\deg \partial_r = r$ , and
- (b) for  $r = 0$  we have  $E_0 = \text{gr}^\bullet C$  with induced differentials (so that  $E_1^\bullet = H^\bullet \text{gr} C$ ).

If, further, the filtration on  $C$  is both

- (i) **bounded**, i.e. there is a  $p_0 \in \mathbb{Z}$  such that  $F^p C = 0$  for all  $p \geq p_0$ , and
- (ii) **exhaustive**, i.e. such that  $\bigcup_{p \in \mathbb{Z}} F^p C = C$ ,

then

- (c) the sequence  $E$  converges to  $\text{gr}^\bullet HC$ , i.e.  $E_\infty^\bullet \cong \text{gr}^\bullet HC$ , naturally in  $C$ .

In this case, we say that the sequence  $E$  **abuts** to  $HC$ , and write  $E \Rightarrow HC$ .

*Proof.* All that remains to be shown is (c). The conditions (i) and (ii) imply, respectively, that for each  $p \in \mathbb{Z}$  we have

$$Z_\infty^p = \frac{F^p Z + F^{p+1} C}{F^{p+1} C} \text{ and } B_\infty^p = \frac{F^p B + F^{p+1} C}{F^{p+1} C}, \quad (1)$$

and so

$$E_\infty^p = \frac{Z_\infty^p}{B_\infty^p} \cong \frac{F^p Z + F^{p+1} C}{F^p B + F^{p+1} C} \cong \frac{F^p Z}{F^p B + F^{p+1} Z} \cong \text{gr}^p HC.$$

This isomorphism is given by the recipe “lift to  $F^p Z$  and take the image,” and is hence natural in  $C$ . ■

That’s it! That’s all there is to spectral sequences; everything else is addendum. As observed before, Theorem 2.2 is nothing but a massive generalization of Theorem 1.3.

## 2.2 Spectral Sequence associated to a Filtered Cochain Complex

We can combine definitions 1.10 and 1.15 as well, at least for  $G = \mathbb{Z}$ : if  $C$  is a filtered,  $\mathbb{Z}$ -graded module, then for each  $p, q \in \mathbb{Z}$ , we define  $F^{p,q}C := F^p C^{p+q}$ , so that for a fixed  $n \in \mathbb{Z}$ , the sequence of submodules

$$C^n \supset \dots \supset F^{p,n-p}C \supset F^{p+1,n-p-1}C \supset \dots$$

gives a filtration on  $C^n$ . In this case, we define the bigraded<sup>3</sup> module associated to  $C$ , still denoted by  $\text{gr } C$ , by setting

$$\text{gr}^{p,q} C := \text{gr}^p C^{p+q} = F^{p,q}C / F^{p+1,q-1}C$$

for  $p, q \in \mathbb{Z}$ . Similarly, we can combine all three of definitions 1.1, 1.10, 1.15, to arrive at the definition of a filtered cochain complex  $C$ : this is a filtered,  $\mathbb{Z}$ -graded differential module with differential of degree  $\deg \partial = 1$  preserving the filtration. In this case, the associated graded module to  $HC$  is also a filtered,  $\mathbb{Z}$ -graded module with

$$\text{gr}^{p,q} HC = \frac{F^p H^{p+q} C}{F^{p+1} H^{p+q} C} = \frac{\text{im}(H^{p+q} F^p C \rightarrow H^{p+q} C)}{\text{im}(H^{p+q} F^{p+1} C \rightarrow H^{p+q} C)}.$$

In this case, if for each  $p, q \in \mathbb{Z}$  and  $r \geq 0$ , we set

$$S_r^{p,q} = \{x \in F^p C^{p+q} : \partial x \in F^{p+r} C^{p+q+1}\},$$

and let

$$B_r^{p,q} := \frac{\partial S_{r-1}^{p-r+1,q+r-2} + F^{p+1} C^{p+q}}{F^{p+1} C^{p+q}} \subset \frac{S_r^{p,q} + F^{p+1} C^{p+q}}{F^{p+1} C^{p+q}} =: Z_r^{p,q}, \text{ and } E_r^{p,q} = \frac{Z_r^{p,q}}{B_r^{p,q}},$$

then we obtain a bigrading on the spectral sequence  $E$  from the previous section. We see also that in this case, the map  $\partial_r^{p,q}$  has to shift  $p$  degree by  $r$  as before, but only increase the “total”  $p+q$  degree by 1, so that  $\partial_r^{p,q} : E_r^{p,q} \rightarrow E^{p+r,q-r+1}$ . The analogous result to Theorem 2.2 is then

