

Algebraic Geometry

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Abstract

Algebraic Geometry Reading Notes

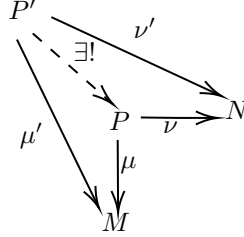
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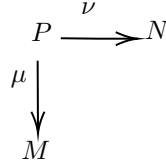
1 Category theory

1.1 Categories and functors

universal property : Given two sets M and N , a product is a set P , along with maps $\mu : P \rightarrow M$ and $\nu : P \rightarrow N$, such that for any set P' with maps $\mu' : P' \rightarrow M$ and $\nu' : P' \rightarrow N$, these maps must factor uniquely through P



product : a product is a diagram



category \mathcal{C} : a category consists of a collection of **objects**, and for each pair of objects, a set of **morphisms** (or **arrows**) between them

Morphisms are often informally called **maps**

obj(\mathcal{C}) : The collection of objects of a category \mathcal{C} is often denoted $\text{obj}(\mathcal{C})$, but we will usually denote the collection also by \mathcal{C}

Mor(A, B) : If $A, B \in \mathcal{C}$, then the set of morphisms from A to B is denoted $\text{Mor}(A, B)$

A morphism is often written $f : A \rightarrow B$, and A is said to be the **source** of f , and B the **target** of f

$\text{Mor}(B, C) \times \text{Mor}(A, B) \rightarrow \text{Mor}(A, C)$, and if $f \in \text{Mor}(A, B)$ and $g \in \text{Mor}(B, C)$, then their composition is denoted $g \circ f$. Composition is associative: if $f \in \text{Mor}(A, B)$, $g \in \text{Mor}(B, C)$, and $h \in \text{Mor}(C, D)$, then $h \circ (g \circ f) = (h \circ g) \circ f$

identity morphism : For each object $A \in \mathcal{C}$, there is always an identity morphism $\text{id}_A : A \rightarrow A$, such that when you (left- or right-)compose a morphism with the identity, you get the same morphism. More precisely, for any morphisms $f : A \rightarrow B$ and $g : B \rightarrow C$, $\text{id}_B \circ f = f$ and $g \circ \text{id}_B = g$

isomorphism : a notion of isomorphism between two objects of a category (a morphism $f : A \rightarrow B$ such that there exists some — necessarily unique — morphism $g : B \rightarrow A$, where $f \circ g$ and $g \circ f$ are the identity on B and A respectively)

automorphism : an isomorphism of the object with itself

Example 1.1 the category of sets, denoted **Sets**. The objects are sets, and the morphisms are maps of sets

Example 1.2 the category \mathbf{Vec}_k of vector spaces over a given field k . The objects are k -vector spaces, and the morphisms are linear transformations

Example 1.3 A category in which each morphism is an isomorphism is called a **groupoid**

- (a) A perverse definition of a group is: a groupoid with one object. Make sense of this
- (b) Describe a groupoid that is not a group

automorphism group : If A is an object in a category \mathcal{C} , then the invertible elements of $\mathbf{Mor}(A, A)$ form a group (called the automorphism group of A , denoted $\mathbf{Aut}(A)$)

the automorphism groups of the objects in

Example 1.1 : {bijections between A }

Example 1.2 : {linear isomorphism on A }

Two isomorphic objects have isomorphic automorphism groups, but these groups are not canonically isomorphic : if X is a topological space, then the fundamental groupoid is the category where the objects are points of X , and the morphisms $x \rightarrow y$ are paths from x to y , up to homotopy. Then the automorphism group of x_0 is the (pointed) fundamental group $\pi_1(X, x_0)$. In the case where X is connected, and $\pi_1(X)$ is not abelian, this illustrates the fact that for a connected groupoid, $\{x\}$ and $\{y\}$ have isomorphic automorphism groups, but $\pi_1(X, x)$ and $\pi_1(X, y)$ are not canonically isomorphic

Example 1.4 abelian groups: The abelian groups, along with group homomorphisms, form a category \mathbf{Ab}

Example 1.5 Modules over a ring. If A is a ring, then the A -modules form a category \mathbf{Mod}_A

Taking $A = k$, we obtain Example 1.2; taking $A = \mathbb{Z}$, we obtain Example 1.4

Example 1.6 rings. There is a category \mathbf{Rings} , where the objects are rings, and the morphisms are maps of rings in the usual sense

Example 1.7 topological spaces. The topological spaces, along with continuous maps, form a category \mathbf{Top} . The isomorphisms are homeomorphisms.

Example 1.8 partially ordered sets. A **partially ordered set**, (or **poset**), is a set S along with a binary relation \geq on S satisfying:

- (i) $x \geq x$ (reflexivity)
- (ii) $x \geq y$ and $y \geq z$ imply $x \geq z$ (transitivity)
- (iii) if $x \geq y$ and $y \geq x$ then $x = y$ (antisymmetry)

A partially ordered set (S, \geq) can be interpreted as a category whose objects are the elements of S , and with a single morphism from x to y if and only if $x \geq y$ (and no morphism otherwise).

Example 1.9 the category of subsets of a set, and the category of open subsets of a topological space. If X is a set, then the subsets form a partially ordered set, where the order is given by inclusion. Informally, if $U \subset V$, then we have exactly one morphism $U \rightarrow V$ in the category (and otherwise

none). Similarly, if X is a topological space, then the open sets form a partially ordered set, where the order is given by inclusion.

subcategory : a subcategory \mathcal{A} of a category \mathcal{B} has as its objects some of the objects of \mathcal{B} , and some of the morphisms, such that the morphisms of \mathcal{A} include the identity morphisms of the objects of \mathcal{A} , and are closed under composition

covariant functor : a covariant functor F from a category \mathcal{A} to a category \mathcal{B} , denoted $F : \mathcal{A} \rightarrow \mathcal{B}$, is the following data. It is a map of objects $F : \text{obj}(\mathcal{A}) \rightarrow \text{obj}(\mathcal{B})$, and for each $A_1, A_2 \in \mathcal{A}$, and morphism $m : A_1 \rightarrow A_2$, a morphism $F(m) : F(A_1) \rightarrow F(A_2)$ in \mathcal{B}

We require that F preserves identity morphisms (for $A \in \mathcal{A}$, $F(id_A) = id_{F(A)}$), and that F preserves composition ($F(m_2 \circ m_1) = F(m_2) \circ F(m_1)$)

A trivial example is the **identity functor** $id : \mathcal{A} \rightarrow \mathcal{A}$

forgetful functor : Consider the functor from the category of vector spaces (over a field k) Vec_k to $Sets$, that associates to each vector space its underlying set. The functor sends a linear transformation to its underlying map of sets. This is an example of a forgetful functor, where some additional structure is forgotten

Another example of a forgetful functor is $Mod_A \rightarrow Ab$ from A -modules to abelian groups, remembering only the abelian group structure of the A -module

Example 1.10 *Topological examples. (Examples of covariant functors)*

fundamental group functor π_1 , which sends a topological space X with choice of a point $x_0 \in X$ to a group $\pi_1(X, x_0)$

The i th homology functor $\mathbf{Top} \rightarrow \mathbf{Ab}$, which sends a topological space X to its i th homology group $H_i(X, \mathbb{Z})$

The covariance corresponds to the fact that a (continuous) morphism of pointed topological spaces $\phi : X \rightarrow Y$ with $\phi(x_0) = y_0$ induces a map of fundamental groups $\pi_1(X, x_0) \rightarrow \pi_1(Y, y_0)$, and similarly for homology groups

Example 1.11 *Suppose A is an object in a category \mathcal{C} . Then there is a functor $\mathbf{h}^A : \mathcal{C} \rightarrow \mathbf{Sets}$ sending $B \in \mathcal{C}$ to $\text{Mor}(A, B)$, and sending $f : B_1 \rightarrow B_2$ to $\text{Mor}(A, B_1) \rightarrow \text{Mor}(A, B_2)$ described by*

$$[g : A \rightarrow B_1] \mapsto [f \circ g : A \rightarrow B_1 \rightarrow B_2]$$

composition : If $F : \mathcal{A} \rightarrow \mathcal{B}$ and $G : \mathcal{B} \rightarrow \mathcal{C}$ are covariant functors, then we define a functor $G \circ F : \mathcal{A} \rightarrow \mathcal{C}$ (the composition of G and F) in the obvious way

A covariant functor $F : \mathcal{A} \rightarrow \mathcal{B}$ is **faithful** if for all $A, A' \in \mathcal{A}$, the map $\text{Mor}_{\mathcal{A}}(A, A') \rightarrow \text{Mor}_{\mathcal{B}}(F(A), F(A'))$ is injective, and **full** if it is surjective. A functor that is full and faithful is **fully faithful**

A subcategory $i : \mathcal{A} \rightarrow \mathcal{B}$ is a full subcategory if i is full. (Inclusions are always faithful, so there is no need for the phrase “faithful subcategory”.) Thus a subcategory \mathcal{A}' of \mathcal{A} is full if and only if for all $A, B \in \text{obj}(\mathcal{A}')$, $\text{Mor}_{\mathcal{A}'}(A, B) = \text{Mor}_{\mathcal{A}}(A, B)$

Example 1.12 *the forgetful functor $\text{Vec}_k \rightarrow \text{Sets}$ is faithful, but not full; and if A is a ring, the category of finitely generated A -modules is a full subcategory of the category Mod_A of A -modules*

contravariant functor : A contravariant functor is defined in the same way as a covariant functor, except the arrows switch directions: in the above language, $F(A_1 \rightarrow A_2)$ is now an arrow from $F(A_2)$ to $F(A_1)$. (Thus $F(m_2 \circ m_1) = F(m_1) \circ F(m_2)$, not $F(m_2) \circ F(m_1)$.)

It is wise to state whether a functor is covariant or contravariant, unless the context makes it very clear. If it is not stated (and the context does not make it clear), the functor is often assumed to be covariant

opposite category : \mathcal{C}^{opp} is the same category as \mathcal{C} except that the arrows go in the opposite direction. Here \mathcal{C}^{opp} is said to be the opposite category to \mathcal{C}

Sometimes people describe a contravariant functor $\mathcal{C} \rightarrow \mathcal{D}$ as a covariant functor $\mathcal{C}^{opp} \rightarrow \mathcal{D}$

Example 1.13 *Linear algebra example 1.2*

If Vec_k is the category of k -vector spaces, then taking duals gives a contravariant functor $()^\vee : \text{Vec}_k \rightarrow \text{Vec}_k$. Indeed, to each linear transformation $f : V \rightarrow W$, we have a dual transformation $f^\vee : W^\vee \rightarrow V^\vee$, and $(f \circ g)^\vee = g^\vee \circ f^\vee$

Example 1.14 *Topological example 1.10*

The i th cohomology functor $H_i(\cdot, \mathbb{Z}) : \text{Top} \rightarrow \text{Ab}$ is a contravariant functor

Example 1.15 *There is a contravariant functor $\text{Top} \rightarrow \text{Rings}$ taking a topological space X to the ring of real-valued continuous functions on X . A morphism of topological spaces $X \rightarrow Y$ (a continuous map) induces the pullback map from functions on Y to functions on X*

Example 1.16 *the functor of points 1.11*

Suppose A is an object of a category \mathcal{C} . Then there is a contravariant functor $h_A : \mathcal{C} \rightarrow \text{Sets}$ sending $B \in \mathcal{C}$ to $\text{Mor}(B, A)$, and sending the morphism $f : B_1 \rightarrow B_2$ to the morphism $\text{Mor}(B_2, A) \rightarrow \text{Mor}(B_1, A)$ via

$$[g : B_2 \rightarrow A] \mapsto [g \circ f : B_1 \rightarrow B_2 \rightarrow A]$$

Examples 1.13 and 1.15 may be interpreted as special cases

natural transformation of covariant functors $F \rightarrow G$: Suppose F and G are two covariant functors from \mathcal{A} to \mathcal{B} . A natural transformation of covariant functors $F \rightarrow G$ is the data of a morphism $\mathbf{m}_A : F(A) \rightarrow G(A)$ for each $A \in \mathcal{A}$ such that for each $f : A \rightarrow A'$ in \mathcal{A} , the diagram commutes:

$$\begin{array}{ccc}
F(A) & \xrightarrow{F(f)} & F(A') \\
\mathfrak{m}_A \downarrow & & \downarrow \mathfrak{m}_{A'} \\
G(A) & \xrightarrow{G(f)} & G(A')
\end{array}$$

natural isomorphism : A natural isomorphism of functors is a natural transformation such that each m_A is an isomorphism. (We make analogous definitions when F and G are both contravariant.)

equivalence of categories : The data of functors $F : \mathcal{A} \rightarrow \mathcal{B}$ and $F' : \mathcal{B} \rightarrow \mathcal{A}$ such that $F' \circ F$ is naturally isomorphic to the identity functor $id_{\mathcal{A}}$ on \mathcal{A} and $F \circ F'$ is naturally isomorphic to $id_{\mathcal{B}}$ is said to be an equivalence of categories

Example 1.17 Let $f.d.Vec_k$ be the category of finite-dimensional vector spaces over k

Let $(\cdot)^{\vee\vee} : f.d.Vec_k \rightarrow f.d.Vec_k$ be the double dual functor from the category of finite-dimensional vector spaces over k to itself. Then $(\cdot)^{\vee\vee}$ is naturally isomorphic to the identity functor on $f.d.Vec_k$. (Without the finite-dimensionality hypothesis, we only get a natural transformation of functors from id to $(\cdot)^{\vee\vee}$)

Let \mathcal{V} be the category whose objects are the k -vector spaces k^n for each $n \geq 0$ (there is one vector space for each n), and whose morphisms are linear transformations. The objects of \mathcal{V} can be thought of as vector spaces with bases, and the morphisms as matrices. There is an obvious functor $\mathcal{V} \rightarrow f.d.Vec_k$, as each k^n is a finite-dimensional vector space

Example 1.18 $\mathcal{V} \rightarrow f.d.Vec_k$ gives an equivalence of categories, by describing an “inverse” functor

1.2 Universal properties determine an object up to unique isomorphism

Products were defined by a universal property

initial objects : An object of a category \mathcal{C} is an initial object if it has precisely one map to every object

final objects : It is a final object if it has precisely one map from every object

zero objects : It is a zero object if it is both an initial object and a final object

Example 1.19 *Any two initial objects are uniquely isomorphic. Any two final objects are uniquely isomorphic*

This (partially) justifies the phrase “the initial object” rather than “an initial object”, and similarly for “the final object” and “the zero object”

(Convention: we often say “the”, not “a”, for anything defined up to unique isomorphism)

Example 1.20 *The initial and final objects in Sets, Rings, and Top (if they exist)?*

Localization of rings and modules

$A \rightarrow S^{-1}A$ satisfies the following universal property:

$S^{-1}A$ is initial among A -algebras B where every element of S is sent to an invertible element in B .

(Recall: the data of “an A -algebra B ” and “a ring map $A \rightarrow B$ ” are the same)

Translation: any map $A \rightarrow B$ where every element of S is sent to an invertible element must factor uniquely through $A \rightarrow S^{-1}A$

Another translation: a ring map out of $S^{-1}A$ is the same thing as a ring map from A that sends every element of S to an invertible element

Category theoretic description : If A is a ring and S is a subset, consider all A -algebras B , so that, under the canonical homomorphism $A \rightarrow B$, every element of S is mapped to a unit. These algebras are the objects of a category, with A -algebra homomorphisms as morphisms. Then, the localization of A at S is the initial object of this category. (This is a more abstract way of expressing the universal property above.)

Furthermore, an $S^{-1}A$ -module is the same thing as an A -module for which $s \times \cdot : M \rightarrow M$ is an A -module isomorphism for all $s \in S$

Let’s get some practice with this by defining localizations of modules by universal property. Suppose M is an A -module. We define the A -module map $\phi : M \rightarrow S^{-1}M$ as being initial among A -module maps $M \rightarrow N$ such that elements of S are invertible in N ($s \times \cdot : N \rightarrow N$ is an isomorphism for all $s \in S$). More precisely, any such map $\alpha : M \rightarrow N$ factors uniquely through ϕ :

$$\begin{array}{ccc}
M & \xrightarrow{\phi} & S^{-1}M \\
& \searrow \alpha & \downarrow \exists! \\
& & N
\end{array}$$

(Translation: $M \rightarrow S^{-1}M$ is universal (initial) among A -module maps from M to modules that are actually $S^{-1}A$ -modules)

Tensor products

Another important example of a universal property construction is the notion of a tensor product of A -modules

$$\begin{aligned}
\otimes_A : \text{obj}(\text{Mod}_A) \times \text{obj}(\text{Mod}_A) &\rightarrow \text{obj}(\text{Mod}_A) \\
(M, N) &\rightarrow M \otimes_A N
\end{aligned}$$

Proposition 1.21 $(\cdot) \otimes_A N$ gives a covariant functor $\text{Mod}_A \rightarrow \text{Mod}_A$. Then $(\cdot) \otimes_A N$ is a **right-exact** functor, i.e., if $M' \rightarrow M \rightarrow M'' \rightarrow 0$ is an exact sequence of A -modules, then the induced sequence is also exact:

$$M' \otimes_A N \rightarrow M \otimes_A N \rightarrow M'' \otimes_A N \rightarrow 0$$

Category theoretic description : a tensor product of M and N is an A -module T along with an A -bilinear map $t : M \times N \rightarrow T$, such that given any A -bilinear map $t' : M \times N \rightarrow T'$, there is a unique A -linear map $f : T \rightarrow T'$ such that $t' = f \circ t$

$$\begin{array}{ccc}
M \times N & \xrightarrow{t} & T = M \otimes_A N \\
& \searrow t' & \downarrow \exists! f \\
& & T'
\end{array}$$

Remark 1.22 (a) If M is an A -module and $A \rightarrow B$ is a morphism of rings, give $B \otimes_A M$ the structure of a B -module. This describes a functor $\text{Mod}_A \rightarrow \text{Mod}_B$

(b) If further $A \rightarrow C$ is another morphism of rings, show that $B \otimes_A C$ has a natural structure of a ring. Hint: multiplication will be given by $(b_1 \otimes c_1)(b_2 \otimes c_2) = (b_1 b_2) \otimes (c_1 c_2)$

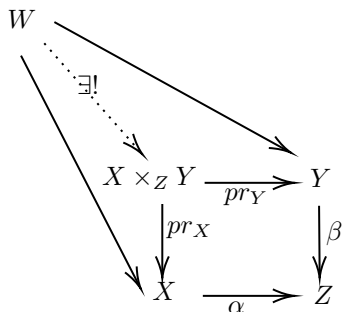
Remark 1.23 If S is a multiplicative subset of A and M is an A -module, there is a natural isomorphism $(S^{-1}A) \otimes_A M \cong S^{-1}M$ (as $S^{-1}A$ -modules and as A -modules)

Remark 1.24 tensor products commute with arbitrary direct sums: if M and $\{N_i\}_{i \in I}$ are all A -modules, describe an isomorphism

$$M \otimes (\oplus_{i \in I} N_i) \cong \oplus_{i \in I} (M \otimes N_i)$$

Fibered products

Suppose we have morphisms $\alpha : X \rightarrow Z$ and $\beta : Y \rightarrow Z$ (in any category). Then the fibered product (or fibred product) is an object $X \times_Z Y$ along with morphisms $pr_X : X \times_Z Y \rightarrow X$ and $pr_Y : X \times_Z Y \rightarrow Y$, where the two compositions $\alpha \circ pr_X, \beta \circ pr_Y : X \times_Z Y \rightarrow Z$ agree, such that given any object W with maps to X and Y (whose compositions to Z agree), these maps factor through some unique $W \rightarrow X \times_Z Y$:



Depending on your religion, the diagram

$$\begin{array}{ccc} X \times_Z Y & \xrightarrow{pr_Y} & Y \\ \downarrow pr_X & & \downarrow \beta \\ X & \xrightarrow{\alpha} & Z \end{array}$$

is called a **fibered/pullback/Cartesian diagram/square** (six possibilities — even more are possible if you prefer “fibred” to “fibered”)

Example 1.25 In *Sets*, $X \times_Z Y = \{(x, y) \in X \times Y : \alpha(x) = \beta(y)\}$.

Example 1.26 If Z is the final object in a category \mathcal{C} , and $X, Y \in \mathcal{C}$, then $X \times_Z Y = X \times Y$: “the” fibered product over Z is uniquely isomorphic to “the” product. (Assume all relevant (fibered) products exist)

Example 1.27 If the two squares in the following commutative diagram are Cartesian diagrams, show that the “outside rectangle” (involving U, V, Y , and Z) is also a Cartesian diagram

$$\begin{array}{ccc} U & \longrightarrow & V \\ \downarrow & & \downarrow \\ W & \longrightarrow & X \\ \downarrow & & \downarrow \\ Y & \longrightarrow & Z \end{array}$$

Example 1.28 Given morphisms $X_1 \rightarrow Y, X_2 \rightarrow Y$, and $Y \rightarrow Z$, then there is a natural morphism $X_1 \times_Y X_2 \rightarrow X_1 \times_Z X_2$

Remark 1.29 *The magic diagram*

Suppose we are given morphisms $X_1, X_2 \rightarrow Y$ and $Y \rightarrow Z$. Then the following diagram is a Cartesian square :

$$\begin{array}{ccc} X_1 \times_Y X_2 & \longrightarrow & X_1 \times_Z X_2 \\ \downarrow & & \downarrow \\ Y & \longrightarrow & Y \times_Z Y \end{array}$$

(Assume all relevant (fibered) products exist)

(Hint : if $Y \times_Z Y$ exists, then $X_1 \times_Z X_2 \rightarrow X_2 \rightarrow Y$ and $X_1 \times_Z X_2 \rightarrow X_1 \rightarrow Y$ are equal)

Coproducts

Define coproduct in a category by reversing all the arrows in the definition of product.

For \mathcal{C} a category and $X, Y \in \text{Obj}(\mathcal{C})$ two objects, their coproduct is an object $X \amalg Y$ in \mathcal{C} equipped with two morphisms

$$\begin{array}{ccc} & Y & \\ & \downarrow i_Y & \\ X & \xrightarrow{i_X} & X \amalg Y \end{array}$$

such that this is universal with this property, meaning such that for any other object with maps like this

$$\begin{array}{ccc} & Y & \\ & \downarrow g & \\ X & \xrightarrow{f} & Q \end{array}$$

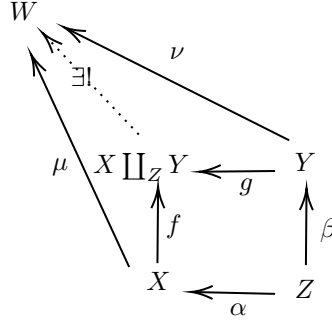
there exists a unique morphism $(f, g) : X \amalg Y \rightarrow Q$ such that we have the following commuting diagram:

$$\begin{array}{ccc} & Y & \\ & \downarrow i_Y & \searrow g \\ X & \xrightarrow{i_X} & X \amalg Y \\ & \searrow f & \swarrow \exists!(f, g) \\ & & Q \end{array}$$

This morphism (f, g) are called copairing of f and g . The morphism $X \rightarrow X \amalg Y$ and $Y \rightarrow X \amalg Y$ coprojections or sometimes “injections” or “inclusions”, although in general they may not be monomorphisms

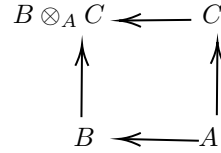
fibred coproduct

Define fibred coproduct in a category by reversing all the arrows in the definition of fibred product.



