

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* [AG1] 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 ([AG1, Definitions 1.5.2 and 1.5.9(b)]). (a) A **prescheme** (Professor Franke prefers “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 $T \xrightarrow[a]{b} X$, the equalizer $\text{Eq}\left(T \xrightarrow[a]{b} X\right)$ 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. [AG1, 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 [AG1, 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 ([AG1, 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 ([AG1, 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 ([AG1, 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 [AG1, 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. [AG1, 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 ([AG1, 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 [AG1, Fact 2.1.1] for quasi-compactness and in [AG1, 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 [AG1, 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-coherentntness, this follows for all preschemes X .

Closedness under taking kernels was proved in [AG1, 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

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

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 [AG1, 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 [AG1, 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. [AG1, 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** $\check{C}^\bullet(\mathcal{U}, \mathcal{M})$ 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** $\check{H}^\bullet(\mathcal{U}, \mathcal{M})$ is defined as the cohomology of the Čech complex, i.e.,

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

To see that $\check{C}^\bullet(\mathcal{U}, \mathcal{M})$ 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 $\check{C}^\ell(\mathcal{U}, \mathcal{M}) \xrightarrow{d_\ell} \check{C}^{\ell+1}(\mathcal{U}, \mathcal{M})$ be given by

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

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 $(d_m d_\ell \psi)_i = \psi_j|_{U_i}$, 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^\bullet be any family of abelian groups (or objects of an abelian category) and $C^\ell \xrightarrow{d_\ell} C^{\ell+1}$ morphisms for $\ell = 0, \dots, n+1$. Suppose that $C^n = 0$ for $n < 0$ and that (2) holds. Then d^\bullet with

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

satisfies $d^{n+1}d^n = 0$. Indeed,

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

as required. *q.e.d.*

Remark. Our program is to show that $\check{H}^\bullet(\mathcal{U}, \mathcal{M})$ 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 $\check{C}^\bullet(\mathcal{U}, \mathcal{M})$.

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. $\check{C}_{\text{alt}}^\bullet(\mathcal{U}, \mathcal{M}) \subseteq \check{C}^\bullet(\mathcal{U}, \mathcal{M})$ 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 $\check{C}_{\text{alt}}^\bullet(\mathcal{U}, \mathcal{M})$ is indeed a subcomplex of $\check{C}^\bullet(\mathcal{U}, \mathcal{M})$ 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 $\check{H}_{\text{alt}}^i(\mathcal{U}, \mathcal{M}) = H^i(\check{C}_{\text{alt}}^\bullet(\mathcal{U}, \mathcal{M}))$ 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 $\check{C}^\bullet(\mathcal{U}_0, \mathcal{M})$ has the form

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

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

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

and, more general,

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

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

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

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

and

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

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

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

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

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

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*

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

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 $\check{H}^n(\mathcal{U}, \mathcal{M}) = 0$ 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 $\check{C}_{\text{alt}}^\bullet(-, \mathcal{M}) \subseteq \check{C}^\bullet(-, \mathcal{M})$. However, Corollary 1(c) for $\check{H}_{\text{alt}}^\bullet(\mathcal{U}, \mathcal{M})$ can still be obtained, using the *cochain contraction* $h: \check{C}^\bullet(\mathcal{U}, \mathcal{M}) \rightarrow \check{C}^\bullet(\mathcal{U}, \mathcal{M})$, 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 $\check{C}_{\text{alt}}^\bullet(\mathcal{U}, \mathcal{M}) \subseteq \check{C}^\bullet(\mathcal{U}, \mathcal{M})$. 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*

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

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

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

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

(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 $\check{C}^\bullet(f^{-1}(\mathcal{U}), \mathcal{F})$ and $\check{C}^\bullet(\mathcal{U}, f_*\mathcal{F})$ 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. [AG1, 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 $\check{H}_{\text{alt}}^\bullet(\mathcal{V}, \mathcal{M})$ 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*

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

are isomorphisms compatible with the (iso)morphisms $\check{H}^\bullet(\mathcal{U}, \mathcal{M}) \xrightarrow{\tau_{\mathcal{U}, \mathcal{V}}} \check{H}^\bullet(\mathcal{V}, \mathcal{M})$ 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-compact scheme.*

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

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

then \mathcal{K} 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*

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

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

Remark. The structure of an $\mathcal{O}_X(X)$ -module on $\check{C}^\bullet(\mathcal{U}, \mathcal{M})$ 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 $\check{C}^\bullet(\mathcal{U}, \mathcal{M})$, 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*

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

Proof. Follows from Lemma 3. Note that the open subset $X \setminus V(f) \subseteq X$ is a scheme again by [AG1, Fact 1.5.9(c)] and quasi-compact by [AG1, 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^\bullet defined as a derived functor on $\mathcal{O}_X\text{-Mod}$.

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 [AG1, 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 $\text{QCoh}(X)$ 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 $\mathcal{M} \subseteq \mathcal{O}_X^{\oplus n}$ 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 $\mathcal{O}_X^{\oplus n-1}(U)$ is identified with $\{(f_1, \dots, f_{n-1}, 0) \in \mathcal{O}_X(V)^n\} \subseteq \mathcal{O}_X(U)^n$, then $\mathcal{M}' = \mathcal{M} \cap \mathcal{O}_X^{\oplus n-1}$ 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 [AG1, 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 $\mathcal{O}_X \xrightarrow{\cdot f_i} \mathcal{O}_X$ given by multiplication with f_i and let $f: \mathcal{O}_X^{\oplus n} \rightarrow \mathcal{O}_X$ 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 quasi-compact scheme and $Z \subseteq X$ a closed subset which is Noetherian as topological space. 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 $H^p(X, \mathcal{M}) = 0$.*

Remark. Grothendieck shows $H^p(Z, \mathcal{G}) = 0$ when Z is a Noetherian topological space, \mathcal{G} a sheaf of abelian groups on it and $p > \dim(Z)$. This, however, requires the construction of H^p as a derived functor.

In our situation, the bound may fail to be sharp.

Proof of Proposition 1. There is nothing to show if $\dim(Z) = \pm\infty$, 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 $\dim(Z_i) = 0$.

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 $d = \dim(Z)$ be finite and the assertion be proved for quasi-coherent \mathcal{M} supported on closed subsets of smaller Krull dimension. Let $Z = \bigcup_{i=1}^n Z_i$ be the decomposition into irreducible components Z_i . Then $Z_i \setminus \bigcup_{j \neq i} Z_j$ is non-empty, as $Z_i \subseteq Z_j$ otherwise by irreducibility of Z_i . Hence we find affine open subsets $W_i \subseteq X$ such that W_i intersects Z_i but no Z_j for $j \neq i$.

Let $\mathcal{N}_i = (j_i)_*\mathcal{M}|_{W_i}$ where $W_i \xrightarrow{j_i} X$ is the inclusion of the open subset $W_i \subseteq X$ and let $\mathcal{N} = \bigoplus_{i=1}^n \mathcal{N}_i$. We consider the morphism $\mathcal{M} \rightarrow \mathcal{N}$ given by

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

As was seen in Corollary 1.2.3(b), $H^p(X, \mathcal{N}) = 0$ when $p > 0$ and also $\mathcal{M} \rightarrow \mathcal{N}$ is a monomorphism outside $\tilde{X} = X \setminus \bigcup_{i=1}^n W_i$ (well, this is the same construction as in Claim 1.2.2). Let $\tilde{Z} = Z \cap \tilde{X}$. We have $\mathcal{M}|_{X \setminus Z} = 0 = \mathcal{N}|_{X \setminus Z}$, hence $\mathcal{M} \rightarrow \mathcal{N}$ is also a monomorphism outside Z , hence a monomorphism outside \tilde{Z} . We claim:

Claim 1. The morphism $\mathcal{M} \rightarrow \mathcal{N}$ is also an epimorphism outside \tilde{Z} .

Assuming this for the moment, we have an exact sequence

$$0 \longrightarrow \mathcal{K} \longrightarrow \mathcal{M} \longrightarrow \mathcal{N} \longrightarrow \mathcal{C} \longrightarrow 0 \quad (\S)$$

(with $\mathcal{K} = \ker(\mathcal{M} \rightarrow \mathcal{N})$ and $\mathcal{C} = \operatorname{coker}(\mathcal{M} \rightarrow \mathcal{N})$), where \mathcal{K} and \mathcal{C} vanish outside \tilde{Z} . Since W_i intersects Z_i , we have $Z_i \not\subseteq \tilde{X}$, hence no irreducible component of Z is contained in \tilde{Z} and we obtain $\dim(\tilde{Z}) < \dim(Z) = d$. If $d = 0$, this implies $\tilde{Z} = 0$, hence $\mathcal{M} \simeq \mathcal{N}$ has vanishing cohomology in positive degrees. Otherwise, the induction assumption implies $H^p(X, \mathcal{K}) = 0 = H^p(X, \mathcal{C})$ when $p \geq d$. We split (§) into $0 \rightarrow \mathcal{B} \rightarrow \mathcal{N} \rightarrow \mathcal{C} \rightarrow 0$ and $0 \rightarrow \mathcal{K} \rightarrow \mathcal{M} \rightarrow \mathcal{B} \rightarrow 0$, where $\mathcal{B} = \ker(\mathcal{N} \rightarrow \mathcal{C})$ which is also the image of $\mathcal{M} \rightarrow \mathcal{N}$. These give

$$\dots \longrightarrow H^{p-1}(X, \mathcal{C}) \longrightarrow H^p(X, \mathcal{B}) \longrightarrow H^p(X, \mathcal{N}) \longrightarrow \dots,$$

hence $H^p(X, \mathcal{B}) = 0$ when $p > d$, and then

$$\dots \longrightarrow H^p(X, \mathcal{K}) \longrightarrow H^p(X, \mathcal{M}) \longrightarrow H^p(X, \mathcal{B}) \longrightarrow \dots,$$

implying $H^p(X, \mathcal{M}) = 0$ when $p > d$. The vanishing assertion follows.

It remains to prove Claim 1 that $\mathcal{C}|_{X \setminus \tilde{Z}}$ vanishes. For this, we use that

$$(\mathcal{N}_i)_x \simeq \begin{cases} \mathcal{M}_x & \text{if } x \in Z_i \cap W_i \\ 0 & \text{if } x \notin Z_i \end{cases}. \quad (\%)$$

When $x \in Z$ this implies $\mathcal{N}_x = 0$, hence $\mathcal{M}_x \rightarrow \mathcal{N}_x$ is surjective. When $x \in Z \setminus \tilde{Z}$, then $x \in Z \cap W_i$ for some i , hence $x \in Z_i$ since W_i doesn't intersect Z_j for $j \neq i$. Thus

$$(\mathcal{N}_j)_x \simeq \begin{cases} \mathcal{M}_x & \text{if } j = i \\ 0 & \text{else} \end{cases}$$

by $(\%)$ and $\mathcal{M}_x \xrightarrow{\sim} \mathcal{N}_x$. To see $(\%)$, note that $\mathcal{N}_i(U) = \mathcal{M}(U)$ when $U \subseteq W_i$ and $x \in Z_i \cap W_i$, hence $(\mathcal{N}_i)_x \simeq \mathcal{M}_x$ in this case. Suppose $x \notin Z_i$. When $x \notin W_i$, then clearly $(\mathcal{N}_i)_x = 0$. When $x \in W_i \setminus Z_i$, then also $x \notin Z$ as W_i doesn't intersect the other irreducible components, hence $(\mathcal{N}_i)_x = 0$ follows from the fact that $\mathcal{M}|_{X \setminus Z} = 0$. *q.e.d.*

1.5. Cohomology of morphisms and functorial properties of cohomology

Let $X \xrightarrow{f} Y$ be a quasi-compact and separated morphism of preschemes. The set \mathcal{B} of quasi-compact open subsets $U \subseteq Y$ which are schemes form a topology base on Y (well, it contains all affine open subsets). By well-known properties of quasi-compact and of separated morphisms, $f^{-1}(U)$ is a quasi-compact scheme when $U \in \mathcal{B}$ (quasi-compactness is just Definition 1.1.5 and $f^{-1}(U) \rightarrow \text{Spec } \mathbb{Z}$ is separated as the composition of the separated morphisms f and $U \rightarrow \text{Spec } \mathbb{Z}$, cf. [AG1, Fact 1.5.7(c)]). We thus have for any quasi-coherent \mathcal{O}_X -module \mathcal{M} a presheaf

$$\Phi^p \mathcal{M}: U \mapsto H^p(f^{-1}(U), \mathcal{M}) \quad (*)$$

on \mathcal{B} . The presheaf structure on $(*)$ is defined as follows. Let $V \subseteq U$ be elements of \mathcal{B} and \mathcal{U}, \mathcal{V} the covers of $f^{-1}(U)$ and $f^{-1}(V)$ by their affine open subsets. Then the morphism of restricting to the intersection with $f^{-1}(V)$ gives $\check{C}^\bullet(\mathcal{U}, \mathcal{M}) \rightarrow \check{C}^\bullet(\mathcal{U} \cap f^{-1}(V), \mathcal{M})$ which may be followed by any morphism $\check{C}^\bullet(\mathcal{U} \cap f^{-1}(V), \mathcal{M}) \rightarrow \check{C}^\bullet(\mathcal{V}, \mathcal{M})$ coming from a refinement map for the pair $(\mathcal{V}, \mathcal{U} \cap f^{-1}(V))$ (we proved in Lemma 1.2.1(c) that any two refinement maps induce the same morphism on cohomology, so this choice doesn't matter), which gives

$$H^p(f^{-1}(U), \mathcal{M}) = \check{H}^p(\mathcal{U}, \mathcal{M}) \longrightarrow \check{H}^p(\mathcal{V}, \mathcal{M}) = H^p(f^{-1}(V), \mathcal{M}),$$

and this is the desired presheaf structure.

Definition 1. Sheafifying $\Phi^p \mathcal{M}$ gives an \mathcal{O}_Y -module called the p^{th} **direct image** of \mathcal{M} under f and denoted $R^p f_* \mathcal{M}$.

We have a morphism

$$H^p(f^{-1}(U), \mathcal{M}) \longrightarrow R^p f_* \mathcal{M}(U) = H^0(U, R^p f_* \mathcal{M}) \quad (1)$$

(for $U \in \mathcal{B}$) as a special case of the morphism from a presheaf to its sheafification.

Proposition 1. *Let $X \xrightarrow{f} Y$ is a quasi-compact and separated morphism of preschemes and \mathcal{M} a quasi-coherent \mathcal{O}_X -module.*

- (a) $R^0 f_* \mathcal{M} \simeq f_* \mathcal{M}$ canonically.
- (b) The \mathcal{O}_X -modules $R^p f_* \mathcal{M}$ are quasi-coherent.
- (c) 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 a long exact cohomology sequence

$$\begin{array}{ccccccc} 0 & \longrightarrow & f_* \mathcal{M}' & \longrightarrow & f_* \mathcal{M} & \longrightarrow & f_* \mathcal{M}'' \\ & & \uparrow \wr & & \uparrow \wr & & \uparrow \wr \\ 0 & \longrightarrow & R^0 f_* \mathcal{M}' & \longrightarrow & R^0 f_* \mathcal{M} & \longrightarrow & R^0 f_* \mathcal{M}'' \xrightarrow{\delta} R^1 f_* \mathcal{M}' \longrightarrow \dots \\ & & & & & & \dots \longrightarrow R^{p-1} f_* \mathcal{M}'' \xrightarrow{\delta} R^p f_* \mathcal{M}' \longrightarrow R^p f_* \mathcal{M} \longrightarrow R^p f_* \mathcal{M}'' \xrightarrow{\delta} \dots \end{array}$$

- (d) When $U \subseteq Y$ is affine, (1) becomes an isomorphism $H^p(f^{-1}(U), \mathcal{M}) \xrightarrow{\sim} R^p f_* \mathcal{M}(U)$.

Proof. Part (a). We have $\Phi^0(U) = H^0(f^{-1}(U), \mathcal{M}) \simeq \mathcal{M}(f^{-1}(U)) = f_* \mathcal{M}(U)$, hence $\Phi^0 \simeq f_* \mathcal{M}|_{\mathcal{B}}$. Then sheafifying gives $f_* \mathcal{M}$ again by [AG1, Proposition 1.2.1(c),(d)].

Part (c). By Theorem 1 we have a similar long exact cohomology sequence of presheaves on \mathcal{B} . Sheafifying it gives the desired sequence, as sheafification is an exact functor (exactness may be tested on stalks and sheafification preserves stalks by [AG1, Proposition 1.2.1(a)]).

It is easy to see that our construction of $R^p f_*$ is base-local, i.e.,

$$R^p f_* \mathcal{M}|_U \simeq R^p \left(f|_{f^{-1}(U)} \right)_* \mathcal{M}|_{f^{-1}(U)}.$$

Thus we may assume $Y = \text{Spec } R$ to be affine (quasi-coherentness is a local property) for (b) and $Y = U = \text{Spec } R$ in (d).

Let $\mathcal{B} = \{U \subseteq Y \mid U \text{ open and a quasi-compact scheme}\}$ the topology base on which Φ^p is defined, then $\tilde{\mathcal{B}} = \{Y \setminus V(\lambda) \mid \lambda \in R\}$ is another topology base of Y , and $(\mathcal{G}|_{\tilde{\mathcal{B}}})^{\text{sh}} = \mathcal{G}^{\text{sh}}$ for any presheaf \mathcal{G} on \mathcal{B} by [AG1, Proposition 1.2.1(c)]. But for $U = Y \setminus V(\lambda) \in \tilde{\mathcal{B}}$ we have

$$H^p(f^{-1}(U), \mathcal{M}) = H^p(f^{-1}(Y \setminus V(\lambda)), \mathcal{M}) = H^p(X \setminus V(f^* \lambda), \mathcal{M}) \simeq H^p(X, \mathcal{M})_{f^* \lambda} = M_\lambda$$

by Proposition 1.2.3, where we consider $M = H^p(X, \mathcal{M})$ as an $R = \mathcal{O}_Y(Y)$ -module via $f^*: \mathcal{O}_Y(Y) \rightarrow f_* \mathcal{O}_X(Y) = \mathcal{O}_X(X)$. We also used $f^{-1}(Y \setminus V(\lambda)) = X \setminus V(f^* \lambda)$ as f is a morphism of locally ringed spaces (cf. [AG1, Definition 1.3.4(b)]). It follows that $R^p f_* \mathcal{M}$ is canonically isomorphic to the sheafification of $U \setminus V(\lambda) \mapsto M_\lambda$, which is just \tilde{M} by definition of the twiddelization ([AG1, Definition 1.5.1], actually). As \tilde{M} is a quasi-coherent \mathcal{O}_Y -module, (b) follows. Then $M \simeq \tilde{M}(Y)$, which shows (d). *q.e.d.*

In general, the morphism (1) fails to be an isomorphism: The *restriction to fibres* (for Y a quasi-compact scheme)

$$H^p(X, \mathcal{M}) \longrightarrow R^p f_* \mathcal{M} = E_2^{0,p} \quad (2)$$

as a special case of (1) is normally not an isomorphism when Y is not affine. There is another morphism, the *pull-back* (for Y again a quasi-compact scheme)

$$E_2^{p,0} = H^p(Y, f_* \mathcal{M}) \longrightarrow H^p(X, \mathcal{M}) \quad (3)$$

(also not an isomorphism unless f is affine) which can be constructed as follows. Let \mathcal{U}_Y be the open cover of Y by its affine subsets and \mathcal{V} any affine refinement of $f^{-1}(\mathcal{U}_Y)$. Then, using Lemma 1.2.2(b) and Proposition 1.2.2(a) we obtain

$$H^p(Y, f_* \mathcal{M}) = \check{H}^p(\mathcal{U}_Y, f_* \mathcal{M}) = \check{H}^p(f^{-1}(\mathcal{U}_Y), \mathcal{M}) \longrightarrow \check{H}^p(\mathcal{V}, \mathcal{M}) \xleftarrow{\sim} H^p(X, \mathcal{M})$$

defining the above pull-back morphism (3).

There is also an inverse image functor $f^*: \mathcal{O}_Y\text{-Mod} \rightarrow \mathcal{O}_X\text{-Mod}$ which preserves quasi-coherence and is left-adjoint to f_* ¹. Thus, for \mathcal{N} a quasi-coherent \mathcal{O}_Y -module, there is a canonical morphism $\mathcal{N} \rightarrow f_* f^* \mathcal{M}$ which gives another type of pull-back morphism

$$H^p(Y, \mathcal{N}) \longrightarrow H^p(Y, f_* f^* \mathcal{N}) \xrightarrow{(3)} H^p(X, f^* \mathcal{N}) .$$

In general, (2) and (3) will fail to be isomorphisms but are part of the *Leray spectral sequence*

$$E_2^{p,q} = H^p(Y, R^q f_* \mathcal{M}) \implies H^{p+q}(X, \mathcal{M})$$

converging “to $H^{p+q}(X, \mathcal{M})$ ” (actually to some limit filtration of this).

This means the following: One has a sequence $(E_k^{\bullet,\bullet})_{k=2}^\infty$ of doubly graded abelian groups (or R -modules or objects of any other abelian category) equipped with morphisms (the *differentials*) $d_k = d_k^{p,q}: E_k^{p,q} \rightarrow E_k^{p+k, q+1-k}$ such that

$$E_k^{p,q} \xrightarrow{d_k} E_k^{p+k, q+1-k} \xrightarrow{d_k} E_k^{p+2k, q+1-2k}$$

vanishes and such that $E_{k+1}^{\bullet,\bullet} = H^\bullet(E_k^{\bullet,\bullet}, d_k^{\bullet,\bullet})$ in the sense that

$$E_{k+1}^{p,q} = \ker \left(E_k^{p,q} \xrightarrow{d_k} E_k^{p+k, q+1-k} \right) / \text{Im} \left(E_k^{p-k, q+k-1} \xrightarrow{d_k} E_k^{p,q} \right) . \quad (\eta)$$

Thus $E_k^{p,q} = 0$ for all $k \geq 2$ when $E_2^{p,q} = 0$. When $E_2^{\bullet,\bullet}$ is supported in the 1st quadrant (i.e., $E_2^{p,q} = 0$ if $p < 0$ or $q < 0$), the same is true for all $E_k^{\bullet,\bullet}$ and (η) becomes

$$E_{k+1}^{p,q} = \text{coker} \left(E_k^{p-k, q+k-1} \xrightarrow{d_k} E_k^{p,q} \right) \quad \text{for } k > q + 1 \quad (\eta')$$

¹ We constructed f^* on exercise sheet #10 of Algebraic Geometry I, and also proved the relevant properties there. It is given by $f^* \mathcal{M} = f^\sharp \mathcal{M} \otimes_{f^\sharp \mathcal{O}_Y} \mathcal{O}_X$, where f^\sharp is constructed as in [AG1, Remark 1.2.4].

EDIT: Eventually, Professor Franke realized he can no longer procrastinate defining sheaf inverse images. Have a look at Remark 2.3.1.

and

$$E_{k+1}^{p,q} = \ker \left(E_k^{p,q} \xrightarrow{d_k} E_k^{p+k, q-k+1} \right) \quad \text{for } k > p \quad (\eta'')$$

and we deduce $E_{k+1}^{p,q} = E_k^{p,q}$ for $k > \max\{p, q+1\}$.

For 1st quadrant sequences (like Leray's) we put $E_\infty^{p,q} = E_k^{p,q}$ where k is large enough. When the spectral sequence *converges to some filtration on its limit* L^\bullet (we have $L^\bullet = H^\bullet(X, \mathcal{M})$ for Leray), it is meant that there is a filtration $F^\bullet L^\bullet: L^\bullet = F^0 L^\bullet \supseteq F^1 L^\bullet \supseteq \dots$ with $E_\infty^{p,q} \simeq F^p L^{p+q} / F^{p+1} L^{p+q}$. Thus, for 1st quadrant sequences,

$$F^1 L^p = \ker \left(L^p \longrightarrow E_\infty^{0,p} \right) = \ker \left(L^p \longrightarrow E_2^{p,q} \right)$$

(where we use $E_\infty^{0,p} \subseteq E_2^{0,p}$ by (η'')) has (2) as a special case. Also, using $F^{p+1} L^p = 0$ for 1st quadrant sequences we obtain an epimorphism

$$F^p L^p \simeq E_\infty^{p,q} \twoheadrightarrow E_2^{p,0}$$

by (η') . The resulting morphism $E_2^{p,0} \rightarrow L^p$ has (3) as a special case.

There is also a Leray spectral sequence $R^p g_* R^q f_* \mathcal{M} \Rightarrow R^{p+q}(gf)_* \mathcal{M}$.

1.6. Affine morphisms and the relative **Spec** functor

Proposition 1. *Let $X \xrightarrow{f} Y$ be a morphism of preschemes, then the following conditions are equivalent.*

- (a) *If $U \subseteq Y$ is an affine open subset, then so is $f^{-1}(U) \subseteq X$.*
- (b) *It is possible to cover Y by affine open U such that $f^{-1}(U)$ is affine open.*

When X is, in addition, quasi-separated, this is moreover equivalent to

- (c) *f is separated and quasi-compact and we have $R^p f_* \mathcal{M} = 0$ when \mathcal{M} is a quasi-coherent \mathcal{O}_X -module and $p > 0$.*

Proof. An unconditional proof of $(a) \Leftrightarrow (b)$ was given in [AG1, Lemma 2.5.1].

The implication $(a) \Rightarrow (b)$ is trivial. For $(b) \Rightarrow (c)$, it is obvious that f is quasi-compact and separatedness was proved in [AG1, Fact 2.6.1]. To show $R^p f_* \mathcal{M} = 0$, note that if $U \subseteq Y$ is affine open such that $f^{-1}(U)$ is affine and $\lambda \in \mathcal{O}_X(U)$, then $f^{-1}(U \setminus V(\lambda)) = f^{-1}(U) \setminus V(f^* \lambda)$ is affine as well. In particular, the $U \subseteq Y$ such that $f^{-1}(U)$ is affine form a topology base on Y . By Theorem 1(b) and Proposition 1.5.1(b), $\Phi^p \mathcal{M}$ thus vanishes on a topology base of Y . Hence $R^p f_* \mathcal{M} = 0$ as the sheafification of $\Phi^p \mathcal{M}$. In particular, we didn't need the additional assumption.

Now for $(c) \Rightarrow (a)$ assuming that X is quasi-separated. If $U \subseteq Y$ is affine and $\mathcal{M} \in \text{Ob}(\text{QCoh}(f^{-1}(U)))$, then \mathcal{M} extends to X by Lemma 1 and by Proposition 1.5.1(d)

$$H^p \left(f^{-1}(U), \mathcal{M} \right) \simeq R^p f_* \mathcal{M}(U) = 0.$$

By Serre's affinity criterion (Proposition 1.3.1), $f^{-1}(U)$ is affine.

q.e.d.

Lemma 1. *Let X be a quasi-separated prescheme and \mathcal{N} a quasi-coherent \mathcal{O}_U -module for some quasi-compact open subset $U \subseteq X$. Then there is a quasi-coherent \mathcal{O}_X -module \mathcal{M} such that $\mathcal{M}|_U \simeq \mathcal{N}$.*

Proof. The open immersion $U \xhookrightarrow{j} X$ is quasi-separated (in fact, separated as is any monomorphism between preschemes, cf. [AG1, Fact 1.5.7(a)]) and quasi-compact since X is quasi-separated and U is quasi-compact. Hence $\mathcal{M} = j_*\mathcal{N}$ is quasi-coherent by Proposition 1.1.2 and $\mathcal{M}|_U \simeq \mathcal{N}$. *q.e.d.*

Definition 1. (a) A morphism $X \xrightarrow{f} Y$ between preschemes is called **affine** if it satisfies the equivalent conditions from Proposition 1(a) and (b).

(b) It is called **finite** if in addition for any affine open $U \subseteq Y$, $\mathcal{O}_X(f^{-1}(U))$ is a finitely generated $\mathcal{O}_Y(U)$ -module, or, equivalently, if this holds for sufficiently many U to cover Y (by Lemma 1.1.1).

Remark. In other words, f is finite iff f is affine and $f_*\mathcal{O}_X$ is a locally finitely generated \mathcal{O}_Y -module in the sense of Definition 1.1.6(a). If Y is Noetherian, this is equivalent to f being affine and $f_*\mathcal{O}_X$ a *coherent* \mathcal{O}_Y -module in the sense of Definition 1.1.6(b).

Corollary 1. *If $X \xrightarrow{f} Y$ is an affine morphism and \mathcal{M} a quasi-coherent \mathcal{O}_X -module, then $R^p f_*\mathcal{M} = 0$ when $p > 0$. When Y is a quasi-compact scheme, the morphism*

$$H^p(Y, f_*\mathcal{M}) \xrightarrow{(1.5.3)} H^p(X, \mathcal{M})$$

is an isomorphism.

Proof. The first assertion follows from the fact that $R^p f_*\mathcal{M}$ is the sheafification of $U \mapsto H^p(f^{-1}(U), \mathcal{M})$, which vanishes on the topology base of affine open subsets $U \subseteq Y$ when $p > 0$ by Theorem 1(b).

When Y is a quasi-compact scheme, then X is a scheme as well since $X \rightarrow \operatorname{Spec} \mathbb{Z}$ is separated as the composition of the separated morphisms f and $Y \rightarrow \operatorname{Spec} \mathbb{Z}$. Also, X is quasi-compact as f and Y are quasi-compact. Let \mathcal{U}_Y be the open cover of Y by its affine open subsets, then

$$H^p(Y, f_*\mathcal{M}) \simeq \check{H}^p(\mathcal{U}_Y, f_*\mathcal{M}) \simeq \check{H}^p(f^{-1}(\mathcal{U}_Y), \mathcal{M}) \simeq H^p(X, \mathcal{M})$$

(which was our description of (1.5.3)) where the last isomorphism holds as f is affine, hence $f^{-1}(\mathcal{U})$ is an affine open cover of X .

This proves the second assertion under the assumptions which we constructed the relevant cohomology groups. *q.e.d.*

Remark. Using the general derived functor construction it follows from the Leray spectral sequence

$$E_2^{p,q} = H^p(X, R^q f_*\mathcal{M}) \implies H^{p+q}(Y, \mathcal{M})$$

and the vanishing of $R^q f_*\mathcal{M}$ when $q > 0$, \mathcal{M} is quasi-coherent and f affine.