**Theorem 2.3** (The Fundamental Theorem of Spectral Sequences, Bigraded Version). If  $C$  is a filtered cochain complex, then there is a bigraded spectral sequence  $E = (E_r, \partial_r)_{r \geq 0}$ , natural in  $C$ , such that

- (a) for each  $r \geq 0$ , we have  $\deg \partial_r = (r, -r+1)$ , and
- (b) for  $r = 0$ , we have  $E_0^{\bullet,\bullet} = \text{gr}^{\bullet,\bullet} C$  with induced (“vertical”) differentials.

If, further, the filtration on  $C$  is both

- (i) locally bounded, i.e. for each  $n \in \mathbb{Z}$  there is an  $r_0 \geq 0$  such that  $F^r C^n = 0$  for all  $r \geq r_0$ , and
- (ii) locally exhaustive, i.e. such that for each  $n \in \mathbb{Z}$  we have  $\bigcup_{r \in \mathbb{Z}} F^r C^n = C^n$ ,

then

- (c) the sequence  $E$  converges to  $\text{gr}^{\bullet,\bullet} HC$ , i.e.  $E_\infty^{\bullet,\bullet} \cong \text{gr}^{\bullet,\bullet} HC$ , naturally in  $C$ .

*Proof.* The proof is identical to that of Theorem 2.2, since the equalities similar to (1) are obtained for a fixed pair  $(p, q)$  by applying the new conditions (i) and (ii) to  $n = p + q + 1$  and  $n = p + q - 1$  respectively—this is why it suffices to work with locally bounded and exhaustive filtrations. ■

<sup>3</sup>Here, and in what follows, “bigraded” simply means graded by  $G = \mathbb{Z} \oplus \mathbb{Z}$ .

### 2.3 Spectral Sequence(s) associated to a Double Complex

One important context in which filtered cochain complexes arise is through double complexes. Let  $K^{\bullet,\bullet}$  be a double complex with differentials  $\partial_v$  and  $\partial_h$  of bidegrees  $(1, 0)$  and  $(0, 1)$  satisfying

$$\partial_v^2 = \partial_h^2 = (\partial_v + \partial_h)^2 = 0.$$

Then the total cochain complex  $(\text{Tot}(K)^{\bullet}, \partial)$  defined by

$$\text{Tot}(K)^n = \bigoplus_{p+q=n} K^{p,q}$$

with differential  $\partial = \partial_v + \partial_h$  of degree  $\deg \partial = 1$  admits a filtration by taking

$$F^r \text{Tot}(K)^n = \bigoplus_{\substack{p+q=n \\ p \geq r}} K^{p,q}$$

with  $\text{gr}^{\bullet,\bullet} \text{Tot}(K) \cong K^{\bullet,\bullet}$ , called for obvious reasons the filtration by columns. This filtered cochain complex gives rise to a bigraded spectral sequence  $(E_r^{\bullet,\bullet})_{r \geq 0}$  thanks to Theorem 2.3, with

$$B_r^{p,q} \subset Z_r^{p,q} \subset K^{p,q}$$

and differentials  $\partial_r^{p,q} : E_r^{p,q} \rightarrow E_r^{p+r, q-r+1}$ . The zeroth page  $E_0$  is simply  $K$  itself with the vertical differential  $\partial_v$ ; the first page is the vertical cohomology  $H_v K$  with the horizontal differential induced by  $\partial_h$ . In general, we have for  $r \geq 1$  that

$$Z_r^{p,q} = \{x \in K^{p,q} : \partial_v x = 0 \text{ and there are } x_j \in K^{p+j, q-j} : \partial_h x_{j-1} = \partial_v x_j \text{ for } 1 \leq j \leq r-1, \\ \text{where } x_0 = x\}$$

and

$$B_r^{p,q} = \{x \in K^{p,q} : \text{there are } y_j \in K^{p-r+j, q+r-1-j} : \partial_h y_{j-1} = \partial_v y_j \text{ for } 1 \leq j \leq r-1, \\ \text{where } y_0 = 0, \text{ and } \partial_h y_{r-1} = x + \partial_v z \text{ for some } z \in K^{p, q-1}\},$$

with the map  $\partial_r^{p,q} : E_r^{p,q} \rightarrow E_r^{p+r, q-r+1}$  given by the recipe: lift  $[x] \in E_r^{p,q}$  to  $x \in Z_r^{p,q}$ , pick a sequence  $(x_j)_{j=1}^{r-1}$  as described, and then  $\partial_r^{p,q}[x] = [(-1)^{r-1} \partial_h x_{r-1}]$  in  $E_r^{p+r, q-r+1}$ .

