

# SOME ASPECTS OF HOMOLOGICAL ALGEBRA

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## §1. GENERALITIES ON ABELIAN CATEGORIES

### 1.1. Categories

**(1.1.1).** Recall that a *category* consists of a non-empty class  $\mathcal{C}$  of objects together with, for  $A, B \in \mathcal{C}$ , a set  $\text{Hom}(A, B)$  collectively called morphisms of  $A$  into  $B$ , and for three objects  $A, B, C \in \mathcal{C}$  a function (called composition of morphisms)  $(u, v) \mapsto vu$  of  $\text{Hom}(A, B) \times \text{Hom}(B, C)$  to  $\text{Hom}(A, C)$ , which satisfy the following two axioms:

- (1) the composition of morphisms is *associative*;
- (2) for  $A \in \mathcal{C}$ , there is an element  $i_A \in \text{Hom}(A, A)$  (called the identity morphism of  $A$ ) which is a right and left unit for the composition of morphisms. (The element  $i_A$  is then unique.)

Finally, it will be prudent to suppose that a morphism  $u$  determines its source and target. In other words, if  $A, B$  and  $A', B'$  are two distinct pairs of objects of  $\mathcal{C}$ , then  $\text{Hom}(A, B)$  and  $\text{Hom}(A', B')$  are disjoint sets.

**(1.1.2).** If  $\mathcal{C}$  is a category, we define the *dual category*  $\mathcal{C}^{\text{op}}$  as the category with the same objects as  $\mathcal{C}$ , and where the set  $\text{Hom}(A, B)^{\text{op}}$  of morphisms of  $A$  into  $B$  is identical to  $\text{Hom}(B, A)$ , with the composite of  $u$  and  $v$  in  $\mathcal{C}^{\text{op}}$  being identified as the composite of  $v$  and  $u$  in  $\mathcal{C}$ .

Any concept or statement about an arbitrary category admits a dual concept or statement (the process of reversing arrows), which will be just as useful in the applications. Making this more explicit is usually left to the reader.

**(1.1.3).** Suppose we are given a category  $\mathcal{C}$  and a morphism  $u : A \rightarrow B$  in  $\mathcal{C}$ . For any  $C \in \mathcal{C}$ , we define a function  $v \mapsto uv : \text{Hom}(C, A) \rightarrow \text{Hom}(C, B)$  and a function  $w \mapsto wu : \text{Hom}(B, C) \rightarrow \text{Hom}(A, C)$ .

We say that  $u$  is a *monomorphism* or that  $u$  is *injective* (respectively,  $u$  is an *epimorphism* or  $u$  is *surjective*) if the first (respectively, the second) of the two preceding function is always injective;  $u$  is called *bijective* if  $u$  is both injective and surjective.

We call a *left inverse* (respectively, a *right inverse*) of  $u$  a  $v \in \text{Hom}(B, A)$  such that  $vu = i_A$  (respectively  $uv = i_B$ );  $v$  is called the *inverse* of  $u$  if it is both a left inverse and a right inverse of  $u$  (in which case it is uniquely determined).  $u$  is called an *isomorphism* if it has an inverse. If  $u$  has a left inverse (respectively, a right inverse) it is injective (respectively surjective). Thus an isomorphism is bijective (the converse being, in general, false).

**(1.1.4).** The composite of two monomorphisms (respectively, epimorphisms) is monomorphism (respectively, epimorphisms), hence the composite of two bijections is a bijection; similarly the composite of two isomorphisms is an isomorphism. If the composite  $vu$  of two morphisms  $u, v$  is a monomorphism (respectively, an epimorphism), then  $u$  (respectively,  $v$ ) is as well.

Although the development of such trivialities is clearly necessary, we will subsequently refrain from setting them forth explicitly, feeling it sufficient to indicate the definitions carefully.

(1.1.5). Consider two monomorphisms  $u : B \rightarrow A$  and  $u' : B' \rightarrow A$ . We say that  $u'$  *majorizes* or *contains*  $u$  and we write  $u \leq u'$  if we can factor  $u$  as  $u'v$  where  $v$  is a morphism from  $B$  to  $B'$  (which is then uniquely determined). That is a *preorder* in the class of monomorphism with target  $A$ . We will say that two such monomorphisms  $u, u'$  are *equivalent* if each one contains the other. Then the corresponding morphisms  $B \rightarrow B'$  and  $B' \rightarrow B$  are inverse isomorphism.