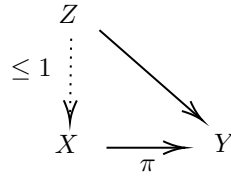
Example 1.30 Coproduct for Sets is disjoint union

Remark 1.31 Suppose $A \rightarrow B$ and $A \rightarrow C$ are two ring morphisms, so in particular B and C are A -modules. Recall that $B \otimes_A C$ has a ring structure. Then there is a natural morphism $B \rightarrow B \otimes_A C$ given by $b \mapsto b \otimes 1$. (This is not necessarily an inclusion) Similarly, there is a natural morphism $C \rightarrow B \otimes_A C$. This gives a fibred coproduct on rings, i.e., that



satisfies the universal property of fibred coproduct

monomorphism : a morphism $\pi : X \rightarrow Y$ is a monomorphism if any two morphisms $\mu_1 : Z \rightarrow X$ and $\mu_2 : Z \rightarrow X$ such that $\pi \circ \mu_1 = \pi \circ \mu_2$ must satisfy $\mu_1 = \mu_2$. In other words, there is at most one way of filling in the dotted arrow so that the diagram



commutes — for any object Z , the natural map $\text{Mor}(Z, X) \rightarrow \text{Mor}(Z, Y)$ is an injection

Remark 1.32 The composition of two monomorphisms is a monomorphism

Remark 1.33 A morphism $\pi : X \rightarrow Y$ is a monomorphism \Leftrightarrow the fibred product $X \times_Y X$ exists, and the induced morphism $X \rightarrow X \times_Y X$ is an isomorphism

Remark 1.34 If $Y \rightarrow Z$ is a monomorphism, then the morphism $X_1 \times_Y X_2 \rightarrow X_1 \times_Z X_2$ is an isomorphism

epimorphism : a morphism $\pi : Y \rightarrow X$ is an epimorphism if any two morphisms $\mu_1 : X \rightarrow Z$ and $\mu_2 : X \rightarrow Z$ such that $\mu_1 \circ \pi = \mu_2 \circ \pi$ must satisfy $\mu_1 = \mu_2$. In other words, there is at most one way of filling in the dotted arrow so that the diagram

$$\begin{array}{ccc} & Z & \\ \uparrow \scriptstyle \leq 1 & \nearrow & \\ X & \xleftarrow{\pi} & Y \end{array}$$

commutes — for any object Z , the natural map $\text{Mor}(X, Z) \rightarrow \text{Mor}(Y, Z)$ is an injection

Representable functors and Yoneda's Lemma Suppose A is an object of category \mathcal{C} . For any object $C \in \mathcal{C}$, we have a set of morphisms $\text{Mor}(C, A)$. If we have a morphism $f : B \rightarrow C$, we get a map of sets

$$\text{Mor}(C, A) \rightarrow \text{Mor}(B, A)$$

by composition: given a map from C to A , we get a map from B to A by precomposing with $f : B \rightarrow C$. Hence this gives a contravariant functor $h_A : \mathcal{C} \rightarrow \text{Sets}$. Yoneda's Lemma states that the functor h_A determines A up to unique isomorphism. More precisely:

Lemma 1.35 (a) Suppose you have two objects A and A' in a category \mathcal{C} , and morphisms

$$i_C : \text{Mor}(C, A) \rightarrow \text{Mor}(C, A')$$

that commute with the maps

$$\text{Mor}(C, A) \rightarrow \text{Mor}(B, A)$$

for all the (B, C, f) that $f : B \rightarrow C$

Then the i_C (as C ranges over the objects of \mathcal{C}) are induced from a unique morphism $g : A \rightarrow A'$. More precisely, there is a unique morphism $g : A \rightarrow A'$ such that for all $C \in \mathcal{C}$, i_C is $u \mapsto g \circ u$

(b) If furthermore the i_C are all bijections, then the resulting g is an isomorphism

(Hint : looking for an element $\text{Mor}(A, A')$. So just plug in $C = A$ to the first equation, and see where the identity goes

There is an analogous statement with the arrows reversed, where instead of maps into A , you think of maps from A . The role of the contravariant functor h_A is played by the covariant functor h^A . The proof is the same (with the arrows reversed)

Lemma 1.36 (a) Suppose A and B are objects in a category \mathcal{C} . There is a bijection between the natural transformations $h_A \rightarrow h_B$ of covariant functors $\mathcal{C} \rightarrow \text{Sets}$ and the morphisms $B \rightarrow A$

(b) Suppose A and B are objects in a category \mathcal{C} . There is a bijection between the natural transformations $h_A \rightarrow h_B$ of contravariant functors $\mathcal{C} \rightarrow \text{Sets}$ and the morphisms $A \rightarrow B$

Representable functors : a contravariant functor F from \mathcal{C} to *Sets* is said to be **representable** if there is a natural isomorphism :

$$\xi : F \cong h_A$$

Thus the representing object A is determined up to unique isomorphism by the pair (F, ξ) . There is a similar definition for covariant functors. (The element $\xi^{-1}(id_A) \in F(A)$ is often called the “universal object”; do you see why?)

(c) **Yoneda’s Lemma.** Suppose F is a covariant functor $\mathcal{C} \rightarrow \text{Sets}$, and $A \in \mathcal{C}$. There is a bijection between the natural transformations $h^A \rightarrow F$ and $F(A)$

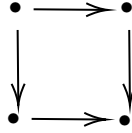
1.3 Limits and colimits

Limits

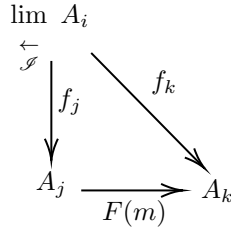
small category : we say that a category is a small category if the objects and the morphisms are sets

index category : Suppose \mathcal{I} is any small category, and \mathcal{C} is any category. Then a functor $F : \mathcal{I} \rightarrow \mathcal{C}$ (i.e., with an object $A_i \in \mathcal{C}$ for each element $i \in \mathcal{I}$, and appropriate commuting morphisms dictated by \mathcal{I}) is said to be a **diagram indexed by \mathcal{I}** . We call \mathcal{I} an index category

Example 1.37 if \square is the category in the figure below, and \mathcal{A} is a category, then a functor $\square \rightarrow \mathcal{A}$ is precisely the data of a commuting square in \mathcal{A}



limit of the diagram (inverse limit / projective limit) : the limit of the diagram is an object $\varprojlim_{\mathcal{I}} A_i$ of \mathcal{C} along with morphisms $f_j : \varprojlim_{\mathcal{I}} A_i \rightarrow A_j$ for each $j \in \mathcal{I}$, such that if $m : j \rightarrow k$ is a morphism in \mathcal{I} , then



commutes, and this object and maps to each A_i are universal (final) with respect to this property

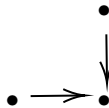
More precisely, given any other object W along with maps $g_i : W \rightarrow A_i$ commuting with the $F(m)$ (if $m : j \rightarrow k$ is a morphism in I , then $g_k = F(m) \circ g_j$), then there is a unique map

$$g : W \rightarrow \varprojlim_{\mathcal{I}} A_i$$

so that $g_i = f_i \circ g$ for all i .

Example 1.38 fibered product

If \mathcal{I} is the partially ordered set:



we obtain the fibered product

Example 1.39 product

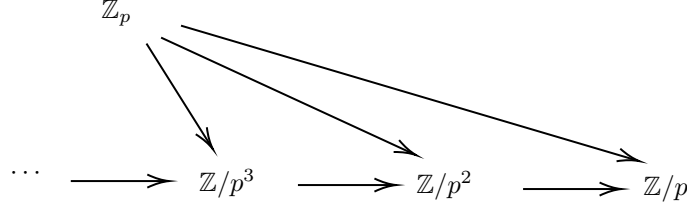
If \mathcal{I} is $\bullet \rightarrow \bullet$, we obtain the product

If \mathcal{I} is a set (i.e., the only morphisms are the identity maps), then the limit is called the **product** of the A_i , and is denoted $\prod_i A_i$. The special case where \mathcal{I} has two elements is the example of the previous paragraph

Example 1.40 If \mathcal{I} has an initial object e , then A_e is the limit, and in particular the limit always exists

Example 1.41 *p*-adic integers

a *p*-adic integer is an element of the inverse limit in the category of the rings :



Remark 1.42 In the category *Sets*

$$\left\{ (a_i)_{i \in \mathcal{I}} \in \prod_i A_i : F(m)(a_j) = a_k \text{ for all } m \in \text{Mor}_{\mathcal{I}}(j, k) \in \text{Mor}(\mathcal{I}) \right\}$$

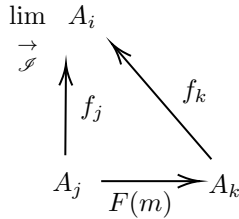
along with the obvious projection maps to each A_i , is the limit $\varprojlim_{\mathcal{I}} A_i$

This clearly also works in the category Mod_A of A -modules (in particular Vec_k and Ab), as well as *Rings*

From this point of view, $2 + 3p + 2p^2 + \cdots \in \mathbb{Z}_p$ can be understood as the sequence $(2, 2 + 3p, 2 + 3p + 2p^2, \cdots)$

colimits (direct limit / inductive limit / injective limit)

the colimit of the diagram is an object $\varinjlim_{\mathcal{I}} A_i$ of \mathcal{C} along with morphisms $f_j : A_j \rightarrow \varinjlim_{\mathcal{I}} A_i$ for each $j \in \mathcal{I}$, such that if $m : j \rightarrow k$ is a morphism in \mathcal{I} , then



commutes, and this object and maps to each A_i are universal (final) with respect to this property

More precisely, given any other object W along with maps $g_i : A_i \rightarrow W$ commuting with the $F(m)$ (if $m : j \rightarrow k$ is a morphism in \mathcal{I} , then $g_j = g_k \circ F(m)$), then there is a unique map $g : \varinjlim_{\mathcal{I}} A_i \rightarrow W$ so that $g_i = g \circ f_i$ for all i

Example 1.43 The set $5^{-\infty}\mathbb{Z}$ of rational numbers whose denominators are powers of 5 is a colimit $\varinjlim_{\mathcal{I}} 5^{-i}\mathbb{Z}$. More precisely, $5^{-\infty}\mathbb{Z}$ is the colimit of the diagram

$$\mathbb{Z} \longrightarrow 5^{-1}\mathbb{Z} \longrightarrow 5^{-2}\mathbb{Z} \longrightarrow \cdots$$

Example 1.44 *coproduct*

If \mathcal{I} is $\bullet \bullet$, we obtain the coproduct

If \mathcal{I} is a set (i.e., the only morphisms are the identity maps), then the colimit is called the **coproduct** of the A_i , and is denoted $\coprod_i A_i$. The special case where \mathcal{I} has two elements is the example of the previous paragraph

Example 1.45 $\mathbb{Q} = \varinjlim \frac{1}{n}\mathbb{Z}$

Example 1.46 Define $U \rightarrow V$ iff $V \subset U$, then some subsets of a given set as a colimit. (Dually, the intersection can be interpreted as a limit.) The objects of the category in question are the subsets of the given set.

filtered (directed partially ordered set / filtered index category) :

a nonempty partially ordered set (S, \geq) is filtered (or is said to be a filtered set) if for each $x, y \in S$, there is a z such that $x \geq z$ and $y \geq z$. More generally, a nonempty category \mathcal{I} is filtered if:

- (i) for each $x, y \in \mathcal{I}$, there is $az \in \mathcal{I}$ and arrows $x \rightarrow z$ and $y \rightarrow z$, and
- (ii) for every two arrows $u : x \rightarrow y$ and $v : x \rightarrow y$, there is an arrow $w : y \rightarrow z$ such that $w \circ u = w \circ v$

Remark 1.47 Suppose \mathcal{I} is filtered. (We will almost exclusively use the case where \mathcal{I} is a filtered set.) Recall the symbol \coprod for disjoint union of sets. Then any diagram in *Sets* indexed by \mathcal{I} has the following, with the obvious maps to it, as a colimit:

$$\left\{ (a_i, i) \in \coprod_{i \in \mathcal{I}} A_i \right\} / ((a_i, i) \sim (a_j, j) \text{ if and only if there are } f : A_i \rightarrow A_k \text{ and } g : A_j \rightarrow A_k \text{ in the diagram for which } f(a_i) = g(a_j) \text{ in } A_k)$$

Example 1.48 The colimit $\varinjlim M_i$ in the category of A -modules Mod_A can be described as follows. The set underlying $\varinjlim M_i$ is defined as in Remark 1.47. To add the elements $m_i \in M_i$ and $m_j \in M_j$, choose an $l \in \mathcal{I}$ with arrows $u : i \rightarrow l$ and $v : j \rightarrow l$, and then define the sum of m_i and m_j to be $F(u)(m_i) + F(v)(m_j) \in M_l$. The element $m_i \in M_i$ is 0 if and only if there is some arrow $u : i \rightarrow k$ for which $F(u)(m_i) = 0$, i.e., if it becomes 0 “later in the diagram”. Last, multiplication by an element of A is defined in the obvious way

The A -module described above is indeed the colimit

Example 1.49 Direct limits exist in the category (Set) and (Ab) of sets and abelian groups. More precisely:

(1) Let $(\{A_i\}_{i \in I}, \{\rho_{ij}\}_{i, j \in I})$ be a direct system in (Set) . Then $\varinjlim_{i \in I} A_i = \coprod_{i \in I} A_i / \sim$, where $a_i \sim a_j$ if and only if there exists $k \in I$ such that $i, j \leq k$ and $\rho_{ik}(a_i) = \rho_{jk}(a_j)$, together with the maps $\rho_i : A_i \rightarrow \coprod_{i \in I} A_i / \sim$ induced by the inclusions is a direct limit of $(\{A_i\}_{i \in I}, \{\rho_{ij}\}_{i, j \in I})$.

(2) Let $(\{A_i\}_{i \in I}, \{\rho_{ij}\}_{i,j \in I})$ be a direct system in (Ab) . Then $\lim_{\rightarrow} A_i = \bigoplus_{i \in I} A_i / N$ where N is the subgroup generated by elements of the form $a_i - \rho_{ij}(a_j)$ together with the maps $\rho_i : A_i \rightarrow \bigoplus_{i \in I} A_i / N$ induced by the inclusions is a direct limit of $(\{A_i\}_{i \in I}, \{\rho_{ij}\}_{i,j \in I})$.

(3) Let $(\{A_i\}_{i \in I}, \{\rho_{ij}\}_{i,j \in I})$ be a direct system in (Ab) . Forgetting the group structure, it becomes a direct system in (Set) . The induced map $\prod_{i \in I} A_i / \sim \rightarrow \bigoplus_{i \in I} A_i / N$ is a bijection that identifies the f_i in (1) and (2).

Similarly, if $(\{A_i\}_{i \in I}, \{\rho_{ij}\}_{i,j \in I})$ is a direct system of modules or rings, then the direct limit exists and the underlying set is the direct limit of the underlying sets.

Example 1.50 Suppose S is a multiplicative set of integral domain A , then $S^{-1}A = \lim_{\rightarrow} \frac{1}{s}A$ where the limit is over $s \in S$, and in the category of A -modules

Example 1.51 COLIMITS OF A -MODULES WITHOUT THE FILTERED CONDITION

Suppose you are given a diagram of A -modules indexed by $\mathcal{I} : F : \mathcal{I} \rightarrow Mod_A$, where we let $M_i := F(i)$. Show that the colimit is $\bigoplus_{i \in \mathcal{I}} M_i$ modulo the relations $m_i - F(n)(m_j)$ for every $n : i \rightarrow j$ in \mathcal{I} (i.e., for every arrow in the diagram). (Some what more precisely: “modulo” means “quotiented by the submodule generated by”)

1.4 Adjoints

adjoints :

Two covariant functors $F : \mathcal{A} \rightarrow \mathcal{B}$ and $G : \mathcal{B} \rightarrow \mathcal{A}$ are adjoint if there is a natural bijection for all $A \in \mathcal{A}$ and $B \in \mathcal{B}$

$$\tau_{AB} : \text{Mor}_{\mathcal{B}}(F(A), B) \rightarrow \text{Mor}_{\mathcal{A}}(A, G(B))$$

We say that (F, G) form an **adjoint pair**, and that F is **left-adjoint** to G (and G is **right-adjoint** to F). We say F is a **left adjoint** (and G is a **right adjoint**)

By “natural” we mean the following. For all $f : A \rightarrow A'$ in \mathcal{A} , we require

$$\begin{array}{ccc} \text{Mor}_{\mathcal{B}}(F(A'), B) & \xrightarrow{Ff^*} & \text{Mor}_{\mathcal{B}}(F(A), B) \\ \tau_{A'B} \downarrow & & \downarrow \tau_{AB} \\ \text{Mor}_{\mathcal{A}}(A', G(B)) & \xrightarrow{f^*} & \text{Mor}_{\mathcal{A}}(A, G(B)) \end{array}$$

to commute, and for all $g : B \rightarrow B'$ in \mathcal{B} we want a similar commutative diagram to commute

$$\begin{array}{ccc} \text{Mor}_{\mathcal{B}}(F(A), B) & \xrightarrow{g^*} & \text{Mor}_{\mathcal{B}}(F(A), B') \\ \tau_{AB} \downarrow & & \downarrow \tau_{AB'} \\ \text{Mor}_{\mathcal{A}}(A, G(B)) & \xrightarrow{Gg^*} & \text{Mor}_{\mathcal{A}}(A, G(B')) \end{array}$$

(Here f^* is the map induced by $f : A \rightarrow A'$, and Ff^* is the map induced by $Ff : F(A) \rightarrow F(A')$)

In fact, we have :

$$\begin{array}{ccccc} \text{Mor}_{\mathcal{B}}(F(A'), B) & \xrightarrow{Ff^*} & \text{Mor}_{\mathcal{B}}(F(A), B) & \xrightarrow{g^*} & \text{Mor}_{\mathcal{B}}(F(A), B') \\ \tau_{A'B} \downarrow & & \downarrow \tau_{AB} & & \downarrow \tau_{AB'} \\ \text{Mor}_{\mathcal{A}}(A', G(B)) & \xrightarrow{f^*} & \text{Mor}_{\mathcal{A}}(A, G(B)) & \xrightarrow{Gg^*} & \text{Mor}_{\mathcal{A}}(A, G(B')) \end{array}$$

Remark 1.52 The map τ_{AB} has the following properties :

For each A there is a map $\eta_A : A \rightarrow GF(A)$ so that for any $g : F(A) \rightarrow B$, the corresponding $\tau_{AB}(g) : A \rightarrow G(B)$ is given by the composition

$$A \xrightarrow{\eta_A} GF(A) \xrightarrow{Gg} G(B)$$

Similarly, there is a map $\epsilon_B : FG(B) \rightarrow B$ for each B so that for any $f : A \rightarrow G(B)$, the corresponding map $\tau_{AB}^{-1}(f) : F(A) \rightarrow B$ is given by the composition

$$F(A) \xrightarrow{Ff} FG(B) \xrightarrow{\epsilon_B} B$$

Proof:

$$\begin{array}{ccc}
\text{Mor}_{\mathcal{B}}(F(A), F(A)) & \xrightarrow{g^*} & \text{Mor}_{\mathcal{B}}(F(A), B) \\
\tau_{A, F(A)} \downarrow & & \downarrow \tau_{AB} \\
\text{Mor}_{\mathcal{A}}(A, GF(A)) & \xrightarrow{Gg^*} & \text{Mor}_{\mathcal{A}}(A, G(B))
\end{array}$$

So $\eta_A = \tau_{A, F(A)}(1_{F(A)})$

□

Example 1.53 Suppose M, N , and P are A -modules (where A is a ring). There is a bijection

$$\text{Hom}_A(M \otimes_A N, P) \leftrightarrow \text{Hom}_A(M, \text{Hom}_A(N, P))$$

(Hint : try to use the universal property of \otimes)

$(\cdot) \otimes_A N$ and $\text{Hom}_A(N, \cdot)$ are adjoint functors

Example 1.54 Suppose $B \rightarrow A$ is a morphism of rings. If M is an A -module, We can create a B -module M_B by considering it as a B -module. This gives a functor $\cdot_B : \text{Mod}_A \rightarrow \text{Mod}_B$. Then this functor is right-adjoint to $\cdot \otimes_B A$. In other words, there is a bijection

$$\text{Hom}_A(N \otimes_B A, M) \cong \text{Hom}_B(N, M_B)$$

Example 1.55 For those familiar with representation theory:

Frobenius reciprocity may be understood in terms of adjoints. Suppose V is a finite-dimensional representation of a finite group G , and W is a representation of a subgroup $H < G$. Then induction and restriction are an adjoint pair $(\text{Ind}_H^G, \text{Res}_H^G)$ between the category of G -modules and the category of H -modules

Example 1.56 The loop space is dual to the suspension of the same space; this duality is sometimes called Eckmann–Hilton duality. The basic observation is that $[\sum Z, X] \cong [Z, \Omega X]$

Example 1.57 groupification of abelian semigroups

Here is another motivating example: getting an abelian group from an abelian semigroup. (An abelian semigroup is just like an abelian group, except we don't require an identity or an inverse. Morphisms of abelian semigroups are maps of sets preserving the binary operation. One example is the non-negative integers \mathbb{N} under addition. Another is the positive integers \mathbb{N}^* under multiplication. You may enjoy groupifying both.) From an abelian semigroup, you can create an abelian group. Here is a formalization of that notion.

A groupification of a semigroup S is a map of abelian semigroups $\pi : S \rightarrow G$ such that G is an abelian group, and any map of abelian semigroups from S to an abelian group G' factors uniquely through G :

$$\begin{array}{ccc}
S & \xrightarrow{\pi} & G \\
& \searrow & \vdots \exists! \\
& & G'
\end{array}$$

Construct the “groupification functor” H from the category of nonempty abelian semigroups to the category of abelian groups.

Let F be the forgetful functor from the category of abelian groups \mathbf{Ab} to the category of abelian semigroups. Then H is left-adjoint to F .

Example 1.58 $S^{-1}A$ -modules are a fully faithful subcategory of the category of A -modules (via the obvious inclusion $\text{Mod}_{S^{-1}A} \hookrightarrow \text{Mod}_A$). Then $\text{Mod}_A \rightarrow \text{Mod}_{S^{-1}A}$ can be interpreted as an adjoint to the forgetful functor $\text{Mod}_{S^{-1}A} \rightarrow \text{Mod}_A$

Remark 1.59 Here is a table of most of the adjoints that will come up for us.

situation	category \mathcal{A}	category \mathcal{B}	left adjoint $F : \mathcal{A} \rightarrow \mathcal{B}$	right adjoint $G : \mathcal{B} \rightarrow \mathcal{A}$
A -modules			$(\cdot) \otimes_A N$	$\text{Hom}_A(N, \cdot)$
ring maps $B \rightarrow A$	Mod_B	Mod_A	$(\cdot) \otimes_B$ (extension of scalars)	$M \rightarrow M_B$ (restriction of scalars)
(pre)sheaves on a topological space X	presheaves on X	sheaves on X	sheafification	forgetful
(semi)groups	semigroups	groups	groupification	forgetful
sheaves, $\pi : X \rightarrow Y$	sheaves on Y	sheaves on X	π^{-1}	π_*
sheaves of abelian groups or \mathcal{O} -modules, open embeddings $\pi : U \hookrightarrow Y$	sheaves on U	sheaves on Y	$\pi_!$	π^{-1}
ring maps $B \rightarrow A$	Mod_A	Mod_B	$M \mapsto M_B$ (restriction of scalars)	$N \mapsto \text{Hom}_B(A, N)$
quasicoherent sheaves, affine $\pi : X \rightarrow Y$	$QCoh_X$	$QCoh_Y$	π_*	$\pi_{sh}^!$

1.5 Abelian categories

preadditive category : a category \mathcal{A} is called preadditive if each morphism set $Mor_{\mathcal{A}}(x, y)$ is endowed with the structure of an abelian group such that the compositions

$$Mor(x, y) \times Mor(y, z) \rightarrow Mor(x, z)$$

are bilinear

additive functor : a functor $F : \mathcal{A} \rightarrow \mathcal{B}$ of preadditive categories is called additive if and only if $F : Mor(x, y) \rightarrow Mor(F(x), F(y))$ is a homomorphism of abelian groups for all $x, y \in Ob(\mathcal{A})$

In particular for every x, y there exists at least one morphism $x \rightarrow y$, namely the zero map.

Let 0 be the zero map from x to y , by bilinearity, for an arbitrary object of $\mathcal{A} : z, f \in Mor(y, z), g \in Mor(z, x)$, we have $f \circ 0 =$ the zero map from x to z , $0 \circ g =$ the zero map from z to y . (Hint : $f \circ 0 = f \circ (0 + 0)$)

Lemma 1.60 *Let \mathcal{A} be a preadditive category. Let x be an object of \mathcal{A} . The following are equivalent:*

- (1) x is an initial object,
- (2) x is a final object, and
- (3) $id_x = 0$ in $Mor_{\mathcal{A}}(x, x)$.

Furthermore, if such an object 0 exists, then a morphism $\alpha : x \rightarrow y$ factors through 0 if and only if $\alpha = 0$.

Proof: First assume that x is either (1) initial or (2) final. In both cases, it follows that $Mor(x, x)$ is a trivial abelian group containing id_x , thus $id_x = 0$ in $Mor(x, x)$, which shows that each of (1) and (2) implies (3).

Now assume that $id_x = 0$ in $Mor(x, x)$. Let y be an arbitrary object of \mathcal{A} and let $f \in Mor(x, y)$. Denote $C : Mor(x, x) \times Mor(x, y) \rightarrow Mor(x, y)$ the composition map. Then $f = C(0, f)$ and since C is bilinear we have $C(0, f) = 0$. Thus $f = 0$. Hence x is initial in \mathcal{A} . A similar argument for $f \in Mor(y, x)$ can be used to show that x is also final. Thus (3) implies both (1) and (2). \square

Lemma 1.61 *Let \mathcal{A} be a preadditive category. Let $x, y \in Ob(\mathcal{A})$. If the product $x \times y$ exists, then so does the coproduct $x \amalg y$. If the coproduct $x \amalg y$ exists, then so does the product $x \times y$. In this case also $x \amalg y \cong x \times y$.*

Proof: Suppose that $z = x \times y$ with projections $p : z \rightarrow x$ and $q : z \rightarrow y$. Denote $i : x \rightarrow z$ the morphism corresponding to $(1, 0)$. Denote $j : y \rightarrow z$ the morphism corresponding to $(0, 1)$. Thus we have the commutative diagram

$$\begin{array}{ccc}
 x & \xrightarrow{1} & x \\
 & \searrow i & \swarrow p \\
 & & z \\
 & \swarrow j & \searrow q \\
 y & \xrightarrow{1} & y
 \end{array}$$

where the diagonal compositions are zero. It follows that $i \circ p + j \circ q : z \rightarrow z$ is the identity since it is a morphism which upon composing with p gives p and upon composing with q gives q . Suppose given morphisms $a : x \rightarrow w$ and $b : y \rightarrow w$. Then we can form the map $a \circ p + b \circ q : z \rightarrow w$. In this way we get a bijection $Mor(z, w) = Mor(x, w) \times Mor(y, w)$ which show that $z = x \coprod y$. \square

direct sum $x \oplus y$: given a pair of objects x, y in a preadditive category \mathcal{A} , the direct sum $x \oplus y$ of x and y is the direct product $x \times y$ endowed with the morphisms i, j, p, q as in the Lemma above.