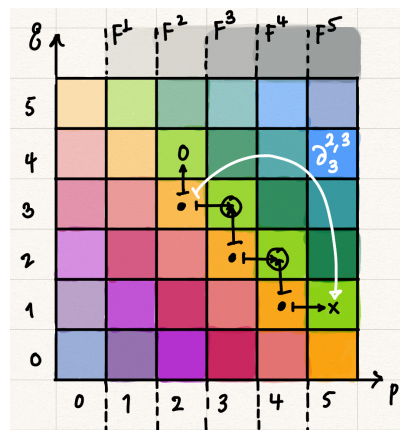


Figure 1: A pictorial representation of the differential  $\partial_3^{2,3} : E_3^{2,3} \rightarrow E_3^{5,1}$  for a first quadrant double complex. Each color denotes a fixed total degree, and the saturation indicates how deep we are in the filtration.

One sufficient condition that implies the convergence requirements of Theorem 2.3 is that  $K^{\bullet,\bullet}$  be a first quadrant double complex, i.e.  $K^{p,q} = 0$  if  $p < 0$  or  $q < 0$ . We have proven

**Theorem 2.4** (Spectral Sequence of a Double Complex I). Given a double complex  $(K^{\bullet,\bullet}, \partial_v, \partial_h)$ , there is a bigraded spectral sequence  $E = (E_r, \partial_r)_{r \geq 0}$ , natural in  $K$ , such that

- (a) for each  $r \geq 0$ , we have  $\deg \partial_r = (r, -r + 1)$ ,
- (b) for  $r = 0, 1, 2$ , the pages  $E_r$  can be described as

$$\begin{aligned} E_0^{p,q} &= K^{p,q} & \text{and } \partial_0^{p,q} &= \partial_v, \\ E_1^{p,q} &= H_v^q(K^{p,\bullet}) & \text{and } \partial_1^{p,q} &= [\partial_h], \text{ and} \\ E_2^{p,q} &= H_h^p H_v^q(K). \end{aligned}$$

If, further,  $K$  is a first quadrant double complex, then

- (c)  $E$  is a first quadrant spectral sequence that abuts to  $H^\bullet \text{Tot}(K)$ .

The theorem is often expressed by writing

$$H_h^p H_v^q(K) \Rightarrow H^{p+q} \text{Tot}(K).$$

The abutment statement means that, once the spectral sequence mechanism has run, then for each  $n \geq 0$ , we can recover  $H^n \text{Tot}(K)$  by working “right to left”, namely starting with  $E_\infty^{n,0}$ , which is a subobject of  $H^n \text{Tot}(K)$ , and successively solving extension problems moving left and upwards along the diagonal. In other words, we have that

$$F^n H^n \text{Tot}(K) = E_\infty^{n,0},$$

and for each  $j$  with  $1 \leq j \leq n$ , we have a short exact sequence

$$0 \rightarrow F^{n-j+1} H^n \text{Tot}(K) \rightarrow F^{n-j} H^n \text{Tot}(K) \rightarrow E_\infty^{n-j,j} \rightarrow 0,$$

with  $F^0 H^n \text{Tot}(K) = H^n \text{Tot}(K)$  at the last stage.

**Remark 2.5.** If  $K$  is a first quadrant double complex, then for each fixed  $(p, q)$ , the module  $E_\infty^{p,q}$  is obtained already at a finite stage; namely, if  $r > p$  then  $E_r^{p,q} \supset E_{r+1}^{p,q}$  and if  $r > q + 1$ , then  $E_r^{p,q} \twoheadrightarrow E_{r+1}^{p,q}$ , so that in any case  $E_{\max\{p+1, q+2\}}^{p,q} \cong E_\infty^{p,q}$ .

