

Algebraic Geometry II

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Introduction

This lecture will develop the cohomology of (quasi)coherent sheaves of modules. Professor Franke assumes familiarity with the contents of last term's Algebraic Geometry I. In particular, this includes the category of (pre)schemes, equalizers and fibre products of preschemes as well as in arbitrary categories and quasi-coherent \mathcal{O}_X -modules. If you want to brush up your knowledge about these topics, the *lecture notes from Algebraic Geometry I* [1] might be your friend.

Professor Franke started the lecture with an example of sheaf cohomology entering the game. Let X be a topological space, \mathcal{C}_X the sheaf of continuous \mathbb{C} -valued functions on X and \mathbb{Z}_X the sheaf of locally constant (i.e., continuous) functions on X with values in \mathbb{Z} . Then there is a short exact sequence

$$0 \longrightarrow \mathbb{Z}_X \xrightarrow{\cdot 2\pi i} \mathcal{C}_X \xrightarrow{\exp} \mathcal{C}_X^\times \longrightarrow 0$$

of sheaves of abelian groups. In general, taking global section doesn't preserve exactness but gives rise to a long exact sequence

$$\begin{array}{ccccccc} 0 & \longrightarrow & \mathbb{Z}_X(X) & \longrightarrow & \mathcal{C}_X(X) & \longrightarrow & \mathcal{C}_X^\times(X) \xrightarrow{d} H^1(X, \mathbb{Z}_X) \longrightarrow H^1(X, \mathcal{C}_X) \longrightarrow \dots \\ & & \downarrow \wr & & \downarrow \wr & & \downarrow \wr \nearrow \\ 0 & \longrightarrow & H^0(X, \mathbb{Z}_X) & \longrightarrow & H^0(X, \mathcal{C}_X) & \longrightarrow & H^0(X, \mathcal{C}_X^\times) \end{array}$$

in which the $H^k(X, \mathbb{Z}_X)$, $H^k(X, \mathcal{C}_X)$, and $H^k(X, \mathcal{C}_X^\times)$ are *sheaf cohomology groups*. There is the more general notion of *derived functors* (Grothendieck, Tôhoku paper), but this won't appear in the lecture.

Background in homological algebra is not required save for cohomology groups of cochain complexes, the long exact cohomology sequence and the following famous lemma.

Lemma (Five lemma). *Given a diagram*

$$\begin{array}{ccccccccc} A & \longrightarrow & B & \longrightarrow & C & \longrightarrow & D & \longrightarrow & E \\ \alpha \downarrow & & \beta \downarrow & & \gamma \downarrow & & \delta \downarrow & & \varepsilon \downarrow \\ A' & \longrightarrow & B' & \longrightarrow & C' & \longrightarrow & D' & \longrightarrow & E' \end{array}$$

of (abelian) groups/R-modules/etc. with exact rows, in which β and δ are isomorphisms, α is an epimorphism and ε a monomorphism, then γ is an isomorphism as well.

Proof. Easy diagram chase.

q.e.d.

1. Cohomology of quasi-coherent sheaves of modules

1.1. Recollection of basic definitions and results

Definition 1 ([1, Definition 1.5.2 and Definition 1.5.9(b)]). (a) A **prescheme** (Franke uses “EGA terminology”) is a locally ringed space (X, \mathcal{O}_X) which locally has the form $\text{Spec } R$ for some rings R .

(b) A prescheme X is called a **scheme**, if, for any prescheme T and any pair of morphisms $T \xrightarrow[a]{a} X$, the equalizer $\text{Eq} \left(T \xrightarrow[a]{a} X \right)$ is a closed subprescheme of X .

Remark. Equivalently, a prescheme X is a scheme iff the diagonal $\Delta: X \xrightarrow{(\text{id}_X, \text{id}_X)} X \times X$ is a closed immersion (cf. [1, Fact 1.5.8]). In other words, schemes are *separated* preschemes

Proposition 1. *If U and V are affine open subsets of a scheme X , then their intersection $U \cap V$ is again affine (and open of course).*

Proof. This was proved in [1, Proposition 1.5.4]. *q.e.d.*

Note that open subsets of the form $\text{Spec}(R_f) \simeq \text{Spec } R \setminus V(f)$ form a topology base on $\text{Spec } R$ and that the *saturation* of $\{1, f, f^2, \dots\}$ (i.e. the largest multiplicative subset of R which still gives the same localization) depends only on $\text{Spec } R \setminus V(f)$. Hence, for any R -module M , the localization M_f depends (up to canonical isomorphism) only on $\text{Spec } R \setminus V(f)$ and M . One defines a sheaf of modules \tilde{M} on $\text{Spec } R$ as the sheafification of $\text{Spec}(R_f) \mapsto M_f$. Then

$$\tilde{M}(U) = \left\{ (m_{\mathfrak{p}}) \in \prod_{\mathfrak{p} \in U} M_{\mathfrak{p}} \left| \begin{array}{l} \text{for every } \mathfrak{q} \in U \text{ there are } f \in R \setminus \mathfrak{q} \text{ and } \mu \in M_f \text{ such that} \\ m_{\mathfrak{p}} = (\text{image of } \mu \text{ under } M_f \rightarrow M_{\mathfrak{p}}) \text{ for all } \mathfrak{p} \in \text{Spec}(R_f) \end{array} \right. \right\}.$$

In the following, I will deviate from Franke’s numbering in the lecture, but I simply refuse to call a definition “remark”.

Definition 2 ([1, Definition 1.4.2]). A sheaf of modules \mathcal{M} on $\text{Spec } R$ is called **quasi-coherent** if $\mathcal{M} \simeq \tilde{M}$ for some R -module M .

Definition 3 ([1, Definition 1.5.3]). A prescheme is called **quasi-compact** if the underlying topological space is quasi-compact and **quasi-separated** if the intersection of any two quasi-compact open subsets is quasi-compact.

Definition 4 ([1, Definition 1.5.4]). Let X be a prescheme. An \mathcal{O}_X -module \mathcal{M} is called **quasi-coherent** if it satisfies the following equivalent conditions.

- (a) X may be covered by affine open subsets U such that $\mathcal{M}|_U$ is quasi-coherent in the sense of Definition 2.
- (b) For any affine open $U \subseteq X$, $\mathcal{M}|_U$ is quasi-coherent.
- (c) For any quasi-compact and quasi-separated open $U \subseteq X$ and $f \in \mathcal{O}_X(U)$, the canonical morphism

$$\mathcal{M}(U)_f \longrightarrow \mathcal{M}(U \setminus V(f)) \quad (1)$$

(coming from the universal property of localization) is an isomorphism.

- (d) The morphism (1) is an isomorphism when U is quasi-compact and quasi-separated and injective when U is only quasi-compact.
- (e) When $U \subseteq X$ is affine, the canonical morphism

$$\mathcal{M}(U)_{\mathfrak{p}_x} \longrightarrow \mathcal{M}_x \quad (2)$$

is an isomorphism for all $x \in U$, where $\mathfrak{p}_x = \{f \in \mathcal{O}_X(U) \mid x \in V(f)\}$ is the prime ideal in $\text{Spec } \mathcal{O}_X(U)$ corresponding to x .

Remark. To be fair: Despite Professor Franke's usual fondness of proving definitions (or rather stating definitions in a way they need a proof), the equivalence of (a) to (d) wasn't proposed as a definition in Algebraic Geometry I.

Proof of Definition 4. The equivalence of (a) to (d) was proved in [1, Proposition 1.5.1], but property (e) is something we haven't seen yet. Recall the *adjunction* (cf. Definition A.1.5)

$$\text{Hom}_{\mathcal{O}_{\text{Spec } R}}(\tilde{M}, \mathcal{N}) \xrightarrow{\sim} \text{Hom}_R(M, \mathcal{N}(\text{Spec } R)) \quad (3)$$

for M an R -module and \mathcal{N} a sheaf of $\mathcal{O}_{\text{Spec } R}$ -modules (cf. [1, Proposition 1.4.3]). When (2) is an isomorphism for all $x \in U \simeq \text{Spec } R$, it follows that the canonical morphism $\tilde{M} \rightarrow \mathcal{M}|_U$ (with $M = \mathcal{M}(U)$) coming from (3) is an isomorphism on stalks, hence an isomorphism. This shows (e) \Rightarrow (b).

Conversely, if (b) holds, then $\tilde{M} \rightarrow \mathcal{M}|_U$ (with $M = \mathcal{M}(U)$) is an isomorphism for all affine open $U \subseteq X$, hence induces isomorphisms on stalks, which shows (b) \Rightarrow (e). Hence, (e) is equivalent to the other properties. *q.e.d.*

Let \mathcal{A} be the category $R\text{-Mod}$ and \mathcal{B} be $\mathcal{O}_{\text{Spec } R}\text{-Mod}$, then the functor L given by $M \mapsto \tilde{M}$ and the functor $\mathcal{M} \mapsto \mathcal{M}(\text{Spec } R)$ are an adjoint pair of functors by (3). It follows that L commutes with cokernels and coproducts. In particular, the full subcategory $\text{QCoh}(X) \subseteq \mathcal{O}_X\text{-Mod}$ of quasi-coherent \mathcal{O}_X -modules is closed under taking cokernels and direct sums for $X = \text{Spec } R$, and by locality of quasi-coherentness this holds for all preschemes X .

Definition 5 ([1, Definition 2.1.1 and Definition 2.1.2]). A morphism $X \xrightarrow{f} Y$ of preschemes is **quasi-compact** if it satisfies the following equivalent conditions.

- (a) For quasi-compact open $U \subseteq Y$, $f^{-1}(U)$ is quasi-compact.
- (b) For affine open $U \subseteq Y$, $f^{-1}(U)$ is quasi-compact.

(c) One can cover Y by affine open U such that $f^{-1}(U)$ is quasi-compact.

It is called **quasi-separated** if it satisfies the following equivalent conditions.

(d) For an open quasi-separated $U \subseteq Y$, $f^{-1}(U)$ is quasi-separated again.

(e) For affine open subsets $U \subseteq Y$, $f^{-1}(U)$ is quasi-separated.

(f) It is possible to cover Y by affine open U such that $f^{-1}(U)$ is quasi-separated.

Proof. Equivalence was proved in [1, Fact 2.1.1] for quasi-compactness and [1, Lemma 2.1.1] for quasi-separatedness. q.e.d.

Proposition 2. *If $X \xrightarrow{f} Y$ is quasi-compact and quasi-separated morphism of preschemes and $\mathcal{M} \in \text{Ob}(\text{QCoh}(X))$, then $f_*\mathcal{M} \in \text{Ob}(\text{QCoh}(Y))$.*

Proof. This is [1, Proposition 1.5.2(b)]. q.e.d.

Proposition 3. (a) *The full subcategory $\text{QCoh}(X) \subseteq \mathcal{O}_X\text{-Mod}$ of quasi-coherent sheaves of \mathcal{O}_X -modules on a prescheme X is closed under taking kernels and cokernels of morphisms and under taking (finite) direct sums.*

(b) *If \mathcal{M} is a quasi-coherent \mathcal{O}_X -module and $U \subseteq X$ open, then $\mathcal{M}|_U \in \text{Ob}(\text{QCoh}(U))$.*

Proof. Part (a). For cokernels and finite direct sums (which are finite coproducts since $\mathcal{O}_X\text{-Mod}$ is an abelian category by Proposition A.1.1), consider the case $X = \text{Spec } R$ first. Then $R\text{-Mod} \xrightarrow{L} \mathcal{O}_X\text{-Mod}$, $M \mapsto \tilde{M}$ and $\mathcal{O}_X\text{-Mod} \rightarrow R\text{-Mod}$, $\mathcal{M} \mapsto \mathcal{M}(X)$ are adjoint functors by (3). By Remark A.1.4, L preserves cokernels and coproducts. By locality of quasi-coherentness, this follows for all preschemes X .

Closedness under taking kernels was proved in [1, Fact 1.5.3]. It's worth pointing out that in fact, the proof given there shows that $M \mapsto \tilde{M}$ preserves kernels as well.

Part (b) follows immediately from (e.g.) Definition 4(b). q.e.d.

Corollary 1. *Let X be a prescheme, $\mathcal{M} \xrightarrow{f} \mathcal{N}$ a morphism of quasi-coherent \mathcal{O}_X -modules and $U \subseteq X$ open, then*

$$\ker(\mathcal{M}(U) \xrightarrow{f} \mathcal{N}(U)) \simeq \ker(f)(U).$$

If U is, in addition, affine, then

$$\text{coker}(\mathcal{M}(U) \xrightarrow{f} \mathcal{N}(U)) \simeq \text{coker}(f)(U).$$

Proof. The first assertion holds by our explicit construction of $\ker(f)$ in Lemma A.1.2. For the second one, we may assume $X = U = \text{Spec } R$. Denoting $M = \mathcal{M}(X)$, $N = \mathcal{N}(X)$, then

$$\text{coker}(\mathcal{M} \xrightarrow{f} \mathcal{N}) = \text{coker}(\tilde{M} \xrightarrow{f} \tilde{N}) \simeq (\text{coker}(M \xrightarrow{f} N))^\sim$$

as $M \mapsto \tilde{M}$ preserves cokernels. q.e.d.

Corollary 2. *Let $0 \rightarrow \mathcal{M}' \rightarrow \mathcal{M} \rightarrow \mathcal{M}'' \rightarrow 0$ be a short exact sequence of quasi-coherent \mathcal{O}_X -modules on a prescheme X and $U \subseteq X$ be affine open, then*

$$0 \rightarrow \mathcal{M}'(U) \rightarrow \mathcal{M}(U) \rightarrow \mathcal{M}''(U) \rightarrow 0$$

is exact as well.

Proof. Follows from Corollary 1. q.e.d.

Remark. It turns out to be sufficient to assume that two of the above three sheaves \mathcal{M}' , \mathcal{M} , \mathcal{M}'' are quasi-coherent. Indeed, we proved in Proposition 3 that kernels and cokernels of morphisms between quasi-coherent sheaves are quasi-coherent again, so the only case in question is where \mathcal{M} is not required to be quasi-coherent. This case, however, will be treated by cohomological methods.

Our plan is to associate to any quasi-coherent \mathcal{O}_X -module on a scheme X cohomology groups $H^i(X, \mathcal{M})$ such that

- $H^0(X, \mathcal{M}) \simeq \mathcal{M}(X)$.
- when $0 \rightarrow \mathcal{M}' \rightarrow \mathcal{M} \rightarrow \mathcal{M}'' \rightarrow 0$ is an exact sequence of \mathcal{O}_X -modules, we have a canonical long exact sequence

$$\begin{aligned} 0 \rightarrow H^0(X, \mathcal{M}') \rightarrow H^0(X, \mathcal{M}) \rightarrow H^0(X, \mathcal{M}'') \\ \xrightarrow{d} H^1(X, \mathcal{M}') \rightarrow H^1(X, \mathcal{M}) \rightarrow H^1(X, \mathcal{M}'') \xrightarrow{d} H^2(X, \mathcal{M}') \rightarrow \dots \end{aligned}$$

But before we do this, we to introduce the notion of *coherent* \mathcal{O}_X -modules.