Let X be any prescheme. Recall the construction of the $\mathbf{Spec}_X(-)$ functor from [AG1, Subsection 2.5.1], which is given as follows. When \mathcal{A} is a quasi-coherent \mathcal{O}_X -algebra, one has schemes $\mathbf{Spec} \mathcal{A}(U) \rightarrow \mathbf{Spec} \mathcal{O}_X(U) \simeq U$ when $U \subseteq X$ is an affine open subset. When $V \subseteq U$ is another affine open subset, then $\mathbf{Spec} \mathcal{A}(V)$ is isomorphic to the preimage of V under $\mathbf{Spec} \mathcal{A}(U) \rightarrow U$. This allows one to glue the different $\mathbf{Spec} \mathcal{A}(U)$ together to one prescheme $\mathbf{Spec}_X(\mathcal{A}) \rightarrow X$ which also admits the following description:

- *Points.* As a set,

$$\mathbf{Spec}_X(\mathcal{A}) = \left\{ (x, \mathfrak{p}) \mid \begin{array}{l} x \in X, \mathfrak{p} \in \mathbf{Spec}(\mathcal{A}_x) \text{ such that the preimage of } \mathfrak{p} \\ \text{under } \mathcal{O}_{X,x} \rightarrow \mathcal{A}_x \text{ is } \mathfrak{m}_{X,x} \text{ (the maximal ideal of } \mathcal{A}_x) \end{array} \right\}$$

- *Topology base.* Let

$$\Omega(U, \lambda) = \{ (x, \mathfrak{p}) \mid x \in U \text{ and } \mathfrak{p} \nexists (\text{image of } \lambda \text{ under } \mathcal{A}(U) \rightarrow \mathcal{A}_x) \}$$

where $U \subseteq X$ is open and $\lambda \in \mathcal{A}(U)$. As $\Omega(U, \lambda) \cap \Omega(V, \vartheta) = \Omega(U \cap V, \lambda|_{U \cap V} \cdot \vartheta|_{U \cap V})$ this is indeed a base for some topology.

- *Local rings.* There is only one reasonable choice and this is $\mathcal{O}_{Y,[x,\mathfrak{p}]} := (\mathcal{A}_x)_{\mathfrak{p}}$. Here, $Y = \mathbf{Spec}_X(\mathcal{A})$ for brevity.
- *Structure sheaf.* For $\Omega \subseteq Y$ open, let

$$\mathcal{O}_Y(\Omega) = \left\{ \alpha = (\alpha_{x,\mathfrak{p}}) \in \prod_{(x,\mathfrak{p}) \in \Omega} \mathcal{O}_{Y,[x,\mathfrak{p}]} \mid \alpha \text{ fulfills the coherence condition}^{\text{TM}} \right\}.$$

Here, the *coherence condition*TM says that every $\omega \in \Omega$ has a neighbourhood $\Omega(U, \lambda)$ together with an $a \in \mathcal{A}(U)_{\lambda}$ such that whenever $(x, \mathfrak{p}) \in \Omega \cap \Omega(U, \lambda)$, we have

$$\alpha_{x,\mathfrak{p}} = \left(\text{image of } a \text{ under } \mathcal{A}(U)_{\lambda} \rightarrow (\mathcal{A}_x)_{\lambda} \rightarrow (\mathcal{A}_x)_{\mathfrak{p}} = \mathcal{O}_{Y,[x,\mathfrak{p}]} \right).$$

Proposition 2. *Let Y be a prescheme, \mathcal{A} an \mathcal{O}_Y -algebra and $X \xrightarrow{\xi} Y$ a morphism of preschemes.*

- (a) *The morphism $\mathbf{Spec}_Y(\mathcal{A}) \rightarrow Y$ is affine.*
- (b) *One has a bijection*

$$\mathrm{Hom}_{\mathcal{O}_Y\text{-Alg}}(\mathcal{A}, \xi_* \mathcal{O}_X) \xleftarrow{\sim} \mathrm{Hom}_{Y\text{-PreSch}}(X, \mathbf{Spec}_Y(\mathcal{A})) \quad (1)$$

by gluing the adjunctions

$$\mathrm{Hom}_{\mathcal{O}_Y(U)\text{-Mod}}(\mathcal{A}(U), \mathcal{O}_X(\xi^{-1}U)) \simeq \mathrm{Hom}_{\mathrm{PreSch}}(\xi^{-1}U, \mathbf{Spec} \mathcal{A}(U))$$

together.

- (c) *The morphism ξ is affine iff $\xi_* \mathcal{O}_X$ is a quasi-coherent \mathcal{O}_Y -algebra and the morphism $X \rightarrow \mathbf{Spec}_Y(\xi_* \mathcal{O}_X)$ corresponding to $\mathrm{id}_{\xi_* \mathcal{O}_X}$ under (1) is an isomorphism.*

Sketch of a proof. For (a), the preimage of an affine open $U \subseteq Y$ is $\mathrm{Spec} \mathcal{A}(U)$, hence affine. Part (b) was sketched in [AG1, Proposition 2.5.1] and part (c) is [AG1, Lemma 2.5.1]. *q.e.d.*

Corollary 2. *Let $\tilde{Y} \xrightarrow{f} Y$ be a morphism of preschemes. Let $f^*: \mathcal{O}_Y\text{-Alg} \rightarrow \mathcal{O}_{\tilde{Y}}\text{-Alg}$ be the inverse image functor from [this](#) footnote. If \mathcal{A} is a \mathcal{O}_Y -algebra, we have $\mathbf{Spec}_{\tilde{Y}}(f^*\mathcal{A}) \simeq \mathbf{Spec}_Y(\mathcal{A}) \times_Y \tilde{Y}$.*

Proof. Recall that f^* is left-adjoint to f_* . Let $X \xrightarrow{\xi} \tilde{Y}$ be a \tilde{Y} -prescheme (cf. [AG1, Definition 1.5.7]). Repeatedly applying Proposition 2(b) we get

$$\begin{aligned} \mathrm{Hom}_{\tilde{Y}\text{-PreSch}}(X, \mathbf{Spec}_{\tilde{Y}}(f^*\mathcal{A})) &\simeq \mathrm{Hom}_{\mathcal{O}_{\tilde{Y}}\text{-Alg}}(f^*\mathcal{A}, \xi_*\mathcal{O}_X) \\ &\simeq \mathrm{Hom}_{\mathcal{O}_Y\text{-Alg}}(\mathcal{A}, f_*\xi_*\mathcal{O}_X) \\ &\simeq \mathrm{Hom}_{Y\text{-PreSch}}(X, \mathbf{Spec}_Y(\mathcal{A})) . \end{aligned}$$

In the last line, the Y -prescheme structure on X is given by $X \xrightarrow{\xi} \tilde{Y} \xrightarrow{f} Y$. If you think about it for a moment, a morphism of Y -preschemes from X to $\mathbf{Spec}_Y(\mathcal{A})$, where the Y -prescheme structure on X factors over \tilde{Y} is exactly the commuting square from the universal property of the fibre product $\mathbf{Spec}_Y(\mathcal{A}) \times_Y \tilde{Y}$ and we're done. *q.e.d.*

1.7. The relation between \check{H}^1 and torsors

The usual term for these things seems to be *torsor* rather than *torseur*, so we will deviate from the lecture's notation here.

Definition 1. Let X be any topological space, \mathcal{G} a sheaf of groups on X . A \mathcal{G} -torsor or \mathcal{G} -principal homogeneous space is a sheaf of sets \mathcal{X} on X with a morphism

$$\mathcal{G} \times \mathcal{X} \longrightarrow \mathcal{X}$$

of sheaves of sets indicated by $(g, \xi) \mapsto g \cdot \xi$, with the property that $1_{\mathcal{G}(U)} \cdot \xi = \xi$ and $g \cdot (h \cdot \xi) = (gh) \cdot \xi$ for $g, h \in \mathcal{G}(U)$ and $\xi \in \mathcal{X}(U)$ and such that $\mathcal{X}_x \neq \emptyset$ for any $x \in X$ and the action of \mathcal{G}_x on \mathcal{X}_x is simply transitive for each $x \in X$.

The torsor is called **trivial** if $\mathcal{X}(X) \neq \emptyset$ (and *yes*, the \neq is correct here).

Example 1. \mathcal{G} with its group multiplication is a \mathcal{G} -torsor and trivial as $1_{\mathcal{G}(X)} \in \mathcal{G}(X)$.

Remark 1. (a) If $\xi \in \mathcal{X}(X)$ then

$$\begin{aligned} \mathcal{G} &\longrightarrow \mathcal{X} \\ g \in \mathcal{G}(U) &\longmapsto g \cdot \xi|_U \end{aligned}$$

is an isomorphism (by the simple transitivity stuff it is an isomorphism on stalks).

(b) If \mathcal{X} and \mathcal{Y} are \mathcal{G} -torsors then any morphism $\mathcal{X} \xrightarrow{f} \mathcal{Y}$ of sheaves of sets compatible with the \mathcal{G} -actions induces isomorphisms on stalks, i.e., is automatically an isomorphism of sheaves. Thus, the category of \mathcal{G} -torsors is a *groupoid* – a category, in which every morphism is an isomorphism.

- (c) I think the following should be pointed out separately (though it wasn't in the lecture). Let \mathcal{X} be a \mathcal{G} -torsor, $U \subseteq X$ open. Then $\mathcal{G}(U)$ acts simply transitively on $\mathcal{X}(U)$. Indeed, If $\mathcal{X}(U) = \emptyset$ this is trivial. Otherwise, $\mathcal{X}|_U$ clearly is a trivial $\mathcal{G}|_U$ -torsor by (a) and the assertion is just as trivial.

For $\xi, v \in \mathcal{G}(U)$ the unique element g such that $g \cdot v = \xi$ will be denoted $g = \frac{\xi}{v}$ (or $\xi - v$, if the \mathcal{G} -action is written additively).

Example 2. (a) Let (X, \mathcal{O}_X) be a ringed space. If \mathcal{L} is a *line bundle* on X (i.e., a locally free \mathcal{O}_X -module of rank 1) then

$$\begin{aligned} U \mapsto \mathcal{L}^\times(U) &= \left\{ \ell \in \mathcal{L}(U) \mid \mathcal{O}_U \xrightarrow{\cdot \ell} \mathcal{L}|_U \text{ is an isomorphism} \right\} \\ &= \left\{ \ell \in \mathcal{L}(U) \mid \begin{array}{l} \text{the image of } \ell \text{ in } \mathcal{L}_x \text{ is a generator of} \\ \text{that free } \mathcal{O}_{X,x}\text{-module for all } x \in U \end{array} \right\} \end{aligned}$$

is an \mathcal{O}_X^\times -torsor when equipped with the \mathcal{O}_X^\times -action given by $(f, \ell) \mapsto f \cdot \ell$.

If (X, \mathcal{O}_X) is locally ringed with maximal ideals $\mathfrak{m}_x \subseteq \mathcal{O}_{X,x}$ and $\ell \in \mathcal{L}(U)$ for some open subset $U \subseteq X$, we put

$$V(\ell) = \{x \in U \mid (\text{image of } \ell \text{ in } \mathcal{L}_x) \in \mathfrak{m}_x \mathcal{L}_x\} .$$

If $\lambda \in \mathcal{L}(U)$ happens to be a free generator of $\mathcal{L}|_U$, then $V(\ell)$ coincides with $V\left(\frac{\ell}{\lambda}\right)$, the latter vanishing set being taken in \mathcal{O}_X as usual (that is, as in [Alg1, Definition 1.3.3]). Then

$$\mathcal{L}^\times(U) = \{\ell \in \mathcal{L}(U) \mid V(\ell) = \emptyset\} .$$

The line bundle \mathcal{L} is trivial iff \mathcal{L}^\times has a global section, i.e., iff it's a *trivial* torsor in the sense of Definition 1. It is obvious that for an isomorphism $\varphi: \mathcal{L} \xrightarrow{\sim} \mathcal{M}$ of line bundles, we have an isomorphism $\Phi: \mathcal{L}^\times \xrightarrow{\sim} \mathcal{M}^\times$ sending $\ell \in \mathcal{L}^\times(U)$ to $\varphi(\ell) \in \mathcal{M}^\times(U)$. Vice versa, if $\Phi: \mathcal{L}^\times \xrightarrow{\sim} \mathcal{M}^\times$ is an isomorphism of \mathcal{O}_X^\times -torsors (or just a morphism – it's automatically an isomorphism by Remark 1(b)), there is a unique isomorphism $\varphi: \mathcal{L} \xrightarrow{\sim} \mathcal{M}$ such that $\Phi(\ell) = \varphi(\ell)$ for all open $U \subseteq X$ and $\ell \in \mathcal{L}^\times(U)$.

We thus get a bijection between the isomorphism classes of line bundles and the isomorphism classes of \mathcal{O}_X^\times -torsors. As was pointed out, we need to check that every \mathcal{O}_X^\times -torsor is given as \mathcal{L}^\times for some line bundle \mathcal{L} . If \mathcal{X} is an \mathcal{O}_X^\times -torsor, define \mathcal{L} as the sheafification of

$$U \mapsto (f, \xi)/\sim \quad \text{where } f \in \mathcal{O}_X(U), \xi \in \mathcal{X}(U)$$

and the equivalence relation \sim is defined by $(f, \xi) \sim (g, v)$ iff $f = g \cdot \frac{\xi}{v}$. \mathcal{L} becomes an \mathcal{O}_X -module via $h \cdot (f, \xi)/\sim = (fh, \xi)/\sim$ and $(f, \xi)/\sim + (g, v)/\sim = (g + f \cdot \frac{\xi}{v}, v)/\sim$.

- (b) Let (X, \mathcal{O}_X) be a locally ringed space again. Define a sheaf $\text{GL}_n(\mathcal{O}_X)$ by

$$\begin{aligned} \text{GL}_n(\mathcal{O}_X)(U) &= \{g \in \mathcal{O}_X(U)^{n \times n} \mid V(\det g) = \emptyset\} \\ &= \{g \in \mathcal{O}_X(U)^{n \times n} \mid g \text{ has an inverse matrix}\} \end{aligned}$$

Then there is a similar bijection

$$\left\{ \begin{array}{c} \text{isomorphism classes of } n\text{-dimen-} \\ \text{sional vector bundles on } X \end{array} \right\} \xrightarrow{\sim} \left\{ \begin{array}{c} \text{isomorphism classes of} \\ \text{GL}_n(\mathcal{O}_X)\text{-torsors} \end{array} \right\}$$

$$[\mathcal{E}] \longmapsto \left[\left\{ e \in \mathcal{E}(U)^n \mid \begin{array}{l} e \text{ is a vector of free} \\ \text{generators of } \mathcal{E}|_U \end{array} \right\} \right],$$

where $\text{GL}_n(\mathcal{O}_X)$ acts by right multiplication with the column vector e .

Let \mathcal{G} be a sheaf of abelian groups, \mathcal{X} a \mathcal{G} -torsor, $\mathcal{U}: X = \bigcup_{i \in I} U_i$ an open cover such that $\mathcal{X}|_{U_i}$ is trivial (we will then say that \mathcal{X} is trivial on \mathcal{U}). To be compatible with our notation for Čech cohomology we will write the \mathcal{G} -action on \mathcal{X} additively. If $\xi_i \in \mathcal{X}(U_i)$ for all $i \in I$ are given, there are unique $\psi_{i,j} := \xi_i|_{U_{i,j}} - \xi_j|_{U_{i,j}} \in \mathcal{G}(U_{i,j})$ as in Remark 1(c). Let $\psi = (\psi_{i,j})_{(i,j) \in I^2} \in \check{C}^1(\mathcal{U}, \mathcal{G})$. One easily verifies the correctness of the formal calculation

$$\begin{aligned} (d^1\psi)_{i,j,k} &= \psi_{j,k}|_{U_{i,j,k}} - \psi_{i,k}|_{U_{i,j,k}} + \psi_{i,j}|_{U_{i,j,k}} \\ &= (\xi_j|_{U_{i,j,k}} - \xi_k|_{U_{i,j,k}}) - (\xi_i|_{U_{i,j,k}} - \xi_k|_{U_{i,j,k}}) + (\xi_i|_{U_{i,j,k}} - \xi_j|_{U_{i,j,k}}) \\ &= 0, \end{aligned}$$

that is, ψ is a cocycle.

Proposition 1. (a) *The cohomology class $[\psi] \in \check{H}^1(\mathcal{U}, \mathcal{G})$ depends only on the isomorphism class of the \mathcal{G} -torsor \mathcal{X} , not on the choice of trivializations.*

(b) *One gets a bijection between the isomorphism classes of \mathcal{G} -torsors trivial on \mathcal{U} and $\check{H}^1(\mathcal{U}, \mathcal{G})$.*

Proof. Part (a). If $\tilde{\xi}$ is another trivialization yielding $\tilde{\psi}_{i,j} = \tilde{\xi}_i|_{U_{i,j}} - \tilde{\xi}_j|_{U_{i,j}}$, then $\tilde{\xi}_i = \gamma_i + \xi_i$ where $\gamma_i = \tilde{\xi}_i - \xi_i \in \mathcal{G}(U_i)$ (Remark 1(c)) and putting $\gamma = (\gamma_i)_{i \in I} \in \check{C}^0(\mathcal{U}, \mathcal{G})$ we get $\tilde{\psi} = d^0\gamma + \psi$.

Part (b). By (a) it is clear that we have a map from isomorphism classes of \mathcal{G} -torsors trivial on \mathcal{U} to $\check{H}^1(\mathcal{U}, \mathcal{G})$. To construct a converse map, let $\eta \in \check{H}^1(\mathcal{U}, \mathcal{G})$ and let $\psi \in \check{C}^1(\mathcal{U}, \mathcal{G})$ be a representative of η (so that $d^1\psi = 0$) and let \mathcal{X}_ψ be the sheaf of sets on X given by

$$\mathcal{X}_\psi(V) = \left\{ \gamma \in \check{C}^0(\mathcal{U} \cap V, \mathcal{G}) \mid d^0\gamma = \psi|_V \right\}.$$

We get a \mathcal{G} -action on \mathcal{X}_ψ via $g + \gamma = (g|_{U_i \cap V} + \gamma_i)_{i \in I}$ for $g \in \mathcal{G}(V)$, $\gamma \in \check{C}^0(\mathcal{U} \cap V, \mathcal{G})$. We verify that \mathcal{G} acts simply transitively on stalks and that \mathcal{G} trivializes on \mathcal{U} . Note that if $\gamma, \gamma' \in \mathcal{X}(V)$, then $d^0(\gamma - \gamma') = 0$, hence $\gamma - \gamma' \in \check{C}^0(\mathcal{U} \cap V, \mathcal{G})$ corresponds to (unique) element of $\mathcal{G}(V)$. So the action on $\mathcal{X}_\psi(V)$ is simply transitive for every $V \subseteq X$ open and the only thing left to check is triviality on \mathcal{U} . For this, note that $\check{H}^1(\mathcal{U} \cap V, \mathcal{G}|_V) = 0$ by Corollary 1.2.1(c), so $\psi|_V$ has a preimage in $\check{C}^0(\mathcal{U} \cap V, \mathcal{G})$ and consequently $\mathcal{X}_\psi(V) \neq \emptyset$. In particular, the stalks $(\mathcal{X}_\psi)_x$ are non-empty and \mathcal{X}_ψ is a \mathcal{G} -torsor trivial on \mathcal{U} .

If $\tilde{\psi} = \psi + d^0\varphi$ with $\varphi \in \check{C}^0(\mathcal{U}, \mathcal{G})$ then we have an isomorphism of \mathcal{G} -torsors

$$\begin{aligned} \mathcal{X}_\psi &\xrightarrow{\sim} \mathcal{X}_{\tilde{\psi}} \\ \gamma \in \mathcal{X}_\psi(V) &\mapsto \gamma + \varphi|_V. \end{aligned}$$

Therefore, we get a map in the opposite direction

$$\check{H}^1(\mathcal{U}, \mathcal{G}) \longrightarrow \left\{ \begin{array}{l} \text{isomorphism classes of} \\ \mathcal{G}\text{-torsors trivial on } \mathcal{U} \end{array} \right\}$$

$$\eta = [\psi] \longmapsto [\mathcal{X}_\psi].$$

We claim that the maps we constructed from $\check{H}^1(\mathcal{U}, \mathcal{G})$ to the set of isomorphism classes of \mathcal{U} -trivial \mathcal{G} -torsors and vice versa are inverse to each other.

Indeed, we may choose $\xi_i \in \mathcal{X}_\psi(U_i)$ such that $(\xi_i)_j = \psi_{ij}$ – using $\check{d}^1\psi = 0$ they indeed satisfy $\check{d}^0\xi_i = \psi|_{U_{i,j}}$ – and using $\check{d}^1\psi = 0$ again we find $\xi_i|_{U_{i,j}} - \xi_j|_{U_{i,j}} = \psi_{i,j}$. So we send $[\mathcal{X}_\psi]$ to the cohomology class $[\psi]$ and then back to $[\mathcal{X}_\psi]$.

And for the other direction, if an arbitrary \mathcal{U} -trivial \mathcal{G} -torsor \mathcal{X} is given, choose trivializations $\xi_i \in \mathcal{X}(U_i)$ and put $\psi = (\xi_i|_{U_{i,j}} - \xi_j|_{U_{i,j}})_{(i,j) \in I^2} \in \check{C}^1(\mathcal{U}, \mathcal{G})$. Then we get an isomorphism $\mathcal{X} \xrightarrow{\sim} \mathcal{X}_\psi$ via

$$\mathcal{X}(V) \longrightarrow \mathcal{X}_\psi(V)$$

$$v \longmapsto (v|_{U_i \cap V} - \xi_i|_{U_i \cap V})_{i \in I} \in \check{C}^1(\mathcal{U} \cap V, \mathcal{G})$$

(this is a morphism of \mathcal{G} -torsors, hence an isomorphism by Remark 1(b)), so $[\mathcal{X}]$ is mapped to $[\psi]$ and then back to $[\mathcal{X}_\psi] = [\mathcal{X}]$ again. *q.e.d.*

Remark. When \mathcal{G} is any sheaf of groups on X , one can define $H^1(X, \mathcal{G})$ as the set of isomorphism classes of \mathcal{G} -torsors on X . This is a pointed set, the base point being the isomorphism class of the trivial torsor. Thus, the isomorphism classes of line bundles and of n -dimensional vector bundles on X are in canonical bijection with $H^1(X, \mathcal{O}_X^\times)$ and $H^1(X, \mathrm{GL}_n(\mathcal{O}_X))$ respectively by Example 2.

Corollary 1. *If X is an affine scheme, \mathcal{M} a quasi-coherent \mathcal{O}_X -module and \mathcal{X} an \mathcal{M} -torsor on X , then \mathcal{X} is trivial.*

Proof. Let \mathcal{U} be an open cover of X on which \mathcal{X} trivializes. We may replace \mathcal{U} by an affine refinement. Then $\check{H}^1(\mathcal{U}, \mathcal{M}) = H^1(X, \mathcal{M}) = 0$ by Theorem 1(a) and (b), proving that \mathcal{X} is trivial by Proposition 1(b). *q.e.d.*

Let X be an S -prescheme (cf. [AG1, Definition 1.5.7]). Recall the construction of the sheaf of Kähler differentials $\Omega_{X/S}$ from exercise 5 on sheet #5 from Algebraic Geometry I. We have a homomorphism of abelian groups

$$d\log: \mathcal{O}_X^\times \longrightarrow \Omega_{X/S}$$

$$f \longmapsto d\log f = \frac{d_{X/S}f}{f}$$

defining a morphism of Čech cohomology groups $\check{H}^1(X, \mathcal{O}_X^\times) \rightarrow \check{H}^1(X, \Omega_{X/S})$. When no open cover is specified, we put $\check{H}^1(X, \mathcal{F}) = \varinjlim_{\mathcal{U}} \check{H}^1(\mathcal{U}, \mathcal{F})$ for a presheaf \mathcal{F} on X , where the colimit is taken over all open covers \mathcal{U} of X , partially ordered by refinement. We have to use Čech cohomology here since we don't have any other available, unless X is a quasi-compact scheme and \mathcal{F} a quasi-coherent \mathcal{O}_X -module. In this case, the affine open covers are cofinal in the poset of open covers and $\check{H}^1(X, \mathcal{F}) = H^1(X, \mathcal{F})$ is what we expect.

Definition 2. Let \mathcal{L} be line bundle on X . The image under the above map of the element of $\check{H}^1(X, \mathcal{O}_X^\times)$ associated to the torsor \mathcal{L}^\times by Proposition 1(b) is called the **first Chern class** of \mathcal{L} and is denoted

$$c_1(\mathcal{L}) \in \check{H}^1(X, \Omega_{X/S}).$$

Definition 3. Let \mathcal{V} and \mathcal{W} be vector bundles on the locally ringed space (X, \mathcal{O}_X) . An **extension** of \mathcal{W} by \mathcal{V} is a short exact sequence

$$0 \longrightarrow \mathcal{V} \xrightarrow{a} \mathcal{E} \xrightarrow{b} \mathcal{W} \longrightarrow 0.$$

A **morphism of extensions** is a commutative diagram

$$\begin{array}{ccccccccc} 0 & \longrightarrow & \mathcal{V} & \xrightarrow{a} & \mathcal{E} & \xrightarrow{b} & \mathcal{W} & \longrightarrow & 0 \\ & & \parallel & & \downarrow \varepsilon & & \parallel & & \\ 0 & \longrightarrow & \mathcal{V} & \xrightarrow{a'} & \mathcal{E}' & \xrightarrow{b'} & \mathcal{W} & \longrightarrow & 0 \end{array}$$

Note that ε in the above diagram is automatically an isomorphism. Indeed, this follows immediately from the five lemma in the abelian category $\mathcal{O}_X\text{-Mod}$.

For sheaves \mathcal{F} and \mathcal{G} on a topological space X , we get another sheaf on X via

$$U \longmapsto \mathrm{Hom}_{\mathrm{Shv}(U)}(\mathcal{F}|_U, \mathcal{G}|_U) \quad \text{for open subsets } U \subseteq X.$$

This sheaf is denoted $\mathcal{H}\mathrm{om}(\mathcal{F}, \mathcal{G})$. If \mathcal{R} is a sheaf of rings on X and \mathcal{F} and \mathcal{G} are \mathcal{R} -modules, we can restrict to homomorphisms respecting the \mathcal{R} -module structures and obtain a sheaf $\mathcal{H}\mathrm{om}_{\mathcal{R}}(\mathcal{F}, \mathcal{G})$ by $\mathcal{H}\mathrm{om}_{\mathcal{R}}(\mathcal{F}, \mathcal{G})(U) = \mathrm{Hom}_{\mathcal{R}|_U\text{-Mod}}(\mathcal{F}|_U, \mathcal{G}|_U)$ for $U \subseteq X$ open.

Proposition 2. Let (X, \mathcal{O}_X) be a locally ringed space and \mathcal{V}, \mathcal{W} vector bundles on X . Associating to any extension \mathcal{E} of \mathcal{W} by \mathcal{V} the $\mathcal{H}\mathrm{om}_{\mathcal{O}_X}(\mathcal{W}, \mathcal{V})$ -torsor \mathcal{X} given by

$$\mathcal{X}(U) = \left\{ \text{morphisms } \mathcal{E}|_U \xrightarrow{\pi} \mathcal{V}|_U \text{ of } \mathcal{O}_U\text{-modules} \mid \pi a = \mathrm{id}_{\mathcal{V}|_U} \right\}$$

for $U \subseteq X$ open, whose $\mathcal{H}\mathrm{om}_{\mathcal{O}_X}(\mathcal{W}, \mathcal{V})$ -action is given by $h \in \mathrm{Hom}_{\mathcal{O}_U\text{-Mod}}(\mathcal{W}|_U, \mathcal{V}|_U)$ sending π to $\pi + hb$ is an equivalence of groupoids between extensions of \mathcal{W} by \mathcal{V} and $\mathcal{H}\mathrm{om}_{\mathcal{O}_X}(\mathcal{W}, \mathcal{V})$ -torsors on X .

Franke didn't prove this in the lecture. For the sake of completeness, however, I will do my best to sketch the important steps.

Sketch of a proof. Denote $\mathcal{H} = \mathcal{H}\mathrm{om}_{\mathcal{O}_X}(\mathcal{W}, \mathcal{V})$ for short and let $\mathcal{X}_{\mathcal{E}}$ be the \mathcal{H} -torsor associated to an extension \mathcal{E} . Let's first give an argument why $\mathcal{X}_{\mathcal{E}}$ is even an \mathcal{H} -torsor. If $\pi, \pi' \in \mathcal{X}_{\mathcal{E}}(U)$ are two sections of a on U , then $(\pi - \pi')a = 0$, hence $\pi - \pi'$ factors uniquely over the cokernel of $\mathcal{V}|_U \xrightarrow{a} \mathcal{E}|_U$, which is $\mathcal{W}|_U$. That is, there is a unique morphism $\mathcal{W}|_U \xrightarrow{h} \mathcal{V}|_U$ of \mathcal{O}_U -modules such that $\pi - \pi' = hb$. This shows that $\mathcal{H}(U)$ acts simply transitively on $\mathcal{X}_{\mathcal{E}}(U)$. It remains to show that the stalks $\mathcal{X}_{\mathcal{E},x}$ are non-empty. But \mathcal{V} and \mathcal{W} are vector bundles, so every $x \in X$ has a neighbourhood U in which $\mathcal{W}|_U$ and $\mathcal{V}|_U$ are free \mathcal{O}_U -modules. In particular, $\mathcal{W}|_U$ is

projective and the extension $\mathcal{E}|_U$ is split, i.e., $\mathcal{E}|_U \simeq \mathcal{W}|_U \oplus \mathcal{V}|_U$. Then $\mathcal{X}_{\mathcal{E}}(V)$ is non-empty for all open subsets $V \subseteq U$, hence $\mathcal{X}_{\mathcal{E},x} \neq \emptyset$.

Now about the functoriality properties. To a morphism $\mathcal{E} \xrightarrow{\varepsilon} \mathcal{E}'$ of extensions we associate the morphism $\mathcal{X}_{\mathcal{E}} \rightarrow \mathcal{X}_{\mathcal{E}'}$ which takes $\pi \in \mathcal{X}_{\mathcal{E}}(U)$ to $\varepsilon^{-1}\pi \in \mathcal{X}_{\mathcal{E}'}(U)$ (recall that ε is automatically an isomorphism; we could have taken $\varepsilon\pi$ instead to get a contravariant equivalence of groupoids). This gives a functor Φ from the groupoid of extensions of \mathcal{W} by \mathcal{V} to the groupoid of \mathcal{H} -torsors.