Remark 1.62 *Note that the proof of Lemma above shows that given p and q the morphisms i, j are uniquely determined by the rules $p \circ i = id_x, q \circ j = id_y, p \circ j = 0, q \circ i = 0$. Moreover, we automatically have $i \circ p + j \circ q = id_{x \oplus y}$. Similarly, given i, j the morphisms p and q are uniquely determined. Finally, given objects x, y, z and morphisms $i : x \rightarrow z, j : y \rightarrow z, p : z \rightarrow x$ and $q : z \rightarrow y$ such that $p \circ i = id_x, q \circ j = id_y, p \circ j = 0, q \circ i = 0$ and $i \circ p + j \circ q = id_z$, then z is the direct sum of x and y with the four morphisms equal to i, j, p, q .*

Lemma 1.63 *Let \mathcal{A}, \mathcal{B} be preadditive categories. Let $F : \mathcal{A} \rightarrow \mathcal{B}$ be an additive functor. Then F transforms direct sums to direct sums and zero to zero.*

Proof: Suppose F is additive. A direct sum z of x and y is characterized by having morphisms $i : x \rightarrow z, j : y \rightarrow z, p : z \rightarrow x$ and $q : z \rightarrow y$ such that $p \circ i = id_x, q \circ j = id_y, p \circ j = 0, q \circ i = 0$ and $i \circ p + j \circ q = id_z$, according to Remark above. Clearly $F(x), F(y), F(z)$ and the morphisms $F(i), F(j), F(p), F(q)$ satisfy exactly the same relations (by additivity) and we see that $F(z)$ is a direct sum of $F(x)$ and $F(y)$. Hence, F transforms direct sums to direct sums. \square

additive category : a category \mathcal{C} is said to be additive if it satisfies the following properties.

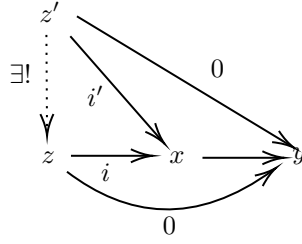
- Ad1. For each $A, B \in \mathcal{C}$, $Mor(A, B)$ is an abelian group, such that composition of morphisms distributes over addition (bilinear)
- Ad2. \mathcal{C} has a zero object, denoted 0 . (This is an object that is simultaneously an initial object and a final object)
- Ad3. It has products of two objects (a product $A \times B$ for any pair of objects), and hence by induction, products of any finite number of objects

In an additive category, the morphisms are often called **homomorphisms**, and Mor is denoted by Hom . In fact, this notation Hom is a good indication that you're working in an additive category

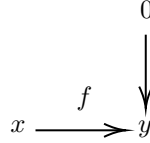
The 0-morphism in the abelian group $Hom(A, B)$ is the composition $A \rightarrow 0 \rightarrow B$. (We also remark that the notion of 0-morphism thus makes sense in any category with a 0-object)

Let \mathcal{A} be a preadditive category. Let $f : x \rightarrow y$ be a morphism

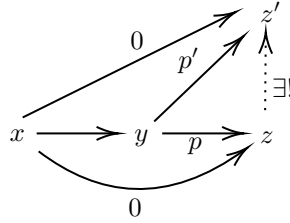
kernel : a kernel of f is a morphism $i : z \rightarrow x$ such that (a) $f \circ i = 0$ and (b) for any $i' : z' \rightarrow x$ such that $f \circ i' = 0$ there exists a unique morphism $g : z' \rightarrow z$ such that $i' = i \circ g$.



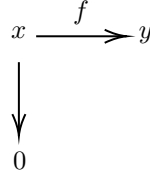
The kernel is written $\ker f \rightarrow x$ The kernel of $f : x \rightarrow y$ is the limit of the diagram



cokernel : a cokernel of f is a morphism $p : y \rightarrow z$ such that (a) $p \circ f = 0$ and (b) for any $p' : y \rightarrow z'$ such that $p' \circ f = 0$ there exists a unique morphism $g : z \rightarrow z'$ such that $p' = g \circ p$.



The cokernel of $f : x \rightarrow y$ is the colimit of the diagram



coimage : if a kernel of f exists, then a coimage of f is a cokernel for the morphism $\ker(f) \rightarrow x$. If a kernel and coimage exist then we denote this $x \rightarrow \text{Coim}(f)$.

image : if a cokernel of f exists, then the image of f is a kernel of the morphism $y \rightarrow \text{coker}(f)$. If a cokernel and image of f exist then we denote this $\text{Im}(f) \rightarrow y$.

Lemma 1.64 Let \mathcal{C} be a preadditive category. Let $f : x \rightarrow y$ be a morphism in \mathcal{C} .

- (1) If a kernel of f exists, then this kernel is a monomorphism.
- (2) If a cokernel of f exists, then this cokernel is an epimorphism.
- (3) If a kernel and coimage of f exist, then the coimage is an epimorphism.
- (4) If a cokernel and image of f exist, then the image is a monomorphism.

Lemma 1.65 Let $f : x \rightarrow y$ be a morphism in a preadditive category such that the kernel, cokernel, image and coimage all exist. Then f can be factored uniquely as

$$x \rightarrow \text{Coim}(f) \rightarrow \text{Im}(f) \rightarrow y$$

If $i : A \rightarrow B$ is a monomorphism, then we say that A is a **subobject** of B , where the map i is implicit. There is also the notion of **quotient object**, defined dually to subobject

abelian category : an abelian category is an additive category satisfying three additional properties :

- (1) Every map has a kernel and cokernel
- (2) Every monomorphism is the kernel of its cokernel
- (3) Every epimorphism is the cokernel of its kernel

quotient : the cokernel of a monomorphism is called the quotient. The quotient of a monomorphism $A \rightarrow B$ is often denoted B/A (with the map from B implicit)

Theorem 1.66 *Freyd-Mitchell Embedding Theorem:*

If \mathcal{C} is an abelian category such that $\text{Hom}(X, Y)$ is a set for all $X, Y \in \mathcal{C}$, then there is a ring A and an exact, fully faithful functor from \mathcal{C} into Mod_A , which embeds \mathcal{C} as a full subcategory

In the sense that $\text{Hom}_{\mathcal{C}}(X, Y) \cong \text{Hom}_A(M, N)$

(Unfortunately, the ring A need not be commutative)

The upshot is that to prove something about a diagram in some abelian category, we may assume that it is a diagram of modules over some ring, and we may then “diagram-chase” elements. Moreover, any fact about kernels, cokernels, and so on that holds in Mod_A holds in any abelian category)

Complexes, exactness, and homology (In this entire discussion, we assume we are working in an abelian category.) We say a sequence :

$$\cdots \rightarrow A \xrightarrow{f} B \xrightarrow{g} C \rightarrow \cdots \quad (1)$$

is a **complex** at B if $g \circ f = 0$, and is **exact** at B if $\ker g = \text{im} f$. (More specifically, g has a kernel that is an image of f . Exactness at B implies being a complex at B)

Lemma 1.67 *The above sequence 1 is exact at B if and only if $\text{Coker}(f) = \text{Coim}(g)$*

A sequence is a **complex** (resp. **exact**) if it is a complex (resp. exact) at each (internal) term.

A **short exact sequence** is an exact sequence with five terms, the first and last of which are zeros – in other words, an exact sequence of the form :

$$0 \rightarrow A \rightarrow B \rightarrow C \rightarrow 0$$

Lemma 1.68 *Fix an abelian category \mathcal{A} . In this category,*

- (i) $0 \rightarrow A \xrightarrow{f} B$ is exact if and only if $A \xrightarrow{f} B$ is a monomorphism. In this sense, $f = \text{Im}(f)$
- (ii) $A \xrightarrow{f} B \rightarrow 0$ is exact if and only if $A \xrightarrow{f} B$ is an epimorphism. In this sense, $f = \text{Coim}(f)$
- (iii) $0 \rightarrow A \rightarrow B \rightarrow 0$ is exact if and only if $A \rightarrow B$ is an isomorphism

- (iv) $0 \rightarrow A \xrightarrow{f} B \xrightarrow{g} C$ is exact if and only if f is a kernel of g
(V) $A \xrightarrow{f} B \xrightarrow{g} C \rightarrow 0$ is exact if and only if g is a cokernel of f

Proof: (i) The cokernel of $0 \rightarrow A$ is the identity map $A \xrightarrow{1_A} A$, which has as kernel $0 \rightarrow A$. So the image of $0 \rightarrow A$ is $0 \rightarrow A$. Thus $0 \rightarrow A \rightarrow B$ is exact if and only if $0 \rightarrow A$ is the kernel of $A \rightarrow B$.

So we are showing that being a monomorphism is the same as having kernel $0 \rightarrow A$. Suppose first that $A \xrightarrow{f} B$ has kernel $0 \rightarrow A$. Let g, h be two morphisms $Z \rightarrow A$ so that $f \circ g = f \circ h$. Then, by linearity, $f \circ (g - h) = 0$. By the universal property of kernels, $g - h$ factors through $0 \rightarrow A$, so $g - h$ must be the zero morphism. This implies $g = h$, so the defining property of monomorphisms is verified.

Conversely, suppose $A \xrightarrow{f} B$ is a monomorphism. Suppose $g : Z \rightarrow A$ is a morphism so that $f \circ g = 0$. Note that there is another map with this property, namely the zero morphism, $0 : Z \rightarrow A$. Since f is a monomorphism, $g = 0$. It follows that g factors uniquely through $0 \rightarrow A$. Since g was arbitrary, this verifies that $0 \rightarrow A$ has the universal property of the kernel.

(Note: So far, we have only used that \mathcal{A} is additive and kernels and cokernels exist.)

(ii) Duality.

(iii) Suppose first that $A \rightarrow B$ is an isomorphism. Then $A \rightarrow B$ is both monic and epic, so the sequence is exact by parts (i) and (ii).

Suppose conversely that $0 \rightarrow A \rightarrow B \rightarrow 0$ is exact. Then $B \rightarrow 0$ is the cokernel of $A \rightarrow B$ and $0 \rightarrow A$ is the kernel of $A \rightarrow B$. This makes the image of $A \rightarrow B$ the morphism $id_B : B \rightarrow B$ and the coimage of $A \rightarrow B$ the morphism $id_A : A \rightarrow A$.

From (i) and (ii), we can get f is both a monomorphism and an epimorphism. By definition of abelian category, f is the kernel of its cokernel. So the image of $A \rightarrow B$ is $f : A \rightarrow B$. So f is an isomorphism.

□

homology : If (1) is a complex at B , then its homology at B (often denoted by H) is $ker g / im f$. (More precisely, there is some monomorphism $im f \rightarrow ker g$, and that H is the cokernel of this monomorphism.) Therefore, (1) is exact at B if and only if its homology at B is 0. We say that elements of $ker g$ are the **cycles**, and elements of $im f$ are the **boundaries** (so homology is “cycles mod boundaries”).

If the complex is indexed in decreasing order, the indices are often written as subscripts, and H_i is the homology at $A_{i+1} \rightarrow A_i \rightarrow A_{i-1}$. If the complex is indexed in increasing order, the indices are often written as superscripts, and the homology H^i at $A^{i-1} \rightarrow A^i \rightarrow A^{i+1}$ is often called **cohomology**.

An exact sequence

$$A^\bullet : \dots \rightarrow A^{i-1} \xrightarrow{f^{i-1}} A^i \xrightarrow{f^i} A^{i+1} \xrightarrow{f^{i+1}} \dots \quad (2)$$

can be “factored” into short exact sequences

$$0 \rightarrow ker f^i \rightarrow A^i \rightarrow ker f^{i+1} \rightarrow 0$$

More generally, if (1) is assumed only to be a complex, then it can be “factored” into short exact

sequences.

$$\begin{aligned} 0 \rightarrow \ker f^i \rightarrow A^i \rightarrow \operatorname{im} f^i \rightarrow 0 \\ 0 \rightarrow \operatorname{im} f^{i-1} \rightarrow \ker f^i \rightarrow H^i(A^\bullet) \rightarrow 0 \end{aligned} \tag{3}$$

We also have :

$$\begin{aligned} 0 \rightarrow \operatorname{im} f^i \rightarrow A^{i+1} \rightarrow \operatorname{coker} f^i \rightarrow 0 \\ 0 \rightarrow H^i(A^\bullet) \rightarrow \operatorname{coker} f^{i-1} \rightarrow \operatorname{im} f^i \rightarrow 0 \end{aligned} \tag{4}$$

(These are somehow dual to (3))

Remark 1.69 Suppose

$$0 \xrightarrow{d^0} A^1 \xrightarrow{d^1} \dots \xrightarrow{d^{n-1}} A^n \xrightarrow{d^n} 0$$

is a complex of finite-dimensional k -vector spaces (often called A^\bullet for short).

Define $h^i(A^\bullet) := \dim H^i(A^\bullet)$.

Then $\sum (-1)^i \dim A^i = \sum (-1)^i h^i(A^\bullet)$. In particular, if A^\bullet is exact, then $\sum (-1)^i \dim A^i = 0$.

Remark 1.70 Suppose \mathcal{C} is an abelian category. Define the category $\operatorname{Com}_{\mathcal{C}}$ of complexes as follows. The objects are infinite complexes

$$A^\bullet : \dots \rightarrow A^{i-1} \xrightarrow{f^{i-1}} A^i \xrightarrow{f^i} A^{i+1} \xrightarrow{f^{i+1}} \dots \tag{5}$$

in \mathcal{C} , and the morphisms $A^\bullet \rightarrow B^\bullet$ are commuting diagrams

$$\begin{array}{ccccccc} \dots & \rightarrow & A^{i-1} & \xrightarrow{f^{i-1}} & A^i & \xrightarrow{f^i} & A^{i+1} \xrightarrow{f^{i+1}} \dots \\ & & \downarrow & & \downarrow & & \downarrow \\ \dots & \rightarrow & B^{i-1} & \xrightarrow{g^{i-1}} & B^i & \xrightarrow{g^i} & B^{i+1} \xrightarrow{g^{i+1}} \dots \end{array} \tag{6}$$

Then $\operatorname{Com}_{\mathcal{C}}$ is an abelian category.

(Remark for experts: Essentially the same argument shows that the $\mathcal{C}^{\mathcal{J}}$ is an abelian category for any small category \mathcal{J} and any abelian category \mathcal{C} . This immediately implies that the category of presheaves on a topological space X with values in an abelian category \mathcal{C} is automatically an abelian category)

Remark 1.71 (6) induces a map of homology $H^i(A^\bullet) \rightarrow H^i(B^\bullet)$

Furthermore, H^i is a covariant functor $\operatorname{Com}_{\mathcal{C}} \rightarrow \mathcal{C}$

Theorem 1.72 (Long exact sequence). – A short exact sequence of complexes

$$\begin{array}{ccccccc}
0^\bullet & : & \dots & \longrightarrow & 0 & \longrightarrow & 0 & \longrightarrow & 0 & \longrightarrow & \dots \\
\downarrow & & & & \downarrow & & \downarrow & & \downarrow & & \\
A^\bullet & : & \dots & \longrightarrow & A^{i-1} & \longrightarrow & A^i & \longrightarrow & A^{i+1} & \longrightarrow & \dots \\
\downarrow & & & & \downarrow & & \downarrow & & \downarrow & & \\
B^\bullet & : & \dots & \longrightarrow & B^{i-1} & \longrightarrow & B^i & \longrightarrow & B^{i+1} & \longrightarrow & \dots \\
\downarrow & & & & \downarrow & & \downarrow & & \downarrow & & \\
C^\bullet & : & \dots & \longrightarrow & C^{i-1} & \longrightarrow & C^i & \longrightarrow & C^{i+1} & \longrightarrow & \dots \\
\downarrow & & & & \downarrow & & \downarrow & & \downarrow & & \\
0^\bullet & : & \dots & \longrightarrow & 0 & \longrightarrow & 0 & \longrightarrow & 0 & \longrightarrow & \dots
\end{array}$$

induces a *long exact sequence in cohomology*

$$\begin{aligned}
& \dots \rightarrow H^{i-1}(C^\bullet) \rightarrow \\
& H^i(A^\bullet) \rightarrow H^i(B^\bullet) \rightarrow H^i(C^\bullet) \rightarrow \\
& H^{i+1}(A^\bullet) \rightarrow \dots
\end{aligned} \tag{7}$$

Exactness of functors If $F : \mathcal{A} \rightarrow \mathcal{B}$ is a covariant additive functor from one abelian category to another, we say that F is **right-exact** if the exactness of

$$A' \rightarrow A \rightarrow A'' \rightarrow 0$$

in \mathcal{A} implies that

$$F(A') \rightarrow F(A) \rightarrow F(A'') \rightarrow 0$$

is also exact.

Dually, we say that F is **left-exact** if the exactness of

$$0 \rightarrow A' \rightarrow A \rightarrow A'' \quad \text{implies}$$

$$0 \rightarrow F(A') \rightarrow F(A) \rightarrow F(A'') \quad \text{is exact}$$

A contravariant functor is **left-exact** if the exactness of

$$A' \rightarrow A \rightarrow A'' \rightarrow 0 \quad \text{implies}$$

$$0 \rightarrow F(A'') \rightarrow F(A) \rightarrow F(A') \quad \text{is exact}$$

Dually, we say that F is **right-exact** if the exactness of

$$0 \rightarrow A' \rightarrow A \rightarrow A'' \quad \text{implies}$$

$$F(A'') \rightarrow F(A) \rightarrow F(A') \rightarrow 0 \quad \text{is exact}$$

A covariant or contravariant functor is **exact** if it is both left-exact and right-exact.

Remark 1.73 Suppose F is an exact functor. Then applying F to an exact sequence preserves exactness

For example, if F is covariant, and $A' \rightarrow A \rightarrow A''$ is exact, then $FA' \rightarrow FA \rightarrow FA''$ is exact

Proof: Need to proof : If $F : \mathcal{C} \rightarrow \mathcal{D}$ is an exact functor between abelian categories and

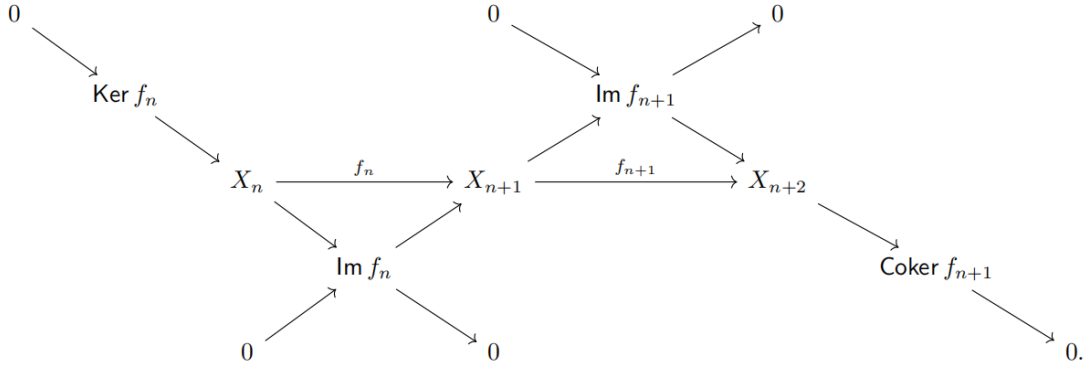
$$\dots \rightarrow X_n \xrightarrow{f_n} X_{n+1} \xrightarrow{f_{n+1}} X_{n+2} \rightarrow \dots$$

is an exact sequence in \mathcal{C} , then its image

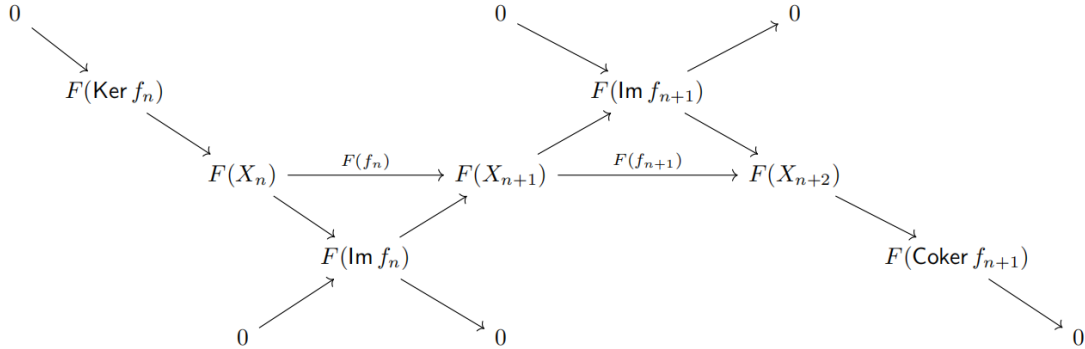
$$\dots \rightarrow F(X_n) \xrightarrow{F(f_n)} F(X_{n+1}) \xrightarrow{F(f_{n+1})} F(X_{n+2}) \rightarrow \dots$$

is exact.

We want to prove exactness at X_{n+1} . We can construct a commutative diagram:



The diagonals are exact. (Proving this is a straightforward exercise.) The image of this diagram in \mathcal{D} :



also has exact diagonals. (Here we used the fact that $F(0) \cong 0$)

We can compute

$$\text{Im } F(f_n) = \text{Im}(F(X_n) \rightarrow F(\text{Im } f_n) \rightarrow F(X_{n+1})) = \text{Im}(F(\text{Im } f_n) \rightarrow F(X_{n+1}))$$

since $F(X_n) \rightarrow F(\text{Im } f_n)$ is epic. Also

$$\text{Im}(F(\text{Im } f_n) \rightarrow F(X_{n+1})) = \text{Ker}(F(X_{n+1}) \rightarrow F(\text{Im } f_{n+1})) = \text{Ker}(F(X_{n+1}) \rightarrow F(\text{Im } f_{n+1}) \rightarrow F(X_{n+2}))$$

since $F(\text{Im } g) \rightarrow F(X_{n+2})$ is monic. Thus, $\text{Im } F(f_n) = \text{Ker } F(f_{n+1})$. \square

Remark 1.74 Suppose A is a ring, $S \subset A$ is a multiplicative subset, and M is an A -module.

- (a) Localization of A -modules $\text{Mod}_A \rightarrow \text{Mod}_{S^{-1}A}$ is an exact covariant functor
- (b) $(\cdot) \otimes_A M$ is a right-exact covariant functor $\text{Mod}_A \rightarrow \text{Mod}_A$. (This is a repeat of Exercise 1.3.H.)
- (c) $\text{Hom}(M, \cdot)$ is a left-exact covariant functor $\text{Mod}_A \rightarrow \text{Mod}_A$

If \mathcal{C} is any abelian category, and $C \in \mathcal{C}$, then $\text{Hom}(C, \cdot)$ is a left-exact covariant functor $\mathcal{C} \rightarrow \text{Ab}$

- (d) $\text{Hom}(\cdot, M)$ is a left-exact contravariant functor $\text{Mod}_A \rightarrow \text{Mod}_A$

If \mathcal{C} is any abelian category, and $C \in \mathcal{C}$, then $\text{Hom}(\cdot, C)$ is a left-exact contravariant functor $\mathcal{C} \rightarrow \text{Ab}$

Example 1.75 Suppose M is a **finitely presented A -module**: M has a finite number of generators, and with these generators it has a finite number of relations; or usefully equivalently, fits in an exact sequence

$$A^{\oplus q} \rightarrow A^{\oplus q} \rightarrow M \rightarrow 0$$

We can use this exact sequence and the left-exactness of Hom to describe an isomorphism

$$S^{-1}\text{Hom}_A(M, N) \cong \text{Hom}_{S^{-1}A}(S^{-1}M, S^{-1}N)$$

Proof: From

$$A^{\oplus q} \rightarrow A^{\oplus q} \rightarrow M \rightarrow 0$$

We get

$$\begin{aligned} 0 \rightarrow \text{Hom}_A(M, N) &\rightarrow \text{Hom}_A(A^{\oplus q}, N) \rightarrow \text{Hom}_A(A^{\oplus q}, N) \\ 0 \rightarrow S^{-1}\text{Hom}_A(M, N) &\rightarrow S^{-1}\text{Hom}_A(A^{\oplus q}, N) \rightarrow S^{-1}\text{Hom}_A(A^{\oplus q}, N) \end{aligned}$$

and

$$\begin{aligned} S^{-1}A^{\oplus q} \rightarrow S^{-1}A^{\oplus q} &\rightarrow S^{-1}M \rightarrow 0 \\ 0 \rightarrow \text{Hom}_{S^{-1}A}(S^{-1}M, S^{-1}N) &\rightarrow \text{Hom}_{S^{-1}A}(S^{-1}A^{\oplus q}, S^{-1}N) \rightarrow \text{Hom}_{S^{-1}A}(S^{-1}A^{\oplus q}, S^{-1}N) \end{aligned}$$

So we just need to consider $M = A^{\oplus k}$

We know

$$\text{Hom}_A(A^{\oplus k}, N) \cong (\text{Hom}_A(A, N))^{\oplus k}, \text{Hom}_A(A, N) \cong N$$

So

$$\begin{aligned} S^{-1}\text{Hom}_A(A^{\oplus k}, N) &\cong S^{-1}(N^{\oplus k}) \cong \text{Hom}_{S^{-1}A}(S^{-1}A^{\oplus k}, S^{-1}N) \\ \frac{(n_1, \dots, n_k)}{s} &\mapsto \left(\frac{(a_1, \dots, a_k)}{s} \mapsto \frac{a_1 n_1 + \dots + a_k n_k}{s} \right) \end{aligned}$$

\square

Example 1.76 *Hom doesn't always commute with localization :*

In the language of Example 1.75, take $A = N = \mathbb{Z}$, $M = \mathbb{Q}$, and $S = \mathbb{Z} \setminus \{0\}$

$$S^{-1} \text{Hom}_A(M, N) = S^{-1}0 = 0, \text{Hom}_{S^{-1}A}(S^{-1}M, S^{-1}N) = \text{Hom}_{\mathbb{Q}}(\mathbb{Q}, \mathbb{Q}) = \mathbb{Q}$$

Remark 1.77 *Interaction of homology and (right/left-)exact functors*

Suppose $F : \mathcal{A} \rightarrow \mathcal{B}$ is a covariant functor of abelian categories, and C^\bullet is a complex in \mathcal{A}

(a) *(F right-exact yields $FH^\bullet \rightarrow H^\bullet F$) If F is right-exact, describe a natural morphism $FH^\bullet \rightarrow H^\bullet F$. (More precisely, for each i , the left side is F applied to the cohomology at piece i of C^\bullet , while the right side is the cohomology at piece i of FC^\bullet .)*

(b) *(F left-exact yields $FH^\bullet \leftarrow H^\bullet F$) If F is left-exact, describe a natural morphism $H^\bullet F \rightarrow FH^\bullet$.*

(c) *(F exact yields $FH^\bullet \xrightarrow{\sim} H^\bullet F$) If F is exact, show that the morphisms of (a) and (b) are inverses and thus isomorphisms.*

Hint for (a): use $C^i \xrightarrow{d^i} C^{i+1} \rightarrow \text{coker } d^i \rightarrow 0$ to give an isomorphism $F \text{coker } d^i \cong \text{coker } F d^i$. Then use the first line of (4) to give an epimorphism $F \text{im } d^i \rightarrow \text{im } F d^i$. Then use the second line of (4) to give the desired map $FH^i C^\bullet \rightarrow H^i F C^\bullet$. While you are at it, you may as well describe a map for the fourth member of the quartet $\{\text{coker}, \text{im}, H, \ker\}$: $F \ker d^i \rightarrow \ker F d^i$

Remark 1.78 *If this makes your head spin, you may prefer to think of it in the following specific case, where both \mathcal{A} and \mathcal{B} are the category of A -modules, and F is $(\cdot) \otimes N$ for some fixed N -module. Your argument in this case will translate without change to yield a solution to Remark 1.74(a) and (c) in general. If $\otimes N$ is exact, then N is called a flat A -module.*

For example, localization is exact (Remark 1.74), so $S^{-1}A$ is a flat A -algebra for all multiplicative sets S ($S^{-1}M \cong M \otimes_A S^{-1}A$). Thus taking cohomology of a complex of A -modules commutes with localization

Remark 1.79 *Interaction of adjoints, (co)limits, and (left- and right-) exactness*

A surprising number of arguments boil down to the statement:

Limits commute with limits and right adjoints. In particular, in an abelian category, because kernels are limits, both right adjoints and limits are left-exact.

as well as its dual:

Colimits commute with colimits and left adjoints. In particular, because cokernels are colimits, both left adjoints and colimits are right-exact.