Proposition 4. *If X is a prescheme, associating to (the isomorphism class of) a closed embedding $Y \xrightarrow{i} X$ the sheaf of ideals $\mathcal{J} = \ker(\mathcal{O}_X \xrightarrow{i^*} i_*\mathcal{O}_Y)$ gives a bijection between the set of closed subschemes of X and the quasi-coherent sheaves of ideals in \mathcal{O}_X .*

Proof. This is [1, Proposition 1.5.3]. q.e.d.

Lemma 1. *For a quasi-coherent \mathcal{O}_X -module \mathcal{M} on a prescheme X , the following conditions are equivalent.*

- (a) *For any affine open $U \subseteq X$, $\mathcal{M}(U)$ is a finitely generated $\mathcal{O}_X(U)$ -module.*
- (b) *It is possible to cover X by affine open subsets $U \subseteq X$, for which $\mathcal{M}(U)$ is a finitely generated $\mathcal{O}_X(U)$ -module.*

Proof. This will follow from Lemma 2 and Lemma 3 below. q.e.d.

Lemma 2. *Let \mathcal{P} be a property of affine open subsets of a prescheme X such that*

- (α) *If $U \subseteq X$ is affine and $f \in \mathcal{O}_X(U)$, then $\mathcal{P}(U)$ implies $\mathcal{P}(U \setminus V(f))$.*
- (β) *If U is affine and $f_1, \dots, f_n \in \mathcal{O}_X(U)$ are such that $\bigcap_{i=1}^n V(f_i) = \emptyset$ and such that $\mathcal{P}(U \setminus V(f_i))$ holds for all $i = 1, \dots, n$, then $\mathcal{P}(U)$ holds.*

Then the following assertions about X are equivalent.

- (a) If $U \subseteq X$ is affine open, $\mathcal{P}(U)$ holds.
- (b) X may be covered by affine open U for which $\mathcal{P}(U)$ holds.

Proof. We proved this in [1, Lemma 2.2.2].

q.e.d.

Lemma 3. (a) If M is a finitely generated R -module, then M_f is a finitely generated R_f -module.

- (b) If M is an R -module and $f_1, \dots, f_n \in R$ such that $\bigcap_{i=1}^n V(f_i) = \emptyset$ in $\text{Spec } R$ and such that M_{f_i} is finitely generated over R_{f_i} , then M is finitely generated over R .

Proof. Part (a) is trivial, as the images of R -generators of M in M_f generate it as an R_f -module.

Now for part (b). As M_{f_i} is finitely generated over R_{f_i} , there are $k \in \mathbb{N}$ and $m_{i,j} \in M$, $j = 1, \dots, N_i$ such that $m_{i,j} f_i^{-k}$ generate M_{f_i} over R_{f_i} (as there are only finitely many generators, we can choose a common exponent k for all of them). Then also the $m_{i,j}$ generate M_{f_i} since f_i is a unit in R_{f_i} . We claim that the $\{m_{i,j} \mid i = 1, \dots, n \text{ and } j = 1, \dots, N_i\}$ generate M as an R -module. Indeed, let $m \in M$, then

$$m = \sum_{j=1}^{N_i} \frac{r_{i,j}}{f_i^\ell} m_{i,j} \quad \text{in } M_{f_i},$$

where $r_{i,j} \in R$ and $\ell \in \mathbb{N}$ (again, we can choose a common exponent ℓ). Then there is some $\ell' \in \mathbb{N}$ such that

$$f_i^{\ell+\ell'} m = \sum_{j=1}^{N_i} r_{i,j} f_i^{\ell'} m_{i,j} \quad \text{in } M.$$

Replacing ℓ by $\ell + \ell'$ and $r_{i,j}$ by $f_i^{\ell'} r_{i,j}$ we may assume $\ell' = 0$, i.e.

$$f_i^\ell m = \sum_{j=1}^{N_i} r_{i,j} m_{i,j} \quad \text{in } M.$$

We now have $\bigcap_{i=1}^n V(f_i^\ell) = \bigcap_{i=1}^n V(f_i) = \emptyset$, hence the ideal generated by the f_i^ℓ is R and we thus find $g_1, \dots, g_n \in R$ such that $\sum_{i=1}^n f_i^\ell g_i = 1$ in R . It follows that

$$m = \sum_{i=1}^n f_i^\ell g_i m = \sum_{i=1}^n \sum_{j=1}^{N_i} r_{i,j} g_i m_{i,j}$$

is an element of the submodule generated by the $m_{i,j}$.

q.e.d.

Definition 6. (a) We call a quasi-coherent \mathcal{O}_X -module **locally finitely generated** if it satisfies the equivalent conditions from Lemma 1.

- (b) When X is locally Noetherian (cf. [1, Definition 2.2.2]), an \mathcal{O}_X -module is called **coherent** if it is quasi-coherent and locally finitely generated.

Remark. There is a general definition of *coherent* sheaves of modules on arbitrary ringed spaces, which in the case of a locally Noetherian prescheme is equivalent to the above.

1.2. Čech cohomology

Let $\mathcal{U}: X = \bigcup_{i \in I} U_i$ be an open cover of a topological space X . In the following, we will use the convention

$$U_{i_0, \dots, i_n} = \bigcap_{k=0}^n U_{i_k} . \quad (1)$$

Definition 1. For an open cover \mathcal{U} of a topological space X (e.g., a prescheme) and \mathcal{M} a presheaf of abelian groups (e.g., a quasi-coherent \mathcal{O}_X -module) on X the **Čech complex** $\check{C}^*(\mathcal{U}, \mathcal{M})$ is the cochain complex defined as follows. Let

$$\check{C}^n(\mathcal{U}, \mathcal{M}) := \prod_{(i_0, \dots, i_n) \in I^{n+1}} \mathcal{M}(U_{i_0, \dots, i_n}) .$$

Let the elements of $\check{C}^n(\mathcal{U}, \mathcal{M})$ be denoted $\psi = (\psi_{i_0, \dots, i_n})_{(i_0, \dots, i_n) \in I^{n+1}}$. The differentials $\check{C}^n(\mathcal{U}, \mathcal{M}) \xrightarrow{\check{d}^n} \check{C}^{n+1}(\mathcal{U}, \mathcal{M})$ are defined by

$$(\check{d}^n \psi)_{i_0, \dots, i_{n+1}} = \sum_{j=0}^{n+1} (-1)^j \psi_{i_0, \dots, \hat{i}_j, \dots, i_{n+1}}|_{U_{i_0, \dots, i_{n+1}}}$$

where \hat{i}_j denotes the omission of the index i_j . For instance,

$$(\check{d}^0 \psi)_{i,j} = \psi_j|_{U_{i,j}} - \psi_i|_{U_{i,j}} \quad \text{and} \quad (\check{d}^1 \psi)_{i,j,k} = \psi_{j,k}|_{U_{i,j,k}} - \psi_{i,k}|_{U_{i,j,k}} + \psi_{i,j}|_{U_{i,j,k}} .$$

The **Čech cohomology** $\check{H}^*(\mathcal{U}, \mathcal{M})$ is defined as the cohomology of the Čech complex, i.e.,

$$\check{H}^i(\mathcal{U}, \mathcal{M}) = H^i(\check{C}^*(\mathcal{U}, \mathcal{M})) .$$

To see that $\check{C}^*(\mathcal{U}, \mathcal{M})$ is indeed a cochain complex, we need to prove $\check{d}^2 = 0$ – and we won't do this in a remark!

Proof of Definition 1. For $\ell = 0, \dots, n+1$ let $\check{C}^n(\mathcal{U}, \mathcal{M}) \xrightarrow{d_\ell} \check{C}^{n+1}(\mathcal{U}, \mathcal{M})$ be given by

$$(d_\ell \psi)_{i_0, \dots, i_{n+1}} = \psi_{i_0, \dots, \hat{i}_\ell, \dots, i_{n+1}}|_{U_{i_0, \dots, i_{n+1}}} .$$

Again, \hat{i}_ℓ denotes the omission of the index i_ℓ .

Step 1. We prove that

$$d_m d_\ell = d_{\ell+1} d_m \quad \text{when } \ell \geq m . \quad (2)$$

Indeed, we have $(d_m d_\ell \psi)_{\mathbf{i}} = \psi_{\mathbf{j}}|_{U_{\mathbf{i}}}$, where \mathbf{j} is obtained from \mathbf{i} by omitting the indices i_ℓ and i_m when $\ell < m$ and the indices $i_{\ell+1}$ and i_m when $\ell \geq m$. The assertion follows.

Step 2. We prove the following. Let C^* is any family of abelian groups (or objects of an abelian category) and $C^n \xrightarrow{d_\ell} C^{n+1}$ morphisms for $\ell = 0, \dots, n+1$. Suppose that $C^n = 0$ for $n < 0$ and that (2) holds. Then

$$d = \sum_{i=0}^{n+1} (-1)^i d_i$$

satisfies $d^2 = 0$. Indeed,

$$\begin{aligned} d^2 &= \sum_{m=0}^{n+2} \sum_{\ell=0}^{n+1} (-1)^{\ell+m} d_m d_\ell = \sum_{m=0}^{n+2} \sum_{\ell=0}^{m-1} (-1)^{\ell+m} d_m d_\ell + \sum_{m=0}^{n+2} \sum_{\ell=m}^{n+1} (-1)^{\ell+m} d_m d_\ell \\ &= \sum_{m=0}^{n+2} \sum_{\ell=0}^{m-1} (-1)^{\ell+m} d_m d_\ell + \sum_{m=0}^{n+1} \sum_{\ell=m}^{n+1} (-1)^{\ell+m} d_{\ell+1} d_m \\ &= \sum_{i>j} (-1)^{i+j} d_i d_j + \sum_{i>j} (-1)^{i+j-1} d_i d_j = 0, \end{aligned}$$

as required. *q.e.d.*

Remark. Our program is to show that $\check{H}^*(\mathcal{U}, \mathcal{M})$ is independent of \mathcal{U} and has the desired properties, when X is a scheme, $\mathcal{M} \in \text{Ob}(\text{QCoh}(X))$ and \mathcal{U} is an affine open cover.

Remark. For instance, the cohomology of $\mathbb{P}_R^1 = \text{Proj}(R[X_0, X_1])$ can be calculated using the affine open cover

$$U_i = \mathbb{P}_R^1 \setminus V(X_i) \simeq \text{Spec}(R[X_0, X_1]_{X_i})_0 \simeq \text{Spec } R[t_i] \quad \text{where } t_i = \begin{cases} X_1 \cdot X_0^{-1} & \text{if } i = 0 \\ X_0 \cdot X_1^{-1} & \text{if } i = 1 \end{cases}.$$

Unfortunately, calculations become complicated by the fact that there are infinitely many non-zero terms in $\check{C}^*(\mathcal{U}, \mathcal{M})$.

Let $\check{C}_{\text{alt}}^n(\mathcal{U}, \mathcal{M}) \subseteq \check{C}^n(\mathcal{U}, \mathcal{M})$ be the subgroup containing all $\psi \in \check{C}^n(\mathcal{U}, \mathcal{M})$ such that

$$\psi_{i_{\pi(0)}, \dots, i_{\pi(n)}} = \text{sgn}(\pi) \psi_{i_0, \dots, i_n} \in \mathcal{M}(U_{i_0, \dots, i_n}) \quad \text{and} \quad \psi_{i_0, \dots, i_{n-1}, i_{n-1}} = 0 \in \mathcal{M}(U_{i_0, \dots, i_{n-1}})$$

for all permutations $\pi \in \mathfrak{S}_n$. Note that $U_{i_0, \dots, i_n} = U_{i_{\pi(0)}, \dots, i_{\pi(n)}}$ as permuting indices doesn't change intersections, so the first property makes sense. Also note that both properties together imply that $\psi_{i_0, \dots, i_n} = 0$ whenever (i_0, \dots, i_n) contains a repeated index.

Definition 2. $\check{C}_{\text{alt}}^*(\mathcal{U}, \mathcal{M}) \subseteq \check{C}^*(\mathcal{U}, \mathcal{M})$ is a subcomplex, called the **alternating Čech complex**.

Proof. We need to confirm that the differential \check{d}^n maps $\check{C}_{\text{alt}}^n(\mathcal{U}, \mathcal{M})$ into $\check{C}_{\text{alt}}^{n+1}(\mathcal{U}, \mathcal{M})$. To do this, define *codegeneracy maps*

$$\check{C}^n(\mathcal{U}, \mathcal{M}) \xrightarrow{s_\ell} \check{C}^{n-1}(\mathcal{U}, \mathcal{M}), \quad (s_\ell \psi)_{i_0, \dots, i_{n-1}} = \psi_{i_0, \dots, i_\ell, i_\ell, \dots, i_{n-1}} \quad \text{for } \ell = 0, \dots, n-1$$

(i.e., s_ℓ repeats the ℓ^{th} index) as well as *transposition maps*

$$\check{C}^n(\mathcal{U}, \mathcal{M}) \xrightarrow{t_\ell} \check{C}^n(\mathcal{U}, \mathcal{M}), \quad (t_\ell \psi)_{i_0, \dots, i_n} = \psi_{i_0, \dots, i_{\ell-1}, i_{\ell+1}, i_\ell, i_{\ell+2}, \dots, i_{n-1}} \quad \text{for } \ell = 0, \dots, n-1$$

(i.e., t_ℓ swaps the ℓ^{th} and $(\ell+1)^{\text{st}}$ index). As any permutation may be expressed as a composition of elementary transpositions, $\check{C}_{\text{alt}}^n(\mathcal{U}, \mathcal{M}) \subseteq \check{C}^n(\mathcal{U}, \mathcal{M})$ is given by the relations

$$s_\ell \psi = 0 \quad \text{and} \quad t_\ell \psi = -\psi \quad \text{for } \ell = 0, \dots, n-1$$

So what we need to check to confirm that $\check{C}_{\text{alt}}^*(\mathcal{U}, \mathcal{M})$ is indeed a subcomplex of $\check{C}^*(\mathcal{U}, \mathcal{M})$ is that the above relations are preserved by the differential \check{d} .