We show fully faithfulness first. Faithfulness of Φ is straightforward: If $\varepsilon, \varepsilon': \mathcal{E} \rightarrow \mathcal{E}'$ are morphisms of extensions such that $\Phi(\varepsilon) = \Phi(\varepsilon')$, then choose an open cover $\mathcal{U}: X = \bigcup_{i \in I} U_i$ on which \mathcal{V} and \mathcal{W} trivialize (i.e., $\mathcal{V}|_{U_i}$ is a free \mathcal{O}_{U_i} -module for all $i \in I$ and same for \mathcal{W}). Then $\mathcal{E}|_{U_i} \simeq \mathcal{W}|_{U_i} \oplus \mathcal{V}|_{U_i}$ is a split extension (and same for $\mathcal{E}'|_{U_i}$), hence the $\mathcal{X}_{\mathcal{E}}(U_i)$ are non-empty and we may choose $\pi_i \in \mathcal{X}_{\mathcal{E}}(U_i)$ for all $i \in I$. From $\varepsilon^{-1}\pi_i = (\varepsilon')^{-1}\pi_i$ and splitness of $\mathcal{E}|_{U_i}, \mathcal{E}'|_{U_i}$ it's easy to deduce $\varepsilon = \varepsilon'$ on U_i . Since the U_i cover X , this holds on all of X and we are done.

Now suppose $\mathcal{X}_{\mathcal{E}} \xrightarrow{\varphi} \mathcal{X}_{\mathcal{E}'}$ is a morphism of \mathcal{H} -torsors. We need to construct a morphism $\mathcal{E} \xrightarrow{\varepsilon} \mathcal{E}'$ of extensions such that $\Phi(\varepsilon) = \varphi$. If $\pi \in \mathcal{X}_{\mathcal{E}}(U)$ is a section of a on U , then π and $\varphi(\pi)$ induce splittings $\mathcal{E}|_U \simeq \mathcal{W}|_U \oplus \mathcal{V}|_U \simeq \mathcal{E}'|_U$, which immediately gives a morphism $\mathcal{E}|_U \xrightarrow{\varepsilon_U} \mathcal{E}'|_U$ of extensions of $\mathcal{W}|_U$ by $\mathcal{V}|_U$. It can be easily checked that ε_U is actually independent of π . So choosing a trivializing open cover \mathcal{U} as above, we get ε_{U_i} for all $i \in I$ which can be glued together (by naturality of their construction) to a morphism $\mathcal{E} \xrightarrow{\varepsilon} \mathcal{E}'$ which indeed satisfies $\Phi(\varepsilon) = \varphi$.

And essential surjectivity. Let \mathcal{X} be an \mathcal{H} -torsor. To construct an extension \mathcal{E} such that $\mathcal{X} \simeq \mathcal{X}_{\mathcal{E}}$, the idea is – of course – to choose $\mathcal{E}|_U \simeq \mathcal{W}|_U \oplus \mathcal{V}|_U$ on small neighbourhoods where \mathcal{X} trivializes, and then to glue them together somehow. Actually we will take the smallest possible “neighbourhoods” – the stalks $\mathcal{E}_x \simeq \mathcal{W}_x \oplus \mathcal{V}_x$ and impose a suitable coherence condition. To do this, choose an element $\pi_x \in \mathcal{X}_x$ for every $x \in X$ and put

$$\mathcal{E}(U) = \left\{ e = (w_x, v_x)_{x \in U} \in \prod_{x \in U} \mathcal{W}_x \oplus \mathcal{V}_x \mid e \text{ fulfills the coherence condition}^{\text{TM}} \right\},$$

where the *coherence condition*TM says that every $x \in U$ has a neighbourhood $V \subseteq U$ on which π_x, w_x and v_x have preimages $\pi_V \in \mathcal{X}(V)$, $w_V \in \mathcal{W}(V)$ and $v_V \in \mathcal{V}(V)$ such that the following holds: $\pi_{V,y}, w_{V,y}$ and $v_{V,y}$ denote the respective images in $\mathcal{X}_y, \mathcal{W}_y$ and \mathcal{V}_y , then $w_y = w_{V,y}$ and $v_y = v_{V,y} + h(w_y)$, where $h = \pi_y - \pi_{V,y} \in \mathcal{H}_y$. It is possible to show that this indeed defines an extension of \mathcal{W} by \mathcal{V} and that $\mathcal{X} \simeq \mathcal{X}_{\mathcal{E}}$. *q.e.d.*

2. Cohomology of projective spaces

2.1. Regular sequences and the Koszul complex

We will use the following conventions:

Definition 1. (a) For a cochain complex (C^\bullet, d_C^\bullet) let the **shift** $C[p]^\bullet$ be the cochain complex defined by $C[p]^q = C^{p+q}$ and whose differential $d_{C[p]}^\bullet$ is given by $d_{C[p]}^q = (-1)^p d_C^{p+q}$.

(b) Let $A^\bullet \xrightarrow{\varphi} B^\bullet$ be a morphism of cochain complexes. Then the **cone** $\text{Cone}(\varphi)$ is the cochain complex defined by

$$\text{Cone}(\varphi)^p = B^p \oplus A^{p+1} \quad \text{and} \quad d_{\text{Cone}(\varphi)}^p(b, a) = \left(d_B^p(b) + \varphi(a), -d_A^{p+1}(a) \right). \quad (1)$$

Remark 1. (a) Obviously, $H^q(C[p]^\bullet) = H^{p+q}(C^\bullet)$.

(b) Note that $d^\bullet = d_{\text{Cone}(\varphi)}^\bullet$ is indeed a differential of cochain complexes, as

$$\begin{aligned} d^{p+1} d^p(b, a) &= d^{p+1} \left(d_B^p(b) + \varphi(a), -d_A^{p+1}(a) \right) \\ &= \left(d_B^{p+1} d_B^p(b) + d_B^{p+1} \varphi(a) - \varphi d_A^{p+1}(a), d_A^{p+2} d_A^{p+1}(a) \right) \\ &= 0. \end{aligned}$$

(c) We get a short exact sequence

$$0 \longrightarrow B^\bullet \longrightarrow \text{Cone}(\varphi) \longrightarrow A[1]^\bullet \longrightarrow 0$$

of cochain complexes. The connecting homomorphism $H^{p+1}(A^\bullet) = H^p(A[1]^\bullet) \xrightarrow{\partial} H^{p+1}(B^\bullet)$ coincides with the morphism induced by φ . We thus get a long exact cohomology sequence

$$\dots \longrightarrow H^p(A^\bullet) \xrightarrow{\varphi} H^p(B^\bullet) \longrightarrow H^p(\text{Cone}(\varphi)) \longrightarrow H^{p+1}(A^\bullet) \longrightarrow \dots \quad (2)$$

In particular, φ induces isomorphisms on cohomology iff $H^\bullet(\text{Cone}(\varphi))$ vanishes.

Naturally arising in the computation of cohomology of projective spaces, *regular sequences* are interesting enough to be studied on their own.

Definition 2. Let R be a ring and M an R -module. A sequence (x_0, \dots, x_n) of elements of R is called **M -regular** if for $i = 0, \dots, n$

$$M/(x_0 M + \dots + x_{i-1} M) \xrightarrow{x_i} M/(x_0 M + \dots + x_{i-1} M)$$

is an injective map. A **regular sequence** in R is an M -regular sequence where $M = R$.

Example 1. (a) If S is any ring and $R = S[X_0, \dots, X_n]$, then the sequence (X_0, \dots, X_n) is R -regular. Indeed, $R/(X_0R + \dots + X_{i-1}R) \simeq S[X_i, \dots, X_n]$ and multiplication by X_i in the polynomial ring $S[X_i, \dots, X_n]$ is clearly injective.

(b) The sequence $(1, 0)$ is always regular, but $(0, 1)$ is only regular when $R = 0$.

The following definition was lacking the $m = 0$ exception in the lecture (let alone the indices), but I think the following is what Professor Franke intended.

Definition 3. Let R be a ring, M be an R -module, (x_0, \dots, x_n) a sequence of elements of R . The **Koszul complex** $K^\bullet((x_0, \dots, x_n), M)$ is a cochain complex defined as follows. Let $[n] = \{0, \dots, n\}$. For $m \geq 1$, $K^m((x_0, \dots, x_n), M)$ is the collection of maps $f: [n]^m \rightarrow M$ with the following properties:

(a) $f(i_1, \dots, i_m) = 0$ when $i_k = i_\ell$ for some integers $1 \leq k < \ell \leq m$.

(b) $f(i_{\pi(1)}, \dots, i_{\pi(m)}) = \text{sgn}(\pi)f(i_1, \dots, i_m)$ for every permutation $\pi \in \mathfrak{S}_m$.

The differential $d^m: K^m((x_0, \dots, x_n), M) \rightarrow K^{m+1}((x_0, \dots, x_n), M)$ is given by

$$d^m f = \sum_{j=0}^m (-1)^j d_j f \quad \text{where} \quad d_j f(i_1, \dots, i_{m+1}) = x_{i_{j+1}} f(i_1, \dots, \hat{i}_{j+1}, \dots, i_{m+1}).$$

As in Definition 1.2.1, the hat \hat{i}_{j+1} denotes the omission of i_{j+1} . Moreover, for $m = 0$ we put $K^0((x_0, \dots, x_n), M) = M$ and $d^0 \mu$ for $\mu \in M$ is the coaugmentation given by $d^0 \mu(i) = x_i \mu$ for $i = 0, \dots, n$.

Remark 2. Before we check that $K^\bullet((x_0, \dots, x_n), M)$ is indeed a cochain complex, let's answer the question *how on earth* Definition 3 is related to the definition you may find in the literature (e.g., [Ei, p. 423])? Well, they are equivalent (duh!) and here is how.

Let $0 \leq \ell_1 < \dots < \ell_m \leq n$ and $\delta_{\ell_1, \dots, \ell_m}: [n]^m \rightarrow R$ be the map satisfying

$$\delta_{\ell_1, \dots, \ell_m}(i_1, \dots, i_m) = \begin{cases} \text{sgn}(\pi) & \text{when } (i_1, \dots, i_m) = (\ell_{\pi(1)}, \dots, \ell_{\pi(m)}) \text{ for } \pi \in \mathfrak{S}_m \\ 0 & \text{when } (i_1, \dots, i_m) \text{ is no permutation of } (\ell_1, \dots, \ell_m) \end{cases}.$$

Clearly, $K^m((x_0, \dots, x_n), M)$ is generated by the $\delta_{\ell_1, \dots, \ell_m} \cdot \mu$ for $\mu \in M$. For $K^m(x_0, \dots, x_n) := K^m((x_0, \dots, x_n), R)$ the $\delta_{\ell_1, \dots, \ell_m}$ even form a basis and we easily get an isomorphism

$$K^\bullet((x_0, \dots, x_n), M) \simeq K^\bullet(x_0, \dots, x_n) \otimes_R M$$

of cochain complexes. Moreover, if e_0, \dots, e_n denote the standard basis vectors of R^{n+1} , mapping $\delta_{\ell_1, \dots, \ell_m} \mapsto e_{\ell_1} \wedge \dots \wedge e_{\ell_m}$ sends a basis of $K^m(x_0, \dots, x_n)$ to a basis of $\bigwedge^m R^{n+1}$ and we find that they are isomorphic.

Let us also find out which map d^m corresponds to. Note that $d_j \delta_{\ell_1, \dots, \ell_m}(i_1, \dots, i_{m+1})$ is only non-zero when (i_1, \dots, i_{m+1}) is a permutation of $(k, \ell_1, \dots, \ell_m)$ for some $k \in [n]$ with k at the $(j+1)^{\text{st}}$ position. In this case, it takes the value $\pm x_k$, depending on the sign of the permutation

of the ℓ_i . If you think about this for a while, $d^m \delta_{\ell_1, \dots, \ell_m}$ corresponds to $\sum_{k=0}^n x_k e_k \wedge e_{\ell_1} \wedge \dots \wedge e_{\ell_m}$. So d^m in $K^\bullet(x_0, \dots, x_n)$ simply corresponds to the map

$$(x_0, \dots, x_n) \wedge -: \bigwedge^m R^{n+1} \longrightarrow \bigwedge^{m+1} R^{n+1}.$$

In $K^\bullet((x_0, \dots, x_n), M) \simeq K^\bullet(x_0, \dots, x_n) \otimes_R M$, this just gets tensored with M .

Also note that $\bigwedge^0 N = R$ for every R -module N by definition, so the above special case $m = 0$ now fits naturally with the rest.

Remark 3. (a) It is easy to check that the d_j satisfy relations similar to (1.2.2), (1.2.3), and (1.2.4). As in the proofs of Definition 1.2.1 and Definition 1.2.2, we deduce that d^\bullet preserves the antisymmetry conditions and is a differential in a cochain complex.

Alternatively, from the above considerations it's immediately clear that d^\bullet is well-defined and satisfies $d^{m+1} d^m = 0$, since wedging with (x_0, \dots, x_n) two times in a row obviously gives 0.

(b) A short exact sequence of R -modules induces a short exact sequence of Koszul complexes. Indeed, in the representation $K^m((x_0, \dots, x_n), M) \simeq \bigwedge^m R^{n+1} \otimes_R M \simeq M^{\binom{n+1}{m}}$ this is pretty obvious.

(c) Let φ be the map $\varphi: K^\bullet((x_0, \dots, x_{n-1}), M) \xrightarrow{x_n} K^\bullet((x_0, \dots, x_n), M)$. We have a canonical isomorphism

$$\begin{aligned} K^\bullet((x_0, \dots, x_n), M) &\xrightarrow{\sim} \text{Cone}(\varphi)[-1] \\ f \in K^m((x_0, \dots, x_n), M) &\longmapsto \left(f(n, -)|_{[n-1]^{m-1}}, -f|_{[n-1]^m} \right) \end{aligned} \quad (3)$$

(I'm pretty sure there should be a minus in the second component for the differentials to be compatible, i.e., consistent with the *two* sign conventions from Definition 1(a) and (b) which are in play here, though we didn't put a minus there in the lecture). This isomorphism corresponds to the decomposition $\bigwedge^m R^{n+1} = e_n \wedge \bigwedge^{m-1} R^n \oplus \bigwedge^m R^n \simeq \bigwedge^{m-1} R^n \oplus \bigwedge^m R^n$, sending $e_n \wedge y + z$ to $(y, -z)$ (and you have to tensor it with M , of course). If you think about this long enough, this is compatible.

In the following we put $H^j((x_0, \dots, x_n), M) := H^j(K^\bullet((x_0, \dots, x_n), M))$ for “short”.

Example 2. (a) For small values of n , we have

$$\begin{aligned} K^\bullet(\emptyset, M) &= (0 \longrightarrow M \longrightarrow 0 \longrightarrow \dots) \\ K^\bullet((x_0), M) &= (0 \longrightarrow M \xrightarrow{x_0} M \longrightarrow 0 \longrightarrow \dots) \\ K^\bullet((x_0, x_1), M) &= (0 \longrightarrow M \xrightarrow{(x_0, x_1)} M \oplus M \xrightarrow{\begin{pmatrix} -x_1 \\ x_0 \end{pmatrix}} M \longrightarrow 0 \longrightarrow \dots). \end{aligned}$$

- (b) In general, $K^\bullet((x_0, \dots, x_n), M)$ vanishes in degrees < 0 and $> n + 1$ (as $\bigwedge^m R^{n+1}$ is only non-zero for $0 \leq m \leq n + 1$). The differentials d^0, d^n are given by $d^0 \mu = \sum_{j=0}^n x_j e_j \otimes \mu$ and $d^n \left(\sum_{j=0}^n (e_0 \wedge \dots \wedge \widehat{e_j} \wedge \dots \wedge e_n) \otimes \mu_j \right) = \sum_{j=0}^n (-1)^j x_j (e_0 \wedge \dots \wedge e_n) \otimes \mu_j$. This shows

$$H^0((x_0, \dots, x_n), M) \simeq \bigcap_{i=0}^n \ker \left(M \xrightarrow{x_i \cdot} M \right)$$

and

$$H^{n+1}((x_0, \dots, x_n), M) \simeq M / (x_0 M + \dots + x_n M) .$$

Fact 1. Let R be a ring, (x_0, \dots, x_n) a sequence of elements of R and M an R -module.

- (a) Let $0 \leq i \leq n$, then (x_0, \dots, x_n) is M -regular iff (x_0, \dots, x_{i-1}) is M -regular and (x_i, \dots, x_n) is $M / (x_0 M + \dots + x_{i-1} M)$ -regular.
- (b) A sequence (x_0, \dots, x_n) is M -regular iff $H^j((x_0, \dots, x_i), M) = 0$ for all i, j such that $0 \leq i \leq n$ and $j \neq i + 1$.
- (c) Let $0 \rightarrow M' \rightarrow M \rightarrow M'' \rightarrow 0$ be a short exact sequence of R -modules. If (x_0, \dots, x_n) is M' -regular and M'' -regular, then it is M -regular.
- (d) If (x_0, \dots, x_n) is M -regular and $k_0, \dots, k_n \in \mathbb{N}$ are natural exponents, then $(x_0^{k_0}, \dots, x_n^{k_n})$ is also M -regular.

Proof. Part (a) is obvious. For (b), we use induction on n . For $n = -1$, there is nothing to show. Now suppose that $n \geq 0$ and the assertion holds for $n - 1$. From (2) and (3) we get a long exact sequence

$$\begin{aligned} \dots \longrightarrow H^{j-1}((x_0, \dots, x_{n-1}), M) &\xrightarrow{x_n \cdot} H^{j-1}((x_0, \dots, x_{n-1}), M) \longrightarrow H^j((x_0, \dots, x_n), M) \\ &\longrightarrow H^j((x_0, \dots, x_{n-1}), M) \xrightarrow{x_n \cdot} H^j((x_0, \dots, x_{n-1}), M) \longrightarrow \dots \end{aligned} \quad (*)$$

Suppose that $H^j((x_0, \dots, x_i), M)$ vanishes for $0 \leq i \leq n$ and $j \neq i + 1$. Then (x_0, \dots, x_{n-1}) is M -regular by induction. Using $H^{n-1}((x_0, \dots, x_{n-1}), M) = 0$ and Example 2(b), for $j = n$ the sequence (*) becomes

$$0 \longrightarrow H^n((x_0, \dots, x_n), M) \longrightarrow M / (x_0 M + \dots + x_{n-1} M) \xrightarrow{x_n \cdot} M / (x_0 M + \dots + x_{n-1} M) \quad (\#)$$

The vanishing of $H^n((x_0, \dots, x_n), M)$ in (#) and exactness show that $x_n \cdot$ is injective on $M / (x_0 M + \dots + x_{n-1} M)$, hence (x_0, \dots, x_n) is M -regular.

Conversely, assume that (x_0, \dots, x_n) is M -regular. Vanishing of $H^j((x_0, \dots, x_i), M)$ for $0 \leq i \leq n - 1$ and $j \neq i + 1$ follows from induction (in particular, we still get (#)) and for $i = n$ and $j > n + 1$ this is also clear. From (*) we get $H^j((x_0, \dots, x_n), M) = 0$ for $j < n$ and for $j = n$ this follows from (#) and injectivity of $x_n \cdot$ on $M / (x_0 M + \dots + x_{n-1} M)$.

Part (c) follows from (b) and the long exact cohomology sequence associated to the short exact sequence $0 \rightarrow K^\bullet((x_0, \dots, x_n), M') \rightarrow K^\bullet((x_0, \dots, x_n), M) \rightarrow K^\bullet((x_0, \dots, x_n), M'') \rightarrow 0$ of Koszul complexes due to Remark 3(b).

Part (d). We use induction on n . For $n = -1$, there is nothing to show. Let $n \geq 0$ and assume that (d) holds for $n - 1$ and any R -module M . Then $M / x_0^{k_0} M$ has a filtration by

submodules $x_0^i M / x_0^{k_0} M$ for $i = 0, \dots, k_0$ and with filtration quotients $x_0^i M / x_0^{i+1} M$. Since $x_0 \cdot$ is injective on M , $x_0^i \cdot$ induces an isomorphism $x_0^i M / x_0^{i+1} M \xleftarrow{\sim} M / x_0 M$. Since (x_1, \dots, x_n) is $M / x_0 M$ -regular by (a), repeatedly applying (c) implies that (x_1, \dots, x_n) is $M / x_0^{k_0} M$ -regular. By the induction assumption, $(x_1^{k_1}, \dots, x_n^{k_n})$ is $(M / x_0^{k_0})$ -regular as well. An application of (a) completes the proof. *q.e.d.*

Definition 4. Let R be a ring, M and N be finitely generated free (or projective) R -modules. A **perfect pairing**¹ $\langle -, - \rangle: M \times N \rightarrow R$ is a R -bilinear map such that one of the induced maps $M \rightarrow \operatorname{Hom}_R(N, R)$ or $N \rightarrow \operatorname{Hom}_R(M, R)$ is an isomorphism.

Remark. Note that if $M \rightarrow \operatorname{Hom}_R(N, R)$ is an isomorphism, then so is $N \rightarrow \operatorname{Hom}_R(M, R)$. To show this, denote $L^* := \operatorname{Hom}_R(L, R)$ for R -modules L . Our first claim is that for finitely generated projective R -modules P and $f \in R$ the canonical morphism $\operatorname{Hom}_R(P, R)_f \rightarrow \operatorname{Hom}_{R_f}(P_f, R_f)$ is an isomorphism. Indeed, if P is free, then $P \simeq P^*$ and this is clear. For projective P , choose another finitely generated projective R -module Q such that $P \oplus Q$ is free, then

$$\begin{aligned} \operatorname{Hom}_R(P, R)_f \oplus \operatorname{Hom}_R(Q, R)_f &\simeq \operatorname{Hom}_R(P \oplus Q, R)_f \\ &\simeq \operatorname{Hom}_{R_f}(P_f \oplus Q_f, R_f) \\ &\simeq \operatorname{Hom}_{R_f}(P_f, R_f) \oplus \operatorname{Hom}_{R_f}(Q_f, R_f) \end{aligned}$$

proves this also for P . Thus, $N \rightarrow M^*$ being an isomorphism can be checked locally and we may replace R by R_f such that M_f and N_f are free. That is, we have reduced the situation to the case where M and N are free. Let $B = (m_1, \dots, m_k)$ and $C = (n_1, \dots, n_\ell)$ be bases of M and N . Let B^* and C^* be the corresponding dual bases of M^* , N^* respectively. Since $M \rightarrow N^*$ is an isomorphism, we must have $k = \ell$ and the coordinate matrix $A = (\langle m_j, n_i \rangle)_{i,j}$ with respect to B and C^* must be invertible. Then its transpose A^T is invertible as well and the coordinate matrix of $N \rightarrow M^*$ with respect to the bases C and B^* , thus $N \rightarrow M^*$ is an isomorphism as well.

Corollary 1. Let R be any ring, $S = R[X_0, \dots, X_n]$. The Koszul complex $K^\bullet((X_0^\ell, \dots, X_n^\ell), S)$ is acyclic in cohomological degree $\neq n+1$. Its cohomology in dimension $n+1$ is a free R -module.

The Koszul complex becomes a complex of graded S -modules via

$$K^m((X_0^\ell, \dots, X_n^\ell), S)_k := \left\{ f \in K^m((X_0^\ell, \dots, X_n^\ell), S) \mid f([n]^m) \subseteq S_{k+\ell m} \right\},$$

where $S_{k+\ell m}$ denotes the degree- $(k + \ell m)$ part of $S = R[X_0, \dots, X_n]$, and

$$(a) \ H^{n+1}((X_0^\ell, \dots, X_n^\ell), S)_k = 0 \text{ when } k > -n-1.$$

(b) We have an isomorphism

$$\begin{aligned} \tau: H^{n+1}((X_0^\ell, \dots, X_n^\ell), S)_{-n-1} &\xrightarrow{\sim} R \\ [f] &\longmapsto \text{coefficient of } (X_0 X_1 \cdots X_n)^{\ell-1} \text{ in } f(0, 1, \dots, n) \end{aligned} \quad (4)$$

(where $[f]$ denotes the cohomology class of $f \in K^{n+1}((X_0^\ell, \dots, X_n^\ell), S)$ which is a cocycle).

¹Note that Professor Franke used the term *non-degenerate pairing* in the lecture. However, it seems that this is not necessarily the common terminology. Non-degeneracy sometimes only means that one of $M \rightarrow \operatorname{Hom}_R(N, R)$ or $N \rightarrow \operatorname{Hom}_R(M, R)$ is injective. In particular, this is *not* symmetric in M, N . So to avoid any ambiguity we will use the term *perfect* instead.

(c) For $0 < k < \ell$ we have a perfect pairing

$$S_k \times H^{n+1}((X_0^\ell, \dots, X_n^\ell), S)_{-n-1-k} \longrightarrow H^{n+1}((X_0^\ell, \dots, X_n^\ell), S)_{-n-1} \stackrel{(4)}{\simeq} R. \quad (5)$$

(simply given by multiplication).

Proof. By Example 1(a), (X_0, \dots, X_n) is an S -regular sequence, hence so is $(X_0^\ell, \dots, X_n^\ell)$ by Fact 1(d). Hence the vanishing of $H^i((X_0^\ell, \dots, X_n^\ell), S)$ is a consequence of Fact 1(b). Moreover, by Example 2(b) we have

$$H^{n+1}((X_0^\ell, \dots, X_n^\ell), S) \simeq S/(X_0^\ell, \dots, X_n^\ell)$$

which is a free R -module with basis $[X_0^{\alpha_0} \cdots X_n^{\alpha_n}] = X_0^{\alpha_0} \cdots X_n^{\alpha_n} + (X_0^\ell, \dots, X_n^\ell)$ for $\alpha_0, \dots, \alpha_n \in \mathbb{N}_0$ such that $\alpha_i < \ell$. The elements of this basis are homogeneous for the above grading and to get an element of homogeneous degree $-n-1$ we need $\alpha_0 + \dots + \alpha_n = -n-1 + \ell(n+1) = (\ell-1)(n+1)$ and there is no other way to have this than $\alpha_i = \ell-1$ for $i = 0, \dots, n$. This proves (b).

Along the same lines we see that (a) holds. Indeed, for an element of degree $k > -n-1$ we would need $\alpha_0 + \dots + \alpha_n > (\ell-1)(n+1)$ and then there is some $\alpha_i \geq \ell$, contradiction.

The pairing from (c) pairs $X_0^{\beta_0} \cdots X_n^{\beta_n}$ with $[X_0^{\alpha_0} \cdots X_n^{\alpha_n}] \in H^{n+1}((X_0^\ell, \dots, X_n^\ell), S)_{-n-1-k}$ to a non-zero element (which is then automatically $(X_0 \cdots X_n)^{\ell-1}$) iff $\alpha + \beta = (\ell-1, \dots, \ell-1)$. For every α contributing to our basis of $H^{n+1}((X_0^\ell, \dots, X_n^\ell), S)_{-n-1-k}$ the corresponding $\beta = (\ell-1, \dots, \ell-1) - \alpha$ is an element of \mathbb{N}_0^{n+1} and $\beta_0 + \dots + \beta_n = k$. If $k < \ell$ and $\beta \in \mathbb{N}_0^{n+1}$ satisfies $\beta_0 + \dots + \beta_n = k$, then $\beta_i \leq k \leq \ell-1$ for all components of β , hence $\alpha = (\ell-1, \dots, \ell-1) - \beta \in \mathbb{N}_0^{n+1}$ contributes to our basis of $H^{n+1}((X_0^\ell, \dots, X_n^\ell), S)_{-n-1-k}$, showing perfectness of the pairing. *q.e.d.*

And finally for a lemma which is perhaps worthwhile to know.

Lemma 1. *Let R be a Noetherian local ring with maximal ideal \mathfrak{m} , M a finitely generated R -module and $x_0, \dots, x_n \in \mathfrak{m}$. Then (x_0, \dots, x_n) is M -regular iff $H^i((x_0, \dots, x_n), M) = 0$ for $i \neq n+1$. In particular, reordering (x_0, \dots, x_n) will again produce an M -regular sequence.*

Proof. The *only if* part being trivial after Fact 1(b), we assume now that $H^i((x_0, \dots, x_n), M)$ vanishes for $i \neq n+1$. From (3) and the cone sequence (2) we obtain a part of a long exact sequence

$$\begin{aligned} H^j((x_0, \dots, x_n), M) &\longrightarrow H^j((x_0, \dots, x_{n-1}), M) \xrightarrow{x_n} H^j((x_0, \dots, x_{n-1}), M) \\ &\longrightarrow H^{j+1}((x_0, \dots, x_n), M). \end{aligned}$$

For $j < n$ the outer terms vanish by assumption, hence

$$H^j((x_0, \dots, x_{n-1}), M) \xrightarrow{x_n} H^j((x_0, \dots, x_{n-1}), M)$$

is an isomorphism. But we are working over a Noetherian ring R and M is finitely generated, so all involved constructions are finitely generated as well. In particular, $H^j((x_0, \dots, x_{n-1}), M)$ is finitely generated. As $x_n \in \mathfrak{m}$, Nakayama's lemma shows $H^j((x_0, \dots, x_{n-1}), M) = 0$ for $j < n$. For $j > n$ this holds as well, obviously. Inductively, this shows $H^j((x_0, \dots, x_i), M) = 0$ for all $i < n$ and $j \neq i+1$, hence (x_0, \dots, x_n) is regular by Fact 1(b). *q.e.d.*

2.2. The scheme \mathbb{P}_R^n and its cohomology

2.2.1. The Proj construction

Let R be an \mathbb{N}_0 -graded ring. Let $R_+ \subseteq R$ be the ideal of elements of R of positive homogeneous degree. Recall that there is a bijection

$$\begin{aligned} \{\text{homogeneous } \mathfrak{p} \in \text{Spec } R \mid \mathfrak{p} \supseteq R_+\} &\xrightarrow{\sim} \text{Spec } R_0 \\ \mathfrak{p} &\longmapsto \mathfrak{q} = \mathfrak{p} \cap R_0 \\ \mathfrak{p} = \mathfrak{q} + R_+ &\longleftarrow \mathfrak{q} . \end{aligned}$$

We recapitulate the construction and basic properties of $\text{Proj } R$, which has been introduced in [AG1, Definition 2.6.2] and exercise sheet #11 of Algebraic Geometry I. As a set, put

$$\text{Proj } R = \{\text{homogeneous } \mathfrak{p} \in \text{Spec } R \mid \mathfrak{p} \not\supseteq R_+\}$$

and for $I \subseteq R$ a homogeneous ideal, let

$$V_{\text{proj}}(I) = V(I) = \{\mathfrak{p} \in \text{Proj } R \mid \mathfrak{p} \supseteq I\} .$$

As $\bigcap_{\lambda \in \Lambda} V(I_\lambda) = V(\sum_{\lambda \in \Lambda} I_\lambda)$ and $V(I) \cup V(J) = V(I \cap J) = V(IJ)$ and $V(R) = V(R_+) = \emptyset$ and $V(0) = \text{Proj } R$ the $V(I)$ are the closed subsets of some topology on $\text{Proj } R$.