Choose (for example, using Hilbert's all-purpose symbol  $\tau$ ) a monomorphism in each class of equivalent monomorphisms: the selected monomorphisms will be called *subobjects* of  $A$ . Thus a subobject of  $A$  is not simply an object of  $\mathcal{C}$ , but an object  $B$ , together with a monomorphism  $u : B \rightarrow A$  called the *canonical injection* of  $B$  into  $A$ . (Nonetheless, by abuse of language, we will often designate a subobject of  $A$  by the name  $B$  of the corresponding object of  $\mathcal{C}$ .) The containment relation defines an *order relation* (not merely a preorder relation) on the class of subobjects of  $A$ .

It follows from the above that the subobjects of  $A$  that are contained in a subobject  $B$  are identified with the subobjects of  $B$ , this correspondence respecting the natural order. (This does not mean, however, that a subobject of  $B$  is equal to a subobject of  $A$ , which would require  $A = B$ .)

(1.1.6). Dually, consideration of a preorder on the class of epimorphisms of  $A$  makes it possible to define the ordered class of *quotient objects* of  $A$ .

(1.1.7). Let  $A \in \mathcal{C}$  and let  $(u_i)_{i \in I}$  be a non-empty family of morphisms  $u_i : A \rightarrow A_i$ . Then for any  $B \in \mathcal{C}$ , the functions  $v \mapsto u_i v : \text{Hom}(B, A) \rightarrow \text{Hom}(B, A_i)$  define a natural transformation

$$(1.1.7.1) \quad \text{Hom}(B, A) \longrightarrow \prod_{i \in I} \text{Hom}(B, A_i)$$

We say that the  $u_i$  define a *representation of  $A$  as a direct product of the  $A_i$*  if for any  $B$ , the preceding displayed function is bijective.

If this holds and if  $A'$  is another object of  $\mathcal{C}$  represented as a product of the  $A'_i$  by morphisms  $u'_i : A' \rightarrow A'_i$  (the set of indices being the same), then for any family  $(v_i)$  of morphisms  $v_i : A_i \rightarrow A'_i$ , there is a unique morphism  $v : A \rightarrow A'$  such that  $u_i v = v_i u_i$  for each  $i \in I$ . From this we conclude that if the  $v_i$  are equivalences, this holds for  $v$ : in particular, if the  $v_i$  are identity  $I_{A_i}$  we see that two objects  $A, A'$  represented as products of the family  $A_i$  are canonically isomorphic. It is therefore natural to select among all the  $(A, (u_i))$ , as above, a particular system, for example using Hilbert's  $\tau$  symbol that will be called the *product* of the family of objects  $(A_i)_{i \in I}$ . It is therefore not a simple object  $A$  of  $\mathcal{C}$ , but such an object equipped with a family  $(u_i)$  of morphisms to  $A_i$ , called the *canonical projections from the product to its factors  $A_i$* . We indicate the product of the  $A_i$  (if it exists) by  $\prod_{i \in I} A_i$ . If  $I$  is reduced to a single element  $i$ , then the product can be identified with  $A_i$  itself.

We say that  $\mathcal{C}$  is a *category with products* if the product of two objects of  $\mathcal{C}$  always exists (then it holds for the product of any nonempty finite family of objects of  $\mathcal{C}$ ). We say that  $\mathcal{C}$  is a *category with infinite products* if the product of any non-empty family of objects of  $\mathcal{C}$  always exists. We have seen that if there are two products,  $A = \prod_{i \in I} A_i$  and  $B = \prod_{i \in I} B_i$  corresponding to the same set  $I$  of indices, then a family  $(v_i)$  of morphisms  $A_i$  to  $B_i$  canonically defines a morphism  $v$  from  $A$  to  $B$ , called *product of the morphisms  $v_i$*  and sometimes denoted  $\prod_{i \in I} v_i$ . If the  $v_i$  are monomorphisms, so is their product. But the analogous statement for epimorphisms fails in general (as we see, for example, in the category of sheaves over a fixed topological space).