One may easily check the relations

$$s_\ell d_i = \begin{cases} d_i s_{\ell-1} & \text{if } i < \ell \\ \text{id} & \text{if } i = \ell \text{ or } i = \ell + 1 \\ d_{i-1} s_\ell & \text{if } i > \ell + 1 \end{cases} \quad (3)$$

and

$$t_\ell d_j = \begin{cases} d_j t_\ell & \text{if } \ell < j - 1 \\ d_\ell & \text{if } \ell = j - 1 \\ d_{\ell+1} & \text{if } \ell = j \\ d_j t_{\ell-1} & \text{if } \ell > j \end{cases}. \quad (4)$$

Now let $\psi \in \check{C}^n(\mathcal{U}, \mathcal{M})$ such that $t_j \psi = -\psi$ for all $j = 0, \dots, n-1$. Using (4), we get

$$\begin{aligned} t_\ell \check{d} \psi &= \sum_{j=0}^{\ell-1} (-1)^j t_\ell d_j \psi + (-1)^\ell t_\ell d_\ell \psi + (-1)^{\ell+1} t_\ell d_{\ell+1} \psi + \sum_{j=\ell+2}^n (-1)^j t_\ell d_j \psi \\ &= \sum_{j=0}^{\ell-1} (-1)^j d_j t_{\ell-1} \psi + (-1)^\ell d_{\ell+1} \psi + (-1)^{\ell+1} d_\ell \psi + \sum_{j=\ell+2}^n (-1)^j d_j t_\ell \psi \\ &= - \sum_{j=0}^{\ell-1} (-1)^j d_j \psi - (-1)^\ell d_\ell \psi - (-1)^{\ell+1} d_{\ell+1} \psi - \sum_{j=\ell+2}^n (-1)^j d_j \psi \\ &= -\check{d} \psi. \end{aligned}$$

Similarly, one can check that $s_\ell \check{d} \psi = 0$ when $s_j \psi = 0$ for all $j = 0, 1, \dots, n-1$. This shows that \check{d} restricts to a differential on $\check{C}_{\text{alt}}^n(\mathcal{U}, \mathcal{M})$, as required. *q.e.d.*

It will eventually turn out that the cohomology groups $\check{H}_{\text{alt}}^i(\mathcal{U}, \mathcal{M}) = H^i(\check{C}_{\text{alt}}^*(\mathcal{U}, \mathcal{M}))$ obtained from the alternating Čech complex are the same as the regular Čech cohomology groups $\check{H}^i(\mathcal{U}, \mathcal{M})$.

Remark 1. A *cosimplicial object* of a category \mathcal{A} is a sequence of objects $(X^n)_{n \geq 0}$ with morphisms $d_j: X^n \rightarrow X^{n+1}$ for $j = 0, \dots, n+1$ satisfying (2) and $s_j: X^n \rightarrow X^{n-1}$ for $j = 0, \dots, n$ satisfying a version of (2) together with (3). In other words, a cosimplicial object is a covariant functor from the *simplex category* Δ to \mathcal{A} .

There is a *Dold–Puppe correspondence* between cochain complexes concentrated in nonnegative degrees and cosimplicial objects of an abelian category.

Example 1. (a) By the sheaf axiom,

$$\begin{aligned} \mathcal{M}(X) &\simeq \left\{ (m_i)_{i \in I} \in \prod_{i \in I} \mathcal{M}(U_i) \mid m_i|_{U_{i,j}} = m_j|_{U_{i,j}} \right\} \\ &= \ker \left(\check{C}^0(\mathcal{U}, \mathcal{M}) \xrightarrow{\check{d}^0} \check{C}^1(\mathcal{U}, \mathcal{M}) \right) \simeq \check{H}^0(\mathcal{U}, \mathcal{M}) \\ &= \ker \left(\check{C}_{\text{alt}}^0(\mathcal{U}, \mathcal{M}) \xrightarrow{\check{d}^0} \check{C}_{\text{alt}}^1(\mathcal{U}, \mathcal{M}) \right) \simeq \check{H}_{\text{alt}}^0(\mathcal{U}, \mathcal{M}) \end{aligned}$$

(b) For the trivial cover $\mathcal{U}_0: X = X$, the Čech complex $\check{C}^*(\mathcal{U}_0, \mathcal{M})$ has the form

$$\mathcal{M}(X) \longrightarrow 0 \longrightarrow 0 \longrightarrow 0 \longrightarrow \dots$$

and the alternating Čech complex $\check{C}_{\text{alt}}^*(\mathcal{U}_0, \mathcal{M})$ looks like

$$\mathcal{M}(X) \xrightarrow{0} \mathcal{M}(X) \xrightarrow{\text{id}} \mathcal{M}(X) \xrightarrow{0} \dots,$$

so

$$\check{H}^n(\mathcal{U}_0, \mathcal{M}) = \check{H}_{\text{alt}}^n(\mathcal{U}_0, \mathcal{M}) = \begin{cases} \mathcal{M}(X) & \text{if } n = 0 \\ 0 & \text{else} \end{cases}.$$

(c) If \mathcal{M} and \mathcal{N} are presheaves of modules on X and \mathcal{U} is an open cover of X , then

$$\check{C}^*(\mathcal{U}, \mathcal{M} \oplus \mathcal{N}) = \check{C}^*(\mathcal{U}, \mathcal{M}) \oplus \check{C}^*(\mathcal{U}, \mathcal{N})$$

and, more general,

$$\check{C}^*\left(\mathcal{U}, \prod_{i \in I} \mathcal{M}_i\right) = \prod_{i \in I} \check{C}^*(\mathcal{U}, \mathcal{M}_i).$$

The same holds for $\check{C}_{\text{alt}}^*(\mathcal{U}, -)$.

If $\mathcal{U}: X = \bigcup_{i \in I} U_i$ is a cover of a scheme X by affine open subsets U_i , then all intersections U_{i_0, \dots, i_n} are affine again by Proposition 1.1.1. If $0 \rightarrow \mathcal{M}' \rightarrow \mathcal{M} \rightarrow \mathcal{M}'' \rightarrow 0$ is a short exact sequence in $\text{QCoh}(X)$, Corollary 1.1.2 provides short exact sequences

$$0 \longrightarrow \check{C}^*(\mathcal{U}, \mathcal{M}') \longrightarrow \check{C}^*(\mathcal{U}, \mathcal{M}) \longrightarrow \check{C}^*(\mathcal{U}, \mathcal{M}'') \longrightarrow 0$$

and

$$0 \longrightarrow \check{C}_{\text{alt}}^*(\mathcal{U}, \mathcal{M}') \longrightarrow \check{C}_{\text{alt}}^*(\mathcal{U}, \mathcal{M}) \longrightarrow \check{C}_{\text{alt}}^*(\mathcal{U}, \mathcal{M}'') \longrightarrow 0$$

of chain complexes. For $\check{C}^*(\mathcal{U}, -)$ this is immediate from Definition 1 and from the fact that products of short exact sequences are short exact again. To see this for $\check{C}_{\text{alt}}^*(\mathcal{U}, -)$, choose any linear ordering of I and note that

$$\check{C}_{\text{alt}}^n(\mathcal{U}, \mathcal{M}) \simeq \prod_{i_0 < \dots < i_n \in I} \mathcal{M}(U_{i_0, \dots, i_n}),$$

then the same argument may be applied.

Taking long exact cohomology sequences we just proved

Proposition 1. *If \mathcal{U} is an affine open cover of a scheme X and $0 \rightarrow \mathcal{M}' \rightarrow \mathcal{M} \rightarrow \mathcal{M}'' \rightarrow 0$ a short exact sequence of quasi-coherent sheaves of \mathcal{O}_X -modules, then there is a long exact cohomology sequence*

$$\begin{array}{ccccccc} 0 & \longrightarrow & \check{H}^0(\mathcal{U}, \mathcal{M}') & \longrightarrow & \check{H}^0(\mathcal{U}, \mathcal{M}) & \longrightarrow & \check{H}^0(\mathcal{U}, \mathcal{M}'') \xrightarrow{d} \check{H}^1(\mathcal{U}, \mathcal{M}') \longrightarrow \check{H}^1(\mathcal{U}, \mathcal{M}) \longrightarrow \dots \\ & & \downarrow \wr & & \downarrow \wr & & \downarrow \wr \\ 0 & \longrightarrow & \mathcal{M}'(X) & \longrightarrow & \mathcal{M}(X) & \longrightarrow & \mathcal{M}''(X) \end{array}$$

and similar for $\check{H}_{\text{alt}}^*(\mathcal{U}, -)$.

Remark 2. For arbitrary preschemes, the situation is more difficult (cf. Thomason, *The Grothendieck Festschrift*).

Definition 3. An open cover $\mathcal{V}: X = \bigcup_{j \in J} V_j$ is a **refinement** of $\mathcal{U}: X = \bigcup_{i \in I} U_i$ if there is a map $v: J \rightarrow I$ such that $V_j \subseteq U_{v(j)}$ for all $j \in J$. Such a v is called a **refinement map** for the pair $(\mathcal{V}, \mathcal{U})$.

Note that Professor Franke isn't sure whether *refinement map* is the usual term. Assuming the axiom of choice, the existence of v is equivalent to every V_j being contained in some U_i .

A refinement map v induces a morphism

$$\check{C}^*(\mathcal{U}, \mathcal{M}) \xrightarrow{v^*} \check{C}^*(\mathcal{V}, \mathcal{M}), \quad (v^n \psi)_{j_0, \dots, j_n} = \psi_{v(j_0), \dots, v(j_n)}|_{V_{j_0, \dots, j_n}} \quad \text{for } \psi \in \check{C}^n(\mathcal{U}, \mathcal{M}).$$

Clearly, v^* commutes with the d_j , s_j , and t_j , hence restricts to a morphism of chain complexes $\check{C}_{\text{alt}}^*(\mathcal{U}, \mathcal{M}) \xrightarrow{v^*} \check{C}_{\text{alt}}^*(\mathcal{V}, \mathcal{M})$.

Lemma 1. (a) A refinement \mathcal{W} of a refinement \mathcal{V} of \mathcal{U} is a refinement of \mathcal{U} and if v and w are associated refinement maps for $(\mathcal{V}, \mathcal{U})$ and $(\mathcal{W}, \mathcal{U})$, then vw is a refinement map for $(\mathcal{W}, \mathcal{U})$. Moreover, $(vw)^* = w^*v^*$ and the identity id_I is a refinement map for $(\mathcal{U}, \mathcal{U})$ and $\text{id}_I^* = \text{id}_{\check{C}^*(\mathcal{U}, -)}$.

(b) Two arbitrary open covers have a common refinement. When X is a prescheme, this common refinement can be chosen affine.

(c) If $v_1, v_2: J \rightarrow I$ are two refinement maps for $(\mathcal{V}, \mathcal{U})$, then v_1^* and v_2^* induce the same morphism on Čech cohomology.

Proof. Part (a) is obvious. For (b), let \mathcal{U} and \mathcal{V} be open covers of X . Then $X = \bigcup_{(i,j) \in I \times J} U_i \cap V_j$ is a common refinement. When X is a prescheme, we may cover each $U_i \cap V_j$ by affine open subsets and thus obtain a common affine refinement of \mathcal{U} and \mathcal{V} .

Now for part (c). Define maps $h^n: \check{C}^n(\mathcal{U}, \mathcal{M}) \rightarrow \check{C}^{n-1}(\mathcal{V}, \mathcal{M})$ as follows: We put

$$h^n = \sum_{\ell=0}^{n-1} (-1)^\ell h_\ell,$$

where $h_\ell: \check{C}^n(\mathcal{U}, \mathcal{M}) \rightarrow \check{C}^{n-1}(\mathcal{V}, \mathcal{M})$ is given by

$$(h_\ell \psi)_{j_0, \dots, j_{n-1}} = \psi_{v_1(j_0), \dots, v_1(j_\ell), v_2(j_\ell), \dots, v_2(j_{n-1})}|_{V_{j_0, \dots, j_{n-1}}} \quad \text{for } \psi \in \check{C}^n(\mathcal{U}, \mathcal{M}).$$

Then it's a straightforward but tedious check that the following relations hold:

$$h_\ell d_k = \begin{cases} d_k h_{\ell-1} & \text{if } 0 \leq k < \ell \\ h_{\ell-1} d_k & \text{if } 0 < k = \ell \\ v_2^n & \text{if } 0 = k = \ell \\ h_{\ell+1} d_k & \text{if } k = \ell + 1 < n \\ v_1^n & \text{if } k = \ell + 1 = n \\ d_{k-1} h_\ell & \text{if } k > \ell + 1 \end{cases}. \quad (5)$$

(I tried my best to get the indices right and I claim my hit ratio is way higher than Franke's). Our goal is to show

$$\check{d}^{n-1}h^n + h^{n+1}\check{d}^n = v_2^n - v_1^n,$$

for then h^* is a cochain homotopy between v_1^* and v_2^* and it's a well-known fact from homological algebra that cochain homotopic maps induce the same morphisms on cohomology. Indeed, using (5) we get

$$\begin{aligned} h^{n+1}\check{d}^n &= \sum_{\ell=0}^n \sum_{k=0}^{n+1} (-1)^{\ell+k} h_\ell d_k \\ &= \sum_{\ell=0}^n \sum_{k=0}^{\ell-1} (-1)^{\ell+k} h_\ell d_k + (-1)^0 h_0 d_0 + \sum_{\ell=1}^n (-1)^{2\ell} h_\ell d_\ell \\ &\quad + \sum_{\ell=0}^{n-1} (-1)^{2\ell+1} h_\ell d_{\ell+1} + (-1)^{2n+1} h_n d_{n+1} + \sum_{\ell=0}^n \sum_{k=\ell+2}^{n+1} (-1)^{\ell+k} h_\ell d_k \\ &= \sum_{\ell=0}^n \sum_{k=0}^{\ell-1} (-1)^{\ell+k} d_k h_{\ell-1} + v_2^n + \sum_{\ell=1}^n h_{\ell-1} d_\ell \\ &\quad - \sum_{\ell=0}^{n-1} h_\ell d_{\ell+1} - v_1^n + \sum_{\ell=0}^n \sum_{k=\ell+2}^{n+1} (-1)^{\ell+k} d_{k-1} h_\ell \\ &= \sum_{\ell=0}^{n-1} \sum_{k=0}^{\ell} (-1)^{\ell+1+k} d_k h_\ell + \sum_{\ell=0}^n \sum_{k=\ell+1}^n (-1)^{\ell+k+1} d_k h_\ell + v_2^n - v_1^n \\ &= - \sum_{k=0}^n \sum_{\ell=0}^{n-1} (-1)^{\ell+k} d_k h_\ell + v_2^n - v_1^n \\ &= -\check{d}^{n-1}h^n + v_2^n - v_1^n, \end{aligned}$$

as required. q.e.d.

Corollary 1. *Let \mathcal{M} be a presheaf of modules on a space X and \mathcal{U}, \mathcal{V} be open covers of X .*

(a) *If \mathcal{V} is a refinement of \mathcal{U} , we have a canonical morphism*

$$\tau_{\mathcal{U}, \mathcal{V}}: \check{H}^*(\mathcal{U}, \mathcal{M}) \longrightarrow \check{H}^*(\mathcal{V}, \mathcal{M})$$

satisfying $\tau_{\mathcal{V}, \mathcal{W}} \tau_{\mathcal{U}, \mathcal{V}} = \tau_{\mathcal{U}, \mathcal{W}}$ if \mathcal{W} is another open cover of X which is a refinement of \mathcal{V} , as well as $\tau_{\mathcal{U}, \mathcal{U}} = \text{id}$.