We define a sheaf of graded rings $\mathcal{O} = \bigoplus_{k \in \mathbb{Z}} \mathcal{O}(k)$ on $P = \text{Proj } R$ as follows. Let $\mathcal{O}(k)_{[\mathfrak{p}]} = (R_{\mathfrak{p}})_k$ for homogeneous prime ideals $\mathfrak{p} \subseteq R$, where we use the convention that $R_{\mathfrak{p}}$ is obtained from R by inverting the **homogeneous elements of $R \setminus \mathfrak{p}$ only (!)**. Note that the subsets of the form $P \setminus V(f)$ with $f \in R$ homogenous form a topology base of P . We put

$$\mathcal{O}(k)(U) = \left\{ (g_{\mathfrak{p}})_{\mathfrak{p} \in U} \in \prod_{\mathfrak{p} \in U} (R_{\mathfrak{p}})_k \left| \begin{array}{l} \text{every } x \in U \text{ has a neighbourhood } V = P \setminus V(f) \subseteq U, \\ \text{where } f \text{ is homogeneous, such that there is a } \gamma \in (R_f)_k \\ \text{with } g_{\mathfrak{p}} = (\text{image of } \gamma \text{ under } R_f \rightarrow R_{\mathfrak{p}}) \text{ for all } \mathfrak{p} \in V \end{array} \right. \right\} .$$

Then there are operations

$$\begin{aligned} \mathcal{O}(k) \times \mathcal{O}(k) &\longrightarrow \mathcal{O}(k) \\ ((f_{\mathfrak{p}})_{\mathfrak{p} \in U}, (g_{\mathfrak{p}})_{\mathfrak{p} \in U}) &\longmapsto (f_{\mathfrak{p}})_{\mathfrak{p} \in U} + (g_{\mathfrak{p}})_{\mathfrak{p} \in U} = (f_{\mathfrak{p}} + g_{\mathfrak{p}})_{\mathfrak{p} \in U} \end{aligned}$$

and

$$\begin{aligned} \mathcal{O}(k) \times \mathcal{O}(\ell) &\longrightarrow \mathcal{O}(k + \ell) \\ ((f_{\mathfrak{p}})_{\mathfrak{p} \in U}, (g_{\mathfrak{p}})_{\mathfrak{p} \in U}) &\longmapsto (f_{\mathfrak{p}})_{\mathfrak{p} \in U} \cdot (g_{\mathfrak{p}})_{\mathfrak{p} \in U} = (f_{\mathfrak{p}} g_{\mathfrak{p}})_{\mathfrak{p} \in U} \end{aligned}$$

making \mathcal{O} into a sheaf of graded rings with $\mathcal{O}(0) = \mathcal{O}_{\text{Proj } R}$. Moreover, we get a map

$$\begin{aligned} \mathcal{O}(k)_{\mathfrak{p}} &\longrightarrow \mathcal{O}(k)_{[\mathfrak{p}]} \\ \left(\begin{array}{c} \text{image of} \\ (g_{\mathfrak{q}}) \in \mathcal{O}(k)(U) \text{ in } \mathcal{O}(k)_{\mathfrak{p}} \end{array} \right) &\longmapsto g_{\mathfrak{p}} . \end{aligned} \tag{*}$$

Fact 1. The map $(*)$ is an isomorphism.

Proof. By Proposition 1(a) and (c) below,

$$\mathcal{O}(k)_{\mathfrak{p}} = \varinjlim_{f \notin \mathfrak{p}} \mathcal{O}(k)(\text{Proj } R \setminus V(f)) \simeq \varinjlim_{f \notin \mathfrak{p}} (R_f)_k = (R_{\mathfrak{p}})_k = \mathcal{O}(k)_{[\mathfrak{p}]},$$

the colimits ranging over all f which are homogeneous of positive degree. *q.e.d.*

Proposition 1. (a) *Open subsets of the form $\text{Proj } R \setminus V(f)$ where $f \in R_k$ with $k > 0$ are affine and form a topology base.*

(b) *Every finite subset of $\text{Proj } R$ is contained in an affine open subset. In particular, $\text{Proj } R$ is a scheme.*

(c) *The sheaf of modules $\mathcal{O}(k)$ on $\text{Proj } R$ is quasi-coherent, and for $f \in R$ which is homogeneous of positive degree there is a homeomorphism*

$$\begin{aligned} \text{Proj } R \setminus V(f) &\xrightarrow{\sim} \text{Spec}(R_f)_0 \\ \mathfrak{p} &\longmapsto \mathfrak{q} = \mathfrak{p}R_f \cap (R_f)_0 \\ \mathfrak{p} = \sqrt{\mathfrak{q}R_f} \cap R &\longleftarrow \mathfrak{q} \in \text{Spec}(R_f)_0 \end{aligned} \tag{1}$$

under which $(R_{\mathfrak{p}})_0 \simeq ((R_f)_0)_{\mathfrak{q}}$. We thus get an identification

$$\mathcal{O}(0)|_{\text{Proj } R \setminus V(f)} \simeq \mathcal{O}_{\text{Spec}(R_f)_0}.$$

Moreover, under (1) there is a similar isomorphism $(R_{\mathfrak{p}})_k \simeq ((R_f)_k)_{\mathfrak{q}}$ (the latter denotes the localization of the $(R_f)_0$ -module $(R_f)_k$ with respect to \mathfrak{q} , and here we don't need to restrict to homogeneous elements). This gives an identification

$$\mathcal{O}(k)|_{\text{Proj } R \setminus V(f)} \simeq ((R_f)_k)^{\sim}. \tag{2}$$

(d) *When R is generated by R_1 as an R_0 -algebra (or equivalently, R_+ by R_1 as an ideal in R) the sheaves of modules $\mathcal{O}(k)$ are line bundles and the morphism*

$$\begin{aligned} \mathcal{O}(k) \otimes_{\mathcal{O}_{\text{Proj } R}} \mathcal{O}(\ell) &\longrightarrow \mathcal{O}(k + \ell) \\ f \otimes g &\longmapsto fg \end{aligned}$$

is an isomorphism (the tensor product of sheaves is introduced in Remark 3).

(e) *We have a morphism of preschemes $\pi: \text{Proj } R \rightarrow \text{Spec } R_0$ whose topological component is given by*

$$\begin{aligned} \pi: \text{Proj } R &\longrightarrow \text{Spec } R_0 \\ \mathfrak{p} &\longmapsto \mathfrak{p} \cap R_0 \end{aligned} \tag{3}$$

and the algebraic component $\pi^: \mathcal{O}_{\text{Spec } R_0} \rightarrow \pi_* \mathcal{O}_{\text{Proj } R}$ is defined by sending an element $rf^{-k} \in (R_0)_f \simeq \mathcal{O}_{\text{Spec } R_0}(\text{Spec } R_0 \setminus V(f))$ to precisely that element in $\mathcal{O}(0)(\text{Proj } R \setminus V(f))$. The morphism π is of finite type (cf. [AG1, Definition 2.2.1]) if R is an R_0 -algebra of finite type.*

(f) *If R is Noetherian (which is the case iff R_0 is Noetherian and R of finite type over R_0) then $\text{Proj } R$ is Noetherian (cf. [AG1, Definition 2.2.2]) and the $\mathcal{O}(k)$ are coherent.*

Proof. Most of this follows from exercise sheet #11 of Algebraic Geometry I. We show the topology base part of (a) first: Let I be a homogeneous ideal and $\mathfrak{p} \notin V(I)$ a homogeneous prime ideal. Then $I \not\subset \mathfrak{p}$ contains a homogeneous element f . Clearly $\text{Proj } R \setminus V(f) \subseteq \text{Proj } R \setminus V(I)$. If f has positive degree, we are done. Otherwise choose an element $g \in R_+ \setminus \mathfrak{p}$ and replace f by fg . The fact that the $\text{Proj } R \setminus V(f)$ are affine follows from (1).

For (c), do exercise 1 and apply this to (1). From this, it is clear that for M a graded R -module the sheafification \tilde{M} of the presheaf

$$\text{Proj } R \setminus V(f) \longmapsto (M_f)_0 \quad \text{for } f \text{ homogeneous of positive degree}$$

is quasi-coherent as it equals $((M_f)_0)^\sim$ on $\text{Proj } R \setminus V(f)$ (this is actually the first part of exercise 3). Applying this to $M = R[k]$ (the shift of R as in Definition 2.1.1(a)) shows that $\mathcal{O}(k)$ is quasi-coherent and (2) holds.

Part (b). Let $\mathfrak{p}_1, \dots, \mathfrak{p}_n \in \text{Proj } R$. Since R_+ isn't contained in any \mathfrak{p}_i , it is also not contained in the union $\bigcup_{i=1}^n \mathfrak{p}_i$ by the prime avoidance lemma (cf. [Alg1, Lemma 2.5.1]). Then for any $f \in R_+ \setminus \bigcup_{i=1}^n \mathfrak{p}_i$, $\text{Proj } R \setminus V(f) \simeq \text{Spec}(R_f)_0$ is a common affine open neighbourhood of $\mathfrak{p}_1, \dots, \mathfrak{p}_n$ by (1). From [AG1, Fact 1.5.9(a)] we get that $\text{Proj } R$ is a scheme.

Part (d). If R_+ is generated by R_1 as an ideal in R , a homogeneous prime ideal \mathfrak{p} contains R_+ iff it contains R_1 . Hence the $\text{Proj } R \setminus V(f)$ for $f \in R_1$ cover $\text{Proj } R$. On $U = \text{Proj } R \setminus V(f)$ however, an isomorphism $\mathcal{O}_{\text{Proj } R}|_U = \mathcal{O}(0)|_U \xrightarrow{\sim} \mathcal{O}(k)|_U$ is given by multiplication with f^k . To show that $\mathcal{O}(k) \otimes_{\mathcal{O}_{\text{Proj } R}} \mathcal{O}(\ell) \xrightarrow{\sim} \mathcal{O}(k + \ell)$, it is enough to check this stalk-wise. But $\mathcal{O}(k)_\mathfrak{p} \simeq \mathcal{O}_{\text{Proj } R, \mathfrak{p}} \simeq (R_\mathfrak{p})_0$ holds for $\mathfrak{p} \in \text{Proj } R$ as we just have seen, and similar for $\mathcal{O}(\ell)_\mathfrak{p}$ and $\mathcal{O}(k + \ell)_\mathfrak{p}$, so the isomorphism

$$\mathcal{O}(k)_\mathfrak{p} \otimes_{\mathcal{O}_{\text{Proj } R, \mathfrak{p}}} \mathcal{O}(\ell)_\mathfrak{p} \xrightarrow{\sim} \mathcal{O}(k + \ell)_\mathfrak{p}$$

is pretty much obvious.

Part (e). Let $\alpha_1, \dots, \alpha_n$ be generators of R as an R_0 -algebra. Decomposing them into homogeneous components, we may assume that they are homogeneous of degrees $d_1, \dots, d_n > 0$. By [AG1, Proposition 2.2.1(b)] and (c) it is enough to show that $(R_f)_0 \simeq \mathcal{O}_{\text{Proj } R}(\text{Proj } R \setminus V(f))$ is of finite type over R_0 for all $f \in R_+$. Let d be the homogeneous degree of f . One may check that $(R_f)_0$ is indeed generated as an R_0 -algebra by those

$$\alpha_1^{k_1} \cdots \alpha_n^{k_n} \cdot f^{-k} \quad \text{where } 0 \leq k_i < d \text{ and } 0 \leq k < d \cdot (d_1 + \dots + d_n)$$

which have homogeneous degree 0.

To show that π is quasi-compact, it suffices to show quasi-compactness of $\text{Proj } R$ by [AG1, Fact 2.1.2]. Since R is of finite type over R_0 , the augmentation ideal R_+ is finitely generated. Let f_1, \dots, f_n be homogeneous generators of R_+ . Then the $\text{Proj } R \setminus V(f_i) \simeq \text{Spec}(R_{f_i})_0$ cover $\text{Proj } R$, so $\text{Proj } R$ is a finite union of quasi-compact sets and thus quasi-compact itself.

And finally part (f). The stuff in parentheses was proved in [Alg2, Proposition 2.2.1], by the way. In (e) we have seen that $\text{Proj } R$ is finite type over $\text{Spec } R_0$ which is Noetherian, hence $\text{Proj } R$ is Noetherian by Hilbert's Basissatz. By an argument similar to (e), $(R_f)_k$ is finitely generated as an $(R_f)_0$ -module for all $f \in R_+$, hence $\mathcal{O}(k)$ is locally finitely generated over $\mathcal{O}_{\text{Proj } R}$ by (c) and thus coherent in the sense of Definition 1.1.6(b). *q.e.d.*

Remark 1. For a graded R -module M and open $U \subseteq P = \text{Proj } R$ let

$$\tilde{M}(U) = \left\{ (\mu_{\mathfrak{p}}) \in \prod_{\mathfrak{p} \in U} (M_{\mathfrak{p}})_0 \left| \begin{array}{l} \text{every } x \in U \text{ has a neighbourhood } V = P \setminus V(f) \subseteq U, \\ \text{where } f \text{ is homogeneous, such that there is a } m \in (M_f)_0 \\ \text{with } \mu_{\mathfrak{p}} = (\text{image of } m \text{ under } M_f \rightarrow M_{\mathfrak{p}}) \text{ for all } \mathfrak{p} \in V \end{array} \right. \right\}.$$

This is actually the sheafification of the presheaf

$$\text{Proj } R \setminus V(f) \longmapsto (M_f)_0 \quad \text{for } f \text{ homogeneous of positive degree}$$

we have already seen in the proof of Proposition 1(c). Note that the localizations $M_{\mathfrak{p}}$ appearing here are understood to be obtained by inverting the *homogeneous* elements of $R \setminus \mathfrak{p}$ only. On open subsets of the form $\text{Proj } R \setminus V(f) \simeq \text{Spec}(R_f)_0$ for $f \in R_+$ homogeneous, \tilde{M} equals $((M_f)_0)^\sim$, proving that it is quasi-coherent. In the case $\tilde{M} = R[k]$ we obtain $\tilde{M} \simeq \mathcal{O}(k)$.

Remark 2. In general, the Proj construction is not functorial, not even for graded ring morphisms. However, we do have the following: If $R \xrightarrow{\varphi} S$ is a ring morphism such that there is a positive integer d satisfying $\varphi(R_k) \subseteq S_{dk}$ for all k and such that $S_+ = \sqrt{S\varphi(R_+)}$, then we have a continuous map

$$\begin{aligned} \text{Proj } S &\longrightarrow \text{Proj } R \\ \mathfrak{p} &\longmapsto \varphi^{-1}(\mathfrak{p}) \end{aligned}$$

together with morphisms $(R_{\varphi^{-1}(\mathfrak{p})})_0 \xrightarrow{\varphi} (S_{\mathfrak{p}})_0$, defining a morphism $\text{Proj } S \rightarrow \text{Proj } R$ of preschemes.

For instance, there is a morphism (a closed immersion even) from $\mathbb{P}_A^m := \text{Proj } A[X_0, \dots, X_m]$ to \mathbb{P}_A^n for $m \leq n$ defined by the ring morphism $A[X_0, \dots, X_n] \rightarrow A[X_0, \dots, X_m]$ sending X_{m+1}, \dots, X_n to 0. By contrast, there is no morphism $\mathbb{P}_A^m \rightarrow \mathbb{P}_A^n$ defined by $A[X_0, \dots, X_n] \subseteq A[X_0, \dots, X_m]$ when $n < m$ (because the radical property fails).

As an example with $d > 1$ we may take $R = A[X_0, X_1, X_2]$, $S = A[Y_0, Y_1]$ and $\varphi(X_0) = Y_0^2$, $\varphi(X_1) = Y_0Y_1$, $\varphi(X_2) = Y_1^2$. The condition $S_+ = \sqrt{S\varphi(R_+)}$ holds as all monomials of even degree in Y_0, Y_1 can be decomposed as a product of the three monomials Y_0^2, Y_0Y_1, Y_1^2 . We obtain a closed immersion $\mathbb{P}_A^1 = \text{Proj } S \rightarrow \mathbb{P}_A^2 = \text{Proj } R$ identifying \mathbb{P}_A^1 with the closed subscheme $V(X_0X_2 - X_1^2) \subseteq \mathbb{P}_A^2$.

Remark 3. We will construct a sheaf tensor product. Let \mathcal{R} be a sheaf of rings on some space X and \mathcal{M}, \mathcal{N} be \mathcal{R} -modules. We define $\mathcal{M} \otimes_{\mathcal{R}} \mathcal{N}$ to be the sheafification of the presheaf

$$\mathcal{P}: U \longmapsto \mathcal{M}(U) \otimes_{\mathcal{R}(U)} \mathcal{N}(U) \quad \text{for open subsets } U \subseteq X.$$

It is “easy to see” that the stalk \mathcal{P}_x is given by $\mathcal{M}_x \otimes_{\mathcal{R}_x} \mathcal{N}_x$ ². Then the stalk at x of $\mathcal{M} \otimes_{\mathcal{R}} \mathcal{N}$ is given by $\mathcal{M}_x \otimes_{\mathcal{R}_x} \mathcal{N}_x$ as well and we get

$$(\mathcal{M} \otimes_{\mathcal{R}} \mathcal{N})(U) = \left\{ (f_x) \in \prod_{x \in U} \mathcal{M}_x \otimes_{\mathcal{R}_x} \mathcal{N}_x \left| \begin{array}{l} \text{every } x \in U \text{ has a neighbourhood } V \subseteq U \\ \text{and } \varphi \in \mathcal{M}(V) \otimes_{\mathcal{R}(V)} \mathcal{N}(V) \text{ such that } f_y \text{ is} \\ \text{the image of } \varphi \text{ in } \mathcal{M}_x \otimes_{\mathcal{R}_x} \mathcal{N}_x \text{ for all } y \in V \end{array} \right. \right\}$$

²If you really want to do this, you could use that both the free module and its submodule of relations-to-be-modded-out appearing in the explicit construction of the tensor product commute with colimits, as does taking the quotient. In fact, since $\mathcal{M}_x = \varinjlim_{U \ni x} \mathcal{M}(U)$ is a *filtered* colimit, it is the same as being taken in the category of sets, and the free module functor is left-adjoint to the forgetful functor, hence preserves colimits (Remark A.1.4). So does taking quotients, since colimits commute with colimits (Lemma A.1.4).

This satisfies the universal property

$$\begin{aligned} \mathrm{Hom}_{\mathcal{R}\text{-Mod}}(\mathcal{M} \otimes_{\mathcal{R}} \mathcal{N}, \mathcal{T}) &\xrightarrow{\sim} \mathrm{Bil}_{\mathcal{R}}(\mathcal{M} \times \mathcal{N}, \mathcal{T}) \\ \varphi &\longmapsto (\beta: (m, n) \mapsto \varphi(m \otimes n)) \end{aligned}$$

for every \mathcal{R} -module \mathcal{T} (where the set $\mathrm{Bil}_{\mathcal{R}}(\mathcal{M} \times \mathcal{N}, \mathcal{T})$ of bilinear morphisms of sheaves $\mathcal{M} \times \mathcal{N} \rightarrow \mathcal{T}$ is defined in the obvious way).

Now let $X = \mathrm{Spec} R$ and $\mathcal{M} = \tilde{M}$, $\mathcal{N} = \tilde{N}$ for some R -modules M, N . Then $(M \otimes_R N)_{\mathfrak{p}} = M \otimes_R N \otimes_R R_{\mathfrak{p}} = M_{\mathfrak{p}} \otimes_{R_{\mathfrak{p}}} N_{\mathfrak{p}}$ shows that $\mathcal{M} \otimes_{\mathcal{O}_X} \mathcal{N} = (M \otimes_R N)^{\sim}$. Hence the tensor product over arbitrary preschemes preserves quasi-coherentntness of modules.

When \mathcal{L} is a line bundle on a ringed space (X, \mathcal{O}_X) and \mathcal{M} an \mathcal{O}_X -module, then $\mathcal{M} \otimes_{\mathcal{O}_X} \mathcal{L}$ is locally (non-canonically) isomorphic to \mathcal{M} , a local isomorphism being given by

$$\begin{aligned} \mathcal{M}|_U &\xrightarrow{\sim} (\mathcal{M} \otimes_{\mathcal{O}_X} \mathcal{L})|_U \\ m &\longmapsto m \otimes \lambda, \end{aligned}$$

where $\lambda \in \mathcal{L}(U)$ is a free generator of $\mathcal{L}|_U$. In that sense, $\mathcal{M} \otimes_{\mathcal{O}_X} \mathcal{L}$ may be viewed as a *twist* of \mathcal{M} . Similarly, when \mathcal{V} is an n -dimensional vector bundle on X , then $\mathcal{M} \otimes_{\mathcal{O}_X} \mathcal{V}$ is locally (non-canonically) isomorphic to \mathcal{M}^n .

2.2.2. Cohomology of \mathbb{P}_R^n

Let R be a graded ring such that R_+ is generated by R_1 over R . By Proposition 1(d), the $\mathcal{O}(k)$ are line bundles and for a graded R -module M we get an isomorphism

$$\begin{aligned} \tilde{M} \otimes_{\mathcal{O}_{\mathrm{Proj} R}} \mathcal{O}(k) &\xrightarrow{\sim} (M[k])^{\sim} \\ m \otimes r &\longmapsto rm \end{aligned}$$

(which is easily checked stalk-wise). In particular, this generalizes Proposition 1(d) (which is the special case $M = R[\ell]$). Also keep in mind that the \tilde{M} occurring here is the one from Remark 1.

Now let A be a ring, $R = A[X_0, \dots, X_n]$ be equipped with the usual grading and put $\mathbb{P}_A^n = \mathrm{Proj} R$. Then $\mathcal{U}: \mathbb{P}_A^n = \bigcup_{i=0}^n U_i$ with $U_i = \mathbb{P}_A^n \setminus V(X_i)$ is an affine open cover of \mathbb{P}_A^n and by (1) we have

$$U_{i_0, \dots, i_\ell} = \mathbb{P}_A^n \setminus V(X_{i_0} \cdots X_{i_\ell}) \simeq \mathrm{Spec} R[(X_{i_0} \cdots X_{i_\ell})^{-1}]_0.$$

Theorem 2. *Let A be a ring, $R = A[X_0, \dots, X_n]$ and \mathcal{U} be the affine open cover of $X = \mathbb{P}_A^n$ from above.*

(a) *For $k \geq 0$ there is an isomorphism*

$$\begin{aligned} R_k &\xrightarrow{\sim} \mathcal{O}(k)(X) \\ r &\longmapsto (\text{image of } r \text{ in } (R_{\mathfrak{p}})_k)_{\mathfrak{p} \in X}. \end{aligned} \tag{4}$$

For $k < 0$ we have $\mathcal{O}(k)(X) = 0$.

- (b) For $0 < p < n$ we have $H^p(X, \mathcal{O}(k)) = 0$ for all integers k .
- (c) $H^n(X, \mathcal{O}(k)) = 0$ for $k > -n - 1$ and $n > 0$.
- (d) There is an isomorphism $H^n(X, \mathcal{O}(-n - 1)) \xrightarrow{\sim} A$ defined (up to sign) by

$$\begin{aligned} \check{C}_{\text{alt}}^n(\mathcal{U}, \mathcal{O}(-n - 1)) &\simeq R[(X_0 \cdots X_n)^{-1}]_{-n-1} \longrightarrow A \\ f &= \sum_{\alpha \in \mathbb{Z}^n} f_{\alpha} X_0^{\alpha_0} \cdots X_n^{\alpha_n} \longmapsto f_{(-1, \dots, -1)}. \end{aligned} \quad (5)$$

- (e) For all $k \in \mathbb{Z}$, the groups $H^0(X, \mathcal{O}(k))$ and $H^n(X, \mathcal{O}(k))$ are finitely generated free A -modules and there is a perfect pairing

$$\begin{aligned} H^0(X, \mathcal{O}(k)) \times H^n(X, \mathcal{O}(-n - 1 - k)) &\longrightarrow H^n(X, \mathcal{O}(-n - 1)) \stackrel{(d)}{\simeq} A \\ (f, [g]) &\longmapsto [fg], \end{aligned} \quad (6)$$

where for $f \in \mathcal{O}(k)(X)$ and $g \in \check{C}_{\text{alt}}^n(\mathcal{U}, \mathcal{O}(-n - 1 - k))$, $fg \in \check{C}_{\text{alt}}^n(\mathcal{U}, \mathcal{O}(-n - 1))$ is defined by $(fg)_{i_0, \dots, i_n} = f|_{U_{i_0, \dots, i_n}} \cdot g_{i_0, \dots, i_n}$ for all indices i_0, \dots, i_n .

Remark. The pairing in (6) is canonical but the isomorphism $H^n(X, \mathcal{O}(-n - 1)) \simeq A$ is not.

Proof of Theorem 2. Surprisingly, the proof will be almost trivial once we discover the connection between the Čech complex and the Koszul complex. By (2), on $U_{i_0, \dots, i_{\ell}} = \mathbb{P}_A^n \setminus V(X_{i_0} \cdots X_{i_{\ell}})$ we have

$$\mathcal{O}(k)(U_{i_0, \dots, i_{\ell}}) \simeq R[(X_{i_0} \cdots X_{i_{\ell}})^{-1}]_k$$

for all $k \in \mathbb{Z}$. Considering the sheaf of graded rings $\mathcal{O} = \bigoplus_{k \in \mathbb{Z}} \mathcal{O}(k)$ as before, this can be written in a more compact way as

$$\mathcal{O}(U_{i_0, \dots, i_{\ell}}) \simeq R[(X_{i_0} \cdots X_{i_{\ell}})^{-1}].$$

Note that we have isomorphisms

$$R[(X_{i_0} \cdots X_{i_{\ell}})^{-1}] \xleftarrow{\sim} \varinjlim \left(R \xrightarrow{\cdot(X_{i_0} \cdots X_{i_{\ell}})} R \xrightarrow{\cdot(X_{i_0} \cdots X_{i_{\ell}})} R \xrightarrow{\cdot(X_{i_0} \cdots X_{i_{\ell}})} \dots \right) \quad (*)$$

sending the image of $r \in R$ (as an element of the j^{th} member of the sequence) in the colimit to $r \cdot (X_{i_0} \cdots X_{i_{\ell}})^{-j}$.

For every $j \in \mathbb{N}$ we get a morphism

$$\check{C}_{\text{alt}}^{\ell}(\mathcal{U}, \mathcal{O}) \simeq \prod_{0 \leq i_0 < \dots < i_{\ell} \leq n} R[(X_{i_0} \cdots X_{i_{\ell}})^{-1}] \longleftarrow \bigwedge^{\ell+1} R^{n+1} \simeq K^{\ell+1}((X_0^j, \dots, X_n^j), R)$$

sending $e_{i_0} \wedge \dots \wedge e_{i_{\ell}}$ to $(0, \dots, (X_{i_0} \cdots X_{i_{\ell}})^{-j}, \dots, 0)$ (with the only non-zero entry at position (i_0, \dots, i_{ℓ}) , obviously). Using $\bigwedge^{\ell+1} R^{n+1} \simeq \bigoplus_{0 \leq i_0 < \dots < i_{\ell} \leq n} R$ and (*), these morphisms assemble to an isomorphism

$$\check{C}_{\text{alt}}^{\ell}(\mathcal{U}, \mathcal{O}) \xleftarrow{\sim} \varinjlim_{j \in \mathbb{N}} K^{\ell+1}((X_0^j, \dots, X_n^j), R),$$

where the transition morphisms $K^{\ell+1}((X_0^j, \dots, X_n^j), R) \rightarrow K^{\ell+1}((X_0^{j+1}, \dots, X_n^{j+1}), R)$ (with respect to which the colimit is taken) sends an element $f \in K^{\ell+1}((X_0^j, \dots, X_n^j), R)$ to $\varphi \in K^{\ell+1}((X_0^{j+1}, \dots, X_n^{j+1}), R)$ defined by $\varphi(t_1, \dots, t_{\ell+1}) = X_{t_1} \cdots X_{t_{\ell+1}} f(t_1, \dots, t_{\ell+1})$. Convince yourself that this is compatible with the Koszul differential, so in fact we get a transition map $K^\bullet((X_0^j, \dots, X_n^j), R) \rightarrow K^\bullet((X_0^{j+1}, \dots, X_n^{j+1}), R)$, and using this an isomorphism

$$(R \longrightarrow \check{C}_{\text{alt}}^0(\mathcal{U}, \mathcal{O}) \longrightarrow \check{C}_{\text{alt}}^1(\mathcal{U}, \mathcal{O}) \longrightarrow \dots) \xleftarrow{\sim} \varinjlim_{j \in \mathbb{N}} K^\bullet((X_0^j, \dots, X_n^j), R)[-1] \quad (7)$$

of cochain complexes. The degree-(-1) term S comes from the fact that the $K^\bullet((X_0^j, \dots, X_n^j), R)$ for all $j \in \mathbb{N}$ have such a term in degree 0.

Note that if $n = 0$, then $\mathbb{P}_A^0 = \text{Proj } A[X_0] \simeq \text{Spec } A$ and everything follows from well-known properties of affine schemes. Now assume $n > 0$. By Example 2.1.1(a), the sequence (X_0, \dots, X_n) is a regular sequence in R . By Fact 2.1.1(d), so are (X_0^j, \dots, X_n^j) for $j \in \mathbb{N}$. We can now reduce the various assertions about the cohomology of $X = \mathbb{P}_A^n$ to their Koszul counterparts.