(1.1.8). Dual considerations of the preceding can be used to define the notions of a *representation of an object as a sum* of a family of objects  $A_i$  by means of morphisms  $u_i : A_i \rightarrow A$  (for any  $B \in \mathcal{C}$ , the natural transformation

$$(1.1.8.1) \quad \text{Hom}(A, B) \longrightarrow \prod_{i \in I} \text{Hom}(A_i, B)$$

is bijective), of a *direct sum*  $\oplus_{i \in I} A_i$ , equipped with *canonical injections*  $A_i \rightarrow \oplus_{i \in I} A_i$  (which, however are not necessarily monomorphisms, despite their name), and also equipped with a *sum morphism*  $\oplus_{i \in I} u_i$  of a family of morphisms  $u_i : A_i \rightarrow B_i$ . If the  $u_i$  are epimorphisms, their sum is as well.

## 1.2. Functors

**(1.2.1).** Let  $\mathcal{C}$  and  $\mathcal{C}'$  be categories. Recall that a covariant functor from  $\mathcal{C}$  to  $\mathcal{C}'$  consists of a “function”  $F$  which associates an object  $F(A) \in \mathcal{C}'$  to each  $A \in \mathcal{C}$  and a morphism  $F(u) : F(A) \rightarrow F(B)$  in  $\mathcal{C}'$  to each morphism  $u : A \rightarrow B$  in  $\mathcal{C}$ , such that we have  $F(I_A) = I_{F(A)}$  and  $F(vu) = F(v)F(u)$ . There is an analogous definition of *contravariant functor* from  $\mathcal{C}$  to  $\mathcal{C}'$  (which are also covariant functors from  $\mathcal{C}^{\text{op}}$  to  $\mathcal{C}'$  or from  $\mathcal{C}$  to  $\mathcal{C}'^{\text{op}}$ ). We similarly define functors of several variables (or *multifunctors*), covariant in some variables and contravariant in others. In order to simplify, we will generally limit ourselves to functors of one variable. Functors are composed in the same way as functions are, this composition is associative and “identity functors” play the role of units.

**(1.2.2).** Let  $\mathcal{C}$  and  $\mathcal{C}'$  be fixed categories,  $F$  and  $G$  covariant functors from  $\mathcal{C}$  to  $\mathcal{C}'$ . A *functorial morphism*  $f$  from  $F$  to  $G$  (also called a “natural transformation” from  $F$  to  $G$  by some authors) is a “function” that associates a morphism  $f(A) : F(A) \rightarrow G(A)$  to any  $A \in \mathcal{C}$ , such that for any morphism  $u : A \rightarrow B$  in  $\mathcal{C}$  the following diagram

$$(1.2.2.1) \quad \begin{array}{ccc} F(A) & \xrightarrow{F(u)} & F(B) \\ f(A) \downarrow & & \downarrow f(B) \\ G(A) & \xrightarrow{G(u)} & G(B) \end{array}$$

commutes. Natural transformations  $F \rightarrow G$  and  $G \rightarrow H$  are composed in the usual way. Such composition is associative, and the “identity transformation” of the functor  $F$  is a unit for composition of natural transformations. (Therefore, if  $\mathcal{C}$  is a set the functors from  $\mathcal{C}$  to  $\mathcal{C}'$  again form a category.) Note that the composite  $GF$  of two functors  $F : \mathcal{C} \rightarrow \mathcal{C}'$  and  $G : \mathcal{C}' \rightarrow \mathcal{C}''$  is, in effect, a bifunctor with respect to the arguments  $G$  and  $F$ : a natural transformation  $G \rightarrow G'$  (respectively,  $F \rightarrow F'$ ) defines a natural transformation  $GF \rightarrow G'F$  (respectively,  $GF \rightarrow GF'$ ).