The latter has a useful extension:

In Mod_A , colimits over filtered index categories are exact.

Remark 1.80 *★ Caution. It is not true that in abelian categories in general, colimits over filtered index categories are exact.*

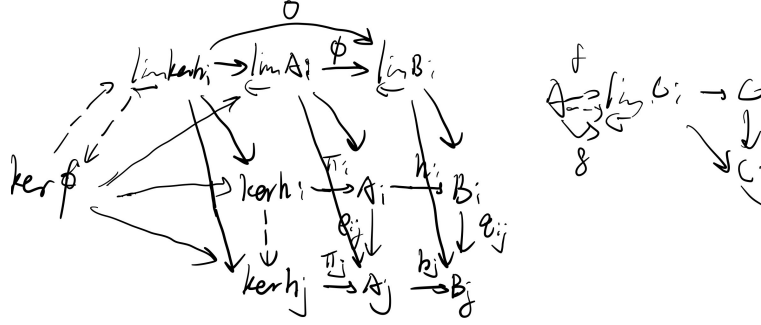
Fix a prime p . In the category Ab of abelian groups, for each positive integer n , we have an exact sequence $\mathbb{Z} \rightarrow \mathbb{Z}/(p^n) \rightarrow 0$. Taking the limit over all n in the obvious way, we obtain $\mathbb{Z} \rightarrow \mathbb{Z}_p \rightarrow 0$, which is certainly not exact.)

Theorem 1.81 (kernels commute with limits)

Suppose \mathcal{C} is an abelian category, and $a: \mathcal{I} \rightarrow \mathcal{C}$ and $b: \mathcal{I} \rightarrow \mathcal{C}$ are two diagrams in \mathcal{C} indexed by \mathcal{I} . For convenience, let $A_i = a(i)$ and $B_i = b(i)$ be the objects in those two diagrams. Let $h_i: A_i \rightarrow B_i$ be maps commuting with the maps in the diagram.

(Translation: h is a natural transformation of functors $a \rightarrow b$) Then the $\ker h_i$ form another diagram in \mathcal{C} indexed by \mathcal{I} . Describe a canonical isomorphism $\varprojlim \ker h_i \cong \ker \left(\varprojlim A_i \rightarrow \varprojlim B_i \right)$, assuming the limits exist.

Proof:



□

Theorem 1.82 (Limits commute with limits)

Let $F: I \times J \rightarrow \mathcal{C}$ be a functor. If $\varprojlim_j F(i, j)$ exists for all $i \in I$ then we find that $\varprojlim_i \varprojlim_j F(i, j)$ exists iff $\varprojlim_{(i,j)} F(i, j)$ exists, in which case they are canonically isomorphic.

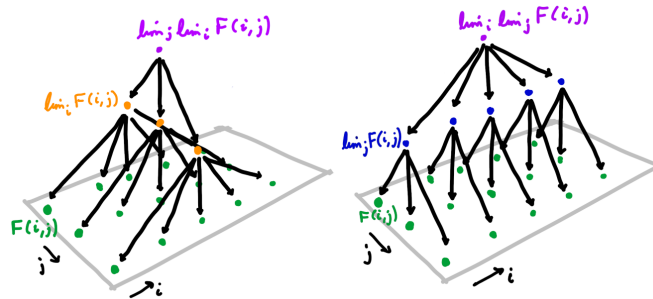
In particular

$$\varprojlim_i \varprojlim_j F(i, j) \cong \varprojlim_j \varprojlim_i F(i, j)$$

if both sides exist.

I should briefly clarify what $\varprojlim_i \varprojlim_j F(i, j)$ actually means. A morphism $f: i \rightarrow i'$ induces a natural transformation $F(i, -) \Rightarrow F(i', -)$, which induces a morphism $\varprojlim_j F(f, j): \varprojlim_j F(i, j) \rightarrow \varprojlim_j F(i', j)$. So the $\varprojlim_j \varprojlim_i F(i, j)$ in fact assemble into a functor $I \rightarrow \mathcal{C}$, and $\varprojlim_i \varprojlim_j F(i, j)$ is the limit of this functor.

Proof:



□

Theorem 1.83 (*right adjoints commute with limits*)

Suppose $(F: \mathcal{C} \rightarrow \mathcal{D}, G: \mathcal{D} \rightarrow \mathcal{C})$ is a pair of adjoint functors. If $A = \varprojlim_i A_i$ is a limit in \mathcal{D} of a diagram indexed by \mathcal{I} , then $GA = \varprojlim_{\mathcal{I}} GA_i$ (with the corresponding maps $GA \rightarrow GA_i$) is a limit in \mathcal{C} .

Proof: We must show that $GA \rightarrow GA_i$ satisfies the universal property of limits. Suppose we have maps $W \rightarrow GA_i$ commuting with the maps of \mathcal{I} . We wish to show that there exists a unique $W \rightarrow GA$ extending the $W \rightarrow GA_i$. By adjointness of F and G , we can restate this as: Suppose we have maps $FW \rightarrow A_i$ commuting with the maps of \mathcal{I} . We wish to show that there exists a unique $FW \rightarrow A$ extending the $FW \rightarrow A_i$. But this is precisely the universal property of the limit. \square

Corollary 1.84 *If F and G are additive functors between abelian categories, and (F, G) is an adjoint pair, then (as kernels are limits and cokernels are colimits) G is left-exact and F is right-exact*

Example 1.85 *In Mod_A , colimits over filtered index categories are exact. (Your argument will apply without change to any abelian category whose objects can be interpreted as "sets with additional structure".) Right-exactness follows from the above discussion, so the issue is left-exactness.*

(Possible hint: After you show that localization is exact, or stalkification is exact, in a hands-on way, you will be easily able to prove this)

Example 1.86 *Filtered colimits commute with homology in Mod_A*

Hint: use the FHHF Theorem, and the previous Exercise

Remark 1.87 *Suppose*

$$\begin{array}{ccccccc}
 & \vdots & & \vdots & & \vdots & \\
 & \downarrow & & \downarrow & & \downarrow & \\
 0 & \longrightarrow & A_{n+1} & \longrightarrow & B_{n+1} & \longrightarrow & C_{n+1} \longrightarrow 0 \\
 & & \downarrow & & \downarrow & & \downarrow \\
 0 & \longrightarrow & A_n & \longrightarrow & B_n & \longrightarrow & C_n \longrightarrow 0 \\
 & & \downarrow & & \downarrow & & \downarrow \\
 & & \vdots & & \vdots & & \vdots \\
 & & \downarrow & & \downarrow & & \downarrow \\
 0 & \longrightarrow & A_0 & \longrightarrow & B_0 & \longrightarrow & C_0 \longrightarrow 0 \\
 & & \downarrow & & \downarrow & & \downarrow \\
 & & 0 & & 0 & & 0
 \end{array}$$

is an inverse system of exact sequences of modules over a ring, such that the maps $A_{n+1} \rightarrow A_n$ are surjective. (We say: "transition maps of the left term are surjective".)

Then the limit

$$0 \longrightarrow \varprojlim A_n \longrightarrow \varprojlim B_n \longrightarrow \varprojlim C_n \longrightarrow 0$$

is also exact. (You will need to define the maps in)

Remark 1.88 *Based on these ideas, you may suspect that rightexact functors always commute with colimits. The fact that tensor product commutes with infinite direct sums may reinforce this idea. Unfortunately, it is not true - "double dual" $\cdot^{\vee\vee} : \text{Vec}_k \rightarrow \text{Vec}_k$ is covariant and right exact (why is it right-exact?), but does not commute with infinite direct sums, as $\prod_{i=1}^{\infty} (k^{\vee\vee})$ is not isomorphic to $(\prod_{i=1}^{\infty} k)^{\vee\vee}$.*

2 Sheaves

2.1 Sheaf and presheaf

Def 2.1 Presheaves

Presheaves are a way of keeping track of algebraic data on a topological space. More precisely:

Let X be a topological space and \mathcal{C} a category. A presheaf \mathcal{F} of \mathcal{C} on X consists of

- (1) For all $U \subseteq X$ open, an object $\mathcal{F}(U)$ in \mathcal{C} .
- (2) For all $V \subseteq U \subseteq X$ open, a morphism $\rho_{UV} : \mathcal{F}(U) \rightarrow \mathcal{F}(V)$ in \mathcal{C} such that
 - (i) For all $U \subseteq X$ open, $\rho_{UU} : \mathcal{F}(U) \rightarrow \mathcal{F}(U)$ is the identity.
 - (ii) For all $W \subseteq V \subseteq U \subseteq X$ open, we have $\rho_{UW} = \rho_{VW} \circ \rho_{UV}$, that is, the following diagram commutes:

$$\begin{array}{ccccc}
 & & \rho_{UW} & & \\
 & \nearrow & & \searrow & \\
 \mathcal{F}(U) & \xrightarrow{\rho_{UV}} & \mathcal{F}(V) & \xrightarrow{\rho_{VW}} & \mathcal{F}(W)
 \end{array}$$

Elements $s \in \mathcal{F}(U)$ are called **sections** of \mathcal{F} over U . The object $\mathcal{F}(U)$ is called space of sections of \mathcal{F} over U .

- Elements $s \in \mathcal{F}(X)$ are called **global sections** of \mathcal{F} . The object $\mathcal{F}(X)$ is called space of global sections of \mathcal{F} .
- Alternative notations for $\mathcal{F}(U)$ are $\Gamma(U, \mathcal{F})$ and $H^0(U, \mathcal{F})$.
- The morphisms ρ_{UV} are called **restriction maps**. For $V \subseteq U$ open and $s \in \mathcal{F}(U)$, we will sometimes write $s|_V$ for $\rho_{UV}(s)$ and call $s|_V$ the **restriction** of s (from U to V).

Example 2.2 Let X be a topological space.

- (1) For any object A in a category \mathcal{C} , the **constant presheaf** with value A is the presheaf A' with $A'(U) = A$ and $\rho_{UV} = \text{id}_A$ for all $V \subseteq U \subseteq X$ open.
- (2) The **presheaf of continuous functions** on X is defined by setting $\mathcal{C}^0(U) := C^0(U) := \{f : U \rightarrow \mathbb{R} \mid f \text{ continuous}\}$ and $\rho_{UV} : \mathcal{C}^0(U) \rightarrow \mathcal{C}^0(V)$, $f \mapsto f|_V$. This can be considered as a presheaf of sets, abelian groups, or even rings.
- (3) More generally, if $\pi : Y \rightarrow X$ is a continuous map of topological spaces, we can look at the presheaf (of sets) of continuous sections of π defined as $\mathcal{F}_\pi(U) := \{s : U \rightarrow Y \mid s \text{ continuous, } \pi \circ s = \text{id}_U\}$ with ρ_{UV} the obvious restriction maps.

Remark 2.3 Let X be a topological space and let Ouv_X be the category of open subsets of X , that is, the category with:

- Objects: $U \subseteq X$ open
- Morphisms:

$$\text{Hom}(U, V) = \begin{cases} \emptyset & \text{if } U \not\subseteq V \\ \iota & \text{if } U \subseteq V \text{ where } \iota \text{ denotes the inclusion} \end{cases}$$

Then, a presheaf on X with values in a category \mathcal{C} is the same as a contravariant functor from Ouv_X to \mathcal{C} .

Def 2.4 The **germ** of a differentiable function. Before we do, we first give another definition, that of the germ of a differentiable function at a point $p \in X$. Intuitively, it is a "shred" of a differentiable function at p . Germs are objects of the form $\{(f, \text{open } U) : p \in U, f \in \mathcal{O}(U)\}$ modulo the relation that $(f, U) \sim (g, V)$ if there is some open set $W \subset U, V$ containing p where $f|_W = g|_W$ (i.e., $\text{res}_{U,W} f = \text{res}_{V,W} g$). In other words, two functions that are the same in an open neighborhood of p (but may differ elsewhere) have the same germ. We call this set of germs the **stalk** at p , and denote it \mathcal{O}_p . Notice that the stalk is a ring: you can add two germs, and get another germ: if you have a function f defined on U , and a function g defined on V , then $f + g$ is defined on $U \cap V$. Moreover, $f + g$ is well-defined: if \tilde{f} has the same germ as f , meaning that there is some open set W containing p on which they agree, and \tilde{g} has the same germ as g , meaning they agree on some open W' containing p , then $\tilde{f} + \tilde{g}$ is the same function as $f + g$ on $U \cap V \cap W \cap W'$.

Notice also that if $p \in U$, you get a map $\mathcal{O}(U) \rightarrow \mathcal{O}_p$. Experts may already see that we are talking about germs as colimits.

We can see that \mathcal{O}_p is a local ring as follows. Consider those germs vanishing at p , which we denote $\mathfrak{m}_p \subset \mathcal{O}_p$. They certainly form an ideal: \mathfrak{m}_p is closed under addition, and when you multiply something vanishing at p by any function, the result also vanishes at p . We check that this ideal is maximal by showing that the quotient ring is a field:

$$0 \longrightarrow \mathfrak{m}_p := \text{ideal of germs vanishing at } p \longrightarrow \mathcal{O}_p \xrightarrow{f \mapsto f(p)} \mathbb{R} \longrightarrow 0$$

Def 2.5 germ, stalk

Define the stalk of a presheaf \mathcal{F} at a point p to be the set of germs of \mathcal{F} at p , denoted \mathcal{F}_p , as in the example above. Germs correspond to sections over some open set containing p , and two of these sections are considered the same if they agree on some smaller open set. More precisely: the stalk is

$$\{(\text{open } U, f) : p \in U, f \in \mathcal{F}(U)\}$$

modulo the relation that $(U, f) \sim (V, g)$ if there is some open set $W \subset U, V$ where $p \in W$ and $\text{res}_{U,W} f = \text{res}_{V,W} g$. Write $\overline{(U, f)}$ for the equivalence class of (U, f) in the stalk

A useful equivalent definition of a **stalk** is as a colimit of all $\mathcal{F}(U)$ over all open sets U containing p :

$$\mathcal{F}_p = \lim_{\longrightarrow_{p \in U}} \mathcal{F}(U).$$

(The index category is a filtered set (given any two such open sets, there is a third such set contained in both))

Given $s \in \mathcal{F}(U)$ and $x \in U \subseteq X$, then we define the **the germ of s at x** to be the image of s in \mathcal{F}_p : $s_x = \overline{(U, s)} \in \mathcal{F}_x$. If \mathcal{B} is a basis for topology on X then we can rewrite the stalk as

$$\mathcal{F}_x \cong \lim_{\longrightarrow_{x \in U, U \in \mathcal{B}}} \mathcal{F}(U),$$

Def 2.6 Sheaf

A presheaf is a sheaf if it satisfies two more axioms. Notice that these axioms use the additional information of when some open sets cover another.

Identity axiom. If $\{U_i\}_{i \in I}$ is an open cover of U , and $f_1, f_2 \in \mathcal{F}(U)$, and $\text{res}_{U, U_i} f_1 = \text{res}_{U, U_i} f_2$ for all i , then $f_1 = f_2$.

(A presheaf satisfying the identity axiom is called a separated presheaf, but we will not use that notation in any essential way.)

Gluability axiom. If $\{U_i\}_{i \in I}$ is an open cover of U , then given $f_i \in \mathcal{F}(U_i)$ for all i , such that $\text{res}_{U_i, U_i \cap U_j} f_i = \text{res}_{U_j, U_i \cap U_j} f_j$ for all i, j , then there is some $f \in \mathcal{F}(U)$ such that $\text{res}_{U, U_i} f = f_i$ for all i .

(In this case, identity means there is at most one way to glue, and gluability means that there is at least one way to glue)

The stalk of a sheaf at a point is just its stalk as a presheaf - the same definition applies - and similarly for the germs of a section of a sheaf.

Remark 2.7 Interpretation in terms of the equaliser exact sequence. The two axioms for a presheaf to be a sheaf can be interpreted as "exactness" of the "equalizer exact sequence":

$$\cdot \longrightarrow \mathcal{F}(U) \longrightarrow \prod \mathcal{F}(U_i) \rightrightarrows \prod \mathcal{F}(U_i \cap U_j)$$

Identity is exactness at $\mathcal{F}(U)$, and gluability is exactness at $\prod \mathcal{F}(U_i)$.

Example 2.8 Let X be a topological space.

(1) (An additional axiom sometimes included is that $\mathcal{F}(\emptyset)$ is a one-element set, and in general, for a sheaf with values in a category, $\mathcal{F}(\emptyset)$ is required to be the final object in the category. This actually follows from the above definitions, assuming that the empty product is appropriately defined as the final object.)

If \mathcal{F} is a sheaf of sets (or abelian groups, rings, etc.), then, by Identity axiom of Def 2.6 applied to $I = \emptyset$, the underlying set of $\mathcal{F}(\emptyset)$ has at most one element, and by Gluability axiom, it has at least one element.

If U and V are disjoint, then $\mathcal{F}(U \cup V) = \mathcal{F}(U) \times \mathcal{F}(V)$. Here we use the fact that $\mathcal{F}(\emptyset)$ is the final object.

(2) The presheaves \mathcal{C}^0 (and \mathcal{C}^∞ if $X = \mathbb{R}^n$) on X are sheaves, since:

(i) Two continuous functions f, g that coincide on an open cover of $U \subseteq X$ coincide at every point, hence they are equal.

(ii) Given $U \subseteq X$ open, a cover $U = \cup_{i \in I} U_i$, and continuous functions $f_i : U_i \rightarrow \mathbb{R}$ that agree on $U_i \cap U_j$, the function

$$\begin{aligned} f : U &\rightarrow \mathbb{R} \\ x &\mapsto f_i(x) \text{ if } x \in U_i \end{aligned}$$

is well-defined. By construction, $f|_{U_i} = f_i$ and f is continuous (resp. differentiable), since continuity (resp. differentiability) at any point can be checked on an open neighborhood.

(3) constant sheaf

Let $\mathcal{F}(U)$ be the maps to S that are locally constant, i.e., for any point p in U , there is an open neighborhood of p where the function is constant. Show that this is a sheaf. (A better description is this: endow S with the discrete topology, and let $\mathcal{F}(U)$ be the continuous maps $U \rightarrow S$.) This is called the constant sheaf (associated to S); (do not confuse it with the constant presheaf)

We denote this sheaf \underline{S}

(4) morphisms glue

Suppose Y is a topological space. Show that "continuous maps to Y " form a sheaf of sets on X . More precisely, to each open set U of X , we associate the set of continuous maps of U to Y . Show that this forms a sheaf. ((2), with $Y = \mathbb{R}$, and (3), with $Y = S$ with the discrete topology, are both special cases)

Example 2.9 Important Example: Restriction of a sheaf

Suppose \mathcal{F} is a sheaf on X , and U is an open subset of X . Define the restriction of \mathcal{F} to U , denoted $\mathcal{F}|_U$, to be the collection $\mathcal{F}|_U(V) = \mathcal{F}(V)$ for all open subsets $V \subset U$. Clearly this is a sheaf on U .

Example 2.10 Important Example: the skyscraper sheaf

Suppose X is a topological space, with $p \in X$, and S is a set. Let $i_p : p \rightarrow X$ be the inclusion. Then $i_{p,*}S$ defined by

$$i_{p,*}S(U) = \begin{cases} S & \text{if } p \in U, \text{ and} \\ \{e\} & \text{if } p \notin U \end{cases}$$

forms a sheaf. Here $\{e\}$ is any one-element set. This is called a skyscraper sheaf.

(Mild caution: this informal picture suggests that the only nontrivial stalk of a skyscraper sheaf is at p , which isn't the case)

There is an analogous definition for sheaves of abelian groups, except $i_{p,*}(S)(U) = \{0\}$ if $p \notin U$; and for sheaves with values in a category more generally, $i_{p,*}S(U)$ should be a final object

Theorem 2.11 Let A be a ring, and let the basis \mathcal{B} of $\text{Spec } A$ be the one made of principle open subsets, then $\mathcal{O}_{\text{Spec } A}$ is a sheaf on \mathcal{B} .

We have a sheaf of rings on $\text{Spec } A$ which on principal open subsets $D(f)$ is simply

$$\mathcal{O}_{\text{Spec } A}(D(f)) = \mathcal{O}(D(f)) = A[f^{-1}].$$

Remark 2.12 ★ The space of sections (espace étalé) of a (pre)sheaf.

Suppose \mathcal{F} is a presheaf (e.g., a sheaf) on a topological space X . Construct a topological space F along with a continuous map $\pi : F \rightarrow X$ as follows: as a set, F is the disjoint union of all the stalks of \mathcal{F} . This naturally gives a map of sets $\pi : F \rightarrow X$. Topologize F as follows. Each s in $\mathcal{F}(U)$ determines

a subset $\{(x, s_x) : x \in U\}$ of F . The topology on F is the weakest topology such that these subsets are open. (These subsets form a base of the topology. For each $y \in F$, there is an open neighborhood V of y and an open neighborhood U of $\pi(y)$ such that $\pi|_V$ is a homeomorphism from V to U .) The topological space F could be thought of as the space of sections of \mathcal{F} (and in French is called the espace étalé of \mathcal{F})

Def 2.13 *The pushforward sheaf/direct image sheaf*

Suppose $\pi : X \rightarrow Y$ is a continuous map, and \mathcal{F} is a presheaf on X . Then define $\pi_*\mathcal{F}$ by $\pi_*\mathcal{F}(V) = \mathcal{F}(\pi^{-1}(V))$, where V is an open subset of Y . Show that $\pi_*\mathcal{F}$ is a presheaf on Y , and is a sheaf if \mathcal{F} is. This is called the **pushforward** or **direct image** of \mathcal{F} . More precisely, $\pi_*\mathcal{F}$ is called the **pushforward of \mathcal{F} by π** .

Once we realize that sheaves form a category, we will see that the pushforward is a functor from sheaves on X to sheaves on Y (see next subsection).

pushforward induces maps of stalks

Suppose $\pi : X \rightarrow Y$ is a continuous map, and \mathcal{F} is a sheaf of sets (or rings or A -modules) on X . If $\pi(p) = q$, we can describe a natural morphism of stalks $(\pi_*\mathcal{F})_q \rightarrow \mathcal{F}_p$. (Use the explicit definition of stalk using representatives, or the universal property)

(If $\phi : \mathcal{F} \rightarrow \mathcal{G}$ is a morphism of presheaves then for each $x \in X$ we have a well-defined induced map $\phi_x : \mathcal{F}_x \rightarrow \mathcal{G}_x$ defined by $\overline{(U, s)} \rightarrow \overline{(U, \phi_U(s))}$. The well-definedness of this map comes from the naturality properties of morphisms of presheaves)

Example 2.14 As the notation suggests, the skyscraper sheaf can be interpreted as the pushforward of the constant sheaf \underline{S} on a one-point space p , under the inclusion morphism $i_p : \{p\} \rightarrow X$.