Part (a). By Fact 2.1.1(b), $H^p((X_0^j, \dots, X_n^j), R) = 0$ in degree $p \neq n+1$. In particular, by exactness of filtered colimits, equation (7) gives

$$H^0(R \longrightarrow \check{C}_{\text{alt}}^\bullet(\mathcal{U}, \mathcal{O})) \xleftarrow{\sim} \varinjlim_{j \in \mathbb{N}} H^1((X_0^j, \dots, X_n^j), R) = 0,$$

hence the kernel $\ker(\check{C}_{\text{alt}}^0(\mathcal{U}, \mathcal{O}) \rightarrow \check{C}_{\text{alt}}^1(\mathcal{U}, \mathcal{O})) \simeq H^0(X, \mathcal{O}) \simeq \mathcal{O}(X)$ equals the image of S in $\check{C}_{\text{alt}}^0(\mathcal{U}, \mathcal{O})$. Thus $\mathcal{O}(X) \simeq S$ and (a) follows by comparing degrees.

Part (b). Just as in (a), for $0 < p < n$ we obtain

$$H^p(R \longrightarrow \check{C}_{\text{alt}}^\bullet(\mathcal{U}, \mathcal{O})) \xleftarrow{\sim} \varinjlim_{j \in \mathbb{N}} H^{p+1}((X_0^j, \dots, X_n^j), R) = 0,$$

from Fact 2.1.1(b), hence $H^p(X, \mathcal{O}(k)) = 0$ for all $k \in \mathbb{Z}$ by comparing degrees.

And finally parts (c), (d), and (e) follow in a similar colimit-taking fashion from Corollary 2.1.1(a), (b), and (c). q.e.d.

Our next aim is to investigate the trivialization of the A -module $H^n(\mathbb{P}_A^n, \mathcal{O}(-n-1))$ by Theorem 2(d), which is non-canonical unless the coordinates and their order are fixed. What happens when the coordinates are changed by an element of $\text{GL}_{n+1}(A)$ (inducing an automorphism of R , hence of $\text{Proj } R = \mathbb{P}_A^n$) with a compatible action on the line bundles $\mathcal{O}(k)$?

Lemma 1. *An element $g \in \text{GL}_{n+1}(A)$ acts on $H^n(\mathbb{P}_A^n, \mathcal{O}(-n-1))$ by multiplication with $\det(g)^{-1}$.*

Proof. We will reduce this to the case where $A = K$ is an algebraically closed field. It is easy to see that changing the trivializations of $H^n(\mathbb{P}_A^n, \mathcal{O}(-n-1))$ gives an action of $\text{GL}_{n+1}(A)$ on A , hence a group homomorphism

$$\varphi_A: \text{GL}_{n+1}(A) \longrightarrow \text{Aut}_A(A) \simeq A^\times,$$

where $\text{Aut}_A(A)$ is the automorphism group of A as an A -module.

If $A \xrightarrow{\alpha} B$ is a ring morphism, we get a graded ring morphism $A[X_0, \dots, X_n] \xrightarrow{\alpha} B[X_0, \dots, X_n]$ defining a morphism of preschemes $\mathbb{P}_B^n \xrightarrow{p} \mathbb{P}_A^n$ together with morphisms $\mathcal{O}_{\mathbb{P}_A^n}(k) \rightarrow p_* \mathcal{O}_{\mathbb{P}_B^n}(k)$ defined by the above ring morphism α on open subsets of the form $\mathbb{P}_A^n \setminus V(X_i)$.

Note that $\mathbb{P}_B^n \xrightarrow{p} \mathbb{P}_A^n$ is an affine morphism by Proposition 1.6.1(b), since the preimage of $\mathbb{P}_A^n \setminus V(X_i)$ (which is affine by Proposition 1(c)) is $\mathbb{P}_B^n \setminus V(X_i)$ (which is affine). In particular, we get

$$H^n(\mathbb{P}_A^n, \mathcal{O}_{\mathbb{P}_A^n}(-n-1)) \xrightarrow{p^*} H^n(\mathbb{P}_A^n, p_* \mathcal{O}_{\mathbb{P}_B^n}(-n-1)) \xrightarrow{\sim} H^n(\mathbb{P}_B^n, \mathcal{O}_{\mathbb{P}_B^n}(-n-1)) ,$$

the isomorphism coming from Corollary 1.6.1. By naturality of our cohomology constructions³

$$\begin{array}{ccc} H^n(\mathbb{P}_A^n, \mathcal{O}_{\mathbb{P}_A^n}(-n-1)) & \xrightarrow{p^*} & H^n(\mathbb{P}_B^n, \mathcal{O}_{\mathbb{P}_B^n}(-n-1)) \\ g \downarrow & & \downarrow \alpha(g) \\ H^n(\mathbb{P}_A^n, \mathcal{O}_{\mathbb{P}_A^n}(-n-1)) & \xrightarrow{p^*} & H^n(\mathbb{P}_B^n, \mathcal{O}_{\mathbb{P}_B^n}(-n-1)) \end{array}$$

is a commutative diagram, showing that $\varphi_B(\alpha(g)) = \alpha(\varphi_A(g))$. In general, there is a ring morphism

$$B = \mathbb{Z}[Y_{i,j} \mid i, j = 0, \dots, n] [\det(Y_{i,j})^{-1}] \longrightarrow A$$

sending $Y_{i,j}$ to the corresponding entry in the matrix g and $\det(Y_{i,j})^{-1}$ to $\det(g)^{-1}$. This reduces the assertion to the case of the infinite domain B . Embedding B into an algebraic closure K of its field of quotients, we did the advertised reduction.

In this case, the morphism $\varphi_K: \mathrm{GL}_{n+1}(K) \rightarrow K^\times$ factors over the abelianization of $\mathrm{GL}_{n+1}(K)$. For algebraically closed fields (actually, for fields with more than 3 elements) the commutator subgroup of $\mathrm{GL}_{n+1}(K)$ is $\mathrm{SL}_{n+1}(K)$. Moreover, every element $C \in \mathrm{GL}_{n+1}(K)$ can be written as the product of a matrix $\lambda \mathrm{id}_{K^{n+1}}$ and a matrix in $\mathrm{SL}_{n+1}(K)$ (using that $\det C$ has an $(n+1)^{\mathrm{st}}$ root in the algebraically closed field K). This reduces to the case $g = \lambda \mathrm{id}_{K^{n+1}}$. In this case, it is easily seen from Proposition 1(c) that g acts as the identity on \mathbb{P}_K^n and as multiplication by λ^k on $\mathcal{O}_{\mathbb{P}_K^n}(k)$. This proves our claim. *q.e.d.*

Definition 1. A line bundle \mathcal{L} on a quasi-compact prescheme X is called **ample** if it satisfies the following equivalent conditions.

- (a) For every locally finitely generated quasi-coherent \mathcal{O}_X -module \mathcal{M} there is an integer $m(\mathcal{M})$ such that for all $m < m(\mathcal{M})$, there is an epimorphism

$$(\mathcal{L}^{\otimes m})^{\oplus n} \twoheadrightarrow \mathcal{M} ,$$

for some natural number $n = n(m)$.

³If $\mathcal{U}: \mathbb{P}_A^n = \bigcup_{i=0}^n \mathbb{P}_A^n \setminus V(X_i)$ is our standard affine open cover, let $g(\mathcal{U}): \mathbb{P}_A^n = \bigcup_{i=0}^n \mathbb{P}_A^n \setminus V(g(X_i))$ be its image under g . Then g induces a map of Čech complexes $\check{C}^\bullet(\mathcal{U}, \mathcal{O}(k)) \rightarrow \check{C}^\bullet(g(\mathcal{U}), \mathcal{O}(k))$ and this is all natural and stuff; and both Čech complexes give $H^n(\mathbb{P}_A^n, \mathcal{O}(k))$ by Theorem 1(a).

- (b) For every quasi-coherent locally finitely generated \mathcal{O}_X -module \mathcal{M} there is an integer $k(\mathcal{M})$ such that for all $k > k(\mathcal{M})$, $\mathcal{L}^{\otimes k} \otimes_{\mathcal{O}_X} \mathcal{M}$ is **generated by its global sections**. This shall mean the following: There is a family of global sections $(\lambda_i)_{i \in I}$ such that each stalk $\mathcal{L}_x^{\otimes k} \otimes_{\mathcal{O}_{X,x}} \mathcal{M}_x$ is generated as an $\mathcal{O}_{X,x}$ -module by the images of the λ_i .

Remark 4. (a) In Definition 1 we put $\mathcal{L}^{-1} = \mathcal{H}om_{\mathcal{O}_X}(\mathcal{L}, \mathcal{O}_X)$ and $\mathcal{L}^{\otimes m} = (\mathcal{L}^{-1})^{\otimes (-m)}$ if $m \in \mathbb{Z}$ is negative. These are line bundles again, because in the case $\mathcal{L} = \mathcal{O}_X$ they are canonically isomorphic to \mathcal{O}_X , which locally and up to isomorphism is always the case. For the same reason, the morphism

$$\mathcal{L} \otimes_{\mathcal{O}_X} \mathcal{L}^{-1} \longrightarrow \mathcal{O}_X$$

defined by the bilinear map of evaluation $\mathcal{L} \times \mathcal{H}om_{\mathcal{O}_X}(\mathcal{L}, \mathcal{O}_X) \rightarrow \mathcal{O}_X$, $(\lambda, \eta) \mapsto \eta(\lambda)$ and the universal property of the (sheaf) tensor product (cf. Remark 3) is an isomorphism.

More generally, evaluation gives an isomorphism

$$\mathcal{L} \otimes_{\mathcal{O}_X} \mathcal{H}om_{\mathcal{O}_X}(\mathcal{L}, \mathcal{M}) \xrightarrow{\sim} \mathcal{M}$$

for every quasi-coherent \mathcal{O}_X -module \mathcal{M} . Isomorphism classes of line bundles on X thus get an abelian group structure with $- \otimes_{\mathcal{O}_X} -$ defining multiplication, \mathcal{O}_X the neutral element and \mathcal{L}^{-1} the inverse to \mathcal{L} . This group is called the **Picard group** $\text{Pic}(X)$.

Ok, actually, we have yet to check that our construction of inverse elements is compatible with the group structure, i.e., $(\mathcal{L} \otimes_{\mathcal{O}_X} \mathcal{M})^{-1} \xleftarrow{\sim} \mathcal{L}^{-1} \otimes_{\mathcal{O}_X} \mathcal{M}^{-1}$. To obtain a sheaf isomorphism

$$\mathcal{H}om_{\mathcal{O}_X}(\mathcal{L}, \mathcal{O}_X) \otimes_{\mathcal{O}_X} \mathcal{H}om_{\mathcal{O}_X}(\mathcal{M}, \mathcal{O}_X) \xrightarrow{\sim} \mathcal{H}om_{\mathcal{O}_X}(\mathcal{L} \otimes_{\mathcal{O}_X} \mathcal{M}, \mathcal{O}_X)$$

we can map $f \otimes g \in \mathcal{H}om_{\mathcal{O}_U\text{-Mod}}(\mathcal{L}|_U, \mathcal{O}_U) \otimes_{\mathcal{O}_X(U)} \mathcal{H}om_{\mathcal{O}_U\text{-Mod}}(\mathcal{M}|_U, \mathcal{O}_U)$ (for an open subset $U \subseteq X$) to the morphism $(\mathcal{L} \otimes_{\mathcal{O}_X} \mathcal{M})|_U \rightarrow \mathcal{O}_U$ sending $\lambda \otimes \mu$ to $f(\lambda) \cdot g(\mu)$. It is clear that this is locally (where \mathcal{L} and \mathcal{M} trivialize) an isomorphism, hence an isomorphism in total.

- (b) On $X = \mathbb{P}_A^n$, there is an isomorphism

$$\begin{aligned} \mathcal{O}(k) &\xrightarrow{\sim} \mathcal{H}om_{\mathcal{O}_{\mathbb{P}_A^n}}(\mathcal{O}(\ell), \mathcal{O}(\ell + k)) \\ f &\longmapsto (g \mapsto f \cdot g). \end{aligned}$$

- (c) Definition 1(b) seems way more common in the literature.

- (d) Don't confuse Definition 1 with a *relative* notion of ampleness.

Proof of Definition 1 (this has to be). First note that $\mathcal{L}^{\otimes k} \otimes_{\mathcal{O}_X} \mathcal{M}$ is still locally finitely generated, so by quasi-compactness of X the family in (b) can be chosen finite (I will leave that to you).

We show (a) \Rightarrow (b) first. Let $k > -m(\mathcal{M})$. Then there is an epimorphism $(\mathcal{L}^{\otimes (-k)})^{\oplus n} \twoheadrightarrow \mathcal{M}$. Tensoring with $\mathcal{L}^{\otimes k}$ gives an epimorphism $\mathcal{O}_X^{\oplus n} \twoheadrightarrow \mathcal{L}^{\otimes k} \otimes_{\mathcal{O}_X} \mathcal{M}$ (tensor products of sheaves preserve epimorphisms, since this clearly holds on stalks). Then the images of the standard unit vectors in $\mathcal{O}_X(X)^{\oplus n}$ generate $\mathcal{L}^{\otimes k} \otimes_{\mathcal{O}_X} \mathcal{M}$.

And (b) \Rightarrow (a). Let $m < -k(\mathcal{M})$. Since $\mathcal{L}^{\otimes(-m)} \otimes_{\mathcal{O}_X} \mathcal{M}$ is generated by finitely many global sections, say, n of them, there is an epimorphism $\mathcal{O}_X^{\oplus n} \rightarrow \mathcal{L}^{\otimes(-m)} \otimes_{\mathcal{O}_X} \mathcal{M}$. Tensoring with $\mathcal{L}^{\otimes m}$ gives an epimorphism $(\mathcal{L}^{\otimes m})^{\oplus n} \rightarrow \mathcal{M}$. q.e.d.

Definition 2. Let \mathcal{L} be a line bundle on a locally ringed space (X, \mathcal{O}_X) , with $\mathfrak{m}_x \subseteq \mathcal{O}_{X,x}$ the maximal ideal of the local ring at x . If $U \subseteq X$ is open and $\lambda \in \mathcal{L}(U)$, its **vanishing set** is

$$V(\lambda) = \{x \in U \mid \text{the image of } \lambda \text{ in } \mathcal{L}_x \text{ is in } \mathfrak{m}_x \mathcal{L}_x\}.$$

Remark. When $\mathcal{L} = \mathcal{O}_X$, this coincides with the vanishing sets introduced in [AG1, Definition 1.3.3]. Since locally and up to isomorphism this is always the case, $V(\lambda)$ is closed in U by [AG1, Fact 1.3.1] and the usual trick in such situations ([AG1, Remark 1.1.4(a)]). Similarly, $V(\lambda \otimes \mu) = V(\lambda) \cup V(\mu)$ for the section $\lambda \otimes \mu$ of $\mathcal{L} \otimes_{\mathcal{O}_X} \mathcal{M}$ when \mathcal{L} and \mathcal{M} are line bundles.

Lemma 2. Let X be a quasi-compact prescheme, \mathcal{L} a line bundle on X , $\lambda \in \mathcal{L}(X)$ and \mathcal{M} a quasi-coherent \mathcal{O}_X -module.

- (a) If $m \in \mathcal{M}(X)$ with $m|_{X \setminus V(\lambda)} = 0$, then there is $k \in \mathbb{N}$ such that the section $\lambda^{\otimes k} \otimes m = 0$ in $\mathcal{L}^{\otimes k} \otimes_{\mathcal{O}_X} \mathcal{M}$.
- (b) If X is in addition quasi-separated and $m \in \mathcal{M}(X \setminus V(\lambda))$, then there is $k \in \mathbb{N}$ such that $\lambda^{\otimes k} \otimes m \in (\mathcal{L}^{\otimes k} \otimes_{\mathcal{O}_X} \mathcal{M})(X \setminus V(\lambda))$ extends to a global section of $\mathcal{L}^{\otimes k} \otimes_{\mathcal{O}_X} \mathcal{M}$ on X .

Remark. When $\mathcal{L} = \mathcal{O}_X$, this is identical with one of our definitions of quasi-coherentness for sheaves of \mathcal{O}_X -modules, as we will immediately see.

Proof of Lemma 2. When $\mathcal{L} = \mathcal{O}_X$, assertion (a) is equivalent to the injectivity and (b) to the surjectivity of

$$\mathcal{M}(X)_\lambda \xrightarrow{(1.1.1)} \mathcal{M}(X \setminus V(\lambda)).$$

Since this holds when \mathcal{M} is quasi-coherent and X is quasi-compact (resp. quasi-compact and quasi-separated) by Definition 1.1.4(d), the assertion is true for $\mathcal{L} = \mathcal{O}_X$.

Since X is quasi-compact, we have a finite cover $X = \bigcup_{i=1}^n U_i$ by affine open subsets U_i such that $\mathcal{L}|_{U_i}$ is trivial. Also put $U_{i,j} = U_i \cap U_j$ as in our Čech complex convention.

For (a), we have $(m|_{U_i})|_{U_i \setminus V(\lambda)} = 0$, hence by the special case treated above there is $k_i \in \mathbb{N}$ such that $\lambda^{\otimes k_i} \otimes m = 0$ on U_i . Taking $k = \max_i k_i$ we get $\lambda^{\otimes k} \otimes m = 0$ on all of X .

For (b) we use the above special case again to obtain $\ell_i \in \mathbb{N}$ and $\mu_i \in (\mathcal{L}^{\otimes \ell_i} \otimes_{\mathcal{O}_X} \mathcal{M})(U_i)$ such that $\lambda^{\otimes \ell_i} \otimes m = \mu_i$ on U_i . Putting $\ell = \max_i \ell_i$ and replacing μ_i by $\lambda^{\otimes(\ell-\ell_i)} \otimes \mu_i$ we may assume $\ell_1 = \dots = \ell_n = \ell$. As X is quasi-separated, the $U_{i,j} = U_i \cap U_j$ are quasi-compact. Since $\mu_i|_{U_{i,j} \setminus V(\lambda)} = \mu_j|_{U_{i,j} \setminus V(\lambda)}$, by (a) there are $k_{i,j}$ such that $\lambda^{\otimes k_{i,j}} \otimes \mu_i = \lambda^{\otimes k_{i,j}} \otimes \mu_j$ on $U_{i,j}$. Put $k = \max_{i,j} k_{i,j}$, then $\lambda^{\otimes k} \otimes \mu_i|_{U_{i,j}} = \lambda^{\otimes k} \otimes \mu_j|_{U_{i,j}}$, hence by the sheaf axiom the $\lambda^{\otimes k} \otimes \mu_i$ extend to a global section $\mu \in \mathcal{L}^{\otimes k} \otimes_{\mathcal{O}_X} \mathcal{M}$. Then $\mu|_{X \setminus V(\lambda)} = \lambda^{\otimes(k+\ell)} \otimes m$, so μ extends $\lambda^{\otimes(k+\ell)} \otimes m$. q.e.d.

Proposition 2. Let X be a quasi-compact and quasi-separated prescheme and \mathcal{L} a line bundle on X such that X may be covered by affine open subsets of the form $X \setminus V(\lambda)$ where $\lambda \in \mathcal{L}(X)$. Then \mathcal{L} is ample.

Proof. By quasi-compactness of X and the assumption we find a finite cover $X = \bigcup_{i=1}^n U_i$, where $U_i = X \setminus V(\lambda_i)$ is affine with $\lambda_i \in \mathcal{L}(X)$. Let \mathcal{M} be a locally finitely generated quasi-coherent \mathcal{O}_X -module, then $M_i = \mathcal{M}(U_i)$ is finitely generated over $\mathcal{O}_X(U_i)$, say by $m_{i,j}$ for $j = 1, \dots, n_i$. By Lemma 2(b) we can choose k_0 sufficiently large so that the $\lambda^{\otimes k_0} \otimes m_{i,j}$ extend to a global section of $\mathcal{L}^{\otimes k_0} \otimes_{\mathcal{O}_X} \mathcal{M}$ on X . Then $\mathcal{L}^{\otimes k} \otimes_{\mathcal{O}_X} \mathcal{M}$ is generated by its global sections $\lambda^{\otimes k} \otimes m_{i,j}$ (or more precisely their extensions) for all $k > k_0$, hence \mathcal{L} is ample by Definition 1(b). *q.e.d.*

Corollary 1. (a) *The line bundle $\mathcal{O}(1)$ on \mathbb{P}_A^n is ample.*

(b) *If X is quasi-affine (i.e., an open subscheme of an affine scheme), then \mathcal{O}_X is ample.*

Proof. For part (a), note that the $\mathbb{P}_A^n \setminus V(X_i)$ are affine and cover \mathbb{P}_A^n . For (b), write $X = \bar{X} \setminus Z$ with \bar{X} affine and Z closed, then the open subsets of the form $X \setminus V(f|_X) = \bar{X} \setminus V(f)$ with $f \in \mathcal{O}_{\bar{X}}(\bar{X})$ such that $V(f) \supseteq Z$ are affine and cover X . In both cases we win by Proposition 2. *q.e.d.*

Let \mathcal{M} be a quasi-coherent module on \mathbb{P}_A^n . For every $k \in \mathbb{Z}$ we put $\mathcal{M}(k) = \mathcal{M} \otimes_{\mathcal{O}_X} \mathcal{O}(k)$ and call this a *Serre twist* of \mathcal{M} .

Theorem 3 (Serre). *Let A be a Noetherian ring. If \mathcal{M} is a coherent sheaf of modules on $X = \mathbb{P}_A^n$, then the groups $H^p(X, \mathcal{M})$ are finitely generated A -modules and vanish for $p > n$. When $p > 0$ and k is sufficiently large, $H^p(X, \mathcal{M}(k)) = 0$.*

Proof. We prove both assertions by downward induction on p . When $p > n$, by Proposition 1.2.2(b) we can use the alternating Čech complex associated to the standard affine open cover $\mathcal{U}: \mathbb{P}_A^n = \bigcup_{i=0}^n \mathbb{P}_A^n \setminus V(X_i)$ to compute $H^p(X, \mathcal{M}) = \check{H}_{\text{alt}}^p(\mathcal{U}, \mathcal{M}) = 0$ since $\check{C}_{\text{alt}}^\bullet(\mathcal{U}, \mathcal{M})$ is concentrated in degrees $\leq n$.

Now suppose the assertion is proved in cohomological dimension $p + 1$. Since $\mathcal{O}(1)$ is ample by Corollary 1(a), there is an epimorphism $\mathcal{O}(-j)^{\oplus \ell} \xrightarrow{p} \mathcal{M}$ when j is large enough (Definition 1(a)). Putting $\mathcal{K} = \ker(p)$, we get a short exact sequence $0 \rightarrow \mathcal{K} \rightarrow \mathcal{O}(-j)^{\oplus \ell} \rightarrow \mathcal{M} \rightarrow 0$ of quasi-coherent \mathcal{O}_X -modules (\mathcal{K} is quasi-coherent by Proposition 1.1.3) and hence an exact sequence

$$H^p(X, \mathcal{O}(-j))^{\oplus \ell} \simeq H^p(X, \mathcal{O}(-j)^{\oplus \ell}) \longrightarrow H^p(X, \mathcal{M}) \longrightarrow H^{p+1}(X, \mathcal{K})$$

as part of the long exact cohomology sequence from Theorem 1(d). Since A is Noetherian, \mathcal{K} is coherent. Indeed, by Proposition 1(f), $X = \mathbb{P}_A^n$ is a Noetherian scheme. Then $\mathcal{K}(U)$ is a $\mathcal{O}_X(U)$ -submodule of $\mathcal{O}(-j)(U)^{\oplus \ell}$ for every affine open subset $U \subseteq X$, hence $\mathcal{K}(U)$ is finitely generated by Noetherianness of $\mathcal{O}_X(U)$. That is, \mathcal{K} is locally finitely generated and thus coherent by Definition 1.1.6(b), as claimed.

Now the right end of the above sequence is a finitely generated A -module by the induction assumption. For the left end, this holds by Theorem 2(b) and (e). It follows that $H^p(X, \mathcal{M})$ in the middle is finitely generated as well.

Since tensoring with $\mathcal{O}(k)$ is exact (it preserves exactness on stalks since $\mathcal{O}(k)$ is a line bundle by Proposition 1(d), hence preserves exactness in general), we get short exact sequences $0 \rightarrow \mathcal{K}(k) \rightarrow \mathcal{O}(k-j)^{\oplus \ell} \rightarrow \mathcal{M}(k) \rightarrow 0$. Thus

$$H^p(X, \mathcal{O}(k-j))^{\oplus \ell} \simeq H^p(X, \mathcal{O}(k-j)^{\oplus \ell}) \longrightarrow H^p(X, \mathcal{M}(k)) \longrightarrow H^{p+1}(X, \mathcal{K}(k))$$

is exact. For $k > j - n$ and $p > 0$ the left term vanishes by Theorem 2(b) and (c). So does $H^{p+1}(X, \mathcal{K}(k))$ for sufficiently large k by the induction assumption. Hence $H^p(X, \mathcal{M}(k))$ vanishes as well when $k \gg 0$. *q.e.d.*

Proposition 3. *Let A be a Noetherian ring and X a closed subscheme of \mathbb{P}_A^n . For sufficiently large k the restriction map*

$$A[X_0, \dots, X_n]_k \simeq H^0(\mathbb{P}_A^n, \mathcal{O}_{\mathbb{P}_A^n}(k)) \longrightarrow H^0(X, \mathcal{O}_X(k))$$

is surjective.

Remark 5. (a) In the case where A is a field, this was (essentially) shown on exercise sheet #10 of Algebra II.

(b) The isomorphism $A[X_0, \dots, X_n]_k \simeq H^0(\mathbb{P}_A^n, \mathcal{O}_{\mathbb{P}_A^n}(k))$ comes from Theorem 2(a).

(c) Did we define $\mathcal{O}_X(k)$? No, we didn't, but we will now. Let $Y = \mathbb{P}_A^n$ and $X \xrightarrow{i} Y$ be the closed embedding we're talking about. Then we put $\mathcal{O}_X(k) = i^*\mathcal{O}_Y(k)$. Here, $i^*: \mathcal{O}_Y\text{-Mod} \rightarrow \mathcal{O}_X\text{-Mod}$ denotes the pull-back functor from [this](#) footnote. Since i^* is left-adjoint to i_* , we have a canonical morphism $\mathcal{O}_Y(k) \rightarrow i_*\mathcal{O}_X(k)$, giving $H^0(Y, \mathcal{O}_Y(k)) \rightarrow H^0(Y, i_*\mathcal{O}_X(k))$.

Since i is affine⁴, Corollary 1.6.1 gives $H^0(Y, i_*\mathcal{O}_X(k)) \simeq H^0(X, \mathcal{O}_X(k))$. From this we get the restriction map in the formulation of Proposition 3.

(d) There is a canonical isomorphism $i_*\mathcal{M} \otimes_{\mathcal{O}_Y} \mathcal{N} \simeq i_*(\mathcal{M} \otimes_{\mathcal{O}_X} i^*\mathcal{N})$ for all \mathcal{O}_X -modules \mathcal{M} and \mathcal{O}_Y -modules \mathcal{N} (quasi-coherent or not). To prove this, we first construct the morphism and then prove that it is isomorphic. We get a morphism $i_*\mathcal{M} \rightarrow i_*(\mathcal{M} \otimes_{\mathcal{O}_X} i^*\mathcal{N})$ from the push-forward of $\mathcal{M} \rightarrow \mathcal{M} \otimes_{\mathcal{O}_X} i^*\mathcal{N}$. Similarly, we get a canonical morphism $i_*i^*\mathcal{N} \rightarrow i_*(\mathcal{M} \otimes_{\mathcal{O}_X} i^*\mathcal{N})$, which can be composed with $\mathcal{N} \rightarrow i_*i^*\mathcal{N}$. Together, they define a bilinear map $i_*\mathcal{M} \times \mathcal{N} \rightarrow i_*(\mathcal{M} \otimes_{\mathcal{O}_X} i^*\mathcal{N})$ and thus a canonical morphism

$$i_*\mathcal{M} \otimes_{\mathcal{O}_Y} \mathcal{N} \longrightarrow i_*(\mathcal{M} \otimes_{\mathcal{O}_X} i^*\mathcal{N}) \quad (\$)$$

of \mathcal{O}_Y -modules. Checking that it is an isomorphism is a job done stalk-wise. First of all, note that for every \mathcal{O}_X -module \mathcal{F} , the stalk of $i_*\mathcal{F}$ at $y \in Y$ is given by

$$(i_*\mathcal{F})_y = \begin{cases} \mathcal{F}_x & \text{if } y = i(x) \\ 0 & \text{if } y \text{ isn't in the image of } i \end{cases}.$$

Indeed, since i is an embedding, every open neighbourhood of $x \in X$ is of the form $X \cap U = i^{-1}(U)$ for some open neighbourhood U of $i(x)$, hence the first case, and the embedding is closed, hence the second. Also recall that the stalk of $i^*\mathcal{N}$ at $x \in X$ is given by $\mathcal{O}_{X,x} \otimes_{\mathcal{O}_{Y,i(x)}} \mathcal{N}_{i(x)}$ (we proved this on exercise sheet #10 of Algebraic Geometry I). Hence the stalks at $y \in Y$ of the two guys from (§) are either both 0 or given by

$$\mathcal{M}_x \otimes_{\mathcal{O}_{Y,i(x)}} \mathcal{N}_{i(x)} \quad \text{and} \quad \mathcal{M}_x \otimes_{\mathcal{O}_{X,x}} (\mathcal{O}_{X,x} \otimes_{\mathcal{O}_{Y,i(x)}} \mathcal{N}_{i(x)})$$

(for $y = i(x)$) respectively. Clearly they are isomorphic and it's easy to see that (§) actually induces that isomorphism.

⁴Every closed embedding is. Indeed, locally a closed embedding looks like $\text{Spec } R/I \hookrightarrow \text{Spec } R$ for some ring R and some ideal $I \subseteq R$ (cf. the proof of [AG1, Proposition 1.5.3]) which is clearly affine.