Further, we get by taking  $q = 0$  that for each  $n$  we have

$$E_2^{n,0} \twoheadrightarrow E_3^{n,0} \twoheadrightarrow \cdots \twoheadrightarrow E_{n+1}^{n,0} \xrightarrow{\sim} E_\infty^{n,0},$$

so that the “ $x$ -axis” starting on the  $E_2$  pages consists of progressive smaller quotient objects leading to the first graded piece. The resulting map  $e_B^n : E_2^{n,0} \twoheadrightarrow E_\infty^{n,0} \hookrightarrow H^n \text{Tot}(K)$ , called the **base edge map**,<sup>4</sup> can be described as follows: for any  $n \geq 0$  and  $r \geq 2$ , we have

$$Z_r^{n,0} = Z^n(F^r \text{Tot}(K)) = \{x \in K^{n,0} : \partial_v x = \partial_h x = 0\} \subset Z^n \text{Tot}(K).$$

The edge map  $e_B^n$  is therefore induced by

$$\begin{array}{ccccc} Z_2^{n,0} & \xrightarrow{\sim} & Z^n F^n \text{Tot}(K) & \hookrightarrow & Z^n \text{Tot}(K) \\ \downarrow & & & & \downarrow \\ E_2^{n,0} & \dashrightarrow & & & H^n \text{Tot}(K), \end{array}$$

or in English by the recipe “lift to  $Z_2^{n,0}$  and take image in  $H^n \text{Tot}(K)$ ”.

Similarly, we get by taking  $p = 0$  that for each  $n$  we have

$$E_1^{0,n} \supset E_2^{0,n} \supset \cdots \supset E_{n+2}^{0,n} = E_\infty^{0,n},$$

so that “ $y$ -axis” starting on the  $E_1$  page consists of progressively smaller subobjects leading to the final graded piece. The resulting map  $e_F^n : H^n \text{Tot}(K) \twoheadrightarrow E_\infty^{0,n} \hookrightarrow E_2^{0,n}$ , called the **fiber edge map**, can be described by the diagram

<sup>4</sup>For an explanation of the terminology, see §3.6.1.

$$\begin{array}{ccc}
 Z^n \operatorname{Tot}(K) & \longrightarrow & \frac{Z^n \operatorname{Tot}(K) + F^1 \operatorname{Tot}(K)^n}{F^1 \operatorname{Tot}(K)^n} = Z_\infty^{0,n} \hookrightarrow Z_2^{0,n} \\
 \downarrow & & \downarrow \\
 H^n \operatorname{Tot}(K) & \dashrightarrow & E_2^{0,n},
 \end{array}$$

or again in English by “lift to  $Z^n \operatorname{Tot}(K)$ , take the piece in  $K^{0,n}$ ; this is in  $Z_2^{0,n}$ , and now take the image in  $E_2^{0,n}$ ”.

This “finite-stage stabilization” property of spectral sequences arising from first quadrant double complexes allows us to write down this extension problem of recovering  $H^n \operatorname{Tot}(K)$  for low  $n$  explicitly as the five-term exact sequence of low degree terms. Namely,

**Proposition 2.6.** Given a first quadrant double complex  $K$  and the clockwise spectral sequence  $E$  arising from it, there is an exact sequence

$$0 \rightarrow E_2^{1,0} \xrightarrow{e_B^1} H^1 \operatorname{Tot}(K) \xrightarrow{e_F^1} E_2^{0,1} \xrightarrow{\partial_2^{0,1}} E_2^{2,0} \xrightarrow{e_F^2} H^2 \operatorname{Tot}(K). \quad (2)$$

The only map in the sequence that is not an edge map is  $\partial_2^{0,1}$ . This map, or more generally for  $r \geq 2$  the map  $\partial_r^{0,r-1} : E_r^{0,r-1} \rightarrow E_r^{r,0}$ , is called the **transgression map**, and is a map from a subobject of  $E_2^{0,r-1}$  to a quotient object of  $E_2^{r,0}$ .