(b) *If \mathcal{U} is a refinement of \mathcal{V} and \mathcal{V} a refinement of \mathcal{U} , then $\tau_{\mathcal{U}, \mathcal{V}}$ and $\tau_{\mathcal{V}, \mathcal{U}}$ are isomorphisms which are inverse to each other.*

(c) *If there is an $i^* \in I$ such that $U_{i^*} = X$, then $\check{H}^n(\mathcal{U}, \mathcal{M})$ vanishes for $n \geq 1$.*

Proof. Part (a) follows from Lemma 1. Part (b) follows from (a) as $\tau_{\mathcal{V}, \mathcal{U}} \tau_{\mathcal{U}, \mathcal{V}} = \tau_{\mathcal{U}, \mathcal{U}} = \text{id}$. Part (c) follows from (b) and Example 1 as \mathcal{U} and the trivial cover $\mathcal{U}_0: X = X$ are refinements of each other in this case. q.e.d.

Remark 3. In general, the cochain homotopy used in the proof of Lemma 1 won't preserve the subcomplex $\check{C}_{\text{alt}}^*(-, \mathcal{M}) \subseteq \check{C}^*(-, \mathcal{M})$. However, Corollary 1(c) for $\check{H}_{\text{alt}}^*(\mathcal{U}, \mathcal{M})$ can still be obtained, using the *cochain contraction* $h^*: \check{C}^*(\mathcal{U}, \mathcal{M}) \rightarrow \check{C}^*(\mathcal{U}, \mathcal{M})$, where $h^n: \check{C}^n(\mathcal{U}, \mathcal{M}) \rightarrow \check{C}^{n-1}(\mathcal{U}, \mathcal{M})$ for $n \geq 1$ is given by

$$(h^n \psi)_{i_0, \dots, i_n} = \psi_{i^*, i_0, \dots, i_n}.$$

It's a straightforward check that h^* preserves $\check{C}_{\text{alt}}^*(\mathcal{U}, \mathcal{M}) \subseteq \check{C}^*(\mathcal{U}, \mathcal{M})$. Moreover, one has the relations

$$h^n d_k = \begin{cases} \text{id} & \text{if } k = 0 \\ d_{k-1} h^{n-1} & \text{if } k > 0 \end{cases},$$

hence

$$\begin{aligned} \check{d}^{n-1} h^n + h^{n+1} \check{d}^n &= \sum_{k=0}^n (-1)^k d_k h^n + \sum_{k=0}^{n+1} (-1)^k d_k h^{n+1} \\ &= \text{id} + \sum_{k=0}^n \left((-1)^k + (-1)^{k+1} \right) d_k h^n \\ &= \text{id}, \end{aligned}$$

proving that h^* is indeed a cochain contraction, hence $\check{H}_{\text{alt}}^i(\mathcal{U}, \mathcal{M}) = 0$ for $i > 0$. For our purposes, this will turn out to be sufficient.

We now arrive at the main result of this section.

Proposition 2. *Let X be a quasi-compact scheme, \mathcal{M} be a quasi-coherent \mathcal{O}_X -module and \mathcal{U} and affine open cover of X .*

(a) *If \mathcal{V} is another affine open cover of X which is a refinement of \mathcal{U} , then*

$$\tau_{\mathcal{U}, \mathcal{V}}: \check{H}^*(\mathcal{U}, \mathcal{M}) \xrightarrow{\sim} \check{H}^*(\mathcal{V}, \mathcal{M}).$$

(b) *The inclusion $\check{C}_{\text{alt}}^*(\mathcal{U}, \mathcal{M}) \subseteq \check{C}^*(\mathcal{U}, \mathcal{M})$ of cochain complexes induces an isomorphism*

$$\check{H}_{\text{alt}}^*(\mathcal{U}, \mathcal{M}) \xrightarrow{\sim} \check{H}^*(\mathcal{U}, \mathcal{M}).$$

(c) *If X is affine and $i > 0$, then $\check{H}_{\text{alt}}^i(\mathcal{U}, \mathcal{M}) = \check{H}^i(\mathcal{U}, \mathcal{M}) = 0$.*

Before the proof, a lemma.

Lemma 2. *For an open cover $\mathcal{U}: X = \bigcup_{i \in I} \mathcal{U}_i$ of a topological space X and a continuous map $f: Y \rightarrow X$, let $f^{-1}(\mathcal{U})$ be the cover $Y = \bigcup_{i \in I} f^{-1}(\mathcal{U}_i)$. Let \mathcal{F} be a sheaf of abelian groups on Y .*

(a) *We have an isomorphism of cochain complexes $\check{C}^*(f^{-1}(\mathcal{U}), \mathcal{F}) \simeq \check{C}^*(\mathcal{U}, f_* \mathcal{F})$ and this isomorphism restricts to an isomorphism $\check{C}_{\text{alt}}^*(f^{-1}(\mathcal{U}), \mathcal{F}) \simeq \check{C}_{\text{alt}}^*(\mathcal{U}, f_* \mathcal{F})$.*

(b) *If the image of f is contained in one of the open subsets \mathcal{U}_i , then $\check{H}^i(\mathcal{U}, f_* \mathcal{F}) = \check{H}_{\text{alt}}^i(\mathcal{U}, f_* \mathcal{F}) = 0$ for $i > 0$.*

Proof. Part (a) is pretty much tautological. Let $\mathcal{V} = f^{-1}(\mathcal{U})$, $V_i = f^{-1}(U_i)$, then we have $V_{i_0, \dots, i_n} = f^{-1}(U_{i_0, \dots, i_n})$, hence $f_*\mathcal{F}(V_{i_0, \dots, i_n}) = \mathcal{F}(U_{i_0, \dots, i_n})$ by definition of the *direct image* $f_*\mathcal{F}$. The differentials \check{d} as well as the degeneracy and transposition maps s_ℓ, t_ℓ of $\check{C}^*(f^{-1}(\mathcal{U}), \mathcal{F})$ and $\check{C}^*(\mathcal{U}, f_*\mathcal{F})$ clearly coincide, proving the asserted isomorphisms of cochain complexes.

Part (b) follows from (a), Corollary 1(c) and Remark 3. *q.e.d.*

Proof of Proposition 2. Part (a). We fix the covers \mathcal{U} and \mathcal{V} and consider the following conditions on \mathcal{M} :

\mathcal{M} satisfies $A_i(\mathcal{M})$ iff $\check{H}^j(\mathcal{U}, \mathcal{M}) \xrightarrow{\tau_{\mathcal{U}, \mathcal{V}}} \check{H}^j(\mathcal{V}, \mathcal{M})$ is an isomorphism for $j < i$ and injective for $i = j$.

Claim 1. For a short exact sequence $0 \rightarrow \mathcal{M}' \rightarrow \mathcal{M} \rightarrow \mathcal{M}'' \rightarrow 0$ of quasi-coherent \mathcal{O}_X -modules one has the implication

$$[A_{i+1}(\mathcal{M}) \text{ and } A_i(\mathcal{M}'')] \implies A_{i+1}(\mathcal{M}').$$

To prove Claim 1, consider the commutative diagram

$$\begin{array}{ccccccccc} \check{H}^{j-1}(\mathcal{U}, \mathcal{M}) & \longrightarrow & \check{H}^{j-1}(\mathcal{U}, \mathcal{M}'') & \longrightarrow & \check{H}^j(\mathcal{U}, \mathcal{M}') & \longrightarrow & \check{H}^j(\mathcal{U}, \mathcal{M}) & \longrightarrow & \check{H}^j(\mathcal{U}, \mathcal{M}'') \\ \alpha \downarrow & & \beta \downarrow & & \gamma \downarrow & & \delta \downarrow & & \varepsilon \downarrow \\ \check{H}^{j-1}(\mathcal{V}, \mathcal{M}) & \longrightarrow & \check{H}^{j-1}(\mathcal{V}, \mathcal{M}'') & \longrightarrow & \check{H}^j(\mathcal{V}, \mathcal{M}') & \longrightarrow & \check{H}^j(\mathcal{V}, \mathcal{M}) & \longrightarrow & \check{H}^j(\mathcal{V}, \mathcal{M}'') \end{array}$$

When $j \leq i$, then α, β , and δ are isomorphisms, while ε is injective, proving γ to be an isomorphism by the five lemma. When $j = i + 1$, α is an isomorphism by $A_{i+1}(\mathcal{M})$ while β and δ are injective, proving γ to be injective by the four lemma. Claim 1 follows.

Claim 2. For any quasi-coherent \mathcal{O}_X -module \mathcal{M} there are a quasi-coherent \mathcal{O}_X -module \mathcal{N} such that $A_i(\mathcal{N})$ holds for arbitrary i , and a monomorphism $\mathcal{M} \hookrightarrow \mathcal{N}$.

To show this, let $j_W: W \rightarrow X$ be the embedding of any affine open subset W contained in one of the open subsets forming the cover \mathcal{V} . As X is a scheme, the morphism j_W is affine, i.e., preimages of affine open subsets are affine (cf. [1, Definition 2.5.1]). Indeed, since preimages in this case are intersections with W , this follows from Proposition 1.1.1. Being an open embedding, j_W is also quasi-separated. By Proposition 1.1.2 and Proposition 1.1.3(b), $(j_W)_*\mathcal{M}|_W$ is a quasi-coherent \mathcal{O}_X -module. Since X is quasi-compact, we find finitely many affine open subsets W_1, \dots, W_n covering X , each W_i contained in an element of \mathcal{V} (that is, $X = \bigcup_{i=1}^n W_i$ is a finite affine refinement of \mathcal{V}). Then

$$\mathcal{N} := \bigoplus_{i=1}^n (j_{W_i})_*\mathcal{M}|_{W_i}$$

is quasi-coherent by Proposition 1.1.3(a).

We have morphisms

$$\begin{aligned} \mathcal{M}(U) &\longrightarrow \mathcal{N}(U) = \bigoplus_{i=1}^n (j_{W_i})_*(\mathcal{M}|_{W_i})(U) = \bigoplus_{i=1}^n \mathcal{M}(U \cap W_i) \\ m &\longmapsto (m|_{U \cap W_i})_{i=1}^n \end{aligned}$$

which are injective as \mathcal{M} satisfies the sheaf axiom and form a morphism of \mathcal{O}_X -modules $\mathcal{M} \rightarrow \mathcal{N}$, which is thus a monomorphism.

By Example 1(c),

$$\check{H}^k(\mathcal{U}, \mathcal{N}) = \bigoplus_{i=1}^n \check{H}^k(\mathcal{U}, (j_{W_i})_* \mathcal{M}|_{W_i})$$

and same for \mathcal{V} . But Example 1(a) and Lemma 2(b) (which applies here as every W_i is contained in an element of \mathcal{V} , thus also of \mathcal{U}) show that

$$\check{H}^k(\mathcal{U}, (j_{W_i})_* \mathcal{M}|_{W_i}) = \check{H}^k(\mathcal{V}, (j_{W_i})_* \mathcal{M}|_{W_i}) = \begin{cases} \mathcal{M}(W_i) & \text{if } k = 0 \\ 0 & \text{else} \end{cases},$$

hence $(j_{W_i})_* \mathcal{M}|_{W_i}$ has property A_i for arbitrary i . Now \mathcal{N} inherits the property A_i from its summands, proving Claim 2.

We are now able to finish the proof of Proposition 2(a). We prove by induction on i that $A_i(\mathcal{M})$ holds for arbitrary quasi-coherent \mathcal{O}_X -modules \mathcal{M} . For $i = 0$, note that $\check{H}^0(\mathcal{U}, \mathcal{M}) \simeq \check{H}^0(\mathcal{V}, \mathcal{M}) \simeq \mathcal{M}(X)$ for all \mathcal{O}_X -modules \mathcal{M} (quasi-coherent or not), i.e., $A_0(\mathcal{M})$ holds.

Now suppose $i \geq 1$ and A_{i-1} holds for every quasi-coherent \mathcal{O}_X -module. Using Claim 2, we choose an embedding $\mathcal{M} \xrightarrow{\iota} \mathcal{N}$ where \mathcal{N} is quasi-coherent and satisfies A_i , then apply Claim 1 to the exact sequence

$$0 \longrightarrow \mathcal{M} \xrightarrow{\iota} \mathcal{N} \longrightarrow \text{coker}(\iota) \longrightarrow 0$$

to derive $A_i(\mathcal{M})$ from $A_i(\mathcal{N})$ and $A_{i-1}(\text{coker}(\iota))$. Here, Proposition 1.1.3(a) ensures that $\text{coker}(\iota)$ is quasi-coherent as well.

Part (b). The proof of part (a) can be carried over with the following modifications.

- $A_i(\mathcal{M})$ is now the condition that $\check{H}_{\text{alt}}^j(\mathcal{U}, \mathcal{M}) \rightarrow \check{H}^j(\mathcal{U}, \mathcal{M})$ is an isomorphism when $j < i$ and injective for $j = i$.
- Claim 1 also holds for the new A_i .
- If $W \subseteq X$ is affine and contained in one of the V_i and $\mathcal{F} \in \text{Ob}(\text{Qcoh}(W))$, then $(j_W)_* \mathcal{F}$ satisfies all A_i (which follows like above from Lemma 2(b) and Example 1).

Part (c). Apply (a) with \mathcal{U} the trivial cover $X = X$ and \mathcal{V} any affine open cover of X to conclude $\check{H}^i(\mathcal{V}, \mathcal{M}) = 0$ when $i > 0$ and \mathcal{M} is a quasi-coherent \mathcal{O}_X -module. Then one uses (b) to show that $\check{H}_{\text{alt}}^*(\mathcal{V}, \mathcal{M})$ also vanishes in positive degrees. *q.e.d.*

Definition 4. Let X be a quasi-compact scheme and \mathcal{M} a quasi-coherent \mathcal{O}_X -module. We put

$$H^i(X, \mathcal{M}) := \check{H}^i(\mathcal{V}_0, \mathcal{M}),$$

where \mathcal{V}_0 is the affine open cover of X consisting of all affine open subsets of X .

Summing up our previous work, we obtain the following Theorem 1 in full glory.