Proof of Proposition 3. Let $\mathcal{J} \subseteq \mathcal{O}_Y$ be the sheaf of ideals defining the closed embedding i (cf. [AG1, Corollary 1.5.3(a)]). Let $k \in \mathbb{Z}$. Then $\mathcal{O}_{X,x} = \mathcal{O}_{Y,i(x)}/\mathcal{J}_x$ and a stalk-wise argument similar to Remark 5(d) shows that $0 \rightarrow \mathcal{J}(k) \rightarrow \mathcal{O}_Y(k) \rightarrow i_*\mathcal{O}_X(k) \rightarrow 0$ is a short exact sequence of coherent \mathcal{O}_Y -modules (coherence of \mathcal{J} and $\mathcal{O}_Y(k)$ follows from A being Noetherian and this implies that the others involved are coherent as well). This gives

$$H^0(Y, \mathcal{O}_Y(k)) \longrightarrow H^0(Y, i_*\mathcal{O}_X(k)) \longrightarrow H^1(Y, \mathcal{J}(k))$$

in which the right end vanishes by Theorem 3 when k is large enough. In view of Remark 5(c), this proves the assertion. *q.e.d.*

Exercise 1. Let k be a field, $n \geq 2$ and $Z \subseteq \mathbb{P}_k^n$ a closed reduced subprescheme whose irreducible components are of codimension 1 (e.g., a curve in \mathbb{P}_k^2). Then

$$k[X_0, \dots, X_n]_\ell \longrightarrow H^0(Z, \mathcal{O}_Z(\ell))$$

is surjective for every $\ell \geq 0$. From this, one can deduce Max Noether's *Restsatz*, cf. [Alg2, Theorem 23].

Sketch of a proof. Let $R = k[X_0, \dots, X_n]$. Since \mathbb{P}_k^n is Noetherian by Proposition 1(f), we may decompose $Z = \bigcup_{i=1}^N Z_i$ into irreducible components, which again have codimension 1. By considering their intersections with the standard affine open cover of \mathbb{P}_k^n and using [Alg1, Proposition 2.1.3] (and probably *locality of codimension* as well, cf. [Alg1, Remark 2.1.3]) one can show that $Z_i \simeq \text{Proj } R/(p_i)$ for some homogeneous prime element $p_i \in R$ (here we use that Z is reduced). Then the ideal $\mathcal{J} \subseteq \mathcal{O}_{\mathbb{P}_k^n}$ that cuts out Z is given by $\mathcal{J} = p_1 \cdots p_N \mathcal{O}_{\mathbb{P}_k^n}$. But then $H^1(\mathbb{P}_k^n, \mathcal{J}(\ell))$ is easily seen to vanish for all $\ell \geq 0$ since \mathcal{J} is actually isomorphic to $\mathcal{O}_{\mathbb{P}_k^n}$ and we know that $H^1(\mathbb{P}_k^n, \mathcal{O}(k))$ vanishes by Theorem 2(b).

The assumption then follows from the long exact cohomology sequence associated to the short exact sequence $0 \rightarrow \mathcal{J}(k) \rightarrow \mathcal{O}(k) \rightarrow i_*\mathcal{O}_Z(k) \rightarrow 0$, with i denoting the embedding of Z . *q.e.d.*

Recall the construction of the quasi-coherent $\mathcal{O}_{\text{Proj } R}$ -module $\mathcal{M} = \tilde{M}$ from Remark 1 when M is a graded module over the graded ring R . When M is over R and R is of finite type over R_0 , an argument similar (but even more technical) to the proof of Proposition 1(e) shows that $(M_f)_0$ is a finitely generated $(R_f)_0$ -module for every homogeneous $f \in R_+$, i.e., \mathcal{M} is locally finitely generated. When R_0 is, in addition, Noetherian, Proposition 1(f) assures that \mathcal{M} is coherent.

Proposition 4 (Serre). *Let A be a Noetherian ring and M a finitely generated graded module over $R = A[X_0, \dots, X_n]$. Put $X = \mathbb{P}_A^n$ and $\mathcal{M} = \tilde{M}$.*

- (a) *When ℓ is sufficiently large, $M_\ell \rightarrow H^0(X, \mathcal{M}(\ell))$ is an isomorphism.*
- (b) *When $A = k$ is a field,*

$$\chi(X, \mathcal{M}(\ell)) := \sum_{p=0}^n (-1)^p \dim_k H^p(X, \mathcal{M}(\ell)) = P_M(\ell),$$

where P_M is the Hilbert polynomial of M , cf. [Alg2, Definition 3.1.3].

Remark. (a) The sum $\chi(X, \mathcal{M}(\ell))$ occurring in Proposition 4(b) reminds of the *Euler–Poincaré characteristic* from topology, and we will occasionally refer to it by that term.

(b) The k -vector spaces $H^p(X, \mathcal{M}(\ell))$ appearing here are all finite-dimensional by Theorem 3, so the alternating sum is well-defined.

Proof of Proposition 4. Part (a). An element $m \in M_\ell$ is in the kernel if and only if the restrictions of its image to $\mathbb{P}_A^n \setminus V(X_i)$ vanish for all $i = 0, \dots, n$, i.e., when $m = 0$ in $(M_{X_i})_k$. Then there is some $j \in \mathbb{N}$ such that $X_i^j m = 0$ for $i = 0, \dots, n$. Thus, the kernel of the map in question is

$$\bigcup_{j=0}^{\infty} \left\{ m \in M \mid X_i^j m = 0 \text{ for all } i = 0, \dots, n \right\} =: N \subseteq M.$$

As M is a finitely generated module over R , which is Noetherian by Hilbert’s Basissatz, N is finitely generated as well, hence there is an $j \in \mathbb{N}$ such that X_i^j annihilate N for $i = 0, \dots, n$. Choose some generators of N and let d be their largest degree. Then N vanishes in degrees $> d + (n + 1)j$, and in such degrees the considered map is injective.

For $M = R$ we have $\mathcal{M} = \mathcal{O}_X$ and the surjectivity of $R_\ell \rightarrow H^0(X, \mathcal{O}_X(\ell))$ follows from Theorem 2(a). In the general case, choosing homogeneous generators of M of degrees d_1, \dots, d_N gives a surjection $\bigoplus_{i=1}^N R[d_i] \rightarrow M$ of graded R -modules. Let K be its kernel and $\mathcal{K} = \tilde{K}$, then we get a short exact sequence

$$0 \longrightarrow \mathcal{K} \longrightarrow \bigoplus_{i=1}^N \mathcal{O}_X(d_i) \longrightarrow \mathcal{M} \longrightarrow 0$$

of coherent \mathcal{O}_X -modules. When ℓ is so large that $H^1(X, \mathcal{K}(\ell)) = 0$ (Theorem 3), the long exact cohomology sequence shows that every element of $H^0(X, \mathcal{M}(\ell))$ comes from an element of

$$H^0\left(X, \bigoplus_{i=1}^N \mathcal{O}_X(\ell + d_i)\right) \simeq \bigoplus_{i=1}^N R_{\ell + d_i}$$

(the isomorphism coming from Theorem 2(a)), hence from an element of M_ℓ .

Part (b). By Theorem 3, the summands in $\chi(X, \mathcal{M}(\ell))$ vanish for $p > 0$ and sufficiently large twists ℓ , while the $p = 0$ summand becomes $\dim_k M_\ell = \text{length}_k M_\ell$ when ℓ is sufficiently large by (a). Hence by [Alg2, Theorem 18] the assertion holds when ℓ is large enough, and in particular, it suffices to show that $\chi(X, \mathcal{M}(\ell))$ is given by a polynomial in ℓ . We will show this by induction on n .

If $n = -1$, we have $\mathbb{P}_k^{-1} = \text{Proj } k = \emptyset$ and everything is trivial (whereas the $n = 0$ case doesn’t seem as obvious to me as Professor Franke made it look like). Now let $n \geq 0$ and the assertion be valid for $n - 1$. Let $0 \rightarrow \mathcal{M}' \rightarrow \mathcal{M} \rightarrow \mathcal{M}'' \rightarrow 0$ be a short exact sequence of coherent \mathcal{O}_X -modules.

Claim 1. For all $\ell \in \mathbb{Z}$ we have

$$\chi(X, \mathcal{M}'(\ell)) + \chi(X, \mathcal{M}''(\ell)) = \chi(X, \mathcal{M}(\ell))$$

Indeed, the long exact cohomology sequence associated to the short exact sequence $0 \rightarrow \mathcal{M}'(\ell) \rightarrow \mathcal{M}(\ell) \rightarrow \mathcal{M}''(\ell) \rightarrow 0$ vanishes in cohomological degrees $> n$ and consists of finite-dimensional k -vector spaces by Theorem 3. Using that dimension behaves additively in exact sequences, the claimed additivity of the Euler–Poincaré characteristic follows after an easy calculation.

In particular, when the Euler–Poincaré characteristic is a polynomial in ℓ for two of \mathcal{M}' , \mathcal{M} , and \mathcal{M}'' , so it is for the third. Now let \mathcal{M} be coherent and consider the sequence

$$0 \longrightarrow \mathcal{K} \longrightarrow \mathcal{M} \xrightarrow{X_n} \mathcal{M}(1) \longrightarrow \mathcal{Q} \longrightarrow 0 ,$$

in which \mathcal{K} and \mathcal{Q} are the appropriate kernel and cokernel. Both are clearly coherent. We may split this 4-term sequence into $0 \rightarrow \mathcal{K} \rightarrow \mathcal{M} \rightarrow \mathcal{N} \rightarrow 0$ and $0 \rightarrow \mathcal{N} \rightarrow \mathcal{M}(1) \rightarrow \mathcal{Q} \rightarrow 0$ for some coherent \mathcal{O}_X -module \mathcal{N} to obtain

$$\chi(X, \mathcal{M}(\ell)) = \chi(X, \mathcal{K}(\ell)) + \chi(X, \mathcal{N}(\ell)) = \chi(X, \mathcal{K}(\ell)) + \chi(X, \mathcal{M}(\ell+1)) - \chi(X, \mathcal{Q}(\ell)) ,$$

hence

$$\chi(X, \mathcal{M}(\ell+1)) - \chi(X, \mathcal{M}(\ell)) = \chi(X, \mathcal{Q}(\ell)) - \chi(X, \mathcal{K}(\ell)) .$$

But the right-hand side of this is a polynomial in ℓ . Indeed, \mathcal{K} and \mathcal{Q} are annihilated by X_n , hence they are direct images of coherent sheaves on \mathbb{P}_A^{n-1} under the closed embedding $\mathbb{P}_A^{n-1} \xrightarrow{\sim} V(X_n) \hookrightarrow \mathbb{P}_A^n$ and we can apply the induction hypothesis (and before that, we use Corollary 1.6.1 to pull cohomology of \mathcal{K} and \mathcal{Q} back to \mathbb{P}_A^{n-1}). From well-known elementary facts like [Alg2, Fact 3.1.1(a)] it follows that $\chi(X, \mathcal{M}(\ell))$ is a polynomial in ℓ as well. *q.e.d.*

To finish this section, Professor Franke briefly introduces a somewhat different topic.

Line bundles and Weil divisors on locally Noetherian schemes. Let R be a local Noetherian normal domain (i.e., a domain which is integrally closed in its field of quotients K). Then

$$R = \bigcap_{\text{ht}(\mathfrak{p})=1} R_{\mathfrak{p}} . \tag{*}$$

The proof of this apparently needs *primary decompositions* and may be found in [Ma, Theorem 11.5]. The $R_{\mathfrak{p}}$ appearing here are one-dimensional Noetherian local normal domains, hence *discrete valuation rings* by [Alg2, Theorem 21(e)].

Now let X be a Noetherian normal connected prescheme (cf. [AG1, Definition 2.2.2, Definition 2.4.5]) with generic point η (cf. [AG1, Definition 2.1.3]) and $K = \mathcal{O}_{X, \eta}$ ⁵. It defines a quasi-coherent sheaf of \mathcal{O}_X -modules \mathcal{K} given by

$$\mathcal{K}(U) = \begin{cases} 0 & \text{if } U = \emptyset \\ K & \text{otherwise} \end{cases} .$$

⁵As usual, Franke gives all necessary information while simultaneously hiding everything essential. Since X is Noetherian, so is its underlying topological space by [AG1, Fact 2.2.3(c)]. Also, the stalks $\mathcal{O}_{X, x}$ are normal, hence, in particular, domains for all $x \in X$. Then X is integral by [AG1, Proposition 2.1.4(d)], in particular, irreducible, and thus has a unique generic point η by [AG1, Fact 2.1.9].

Let $X_1 \subseteq X$ be the subset of codimension 1 points. There is a function

$$\operatorname{div}: \mathcal{K}(U)^\times \longrightarrow \bigoplus_{x \in U \cap X_1} \mathbb{Z}$$

given by $\operatorname{div}(f)_x = v_x(f)$ when $f \in K$ and v_x is the valuation of the DVR $\mathcal{O}_{X,x}$ (whose quotient field is K , so it makes sense to put f in there).

By (*) we have

$$\mathcal{O}_X(U)^\times = \ker \left(\mathcal{K}(U)^\times \xrightarrow{\operatorname{div}} \bigoplus_{x \in U \cap X_1} \mathbb{Z} \right)$$

for all affine open subsets $U \subseteq X$. Similarly,

$$\mathcal{O}_X(U) = \{f \in \mathcal{K}(U) \mid \operatorname{div}(f) \geq 0\} ,$$

where $(d_x) \in \bigoplus_{x \in U \cap X_1} \mathbb{Z}$ is considered ≥ 0 iff $d_x \geq 0$ for all $x \in U \cap X_1$ and $\operatorname{div}(0) := \infty$. Let $\operatorname{Div}(X)$ be the group of all formal \mathbb{Z} -linear combinations of elements of X_1 , i.e., $\operatorname{Div}(X) = \bigoplus_{x \in X_1} \mathbb{Z}$. For $D \in \operatorname{Div}(X)$ and open subsets $U \subseteq X$ let

$$\mathcal{O}_X(D)(U) = \{f \in \mathcal{K}(U) \mid \operatorname{div}(f) + D|_U \geq 0\} .$$

When X is locally factorial, $\mathcal{O}_X(D)$ is a line bundle on X (for general normal X it is only a coherent sheaf).

2.3. Projective morphisms

There are several definitions of *projective morphism* around which are in common use. Professor Franke would like to stick with the EGA version. Also the **Proj** construction occurring in the definition is very important and we will describe it first.

Let \mathcal{R} be a graded quasi-coherent \mathcal{O}_X -algebra, where X is a prescheme. That is,

$$\mathcal{R} = \bigoplus_{i=0}^{\infty} \mathcal{R}_i$$

where the \mathcal{R}_i are quasi-coherent \mathcal{O}_X -modules and are equipped with an \mathcal{O}_X -bilinear multiplication $\mathcal{R}_i \times \mathcal{R}_j \rightarrow \mathcal{R}_{i+j}$ which is commutative and associative. Moreover, this multiplication should make \mathcal{R}_0 into a sheaf of rings and the \mathcal{R}_i into sheaves of \mathcal{R}_0 -modules (in particular, multiplication with $1 \in \mathcal{R}_0(U)$ for open $U \subseteq X$ is the identity). Now we define **Proj** $_X(\mathcal{R})$ as follows.

- *Points.* As a set ,

$$\mathbf{Proj}_X(\mathcal{A}) = \left\{ (x, \mathfrak{p}) \left| \begin{array}{l} x \in X, \mathfrak{p} \in \operatorname{Spec}(\mathcal{R}_x) \text{ a homogeneous prime ideal} \\ \text{not containing the augmentation ideal and such} \\ \text{that its preimage under } \mathcal{O}_{X,x} \rightarrow \mathcal{R}_x \text{ is } \mathfrak{m}_{X,x} \end{array} \right. \right\}$$

- *Topology base.* For $U \subseteq X$ open and $f \in \mathcal{R}_m(U)$ for some $m \in \mathbb{N}_0$ put

$$\Omega(U, f) = \{(x, \mathfrak{p}) \mid x \in U \text{ and } \mathfrak{p} \nmid (\text{image of } f \text{ under } \mathcal{R}_m(U) \rightarrow (\mathcal{R}_m)_x \rightarrow \mathcal{R}_x)\}.$$

Since $\mathbf{Proj}_X(\mathcal{R}) = \Omega(X, 1)$ and $\Omega(U, f) \cap \Omega(V, g) = \Omega(U \cap V, f|_{U \cap V} \cdot g|_{U \cap V})$ this is indeed a base for some topology.

- *Local rings.* Put $P = \mathbf{Proj}_X(\mathcal{R})$ for brevity. There is an obvious candidate for the pretender stalks and it is $\mathcal{O}_{P, [x, \mathfrak{p}]} := ((\mathcal{R}_x)_{\mathfrak{p}})_0$.
- *Structure sheaf.* For $\Omega \subseteq P$ open, let

$$\mathcal{O}_Y(\Omega) = \left\{ \rho = (\rho_{x, \mathfrak{p}}) \in \prod_{(x, \mathfrak{p}) \in \Omega} \mathcal{O}_{P, [x, \mathfrak{p}]} \mid \rho \text{ fulfills the coherence condition}^{\text{TM}} \right\}.$$

Here, the *coherence condition*TM says that every $\omega \in \Omega$ has a neighbourhood $\Omega(U, f)$ contained in Ω together with an $r \in (\mathcal{R}(U)_f)_0$ such that whenever $(x, \mathfrak{p}) \in \Omega(U, f)$, we have

$$\rho_{x, \mathfrak{p}} = \left(\text{image of } a \text{ under } \mathcal{R}(U)_f \rightarrow (\mathcal{R}_x)_f \rightarrow (\mathcal{R}_x)_{\mathfrak{p}} = \mathcal{O}_{P, [x, \mathfrak{p}]} \right).$$

Alternatively, \mathcal{O}_P is the sheafification of the presheaf $\Omega(U, f) \mapsto (\mathcal{R}(U)_f)_0$ on the above topology base. Note that we have to put $\mathcal{R}(U)_f := \bigoplus_{i=0}^{\infty} \mathcal{R}_i(U)_f$.⁶

One obtains a sheaf of rings on $P = \mathbf{Proj}_X(\mathcal{R})$ and has a canonical isomorphism $\mathcal{O}_{P, (x, \mathfrak{p})} \xrightarrow{\sim} \mathcal{O}_{P, [x, \mathfrak{p}]}$ sending the image of $\rho = (\rho_{y, \mathfrak{q}}) \in \mathcal{O}_P(\Omega)$ to $\rho_{x, \mathfrak{p}}$.

It follows that $\mathbf{Proj}_X(\mathcal{R})$ is a locally ringed space. There is a continuous map $\mathbf{Proj}_X(\mathcal{R}) \xrightarrow{\pi} X$ defined by $\pi(x, \mathfrak{p}) = x$ (π is continuous as $\pi^{-1}(U) = \Omega(U, 1)$ for $U \subseteq X$ open). Using $\pi^*: \mathcal{O}_X \rightarrow \pi_* \mathcal{O}_P$ given by

$$\pi^*(f) = \left(\text{image of } f \text{ under } \mathcal{O}_X(U) \rightarrow \mathcal{O}_{X, x} \rightarrow (\mathcal{R}_0)_x \rightarrow ((\mathcal{R}_x)_{\mathfrak{p}})_0 \right)_{(x, \mathfrak{p}) \in \pi^{-1}(U)}$$

as the algebraic component one has a morphism of locally ringed spaces.

This construction is base-local. That is, $\mathbf{Proj}_U(\mathcal{R}|_U) \simeq \pi^{-1}(U)$ for all open subsets (hence subpreschemes) $U \subseteq X$. When R is a graded ring, $X = \text{Spec } R_0$ and $\mathcal{R} = \tilde{R}$, then $\mathbf{Proj}_X(\mathcal{R}) \simeq \text{Proj } R$ by comparing their definitions. Since the following assertions are all base-local, they follow from the corresponding assertions about $\text{Proj } R$ we proved in Proposition 2.2.1.

Fact 1. (a) $\mathbf{Proj}_X(\mathcal{R})$ is a prescheme. In fact, for any affine open $U \subseteq X$, $\pi^{-1}(U)$ is a quasi-compact scheme.

(b) The morphism π is separated. When \mathcal{R} is locally of finite type as an \mathcal{O}_X -algebra, then π is of finite type. If X is in addition Noetherian (resp. locally Noetherian), then so is $\mathbf{Proj}_X(\mathcal{R})$.

⁶This is actually relevant, as Professor Franke explains that $\mathcal{R}(U)$ is the set of all $(r_i) \in \prod_{i=0}^{\infty} \mathcal{R}_i(U)$ such that for every $x \in U$, the image of r_i in $(\mathcal{R}_i)_x$ is non-zero only for finitely many i (that's how infinite coproducts of sheaves of modules work, deal with it). So a priori, $\mathcal{R}(U) \neq \bigoplus_{i=0}^{\infty} \mathcal{R}_i(U)$ unless U is quasi-compact, and naive localization may give the wrong result.

- (c) When \mathcal{R} is generated by \mathcal{R}_0 and \mathcal{R}_1 as an \mathcal{O}_X -algebra, then the $\mathcal{O}_{\mathbf{Proj}_X(\mathcal{R})}$ -module $\mathcal{O}(\ell) = \mathcal{O}_{\mathbf{Proj}_X(\mathcal{R})}(\ell)$ obtained by replacing homogeneous degree 0 in the definition of the pretender stalk and in the coherence conditionTM by homogeneous degree ℓ is a line bundle.

Moreover, in this case $\mathcal{O}(k)^{-1} \simeq \mathcal{O}(-k)$ (where the *inverse* of a line bundle is defined as in Remark 2.2.4(a)) and there is an isomorphism

$$\mathcal{O}(k) \otimes_{\mathcal{O}_{\mathbf{Proj}_X(\mathcal{R})}} \mathcal{O}(\ell) \xrightarrow{\sim} \mathcal{O}(k + \ell)$$

defined by the multiplication $\mathcal{R}_k \times \mathcal{R}_\ell \rightarrow \mathcal{R}_{k+\ell}$.

Finally, we have a canonical morphism $\mathcal{R}_k \xrightarrow{\rho_k} \pi_* \mathcal{O}(k)$ sending $r \in \mathcal{R}_k(U)$ to its images under $\mathcal{R}_k(U) \rightarrow ((\mathcal{R}_x)_{\mathfrak{p}})_k$ with (x, \mathfrak{p}) running over $\pi^{-1}(U)$.

Remark 1. (a) So far, we have seen three kinds of inverse image functors. Let $f: X \rightarrow Y$ be a continuous map of topological spaces, where for f^* we additionally assume that X and Y are ringed with structure sheaves $\mathcal{O}_X, \mathcal{O}_Y$. Then we have

$$\begin{aligned} f^b: \text{PreShv}(Y) &\longrightarrow \text{PreShv}(X) & \text{left-adjoint to} & \text{PreShv}(X) \xrightarrow{f_*} \text{PreShv}(Y) \\ f^\sharp: \text{Shv}(Y) &\longrightarrow \text{Shv}(X) & \text{left-adjoint to} & \text{Shv}(X) \xrightarrow{f_*} \text{Shv}(Y) \\ f^*: \mathcal{O}_Y\text{-Mod} &\longrightarrow \mathcal{O}_X\text{-Mod} & \text{left-adjoint to} & \mathcal{O}_X\text{-Mod} \xrightarrow{f_*} \mathcal{O}_Y\text{-Mod} \end{aligned}$$

defined as follows. For a presheaf \mathcal{G} on Y define $f^b \mathcal{G}$ by

$$f^b \mathcal{G}(U) = \varinjlim_{V \supseteq f(U) \text{ open}} \mathcal{G}(V)$$

for open subsets $U \subseteq X$. This is usually not a sheaf, so we put $f^\sharp \mathcal{G} = (f^b \mathcal{G})^{\text{sh}}$. Note that

$$(f^b \mathcal{G})_x = \varinjlim_{U \ni x} f^b \mathcal{G}(U) = \varinjlim_{U \ni x} \varinjlim_{V \supseteq f(U)} \mathcal{G}(V) = \varinjlim_{V \ni f(x)} \mathcal{G}(V) = \mathcal{G}_{f(x)},$$

thus also $(f^\sharp \mathcal{G})_x = \mathcal{G}_{f(x)}$ since the stalks of the sheafification are the same (cf. [AG1, Proposition 1.2.1(a)]). In fact, the stalk is an inverse image itself: We have $\mathcal{G}_x = i_x^b \mathcal{G}(\{x\})$, where $i_x: \{x\} \rightarrow X$ is the inclusion of $x \in X$. If $g: Y \rightarrow Z$ is another continuous map, we have canonical functor isomorphisms $(gf)^b = f^b g^b$ and $(gf)^\sharp = f^\sharp g^\sharp$.

Now let \mathcal{M} be a sheaf of modules on the ringed space (Y, \mathcal{O}_Y) . In general, $f^\sharp \mathcal{M}$ will only be a $f^\sharp \mathcal{O}_Y$ -module, so we need to tensor it by \mathcal{O}_X to get the pullback $f^* \mathcal{M}$. That is, $f^* \mathcal{M} = f^\sharp \mathcal{M} \otimes_{f^\sharp \mathcal{O}_Y} \mathcal{O}_X$. By Remark 2.2.3, its stalks are given by

$$(f^* \mathcal{M})_x = \mathcal{M}_{f(x)} \otimes_{\mathcal{O}_{Y, f(x)}} \mathcal{O}_{X, x}$$

and from this we can describe $f^* \mathcal{M}$ by another one of our beautiful coherence condition characterizations for (I won't include this here). In particular, we see that f^* is base-local.

- (b) Since $f^* \mathcal{O}_Y = \mathcal{O}_X$ (this is clear on stalks) and f^* preserves direct sums (in fact, as a left-adjoint functor it preserves arbitrary colimits, cf. Remark A.1.4), so inverse images of vector bundles (resp. line bundles) are vector bundles (resp. line bundles) again by base-locality of f^* .

- (c) Moreover, when f is a morphism between affine schemes $X = \operatorname{Spec} B$ and $Y = \operatorname{Spec} A$ (thus) coming from a ring morphism $A \rightarrow B$, then $f^* \tilde{M} = (B \otimes_A M)^\sim$ for all A -modules M (which is easily seen stalk-wise). It follows that f^* restricts to a functor $f^*: \operatorname{QCoh}(Y) \rightarrow \operatorname{QCoh}(X)$.
- (d) Also note that f^* commutes with tensor products, i.e., $f^*(\mathcal{M} \otimes_{\mathcal{O}_Y} \mathcal{N}) = f^* \mathcal{M} \otimes_{\mathcal{O}_X} f^* \mathcal{N}$. Indeed, this can be easily verified by looking at stalks.

An adjunction for Proj. In the lecture the question came up whether **Proj** (or even ordinary Proj) satisfies an adjunction similar to (1.6.1). It turns out that such an adjunction (in an appropriate sense) indeed exists, but it will be way more subtle than you might believe.

Recall the notion of S -preschemes from [AG1, Definition 1.5.7]. Let R be an \mathbb{N}_0 -graded ring generated by R_0 and R_1 , let $S = \operatorname{Spec} R_0$ and $X = \operatorname{Spec} A \xrightarrow{\xi} S$ be an S -prescheme.

- Let \mathfrak{M} be the set of pairs (φ, τ) where $X \xrightarrow{\varphi} \operatorname{Proj} R$ is a morphism of S -preschemes and $\tau: \varphi^* \mathcal{O}_{\operatorname{Proj} R}(1) \xrightarrow{\sim} \mathcal{O}_X$ a trivialization of $\varphi^* \mathcal{O}_{\operatorname{Proj} R}(1)$.
- Let \mathfrak{N} be the set of all surjective morphisms $A \otimes_{R_0} R \xrightarrow{\alpha} A[T]$ of \mathbb{N}_0 -graded A -algebras (where T has degree 1).

Lemma 1. *In the above situation, we have a bijection $\mathfrak{M} \simeq \mathfrak{N}$ which is compatible with restrictions to affine open subsets of X and defined as follows.*

- (a) To $\alpha \in \mathfrak{N}$ we associate the morphism $X \simeq \mathbb{P}_A^0 \simeq \operatorname{Proj} A[T] \rightarrow \operatorname{Proj}(A \otimes_{R_0} R) \rightarrow \operatorname{Proj} R$ and the isomorphism $\varphi^* \mathcal{O}_{\operatorname{Proj} R}(1) \simeq \mathcal{O}_{\mathbb{P}_A^0}(1) \simeq \mathcal{O}_X$.
- (b) Let $(\varphi, \tau) \in \mathfrak{M}$. Every element $r \in R_k$ defines a global section $r \in \mathcal{O}_{\operatorname{Proj} R}(k)(\operatorname{Proj} R)$ and we put $\alpha(a \otimes r) = a \cdot \tau^{\otimes k}(r) \cdot T^k$.

Not quite a proof. Let us first justify that the given descriptions are well-defined. The morphism $\operatorname{Proj} A[T] \rightarrow \operatorname{Proj}(A \otimes_{R_0} R)$ in (a) comes from the fact that $A \otimes_{R_0} R \xrightarrow{\alpha} A[T]$ is surjective, so the conditions from Remark 2.2.2 are clearly satisfied. The other one is the canonical morphism we get from $\operatorname{Proj}(A \otimes_{R_0} R) \simeq X \times_S \operatorname{Proj} R$.⁷

Why is $\varphi^* \mathcal{O}_{\operatorname{Proj} R} \simeq \mathcal{O}_{\mathbb{P}_A^0}(1)$? First of all, we may cover $\operatorname{Proj} R$ by affine open subsets $\operatorname{Proj} R \setminus V(f)$ for $f \in R_1$, by assumption. Moreover, their images $\alpha(1 \otimes f)$ in $A[T]_1$ generate the augmentation ideal of $A[T]$ by surjectivity of α . On such a subset $\operatorname{Proj} R \setminus V(f) \simeq \operatorname{Spec}(R_f)_0$, $\mathcal{O}_{\operatorname{Proj} R}(1)$ is given by $((R_f)_1)^\sim$ (Proposition 2.2.1(c)). Hence $\varphi^* \mathcal{O}_{\operatorname{Proj} R}$ restricted to $\operatorname{Spec}(A[T]_{\alpha(1 \otimes f)})_0$ is given by the $(A[T]_{\alpha(1 \otimes f)})_0$ -module $(A[T]_{\alpha(1 \otimes f)})_0 \otimes_{(R_f)_0} (R_f)_1$ (by Remark 1(c)) and we get an isomorphism

$$\begin{aligned} (A[T]_{\alpha(1 \otimes f)})_0 \otimes_{(R_f)_0} (R_f)_1 &\xrightarrow{\sim} (A[T]_{\alpha(1 \otimes f)})_1 \\ a \otimes \frac{r}{f^k} &\longmapsto \frac{\alpha(1 \otimes r)}{\alpha(1 \otimes f)^k} \cdot a, \end{aligned}$$

which is canonical enough to be easily globalized.