**(1.2.3).** An *equivalence* of a category  $\mathcal{C}$  with a category  $\mathcal{C}'$  is a system  $(F, G, \phi, \psi)$  consisting of covariant functors:

$$(1.2.3.1) \quad F : \mathcal{C} \longrightarrow \mathcal{C}' \quad G : \mathcal{C}' \longrightarrow \mathcal{C}$$

and of natural equivalences

$$(1.2.3.2) \quad \phi : 1_{\mathcal{C}} \longrightarrow GF \quad \psi : 1_{\mathcal{C}'} \longrightarrow FG$$

(where  $1_{\mathcal{C}}$  and  $1_{\mathcal{C}'}$  are the identity functors of  $\mathcal{C}$  and  $\mathcal{C}'$ , respectively) such that for any  $A \in \mathcal{C}$  and  $A' \in \mathcal{C}'$ , the composites

$$(1.2.3.3) \quad \begin{aligned} F(A) &\xrightarrow{F(\phi(A))} FGF(A) \xrightarrow{\psi^{-1}(F(A))} F(A) \\ G(A') &\xrightarrow{G(\psi(A'))} GFG(A') \xrightarrow{\phi^{-1}(G(A'))} G(A') \end{aligned}$$

are the identities of  $F(A)$  and  $G(A')$ , respectively. Then for any pair  $A, B$  of objects of  $\mathcal{C}$ , the functions  $f \mapsto F(f)$  from  $\text{Hom}(A, B)$  to  $\text{Hom}(F(A), F(B))$  is a bijection whose inverse is the function  $g \mapsto G(g)$  from  $\text{Hom}(F(A), F(B))$  to  $\text{Hom}(GF(A), GF(B))$ , which is identified with  $\text{Hom}(A, B)$  thanks to the isomorphisms  $\phi(A) : A \rightarrow GF(A)$  and  $\phi(B) : B \rightarrow GF(B)$ . Equivalences between categories compose like functors. Two categories are called *equivalent* if there is an equivalence between them. Current usage will not distinguish between equivalent categories. It is important, however, to observe the difference between this notion and the stricter notion of isomorphism (which applies if we wish to compare categories that are sets). Let  $\mathcal{C}$  be a non-empty set. For any pair of objects  $A, B \in \mathcal{C}$ , suppose that  $\text{Hom}(A, B)$  consists of one element. Then under the unique composition laws  $\text{Hom}(A, B) \times \text{Hom}(B, C) \rightarrow \text{Hom}(A, C)$ ,  $\mathcal{C}$  becomes a category, and two categories constructed by this procedure are always equivalent, but they are isomorphic only if they have the same cardinality. None of the equivalences of categories that we encounter in practice is an isomorphism.

### 1.3. Additive Categories

(1.3.1). An *additive category* is a category  $\mathcal{C}$  for which is given, for any pair  $A, B$  of objects of  $\mathcal{C}$  an abelian group law in  $\text{Hom}(A, B)$  such that the composition of morphisms is a bilinear operation. We suppose also that the sum and the product of any two objects  $A, B$  of  $\mathcal{C}$  exist. It is sufficient, moreover, to assume the existence of the sum or the product of  $A$  and  $B$  exists; the existence of the other can be easily deduced and, in addition,  $A \oplus B$  is canonically isomorphic to  $A \times B$ . (Supposing, for example, that  $A \times B$  exists, we consider the morphisms  $A \rightarrow A \times B$  and  $B \rightarrow A \times B$  whose components are  $(i_A, 0)$ , respectively,  $(0, i_B)$ , we check that we obtain thereby a representation of  $A \times B$  as a direct sum of  $A$  and  $B$ .) Finally, we assume the existence of an object  $A$  such that  $i_A = 0$ ; we call it a *zero object* of  $\mathcal{C}$ . It comes to the same thing to say that  $\text{Hom}(A, A)$  is reduced to 0, or that for any  $B \in \mathcal{C}$ ,  $\text{Hom}(A, B)$  (or  $\text{Hom}(B, A)$ ) is reduced to 0. If  $A$  and  $A'$  are zero objects, there exists a unique isomorphism of  $A$  to  $A'$  (that is, the unique zero element of  $\text{Hom}(A, A')$ !). We will identify all zero objects of  $\mathcal{C}$  to a single one, denoted 0 by abuse of notation.

(1.3.2). The dual category of an additive category is still additive.