2.2 Morphisms of presheaves and sheaves

Def 2.15 Let X be a topological space. A **morphism** $\varphi : \mathcal{F}_1 \rightarrow \mathcal{F}_2$ **of presheaves of \mathcal{C} on X** consists of a collection of morphisms $\varphi(U) : \mathcal{F}_1(U) \rightarrow \mathcal{F}_2(U)$ in \mathcal{C} for every $U \subseteq X$ open compatible with restrictions, i.e. such that for all $V \subseteq U \subseteq X$ open, the following diagram commutes:

$$\begin{array}{ccc} \mathcal{F}_1(U) & \xrightarrow{\varphi(U)} & \mathcal{F}_2(U) \\ \downarrow \rho_{1,UV} & & \downarrow \rho_{2,UV} \\ \mathcal{F}_1(V) & \xrightarrow{\varphi(V)} & \mathcal{F}_2(V) \end{array}$$

A morphism $\varphi : \mathcal{F}_1 \rightarrow \mathcal{F}_2$ of sheaves \mathcal{F}_i is a morphism $\mathcal{F}_1 \rightarrow \mathcal{F}_2$ between the \mathcal{F}_i considered as presheaves.

Example 2.16 Let X be a topological space.

(1) Every morphism $f : A \rightarrow B$ of objects in \mathcal{C} yields a morphism of presheaves $\varphi : \underline{A} \rightarrow \underline{B}$ by setting $\varphi(U) := f$.

(2) If $X = \mathbb{R}^n$, the association $\mathcal{C}^\infty(U) := C^\infty(U)$ with the usual restriction maps defines a presheaf and the inclusions $C^\infty(U) \subseteq C^0(U)$ define a morphism of presheaves $\mathcal{C}^\infty \rightarrow \mathcal{C}^0$.

(3) If $Y_2 \xrightarrow{\pi_2} Y_1 \xrightarrow{\pi_1} X$ are continuous maps of topological spaces, then there is an associated morphism $\mathcal{F}_{\pi_1 \circ \pi_2} \rightarrow \mathcal{F}_{\pi_1}$ of the presheaves of continuous sections.

Remark 2.17 Note that there is a forgetful functor $\iota : \text{Sh}_{\mathcal{C}}(X) \rightarrow \text{PSh}_{\mathcal{C}}(X)$ that simply forgets the sheaf axioms. By our definition of morphism of sheaves, this functor is fully faithful.

2.3 Properties determined at the level of stalks, and sheafification

Proposition 2.18 *Let X be a space with presheaves \mathcal{F} and \mathcal{G} , and let $\phi, \psi : \mathcal{F} \rightarrow \mathcal{G}$ be morphisms of presheaves.*

1. *If \mathcal{F} is a sheaf and $U \subseteq X$ is open, then*

$$\begin{aligned} \rho_U : \mathcal{F}(U) &\longrightarrow \prod_{x \in U} \mathcal{F}_x \\ s &\longmapsto (s_x)_{x \in U} \end{aligned}$$

is injective

2. *If \mathcal{F} is a sheaf, then ϕ_U is injective for all open $U \subset X$ if and only if $\phi_x : \mathcal{F}_x \rightarrow \mathcal{G}_x$ is injective for all $x \in X$, i.e. sections of sheaves are determined by their germs.*

3. *If \mathcal{F} and \mathcal{G} are sheaves, then ϕ_U is bijective for all open $U \subset X$ if and only if $\phi_x : \mathcal{F}_x \rightarrow \mathcal{G}_x$ is bijective for all $x \in X$*

4. *If \mathcal{G} is a sheaf, then $\phi = \psi$ if and only if $\phi_x = \psi_x$ for all $x \in X$*

Warning: surjectivity of the stalk function is a big deal. We can describe the failure in an equivalence of surjectivity in terms of homological algebra, and this is where we get sheaf cohomology from

Def 2.19 *Let X be a topological space, and let \mathcal{F} and \mathcal{G} be sheaves, and let $\phi : \mathcal{F} \rightarrow \mathcal{G}$ be a morphism of sheaves.*

1. *The maps ϕ is called **injective** (resp. **bijective**) if for all $x \in X$ $\phi_x : \mathcal{F}_x \rightarrow \mathcal{G}_x$ is injective (resp. bijective). This is equivalent to ϕ_U being injective (resp. bijective) for all open subsets $U \subseteq X$*
2. *The map ϕ is called **surjective** if for all $x \in X$ $\phi_x : \mathcal{F}_x \rightarrow \mathcal{G}_x$ is surjective. This is not equivalent to ϕ_U being surjective for all $U \subseteq X$*

Remark 2.20 *surjectivity as sheaves does not imply surjectivity as presheaves :*

$$f : \mathbb{R} \rightarrow S^1, r \mapsto e^{2\pi i r}$$

define $\forall U \in \text{Ouw}_{S^1}, \mathcal{E}(U) = \{g : U \rightarrow \mathbb{R} \mid g \text{ continuous and } f \circ g = \text{id}_U\}$, also consider constant sheaf $\forall U \in \text{Ouw}_{S^1}, \mathcal{C}(U) = \{\text{id} : U \rightarrow U\}$

define the map $\mathcal{E} \rightarrow \mathcal{C}$ takes $g \in \mathcal{E}(U) \mapsto f \circ g$

the surjective map of sheaves $(\mathcal{E}_x = \{g_n \mid g_n(x) = x + 2\pi i n\} \rightarrow \mathcal{C}_x = \{\text{id}_x\})$, but $\mathcal{E}(S^1) = \emptyset$ while $\mathcal{C}(S^1) = \{*\}$

Proposition 2.21 *Let X be a topological space and \mathcal{F} be a presheaf on X , then there exists a sheaf $\tilde{\mathcal{F}}$ with a morphism of presheaves $\iota_{\tilde{\mathcal{F}}} : \mathcal{F} \rightarrow \tilde{\mathcal{F}}$ such that for every morphism of presheaves $\phi : \mathcal{F} \rightarrow \mathcal{G}$ where \mathcal{G} is a sheaf, there exists a unique morphism $\bar{\phi} : \tilde{\mathcal{F}} \rightarrow \mathcal{G}$ such that $\phi = \bar{\phi} \circ \iota_{\tilde{\mathcal{F}}}$. The following also holds:*

1. *The map $\iota_{\tilde{\mathcal{F}}}$ induces bijections on stalks*
2. *The pair $(\tilde{\mathcal{F}}, \iota_{\tilde{\mathcal{F}}})$ is unique up to unique isomorphism*
3. *The pair $(\tilde{\mathcal{F}}, \iota_{\tilde{\mathcal{F}}})$ is natural in the presheaf variable \mathcal{F} and morphisms of presheaves*

4. The assignment $\mathcal{F} \mapsto \tilde{\mathcal{F}}$ and $\phi \mapsto \bar{\phi}$ is a functor, left adjoint to the inclusion functor from the category of sheaves into the category of presheaves

$$\text{Hom}_{\text{Psh}}(\mathcal{F}, \text{Forget}(\mathcal{G})) \cong \text{Hom}_{\text{Shv}}(\tilde{\mathcal{F}}, \mathcal{G})$$

Proof: For some open set $U \subseteq X$ we define

$$\tilde{\mathcal{F}}(U) = \left\{ (s_x)_{x \in U} \in \prod_{x \in U} \mathcal{F}_x \right\} \forall x \in U, \exists V \in \text{Ouv}(U) \text{ such that } x \in V, t \in \mathcal{F}(V) : \forall y \in V, s_y = t_y \}.$$

□

Proposition 2.22 *Let A be a ring, $X = \text{Spec } A$ and $x \in X$, then*

$$\mathcal{O}_{X,x} \cong A_{\mathfrak{p}_x}$$

Proof: Consider the basis for X of principal open subsets, so $\mathcal{B} = \{D(f) \subseteq X \mid f \in A\}$. Then we can rewrite the definition of the stalk of the structure sheaf at a point $x \in X$ as

$$\mathcal{O}_X|_x = \text{colim}_{x \in U, U=D(f)} \mathcal{O}_X(U) = \text{colim}_{x \in U \in \mathcal{B}} A[f^{-1}] =: B.$$

that $B \cong A_{\mathfrak{p}_x}$, The above colimit is taken over the structure maps $\frac{a}{f^n} \mapsto \frac{a}{f^n} = \frac{ag^n}{(fg)^n}$ □

2.4 Sheaves of abelian groups, and \mathcal{O}_X -modules, form abelian categories

Exercise 2 (4 points):

Let I be a filtered partially ordered set. Show that for each I -indexed inductive system

$$0 \rightarrow A_i \xrightarrow{\alpha_i} B_i \xrightarrow{\beta_i} C_i \rightarrow 0$$

of short exact sequences of abelian groups, the sequence

$$0 \rightarrow \varinjlim_{i \in I} A_i \rightarrow \varinjlim_{i \in I} B_i \rightarrow \varinjlim_{i \in I} C_i \rightarrow 0$$

of colimits is again exact.

Exercise 3 (4 points):

Let X be a topological space.

1) Show that the category $\text{Sh}_{\text{ab}}(X)$ of sheaves of abelian groups on X is an abelian category with all colimits and limits.

Hint: First construct colimits and limits of presheaves, and then sheafify the presheaf colimits.

2) Show that a morphism $f: \mathcal{F} \rightarrow \mathcal{G}$ of sheaves of abelian groups is surjective on each stalk if and only if f is an epimorphism in $\text{Sh}_{\text{ab}}(X)$.

3) Let $X = S^1 \subseteq \mathbb{R}^2$ with upper and lower hemisphere $i_+: D_+ \rightarrow S^1$, $i_-: D_- \rightarrow S^1$. Set $i: D_+ \cap D_- \rightarrow S^1$, and $\mathcal{F} := i_{-,*}\underline{\mathbb{Z}} \oplus i_{+,*}\underline{\mathbb{Z}}$, $\mathcal{G} := i_*(\underline{\mathbb{Z}})$. Construct an epimorphism $\mathcal{F} \rightarrow \mathcal{G}$ such that $\mathcal{F}(X) \rightarrow \mathcal{G}(X)$ is not surjective. Here, $\underline{\mathbb{Z}} = C(-, \mathbb{Z})$ denotes the constant sheaf with value on \mathbb{Z} on the respective topological spaces.

2.5 The inverse image sheaf

Def 2.23 Let $f : X \rightarrow Y$ be a continuous map of topological spaces, and let \mathcal{F} be a presheaf on X and \mathcal{G} be a presheaf on Y

1. The **pushforward** $f_*\mathcal{F}$ is the presheaf on Y defined by $(f_*\mathcal{F})(V) = \mathcal{F}(f^{-1}(V))$ for $V \in \text{Ouv}(Y)$
2. The **pullback** $f^+\mathcal{G}$ ($f^*\mathcal{G}$) is the presheaf on X defined by $(f^+\mathcal{G})(U) = \text{colim}_{f(U) \subset V, V \in \text{Ouv}(Y)} \mathcal{G}(V)$ for an open set $U \subset X$

Proposition 2.24 We have the following natural correspondence :

$$\text{PreSh}(X)(f^+\mathcal{G}, \mathcal{F}) \cong \text{PreSh}(Y)(\mathcal{G}, f_*\mathcal{F})$$

We say that f^+ is left adjoint to f_* , it's right adjoint

Recall that the fact we have an adjoint pair of functors tells us a lot of information, like left adjoint preserve all colimits and right adjoints preserve all limits, and stuff like that

Proposition 2.25 Let $x \in X$, then we have a natural identification $(f^+\mathcal{G})_x = \mathcal{G}_{f(x)}$

Def 2.26 Let $f : X \rightarrow Y$ be a continuous map of topological spaces, and let \mathcal{G} be a sheaf on Y

$f^{-1}\mathcal{G} = \widetilde{f^+\mathcal{G}}$ is the sheafification of $f^+\mathcal{G}$

Proposition 2.27 Let $f : X \rightarrow Y$ be a continuous map of topological spaces, and let \mathcal{F} be a sheaf on X and \mathcal{G} be a sheaf on Y

1. $f_*\mathcal{F}$ is a sheaf on Y
2. We have the following adjunction : $\text{Sh}(X)(f^{-1}\mathcal{G}, \mathcal{F}) \cong \text{Sh}(Y)(\mathcal{G}, f_*\mathcal{F})$
3. For all $x \in X$ we have $(f^{-1}\mathcal{G})_x = \mathcal{G}_{f(x)}$

Corollary 2.28 Let (X, \mathcal{O}_X) and (Y, \mathcal{O}_Y) be ringed spaces, then

$$\text{Hom}((X, \mathcal{O}_X), (Y, \mathcal{O}_Y)) \cong \{f : X \rightarrow Y \text{ and } f^\# : f^{-1}\mathcal{O}_Y \rightarrow \mathcal{O}_X\} \cong \{f : X \rightarrow Y \text{ and } f^\flat : \mathcal{O}_Y \rightarrow f_*\mathcal{O}_X\}$$

2.6 Recovering sheaves from a “sheaf on a base”

Let X be a topological space and let \mathcal{B} be a basis of the topology of X , stable under finite intersections. Let $\mathrm{Sh}_{\mathcal{B}}(X)$ be the category of sheaves on the basis \mathcal{B} as defined in the lecture. Prove that the functors

$$\mathrm{Sh}(X) \rightarrow \mathrm{Sh}_{\mathcal{B}}(X), (\mathcal{F}: \mathrm{Ouv}(X)^{\mathrm{op}} \rightarrow \mathrm{Sets}) \mapsto (\mathcal{F}|_{\mathcal{B}^{\mathrm{op}}}: \mathcal{B}^{\mathrm{op}} \rightarrow \mathrm{Sets})$$

and

$$\mathrm{Sh}_{\mathcal{B}}(X) \rightarrow \mathrm{Sh}(X), \mathcal{F} \mapsto (U \mapsto \varprojlim_{V \subseteq U, V \in \mathcal{B}} \mathcal{F}(V))$$

are inverse equivalences of categories.

3 Scheme

3.1 Locally Ringed Spaces and Schemes

Def 3.1 A ring A is a **local ring** if it has a unique maximal ideal \mathfrak{m}_A

In this case, note that all the elements of $A \setminus \mathfrak{m}_A$ are invertible. Conversely, if A is a ring and $I \subseteq A$ is an ideal such that all elements of $A \setminus I$ are invertible, then A is a local ring with $\mathfrak{m}_A = I$

Def 3.2 A spectral space X is called **local** if it has a unique closed point

Lemma 3.3 A ring A is a local ring if and only if $\text{Spec } A$ is a local spectral space

Proof: The closed points of an affine scheme $\text{Spec } A$ are exactly the maximal ideals □

Def 3.4 A morphism $\phi : A \rightarrow B$ of local rings is a **local morphism** if $\phi^{-1}(\mathfrak{m}_B) = \mathfrak{m}_A$ (so it preserves the local structure)

A map $f : X \rightarrow Y$ of local spectral spaces is called **local** if it maps the closed point of X to the closed point of Y

Example 3.5 The map $\mathbb{Z}_{(p)} \rightarrow \mathbb{Q}$ is not a local map

Lemma 3.6 A morphism of local rings $\phi : A \rightarrow B$ is local if and only if $\phi : \text{Spec } B \rightarrow \text{Spec } A$ is local.

Def 3.7 Given a ring A and a prime ideal $\mathfrak{p} \subseteq A$, then the **localisation of A at \mathfrak{p}** is

$$A_{\mathfrak{p}} = A[(A \setminus \mathfrak{p})^{-1}].$$

Given a spectral space X and $x \in X$, then the localisation of X at x is

$$X_x = \bigcap_{x \in U} U$$

Proposition 3.8 Given a spectral space X , a point $x \in X$, a ring A and prime ideal $\mathfrak{p} \subseteq A$

1. The ring $A_{\mathfrak{p}}$ is a local ring with maximal ideal $\mathfrak{p}A_{\mathfrak{p}}$
2. The spectral space X_x is a local spectral space
3. If $X = \text{Spec } A$, then we have a map $A \rightarrow A_{\mathfrak{p}}$ and $\text{Spec } A_{\mathfrak{p}} \cong X_x$ where x corresponds to \mathfrak{p} in $X = \text{Spec } A$

Proof: For part 3, we rewrite $A_{\mathfrak{p}}$ as the following filtered colimit

$$\text{colim}_{f \notin \mathfrak{p}} A[f^{-1}].$$

This implies that $\text{Spec } A_{\mathfrak{p}}$ can be rewritten as the following cofiltered limit

$$\text{Spec } A_{\mathfrak{p}} = \lim_{f \notin \mathfrak{p}} \text{Spec } A[f^{-1}] = \lim_{f \notin \mathfrak{p}} D(f) = \bigcap_{f \notin \mathfrak{p}} D(f) = X_x$$

□

Def 3.9 1. A **ringed space** is a pair (X, \mathcal{O}_X) of a topological space X and a sheaf of rings \mathcal{O}_X

2. A **locally ring space** is a ring space (X, \mathcal{O}_X) , such that for all $x \in X$, the stalk $\mathcal{O}_{X,x}$ at x is a local ring

3. If A is a ring, then **Spec A** is the locally ringed space $(\text{Spec } A, \mathcal{O}_{\text{Spec } A})$

Def 3.10 Let (X, \mathcal{O}_X) and (Y, \mathcal{O}_Y) be ringed spaces, then a **map of ringed spaces** is a continuous map of underlying topological spaces $f : X \rightarrow Y$ plus a map $f^\#_{V \rightarrow U} : \mathcal{O}_Y(V) \rightarrow \mathcal{O}_X(U)$ for all open $U \subset X, V \subset Y$ and $f(U) \subset V$, such that for all open set containments $U' \subset U \subset X$ and $V' \subset V \subset Y$, and $f(U') \subset V'$ and $f(U) \subset V$, we have the following commutative diagram:

$$\begin{array}{ccc} \mathcal{O}_Y(V) & \xrightarrow{f^\#_{V \rightarrow U}} & \mathcal{O}_X(U) \\ \downarrow \text{res}_{V'}^{V'} & & \downarrow \text{res}_{U'}^U \\ \mathcal{O}_Y(V') & \xrightarrow{f^\#_{V' \rightarrow U'}} & \mathcal{O}_X(U') \end{array}$$

i.e. $f^\# : f^{-1}(\mathcal{O}_Y) \rightarrow \mathcal{O}_X$ is a map of ShvRing

Proposition 3.11 Let (X, \mathcal{O}_X) and (Y, \mathcal{O}_Y) be ringed spaces, use prop 2.27:

$$\text{Hom}((X, \mathcal{O}_X), (Y, \mathcal{O}_Y)) \cong \{f : X \rightarrow Y \text{ and } f^\# : f^{-1}\mathcal{O}_Y \rightarrow \mathcal{O}_X\} \cong \{f : X \rightarrow Y \text{ and } f^b : \mathcal{O}_Y \rightarrow f_*\mathcal{O}_X\}$$

Def 3.12 Let $(\phi =)f : B \rightarrow A$ be a map of rings, and let $X = \text{Spec } A$ and $Y = \text{Spec } B$ then spaces, and $\phi : (X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$ is a morphism of ringed spaces given by $\phi : X \rightarrow Y$ on the level of topological spaces, and $\phi^\# = \phi^b : \mathcal{O}_Y \rightarrow \phi_*\mathcal{O}_X$ defined on a basis of principal opens by the natural map for all $s \in B$:

$$\begin{array}{ccc} \mathcal{O}_Y(D(s)) & \xrightarrow{\quad} & \mathcal{O}_X(\phi^{-1}D(s)) \\ \downarrow = & & \downarrow = \\ B[s^{-1}] & \xrightarrow{f[s^{-1}]} & A[f(s)^{-1}] \end{array}$$

where we can identify $\mathcal{O}_X(\phi^{-1}(D(s))) = \mathcal{O}_X(D(f(s)))$.

Remark 3.13 (Warning!). The functor from the category of rings to the category of ringed spaces is not fully faithful yet, because there are maps between affine schemes (now consider only as ringed spaces) that are not yet induced by maps of rings.

Take p some prime, then there is a morphism of ringed spaces $f_p : (\text{Spec } \mathbb{Q}, \mathcal{O}_{\text{Spec } \mathbb{Q}}) \rightarrow (\text{Spec } \mathbb{Z}, \mathcal{O}_{\text{Spec } \mathbb{Z}})$ which is defined by sending the point $\text{Spec } \mathbb{Q} = *$ to $p \in \text{Spec } \mathbb{Z}$. Indeed, take $f^\# : f_p^{-1}\mathcal{O}_{\text{Spec } \mathbb{Z}} = \mathbb{Z}_{(p)} \rightarrow \mathcal{O}_{\text{Spec } \mathbb{Q}}$ to be the natural map, then this does not come from a ring map $\mathbb{Z} \rightarrow \mathbb{Q}$

Def 3.14 Let (X, \mathcal{O}_X) and (Y, \mathcal{O}_Y) be locally ringed spaces, then a **map of locally ringed spaces** is a map of ringed spaces s.t. for all $x \in X$, the map $f^\#_x : (\mathcal{O}_Y)_{f(x)} \rightarrow (\mathcal{O}_X)_x$ is a local map

Def 3.15 An **affine scheme** is a locally ringed space (X, \mathcal{O}_X) such that $(X, \mathcal{O}_X) \cong (\text{Spec } A, \mathcal{O}_{\text{Spec } A})$ for some ring A .

A **morphism of affine schemes** is exactly a morphism of locally ringed spaces.

A **scheme** is a locally ringed space (X, \mathcal{O}_X) such that there exists a covering $X = \bigcup_{i \in \mathcal{I}} U_i$ of X by open subsets such that each $(U_i, \mathcal{O}_{X|U_i})$ is isomorphic to an affine scheme.

A **morphism of schemes** is simply a morphism of locally ringed spaces

Proposition 3.16 *If $f : B \rightarrow A$ is a map of rings inducing a map $(g, g^\#) : (\text{Spec } A, \mathcal{O}_{\text{Spec } A}) \rightarrow (\text{Spec } B, \mathcal{O}_{\text{Spec } B})$, then it is a morphism of locally ringed spaces. For all $x = \mathfrak{p} \in \text{Spec } A$, we have $\mathfrak{p} \subseteq A$, and $f^{-1}(\mathfrak{p}) = \mathfrak{q} \subseteq B$ and we have $g_x^\# : \mathcal{O}_{Y, g(x)} = B_\mathfrak{q} \rightarrow A_\mathfrak{p} = \mathcal{O}_{X, x}$ is a local map. On spectral spaces we have $x \mapsto y = f^{-1}(\mathfrak{p}) \in \text{Spec } B$, which on localised spectral spaces is a map $\text{Spec } A_\mathfrak{p} = X_x \rightarrow Y_y = \text{Spec } B_\mathfrak{q}$*

Theorem 3.17 *The contravariant functor which sends $A \mapsto (\text{Spec } A, \mathcal{O}_{\text{Spec } A})$ is an equivalence of categories between the category of rings and the category of affine schemes*

Theorem 3.18 *The functor $\text{Spec} : \{\text{Ring}\}^{op} \rightarrow \{\text{locally ringed spaces}\}$ is fully faithful onto its image, which we'll call the category of affine schemes*

3.2 Affine Schemes with Strucutre Sheaf are Rings

$$\mathbf{3.2.1} \quad \text{Hom}((X, \mathcal{O}_X), (Y, \mathcal{O}_Y)) \cong \text{Hom}_{\text{Rings}}(B, \Gamma(X, \mathcal{O}_X))$$

Def 3.19 notation $\Gamma(X, \mathcal{F})$ and $\mathcal{F}(X)$ for the global sections of a sheaf \mathcal{F} over the topological space X

We treat $\Gamma(X, -) : \text{Shv}(X) \rightarrow \text{Sets}$ as a functor

We consider $\Gamma(X, \mathcal{O}_X)$ the ring of global sections

Remark 3.20 $\Gamma(-, \mathcal{O}_-) : \{\text{locally ringed spaces}\} \rightarrow \{\text{Ring}\}^{\text{op}}$ a functor

If $(g, g^\#) : (X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$

$g^\# : g^{-1}\mathcal{O}_Y \rightarrow \mathcal{O}_X$ has adjoint $g^\flat : \mathcal{O}_Y \rightarrow g_*\mathcal{O}_X$

$$\Gamma(g, g^\#) : \Gamma(Y, \mathcal{O}_Y) \xrightarrow{g^\flat} \Gamma(Y, g_*\mathcal{O}_X) = \mathcal{O}_X(g^{-1}(Y)) = \mathcal{O}_X(X) = \Gamma(X, \mathcal{O}_X)$$

Theorem 3.21 Let (X, \mathcal{O}_X) be a locally ringed space and let (Y, \mathcal{O}_Y) be an affine scheme, say $Y = \text{Spec } B$, then the map

$$\Gamma(-, -) : \text{Hom}((X, \mathcal{O}_X), (Y, \mathcal{O}_Y)) \longrightarrow \text{Hom}_{\text{Rings}}(B, \Gamma(X, \mathcal{O}_X))$$

is an isomorphism

Proof:

□

Proof of Theorem 7.3 \implies Theorem 7.1. When $(X, \mathcal{O}_X) = \text{Spec } A$ for some ring A , then the isomorphism of Theorem 7.3 shows us the functor Spec is fully faithful. □

Proof of Theorem 7.3. Both of the following parts of this theorem rely on us building maps between spaces by only knowing what these maps do on global sections. This requires the hypothesis for our ringed spaces to be local quite heavily, as one will see in the proof.