Theorem 1. *Let X be a quasi-compact scheme and \mathcal{M} a quasi-coherent \mathcal{O}_X -module.*

(a) *If \mathcal{U} is any affine open over of X , then*

$$H^*(X, \mathcal{M}) \xrightarrow[\tau_{\mathcal{U}, \mathcal{V}_0}]{\sim} \check{H}^*(\mathcal{U}, \mathcal{M}) \xleftarrow{\sim} \check{H}_{\text{alt}}^*(\mathcal{U}, \mathcal{M})$$

are isomorphisms compatible with the (iso)morphisms $\check{H}^(\mathcal{U}, \mathcal{M}) \xrightarrow{\tau_{\mathcal{U}, \mathcal{V}}} \check{H}^*(\mathcal{V}, \mathcal{M})$ when \mathcal{V} is an affine refinement of \mathcal{U} .*

(b) *When X is affine, $H^i(X, \mathcal{M}) = 0$ when $i > 0$.*

(c) *There is a canonical isomorphism $H^0(X, \mathcal{M}) \simeq \mathcal{M}(X)$.*

(d) *When $0 \rightarrow \mathcal{M}' \rightarrow \mathcal{M} \rightarrow \mathcal{M}'' \rightarrow 0$ is a short exact sequence of quasi-coherent \mathcal{O}_X -modules, one has a long exact cohomology sequence*

$$\begin{array}{ccccccc} 0 & \longrightarrow & \mathcal{M}'(X) & \longrightarrow & \mathcal{M}(X) & \longrightarrow & \mathcal{M}''(X) \\ & & \uparrow \wr & & \uparrow \wr & & \uparrow \wr \\ 0 & \longrightarrow & H^0(X, \mathcal{M}') & \longrightarrow & H^0(X, \mathcal{M}) & \longrightarrow & H^0(X, \mathcal{M}'') \xrightarrow{d} H^1(X, \mathcal{M}') \longrightarrow \dots \\ & & & & & & \dots \longrightarrow H^{i-1}(X, \mathcal{M}'') \xrightarrow{d} H^i(X, \mathcal{M}') \longrightarrow H^i(X, \mathcal{M}) \longrightarrow H^i(X, \mathcal{M}'') \xrightarrow{d} \dots \end{array}$$

Proof. Part (a) follows from Proposition 2 and the fact that every affine open cover \mathcal{U} is a refinement of \mathcal{V}_0 . Part (b) is Proposition 2(c). Part (c) was seen in Example 1(a) and (d) follows from Proposition 1. q.e.d.

Corollary 2. *Let $0 \rightarrow \mathcal{M}' \xrightarrow{\alpha} \mathcal{M} \xrightarrow{\beta} \mathcal{M}'' \rightarrow 0$ be a short exact sequence of \mathcal{O}_X -modules, where X is any prescheme. Then if two of $\mathcal{M}', \mathcal{M}, \mathcal{M}''$ are quasi-coherent, so is the third, and for any affine open subset $U \subseteq X$ the sequence*

$$0 \longrightarrow \mathcal{M}'(U) \xrightarrow{\alpha} \mathcal{M}(U) \xrightarrow{\beta} \mathcal{M}''(U) \longrightarrow 0 \tag{*}$$

is exact.

Proof. We have seen in Proposition 1.1.3(a) that the category $\text{QCoh}(X)$ of quasi-coherent \mathcal{O}_X -modules is stable under kernels and cokernels. Therefore, \mathcal{M}' is quasi-coherent when \mathcal{M} and \mathcal{M}'' are and \mathcal{M}'' is quasi-coherent when \mathcal{M}' and \mathcal{M} are. We may thus assume that \mathcal{M}' and \mathcal{M}'' are the quasi-coherent ones.

To show exactness of (*), we may replace X by U and the involved sheaves by their restriction to U and thus assume that $X = U = \text{Spec } R$ is affine. This may also be assumed in the proof of

quasi-coherentness of \mathcal{M} , which is a local question. We then only need to show surjectivity of $\mathcal{M}(X) \xrightarrow{\beta} \mathcal{M}''(X)$. If we had the long exact cohomology sequence available, this would be an immediate consequence of the vanishing of $H^1(X, \mathcal{M}')$ – but we haven't, so what the proof does is mimicking the cohomological argument on foot. For this, let $m'' \in \mathcal{M}''(X)$. As $\mathcal{M} \xrightarrow{\beta} \mathcal{M}''$ is an epimorphism and the affine open subsets form a topology base in X , there is an affine open cover $\mathcal{V}: X = \bigcup_{i \in I} V_i$ such that $m''|_{V_i}$ is in the image of $\beta(m_i)$ for some $m_i \in \mathcal{M}(V_i)$.

The m_i satisfy $\beta(m_i|_{V_{i,j}} - m_j|_{V_{i,j}}) = 0 \in \mathcal{M}''(V_{i,j})$, hence there are $m'_{i,j} \in \mathcal{M}(V_{i,j})$ such that $\alpha(m'_{i,j}) = m_i|_{V_{i,j}} - m_j|_{V_{i,j}}$, the sequence $0 \rightarrow \mathcal{M}'(V_{i,j}) \xrightarrow{\alpha} \mathcal{M}(V_{i,j}) \xrightarrow{\beta} \mathcal{M}''(V_{i,j})$ being exact. Consider the elements $\mu = (m_i)_{i \in I} \in \check{C}^0(\mathcal{V}, \mathcal{M})$ and $\mu' = (m'_{i,j})_{(i,j) \in I^2} \in \check{C}^1(\mathcal{V}, \mathcal{M}')$. Then $\alpha(\mu') = \check{d}\mu$. Thus

$$\alpha(\check{d}\mu') = \check{d}\alpha(\mu') = \check{d}^2\mu = 0,$$

hence $\check{d}\mu' = 0$ by injectivity of α . This means that μ' is a cocycle, and by the vanishing of $\check{H}^1(\mathcal{V}, \mathcal{M}')$ (due to Proposition 2(c)), also a coboundary. That is, $\mu' = \check{d}\lambda'$ for some $\lambda' \in \check{C}^0(\mathcal{V}, \mathcal{M}')$ (note that at this point Professor Franke run out of primes, though there are apparently infinitely many of them). Let $\lambda = \alpha(\lambda')$. As $\check{d}(\mu - \lambda) = \alpha(\mu') - \alpha(\mu') = 0$, the $\mu_i - \lambda_i$ lift by the sheaf axiom to a single element $m^* \in \mathcal{M}(X)$ such that $m^*|_{V_i} = \mu_i - \lambda_i$. Since $\beta(\mu - \lambda) = \beta(\mu) - \beta(\alpha(\lambda')) = \beta(\mu)$, we have $\beta(m^*) = m''$. This proves the surjectivity of $\mathcal{M}(X) \rightarrow \mathcal{M}''(X)$ and thus (*).

To show that \mathcal{M} is quasi-coherent, consider $0 \rightarrow M' \rightarrow M \rightarrow M'' \rightarrow 0$ where $M' = \mathcal{M}'(X)$, $M = \mathcal{M}(X)$, and $M'' = \mathcal{M}''(X)$ which is an exact sequence of R -modules (as we just proved). As pointed out in the proof of Proposition 1.1.3(a), the functor $R\text{-Mod} \rightarrow \text{QCoh}(\text{Spec } R)$ mapping $N \mapsto \tilde{N}$ preserves kernels and cokernels, hence the diagram

$$\begin{array}{ccccccc} 0 & \longrightarrow & \tilde{M}' & \longrightarrow & \tilde{M} & \longrightarrow & \tilde{M}'' \longrightarrow 0 \\ & & \downarrow \wr & & \downarrow & & \downarrow \wr \\ 0 & \longrightarrow & \mathcal{M}' & \longrightarrow & \mathcal{M} & \longrightarrow & \mathcal{M}'' \longrightarrow 0 \end{array}$$

has exact rows. Since $\tilde{M}' \rightarrow \mathcal{M}'$ and $\tilde{M}'' \rightarrow \mathcal{M}''$ are isomorphisms, so is $\tilde{M} \rightarrow \mathcal{M}$ by the five lemma. *q.e.d.*

In the following, if $\mathcal{U}: X = \bigcup_{i \in I} U_i$ is an open cover and $Y \subseteq X$, we will write $\mathcal{U} \cap Y$ for the open cover $Y = \bigcup_{i \in I} (Y \cap U_i)$.

Corollary 3. *Let X be a quasi-coherent scheme.*

- (a) *If $W \xrightarrow{j} X$ is the embedding of the affine open subset W and $\mathcal{M} \in \text{Ob}(\text{QCoh}(X))$, then $H^p(X, j_*\mathcal{M}) = 0$ for $p > 0$.*
- (b) *Let $W_i \xrightarrow{j_i} X$ be the embeddings of affine open subsets W_i for $i = 1, \dots, n$. Let $W = \bigcup_{i=1}^n W_i$. If $\mathcal{M} \in \text{Ob}(\text{QCoh}(X))$, then*

$$H^p\left(X, \bigoplus_{i=1}^n (j_i)_*\mathcal{M}|_{W_i}\right) = 0 \quad \text{for } p > 0$$

and if \mathcal{K} denotes the kernel of $\mathcal{M} \rightarrow \bigoplus_{i=1}^n (j_i)_* \mathcal{M}|_{W_i}$ sending $m \in \mathcal{M}(U)$ to

$$(m|_{U \cap W_i})_{i=1}^n \in \bigoplus_{i=1}^n \mathcal{M}(U \cap W_i) = \bigoplus_{i=1}^n (j_i)_* \mathcal{M}|_{W_i}(U)$$

satisfies $\mathcal{K}|_W = 0$.

Proof. Part (a). Let \mathcal{U} be any affine open cover of X . By Proposition 1.1.1, the $U_i \cap W$ are affine and we have $\check{H}^p(\mathcal{U} \cap W, \mathcal{M}) \simeq \check{H}^p(\mathcal{U}, j_* \mathcal{M}) = 0$ by Lemma 2(a) and Proposition 2(c).

Part (b) follows from the fact that each j_i is a monomorphism and the sheaf axiom. *q.e.d.*

Lemma 3. *Let \mathcal{U} be a finite open cover of the quasi-separated prescheme X by quasi-compact open subsets and $f \in \mathcal{O}_X(X)$. By the universal property of localization, we have morphisms $\mathcal{M}(U)_f \rightarrow \mathcal{M}(U \setminus V(f))$ for arbitrary \mathcal{O}_X -modules \mathcal{M} and open $U \subseteq X$. When applied to $U = U_{i_0, \dots, i_n}$, this gives a morphism*

$$\check{C}^*(\mathcal{U}, \mathcal{M})_f \longrightarrow \check{C}^*(\mathcal{U} \cap (X \setminus V(f)), \mathcal{M})$$

of Čech complexes. When \mathcal{M} is quasi-coherent, this is an isomorphism.

Remark. The structure of an $\mathcal{O}_X(X)$ -module on $\check{C}^*(\mathcal{U}, \mathcal{M})$ is obtained using the $\mathcal{O}_X(U_{i_0, \dots, i_n})$ -module structures on $\mathcal{M}(U_{i_0, \dots, i_n})$ followed by $\mathcal{O}_X(X) \rightarrow \mathcal{O}_X(U_{i_0, \dots, i_n})$. Taking the product over all $(i_0, \dots, i_n) \in I^{n+1}$ gives the structure of a cochain complex of $\mathcal{O}_X(X)$ -modules on $\check{C}^*(\mathcal{U}, \mathcal{M})$, which is used in the formulation of Lemma 3. The morphism under investigation is a morphism of cochain complexes of $\mathcal{O}_X(X)_f$ -modules.

Proof of Lemma 3. As $\check{C}^m(\mathcal{U}, \mathcal{M}) = \prod_{(i_0, \dots, i_n) \in I^{n+1}} \mathcal{M}(U_{i_0, \dots, i_n})$ is a finite product and localization commutes with finite products, it is sufficient to show that

$$\mathcal{M}(U_{i_0, \dots, i_n})_f \xrightarrow{\sim} \mathcal{M}(U_{i_0, \dots, i_n} \setminus V(f)) .$$

By Definition 1.1.4(c), this will hold if U_{i_0, \dots, i_n} is quasi-compact and quasi-separated. It is quasi-separated as an open subset of the quasi-separated prescheme X . It is quasi-compact as an intersection of the quasi-compact subsets U_{i_0}, \dots, U_{i_n} using quasi-separatedness of X . *q.e.d.*

Proposition 3. *Let X be a quasi-compact scheme, \mathcal{M} a quasi-coherent \mathcal{O}_X -module, and $f \in \mathcal{O}_X(X)$. Then we have a canonical isomorphism*

$$H^*(X, \mathcal{M})_f \xrightarrow{\sim} H^*(X \setminus V(f), \mathcal{M}|_{X \setminus V(f)}) .$$

Proof. Follows from Lemma 3. Note that the open subset $X \setminus V(f) \subseteq X$ is a scheme again by [1, Fact 1.5.9(c)] and quasi-compact by [1, Fact 2.1.2]. *q.e.d.*

Remark. In general, there is the notion of *derived functors* (from Grothendieck's famous *Tôhoku paper*) applicable to the left-exact functors on an abelian category with sufficiently many injective objects, like $\mathcal{R}\text{-Mod}$ (\mathcal{R} being any sheaf of rings on any topological space) and $\text{QCoh}(X)$ (X being any prescheme). When \mathcal{M} is an \mathcal{R} -module on any topological space X , the derived functors taken on the category of \mathcal{R} -modules or sheaves of abelian groups are canonically isomorphic. When X is quasi-compact (or paracompact, this is actually sufficient) scheme, these are isomorphic to the cohomology introduced here and also to the derived functor of the global section functor taken for $\text{QCoh}(X)$.

1.3. The affinity criterion of Serre

Proposition 1 (Serre's affinity criterion). *For a quasi-compact scheme X , the following conditions are equivalent.*

- (a) X is affine.
- (b) $H^p(X, \mathcal{M}) = 0$ for $p > 0$ when \mathcal{M} is a quasi-coherent \mathcal{O}_X -module.
- (c) $H^1(X, \mathcal{J}) = 0$ when \mathcal{J} is a quasi-coherent sheaf of ideals on X .

Remark. In EGA III, this is shown under the weaker assumptions that X is quasi-compact and quasi-separated (instead of separated), using H^* defined as a derived functor on \mathcal{O}_X -Mod.

To prove Proposition 1 we need the following.

Proposition 2. (a) *If Z is a non-empty quasi-compact closed subset of a prescheme X , it contains a closed point.*

- (b) *If $Z \subseteq X$ is a closed subset of a prescheme X , then $\mathcal{J}(U) := \{f \in \mathcal{O}_X(U) \mid Z \cap U \subseteq V(f)\}$ defines a quasi-coherent sheaf of ideals.*
- (c) *If $\mathcal{N}_1, \mathcal{N}_2 \subseteq \mathcal{M}$ are quasi-coherent subsheaves of the quasi-coherent sheaf of modules \mathcal{M} , $(\mathcal{N}_1 \cap \mathcal{N}_2)(U) := \mathcal{N}_1(U) \cap \mathcal{N}_2(U)$ defines a quasi-coherent sheaf of modules.*

Proof. Part (a) is proved in [1, Proposition 2.1.1]

Part (b). Let $U \subseteq X$ be quasi-compact and quasi-separated, $f \in \mathcal{O}_X(U)$ and $\varphi \in \mathcal{J}(U)$ such that $\varphi|_{U \cap V(f)} = 0$. Then, as \mathcal{O}_X is quasi-coherent, there exists $n \in \mathbb{N}$ such that $f^n \varphi = 0$ by Definition 1.1.4(c). It follows that the canonical map $\mathcal{J}(U)_f \rightarrow \mathcal{J}(U \setminus V(f))$ is injective.