*Proof.* First, by the abutment property for  $n = 1$  along with the observation  $E_2^{1,0} \cong E_\infty^{1,0}$ , there is a short exact sequence

$$0 \rightarrow E_2^{1,0} \xrightarrow{e_B^1} H^1 \operatorname{Tot} K \rightarrow E_\infty^{0,1} \rightarrow 0.$$

Next, by the finite stage stabilization, we know that  $E_3^{0,1} \cong E_\infty^{0,1}$  and  $E_3^{2,0} \cong E_\infty^{2,0}$ . Since  $E_2^{p,q} = 0$  if  $p < 0$  or  $q < 0$ , we get the sequence

$$0 \rightarrow E_\infty^{0,1} \rightarrow E_2^{0,1} \xrightarrow{\partial_2^{0,1}} E_2^{2,0} \rightarrow E_\infty^{2,0} \rightarrow 0.$$

Finally, since  $F^3 H^2 \operatorname{Tot} K = 0$ , we have that  $E_\infty^{2,0} \subset H^2 \operatorname{Tot} K$ . Stacking these sequences together gives (2). I will leave it the reader to verify that the maps are as claimed. ■

There is nothing sacred about choosing this length for the exact sequence—if needed, we can continue the sequence a little further to

$$0 \rightarrow E_2^{1,0} \xrightarrow{e_B^1} H^1 \operatorname{Tot}(K) \xrightarrow{e_F^1} E_2^{0,1} \xrightarrow{\partial_2^{0,1}} E_2^{2,0} \xrightarrow{e_F^2} F^1 H^2 \operatorname{Tot}(K) \rightarrow E_3^{1,1}.$$

The reason for stopping at five terms is because we often have most direct access to the  $E_2$  page and the cohomology of the total complex, and not the higher pages or the filtered pieces.

Clearly, reversing the roles of  $p, q$  produces another filtration, namely one by rows, and again gives rise to a bigraded sequence, with differentials  $\partial_r$  of bidegree  $(r+1, r)$ . From this we get

**Theorem 2.7 (Spectral Sequence of a Double Complex II).** Given a double complex  $(K^{\bullet,\bullet}, \partial_v, \partial_h)$ , there is a bigraded spectral sequence  $E = (E_r, \partial_r)_{r \geq 0}$ , natural in  $K$ , such that

- (a) for each  $r \geq 0$ , we have  $\deg \partial_r = (-r + 1, r)$ ,
- (b) for  $r = 0, 1, 2$ , the pages  $E_r$  can be described as

$$\begin{aligned} E_0^{p,q} &= K^{p,q} & \text{and } \partial_0^{p,q} &= \partial_h, \\ E_1^{p,q} &= H_h^p(K^{\bullet,q}) & \text{and } \partial_1^{p,q} &= [\partial_v], \text{ and} \\ E_2^{p,q} &= H_v^q H_h^p(K). \end{aligned}$$

If, further,  $K$  is a first quadrant double complex, then

- (c)  $E$  is a first quadrant spectral sequence that abuts to  $H^\bullet \text{Tot}(K)$ .

This theorem is often expressed by writing

$$H_v^q H_h^p(K) \Rightarrow H^{p+q} \text{Tot } K.$$

The abutment statement means now that to recover  $H^n \text{Tot } K$ , we would work “left to right”.

When we need to distinguish these, we’ll call the sequence arising from the filtration by columns the **clockwise spectral sequence** and denote it by  $(^{(c)}E_r^{\bullet,\bullet}, ^{(c)}\partial_r^{\bullet,\bullet})_{r \geq 0}$  and the sequence arising from the filtration by rows the **counterclockwise spectral sequence**, and denote it by  $(^{(r)}E_r^{\bullet,\bullet}, ^{(r)}\partial_r^{\bullet,\bullet})_{r \geq 0}$ . Both of these sequences abut to the same object—namely  $H^\bullet \text{Tot } K$ , and the power of spectral sequences often lies in making the resulting comparisons.

## 3 Examples

### 3.1 Some Named Lemmas

#### 3.1.1 Snake Lemma

#### 3.1.2 Five Lemma

#### 3.1.3 The $n^2$ -Lemma for $n \geq 2$

### 3.2 Spectral Sequences from a Filtration on the Space

#### 3.2.1 Equivalence of Cellular and Singular Homology

#### 3.2.2 Serre Spectral Sequence via CW Complexes

### 3.3 Künneth and Universal Coefficient Spectral Sequences

### 3.4 Čech-de Rham Spectral Sequence

#### 3.4.1 An Application to Symplectic Topology

### 3.5 Frölicher Spectral Sequences

#### 3.5.1 Compact Kähler Manifolds

#### 3.5.2 Stein Manifolds

### 3.6 Grothendieck Spectral Sequence

#### 3.6.1 Leray-Serre Spectral Sequence

#### 3.6.2 Čech-Derived Functor Spectral Sequence

#### 3.6.3 Lyndon-Hochschild-Serre Spectral Sequence