⁷And this behaviour of Proj is easy to see from $\operatorname{Proj} R \setminus V(f) \simeq \operatorname{Spec}(R_f)_0$ for homogeneous $f \in R_+$ (Proposition 2.2.1(c)), since $(A \otimes_{R_0} R)_{1 \otimes f} = A \otimes_{R_0} (R_f)_0$ and fibre products are base-local.

For (b), the question we should really ask is why α is surjective, as not all elements of the global section of $\varphi^* \mathcal{O}_{\text{Proj } R}(k)$ need to come from an element $r \in R_k$. However, we can do the following. Let $f \in R_1$ and $g \in A$ such that $\text{Spec } A_g$ lies in the preimage of $\text{Proj } R \setminus V(f) \simeq (R_f)_0$ under φ . By quasi-compactness, we find finitely many such f_1, \dots, f_n and g_1, \dots, g_n such that the $\text{Spec } A_{g_i}$ cover $X = \text{Spec } A$. On $\text{Spec } A_{g_i}$, $\varphi^* \mathcal{O}_{\text{Proj } R}(k)$ is given by the A_{g_i} -module $A_{g_i} \otimes_{(R_f)_0} (R_f)_k$ and $\tau^{\otimes k}$ induces an isomorphism

$$\tau^{\otimes k}: A_{g_i} \otimes_{(R_f)_0} (R_f)_k \xrightarrow{\sim} A_{g_i},$$

hence there is some preimage $\sum_{j=1}^{n_j} a_j \otimes \rho_j$ of $1 \in A_{g_i}$. Since R is generated by R_0 and R_1 , $\rho_j \in (R_f)_k$ can be written as a sum of products of an element of R_k and an element of $(R_f)_0$. The latter can be sucked into the A_{g_i} factor of the tensor product. Multiplying by a suitable power of g_i , we find an element of $A \otimes_{R_0} R_k$ which is mapped to some power $g_i^{k_i}$ by $\tau^{\otimes k}$. Since g_1, \dots, g_n generate A , so do $g_1^{k_1}, \dots, g_n^{k_n}$ and the desired surjectivity follows quite easily.

To show that (a) and (b) are indeed inverse seems to be a (doable) technical nightmare and I will rely on believing Professor Franke here. *q.e.d.*

Having dealt with the local case, we now proceed to describe an “adjunction” of the desired type in general.

Let S be any prescheme, $X \xrightarrow{\xi} S$ any S -prescheme, \mathcal{L} a line bundle on X and \mathcal{R} a quasi-coherent graded \mathcal{O}_S -algebra generated by \mathcal{R}_0 and \mathcal{R}_1 . Put $\mathbf{Proj}_S(\mathcal{R}) = P$.

- Let $\mathfrak{M}(X)$ be the set of pairs (φ, τ) where $X \xrightarrow{\varphi} P$ is a morphism of S -preschemes and $\tau: \varphi^* \mathcal{O}_P(1) \xrightarrow{\sim} \mathcal{L}$ an isomorphism of line bundles.
- Let $\mathfrak{N}(X)$ be the set of all morphisms of graded \mathcal{O}_X -algebras⁸ $\xi^* \mathcal{R} \rightarrow \bigoplus_{k=0}^{\infty} \mathcal{L}^{\otimes k}$ which induce surjections on stalks.

Recall that we have a projection $P \xrightarrow{\pi} S$. Let $\pi^* \mathcal{R}_k \xrightarrow{\varepsilon_k} \mathcal{O}_P(k)$ be the morphism associated to $\mathcal{R}_k \xrightarrow{\rho_k} \pi_* \mathcal{O}_P(k)$ from Fact 1(d) by the π^* - π_* adjunction.

Proposition 1. *We obtain a bijection $\mathfrak{M}(X) \simeq \mathfrak{N}(X)$ by associating to $(\varphi, \tau) \in \mathfrak{M}(X)$ the morphism*

$$\xi^* \mathcal{R}_k \simeq \varphi^* \pi^* \mathcal{R}_k \xrightarrow{\varphi^*(\varepsilon_k)} \varphi^* \mathcal{O}_P(k) \simeq \varphi^* \mathcal{O}_P(1)^{\otimes k} \xrightarrow{\tau^{\otimes k}} \mathcal{L}.$$

Sketch of a proof. As $U \mapsto \mathfrak{M}(U)$ and $U \mapsto \mathfrak{N}(U)$ (for $U \subseteq X$ open) are easily seen to be sheaves, it is enough to show this on an appropriate topology base of X . We use affine open U such that $\mathcal{L}|_U$ is trivial and $\xi(U)$ is contained in an affine open subset of S , so that Lemma 1 may be applied. *q.e.d.*

By choosing a representative for all possible isomorphism classes of line bundles on X which $\varphi^* \mathcal{O}_P(1)$ may belong to (and by Remark 1(b) it is indeed a line bundle on X), Proposition 1 gives

⁸The multiplication on $\bigoplus_{k=0}^{\infty} \mathcal{L}^{\otimes k}$ is given by the tensor product, clearly making this into a graded \mathcal{O}_X -algebra.

Corollary 1. *In the situation of Proposition 1, $\mathrm{Hom}_{S\text{-PreSch}}(X, \mathbf{Proj}_S(\mathcal{R}))$ is in canonical bijection with the set of pairs (\mathcal{L}, α) , where \mathcal{L} is a representative of an isomorphism class of line bundles on X and α a morphism*

$$\alpha: \xi^* \mathcal{R} \longrightarrow \bigoplus_{k=0}^{\infty} \mathcal{L}^{\otimes k} \quad (1)$$

of graded \mathcal{O}_X -algebras defining surjections on stalks.

Corollary 2. *Under the assumptions of Proposition 1, let $T \xrightarrow{\tau} S$ be an S -prescheme and put $P_T = \mathbf{Proj}_T(\tau^* \mathcal{R})$. Then there is a canonical isomorphism $P_T \xrightarrow{\sim} P \times_S T$ defined by the projection $P_T \xrightarrow{\pi_T} T$ and the morphism $P_T \rightarrow P$ (over S) defined by Proposition 1 and the morphism*

$$(\tau \pi_T)^* \mathcal{R}_k = \pi_T^* \tau^* \mathcal{R}_k \xrightarrow{\varepsilon_k} \mathcal{O}_{P_T}(k),$$

where ε_k is defined similar to ε_k in Proposition 1.

Sketch of a proof. Let $X \xrightarrow{t} T$ and $X \xrightarrow{p} P$ be morphisms of preschemes such that $\tau t = \pi p$. By Corollary 1, p corresponds to a morphism

$$\alpha: p^* \pi^* \mathcal{R} \longrightarrow \bigoplus_{k=0}^{\infty} \mathcal{L}^{\otimes k}.$$

But $p^* \pi^* \mathcal{R} = t^*(\tau^* \mathcal{R})$, so α induces a morphism $X \xrightarrow{\xi} P_T$ by Corollary 1 applied to $\tau^* \mathcal{R}$ this time. One can show that this gives P_T the required universal property. *q.e.d.*

Remark 2. The isomorphism $\mathbf{Proj}_T(\tau^* \mathcal{R}) \xrightarrow{\sim} \mathbf{Proj}_S(\mathcal{R}) \times_S T$ exists in full generality, even when \mathcal{R} is not generated by \mathcal{R}_0 and \mathcal{R}_1 . To prove this, one can reduce this to an affine-local question (as usual) and then use $\mathrm{Proj}(R \otimes_{R_0} A) \simeq \mathrm{Proj} R \times_{\mathrm{Spec} R_0} \mathrm{Spec} A$.

Let \mathcal{R} be an \mathbb{N}_0 -graded quasi-coherent \mathcal{O}_S -algebra, \mathcal{L} a line bundle on S and

$$\mathcal{R}^{(\mathcal{L})} = \bigoplus_{k=0}^{\infty} \mathcal{R}_k \otimes_{\mathcal{O}_S} \mathcal{L}^{\otimes k}$$

with the \mathcal{O}_S -algebra structure defined by $(r \otimes \lambda) \cdot (s \otimes \mu) = (rs) \otimes (\lambda \otimes \mu)$ for $r \in \mathcal{R}_k(U)$, $s \in \mathcal{R}_\ell(U)$, $\lambda \in \mathcal{L}^{\otimes k}(U)$, and $\mu \in \mathcal{L}^{\otimes \ell}(U)$. We put $P^{(\mathcal{L})} = \mathbf{Proj}_S(\mathcal{R}^{(\mathcal{L})})$ and let ρ be the projection $P^{(\mathcal{L})} \rightarrow S$.

Corollary 3. *There is a canonical isomorphism $i: P^{(\mathcal{L})} \xrightarrow{\sim} P$ together with an isomorphism*

$$\iota: i^* \mathcal{O}_P(1) \otimes_{\mathcal{O}_P} \rho^* \mathcal{L} \xrightarrow{\sim} \mathcal{O}_{P^{(\mathcal{L})}}(1)$$

such that

$$\rho^*(\mathcal{R}_1 \otimes_{\mathcal{O}_S} \mathcal{L}) \simeq \rho^* \mathcal{R}_1 \otimes_{\mathcal{O}_P} \rho^* \mathcal{L} \xrightarrow{i^*(\varepsilon_1) \otimes \mathrm{id}_{\rho^* \mathcal{L}}} i^* \mathcal{O}_P(1) \otimes_{\mathcal{O}_P} \rho^* \mathcal{L} \xrightarrow{\sim} \mathcal{O}_{P^{(\mathcal{L})}}(1)$$

coincides with

$$\rho^*(\mathcal{R}_1 \otimes_{\mathcal{O}_S} \mathcal{L}) \xrightarrow{\varepsilon_1} \mathcal{O}_{P^{(\mathcal{L})}}(1).$$

Sketch of a proof (what did you expect). We construct an epimorphism

$$\alpha: \rho^* \mathcal{R}^{(\mathcal{L})} \longrightarrow \bigoplus_{k=0}^{\infty} \mathcal{O}_{P(\mathcal{L})}(k) \otimes_{\mathcal{O}_{P(\mathcal{L})}} \rho^* \mathcal{L}^{\otimes(-k)} \simeq \bigoplus_{k=0}^{\infty} \left(\mathcal{O}_{P(\mathcal{L})}(1) \otimes_{\mathcal{O}_{P(\mathcal{L})}} \mathcal{L}^{-1} \right)^{\otimes k}.$$

By Corollary 1, α induces a morphism $i: \mathbf{Proj}_S(\mathcal{R}^{(\mathcal{L})}) \rightarrow \mathbf{Proj}_S(\mathcal{R})$. Then i is easily seen to be an isomorphism since we can construct an inverse in quite a similar fashion. And the rest of the assertions then follows quite easily.

To construct α , note that

$$\rho^* \mathcal{R} \simeq \rho^* \left(\bigoplus_{k=0}^{\infty} \mathcal{R}_k \otimes_{\mathcal{O}_S} \mathcal{L}^{\otimes k} \otimes_{\mathcal{O}_S} \mathcal{L}^{\otimes(-k)} \right) \simeq \bigoplus_{k=0}^{\infty} \rho^* \mathcal{R}_k^{(\mathcal{L})} \otimes_{\mathcal{O}_{P(\mathcal{L})}} \rho^* \mathcal{L}^{\otimes(-k)}$$

using that ρ^* commutes with direct sums (arbitrary colimits actually, as ρ^* is a left-adjoint functor) and tensor products (by Remark 1(d)). Now all we need to do is to prove the following Lemma 2 (and apply it to ρ and $\mathcal{R}^{(\mathcal{L})}$ instead of π and \mathcal{R}). *q.e.d.*

Lemma 2. *The canonical morphism $\pi^* \mathcal{R}_k \xrightarrow{\varepsilon_k} \mathcal{O}_P(k)$ associated to $\mathcal{R}_k \xrightarrow{\rho_k} \pi_* \mathcal{O}_P(k)$ from Fact 1(d) by the π^* - π_* adjunction is an epimorphism.*

Proof. It suffices to show this for affine open subsets $U \subseteq S$. Let $\mathcal{R}|_U = \tilde{R}$, then $\pi^{-1}(U) = \text{Proj } R$ and we need to show that $\pi^* \tilde{R}_k \rightarrow \mathcal{O}(k)$ is an epimorphism. On affine open subsets of the form $\text{Proj } R \setminus V(f)$ for $f \in R_1$ (and $\text{Proj } R$ may be covered by such subsets as \mathcal{R} is generated by \mathcal{R}_0 and \mathcal{R}_1) we know from Remark 1(c) that $\pi^* \tilde{R}_k$ is given by the $(R_f)_0$ -module $R_k \otimes_{\mathcal{O}_S(U)} (R_f)_0$ and $\mathcal{O}(k)$ by $(R_f)_k$. But since f has homogeneous degree 1 and R_k is generated by R_0 and R_1 , every element of $x \in (R_f)_k$ can be written as $x = \sum_{i=1}^N x_i \varepsilon_i$ with $x_i \in R_k$ and $\varepsilon_i \in (R_f)_0$, so ε_k is easily seen to be surjective on these subsets, hence on stalks and that's all we need. *q.e.d.*

Let \mathcal{R} and \mathcal{S} be \mathbb{N}_0 -graded \mathcal{O}_S -algebras satisfying the assumptions of Proposition 1 and let $\mathcal{T} = \bigoplus_{k=0}^{\infty} \mathcal{T}_k$, where $\mathcal{T}_k = \mathcal{R}_k \otimes_{\mathcal{O}_S} \mathcal{S}_k$, equipped with the obvious \mathcal{O}_S -algebra structure. Let $X = \mathbf{Proj}_S(\mathcal{R}) \xrightarrow{\pi_X} S$, $Y = \mathbf{Proj}_S(\mathcal{S}) \xrightarrow{\pi_Y} S$ and $Z = X \times_S Y$. Let $Z \xrightarrow{p_X} X$ and $Z \xrightarrow{p_Y} Y$ be the projections to the two factors and $\zeta = \pi_X p_X = \pi_Y p_Y$. Finally, let $\mathcal{L} = p_X^* \mathcal{O}_X(1) \otimes_{\mathcal{O}_Z} p_Y^* \mathcal{O}_Y(1)$ be a line bundle on Z .

We have epimorphisms of \mathcal{O}_Z -modules

$$\zeta^* \mathcal{T}_k \simeq \zeta^* \mathcal{R}_k \otimes_{\mathcal{O}_Z} \zeta^* \mathcal{S}_k \longrightarrow p_X^* \mathcal{O}_X(k) \otimes_{\mathcal{O}_Z} p_Y^* \mathcal{O}_Y(k) \simeq \mathcal{L}^{\otimes k}$$

defined by the tensor product of $p_X^* \left(\pi_X^* \mathcal{R}_k \xrightarrow{\varepsilon_X} \mathcal{O}_X(1) \right)$ and $p_Y^* \left(\pi_Y^* \mathcal{S}_k \xrightarrow{\varepsilon_Y} \mathcal{O}_Y(1) \right)$. These epimorphisms intertwine the product $\zeta^* \mathcal{T}_k \times \zeta^* \mathcal{T}_\ell \rightarrow \zeta^* \mathcal{T}_{k+\ell}$ on \mathcal{T} with the tensor multiplication $\mathcal{L}^{\otimes \ell} \otimes_{\mathcal{O}_S} \mathcal{L}^{\otimes k} \rightarrow \mathcal{L}^{\otimes(k+\ell)}$. Application of Proposition 1 gives a morphism $Z \rightarrow \mathbf{Proj}_S(\mathcal{T})$ of S -preschemes.

Proposition 2. *This is an isomorphism.*

Example 1. For a prescheme S , put $\mathbb{P}_S^n = \mathbf{Proj}_S \mathcal{O}_S[X_0, \dots, X_n]$ (note that in the special case $S = \mathrm{Spec} R$ this gives $\mathbb{P}_S^n = \mathbb{P}_R^n$, as one could expect). We have the closed embedding $\mathbb{P}_S^m \times \mathbb{P}_S^n \xrightarrow{\sigma} \mathbb{P}_S^{m+n+nm}$ defined by

$$\mathcal{O}_S[X_0, \dots, X_m]_k \otimes_{\mathcal{O}_S} \mathcal{O}_S[Y_0, \dots, Y_n]_k \longleftarrow \mathcal{O}_S[Z_{i,j} \mid 1 \leq i \leq m, 1 \leq j \leq n]_k$$

sending $Z_{i,j}$ to $X_i \otimes Y_j$. This is the so-called *Segre embedding*.

Sketch of a proof of Proposition 2. One confirms that for any morphism of preschemes $T \xrightarrow{\tau} S$, any line bundle \mathcal{L} on T and any morphism

$$\alpha: \tau^* \mathcal{T} \longrightarrow \bigoplus_{i=0}^{\infty} \mathcal{L}^{\otimes k}$$

of \mathcal{O}_T -algebras which is an epimorphism on stalks one has a decomposition $\mathcal{L} \simeq \mathcal{M} \otimes_{\mathcal{O}_T} \mathcal{N}$ with line bundles \mathcal{M} and \mathcal{N} on T and epimorphisms

$$\beta: \tau^* \mathcal{R} \longrightarrow \bigoplus_{i=0}^{\infty} \mathcal{M}^{\otimes k} \quad \text{and} \quad \gamma: \tau^* \mathcal{S} \longrightarrow \bigoplus_{i=0}^{\infty} \mathcal{N}^{\otimes k}$$

of graded \mathcal{O}_T -algebras, whose (homogeneous component-wise) tensor product is α . This will verify the required universal property for $\mathbf{Proj}_S(\mathcal{T})$.

To construct \mathcal{M} and \mathcal{N} , we can do the following. Choose an affine open subset $U \subseteq S$ where \mathcal{L} trivializes and let $\mathcal{R}|_U = \tilde{A}$, $\mathcal{S}|_U = \tilde{B}$, $\mathcal{T}|_U = \tilde{C}$, and $\mathcal{L}|_U = \tilde{L}$ (with $L \simeq \mathcal{O}_S(U)$). We may take $\mathcal{M}|_U = \tilde{M}$ where $M \subseteq L$ is the image of $\tau^*((A_1 \otimes 1)^\sim) \subseteq \tau^* \tilde{C}_1$ (and for \mathcal{N} we do quite the same). Then $M \otimes_{\mathcal{O}_S(U)} N \simeq L$, so M and N are invertible $\mathcal{O}_S(U)$ -modules and thus locally free of rank one⁹, i.e., $\mathcal{M}|_U$ and $\mathcal{N}|_U$ are line bundles.

Now the construction seems canonical enough that it can be globalized. *q.e.d.*

We are finally ready to define what a *projective morphism* is.

Definition 1. Let $X \xrightarrow{\xi} S$ be a morphism of preschemes.

- (a) The morphism ξ is called **projective** if there is an \mathbb{N}_0 -graded quasi-coherent \mathcal{O}_S -algebra \mathcal{R} generated by \mathcal{R}_1 , and \mathcal{R}_1 is a locally finitely generated \mathcal{O}_S -module, together with an isomorphism $X \xrightarrow{\sim} \mathbf{Proj}_S(\mathcal{R})$ of S -preschemes.
- (b) The morphism ξ is called **strongly projective** if it factors as

$$X \xrightarrow{i} \mathbb{P}_S^n \longrightarrow S,$$

where i is a closed embedding and $\mathbb{P}_S^n = \mathbf{Proj}_S \mathcal{O}_S[X_0, \dots, X_n]$.

⁹See [Stacks, Tag 0AFW]. Note that the *omitted details* in the proof of Lemma 15.99.2 are basically that $\mathrm{Hom}_R(M, R)_f \simeq \mathrm{Hom}_{R_f}(M_f, R_f)$, for which we need that M is finitely presented (compare [Hom, p. 9]). But this always holds for modules which are locally free of finite rank. Actually, being finitely presented is a local property, cf. [Stacks, Tag 00EO].

Remark. Definition 1(a) (at least in the Noetherian case) is the EGA definition while (b) is Hartshorne's. It turns out that (b) implies (a). In between these two is the class of morphisms ξ which may be factored $X \rightarrow \mathbb{P}(\mathcal{E}) \rightarrow S$, where \mathcal{E} is a vector bundle and

$$\mathbb{P}(\mathcal{E}) = \mathbf{Proj}_S \left(\bigoplus_{k=0}^{\infty} \mathcal{E}^{\otimes k} \right).$$

Both definitions are in use.

Fact 2. If $X \xrightarrow{\xi} Y$ is projective (or strongly projective) and the base change

$$\tilde{X} = X \times_Y \tilde{Y} \xrightarrow{\tilde{\xi}} \tilde{Y}$$

is projective (resp. strongly projective) again. If $\tilde{Y} \xrightarrow{v} Y$ is also (strongly) projective, then the same holds for $\tilde{X} \rightarrow Y$.

Proof. First suppose that ξ is projective, i.e., $X \simeq \mathbf{Proj}_Y(\mathcal{R})$ for some suitable \mathcal{R} as in Definition 1(a). By Corollary 2, $\tilde{X} \simeq \mathbf{Proj}_{\tilde{Y}}(v^*\mathcal{R})$, so $\tilde{\xi}$ is projective. Moreover, when v is projective, we have $\tilde{Y} \simeq \mathbf{Proj}_Y(\mathcal{S})$ for some suitable \mathcal{S} , hence $\tilde{X} \simeq \mathbf{Proj}_Y(\mathcal{T})$ with \mathcal{T} as in Proposition 2.

Now let ξ be strongly projective and $X \xrightarrow{i} \mathbb{P}_Y^n \rightarrow Y$ the associated factorization of ξ . We obtain a factorization of $\tilde{\xi}$ via

$$\tilde{X} \xrightarrow{\tilde{i}} \mathbb{P}_Y^n \times_Y \tilde{Y} \longrightarrow \tilde{Y},$$

in which \tilde{i} is a closed immersion (these guys are stable under base change by [AG1, Corollary 1.3.3]) and

$$\mathbb{P}_Y^n \times_Y \tilde{Y} \simeq \mathbf{Proj}_{\tilde{Y}}(v^*\mathcal{O}_Y[X_0, \dots, X_n]) \simeq \mathbf{Proj}_{\tilde{Y}} \mathcal{O}_{\tilde{Y}}[X_0, \dots, X_n] \simeq \mathbb{P}_{\tilde{Y}}^n$$

(using $v^*\mathcal{O}_Y = \mathcal{O}_{\tilde{Y}}$, cf. Remark 1(b)). This shows that $\tilde{\xi}$ is strongly projective again. If moreover v is strongly projective as well, $\tilde{X} \rightarrow Y$ factors over some

$$\tilde{X} \longrightarrow \mathbb{P}_Y^n \times_Y \mathbb{P}_Y^m \xrightarrow{\sigma} \mathbb{P}_Y^{m+n+mn} \longrightarrow Y,$$

in which σ is the Segre embedding from Example 1.

q.e.d.

Proposition 3. Let $X \xrightarrow{i} Y$ be a closed immersion and $Y \xrightarrow{f} S$ a projective (resp. strongly projective) morphism. Then fi is (strongly) projective again.

Proof. For strong projectiveness, this is trivial since the class of closed immersions is closed under composition.

Let f be projective and $Y = \mathbf{Proj}_S(\mathcal{R})$ where \mathcal{R} is as in Definition 1(a). Let \mathcal{I}_X be the sheaf of ideals defining the closed subscheme $X \subseteq Y$ and let $\mathcal{I}_n \subseteq \mathcal{R}_n$ be the preimage of $f_*\mathcal{I}_X(n) \subseteq f_*\mathcal{O}_Y(n)$ under the morphism $\mathcal{R}_n \rightarrow f_*\mathcal{O}_Y(n)$. Let $\mathcal{I} = \bigoplus_{n=0}^{\infty} \mathcal{I}_n$ and put $\tilde{\mathcal{R}} = \mathcal{R}/\mathcal{I}$ and $\tilde{X} = \mathbf{Proj}_S(\tilde{\mathcal{R}})$.

The morphism $\mathcal{R} \rightarrow \tilde{\mathcal{R}}$ defines a closed embedding $\tilde{X} \rightarrow Y$. Indeed, locally, this looks like $\text{Proj } R/I \rightarrow \text{Proj } R$, where $I \subseteq R$ is a homogeneous ideal, and $\text{Proj } R/I$ is mapped homeomorphically onto $V(I) \subseteq \text{Proj } R$. Moreover, $((R/I)_{\mathfrak{p}/I})_0 \simeq (R_{\mathfrak{p}})_0/(I_{\mathfrak{p}})_0$ for all homogeneous prime ideals $\mathfrak{p} \supseteq I$, so we get surjections on stalks and thus have all required properties.

We claim that $\tilde{X} = X$ as closed subpreschemes of Y , proving the claim as $\tilde{X} \rightarrow S$ is projective. How can we picture \tilde{X} ? The closed subprescheme \tilde{X} is surely cut out by some quasi-coherent sheaf of ideals $\mathcal{I}_X \subseteq \mathcal{O}_Y$, so the question is how does \mathcal{I}_X look and how is it related to \mathcal{I} and \mathcal{J}_X ? We may consider this locally and thus assume that $S = \text{Spec } A$ is affine, $Y = \text{Proj } R$ and $\tilde{X} = \text{Proj } R/I$ for some homogeneous ideal $I \subseteq R$ in the graded A -algebra R . On open subsets of the form $U = Y \setminus \lambda$ for homogeneous $\lambda \in R_+$ we have $\mathcal{O}_Y = (R_{\lambda})_0$ and $\mathcal{I}_X(U) = (I_{\lambda})_0$. So what we need to show is that $\mathcal{J}_X(U) = (I_{\lambda})_0$. It is clear that $(I_{\lambda})_0 \subseteq \mathcal{J}_X(U)$ since that's how we constructed I (or rather \mathcal{I}). The converse is shown in Lemma 3 (in somewhat more generality – here we need the case $n = 0$). q.e.d.

Lemma 3. *Let $n \in \mathbb{N}_0$ be arbitrary and $d > 0$. If $\lambda \in R_d$ and $g \in \mathcal{J}_X(n)(U)$ for the open subset $U = Y \setminus V(\lambda)$, then there is some $k \in \mathbb{N}$ and $\gamma \in I_{dk+n}$ such that $g = \gamma r^{-k}$.*

Proof. Apply Lemma 2.2.2(b) to the quasi-coherent \mathcal{O}_Y -module \mathcal{J}_X and the ample line bundle $\mathcal{O}(d)$ to see that $g\lambda^k$ can be extended to a global section $\gamma_k \in \mathcal{J}(dk+n)(U)$ for $k \gg 0$. We may assume $\gamma_{k+1} = \gamma_k \lambda$. On the other hand, g is an element of $\mathcal{O}_Y(n)(U) \simeq (R_{\lambda})_n$ as well, so $\gamma'_k = g\lambda^k \in R_{dk+n}$ for $k \gg 0$. By Lemma 2.2.2(a), $\gamma_k = \gamma'_k$ for $k \gg 0$. But this implies that $\gamma_k = \gamma \in I_{dk+n}$ by definition of I , when k is sufficiently large.

Note that we can do all this because R_1 is finitely generated by Definition 1(a), hence $\text{Proj } R$ is quasi-compact by the proof of Proposition 2.2.1(e). Moreover, $\text{Proj } R$ is a scheme, hence (separated and thus) quasi-separated. So all assumptions of Lemma 2.2.2 are fulfilled. q.e.d.

Corollary 4. (a) *Every strongly projective morphism is projective.*

(b) *If there is an ample line bundle on S , then any projective morphism $X \rightarrow S$ is strongly projective as well.*

Proof. Part (a) follows by applying Proposition 3 to the composition $X \rightarrow \mathbb{P}_S^n \rightarrow S$, where $\mathbb{P}_S^n = \mathbf{Proj}_S \mathcal{O}_S[X_0, \dots, X_n] \rightarrow S$ is projective.

Part (b). Let $X = \mathbf{Proj}_S(\mathcal{R})$. If \mathcal{L} is an ample line bundle on S , then $\mathcal{R}_1 \otimes_{\mathcal{O}_S} \mathcal{L}^{\otimes k}$ is generated by its global sections when $k \gg 0$ (Definition 2.2.1(b)). Replacing \mathcal{R} by $\mathcal{R}^{(\mathcal{L}^{\otimes k})}$ (we can do this by Corollary 3) we may assume \mathcal{R}_1 to be generated by its global sections¹⁰, say, ξ_0, \dots, ξ_n . Then $\mathcal{O}_S[X_0, \dots, X_n] \rightarrow \mathcal{R}$, $X_i \mapsto \xi_i$ is an epimorphism of \mathbb{N}_0 -graded quasi-coherent \mathcal{O}_S -algebras, defining a closed embedding $X \rightarrow \mathbb{P}_S^n$ of S -preschemes. Hence $X \rightarrow S$ is strongly projective. q.e.d.

Proposition 4. *Let $X \xrightarrow{f} Y \xrightarrow{g} Z$ be strongly projective morphisms. Then gf is strongly projective again. If f and g are only projective, we need that Z is quasi-compact and quasi-separated in order to have gf is projective.*

¹⁰And even finitely many of them since \mathcal{R}_1 is locally finitely generated by Definition 1(a) and S is quasi-compact, as quasi-compactness is assumed in Definition 2.2.1.

Proof. We have closed embeddings $X \rightarrow \mathbb{P}_Y^m$ and $Y \rightarrow \mathbb{P}_Z^n$, defining

$$\mathbb{P}_Y^m \longrightarrow \mathbb{P}_{\mathbb{P}_Z^n}^m \simeq \mathbb{P}_Z^m \times_Z \mathbb{P}_Z^n \xrightarrow{\sigma} \mathbb{P}_Z^{m+n+mn}$$

where σ the Segre embedding from Example 1, hence a closed immersion. Thus we find closed immersions

$$X \longrightarrow \mathbb{P}_Y^m \longrightarrow \mathbb{P}_{\mathbb{P}_Z^n}^m \longrightarrow \mathbb{P}_Z^{m+n+mn}.$$

The second assertion is harder and Professor Franke refers to EGA. q.e.d.