(Injectivity) Given $(f, f^\#)$ and some other $(g, g^\#) : (X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$ which induce the same map $\phi : B = \mathcal{O}_Y(Y) \rightarrow \mathcal{O}_X(X)$ on global sections. We first claim that $f = g$. To see this, let $x \in X$, then we have the following commutative diagram,

$$\begin{array}{ccc} \mathcal{O}_X(X) & \longrightarrow & \mathcal{O}_{X,x} \\ \phi \uparrow & & f_x^\# \uparrow \\ \mathcal{O}_Y(Y) = B & \longrightarrow & B_{\mathfrak{q}} = \mathcal{O}_{Y,f(x)} \end{array}, \quad (7.4)$$

where \mathfrak{q} is the prime ideal of B corresponding to $f(x) \in Y = \text{Spec } B$, \mathfrak{m}_x denote the maximal ideal of $\mathcal{O}_{X,x}$, and $f_x^\#$ is a local map¹². The preimage of \mathfrak{m}_x in B is \mathfrak{q} , which corresponds to $f(x)$, by following

the bottom right corner of the diagram, whilst on the other hand the top left corner of the diagram tells us this only depends on ϕ . Repeating this argument but with g , we see that $f(x) = g(x)$, since both these arguments only depend on ϕ , hence $f = g$. Now we want to show that $f^\# = g^\#$, or equivalently that $f^b = g^b$. It suffices to check this on $\mathcal{O}_Y(U)$ for $U = D(s)$ for all $s \in B$ since these principal opens form a basis of our topology on $\text{Spec } B = Y$. We have the following commutative diagram.

$$\begin{array}{ccccc} B = \mathcal{O}_Y(Y) & \xrightarrow{\phi} & \mathcal{O}_X(X) & \xrightarrow{=} & (f_*\mathcal{O}_X)(Y) \\ \downarrow \text{res}_U^Y & & \downarrow \text{res}_{f^{-1}(U)}^Y & & \downarrow \text{res}_U^Y \\ B[s^{-1}] = \mathcal{O}_Y(U) & \xrightarrow{f^b(U), g^b(U)} & \mathcal{O}_X(f^{-1}(U)) & \xrightarrow{=} & (f_*\mathcal{O}_X)(U) \end{array}$$

We notice that $\mathcal{O}_X(f^{-1}(U))$ obtains a B -algebra structure from the map of rings $B \rightarrow \mathcal{O}_X(f^{-1}(U))$. In general, there is at most one map of B -algebras $B[s^{-1}] \rightarrow C$, and it exists if and only if s is invertible in C . This implies that $f^b(U) = g^b(U)$ for all U in the basis of our topology, hence $f^b = g^b \Leftrightarrow f^\# = g^\#$. This shows that our map of Theorem 7.3 is injective.

The fun part is surjectivity, which comes in three separate sections. Let $\phi : B \rightarrow \mathcal{O}_X(X)$ be a map of rings, then we need to produce a map $(f, f^\#) : (X, \mathcal{O}_X) \rightarrow (\text{Spec } B, \mathcal{O}_{\text{Spec } B})$.

(Definition of $f : X \rightarrow Y$) From the argument surrounding Diagram 7.4 we know what we have to do with $x \in X$. We have

$$B \xrightarrow{\phi} \mathcal{O}_X(X) \longrightarrow \mathcal{O}_{X,x} \supseteq \mathfrak{m}_x.$$

We then let $\mathfrak{q} \in B$ be the preimage of \mathfrak{m}_x and define $f(x) = y$, where $y \in \text{Spec } B = Y$ corresponds to $\mathfrak{q} \subseteq B$.

(Continuity) Given a general locally ringed space X , for $t \in \mathcal{O}_X(X)$, we define

$$D(t) = \{x \in X \mid t_x \notin \mathfrak{m}_x \subseteq \mathcal{O}_{X,x}\} = \{x \in X \mid t_x \neq 0 \in k(x)\},$$

which are analogous to our principal opens. When X is an affine scheme these are simply the principal open subsets. We claim that $D(t) \subseteq X$ is always open, and that the section $t|_{D(t)}$ is invertible inside $\mathcal{O}_X(D(t))$. Both these properties can be checked locally around $x \in D(t)$, since an inverse is unique if it exists, so local inverses automatically glue. As $t_x \notin \mathfrak{m}_x \subseteq \mathcal{O}_{X,x}$, we notice that $t_x \in \mathcal{O}_{X,x}$ is invertible¹³, so there exists some open subset U of X containing x such that we have $v \in \mathcal{O}_X(U)$ with $t_x v_x = 1 \in \mathcal{O}_{X,x}$, and after taking U small enough, we have $t|_U v|_U = 1$ in $\mathcal{O}_X(U)$. Thus $t|_U$ is invertible, which implies that $U \subseteq D(t)$, so $D(t)$ contains an open neighbourhood of U , and t is invertible on U .

To prove the continuity of our assignment, we need to check that for each $s \in B$, we have $f^{-1}(D(s))$ is open in X . However we find that,

$$f^{-1}(D(s)) = \{x \in X \mid \phi(s)_x \notin \mathfrak{m}_x \subseteq \mathcal{O}_{X,x}\} = D(\phi(s)).$$

Hence this assignment is continuous.

(Definition of $f^b : \mathcal{O}_Y \rightarrow f_*\mathcal{O}_X$) To suffices to define compatible maps $f^b(D(s)) : \mathcal{O}_Y(D(s)) \rightarrow (f_*\mathcal{O}_X)(D(s))$ such that the following diagram commutes,

$$\begin{array}{ccc} B[s^{-1}] = \mathcal{O}_Y(D(s)) & \xrightarrow{f^b|_{D(s)}} & (f_*\mathcal{O}_X)(D(s)) = \mathcal{O}_X(D(\phi(s))) \\ \uparrow & & \uparrow \\ B & \xrightarrow{\phi} & \mathcal{O}_X(X) = (f_*\mathcal{O}_X)(Y) \end{array}.$$

¹³We really need locally ringed spaces here.

Again, there is at most one $f^b(D(s))$ with the above commutative diagram, which exists if and only if $\phi(s)|_{D(\phi(s))} \in \mathcal{O}_X(D(\phi(s)))$ is invertible, but we proved this is true above. This gives us a map of ringed spaces f^b , but we need to check the adjoint map $f^\#$ induces a local map on stalks.

(The Adjoint Map $f^\# : (f^{-1}\mathcal{O}_Y)_x \rightarrow \mathcal{O}_{X,x}$ is Local) Recall that $f(x) \in Y$ corresponds to $\mathfrak{q} \in B$ given by the preimage of \mathfrak{m}_x under the composition $B \rightarrow \mathcal{O}_X(X) \rightarrow \mathcal{O}_{X,x}$. We now recall that $\mathcal{O}_{Y,f(x)} = B_{\mathfrak{q}}$, so we have the following diagram which determines $f_x^\#$ uniquely.

$$\begin{array}{ccc} B & \xrightarrow{\phi} & \mathcal{O}_X(X) \\ \downarrow & & \downarrow \\ B_{\mathfrak{q}} = \mathcal{O}_{Y,f(x)} & \xrightarrow{f_x^\#} & \mathcal{O}_{X,x} \end{array} . \quad (7.5)$$

We want to have $(f_x^\#)^{-1}(\mathfrak{m}_x = \mathfrak{m}_{f(x)} = \mathfrak{q}B_{\mathfrak{q}} \subseteq B_{\mathfrak{q}})$, and to see this we note that for affine spectra, the canonical map $\text{Spec } B_{\mathfrak{q}} \rightarrow \text{Spec } B$ is injective. This means we can check the equality in $\text{Spec } B$ after pulling this back to $B_{\mathfrak{q}}$. This is then trivial from Diagram 7.5. Hence our map is local, and we're done! \square

3.2.2 Open immersion

Def 3.22 open immersion

A morphism of ringed spaces $(f, f^\#) : (X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$ is an **open immersion** if $f : X \rightarrow Y$ is an open embedding and $f^\# : f^{-1}\mathcal{O}_Y \rightarrow \mathcal{O}_X$ is an isomorphism or equivalently, there exists an open subset $U \subset Y$ such that $(X, \mathcal{O}_X) \cong (U, \mathcal{O}_Y|_U)$, and this isomorphism factors $(X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$ through the inclusion $(U, \mathcal{O}_Y|_U) \rightarrow (Y, \mathcal{O}_Y)$

Proposition 3.23 Let (Y, \mathcal{O}_Y) be a scheme and $(X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$ be an open immersion, then (X, \mathcal{O}_X) is also a scheme

Proof: Let (Y, \mathcal{O}_Y) be a scheme, and U be an open subset of Y , then we'll show $(U, \mathcal{O}_Y|_U)$ is a scheme. In the proposition. $(U, \mathcal{O}_Y|_U)$ is the image of (X, \mathcal{O}_X) . Now let $\{V_i\}$ be a collection of open sets such that $Y = \bigcup V_i$ and $V_i \cong \text{Spec } B_i$, then for all $x \in U$ we can choose i such that $x \in V_i$, so $V_i \cap U \subseteq V_i$ is an open neighbourhood of x . This implies that there exists $f \in B_i$ such that $x \in D_{V_i}(f) \subseteq V_i \cap U$, so call $U_x = D_{V_i}(f) \subseteq V_i$. Then we have

$$\Gamma(U_x, \mathcal{O}_Y|_{U_x}) = \Gamma(U_x, (\mathcal{O}_Y|_{V_i})|_{U_x}) = B_i[f^{-1}],$$

which is an affine scheme, hence as x varies, all the U_x cover U

\square

Proposition 3.24 Morphisms of ringed spaces glue

Suppose (X, \mathcal{O}_X) and (Y, \mathcal{O}_Y) are ringed spaces, $X = \cup_i U_i$ is an open cover of X , and we have morphisms of ringed spaces $\pi_i : U_i \rightarrow Y$ that "agree on the overlaps", i.e. $\pi_i|_{U_i \cap U_j} = \pi_j|_{U_i \cap U_j}$. Then there is a unique morphism of ringed spaces $\pi : X \rightarrow Y$ such that $\pi|_{U_i} = \pi_i$

Let $U_i, i = 1, 2$, be two schemes. Let $V_i \subseteq U_i$ be open subschemes and let $\varphi: V_1 \xrightarrow{\sim} V_2$ be an isomorphism.

1) Show that there exists a scheme X with open subschemes $W_i \subseteq X$ and isomorphisms $\alpha_i: U_i \xrightarrow{\sim} W_i, i = 1, 2$, such that $\alpha_i^{-1}(W_1 \cap W_2) = V_i$ and $\varphi = \alpha_2^{-1} \circ \alpha_1|_{V_1}$.

2) Let A be a ring and let X_{\pm} be the scheme obtained by glueing $U_1 = U_2 = \text{Spec}(A[T])$ along the isomorphism $\varphi_{\pm}: \text{Spec}(A[T, T^{-1}]) \rightarrow \text{Spec}(A[T, T^{-1}]), T \mapsto T^{\pm 1}$. Show that X_{\pm} are not affine schemes and that X_+ is not isomorphic to X_- .

Remark: X_+ is called the affine line over A with doubled origin, X_- is called the projective line over A .

Example 3.25

1) Let (Y, \mathcal{O}_Y) be a locally ringed space. Show that $(Z, \mathcal{O}_Z) \mapsto Z$ induces a bijection between open subsets of Y and equivalence classes of open immersions $(Z, \mathcal{O}_Z) \rightarrow (Y, \mathcal{O}_Y)$ of locally ringed spaces. Here, open immersions are equivalent if they are isomorphic as locally ringed spaces over (Y, \mathcal{O}_Y) .

2) Let k be an algebraically closed field. For a (classical) quasi-projective variety $X \subseteq \mathbb{P}_k^n$ let \mathcal{O} be its sheaf of regular functions $U \mapsto \mathcal{O}(U)$. Let $\pi: X \rightarrow X^{\text{sob}}$ be the soberification (Sheet 3, Exercise 4). Show that $X^{\text{sch}} := (X^{\text{sob}}, \pi_*\mathcal{O})$ is a scheme over $\text{Spec}(k)$ and that $X \mapsto X^{\text{sch}}$ is a fully faithful functor from the category of quasi-projective varieties to the category of schemes over $\text{Spec}(k)$.

Hint: Reduce to the case of affine algebraic sets by glueing morphisms of locally ringed spaces.

Example 3.26

3.3 Scheme Valued Points

Def 3.27 Given a category \mathcal{C} and an object $S \in \mathcal{C}$, then the category \mathcal{C}/S is defined with objects the pairs $A \rightarrow S$, and morphisms $f : A \rightarrow B$ with the following commutative diagram:

$$\begin{array}{ccc} A & \xrightarrow{f} & B \\ & \searrow & \swarrow \\ & S & \end{array}$$

Fix a scheme S and $X \rightarrow S \in \text{Sch}/S$, and define for any $Z \in \text{Sch}$ (the category of schemes) the **Z -valued point of X/S** as

$$X_S(Z) = \text{Hom}_{\text{Sch}/S}(Z, X)$$

We are being a little vague above, we really mean $X_S(Z)$ to be all morphisms of schemes $f : Z \rightarrow X$ such that the following diagram commutes:

$$\begin{array}{ccc} Z & \xrightarrow{f} & X \\ & \searrow & \swarrow \\ & S & \end{array}$$

Since $\text{Spec } \mathbb{Z}$ is final in the category of schemes, if we take $S = \text{Spec } \mathbb{Z}$ then we will write $X(\mathbb{Z})$, since the commutative diagram above becomes irrelevant. If $Y = \text{Spec } B$ or $S = \text{Spec } C$ we might also write $X_S(Y) = X_S(B) = X_C(Y) = X_C(B)$. This explains the notation for **\mathbf{k} -valued points** as $X(\mathbf{k})$ (i.e. $X_{\text{Spec } \mathbb{Z}}(\text{Spec } k)$)

A -valued points of an affine scheme $\text{Spec } \mathbb{Z}[X_1, \dots, X_n]/(f_1, \dots, f_m)$ (where $f_i \in \mathbb{Z}[X_1, \dots, X_n]$ are relations) are precisely the solutions to the equations $f_1(x_1, \dots, x_n) = \dots = f_m(x_1, \dots, x_n) = 0$ in the ring A . For example, the rational solutions to $x^2 + y^2 = 16$ are precisely the \mathbb{Q} -valued points of $\text{Spec } \mathbb{Z}[x, y]/(x^2 + y^2 - 16)$.

$$\begin{aligned} X(A) &= \text{Hom}_{\text{Sch}}(\text{Spec } A, \text{Spec } \mathbb{Z}[X_1, \dots, X_n]/(f_1, \dots, f_m)) \\ &\cong \text{Hom}_{\text{Ring}}(\mathbb{Z}[X_1, \dots, X_n]/(f_1, \dots, f_m), A) \\ &\cong \{x = (x_1, \dots, x_n) \in A^n \mid f_1(x) = \dots = f_m(x) = 0\} \end{aligned}$$

Given a base scheme S , and any $X \rightarrow S \in \text{Sch}/S$, we have a functor $X_S(-) : (\text{Sch}/S)^{\text{op}} \rightarrow \text{Sets}$ defined by $Z \mapsto X_S(Z)$. We can use the Yoneda lemma to say something concrete about this

Proposition 3.28 Let \mathcal{C} be a category. For $X \in \mathcal{C}$ let $h_X := \text{Hom}_{\mathcal{C}}(-, X) : \mathcal{C}^{\text{op}} \rightarrow \text{Sets}$ be the associated functor. Let $F : \mathcal{C}^{\text{op}} \rightarrow \text{Sets}$ be an arbitrary functor

Recall the Yoneda lemma i.e. the map

$$\text{Hom}(h_X, F) \rightarrow F(X), \quad \eta \mapsto \eta_X(\text{Id}_X)$$

is a bijection, natural in X and F

Let S be a scheme and let $X \rightarrow S, Y \rightarrow S$ be two schemes over S . Let $\mathcal{C} = \text{Sch}/S$ be the category of schemes over S and let $\mathcal{D} \subset \mathcal{C}$ be the full subcategory consisting of objects $Z \rightarrow S \in \mathcal{C}$ with Z affine. Let $\text{Hom}_S(X, Y)$ be the set of morphisms $f: X \rightarrow Y$ of schemes over S . Then there are bijections

$$\text{Hom}_S(X, Y) \cong \text{Hom}(h_X, h_Y) \cong \text{Hom}(h_{X|\mathcal{D}}, h_{Y|\mathcal{D}})$$

where $F|_{\mathcal{D}}$ denotes the restriction of a functor $F: \mathcal{C}^{op} \rightarrow \text{Sets}$ to \mathcal{D}^{op}

Corollary 3.29 *Let Sch^{aff}/S be the full subcategory of Sch/S of affine schemes over S , then the functor $\text{Sch}/S \rightarrow \text{Fun}\left(\left(\text{Sch}^{aff}/S\right)^{op}, \text{Sets}\right)$ is also fully faithful*

In particular, if we take $S = \text{Spec } \mathbb{Z}$ and use our equivalence of the category of affine schemes with the category of rings, we find that a scheme is equivalent to giving a functor from the category of rings to the category of sets, $X \mapsto (R \mapsto X(R))$.

Corollary 3.30 *The functor*

$$\Phi: \{\text{schemes}\} \rightarrow \text{Fun}(\text{Rings}, \text{Sets}), X \mapsto \text{Hom}_{lrs}(\text{Spec}(-), X) = (R \mapsto \text{Hom}_{lrs}(\text{Spec}(R), X))$$

is fully faithful

2) Show that the functors $R \mapsto F_n(R) := \{x \in R \mid x^n = 1\}$ for $n \geq 1$, and $R \mapsto G(R) := \{(x, y) \in R^2 \mid R^2 \xrightarrow{(x, y)} R \text{ surjective}\}$ lie in the essential image of Φ .

Example 3.31

3.4 Fiber products

Proposition 3.32 *Coproducts exist in Sch , if I is an index set, $(X_i)_{i \in I}$ is a family of schemes, then $\coprod_i X_i$ is the coproduct*

For example : $Spec(\prod_{i=1}^n R_i) = \prod_{i=1}^n Spec R_i$, but $Spec(\prod_{i=1}^\infty R_i) (quasicompact) \neq \prod_{i=1}^\infty Spec R_i (not quasicompact)$

Recall in a category \mathcal{C} with finite limits, we can take the pullback (fiber product) of two maps $X \rightarrow S$ and $Y \rightarrow S$ to obtain an objects $X \times_S Y$ which is universal in some sense.

The universal property states that the Z -valued points of $X \times_S Y$ are canonically in bijection with the fiber product of the Z -valued points of X and Y over S in the category of sets. In symbols this reads,

$$(X \times_S Y)(Z) \cong X(Z) \times_{S(Z)} Y(Z),$$

Theorem 3.33 *Fiber products exist in Sch*

Proof: [Hartshorne theorem 3.3]

Key: a) $Spec A \times_{Spec B} Spec C \cong Spec (A \otimes_B C)$

$$\begin{aligned} Hom((X, \mathcal{O}_X), Spec A \times_{Spec B} Spec C) &= Hom((X, \mathcal{O}_X), Spec A) \times_{Hom((X, \mathcal{O}_X), Spec B)} Hom((X, \mathcal{O}_X), Spec C) \\ &\cong Hom_{Rings}(A, \Gamma(X, \mathcal{O}_X)) \times_{Hom_{Rings}(B, \Gamma(X, \mathcal{O}_X))} Hom_{Rings}(C, \Gamma(X, \mathcal{O}_X)) \\ &\cong Hom_{Rings}(A \otimes_B C, \Gamma(X, \mathcal{O}_X)) \\ &\cong Hom((X, \mathcal{O}_X), Spec (A \otimes_B C)) \end{aligned}$$

□

Proposition 3.34 1) *Let $X \xrightarrow{f} S, Y \xrightarrow{g} S$ be two morphisms of locally ringed spaces. Let $X = \bigcup_i U_i, Y = \bigcup_j V_j, S = \bigcup_{i,j} S_{i,j}$ be open coverings. We view $U_i, V_j, S_{i,j}$ as locally ringed spaces via the restriction of the structure sheaves on X, Y, S . Using the universal property of fiber products (which exist in locally ringed spaces), we can show that for all i, j the map $U_i \times_{S_{i,j}} V_j \rightarrow X \times_S Y$ identifies the source as an open subspace of the latter and*

$$\bigcup_{i,j} U_i \times_{S_{i,j}} V_j = X \times_S Y$$

2) *Assume that X, Y, S are schemes. Then the natural map $|X \times_S Y| \rightarrow |X| \times_{|S|} |Y|$ is surjective, but not injective in general*

Proposition 3.35 *Let $f: X \rightarrow S, g: S' \rightarrow S$ be morphisms of schemes. Let $f': X' := X \times_S S' \rightarrow S'$ be the projection.*

1) *If f is an open (resp. closed) immersion, then f' is an open (resp. closed) immersion*

2) *Assume $S' = Spec(k(s)) \rightarrow S$ is the canonical morphism for some $s \in S$. Then $|X'| \rightarrow |X| \times_{|S|} \{s\}$ is a homeomorphism*

3.5 Reduced scheme

Def 3.36 A scheme X is called **reduced** if for all $U \subset X$ open, the ring $\mathcal{O}_X(U)$ is a reduced ring (so $f^m = 0$ if and only if $f = 0$)

Proposition 3.37 1. An affine scheme $X = \text{Spec } A$ is reduced if and only if A is reduced

2. A scheme X is reduced if and only if for all open affines $U = \text{Spec } A \subseteq X$, the ring A is reduced if and only if X admits a cover by reduced affine schemes

Proof: 1. If A is reduced then $A[f^{-1}]$ is reduced for all $f \in A$, and if $U \subset X$ is an open subset, then there exists $f_i \in A$ such that $U = \bigcup_i D(f_i)$. We have an injection

$$\mathcal{O}_X(U) \hookrightarrow \prod_i \mathcal{O}_X(D(f_i)) = \prod_i A[f_i^{-1}],$$

since \mathcal{O}_X is a sheaf, and since the product of reduced rings is reduced, we see that $\mathcal{O}_X(U)$ is reduced. Conversely, if $X = \text{Spec } A$ is reduced then in particular $\mathcal{O}_X(X) = A$ is reduced

2. First assume that X is reduced, then $\mathcal{O}_X(U) = A$ is reduced if $U = \text{Spec } A$. It is clear that all $\mathcal{O}_X(U_\alpha)$ are reduced for an affine cover $\{U_\alpha\}$ of X if $\mathcal{O}_X(U)$ is reduced for all affine opens U . Finally, if $U \subseteq U_\alpha$ are reduced for an affine cover $\{U_\alpha\}$ of X where $\mathcal{O}_X(U_\alpha)$ is reduced, then clearly $\mathcal{O}_X(U)$ is reduced, but for any general $U \subset X$ the injection,

$$\mathcal{O}_X(U) \hookrightarrow \prod_\alpha \mathcal{O}_X(U \cap U_\alpha),$$

again shows us that $\mathcal{O}_X(U)$ is reduced □

Just as there is a canonical way to obtain a reduced ring from any commutative ring A (just take $A_{\text{red}} = A/N$ where N is the ideal of nilpotents of A), there is a canonical way to reduce a scheme

Proposition 3.38 1. Given a scheme $X = (|X|, \mathcal{O}_X)$, then the scheme $\mathbf{X}_{\text{red}} = (|X|, \mathcal{O}_{\mathbf{X}_{\text{red}}})$ is a reduced scheme where $\mathcal{O}_{\mathbf{X}_{\text{red}}}$ is defined as the sheafification of the presheaf $\mathcal{O}_{X_{\text{red}}}^0$, which is defined on some open subset $U \subseteq X$ as $\mathcal{O}_{X_{\text{red}}}^0(U) = (\mathcal{O}_X(U))_{\text{red}}$

2. If $X = \text{Spec } A$ is an affine scheme, then

$$X_{\text{red}} = \text{Spec } A_{\text{red}}$$

3. For any reduced scheme Y , we have a bijection

$$\text{Hom}(Y, X_{\text{red}}) \longrightarrow \text{Hom}(Y, X).$$

This means that X_{red} has the same (although dual) universal property with respect to X , that A_{red} does with respect to A

Proof: 2. We know that $|\text{Spec } A|$ and $|\text{Spec } A_{\text{red}}|$ are homeomorphic as topological spaces, so for any $f \in A$, we have $(A[f^{-1}])_{\text{red}} = A_{\text{red}}[\bar{f}^{-1}]$. This means that

$$\mathcal{O}_{(\text{Spec } A)_{\text{red}}}^0(D(f)) = \mathcal{O}_{\text{Spec } A_{\text{red}}}(D(f))$$

which implies $(\mathcal{O}_{\text{Spec } A})_{red} = \mathcal{O}_{\text{Spec } A_{red}}$

1. If $U = \text{Spec } A \subseteq X$ is an open affine then

$$(|U|, \mathcal{O}_{X_{red}}|_U) = (|U|, \mathcal{O}_{U_{red}}) = \text{Spec } A_{red}$$

where the last equality come from part 2. This implies that $\text{Spec } A_{red}$ is an open affine of X_{red} and choosing an open affine cover of X will give us a reduced open affine cover of X_{red}

3. Let Y be a reduced scheme, then for all map $f : Y \rightarrow X$, the map of sheaves $f^b : \mathcal{O}_X \rightarrow f_* \mathcal{O}_Y$ factors uniquely through $\mathcal{O}_{X_{red}}$, so for all open subsets U of X we have the following diagram :

$$\begin{array}{ccc} \mathcal{O}_X(U) & \xrightarrow{f^b(U)} & (f_* \mathcal{O}_Y)(U) = \mathcal{O}_Y(f^{-1}(U)) \\ \downarrow & & \uparrow \tilde{f}(U) \\ \mathcal{O}_{X_{red}}(U) & \longrightarrow & \mathcal{O}_{X_{red}}^0(U) = (\mathcal{O}_X(U))_{red} \end{array}$$

These factorisations $\tilde{f}(U)$ glue to a unique map $Y \rightarrow X_{red}$, a map of schemes, using the universal property of sheafification. □

3.6 Closed immersion

Def 3.39 A map $f : Y \rightarrow X$ of schemes is called a **closed immersion** if

1) the induced map on topological spaces $|f| : |Y| \rightarrow |X|$ is a closed immersion (a homeomorphism onto a closed subset)

2) $f^b : \mathcal{O}_X \rightarrow f_*\mathcal{O}_Y$ is a surjective map of sheaves.