If $\psi \in \mathcal{J}(U \setminus V(f))$, then as \mathcal{O}_X is quasi-coherent, there is $n \in \mathbb{N}$ such that $f^n \psi$ extends to some $g \in \mathcal{O}_X(U)$ (using Definition 1.1.4(c) again). Now fg extends $f^{n+1} \psi$ and is in $\mathcal{J}(U)$. Indeed, we need to show $Z \cap U \subseteq V(fg)$ and this follows from

$$(Z \cap U) \setminus V(f) \subseteq V(\psi) \subseteq V(f^{n+1} \psi) = V(fg|_{U \setminus V(f)}) \subseteq V(fg)$$

(the first inclusion coming from $\psi \in \mathcal{J}(U \setminus V(f))$) and $V(f) \subseteq V(fg)$. Thus we get an isomorphism $\mathcal{J}(U)_f \xrightarrow{\sim} \mathcal{J}(U \setminus V(f))$, which is the criterion from Definition 1.1.4(c) once again.

Part (c). It is directly possible to verify $(\mathcal{N}_1 \cap \mathcal{N}_2)(U)_f \xrightarrow{\sim} (\mathcal{N}_1 \cap \mathcal{N}_2)(U \setminus V(f))$ similar as above. Alternatively, note that $\mathcal{N}_1 \cap \mathcal{N}_2 = \ker(\mathcal{N}_1 \rightarrow \mathcal{M} \rightarrow \mathcal{M}/\mathcal{N}_2)$ and use that $\mathrm{QCoh}(X)$ has kernels and cokernels by Proposition 1.1.3(a). *q.e.d.*

Proof of Proposition 1. The implication (a) \Rightarrow (b) follows from Theorem 1(c) and (b) \Rightarrow (c) is Trivial.

Let's do (c) \Rightarrow (a). We first derive (c) \Rightarrow (c⁺⁺), where (c⁺⁺) is the condition

(c⁺⁺) If $\mathcal{M} \subseteq \mathcal{O}_X^n$ is a quasi-coherent submodule, then $H^1(X, \mathcal{M}) = 0$.

We prove (c^{++}) by induction on n . The case $n = 0$ is trivial. Now let $n \geq 1$ and assume that (c^{++}) holds for $n - 1$. If $\mathcal{O}_X^{n-1}(U)$ is identified with $\{(f_1, \dots, f_{n-1}, 0) \in \mathcal{O}_X(V)^n\} \subseteq \mathcal{O}_X(U)^n$, then $\mathcal{M}' = \mathcal{M} \cap \mathcal{O}_X^{n-1}$ is quasi-coherent by Proposition 2(c). Moreover,

$$\begin{aligned} \mathcal{M}'' &:= \mathcal{M}/\mathcal{M}' \longrightarrow \mathcal{O}_X \\ (f_1, \dots, f_n) \bmod \mathcal{M} &\longmapsto f_n \end{aligned}$$

is a monomorphism. Hence $H^1(X, \mathcal{M}') = 0$ by induction and $H^1(X, \mathcal{M}'') = 0$ by (c). Now looking at the piece

$$\dots \longrightarrow H^1(X, \mathcal{M}') \longrightarrow H^1(X, \mathcal{M}) \longrightarrow H^1(X, \mathcal{M}'') \longrightarrow \dots$$

of the long exact cohomology sequence, we get $H^1(X, \mathcal{M}) = 0$, completing the induction.

Now we prove $(c^{++}) \Rightarrow (a)$. Let $R = \mathcal{O}_X(X)$, so we have a morphism $X \xrightarrow{p} \operatorname{Spec} R$ corresponding to id_R under the adjunction

$$\operatorname{Hom}_{\operatorname{LRS}}(X, \operatorname{Spec} R) \simeq \operatorname{Hom}_{\operatorname{Ring}}(R, \mathcal{O}_X(X))$$

from [1, Proposition 1.4.2]. We have to show that p is an isomorphism. For this it is sufficient to show the following.

- (α) If $f \in R$ is chosen such that $X \setminus V(f)$ is affine, then $X \setminus V(f) = p^{-1}(\operatorname{Spec} R \setminus V(f))$ is isomorphically mapped to $\operatorname{Spec} R \setminus V(f) \simeq \operatorname{Spec}(R_f)$ by p .
- (β) The open subsets $X \setminus V(f)$ with f as in (α) cover X .
- (γ) If $f_1, \dots, f_n \in R$ are as in (α) and $X = \bigcup_{i=1}^n (X \setminus V(f_i))$ then

$$\operatorname{Spec} R = \bigcup_{i=1}^n (\operatorname{Spec} R \setminus V(f_i)) .$$

By (β) and the quasi-compactness of X , it is possible to find $f_1, \dots, f_n \in R$ to which (γ) may be applied. Then the open subsets $U_i = (\operatorname{Spec} R \setminus V(f_i))$ cover $\operatorname{Spec} R$ and $p^{-1}(U_i) \xrightarrow[p]{\sim} U_i$. Then we get $\operatorname{Spec} R \xrightarrow[p]{\sim} X$.

Proof of (α). The fact $X \setminus V(f) = p^{-1}(\operatorname{Spec} R \setminus V(f))$ follows from the explicit construction of p . Namely, p maps a point $x \in X$ to the prime ideal $\mathfrak{p} \subseteq R$ which is the preimage of the maximal ideal $\mathfrak{m}_{X,x} \subseteq \mathcal{O}_{X,x}$ under $R = \mathcal{O}_X(X) \rightarrow \mathcal{O}_{X,x}$. Hence $x \in X \setminus V(f) \Leftrightarrow f \notin \mathfrak{p}(x) \Leftrightarrow p(x) \in \operatorname{Spec} R \setminus V(f)$, showing that p is a bijection on the underlying sets.

If $X \setminus V(f)$ is affine, we get

$$\begin{array}{ccccc} X \setminus V(f) & \xrightarrow{\sim} & \operatorname{Spec}(\mathcal{O}_X(X \setminus V(f))) & \xrightarrow{\sim} & \operatorname{Spec}(R_f) \\ \downarrow & & \downarrow & & \downarrow \\ X & \xrightarrow{p} & \operatorname{Spec} \mathcal{O}_X(X) & \xlongequal{\quad} & \operatorname{Spec} R \end{array}$$

The first isomorphism comes from the fact that $X \setminus V(f)$ is affine. For the second, we use $\mathcal{O}_X(X \setminus V(f)) \xrightarrow{\sim} \mathcal{O}_X(X)_f = R_f$, which follows from Definition 1.1.4(c) using that \mathcal{O}_X is quasi-coherent, and X is both quasi-compact and quasi-separated. This shows (α).

Proof of (β) . Let $U \subseteq X$ be the union of the affine open subsets of the form $X \setminus V(f)$ and $Z = X \setminus U$. If $Z \neq \emptyset$, there is a closed point $z \in Z$ by Proposition 2(a). Choose an affine open neighbourhood V of z . Let $Y_1 \subseteq X$ be the closed subset $X \setminus V$, let $Y_2 = \{z\}$ and $Y = Y_1 \cup Y_2$. The sheaf of ideals \mathcal{J} of functions $f \in \mathcal{O}_X(W)$ such that $Y \cap W \subseteq V(f)$ is quasi-coherent by Proposition 2(b). By (c), we have $H^1(X, \mathcal{J}) = 0$. Note that Y is the closed subscheme of X defined by \mathcal{J} and denote by $Y \hookrightarrow X$ its embedding, i.e., $\mathcal{J} = \ker(\mathcal{O}_X \xrightarrow{i^*} i_*\mathcal{O}_Y)$. We get some $\varphi \in \mathcal{O}_Y(Y) = i_*\mathcal{O}_Y(X)$ such that $\varphi|_{Y_1} = 0$ and $\varphi|_{Y_2} = 1$ as Y is the disjoint union of its open subsets Y_1, Y_2 .

By the cohomology sequence

$$0 \longrightarrow \mathcal{J}(X) \longrightarrow \mathcal{O}_X(X) \xrightarrow{i^*} i_*\mathcal{O}_Y(X) \longrightarrow H^1(X, \mathcal{J}) = 0,$$

there is some $f \in \mathcal{O}_X(X)$ such that $i^*f = \varphi$. Hence $Y_1 \subseteq V(f)$ and $z \notin V(f)$, so $z \in X \setminus V(f) = (X \setminus Y_1) \setminus V(f) = V \setminus V(f)$, which is an affine open subset of X . We get $z \in U$, a contradiction.

Proof of (γ) . Let f_1, \dots, f_n be as requested. Consider the morphisms $\mathcal{O}_X \xrightarrow{f_i} \mathcal{O}_X$ given by multiplication with f_i and let $f: \mathcal{O}_X^n \rightarrow \mathcal{O}_X$ be the morphism induced by the $\cdot f_i$. Then $\cdot f_i$ is an isomorphism on $U_i = X \setminus V(f_i)$, hence induces isomorphisms on stalks $\mathcal{O}_{X,x}$ for $x \in U_i$, and the U_i cover X . Thus f is an epimorphism on stalks, hence an epimorphism of sheaves. Let \mathcal{M} be the kernel of this epimorphism. We have

$$\begin{array}{ccc} (r_1, \dots, r_n) & \longmapsto & \sum r_i f_i \\ R^n & \longrightarrow & R \\ \downarrow \wr & & \downarrow \wr \\ \mathcal{O}_X(X)^n & \xrightarrow{f} & \mathcal{O}_X(X) \longrightarrow H^1(X, \mathcal{M}) \end{array}$$

The lower row is an extract of a long exact cohomology sequence. Note that $H^1(X, \mathcal{M}) = 0$ by (c^{++}) , hence the f_i generate R as an ideal of R and $\bigcap_{i=1}^n V(f_i) = \emptyset$ in $\text{Spec } R$ as stated. *q.e.d.*

Remark. $H^1(X, \mathcal{O}_X) = 0$ is not enough (even when X is a quasi-compact scheme) for affinity of X as it holds, e.g., for $X = \mathbb{P}_R^n$.

1.4. Cohomological dimension

Proposition 1 (Grothendieck). *Let X be a scheme and $Z \subseteq X$ a closed subset which Noetherian as topological space.¹ Let \mathcal{M} be a quasi-coherent sheaf of \mathcal{O}_X -modules satisfying $\mathcal{M}|_{X \setminus Z} = 0$ and let $p > \dim(Z)$ (the Krull dimension of Z , which may be infinite). Then $H^p(X, \mathcal{M}) = 0$.*

Proof. There is nothing to show if $\dim(Z) = \infty$, so we may show this by induction on $\dim(Z)$.

Let $\dim(Z) = 0$ and $Z = \bigcup_{i=1}^n Z_i$ the decomposition of Z into its irreducible components. Each Z_i is Noetherian (as Z is), hence quasi-compact, and closed, thus contains a closed point z_i by Proposition 1.3.2(a). But then $Z_i = \{z_i\}$ as $\{z_i\}$ is irreducible and $\dim(Z_i) = 0$.

¹It is possible that we will later add the further assumption that X is Noetherian as a topological space. The necessity of such an assumption will hopefully be clear once a full proof of this proposition is presented.

As the affine open subsets form a topology base on X , there are affine open neighbourhoods $W_i \subseteq X$ of z_i such that $Z \cap W_i = \{z_i\}$. Let $\mathcal{M}_i := (\iota_i)_*(\mathcal{M}|_{W_i})$ where $W_i \xrightarrow{\iota_i} X$ is the corresponding open immersion. Let $\mathcal{F} = \bigoplus_{i=1}^n \mathcal{M}_i$. We have seen in Corollary 1.2.3(b) that $H^p(X, \mathcal{F}) = 0$ when $p > 0$. Moreover, $(\mathcal{M}_j)_{z_i} = 0$ when $i \neq j$ while $\mathcal{F} \rightarrow \mathcal{M}_i$ is an isomorphism on W_i , hence induces an isomorphism $\mathcal{F}_{z_i} \xrightarrow{\sim} (\mathcal{M}_i)_{z_i} = \mathcal{M}_{z_i}$ on stalks at z_i . Moreover, since \mathcal{M} and \mathcal{M}_i vanish on $X \setminus Z$, we see that $\mathcal{F} \xrightarrow{\sim} \mathcal{M}$ and the assertion follows.

For the inductive step, let $\dim(Z)$ be finite and the assertion be proved for $\mathcal{M} \in \text{Ob}(\text{QCoh}(X))$ supported on closed subsets of smaller Krull dimension. Let $Z = \bigcup_{i=1}^n Z_i$ be the decomposition into irreducible components and let η_i be the generic point of Z_i (cf. [1, Subsection 2.1.2]). We have $\eta_i \notin Z_j$ for $i \neq j$ since otherwise $Z_i = \overline{\{\eta_i\}} \subseteq Z_j$. As the affine open subsets form a topology base, there are affine open neighbourhoods W_i of η_i such that $W_i \cap Z_j = \emptyset$ for $i \neq j$.

Let $\mathcal{M}_i = (\iota_i)_*\mathcal{M}|_{W_i}$ where $W_i \xrightarrow{\iota_i} X$ is the inclusion.

Claim. Kernel and cokernel of $\mathcal{M} \rightarrow \mathcal{F} = \bigoplus_{i=1}^n \mathcal{M}_i$ vanish outside of $\tilde{Z} = Z \setminus \bigcup_{i=1}^n W_i$.

to be continued...

A. Appendix – category theory corner

A.1. Towards abelian categories

Definition 1. (a) A **pointed** category is a category with initial and final objects, such that the canonical (unique) morphism from the initial to the final object is an isomorphism.

(b) An **additive** category \mathcal{A} is a pointed category which has a product $X \times Y$ (i.e., a fibre product over the final object $*$) and coproduct $X \amalg Y$ (i.e., a dual fibre product with respect to the initial object $*$) such that the canonical morphism $X \amalg Y \rightarrow X \times Y$ is an isomorphism for all objects $X, Y \in \text{Ob}(\mathcal{A})$ and such that the resulting addition law on $\text{Hom}_{\mathcal{A}}(X, Y)$ defines a group structure for all $X, Y \in \text{Ob}(\mathcal{A})$.

Remark. (a) When \mathcal{A} is a pointed category and $X, Y \in \text{Ob}(\mathcal{A})$, let the *zero morphism* (which we denote 0) $X \xrightarrow{0} Y$ be defined by $X \rightarrow * \rightarrow Y$, where $*$ is the both initial and final object.