(1.3.3). Let  $\mathcal{C}$  be an additive category and  $u : A \rightarrow B$  a morphism in  $\mathcal{C}$ . For  $u$  to be injective (respectively, surjective) it is necessary and sufficient that there not exist a non-zero morphism whose left, respectively, right, composite with  $u$  is 0. We call a *generalized kernel* of  $u$  any monomorphism  $i : A' \rightarrow A$  such that morphisms from  $C \rightarrow A$  which are right zero divisors of  $u$  are exactly the ones that factor through  $C \rightarrow A' \xrightarrow{i} A$ . Such a monomorphism is defined up to equivalence (cf. (1.1)), so among the generalized kernels of  $u$ , if any, there is exactly one that is a subobject of  $A$ . We call it *the kernel* of  $u$  and denote it by  $\text{Ker } u$ . Dually we define the *cokernel* of  $u$  (which is a quotient object of  $B$ , if it exists), denoted  $\text{Coker } u$ . We call *image* (respectively, *coimage*) of the morphism  $u$  the kernel of its cokernel (respectively, the cokernel of its kernel) if it exists. It is thus a subobject of  $B$  (a quotient object of  $A$ ). We denote them as  $\text{Im } u$  and  $\text{Coim } u$ . If  $u$  has an image and a coimage, there exists a unique morphism  $\bar{u} : \text{Coim } u \rightarrow \text{Im } u$  such that  $u$  is the composite  $A \rightarrow \text{Coim } u \xrightarrow{\bar{u}} \text{Im } u \rightarrow B$ , the extreme morphisms being the canonical ones.

(1.3.4). A functor  $F$  from one additive category  $\mathcal{C}$  to another additive category  $\mathcal{C}'$  is called an *additive functor* if for morphisms  $u, v : A \rightarrow B$  in  $\mathcal{C}$ , we have that  $F(u + v) = F(u) + F(v)$ . The definition for multifunctors is analogous. The composite of additive functors is additive. If  $F$  is an additive functor,  $F$  transforms a finite direct sum of objects  $A_i$  into the direct sum of  $F(A_i)$ .

### 1.4. Abelian Categories

(1.4.1). We call an *abelian category* an additive category  $\mathcal{C}$  that satisfies the following two additional conditions (which are self-dual):

(AB 1). Any morphism admits a kernel and a cokernel (cf. (1.3))

(AB 2). Let  $u$  be a morphism in  $\mathcal{C}$ . Then the canonical morphism  $\bar{u} : \text{Coim } u \rightarrow \text{Im } u$  (cf. (1.3)) is an isomorphism.

In particular, it follows that *a bijection is an isomorphism*. Note that there are numerous additive categories that satisfy (AB 1) and for which the morphism  $\bar{u} : \text{Coim } u \rightarrow \text{Im } u$  is bijective without being an isomorphism. This is true, for example, for the additive category of separated topological modules over some topological ring, taking as morphisms the continuous homomorphisms as well as for the category of *filtered* abelian groups. A less obvious example: the additive category of holomorphic fibered spaces with vector fibers over a holomorphic variety of complex dimension 1. These are some non-abelian additive categories.

(1.4.2). If  $\mathcal{C}$  is an abelian category, then the entire usual formalism of diagrams of homomorphisms between abelian groups can be carried over if we replace homomorphisms by morphisms in  $\mathcal{C}$ , insofar as we are looking at properties of finite type, i.e., not involving infinite direct sums or products (for which special precautions must be taken—see N°5). We content ourselves here with indicating a few particularly important facts, referring the reader to [Buc55] for additional details.

(1.4.3). In what follows we restrict ourselves to a fixed abelian category  $\mathcal{C}$ . Let  $A \in \mathcal{C}$ . To any subobject of  $A$  there corresponds the cokernel of its inclusion (which is thereby a quotient of  $A$ ), and to each

quotient object of  $A$  there corresponds the kernel of its projection (which is thereby a subobject of  $A$ ). We thus obtain *one-one correspondence between the class of subjects of  $A$  and the class of quotient objects of  $A$* . This correspondence is an *anti-isomorphism* between natural order relations. Moreover, the subobjects of  $A$  form a *lattice* (therefore so do the quotient objects): if  $P$  and  $Q$  are subobjects of  $A$ , their sup is the image of the direct sum  $P \oplus Q$  under the morphism whose components are the canonical injections of  $P$  and  $Q$  into  $A$ , and their inf is the kernel of the morphism of  $A$  to the product  $(A/P) \times (A/Q)$ , whose components are the canonical surjections to  $A/P$  and  $A/Q$ . (In accordance with usage, we indicate by  $A/P$  the quotient of  $A$  corresponding to the cokernel of the inclusion of  $P$  into  $A$ ; it seems natural to use a dual notation such as  $A \setminus R$  for the subobject of  $A$  that corresponds to the quotient object  $R$ . There are dual interpretations for the inf and sup of a pair of quotient objects of  $A$ .)