Proposition 3.40 Let $f : Y \rightarrow X$ be a map of schemes, then the following are equivalent :

1) f is a closed immersion

2) For all open subsets $U \subseteq X$ with $U = \text{Spec } A$, $f^{-1}(U) = \text{Spec } B \subseteq Y$ is open affine, and $A \rightarrow B$ is surjective

3) There exists an open cover of X by affine schemes which satisfy the property of part 2)

(i.e. \exists open cover $X = \cup_i U_i$ s.t. $U_i = \text{Spec } A_i$ with $f^{-1}(U_i) = \text{Spec } B_i$ and $A_i \rightarrow B_i$ is surjective)

Proof: clear $2) \Rightarrow 3) \Rightarrow 1)$ □

Remark 3.41 In particular, for $X = \text{Spec } A$ affine, then closed immersions are in bijection with surjections $A \rightarrow B$

$$\{\text{closed immersion } Y \rightarrow X\} \cong \{\text{surjection } A \rightarrow B\}$$

3.7 \mathcal{O}_X -module

Def 3.42 Given a ring A and an A -module M . Then we define a presheaf \widetilde{M} on $X = \text{Spec } A$, defined on the basis of principal opens by

$$\widetilde{M}(D(f)) = M[f^{-1}], f \in A$$

We exactly know this defines a sheaf on this basis of principal opens which we can extend uniquely to a sheaf \widetilde{M} on all of X . The expected thing happens on stalks of \widetilde{M} too

Proposition 3.43 Let $x \in X = \text{Spec } A$, and Let $\mathfrak{p} \subseteq A$ be the corresponding prime ideal in A , then $\widetilde{M}_x = M_{\mathfrak{p}}$

Proof:

$$\widetilde{M}_x = \text{colim}_{D(f) \ni x} M[f^{-1}] = \text{colim}_{f \notin \mathfrak{p}} M[f^{-1}] = M_{\mathfrak{p}}.$$

□

Def 3.44 Let (X, \mathcal{O}_X) be a ringed space, then a sheaf of \mathcal{O}_X -modules is a sheaf of abelian groups \mathcal{M} together with a map $\mathcal{O}_X \times \mathcal{M} \rightarrow \mathcal{M}$ of sheaves such that $\mathcal{M}(U)$ is an $\mathcal{O}_X(U)$ -module for all open subsets $U \subseteq X$

The fact that we ask the action map $\mathcal{O}_X \times \mathcal{M} \rightarrow \mathcal{M}$ to be a map of sheaves assures us that our restriction maps respect this module structure

Just as we have modules over a ring, we have \mathcal{O}_X -modules over a sheaf of rings \mathcal{O}_X . There is only one possible definition that could go with the name \mathcal{O}_X -module – a sheaf of abelian groups \mathcal{F} with the following additional structure

For each U , $\mathcal{M}(U)$ is an $\mathcal{O}_X(U)$ -module. Furthermore, this structure should behave well with respect to restriction maps: if $U \subset V$, then :

$$\begin{array}{ccc} \mathcal{O}_X(V) \times \mathcal{M}(V) & \xrightarrow{\text{action}} & \mathcal{M}(V) \\ \text{res}_{V,U} \times \text{res}_{V,U} \downarrow & & \downarrow \text{res}_{V,U} \\ \mathcal{O}_X(U) \times \mathcal{M}(U) & \xrightarrow{\text{action}} & \mathcal{M}(U) \end{array}$$

commutes

Recall that the notion of A -module generalizes the notion of abelian group, because an abelian group is the same thing as a \mathbb{Z} -module. Similarly, the notion of \mathcal{O}_X -module generalizes the notion of sheaf of abelian groups, because the latter is the same thing as a $\underline{\mathbb{Z}}$ -module, where $\underline{\mathbb{Z}}$ is the constant sheaf associated to \mathbb{Z} . Hence when we are proving things about \mathcal{O}_X -modules, we are also proving things about sheaves of abelian groups

Ex 3.45 If (X, \mathcal{O}_X) is a ringed space, and \mathcal{F} is an \mathcal{O}_X -module, describe how for each $p \in X$, \mathcal{F}_p is an $\mathcal{O}_{X,p}$ -module.

Remark 3.46 *vector bundles*

The motivating example of \mathcal{O}_X -modules is the sheaf of sections of a vector bundle. If (X, \mathcal{O}_X) is a differentiable manifold (so \mathcal{O}_X is the sheaf of differentiable functions, and $\pi : V \rightarrow X$ is a vector bundle over X , then the sheaf of differentiable sections $\sigma : X \rightarrow V$ is an \mathcal{O}_X -module. Indeed, given a section s of π over an open subset $U \subset X$, and a function f on U . we can multiply s by f to get a new section fs of π over U . Moreover, if U' is a smaller subset, then we could multiply f by s and then restrict to U' , or we could restrict both f and s to U' and then multiply, and we would get the same answer

Proposition 3.47 *Given an A -module M and $X = \text{Spec } A$, then \widetilde{M} is a sheaf of \mathcal{O}_X -modules*

Proof: Taken $U = D(f) \subseteq X$ and $f \in A$ we have to give an action map $\mathcal{O}_X(U) \times \widetilde{M}(U) \rightarrow \widetilde{M}(U)$, but this can simply be the $A[f^{-1}]$ -module structure,

$$A[f^{-1}] \times M[f^{-1}] \longrightarrow M[f^{-1}].$$

This clearly commutes with restriction maps etc □

We now have the technical theorem which drives the types of results we desire

Theorem 3.48 *1) Let $X = \text{Spec } A$, M be an A -module and \mathcal{N} an sheaf of \mathcal{O}_X -modules, then*

$$\text{Hom}_{\mathcal{O}_X}(\widetilde{M}, \mathcal{N}) \rightarrow \text{Hom}_A(M, \mathcal{N}(X)),$$

is a bijection.

2) The functor from A -modules to sheaves of \mathcal{O}_X -modules defined by $M \mapsto \widetilde{M}$ is fully faithful

3) Let \mathcal{M} be a sheaf of \mathcal{O}_X -modules. and assume there exists a cover of X by open affines $D(f_i)$ $f_i \in A$ such that $\mathcal{M}|_{D(f_i)} \cong \widetilde{\mathcal{M}_i}$ for some $A[f_i^{-1}]$ -module \mathcal{M}_i , then there exists an A -modules M such that $\mathcal{M} \cong \widetilde{M}$

Necessarily we have $M = \mathcal{M}(X)$ as $M = \widetilde{M}(X)$ but we still don't really know M exists yet. Assuming this theorem is true just for a little bit, we make the following definition.

3.8 Quasi-coherent sheaf

Def 3.49 *quasi-coherent sheaf*

Let X be some scheme, then a **quasi-coherent sheaf** on X is a sheaf of \mathcal{O}_X -modules \mathcal{M} such that there exists a covering $\{U_i = \text{Spec } A_i\}$ of X by open affines, and A_i -modules M_i such that $\mathcal{M}|_{U_i} \cong \widetilde{M}_i$

A morphism of quasi-coherent sheaves is simply a morphism of \mathcal{O}_X -modules

Corollary 3.50 Given an affine scheme $X = \text{Spec } A$, then we have an equivalence of categories between A -modules and quasi-coherent sheaves on X , given by $M \mapsto \widetilde{M}$ with inverse $\mathcal{M} \mapsto \mathcal{M}(X)$

Def 3.51 A space X is called **quasi-compact** if every open cover has a finite subcover, and **quasi-separated** if given two quasi-compact open subsets U and V , then the intersection $U \cap V$ is also a quasi-compact open subset.

A map of schemes is called **quasi-compact** (resp. **quasi-separated**) if the inverse images of quasi-compact (resp. quasi-separated) open subsets of X are quasi-compact (resp. quasi-separated)

Theorem 3.52 X scheme, $\mathcal{M} \in \text{Mod}_{\mathcal{O}_X}$, TFAE :

- a) \mathcal{M} qcoh (quasi-coherent)
- b) \exists open sets $X = \bigcup U_i$ with $\mathcal{M}|_{U_i}$ qcoh
- c) \exists open sets $X = \bigcup U_i$, $U_i = \text{Spec } A_i$ with $\mathcal{M}|_{U_i} = \widetilde{M}_i$ for some A_i -module M_i

Theorem 3.53 Let $f : Y \rightarrow X$ be a map of schemes which is quasi-compact and quasi-separated, and let \mathcal{M} be a quasi-coherent sheaf on Y , then $f_*\mathcal{M}$ is a quasi-coherent sheaf on X with its natural \mathcal{O}_X -structure

Theorem 3.54 *Gluing Modules*

The functor $M \rightarrow M_i = M[f_i^{-1}]$ from the category of A -modules to the category of collections of $A[f_i^{-1}]$ -modules M_i and isomorphisms $\alpha_{ij} : M_i[f_j^{-1}] \rightarrow M_j[f_i^{-1}]$ which satisfy the cocycle condition, is an equivalence of categories.

Proof: We have equivalences of categories:

$$\begin{aligned} \{A\text{-modules}\} &\cong \{\text{quasi-coherent sheaves on } \text{Spec } A\} \\ &\cong \{\text{quasi-coherent sheaves on } D(f_i) + \text{gluing data}\} \\ &\cong \{\text{collections}(M_i, \alpha_{ij}) \text{ as above}\} \end{aligned}$$

□

3.9 Projective Space

This subsection we are going to talk about a scheme \mathbb{P}^n which severely generalises topological projective space \mathbb{RP}^n and \mathbb{CP}^n

Example 3.55 Define the n th complex projective space \mathbb{CP}^n as follows,

$$\mathbb{CP}^n = \mathbb{C}^{n+1} - 0 / (x_0, \dots, x_n) \sim \lambda(x_0, \dots, x_n), \forall \lambda \in \mathbb{C}^\times$$

We denote points in \mathbb{CP}^n by homogenous coordinates, $(x_0 : \dots : x_n)$ where $x_i \in \mathbb{C}$ and not all zero. Notice that each x_i is not well-defined, because we have this equivalence relation by a non-zero is by a non-zero complex number, however the ratios $\frac{x_i}{x_j}$ are well-defined whenever $x_j \neq 0$. The standard cover for \mathbb{CP}^n is by $(n+1)$ -many copies of \mathbb{C}^n (hence \mathbb{CP}^n is an n -dimensional complex manifold) defined by

$$U_i = \{(x_0 : \dots : x_n) \in \mathbb{CP}^n \mid x_i \neq 0\} \longrightarrow \mathbb{C}^n$$

$$(x_0 : \dots : x_n) \mapsto \left(\frac{x_0}{x_i}, \dots, \frac{x_n}{x_i}\right)$$

For all $i \neq j$, we have $U_i \cap U_j \cong \mathbb{C}^{n-1} \times \mathbb{C}^\times$ which we define as $\{(X_{i,k})_{k=0, \dots, n, k \neq i} \mid X_{i,j} \neq 0\}$. We will use these types of sets when we start talking about projective space as schemes. Another way to construct \mathbb{CP}^n would be to glue together all of these U_i along these $U_i \cap U_j = U_{i,j}$

Example 3.56 More generally, for any field k we can define

$$\mathbb{P}^n(k) = k^{n+1} - \{0\} / k^\times.$$

Our goal now is to construct a scheme \mathbb{P}^n such that the k -valued points of \mathbb{P}^n are given exactly by $\mathbb{P}^n(k)$.

There are three ways to go about doing this. There are three ways to go about doing this. We are going to do this super explicitly. We could also generalise the functor Spec to a functor called **Proj**, and then define $\mathbb{P}^n = \mathbb{P}_{\mathbb{Z}}^n = \text{Proj}(\mathbb{Z}[x_0, \dots, x_n])$

Another thing we could do is the functor of points approach, i.e. write down $R \rightarrow \mathbb{P}^n(R)$. We are going and show this is in the essential image of the fully faithful functor $\text{Sch} \rightarrow \text{Fun}(\text{Ring}, \text{Set})$ to do this explicitly, so don't worry Caution! It will usually not be the case that $\mathbb{P}^n(R) = R^{n+1} - 0 / R^\times$, for a general ring R

Def 3.57 (Construction of \mathbb{P}^n)

For any $i = 0, \dots, n$, let

$$U_i = \text{Spec } \mathbb{Z}[(X_j/i)_{j=0, \dots, n, i \neq j}] \cong \mathbb{A}_{\mathbb{Z}}^n.$$

This of $X_{i,j} = X_j/i$ as being the fraction $\frac{X_j}{X_i}$. For each $i \neq j$ we have

$$U_{i,j} = D(X_j/i) \subseteq U_i,$$

so $U_{i,j} = D(X_{j/i}) \cong \text{Spec } \mathbb{Z}[(X_{k/i})_{k \neq i,j}, (X_{j/i})^{\pm 1}]$ We have an isomorphism between $U_{j/i}$ and $U_{j/i}$ denoted as

$$\begin{aligned}\alpha_{i,j} : U_{i,j} &\rightarrow U_{j,i} \\ X_{k/i}, k \neq i &\mapsto X_{k/j} \cdot X_{i/j}^{-1} \\ X_{j/i} &\mapsto X_{i/j}^{-1}\end{aligned}$$

The inverse of this map is simply $X_{k/j}, k \neq j \mapsto X_{k/i} \cdot X_{j/i}^{-1}$

There is a lemma which tells us we can glue schemes together, so long as the pieces slot together coherently

Lemma 3.58 *Let \mathcal{I} be a set and U_i for all $i \in \mathcal{I}$ be schemes. For i, j we have $U_{i,j} \subseteq U_i = U_{i,i}$ is an open subscheme and the isomorphisms $\alpha_{i,j} : U_{i,j} \rightarrow U_{j,i}$ which satisfy the cocycle condition, so $\alpha_{i,k} = \alpha_{j,k} \circ \alpha_{i,j}$ for all $i, j, k \in \mathcal{I}$ on $U_{i,j,k} := U_{i,j} \cap U_{j,k}$. Then we have a scheme*

$$X = \bigcup_{i \in \mathcal{I}} U_i$$

i.e. X admits an open covering $X = \cup V_i$ with $\beta_i : V_i \cong U_i$ such that $\beta_i : V_i \cap V_j \cong U_{i,j}$ and $\beta_j : V_i \cap V_j \cong U_{j,i}$, and $\alpha_{i,j} = \beta_j \circ \beta_i^{-1}$

Noticing that in our case we have $\alpha_{i,k} = \alpha_{j,k} \circ \alpha_{i,j}$, we apply this gluing lemma and obtain the scheme,

$$\mathbb{P}^n = \bigcup_{i=0}^n U_i = \bigcup_{i=0}^n \text{Spec } \mathbb{Z}[(X_{j/i})_{j=0,\dots,n, i \neq j}] = \bigcup_{i=0}^n \mathbb{A}_{\mathbb{Z}}^n$$

In particular, for all fields k we have

$$\mathbb{P}^n(k) = \bigcup_{i=0}^n U_i(k) = \bigcup_{i=0}^n k^n = \mathbb{P}^n(k).$$

Although this line seems tautological, the first $\mathbb{P}^n(k)$ is the k -valued points of a scheme and the latter is our old definition of projective space of a field

Def 3.59 *Let $m \in \mathbb{Z}$, we let $\mathcal{O}_{\mathbb{P}^n}(m)(U_i) = \mathcal{O}(U_i)$ (the def of f^* see 3.73)*

$$\alpha_{i,j}^m : \mathcal{O}_{\mathbb{P}^n}(m)(U_{i,j}) \xrightarrow{\sim} \alpha_{j,i}^* \mathcal{O}_{\mathbb{P}^n}(m)(U_{j,i})$$

$$1 \longmapsto (X_{i/j})^m$$

(notice $(X_{i/j})^m$ is a unit in $\mathcal{O}_{\mathbb{P}^n}(m)(U_{j,i})$)

Check the cocycle condition:

$$1 \xrightarrow{\alpha_{i,j}^m} X_{i/j}^m \xrightarrow{\alpha_{j,k}^m} X_{i/k}^m$$

$$1 \quad X_{i/j}^m \quad (X_{i/k} \cdot X_{j/k}^{-1})^m X_{j/k}^m = X_{i/k}^m$$

Now we get a sheaf of $\mathcal{O}_{\mathbb{P}^n}$ -module : $(\mathbb{P}^n, \mathcal{O}_{\mathbb{P}^n}(m))$

Proposition 3.60 $\Gamma(\mathbb{P}^n, \mathcal{O}_{\mathbb{P}^n}(m)) = \{ \text{degree } m \text{ homogenous polynomials in } n+1\text{-variables} \}$

Proof: We only proof the case $m \geq 0$:

$$\begin{aligned} \mathbb{P}_A^n &= \cup_{i=0}^n U_i, \quad U_i = \text{Spec} A[x_{j/i}, j = 0, \dots, n, j \neq i] \\ U_{i,j} &= D(x_{j/i}) \subseteq U_i, \quad U_{i,j} = \text{Spec} A[x_{k/i}, k \neq i, j, x_{j/i}, (x_{j/i})^{-1}]. \end{aligned}$$

The glueing map is denoted by $\alpha_{i,j} : U_{i,j} \rightarrow U_{j,i}$, and it's induced by

$$\begin{aligned} \alpha'_{i,j} : A[x_{k/j}, k \neq i, j, x_{i/j}, (x_{i/j})^{-1}] &\rightarrow A[x_{k/i}, k \neq i, j, x_{j/i}, (x_{j/i})^{-1}] \\ x_{k/j} &\mapsto x_{k/i} \cdot (x_{j/i})^{-1}, \quad x_{i/j} \mapsto (x_{j/i})^{-1}. \end{aligned}$$

The sheaf $\mathcal{O}_{\mathbb{P}^n_A}(m)$ is defined by letting $\mathcal{O}_{\mathbb{P}^n_A}(m)(U_i) = \mathcal{O}_{U_i}$ as \mathcal{O}_{U_i} -module, and glueing the sheaf by using the following map:

$$\alpha_{i,j}^m : \mathcal{O}_{\mathbb{P}^n}(m)(U_{i,j}) \rightarrow \alpha_{i,j}^* \mathcal{O}_{\mathbb{P}^n}(m)(U_{j,i}), \quad 1 \mapsto (x_{i/j})^m,$$

Remark: Since $U_{j,i}$ is affine, by Prop 3.72 in notes,

$$\alpha_{i,j}^* \mathcal{O}_{\mathbb{P}^n}(m)|_{U_{j,i}} \cong (\mathcal{O}_{\mathbb{P}^n}(m)(U_{j,i})) \otimes_{\mathcal{O}_{\mathbb{P}^n}(m)(U_{j,i})} \widetilde{\mathcal{O}_{\mathbb{P}^n}(m)(U_{j,i})}$$

And from Theorem 3.48 in notes, to give a morphism between two quasi-coherent sheaves, we only need to define on their global sections. The \mathcal{O}_{U_i} -module structure on $\alpha_{i,j}^* \mathcal{O}_{\mathbb{P}^n}(m)(U_{j,i})$ implies:

$$x_{k/i} \cdot 1 \mapsto (x_{i/j})^m \otimes (x_{k/i}) = x_{i/j}^m \cdot x_{k/j} \cdot x_{i/j}^{-1}$$

where the second equality follows from the definition of $\alpha'_{i,j}$.

The map $\Phi : A[x_0, \dots, x_n]_m \rightarrow \Gamma(\mathbb{P}^n_A, \mathcal{O}_{\mathbb{P}^n_A}(m))$ is defined as follows: given a homogeneous polynomial F of degree m , $F \mapsto (f_i)_{i=0}^n$, where $f_i \in \mathcal{O}_{\mathbb{P}^n_A}(U_i) = A[x_{j/i}, j \neq i, j=0, \dots, n]$ s.t. $\beta_i(f_i) = \frac{F}{x_i^m}$, and β_i is defined by

$$\beta_i : A[x_{j/i}, j \neq i, j = 0, \dots, n] \rightarrow A[x_0, \dots, x_n, x_i^{-1}], \quad x_{j/i} \mapsto \frac{x_j}{x_i}.$$

It's easy to check that β_i is injective. Since F is homogeneous of degree m and β_i is injective, f_i exists and is unique. Then we prove that Φ is well-defined: from the remark above, we have

$$\alpha_{i,j}^m(f_i) = f_i(x_{0/j} \cdot (x_{i/j})^{-1}, \dots, x_{i-1/j} \cdot (x_{i/j})^{-1}, x_{i+1/j} \cdot (x_{i/j})^{-1}, \dots, x_{n/j} \cdot (x_{i/j})^{-1}) \cdot (x_{i/j})^m$$

Remark: $x_{j/i} \mapsto (x_{i/j})^{-1}$.

This implies

$$\begin{aligned} \beta_j(\alpha_{i,j}^m(f_i)) &= f_i\left(\frac{x_0}{x_j} \cdot \frac{x_j}{x_i}, \dots, \frac{x_n}{x_j} \cdot \frac{x_j}{x_i}\right) \cdot \frac{x_i^m}{x_j^m} \\ &= f_i\left(\frac{x_0}{x_i}, \dots, \frac{x_n}{x_i}\right) \cdot \frac{x_i^m}{x_j^m} \\ &= \frac{F(x_0, \dots, x_n)}{x_i^m} \cdot \frac{x_i^m}{x_j^m} = \frac{F(x_0, \dots, x_n)}{x_j^m} = \beta_j(f_j). \end{aligned}$$

By injectivity of β_j , we have $\alpha_{i,j}^m(f_i) = f_j$. So $(f_i)_{i=0}^n$ defines a section in $\Gamma(\mathbb{P}_A^n, \mathcal{O}_{\mathbb{P}_A^n}(m))$.

Φ is injective: this follows from the injectivity of β_i .

To prove that Φ is surjective, we first prove that for a section $(f_i)_{i=0}^n$ in $\Gamma(\mathbb{P}_A^n, \mathcal{O}_{\mathbb{P}_A^n}(m))$, we must have $\deg f_i \leq m$. Suppose there is a f_i s.t. $\deg f_i = n > m$. WLOG we can suppose $f_i = g_i + h_i$, where g_i is homogeneous of $\deg n$, and $\deg h_i < n$. Then from the definition of $\alpha_{i,j}$, we get

$$\begin{aligned}\alpha_{i,j}^m(f_i) &= g_i(x_{0/j} \cdot (x_{i/j})^{-1}, \dots, x_{n/j} \cdot (x_{i/j})^{-1}) \cdot (x_{i/j})^m \\ &\quad + h_i(x_{0/j} \cdot (x_{i/j})^{-1}, \dots, x_{n/j} \cdot (x_{i/j})^{-1}) \cdot (x_{i/j})^m \\ &= g_i(x_{0/j}, \dots, x_{n/j}) \cdot (x_{i/j})^{m-n} + h_i(x_{0/j} \cdot (x_{i/j})^{-1}, \dots, x_{n/j} \cdot (x_{i/j})^{-1}) \cdot (x_{i/j})^m\end{aligned}$$

which can't be a restriction of an element in \mathcal{O}_{U_j} since $n > m$. Contradiction.