(b) We will construct the canonical morphism $X \amalg Y \xrightarrow{c} X \times Y$ from Definition 1(b). The product $X \times Y$ comes with canonical projections $X \xleftarrow{p_1} X \times Y \xrightarrow{p_2} Y$ such that given morphisms $T \xrightarrow{\xi} X$ and $T \xrightarrow{v} Y$ there is a unique $T \xrightarrow{\xi \times v} X \times Y$ such that

$$\begin{array}{ccc} X & & \\ \swarrow p_1 & \nearrow \xi & \\ X \times Y & \xleftarrow{\exists! \xi \times v} & T \\ \searrow p_2 & \nwarrow v & \\ Y & & \end{array}$$

commutes.

Similarly, the coproduct $X \amalg Y$ has morphisms $X \xrightarrow{i_1} X \amalg Y \xleftarrow{i_2} Y$ such that given morphisms $X \xrightarrow{\xi} T$ and $Y \xrightarrow{v} T$ there is a unique morphism $X \amalg Y \xrightarrow{\xi \amalg v} T$ such that

$$\begin{array}{ccc} X & & \\ \searrow i_1 & \nearrow \xi & \\ X \amalg Y & \xrightarrow{\exists! \xi \amalg v} & T \\ \swarrow i_2 & \nwarrow v & \\ Y & & \end{array}$$

commutes.

Using the universal property of $X \times Y$, we get a unique morphism $X \xrightarrow{\alpha} X \times Y$ such that $p_1\alpha = \text{id}_X$, $p_2\alpha = 0$ and a unique morphism $Y \xrightarrow{\beta} X \times Y$ such that $p_1\beta = 0$ and $p_2\beta = \text{id}_Y$. Then

$$c: X \amalg Y \xrightarrow{\alpha \amalg \beta} X \times Y$$

is the morphism we are looking for. It is unique with the property that $p_1ci_1 = \text{id}_X$, $p_1ci_2 = 0$, $p_2ci_1 = 0$, and $p_2ci_2 = \text{id}_Y$.

- (c) For abelian groups and modules over a ring, both $X \amalg Y$ and $X \times Y$ are given by $\{(x, y) \mid x \in X, y \in Y\}$ with component-wise operations and $p_1(x, y) = x$, $p_2(x, y) = y$, $i_1(x) = (x, 0)$, and $i_2(y) = (0, y)$.
- (d) For an additive category \mathcal{A} , it follows that finite products $\prod_{i=1}^n X_i$ and coproducts $\coprod_{i=1}^n X_i$ (of some objects $X_1, \dots, X_n \in \text{Ob}(\mathcal{A})$) exist and are canonically isomorphic. We typically denote both by $\bigoplus_{i=1}^n X_i$ in that case.
- (e) We would like to describe the addition on $\text{Hom}_{\mathcal{A}}(X, Y)$. For a pair of morphisms $X \xrightarrow[a]{a} Y$ we denote the composition

$$X \xrightarrow{\text{id}_X \times \text{id}_X} X \oplus X \xrightarrow{a \amalg b} Y$$

by $a + b$. Then 0 is a neutral element and associativity holds, but the existence of inverse elements needs to be imposed to obtain indeed a group structure.

One can show that this is the only possible group structure behaving bilinearly under composition.

- (f) It is, however, automatically abelian. What we need to show is $(a \amalg b) \circ \Delta = (b \amalg a) \circ \Delta$ with $\Delta = \text{id}_X \times \text{id}_X$. The universal property of coproducts gives a unique $X \oplus X \xrightarrow{\sigma} X \oplus X$ such that

$$\begin{array}{ccccc}
 & X & & & \\
 i_2 \swarrow & & \searrow i_1 & a \searrow & \\
 X \oplus X & \xrightarrow[\exists! \sigma]{\Delta} & X \oplus X & \xrightarrow{a \amalg b} & Y \\
 i_1 \swarrow & & \searrow i_2 & b \searrow & \\
 & X & & &
 \end{array}$$

commutes. Then σ is easily seen to be an isomorphism and $b \amalg a = (a \amalg b) \circ \sigma$ by the uniqueness of $b \amalg a$. It thus suffices to show $\sigma\Delta = \Delta$. By the uniqueness of Δ , this is equivalent to $p_1\sigma\Delta = \text{id}_X$ and $p_2\sigma\Delta = \text{id}_X$. We claim that $p_1\sigma = p_2$ and vice versa, which would finish the proof. To see this, note that $p_1\sigma = p_2$ is equivalent to $p_1\sigma i_1 = p_2 i_1 = 0$ and $p_1\sigma i_2 = p_2 i_2 = \text{id}_X$ by the universal property of the coproduct $X \oplus X$. This follows from $\sigma i_1 = i_2$ and $\sigma i_2 = i_1$ by definition of σ .

Example. The following are additive categories.

- (a) Modules over a given ring R (in particular, abelian groups).

- (b) Sheaves of modules.
- (c) Banach spaces with bounded linear maps as morphisms. The common initial and final object is the zero space and $A \oplus B = \{(a, b) \mid a \in A, b \in B\}$ with $\max\{\|a\|, \|b\|\}$ or $\|a\| + \|b\|$ as norm (this category will turn out not to be abelian).
- (d) Free or projective modules over a ring R .

Definition 2. Let $A \xrightarrow{\alpha} B$ be a morphism in an additive category \mathcal{A} . The **kernel** $\ker(A \xrightarrow{\alpha} B)$ of α (if it exists) comes with a morphism $\ker(\alpha) \xrightarrow{\iota} A$ satisfying the universal property

$$\begin{aligned} \text{Hom}_{\mathcal{A}}\left(T, \ker\left(A \xrightarrow{\alpha} B\right)\right) &\xrightarrow{\sim} \{f \in \text{Hom}_{\mathcal{A}} \mid \alpha f = 0\} \\ \left(T \xrightarrow{\tau} A\right) &\longmapsto f = \iota \tau \end{aligned}$$

for any test object $T \in \text{Ob}(\mathcal{A})$.

Definition 2a. Similarly, the **cokernel** of α (if existent) comes with a morphism $B \xrightarrow{\pi} \text{coker}(\alpha)$ and satisfies

$$\begin{aligned} \text{Hom}_{\mathcal{A}}\left(\text{coker}\left(A \xrightarrow{\alpha} B\right), T\right) &\xrightarrow{\sim} \{g \in \text{Hom}_{\mathcal{A}}(B, T) \mid g\alpha = 0\} \\ \left(\text{coker}(\alpha) \xrightarrow{\tau} T\right) &\longmapsto g = \tau \pi \end{aligned}$$

for any test object $T \in \text{Ob}(\mathcal{A})$.

Remark 1. Kernels and cokernels in an additive category \mathcal{A} are special cases of *equalizers* and *coequalizers* (cf. [1, Definition A.3.2 and Definition A.3.4]), respectively. Indeed, we have

$$\ker\left(A \xrightarrow{\alpha} B\right) = \text{Eq}\left(A \xrightarrow[\alpha]{\alpha} B\right) \quad \text{and} \quad \text{coker}\left(A \xrightarrow{\alpha} B\right) = \text{Coeq}\left(A \xrightarrow[\alpha]{\alpha} B\right).$$

But we can reconstruct equalizers and coequalizers from kernels and cokernels via

$$\text{Eq}\left(A \xrightarrow[\beta]{\alpha} B\right) = \ker\left(A \xrightarrow{\alpha-\beta} B\right) \quad \text{and} \quad \text{Coeq}\left(A \xrightarrow[\beta]{\alpha} B\right) = \text{coker}\left(A \xrightarrow{\alpha-\beta} B\right)$$

(the minus here is the one obtained from additivity of \mathcal{A}).

Definition 3. A morphism $A \xrightarrow{i} B$ is an **effective monomorphism**, if the following equivalent conditions hold.

- (a) (In any category) We have a bijection

$$\begin{aligned} \text{Hom}_{\mathcal{A}}(T, A) &\xrightarrow{\sim} \left\{ f \in \text{Hom}_{\mathcal{A}}(T, B) \mid \begin{array}{l} \alpha f = \beta f \text{ if } B \xrightarrow[\beta]{\alpha} S \text{ is any pair of} \\ \text{morphisms such that } \alpha i = \beta i \end{array} \right\} \\ t \in \text{Hom}_{\mathcal{A}}(T, A) &\longmapsto f = it. \end{aligned}$$

- (b) (If the category has finite colimits) i is an equalizer of something.
- (c) (In additive categories with kernels and cokernels) i is the kernel of an appropriate morphism.

(d) (In additive categories with kernels and cokernels) i is the kernel of its cokernel.

Definition 3a. Dually, $A \xrightarrow{p} B$ is an **effective epimorphism** if the following equivalent conditions hold.

(a) (In any category) We have a bijection

$$\begin{aligned} \text{Hom}_{\mathcal{A}}(B, T) &\xrightarrow{\sim} \left\{ f \in \text{Hom}_{\mathcal{A}}(A, T) \mid \begin{array}{l} f\alpha = f\beta \text{ if } S \xrightarrow[\beta]{\alpha} A \text{ is any pair of} \\ \text{morphisms such that } p\alpha = p\beta \end{array} \right\} \\ t \in \text{Hom}_{\mathcal{A}}(B, T) &\longmapsto f = tp. \end{aligned}$$

(b) (If the category has finite limits) p is a coequalizer of something.

(c) (In additive categories with kernels and cokernels) p is the cokernel of an appropriate morphism.

(d) (In additive categories with kernels and cokernels) p is the cokernel of its kernel.

(e) $B^{\text{op}} \xrightarrow{p^{\text{op}}} A^{\text{op}}$ is an effective monomorphism in the dual category \mathcal{A}^{op} .

In any category, a morphism which is mono and effectively epi (or epi and effectively mono) is an isomorphism, but there are examples of morphisms which are simultaneously mono and epi but not an isomorphism (e.g. $\mathbb{Z} \hookrightarrow \mathbb{Q}$ in the category of rings). This needs to be ruled out by a definition, and that's what is happening now!

Definition 4. A category \mathcal{A} is **abelian**, if it is additive, has kernels and cokernels and such that every monomorphism is effectively mono, every epimorphism is effectively epi, and (thus) any morphism which is both a mono- and an epimorphism is an isomorphism.

Remark. (a) The three conditions on mono- and epimorphisms are not independent. The last condition, i.e. that every morphism which is both a mono- and an epimorphism is an isomorphism, follows from either of the former two.

(b) Since equalizers and coequalizers in an abelian category \mathcal{A} can be constructed from kernels and cokernels (cf. Remark 1) and we already have finite products and coproducts from additivity of \mathcal{A} , we deduce that \mathcal{A} has arbitrary finite limits and colimits. Indeed, we proved on exercise sheet #7 from Algebraic Geometry I that finite limits can be constructed from equalizers and finite products, and, given coequalizers and finite coproducts instead, it's just the same for finite colimits.

Conversely, the existence of finite limits and colimits guarantees that \mathcal{A} has equalizers, coequalizers, finite products, and finite coproducts, all of them being special cases of finite limits and colimits.

The category of modules (over a ring R) or sheaves of modules are abelian categories (as we are going to prove in a moment), but not Banach spaces or projective modules over most rings.

Proposition 1. *The category $\mathcal{R}\text{-Mod}$ of sheaves of modules (over a sheaf of rings \mathcal{R} on some topological space X) is abelian.*

For clarity (and to better distinguish between the proof and Professor Franke's remarks about it), we will chop the proof into some lemmas.

Lemma 1. *The category $\mathcal{R}\text{-Mod}$ is additive.*

Proof. First note that the zero sheaf 0 is a common initial and final object. A direct sum of $\mathcal{M}, \mathcal{N} \in \text{Ob}(\mathcal{R}\text{-Mod})$ is given by

$$(\mathcal{M} \oplus \mathcal{N})(U) = \{(m, n) \mid m \in \mathcal{M}(U), n \in \mathcal{N}(U)\} \quad \text{for all } U \subseteq X \text{ open}$$

(it's clear that this is a presheaf and it inherits the sheaf axiom from \mathcal{M} and \mathcal{N}) with component-wise module operations and with $\mathcal{M} \xleftarrow{p} \mathcal{M} \oplus \mathcal{N} \xrightarrow{q} \mathcal{N}$ and $\mathcal{M} \xrightarrow{i} \mathcal{M} \oplus \mathcal{N} \xleftarrow{j} \mathcal{N}$ given by $p(m, n) = m$, $q(m, n) = n$, $i(m) = (m, 0)$, and $j(n) = (0, n)$ on open subsets $U \subseteq X$ and $m \in \mathcal{M}(U)$, $n \in \mathcal{N}(U)$.

If $\mathcal{M} \xrightarrow{\mu} \mathcal{T} \xleftarrow{\nu} \mathcal{N}$ are given, $\mathcal{M} \oplus \mathcal{N} \xrightarrow{\mu \amalg \nu} \mathcal{T}$ sending $(m, n) \in (\mathcal{M} \oplus \mathcal{N})(U)$ to $\mu(m) + \nu(n)$ verifies the universal property of the coproduct for $\mathcal{M} \oplus \mathcal{N}$. Similarly, $\mathcal{T} \xrightarrow{\mu \times \nu} \mathcal{M} \oplus \mathcal{N}$ given by $(\mu \times \nu)(t) = (\mu(t), \nu(t))$ for $t \in \mathcal{T}(U)$ confirms the universal property of the product for $\mathcal{M} \oplus \mathcal{N}$. Also, $c = \text{id}_{\mathcal{M} \oplus \mathcal{N}}$ is the unique endomorphism c of that object such that $pci = \text{id}_{\mathcal{M}}$, $qcj = \text{id}_{\mathcal{N}}$, $pcj = 0$, and $qci = 0$. Thus, $\mathcal{R}\text{-Mod}$ is additive (the group structure on Hom sets being easily verified). *q.e.d.*

Lemma 2. *The category $\mathcal{R}\text{-Mod}$ has kernels.*

Proof. Let $\mathcal{M} \xrightarrow{f} \mathcal{N}$ be a morphism of sheaves of \mathcal{R} -modules and \mathcal{K} be the sheaf given by

$$\mathcal{K}(U) = \ker \left(\mathcal{M} \xrightarrow{f} \mathcal{N} \right)(U) := \ker \left(\mathcal{M}(U) \xrightarrow{f} \mathcal{N}(U) \right)$$

(you should convince yourself that this indeed satisfies the sheaf axiom). Then the inclusion $\mathcal{K} \xrightarrow{\kappa} \mathcal{M}$ is a monomorphism as $\mathcal{K}(U) \hookrightarrow \mathcal{M}(U)$ is injective for every open subset $U \subseteq X$.