**(1.4.4).** Let  $u : A \rightarrow B$  be a morphism. If  $A'$  is a subobject of  $A$ , we define the image of  $A'$  under  $u$ , denoted  $u(A')$ , as  $\text{Im } ui$ , where  $i$  is the canonical injection  $A' \rightarrow A$ . Dually, we define the inverse image  $u^{-1}(B')$  of a quotient  $B'$  of  $B$ ; it is a quotient of  $A$ . If  $B'$  is now a subobject of  $B$ , we define the inverse image of  $B'$  under  $u$ , denoted  $u^{-1}(B')$ , as the kernel of  $ju$ , where  $j$  is the canonical surjection  $B \rightarrow B/B'$ . We define dually, the direct image  $u(A')$  of a quotient  $A'$  of  $A$ ; it is a quotient of  $B$ . We show all the usual formal properties for these notions.

**(1.4.5).** Recall that a pair  $A \xrightarrow{u} B \xrightarrow{v} C$  of two consecutive morphisms is said to be *exact* if  $\text{Ker } u = \text{Im } v$ ; more generally, we can define the notion of an *exact sequence* of morphisms. For a sequence  $0 \rightarrow A \rightarrow B \rightarrow C$  to be exact it is necessary and sufficient that for  $X \in \mathcal{C}$ , the following sequence of homomorphisms of abelian groups be exact:

$$(1.4.5.1) \quad 0 \longrightarrow \text{Hom}(X, A) \longrightarrow \text{Hom}(X, B) \longrightarrow \text{Hom}(X, C)$$

There is a dual criterion for  $A \rightarrow B \rightarrow C \rightarrow 0$  to be exact. Finally, a necessary and sufficient condition that the sequence  $0 \rightarrow A' \xrightarrow{u} A \xrightarrow{v} A'' \rightarrow 0$  be exact is that  $u$  is a monomorphism and that  $v$  is a generalized cokernel of  $u$ .

**(1.4.6).** Let  $F$  be a covariant functor of one abelian category  $\mathcal{C}$  to another  $\mathcal{C}'$ . Following the terminology introduced in [CE56], we say that  $F$  is a *half exact* functor (respectively, *left exact*, respectively, *right exact*) if for any exact sequence  $0 \rightarrow A' \rightarrow A \rightarrow A'' \rightarrow 0$  in  $\mathcal{C}$ , the corresponding sequence of morphisms  $0 \rightarrow F(A') \rightarrow F(A) \rightarrow F(A'') \rightarrow 0$  is exact at  $F(A)$  (respectively, exact at  $F(A)$  and  $F(A')$ , respectively, exact at  $F(A)$  and  $F(A'')$ ).  $F$  is called an *exact functor* if it is both left exact and right exact, i.e., transforms an exact sequence of the preceding type into an exact sequence; then  $F$  transforms *any* exact sequence into an exact sequence. If  $F$  is left exact,  $F$  transforms an exact sequence  $0 \rightarrow A \rightarrow B \rightarrow C$  into an exact sequence  $0 \rightarrow F(A) \rightarrow F(B) \rightarrow F(C)$ . There is a dual statement for the right exact functors. If  $F$  is a contravariant functor, we say that  $F$  is a half exact (respectively,  $F$  is left exact, etc.) if  $F$  has the corresponding property, as a covariant functor  $\mathcal{C}^{\text{op}}$  to  $\mathcal{C}'$ . The composite of left exact, respectively, right exact, covariant functors is of the same type. We refer back to [CE56] for further trivialities and for the study of exactness properties of multifunctors. As a significant example, we note that  $\text{Hom}(A, B)$  is an additive bifunctor on  $\mathcal{C}^{\text{op}} \times \mathcal{C}$ , with values in the abelian category of abelian groups, contravariant in  $A$  and covariant in  $B$ , and left exact with the respect to each argument (that is, in the terminology of [CE56], a left exact bifunctor).

## REFERENCES

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