Then we can prove that Φ is surjective. Given $(f_i)_{i=0}^n, f_i \in \mathcal{O}_{U_i}, \alpha_{i,j}^m(f_i) = f_j, \deg f \leq m$. Take $F = x_0^m \beta_0(f_0)$. Because $\deg f_0 \leq m$, F is a well-defined homogeneous polynomial of degree m . And for any j ,

$$\frac{F}{x_j^m} = \frac{x_0^m}{x_j^m} \beta_0(f_0) = \frac{x_0^m}{x_j^m} \beta_0(\alpha_{j,0}(f_j)) = \frac{x_0^m}{x_j^m} f_j\left(\frac{x_0}{x_j}, \dots, \frac{x_n}{x_j}\right) \cdot \frac{x_j^m}{x_0^m} = f_j\left(\frac{x_0}{x_j}, \dots, \frac{x_n}{x_j}\right) = \beta_j(f_j).$$

So $\Phi(F) = (f_i)_{i=0}^n$. □

3.10 Vector Bundle

3.10.1 Line bundle

Def 3.61 *line bundle*

Let X be a scheme, a **line bundle** of X is an \mathcal{O}_X -module that is locally isomorphic to \mathcal{O}_X

More generally, V is a **rank n vector bundle** if it is locally isomorphism to $\mathcal{O}_X^n = \bigoplus_{i=1}^n \mathcal{O}_X$

Def 3.62 Let \mathcal{L} be a line bundle over X and $\sigma \in \Gamma(X, \mathcal{L})$ a global section. We define $V(\sigma) \subseteq X$ closed subscheme as follows:

On small enough affine $\text{Spec } A = U \subseteq X$ such that $\mathcal{L}|_U \xrightarrow[t]{\sim} \tilde{A}$

We let $V(\sigma)_U = \text{Spec}(A/t(\sigma))$, $V(\sigma)_U \hookrightarrow U$

The ideal $\langle t(\sigma) \rangle \subseteq A$ does not depend on t . If $t_i : \mathcal{L} \xrightarrow{\sim} \tilde{A}$ are two trivializations, then there is a unit $u \in A^\times$ such that $t_2 = t_1 u$

Def 3.63 If $I \subseteq \Gamma(X, \mathcal{L})$, we let $V(I)$ be given by $\text{Spec}(A/t(I))$

Def 3.64 Define $F : \text{Sch}^{\text{op}} \rightarrow \text{Sets}$

$F(X) = \{(\mathcal{L}, s_0, \dots, s_n) \mid \mathcal{L} \text{ is line bundle, } s_0, \dots, s_n \in \Gamma(X, \mathcal{L}), \text{ s.t. } V(\{s_0, \dots, s_n\}) = \emptyset\} / \sim$

$(\mathcal{L}', s'_0, \dots, s'_n) \sim (\mathcal{L}', s'_0, \dots, s'_n)$ if there is a isomorphism of \mathcal{O}_X -module $\alpha : \mathcal{L} \xrightarrow{\sim} \mathcal{L}'$ with $\alpha(s_i) = s'_i$

$F(X) \cong \{\mathcal{O}_X^{n+1} \xrightarrow{s_0, s_1, \dots, s_n} \mathcal{L} \mid \text{surjection, with } \mathcal{L} \text{ an line bundle of } X\} / \sim$

If $Y \xrightarrow{t} X$, define $F(X) \xrightarrow{F(t)} F(Y)$

$F(f)(\mathcal{L}, s_0, \dots, s_n) = (f^* \mathcal{L}, f^* s_0, \dots, f^* s_n)$

$\Gamma(X, \mathcal{L}) \rightarrow \Gamma(X, f_* f^* \mathcal{L}) = \Gamma(Y, f^* \mathcal{L})$

$s_i \mapsto f^* s_i$

global section : $s_i : \mathcal{O}_X \rightarrow \mathcal{L}$

$f^* s_i \cong \mathcal{O}_Y : f^* \mathcal{O}_X \rightarrow f^* \mathcal{L}$

Theorem 3.65 F is representable by $\mathbb{P}_{\mathbb{Z}}^n$. ($F(X) \cong \text{Hom}(X, \mathbb{P}_{\mathbb{Z}}^n)$)

Recall: We say a contravariant functor from \mathcal{C} to Sets is represented by Y if it is naturally isomorphic to the functor h_Y ($h_Y : \mathcal{C} \rightarrow \text{Sets}$ defined by $h_Y(X) = \text{Mor}(X, Y)$). We say it is **representable** if it is represented by some Y

Proposition 3.66

$$\Gamma(X, \mathcal{L}) \xrightarrow{\sim} \text{Hom}_{\mathcal{O}_X}(\mathcal{O}_X, \mathcal{L})$$

$$s \longmapsto [a \mapsto a \cdot s, \forall a \in \mathcal{O}_X(U)]$$

$$\Gamma(f)(1) \in \Gamma(X, \mathcal{L}) \longleftarrow f$$

Def 3.67 For R any ring, define $\mathbb{P}_R^n = \mathbb{P}_{\mathbb{Z}}^n \times_{\text{Spec } \mathbb{Z}} \text{Spec } R$

3.10.2 Picard group

Def 3.68 Let's fix X a scheme

If \mathcal{M}, \mathcal{N} are \mathcal{O}_X -modules, we let $\mathcal{M} \otimes_{\mathcal{O}_X} \mathcal{N} \in \mathcal{O}_X$ -module

$(\mathcal{M} \otimes_{\mathcal{O}_X} \mathcal{N})^{Pre} : \text{Ouv}_X \rightarrow \text{Groups}$

$(\mathcal{M} \otimes_{\mathcal{O}_X} \mathcal{N})^{Pre}(U) = \mathcal{M}(U) \otimes_{\mathcal{O}_X(U)} \mathcal{N}(U)$

$\mathcal{M} \otimes_{\mathcal{O}_X} \mathcal{N} = \text{sheafification}(\mathcal{M} \otimes_{\mathcal{O}_X} \mathcal{N})^{Pre} = \widetilde{\mathcal{M} \otimes_{\mathcal{O}_X} \mathcal{N}}$

Def 3.69 Define $\underline{Hom}_{\mathcal{O}_X}(\mathcal{M}, \mathcal{N}) \in \mathcal{O}_X$ -module :

$\underline{Hom}_{\mathcal{O}_X}(\mathcal{M}, \mathcal{N})(U) = \underline{Hom}_{\mathcal{O}_X|_U}(\mathcal{M}|_U, \mathcal{N}|_U) \subseteq Hom_{\mathcal{O}_X(U)}(\mathcal{M}(U), \mathcal{N}(U))$

Caution : The rule $U \mapsto Hom_{\mathcal{O}_X(U)}(\mathcal{M}(U), \mathcal{N}(U))$ is not a presheaf

Proposition 3.70

$$\underline{Hom}_{\mathcal{O}_X}(\mathcal{O}_X, \mathcal{N}) \cong \mathcal{N}, \mathcal{O}_X \otimes_{\mathcal{O}_X} \mathcal{N} \cong \mathcal{N}$$

Proof:

$$\underline{Hom}_{\mathcal{O}_X}(\mathcal{O}_X, \mathcal{N})(U) = Hom_{\mathcal{O}_X|_U}(\mathcal{O}_X|_U, \mathcal{N}|_U) \xrightarrow{\sim} \mathcal{N}(U)$$

$$f \longmapsto f(U)$$

$$[a \mapsto a \cdot n] \longleftarrow n$$

As presheaves :

$$\mathcal{O}_X(U) \otimes_{\mathcal{O}_X(U)} \mathcal{N}(U) \xrightarrow{\sim} \mathcal{N}(U)$$

$$a \otimes n \longmapsto a \cdot n$$

□

Proposition 3.71 Let $\mathcal{L}, \mathcal{M}, \mathcal{N}$ be \mathcal{O}_X -modules, then

$$Hom_{\mathcal{O}_X}(\mathcal{L}, \underline{Hom}(\mathcal{M}, \mathcal{N})) \cong Hom_{\mathcal{O}_X}(\mathcal{L} \otimes_{\mathcal{O}_X} \mathcal{M}, \mathcal{N})$$

$$\underline{Hom}(\mathcal{M}, -) \perp (-) \otimes_{\mathcal{O}_X} \mathcal{M}$$

Proposition 3.72 1) If \mathcal{M} and \mathcal{N} are qcoh of \mathcal{O}_X -modules, then $\mathcal{M} \otimes_{\mathcal{O}_X} \mathcal{N}$ is also qcho

2) If $X = \text{Spec } A$, then $\widetilde{M} \otimes_{\mathcal{O}_X} \widetilde{N} = \widetilde{M \otimes_A N}$

Proof: 1) follows from 2), now we proof 2): $f \in A$

$$\begin{aligned} (\widetilde{M} \otimes_{\mathcal{O}_X} \widetilde{N})^{Pre}(D(f)) &= \widetilde{M}(D(f)) \otimes_{\mathcal{O}_X(D(f))} \widetilde{N}(D(f)) \\ &= \widetilde{M}[f^{-1}] \otimes_{A[f^{-1}]} \widetilde{N}[f^{-1}] \\ &\cong M \otimes_A N[f^{-1}] \\ &= \widetilde{M \otimes_A N}(D(f)) \end{aligned}$$

□

Caution : $\underline{Hom}_{\mathcal{O}_X}(\mathcal{F}, \mathcal{G})$ might not be quasicoherent even if \mathcal{F} and \mathcal{G} are

Def 3.73 Let (f, f^b) be a map of ringed spaces $(Y, \mathcal{O}_Y) \rightarrow (X, \mathcal{O}_X)$

1) If \mathcal{N} is an \mathcal{O}_Y -module, then the pushforward $f_*\mathcal{N}$ is the \mathcal{O}_X -module with the structure morphism

$$\mathcal{O}_X \times f_*\mathcal{N} \xrightarrow{f^b \times id_{f_*\mathcal{N}}} f_*\mathcal{O}_Y \times f_*\mathcal{N} = f_*(\mathcal{O}_Y \times \mathcal{N}) \xrightarrow{f^b(-)} f_*\mathcal{N}$$

2) If \mathcal{M} is an \mathcal{O}_X -module, then $f^{-1}\mathcal{M}$ is a sheaf of $f^{-1}\mathcal{O}_X$ -modules via

$$f^{-1}\mathcal{O}_X \times f^{-1}\mathcal{M} = f^{-1}(\mathcal{O}_X \times \mathcal{M}) \longrightarrow f^{-1}(\mathcal{M}).$$

We now define the pullback $f^*\mathcal{M}$ as the \mathcal{O}_Y -module

$$f^*\mathcal{M} = f^{-1}\mathcal{M} \otimes_{f^{-1}\mathcal{O}_X} \mathcal{O}_Y$$

Proposition 3.74 There is an adjunction with left adjoint f^* and right adjoint f_* . In other words, for each \mathcal{O}_X -module \mathcal{M} , and each \mathcal{O}_Y -module \mathcal{N} , we have the following natural identification :

$$\mathrm{Hom}_{\mathcal{O}_Y}(f^*\mathcal{M}, \mathcal{N}) \cong \mathrm{Hom}_{\mathcal{O}_X}(\mathcal{M}, f_*\mathcal{N})$$

Proof: Sketch of the Proof :

We already have the adjunction

$$\mathrm{Hom}(f^{-1}\mathcal{M}, \mathcal{N}) \cong \mathrm{Hom}(\mathcal{M}, f_*\mathcal{N}) \supseteq \mathrm{Hom}_{\mathcal{O}_X}(\mathcal{M}, f_*\mathcal{N}),$$

and a subset on the right hand side. There is a subset on the left hand side corresponding to the \mathcal{O}_X -linear maps $\mathcal{M} \rightarrow f_*\mathcal{N}$, and that is $\mathrm{Hom}_{f^{-1}\mathcal{O}_X}(f^{-1}\mathcal{M}, \mathcal{N})$ so we (have to check we) have an adjunction between these subsets,

$$\mathrm{Hom}_{f^{-1}\mathcal{O}_X}(f^{-1}\mathcal{M}, \mathcal{N}) \cong \mathrm{Hom}_{\mathcal{O}_X}(\mathcal{M}, f_*\mathcal{N}).$$

We can now use a change of rings isomorphism to change the left hand side to

$$\mathrm{Hom}_{f^{-1}\mathcal{O}_X}(f^{-1}\mathcal{M}, \mathcal{N}) \cong \mathrm{Hom}_{\mathcal{O}_Y}(f^{-1}\mathcal{M} \otimes_{f^{-1}\mathcal{O}_X} \mathcal{O}_Y, \mathcal{N}) \cong \mathrm{Hom}_{\mathcal{O}_Y}(f^*\mathcal{M}, \mathcal{N}).$$

□

Proposition 3.75 1) Let $f : Y \rightarrow X$ be (any!) map of schemes, and \mathcal{M} a quasi-coherent \mathcal{O}_X -module, then $f^*\mathcal{M}$ is a quasi-coherent \mathcal{O}_Y -module

2) If $Y = \mathrm{Spec} B$ and $X = \mathrm{Spec} A$, then $\mathcal{M} \cong \widetilde{M}$ for some A -module M , and then we have $f^*\mathcal{M} \cong \widetilde{M \otimes_A B}$

Proof: Proof For part 1, we notice that we can cover Y by open affines $V = \mathrm{Spec} B \subseteq Y$ mapping into an open affine $U = \mathrm{Spec} A \subseteq X$, then let $g : V \rightarrow U$ be the restriction of f to V , then $(f^*\mathcal{M})|_V = g^*(\mathcal{M}|_U)$. To check the quasi-coherentntness of $f^*\mathcal{M}$, it suffices to check the quasi-coherentntness of $g^*(\mathcal{M}|_U)$. This implies that we can replace Y by $\mathrm{Spec} B$ and X by $\mathrm{Spec} A$, thus we

only have to prove part 2. In that case $\mathcal{M} = \widetilde{M}$ and for all \mathcal{O}_Y -modules \mathcal{N} we have the following series of isomorphisms :

$$\begin{aligned} \mathrm{Hom}_{\mathcal{O}_Y}(f^*\mathcal{M}, \mathcal{N}) &\cong \mathrm{Hom}_{\mathcal{O}_X}(\mathcal{M}, f_*\mathcal{N}) \cong \mathrm{Hom}_A(M, f_*\mathcal{N}(X)) = \mathrm{Hom}_A(M, \mathcal{N}(Y)) \\ &\cong \mathrm{Hom}_B(M \otimes_A B, \mathcal{N}(Y)) \cong \mathrm{Hom}_{\mathcal{O}_Y}(\widetilde{M \otimes_A B}, \mathcal{N}). \end{aligned}$$

The Yoneda lemma now tells us that $f^*\mathcal{M} \cong \widetilde{M \otimes_A B}$

□

Proposition 3.76 *If W is a vector bundle, then $\underline{\mathrm{Hom}}_{\mathcal{O}_X}(W, \mathcal{O}_X)$ is a vector bundle*

Proof: If $W|_U \cong \mathcal{O}_X^n|_U$, then :

$$\begin{aligned} \underline{\mathrm{Hom}}_{\mathcal{O}_X}(W, \mathcal{O}_X)|_U &\cong \underline{\mathrm{Hom}}_{\mathcal{O}_X}(\mathcal{O}_X^n|_U, \mathcal{O}_X|_U) \\ &= \underline{\mathrm{Hom}}_{\mathcal{O}_X}(\mathcal{O}_U, \mathcal{O}_U)^n \\ &= \mathcal{O}_U^n \quad [f \mapsto (f(e_1, e_2, \dots, e_n))] \end{aligned}$$

□

Def 3.77 Define **dual vector bundle** : $W^\vee = \underline{\mathrm{Hom}}_{\mathcal{O}_X}(W, \mathcal{O}_X)$

Proposition 3.78 1) *For vector bundle W , we have canonical evaluation pairings :*

$$e_V : W \otimes_{\mathcal{O}_X} W^\vee \rightarrow \mathcal{O}_X$$

2) *When $W = \mathcal{L}$ is a line bundle, $e_V : \mathcal{L} \otimes_{\mathcal{O}_X} \mathcal{L}^\vee \rightarrow \mathcal{O}_X$ is an isomorphism*

Proof: 1)

$$\begin{aligned} W(U) \otimes_{\mathcal{O}_X(U)} \mathrm{Hom}(W|_U, \mathcal{O}_U) &\rightarrow \mathcal{O}_U \\ w \otimes f &\mapsto f(w) \end{aligned}$$

2) locally

$$\begin{aligned} \mathcal{O}_X \otimes_{\mathcal{O}_X} \mathrm{Hom}(\mathcal{O}_X, \mathcal{O}_X) &\rightarrow \mathcal{O}_X \\ 1 \otimes \mathrm{id} &\mapsto \mathrm{id}(1) \end{aligned}$$

□

Def 3.79 **Picard group**

Let X be a scheme, we let $\mathrm{Pic}(X) = \{\text{line bundles}\} / \cong$

$$\begin{aligned} \mathrm{Pic}(X) \times \mathrm{Pic}(X) &\rightarrow \mathrm{Pic}(X) \\ (\mathcal{L}_1, \mathcal{L}_2) &\mapsto \mathcal{L}_1 \otimes_{\mathcal{O}_X} \mathcal{L}_2 \\ (-)^{-1} : \mathrm{Pic}(X) &\rightarrow \mathrm{Pic}(X) \\ \mathcal{L} &\mapsto \mathcal{L}^\vee \end{aligned}$$

This is a group

Proposition 3.80 $\mathbb{Z} \cong \text{Pic}(\mathbb{P}_{\mathbb{Z}}^n)$ $m \mapsto \mathcal{O}_{\mathbb{P}^n}(m)$

$$\mathcal{O}_{\mathbb{P}^n}(m) = \begin{cases} \mathcal{O}_{\mathbb{P}^n}(1)^{\oplus m} & m \geq 1 \\ \mathcal{O}_{\mathbb{P}^n} & m = 0 \\ \mathcal{O}_{\mathbb{P}^n}(-m)^{\vee} & m \leq -1 \quad (\mathcal{O}(-1) = \mathcal{O}(1)^{\vee}) \end{cases}$$

Def 3.81 Fix X a scheme and W a vector bundle over X

$\mathbb{V}(W) : \text{Sch}/X \rightarrow \text{Sets}$, then defines a functor $\mathbb{V}(W)$ on all schemes $f : Y \rightarrow X$ over X by

$$\mathbb{V}(W)(Y) := (f^*W)(Y) = \Gamma(Y, f^*W)$$

Theorem 3.82 This functor $\mathbb{V}(W)$ is representable by a scheme over X , also denoted by $\mathbb{V}(W)$ over X , such that there is a cover $X = \bigcup_i U_i$ such that

$$\mathbb{V}(W) \times_X U_i = \mathbb{V}(W)|_{U_i} \cong U_i \times_{\text{Spec } \mathbb{Z}} \mathbb{A}_{\mathbb{Z}}^n$$

Proof: (sketchy) It's enough to prove this result locally on X by general gluing lemmas. So assume that X is affine, $X = \text{Spec } A$ so that $W|_{\text{Spec } A} \cong \mathcal{O}_{\text{Spec } A}^n$

$$\mathbb{V}(W)(Y) = f^*W(Y) = f^*(\mathcal{O}_X^n)(Y) \cong \mathcal{O}_Y(Y)^n \cong \text{Hom}_{\text{Ring}}(\mathbb{Z}[T_1, \dots, T_n], \mathcal{O}_Y(Y)).$$

We then use the universal property of fibre products to obtain,

$$\mathbb{V}(W)(Y) = \mathcal{O}_Y(Y)^n = \text{Hom}_{\text{Ring}}(\mathbb{Z}[T_1, \dots, T_n], \mathcal{O}_Y(Y)) \cong \text{Hom}_{\text{Sch}}(Y, \mathbb{A}^n) \cong \text{Hom}_{\text{Sch}/X}(Y, \mathbb{A}^n \times X)$$

In this way we can see that $\mathbb{V}(W)$ is represented by $X \times \mathbb{A}^n$, locally □

Proposition 3.83 If X is a scheme and W vector bundle of X , then

$$\mathbb{V}(W)(Y) = \{(f, \gamma) | f : Y \rightarrow X, \gamma \in \Gamma(Y, f^*W)\}$$

3.11 Internal Hom Sheaves

3.11.1 Zariski Sheaf

Recall: Prop 3.24 (Gluing of morphisms)

Let X, Y be locally ringed spaces. For every open subset $U \subseteq X$ let $\text{Hom}(U, Y)$ be the set of morphisms $(U, \mathcal{O}_{X|U}) \rightarrow (Y, \mathcal{O}_Y)$ of locally ringed spaces. Then $U \mapsto \text{Hom}(U, Y)$ is a sheaf of sets on X

In other words: If $X = \bigcup_i U_i$ is an open covering, then a family of morphisms $U_i \rightarrow Y$ glues to a morphism $X \rightarrow Y$ if and only if the morphisms coincide on intersections $U_i \cap U_j$, and the resulting morphism $X \rightarrow Y$ is uniquely determined

Def 3.84 A contravariant functor $F : \text{Sch}_S \rightarrow \text{Set}$ is a **Zariski sheaf** (sheaf for the Zariski topology) if it satisfies the following condition:

For every $X \in \text{Obj}(\text{Sch}_S)$ and every open cover $\{U_i\}$ of X , the natural map

$$\{\eta \in F(X)\} \rightarrow \{\{\eta_i \in F(U_i)\} : \forall i, j, \eta_i|_{U_i \cap U_j} = \eta_j|_{U_i \cap U_j}\}$$

is a bijection

i.e. $F(X) \xrightarrow{\sim} \text{Eq}(\prod_{i \in I} F(U_i) \rightrightarrows \prod_{i, j \in I} F(U_i \cap U_j))$

Corollary 3.85 Every representable functor $F : (\text{Sch}_S)^{\text{op}} \rightarrow (\text{Sets})$ is a Zariski sheaf

Theorem 3.86 A Zariski sheaf is representable if and only if it admits an open cover by representable Zariski sheaves

3.11.2 Internal Hom Sheaves

Back to $\text{Hom}_{\mathcal{O}_X}(\mathcal{F}, \mathcal{G})(U) = \text{Hom}_{\mathcal{O}_U}(\mathcal{F}|_U, \mathcal{G}|_U) \rightarrow \text{Hom}_{\mathcal{O}_X(U)}(\mathcal{F}(U), \mathcal{G}(U))$ ($\mathcal{O}_U = \mathcal{O}_X|_U$)

Example 3.87 Suppose that $\mathcal{F}, \mathcal{G} \in \mathcal{O}_X$ -modules are quasicoherent and $\text{Spec } A = U \subseteq X$, then

$$\text{Hom}_{\mathcal{O}_X}(\mathcal{F}, \mathcal{G})(U) = \text{Hom}_{\mathcal{O}_X(U)}(\mathcal{F}(U), \mathcal{G}(U))$$

Example 3.88 In general, even if $\mathcal{F}, \mathcal{G} \in \text{Qcoh}(X)$, $\text{Hom}_{\mathcal{O}_X}(\mathcal{F}, \mathcal{G})$ might not be quasicoherent. A counter example :

$$X = \text{Spec } \mathbb{Z}, \quad \text{Hom}_{\mathcal{O}_X}(\oplus_{i=1}^{\infty} \mathcal{O}_X, \mathcal{O}_X)(D(p)) = \text{Hom}_{\mathbb{Z}[p^{-1}]}(\oplus_{i=1}^{\infty} \mathbb{Z}[\frac{1}{p}], \mathbb{Z}[\frac{1}{p}]) = \prod_{i=1}^{\infty} \mathbb{Z}[\frac{1}{p}]$$

$$\text{Hom}_{\mathcal{O}_X}(\oplus_{i=1}^{\infty} \mathcal{O}_X, \mathcal{O}_X)(X) = \prod_{i=1}^{\infty} \mathbb{Z}$$

$$\text{but } \prod_{i=1}^{\infty} \mathbb{Z}[\frac{1}{p}] \neq (\prod_{i=1}^{\infty} \mathbb{Z})[\frac{1}{p}] \quad (\text{that means } M|_{D(f)} \neq \mathcal{M}(X)_f)$$

Def 3.89 Let $X \in \text{Sch}$, $\mathcal{F} \in \text{Qcoh}(X)$. We say \mathcal{F} is

- 1) **Finitely presented (f.p)**
- 2) **Finitely generated (f.g)**

if there is an open cover $\cup_{i \in I} U_i \in X$ s.t. $U_i = \text{Spec } A_i$ and $\mathcal{F}(U_i)$ is a

1) Finitely presented A_i -module

2) Finitely generated A_i -module

Proposition 3.90 If $\mathcal{F} \in \text{Qcoh}(X)$ is f.p (f.g) and $\text{Spec } A = U \subseteq X$, then $\mathcal{F}(U)$ is a f.p (f.g) A -module

Proposition 3.91 If $X \in \text{Sch}$, $\mathcal{F}, \mathcal{G} \in \text{Qcoh}(X)$ and \mathcal{F} is f.p, then $\text{Hom}_{\mathcal{O}_X}(\mathcal{F}, \mathcal{G})$ is quasicoherent

Proof: Use Ex 1.75 :

Suppose M is a finitely presented A -module, then :

$$S^{-1}\text{Hom}_A(M, N) \cong \text{Hom}_{S^{-1}A}(S^{-1}M, S^{-1}N)$$

□

3.11.3 Properties of morphisms of schemes

Def 3.92 Let P be a property of morphisms of schemes, we say that P is

1) **presented under composition** ($P \in \text{COMP}$) if:

$$(X \xrightarrow{f} Y) \in P \text{ and } (Y \xrightarrow{g} Z) \in P \Rightarrow (X \xrightarrow{g \circ f} Z) \in P$$

2) **presented under base change** ($P \in \text{BC}$) if:

$$(X \xrightarrow{f} Y) \in P \text{ and } (S \xrightarrow{g} Y) \in P \Rightarrow (X \times_Y S \rightarrow S) \in P$$

3) **local on the target** ($P \in \text{LOCT}$) if:

$$\text{whenever } \cup_{i \in I} U_i \rightarrow Y \text{ is an open cover, and } (X \times_Y U_i \xrightarrow{f_i} U_i) \in P, \forall i \Rightarrow (X \xrightarrow{f} Y) \in P$$

4) **local on source** ($P \in \text{LOCS}$) if:

$$\text{whenever } \cup_{i \in I} V_i \rightarrow X \text{ is an open cover, and } (V_i \xrightarrow{f|_{V_i}} Y) \in P, \forall i \Rightarrow (X \xrightarrow{f} Y) \in P$$

Example 3.93 If $P_1 = \{\text{open immersion}\}$, $P_2 = \{\text{closed immersion}\}$

Then $P_1, P_2 \in \text{COMP}, \text{BC}, \text{LOCT}$, but $P_1, P_2 \notin \text{LOCS}$

3.12 Hausdorff Property for Schemes