If $\mathcal{T} \xrightarrow{\tau} \mathcal{M}$ is a morphism of \mathcal{R} -modules such that $f\tau = 0$, then, for every $t \in \mathcal{T}(U)$, we have $f(\tau(t)) = 0$, hence $\tilde{\tau}(t) := \tau(t) \in \ker \left(\mathcal{M}(U) \xrightarrow{f} \mathcal{N}(U) \right) = \mathcal{K}(U)$ and τ factors over

$$\begin{array}{ccc} \mathcal{T} & \xrightarrow{\tau} & \mathcal{M} \\ & \searrow \tilde{\tau} & \nearrow \kappa \\ & \mathcal{K} & \end{array}$$

This proves that \mathcal{K} is indeed a kernel of f in the category $\mathcal{R}\text{-Mod}$. *q.e.d.*

Remark 2. (a) It is a consequence of the exactness of the \varinjlim functor (for filtered systems of abelian groups; exactness of \varinjlim does *not* hold in general, not even for filtered colimits in abelian categories), that

$$\mathcal{K}_x = \varinjlim_{U \ni x} \ker \left(\mathcal{M}(U) \xrightarrow{f} \mathcal{N}(U) \right) \simeq \ker \left(\mathcal{M}_x \xrightarrow{f} \mathcal{N}_x \right).$$

This isomorphism can also be seen in a straightforward way.

(b) One may check that in any additive category (with kernels), a morphism i is a monomorphism iff $\ker(i) = 0$. Thus, in our example we have the equivalent conditions

- (α) $\mathcal{M} \xrightarrow{f} \mathcal{N}$ is a monomorphism.
- (β) $\mathcal{M}(U) \xrightarrow{f} \mathcal{N}(U)$ is injective for all open subsets $U \subseteq X$.
- (γ) $\ker(f) = 0$ (the zero sheaf).
- (δ) $\mathcal{M}_x \xrightarrow{f} \mathcal{N}_x$ is injective for all $x \in X$.

The construction of cokernels won't be that straightforward (duh!), related to the fact that epimorphisms in categories of sheaves aren't as simple as you might think. If \mathcal{G} and \mathcal{H} are sheaves on some topological space X and f is a morphism between them such that $\mathcal{G}(U) \xrightarrow{f} \mathcal{H}(U)$ is surjective for all open U , then f is an epimorphism, but there are epimorphisms f for which this fails.

However, it follows from the fact that a sheaf \mathcal{G} is canonically isomorphic to its sheafification \mathcal{G}^{sh} (cf. [1, Proposition 1.2.1(d)]) that a morphism between sheaves (of sets, groups, ...) is uniquely determined by the maps it induces on stalks. Thus, $\mathcal{G} \rightarrow \mathcal{H}$ is an epimorphism if $\mathcal{G}_x \rightarrow \mathcal{H}_x$ is an epimorphism in the respective target category for all $x \in X$.

Lemma 3. *The category $\mathcal{R}\text{-Mod}$ has cokernels.*

Proof. For a morphism $\mathcal{M} \xrightarrow{f} \mathcal{N}$ of sheaves of \mathcal{R} -modules, the map

$$U \mapsto \text{coker}\left(\mathcal{M}(U) \xrightarrow{f} \mathcal{N}(U)\right) = \mathcal{M}(U)/\mathcal{N}(U) \quad \text{for } U \subseteq X \text{ open}$$

defines a presheaf \mathcal{F} of \mathcal{R} -modules, but in general, \mathcal{F} will fail to be a sheaf. We put $\mathcal{C} = \mathcal{F}^{\text{sh}}$ (the *sheafification* of \mathcal{F} , cf. [1, Definition 1.2.3]) and claim that $\mathcal{N} \rightarrow \mathcal{C}$ is a cokernel of f .

Our first goal is to show that

$$\mathcal{C}_x \simeq \text{coker}\left(\mathcal{M}_x \xrightarrow{f} \mathcal{N}_x\right). \quad (*)$$

In the lecture, we did a direct proof, which was somewhat ugly and (in my opinion) lacking the essential step. From [1, Proposition 1.2.1(a)], we get that $\mathcal{C}_x \simeq \mathcal{F}_x$ (which is basically what we proved in the lecture for this particular special case), so we need to show that

$$\mathcal{F}_x = \varinjlim_{U \ni x} \text{coker}\left(\mathcal{M}(U) \xrightarrow{f} \mathcal{N}(U)\right) \simeq \text{coker}\left(\mathcal{M}_x \xrightarrow{f} \mathcal{N}_x\right).$$

Since $\mathcal{M}_x = \varinjlim_{U \ni x} \mathcal{M}(U)$ and similar for \mathcal{N}_x , this amounts to showing that cokernels and certain colimits commute. But by Remark 1, cokernels are just a special case of colimits, so what we are actually going to show is that colimits commute with colimits – in the following sense.

Lemma 4. Let $(X_{i,j})_{i \in I, j \in J}$ be objects of a category \mathcal{A} . For each $i_1, i_2 \in I$ let there be an indexing set I_{i_1, i_2} and for each $\alpha \in I_{i_1, i_2}$ and $j \in J$ a morphism

$$f_\alpha^j: X_{i_1, j} \longrightarrow X_{i_2, j}.$$

Similarly, for each $j_1, j_2 \in J$ let there be an indexing set J_{j_1, j_2} and for each $\beta \in J_{j_1, j_2}$ and $i \in I$ a morphism

$$g_\beta^i: X_{i, j_1} \longrightarrow X_{i, j_2}.$$

Moreover, suppose that for each $i_1, i_2 \in I$ and $j_1, j_2 \in J$ and $\alpha \in I_{i_1, i_2}$ and $\beta \in J_{j_1, j_2}$ the diagram

$$\begin{array}{ccc} X_{i_1, j_1} & \xrightarrow{f_\alpha^{j_1}} & X_{i_2, j_1} \\ g_\beta^{i_1} \downarrow & & \downarrow g_\beta^{i_2} \\ X_{i_1, j_2} & \xrightarrow{f_\alpha^{j_2}} & X_{i_2, j_2} \end{array} \quad (\#)$$

commutes. Then there is an isomorphism

$$\varinjlim_{i \in I} \varinjlim_{j \in J} X_{i, j} \simeq \varinjlim_{j \in J} \varinjlim_{i \in I} X_{i, j} \simeq \varinjlim_{(i, j) \in I \times J} X_{i, j}.$$

Proof. Clearly, it is enough to show the rightmost isomorphism. What we need to show is that $L := \varinjlim_j \varinjlim_i X_{i, j}$ satisfies the universal property of $L' := \varinjlim_{(i, j)} X_{i, j}$.

Let T be an object of \mathcal{A} and $(X_{i, j} \xrightarrow{\tau_{i, j}} T)_{i \in I, j \in J}$ be a cocone below the diagram $(X_{i, j})_{i, j}$. That is, for every $\alpha \in I_{i_1, i_2}$ and $j \in J$ the diagram

$$\begin{array}{ccc} X_{i_1, j} & \xrightarrow{f_\alpha^j} & X_{i_2, j} \\ & \searrow \tau_{i_1, j} & \swarrow \tau_{i_2, j} \\ & T & \end{array}$$

commutes. By the universal properties of the $L_j := \varinjlim_i X_{i, j}$, the $\tau_{i, j}$ factor over some maps $L_j \xrightarrow{\tau_j} T$. Moreover, for each $j_1, j_2 \in J$ and $\beta \in J_{j_1, j_2}$, the compositions

$$X_{i, j_1} \xrightarrow{g_\beta^i} X_{i, j_2} \longrightarrow L_{j_2}$$

induce a map $L_{j_1} \xrightarrow{g_\beta} L_{j_2}$ by the universal property of L_{j_1} (here, we silently used the commutativity of $(\#)$, otherwise the above compositions wouldn't be a cocone below $(X_{i, j})_{i \in I}$). We thus get a diagram

$$\begin{array}{ccc} X_{i, j_1} & \xrightarrow{g_\beta^i} & X_{i, j_2} \\ & \searrow & \swarrow \\ & L_{j_1} \xrightarrow{g_\beta} L_{j_2} & \\ & \searrow \tau_{j_1} & \swarrow \tau_{j_2} \\ & T & \end{array}$$

in which everything but the bottom-middle triangle commutes. We show that this triangle commutes as well. Indeed, by the universal property of L_{j_1} , τ_{j_1} is the unique morphism $L_{j_1} \rightarrow T$ making each

$$\begin{array}{ccc} X_{i,j_1} & \xrightarrow{\quad} & L_{j_1} \\ & \searrow \tau_{i,j_1} & \swarrow \\ & T & \end{array}$$

commute. But apparently, $\tau_{j_2}g_\beta$ has this property as well, proving $\tau_{j_1} = \tau_{j_2}g_\beta$. Then the morphisms $(L_j \xrightarrow{\tau_j} T)_{j \in J}$ form a cocone below the diagram $(L_j)_{j \in J}$, hence factor uniquely over some $L \xrightarrow{\tau} T$ by the universal property of L .

It remains to prove uniqueness of τ . If $L \xrightarrow{\tau} T$ is a morphism over which each $X_{i,j} \xrightarrow{\tau_{i,j}} T$ factors, then the composition $L_j \rightarrow L \xrightarrow{\tau} T$ must equal τ_j since τ_j is uniquely determined by the universal property of L_j . But τ is uniquely determined by the τ_j , proving uniqueness. *q.e.d.*

Having thus proved (*), we now proceed with the proof of Lemma 3. We have a morphism $\mathcal{N} \rightarrow \mathcal{C}$ sending $n \in \mathcal{N}(U)$ to

$$\left(\text{image of } n \text{ under } \mathcal{N}(U) \longrightarrow \mathcal{N}_x \longrightarrow \text{coker} \left(\mathcal{M}_x \xrightarrow{f} \mathcal{N}_x \right) \right)_{x \in U}.$$

Since $\mathcal{C}_x \simeq \text{coker} \left(\mathcal{M}_x \xrightarrow{f} \mathcal{N}_x \right)$, this morphism $\mathcal{N} \rightarrow \mathcal{C}$ induces surjections on stalks, hence is an epimorphism of sheaves. We show that the morphism $\mathcal{N} \rightarrow \mathcal{C}$ satisfies the universal property of the cokernel.

Let $\mathcal{N} \xrightarrow{\tau} \mathcal{T}$ be a morphism of sheaves of \mathcal{R} -modules such that $\tau f = 0$. Let $U \subseteq X$ be open. For

$$\nu = (\nu_x)_{x \in U} \in \mathcal{C}(U) \subseteq \prod_{x \in U} \text{coker} \left(\mathcal{M}_x \xrightarrow{f} \mathcal{N}_x \right)$$

we define $\tau_1(\nu) \in \prod_{x \in U} \mathcal{T}_x$ by selecting $n \in \mathcal{N}_x$ whose image in $\text{coker} \left(\mathcal{M}_x \xrightarrow{f} \mathcal{N}_x \right)$ equals ν_x , then put $\tau_1(\nu)_x = \tau(n)_x$ which is independent of the choice of n as $\tau f = 0$. It follows from the coherence condition for \mathcal{C} that $\tau_1(\nu)$ satisfies the coherence condition for \mathcal{T}^{sh} , i.e. $\tau_1(\nu) \in \mathcal{T}^{\text{sh}}(U) \subseteq \prod_{x \in U} \mathcal{T}_x$. Hence there is $\mathcal{C} \xrightarrow{\tau_2} \mathcal{T}$ such that $\tau_1 = (\mathcal{T} \xrightarrow{\sim} \mathcal{T}^{\text{sh}}) \circ \tau_2$ and τ_2 makes

$$\begin{array}{ccc} \mathcal{N} & \xrightarrow{\tau} & \mathcal{T} \\ & \searrow \tau_2 & \swarrow \\ & \mathcal{C} & \end{array}$$

commutative. Uniqueness of τ_2 is easy to see stalk-wise. It follows that $\mathcal{N} \rightarrow \mathcal{C}$ is indeed a cokernel of f . *q.e.d.*

Remark 3. One may check that in any additive category (with cokernels) a morphism f is an epimorphism if $\text{coker}(f) = 0$. By our previous construction of cokernels and the description of stalks, we have equivalent conditions

- (a) $\mathcal{M} \xrightarrow{f} \mathcal{N}$ is an epimorphism of sheaves of \mathcal{R} -modules.
- (b) $\mathcal{M}_x \xrightarrow{f} \mathcal{N}_x$ is surjective for all $x \in X$.
- (c) For every open $U \subseteq X$ and $n \in \mathcal{N}(U)$ there are an open covering $U = \bigcup_{\lambda \in \Lambda} U_\lambda$ and $m_\lambda \in \mathcal{M}(U_\lambda)$ such that $n|_{U_\lambda} = f(m_\lambda)$

...but (c) does *not* imply the surjectivity of $\mathcal{M}(U) \xrightarrow{f} \mathcal{N}(U)$, unless, e.g., f is also a monomorphism.

Proof of Proposition 1. We verify the rest of the abelianness conditions. First, let $\mathcal{M} \xrightarrow{f} \mathcal{N}$ be a mono- and epimorphism. Then it induces isomorphisms on stalks (by Remark 2(b) and Remark 3), hence is an isomorphism itself.

Let $\mathcal{M} \xrightarrow{i} \mathcal{N}$ be a monomorphism and $\mathcal{N} \rightarrow \mathcal{C}$ be its cokernel. Then

$$\ker(\mathcal{N} \rightarrow \mathcal{C})_x = \ker(\mathcal{N}_x \rightarrow \mathcal{C}_x) = \ker\left(\mathcal{N}_x \rightarrow \text{coker}\left(\mathcal{M}_x \xrightarrow{i} \mathcal{N}_x\right)\right) \simeq \mathcal{M}_x$$

as $\mathcal{M}_x \xrightarrow{i} \mathcal{N}_x$ is injective. Hence $\mathcal{M} \rightarrow \ker(\mathcal{N} \rightarrow \mathcal{C})$ induces isomorphisms on stalks and thus is an isomorphism itself. It follows by Definition 3(d) that any monomorphism is an effective monomorphism.

Similar arguments apply to epimorphisms. *q.e.d.*

Recall the definition of an adjoint pair of functors.

Definition 5 ([1, Definition A.2.3]). Let \mathcal{A}, \mathcal{B} be categories. A pair $\mathcal{A} \xrightleftharpoons[R]{L} \mathcal{B}$ of (covariant) functors is called **adjoint**, if there is a canonical bijection

$$\text{Hom}_{\mathcal{A}}(X, RY) \xrightarrow{\sim} \text{Hom}_{\mathcal{B}}(LX, Y)$$

which is functorial in both $X \in \text{Ob}(\mathcal{A})$ and $Y \in \text{Ob}(\mathcal{B})$.

Remark 4. It can be easily seen that L preserves colimits (in particular, coproducts, and in particular again, initial objects) and R preserves limits (in particular, products, and in particular again, final objects). When \mathcal{A} and \mathcal{B} are additive, it follows that both L and R map 0 to 0 and are compatible with finite direct sums. Moreover, L preserves cokernels and R preserves kernels since these are special cases of colimits and limits, respectively (in particular, I have no idea what the purpose of Franke's extra calculation was).

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