Example 2. Let \mathcal{A} be a quasi-coherent \mathcal{O}_S -algebra and \mathcal{R} the graded \mathcal{O}_S -algebra defined by

$$\mathcal{R}_k = \begin{cases} \mathcal{O}_S \cdot T^0 & \text{if } k = 0 \\ \mathcal{A} \cdot T^k & \text{if } k > 0 \end{cases},$$

then $\mathbf{Proj}_S(\mathcal{R}) \simeq \mathbf{Spec}_S(\mathcal{A})$ (indeed, we may check this locally where it amounts to [AG1, Example 2.5.2]).

Corollary 5. *Finite morphisms are projective.*

Proof. Apply Example 2 and [AG1, Lemma 2.5.1(c)]. q.e.d.

Theorem 4. *Let $X \xrightarrow{f} S$ be a projective morphism of locally Noetherian preschemes and \mathcal{M} a coherent \mathcal{O}_X -module. Then the \mathcal{O}_S -modules $R^k f_* \mathcal{M}$ are coherent for all $k \in \mathbb{N}$.*

Proof. The assertion is local with respect to S , whence we may assume $S = \mathrm{Spec} A$ to be affine, where A is Noetherian. Then $X = \mathrm{Proj} R$, where R is some graded A -algebra with $R_0 = A$ (we may assume this w.l.o.g. – otherwise exchange R_0 by A and this doesn't change anything) and R is generated by R_0 and R_1 and R_1 is a finitely generated R -module. If $\xi_0, \dots, \xi_n \in R_1$ are such generators, then they define a closed embedding $X \xrightarrow{i} \mathbb{P}_A^n$ of A -preschemes as in the proof of Corollary 4(b). Let $\mathbb{P}_A^n \xrightarrow{p} \mathrm{Spec} A$ be the canonical projection. Then $f = pi$. Moreover, since p is quasi-compact (by an argument as in the proof of Proposition 2.2.1(e)) and i is affine (as is any closed immersion), we can deduce from Corollary 1.6.1 that $R^k f_* \mathcal{M} = R^k p_*(i_* \mathcal{M})$. As $i_* \mathcal{M}$ is coherent (this is easy), $H^k(\mathbb{P}_A^n, i_* \mathcal{M})$ is a finitely generated A -module by Theorem 3, hence $R^k p_*(i_* \mathcal{M})$ is a coherent \mathcal{O}_S -module. q.e.d.

Proposition 5. *Let $X \xrightarrow{f} Y \xrightarrow{g} S$ be morphisms such that g is separated and gf is projective (resp. strongly projective). Then f is (strongly) projective as well.*

Proof. Using Fact 2 and Proposition 3, this follows from the following Lemma 4. q.e.d.

Lemma 4. *Let \mathcal{C} be a class of morphisms contained in the class of separated morphisms, stable under base-change and such that $fi \in \mathcal{C}$ when $f \in \mathcal{C}$ and i is a closed embedding. Then from $gf \in \mathcal{C}$ and g separated it follows that $f \in \mathcal{C}$.*

Proof. Consider the commutative diagram

$$\begin{array}{ccc}
 & X \times_Z Y & \\
 i \nearrow & & \searrow h \\
 X & \xrightarrow{\pi_X} & Y \\
 & \xleftarrow{f} & \\
 & & \\
 & \xrightarrow{gf} & Z \\
 & \nwarrow g &
 \end{array}$$

in which $i = (\text{id}_X, f)$ and h is the base change of $X \xrightarrow{gf} Z$ with respect to $Y \xrightarrow{g} Z$. Then $X \times_Z Y \xrightarrow{\pi_X} X$ is separated as it is a base change of the separated morphism g (and the class of separated morphisms is stable under base change by [AG1, Fact 1.5.7(c)]), hence i is a closed immersion by [AG1, Proposition 1.5.5] as it is a section of π_X . Since \mathcal{C} is closed under base change, we have $h \in \mathcal{C}$. It follows that $f = hi \in \mathcal{C}$. *q.e.d.*

2.4. Proper morphisms

Definition 1. Let $X \xrightarrow{f} Y$ be a morphism of preschemes, where Y is locally Noetherian. We call f **proper** if it is of finite type, separated and *universally closed*.

Definition 2. A morphism $X \xrightarrow{f} Y$ of preschemes is **closed** if the image of any closed subset of X is closed in Y . It is **universally closed** if all its base changes

$$\tilde{X} = X \times_Y \tilde{Y} \xrightarrow{\tilde{f}} \tilde{Y}$$

with respect to any $\tilde{Y} \rightarrow Y$ are closed as well.

Remark. Obviously, the classes of closed and universally closed are stable under composition and base-local. The class of universally closed morphisms is also stable under base change. It follows that the class \mathcal{C} of proper morphisms is base-local and stable under composition and base change as the other properties involved in Definition also have this property (by [AG1, Fact 1.5.7(c) and Fact 2.2.2]).

Also, closed immersions are proper, as are any *finite* morphisms (cf. Definition 1.6.1(b)) by [AG1, Example 2.6.1]. Thus, Lemma 2.3.4 gives

Proposition 1. *The class of proper morphisms is base-local and stable under composition and base change, and if $X \xrightarrow{f} Y \xrightarrow{g} Z$ are morphisms of preschemes such that gf is proper and g separated, then f is proper.*

Proposition 2. *If \mathcal{R} is an \mathbb{N}_0 -graded \mathcal{O}_X -algebra which is locally finitely generated, then $\text{Proj}_X(X) \rightarrow X$ is proper. In particular, projective morphisms are proper.*

Proof. By Proposition 1, the question is local on X and we may assume $X = \text{Spec } A$ and need to show $\text{Proj } R \rightarrow A$ is proper when R is an \mathbb{N}_0 -graded A -algebra of finite type. We already

know that $\text{Proj } R$ is a scheme of finite type over $\text{Spec } A$ (Proposition 2.2.1(b), (e)). Hence only universal closedness has to be shown.

However, morphisms of the form $\mathbf{Proj}_X(\mathcal{R}) \rightarrow X$ with \mathcal{R} as above still have this form when base changed, by Corollary 2.3.2 (or actually Remark 2.3.2 since we potentially need to drop the assumption on \mathcal{R}_0 and \mathcal{R}_1 here). So it suffices to show closedness. This is again base-local, so it suffices to show that $\text{Proj } R \rightarrow \text{Spec } A$ is closed.

We will do this by generalizing (the proof of) [AG1, Proposition 2.6.1], dropping the assumption that R is generated by R_0 . Instead, let R be generated by its homogeneous components R_0, \dots, R_d as an A -algebra (we can do this by choosing finitely many generators of R over A and taking d the maximal homogeneous degree where they are supported). Consider the ideals

$$I_i = \text{Ann}_A \left(\bigoplus_{j \geq i} R_j \right) = \bigcap_{j=i}^{i+d} \text{Ann}_A(R_j) \subseteq A \quad (1)$$

(we used that R is generated by R_0, \dots, R_d). Note that $I_1 \subseteq I_2 \subseteq \dots$ is an ascending chain of ideals and put $I_\infty = \bigcup_{i=0}^\infty I_i$. We will show that the image of $\text{Proj } R$ in $\text{Spec } A$ equals $V(I_\infty)$.

Let $\mathfrak{p} \in \text{Spec } A$ be a prime ideal. We get $\mathfrak{p} \in V(I_i)$ iff there is an $i \leq j \leq i+d$ such that $R_j \otimes_A \mathfrak{K}(\mathfrak{p}) \neq 0$ by the Nakayama argument from the proof of [AG1, Proposition 2.6.1]. Then $\mathfrak{p} \in V(I_\infty)$ iff $\mathfrak{p} \in V(I_i)$ for all $i \geq 0$ iff $\mathfrak{p} \in V(I_i)$ for infinitely many i (the I_i are ascending) iff $R_j \otimes_A \mathfrak{K}(\mathfrak{p}) \neq 0$ for infinitely many j . By [AG1, Corollary 1.3.3], $\text{Proj}(R \otimes_A \mathfrak{K}(\mathfrak{p})) \simeq \text{Proj } R \times_{\text{Spec } A} \text{Spec } \mathfrak{K}(\mathfrak{p})$ is the *fibre* (i.e., the preimage) of \mathfrak{p} under $\text{Proj } R \rightarrow \text{Spec } A$. Since we are interested precisely in those $\mathfrak{p} \in \text{Spec } A$ with non-empty fiber, all we need to show is the following

Claim. If R is an \mathbb{N}_0 -graded algebra of finite type over a field k , then $\text{Proj } R \neq \emptyset$ iff there are infinitely many j such that $R_j \neq 0$.

Indeed, if $R_j = 0$ for $j \gg 0$, then $R_+ \subseteq \sqrt{0}$, implying that $\text{Proj } R = \emptyset$ since every homogeneous prime ideal would contain R_+ . Conversely, if $\text{Proj } R = \emptyset$ and R is generated over A by $\lambda_1, \dots, \lambda_N$ which are homogeneous of positive degrees $< d$, then all λ_i must be nilpotent, since otherwise $\emptyset \neq \text{Spec}(R_{\lambda_i})_0 \subseteq \text{Proj } R$. Choose e_i such that $\lambda_i^{e_i} = 0$. Then $R_j = 0$ for $j > \sum_{i=1}^N d e_i$. *q.e.d.*

Theorem 5. Let $X \xrightarrow{f} Y$ be a proper morphism of locally Noetherian preschemes. If \mathcal{M} is a coherent \mathcal{O}_X -module and $p \geq 0$, then $R^p f_* \mathcal{M}$ is a coherent \mathcal{O}_Y -module.

Corollary 1. If A is a Noetherian ring and X a proper $\text{Spec } A$ -scheme and \mathcal{M} a coherent \mathcal{O}_X -module, then $H^p(X, \mathcal{M})$ is a finitely generated A -module.


Theorem 6. Let $X \xrightarrow{f} \text{Spec } A$ be a proper morphism. For a line bundle \mathcal{L} on X , the following conditions are equivalent.

(a) \mathcal{L} is ample.

- (b) Some power $\mathcal{L}^{\otimes k}$ of \mathcal{L} is **very ample** in the sense that \mathcal{L} is generated by global sections ℓ_0, \dots, ℓ_n and the morphism $X \rightarrow \mathbb{P}_A^n$ defined by Corollary 2.3.1 and the multiplicative epimorphism

$$\mathcal{O}_X[X_0, \dots, X_n] \twoheadrightarrow \bigoplus_{j=0}^{\infty} \mathcal{L}^{\otimes kj}$$

sending $X_i \mapsto \ell_i$, is a closed embedding.

- (c) For some $k \in \mathbb{N}$, $\mathcal{L}^{\otimes k}$ is generated by global sections ℓ_0, \dots, ℓ_n and the above morphism $X \rightarrow \mathbb{P}_A^n$ is finite (or equivalently, affine).
- (d) \mathcal{L} is a **cohomology killer**  in the following sense. If \mathcal{M} is a coherent \mathcal{O}_X -module and $p > 0$, then $H^p(X, \mathcal{M} \otimes_{\mathcal{O}_X} \mathcal{L}^{\otimes k}) = 0$ for $k \gg 0$.

3. Cohomology of curves

Let X be a quasi-compact one-dimensional regular (and thus locally Noetherian since [AG1, Definition 2.4.5] assumes this implicitly; hence even Noetherian by quasi-compactness) integral scheme, X_1 the set of codimension 1 (i.e., closed) points, $\text{Div}(X)$ the free abelian group generated by X_1 which we already encountered [here](#).

Definition 1. For $D \in \text{Div}(X)$, the line bundle $\mathcal{O}_X(D)$ is defined by

$$\mathcal{O}_X(D)(U) = \{f \in K \mid v_x(f) \geq -D(x) \ \forall x \in U \cap X_1\}$$

when $U \neq \emptyset$ (and $\mathcal{O}_X(\emptyset) = 0$ of course). Here, $K = \mathcal{O}_{X,\eta}$ denotes the local ring at the generic point η of X (which is a field) and $v_x: \mathcal{O}_{X,x} \rightarrow \mathbb{Z}$ for $x \in X_1$ denotes the valuation of the DVR $\mathcal{O}_{X,x}$ (all of this is justified [here](#)).

Any line bundle on X is isomorphic to a line bundle of this form, and the *divisor class* of D , i.e., its coset modulo $\{\text{div}(f) = \sum_{x \in X_1} v_x(f) \cdot x \mid f \in K^\times\}$, is uniquely determined.

Let us assume that X is a $\text{Spec } k$ -scheme where k is a field. We have seen that there are bijections

$$\begin{array}{ccc} \text{Pic}(X) := \left\{ \begin{array}{c} \text{isomorphism classes} \\ \text{of line bundles on } X \end{array} \right\} & \xrightarrow{\sim} & \left\{ \begin{array}{c} \text{isomorphism classes} \\ \text{of } \mathcal{O}_X^\times\text{-torsors} \end{array} \right\} \\ \downarrow c_1 & & \downarrow \wr \\ H^1(X, \Omega_{X/k}) & \xleftarrow{d \log} & H^1(X, \mathcal{O}_X^\times) := \varinjlim_{\mathcal{U}} \check{H}^1(\mathcal{U}, \mathcal{O}_X^\times) \end{array}$$

and denoted this composition by c_1 . Also recall the *Picard group* $\text{Pic}(X)$ from Remark [2.2.4\(a\)](#).

3.1. Formulation of results

Let k be algebraically closed. All schemes to appear are supposed to be $\text{Spec } k$ -schemes and $\Omega_X^1 := \Omega_{X/\text{Spec } k}$. Also, we use the term *curve* for one-dimensional schemes.

Theorem 7. *Let $C \rightarrow \text{Spec } k$ be a proper morphism where C is a regular curve.*

(a) *There is a homomorphism $\deg: \text{Pic}(C) \rightarrow \mathbb{Z}$ such that*

$$\deg \mathcal{O}_C(D) =: \deg D = \sum_{x \in C_1} D(x) .$$

(b) $H^1(C, \Omega_C)$ is a one-dimensional k -vector space and there is a unique isomorphism

$$\tau: H^1(C, \Omega_C) \xrightarrow{\sim} k \quad (1)$$

such that the diagram

$$\begin{array}{ccc} \mathrm{Pic}(C) & \xrightarrow{c_1} & H^1(C, \Omega_C) \\ \deg \downarrow & & \tau \downarrow \wr \\ \mathbb{Z} & \xrightarrow{\cdot 1} & k \end{array} \quad (2)$$

commutes.

(c) For every vector bundle \mathcal{V} on C , there is a perfect pairing

$$H^0(C, \mathcal{V}) \times H^1(C, \Omega_C \otimes_{\mathcal{O}_C} \mathcal{V}^*) \xrightarrow{m} H^1(C, \Omega_C) \xrightarrow{\sim} k$$

of finite-dimensional vector spaces. Here, $\mathcal{V}^* := \mathcal{H}\mathrm{om}_{\mathcal{O}_C}(\mathcal{V}, \mathcal{O}_C)$ denotes the **dual bundle** and the pairing m is given by $(v, \ell \otimes \omega) \mapsto \ell(v) \cdot \omega$.

Remark. (a) Theorem 7(b) and (c) are called *Serre duality*. They still hold when C is replaced by a *smooth* scheme X over an arbitrary field k and Ω_C by $\omega_X = \bigwedge^{\dim X} \Omega_X^1$.

(b) When $n = \dim X \geq 2$, Theorem 7(a) will no longer deal with line bundles and c_1 is replaced by c_n .

(c) When k is not algebraically closed, the Theorem 7 still holds as stated as long as C is *smooth* over k , and we need to define

$$\deg D = \sum_{x \in C_1} D(x) \cdot [\mathfrak{K}(x) : k] .$$

Theorem 8 (Riemann–Roch). *Let k be algebraically closed. Let $C \rightarrow \mathrm{Spec} k$ be a proper curve let $g = \dim_k \Omega_C(C)$ denote the **genus** of C . Let \mathcal{V} be a d -dimensional vector bundle on C . Then*

$$\chi(C, \mathcal{V}) := \dim_k \mathcal{V}(C) - \dim_k H^1(C, \mathcal{V}) = \deg(\det \mathcal{V}) + d(1 - g) , \quad (3)$$

where $\det \mathcal{V} = \bigwedge^d \mathcal{V}$ is a line-bundle with a alternating d -linear form $\mathcal{V}^d \rightarrow \det \mathcal{V}$ having the universal property for alternating d -linear forms $\mathcal{V}^d \rightarrow \mathcal{M}$ for \mathcal{O}_C -modules \mathcal{M} .

By Serre duality, we also have

$$\dim_k \mathcal{V}(C) - \dim_k \mathrm{Hom}_{\mathcal{O}_C}(\mathcal{V}, \Omega_C) = \deg(\det \mathcal{V}) + d(1 - g) . \quad (4)$$

Remark. (a) The $\chi(C, \mathcal{V})$ occurring in Theorem 8 is a special case of the *Euler–Poincaré characteristic*

$$\chi(X, \mathcal{M}) = \sum_{p=0}^{\dim X} (-1)^p \dim_k H^p(X, \mathcal{M}) ,$$

which we also encountered in Proposition 2.2.4.

- (b) Professor Franke sketched how to construct $\det \mathcal{V}$ and prove its universal property, but this is really just taking exterior products (which it seems he doesn't like), the construction of which is locally just taking ordinary exterior products of modules.

The \mathcal{O}_C^\times -torseur defined by $\det \mathcal{V}$ is the image of the $\mathrm{GL}_d(\mathcal{O}_C)$ -torseur defined by \mathcal{V} under $\mathrm{GL}_d(\mathcal{O}_C) \xrightarrow{\det} \mathcal{O}_C^\times$.

Remark 1. For a line bundle $\mathcal{V} = \mathcal{L}$, the formula becomes $\chi(C, \mathcal{L}) = \deg \mathcal{L} + 1 - g$. Hence we get the famous formula

$$\ell(D) - \ell(K - D) = \deg D + 1 - g, \quad (5)$$

where we put $\mathcal{L} = \mathcal{O}_C(D)$, $\ell(D) = \dim_k \mathcal{O}_C(D)(C)$ for any divisor $D \in \mathrm{Div}(C)$ and K is a **canonical divisor** such that $\mathcal{O}_C(K) \simeq \Omega_C$. By Corollary 2.4.1, $\mathcal{O}_C(C) = H^0(C, \mathcal{O}_C)$ is a k -algebra of finite dimension, hence an integral ring extension of k . Since C is integral, $\mathcal{O}_C(C)$ is a domain (cf. [AG1, Proposition 2.1.4]), so $\mathcal{O}_C(C)$ is actually a finite field extension of k (which is easily seen from Noether normalization). In particular, $\mathcal{O}_C(C) \simeq k$, since k is algebraically closed. Hence (5) is correct when $D = 0$ (i.e., $\ell(0) = 1$). For $D = K$ we obtain $g - 1 = \deg K + 1 - g$. Hence

Fact 1. We have $\deg K = \deg \Omega_C = 2g - 2$.

Corollary 1. If $D \in \mathrm{Div}(C)$ is a divisor, it fulfills Riemann's inequality $\ell(D) \geq \deg D + 1 - g$.

Example 1. If $C \xrightarrow{i} \mathbb{P}_k^2$ is a regular curve of degree d (cf. – more or less – [Alg2, Definition 3.1.5]) in \mathbb{P}_k^2 it is given as the vanishing scheme of an irreducible homogeneous polynomial $P \in k[X, Y, Z]$ of degree d and multiplication with P gives an isomorphism $\mathcal{O}_{\mathbb{P}_k^2}(-d) \xrightarrow{\sim} \mathcal{I}$, where \mathcal{I} is the sheaf of ideals defining C . That is, \mathcal{I} is given by the short exact sequence

$$0 \longrightarrow \mathcal{I} \longrightarrow \mathcal{O}_{\mathbb{P}_k^2} \longrightarrow i_* \mathcal{O}_C \longrightarrow 0.$$

As i is an affine morphism (it is a closed embedding), we have $H^p(C, \mathcal{O}_C) \simeq H^p(\mathbb{P}_k^2, i_* \mathcal{O}_C)$ by Corollary 1.6.1, hence $\chi(C, \mathcal{O}_C) = \chi(\mathbb{P}_k^2, i_* \mathcal{O}_C)$ and

$$\begin{aligned} 1 - g &= \chi(C, \mathcal{O}_C) = \chi(\mathbb{P}_k^2, i_* \mathcal{O}_C) = \chi(\mathbb{P}_k^2, \mathcal{O}_{\mathbb{P}_k^2}) - \chi(C, \mathcal{I}) = \chi(\mathbb{P}_k^2, \mathcal{O}_{\mathbb{P}_k^2}) - \chi(\mathbb{P}_k^2, \mathcal{O}(-d)) \\ &= 1 - \frac{(d-1)(d-2)}{2} \end{aligned}$$

using Proposition 2.2.4(b) and the fact that the Hilbert polynomial of $R = k[X, Y, Z]$ as a graded module over itself (which gives $\mathcal{O}_{\mathbb{P}_k^2}$) is given by $P_R(\ell) = \binom{\ell+2}{2}$ (cf. [Alg2, Lemma 3.0.1]).

3.2. First proofs

In the following, all curves are assumed to be regular. Let $C \rightarrow \mathrm{Spec} k$ for some field k be a proper curve. Then for C to be integral it suffices that C is connected. Indeed, the underlying space of C is Noetherian (by properness) and the local rings $\mathcal{O}_{C,c}$ for all $c \in C$ are regular, hence domains (cf. [Alg2, Corollary 3.4.9(b)]), so all assumptions required for [AG1, Proposition 2.1.4(d)] are fulfilled.

So let C be integral and k algebraically closed. Since $C \rightarrow \operatorname{Spec} k$ is proper, C is of finite type over $\operatorname{Spec} k$ and in particular Noetherian by Hilbert's Basissatz. Since C is irreducible (by the integrality assumption), it has a unique generic point η by [AG1, Fact 2.1.9]. Let $K = \mathcal{O}_{C,\eta}$ be the local ring there (which is a field).

In order to prove Theorem 7(a), we need to prove two things:

1. that $\deg \mathcal{O}_C(D) = \deg D$ descends to a well-defined map from isomorphism classes of line bundles (i.e., from $\operatorname{Pic}(C)$) to $\operatorname{Div}(C)$...
2. ... which is a group homomorphism $\operatorname{Pic}(C) \rightarrow \operatorname{Div}(C)$.

When we have this, we can compose it with the (obvious) group homomorphism $\operatorname{Div}(C) \rightarrow \mathbb{Z}$ to obtain \deg . Step 1 clearly will follow from (1) below. For Step 2, what we need to prove is

Fact 1. If $D_1, D_2 \in \operatorname{Div}(C)$ are divisors, then $\mathcal{O}_C(D_1) \otimes_{\mathcal{O}_C} \mathcal{O}_C(D_2) \simeq \mathcal{O}_C(D_1 + D_2)$.

Proof. The isomorphism is given by $f \otimes g \mapsto fg$ for $f, g \in K$. This is a well-defined morphism of line bundles (we use $v_x(fg) = v_x(f) + v_x(g)$ in Definition 3.0.1). That it is an isomorphism can be checked on stalks. Actually, it suffices to check this on stalks at closed points. Indeed, restricting to an affine open subset $\operatorname{Spec} R$ a morphism of R -modules being an isomorphism can be checked at the maximal ideals, i.e., the closed points, i.e., the codimension-one points since C is one-dimensional. If $c \in C$ is closed and $\mathcal{O}_{C,c}$ thus a DVR, we have

$$\mathcal{O}_C(D_1)_c = \{f \in K \mid v_c(f) \geq -D_1(c)\} = \pi_c^{-D_1(c)} \mathcal{O}_{C,c},$$

where π_c is a uniformizer of $\mathcal{O}_{C,c}$ (the first equality may be easily checked and the second is obvious). Similarly, $\mathcal{O}_C(D_2)_c = \pi_c^{-D_2(c)} \mathcal{O}_{C,c}$ and multiplication gives

$$\pi_c^{-D_1(c)} \mathcal{O}_{C,c} \otimes_{\mathcal{O}_{C,c}} \pi_c^{-D_2(c)} \mathcal{O}_{C,c} \xrightarrow{\sim} \pi_c^{-(D_1(c)+D_2(c))} \mathcal{O}_{C,c},$$

thus we get the required isomorphisms on stalks. *q.e.d.*

We now start by proving

$$\chi(C, \mathcal{O}_C(D)) = \deg D + \chi(C, \mathcal{O}_C). \quad (1)$$

As pointed out, this already implies Theorem 7(a), and (3.1.5) will follow once Serre duality (Theorem 7(b) and (c)) has been established. The general Riemann–Roch formula for vector bundles \mathcal{V} on a curve also follows because every vector bundle on a regular curve has a filtration $0 = \mathcal{V}_0 \subseteq \mathcal{V}_1 \subseteq \dots \subseteq \mathcal{V}_d = \mathcal{V}$, whose quotients are line bundles (that's an easy application of Lemma A.2.1) and both sides of (3.1.3) are additive for short exact sequences $0 \rightarrow \mathcal{V} \rightarrow \mathcal{U} \rightarrow \mathcal{W} \rightarrow 0$ of vector bundles.

Indeed, $\chi(C, \mathcal{U}) = \chi(C, \mathcal{V}) + \chi(C, \mathcal{W})$ is something we proved in Claim 2.2.1. Also $\dim \mathcal{U} = \dim \mathcal{V} + \dim \mathcal{W}$ is obvious. Finally $\det \mathcal{U} \simeq \det \mathcal{V} \otimes_{\mathcal{O}_C} \det \mathcal{W}$, which can be checked locally, where it amounts to showing that $\det M = \det M' \otimes_R \det M''$ whenever $0 \rightarrow M' \xrightarrow{\alpha} M \xrightarrow{\beta} M'' \rightarrow 0$ is a short exact sequence of free (or just projective) R -modules. If M' has rank n and M'' rank ℓ , this isomorphism is given by

$$(m'_1 \wedge \dots \wedge m'_n) \otimes (m''_1 \wedge \dots \wedge m''_\ell) \longmapsto \alpha(m'_1) \wedge \dots \wedge \alpha(m'_n) \wedge m_1 \wedge \dots \wedge m_\ell$$

for $m'_i \in M'$, $m''_j \in M''$ and the m_j are preimages of the m''_j under β . It's easy to see that this is well-defined and indeed an isomorphism.

Thus, the general Riemann–Roch formula (3.1.3) for arbitrary vector bundles \mathcal{V} will follow, and (3.1.4) follows by Serre duality.

Remark 1. Ok, at least for me the last needs a bit more explanation. The perfect pairing from Theorem 7(c) gives, by definition, an isomorphism

$$H^1(C, \Omega_C \otimes_{\mathcal{O}_C} \mathcal{V}^*) \xrightarrow{\sim} \mathrm{Hom}_k(H^0(C, \mathcal{V}), k) .$$

Replacing \mathcal{V} by $\Omega_C \otimes_{\mathcal{O}_C} \mathcal{V}^*$ precisely switches the roles of \mathcal{V} and $\Omega_C \otimes_{\mathcal{O}_C} \mathcal{V}^*$ (this is easy to see). Also, sending $\omega \otimes \ell \mapsto \omega: \ell(-)$ gives an isomorphism $\Omega_C \otimes_{\mathcal{O}_C} \mathcal{V}^* \simeq \mathcal{H}om_{\mathcal{O}_C}(\mathcal{V}, \Omega_C)$ (this is easy to check on stalks). Thus Serre duality together with our considerations gives

$$\begin{aligned} \dim_k \mathrm{Hom}_{\mathcal{O}_C}(\mathcal{V}, \Omega_C) &= \dim_k H^0(C, \mathcal{H}om_{\mathcal{O}_C}(\mathcal{V}, \Omega_C)) \\ &= \dim_k H^0(C, \Omega_C \otimes_{\mathcal{O}_C} \mathcal{V}^*) \\ &= \dim_k \mathrm{Hom}_k(H^1(C, \mathcal{V}), k) \\ &= \dim_k H^1(C, \mathcal{V}) . \end{aligned}$$

Thus $\dim_k H^1(C, \mathcal{V})$ in the Euler–Poincaré characteristic $\chi(C, \mathcal{V})$ may indeed be replaced by $\dim_k \mathrm{Hom}_{\mathcal{O}_C}(\mathcal{V}, \Omega_C)$ (and $\dim_k H^0(C, \mathcal{V})$ clearly by $\dim_k \mathcal{V}(C)$).

For (1), note that

Fact 2. Let D denote the divisor defined by the closed point x of C . For \mathcal{L} a line bundle on C , put $\mathcal{L}(\pm D) = \mathcal{L} \otimes_{\mathcal{O}_C} \mathcal{O}_C(\pm D)$. Then

$$\chi(C, \mathcal{L}(\pm D)) = \chi(C, \mathcal{L}) \pm 1 ,$$

hence (1) holds for $\mathcal{L}(\pm D)$ iff it holds for \mathcal{L} .

Proof. We only need to show this for $\mathcal{L}(-D)$ as $\mathcal{O}_C(D) \otimes_{\mathcal{O}_C} \mathcal{O}_C(-D) \simeq \mathcal{O}_C$ by Fact 1, so the roles of \mathcal{L} and $\mathcal{L}(-D)$ may be switched to show the other assertion.

The residue field $\mathfrak{K}(x)$ of the local ring $\mathcal{O}_{C,x}$ is a k -algebra of finite type, hence $\mathfrak{K}(x) \simeq k$ by the Nullstellensatz and the fact that k is algebraically closed. We thus get a closed embedding $\mathrm{Spec} k \simeq \{x\} \xrightarrow{i} C$. Let π be a uniformizer of the DVR $\mathcal{O}_{C,x}$ (that is, $v_x(\pi) = 1$, so π generates the maximal ideal of $\mathcal{O}_{C,x}$). Shrinking U if necessary we may moreover assume that \mathcal{L} trivializes. Let $\lambda \in \mathcal{L}_x$ be a generator of this free $\mathcal{O}_{C,x}$ -module of rank 1. We get a short exact sequence

$$0 \longrightarrow \mathcal{L}(-D) \longrightarrow \mathcal{L} \xrightarrow{p} i_* \mathcal{O}_{\mathrm{Spec} k} \longrightarrow 0 ,$$

in which p is given as follows. Let $\ell \in \mathcal{L}(U)$, where $U \subseteq C$ is open and $x \in U$ (otherwise p is just the zero morphism). Let $r \in \mathcal{O}_{C,x}$ be the unique element such that $\ell = \lambda r$ in \mathcal{L}_x . Then $p(\ell) = r \bmod \pi \in \mathcal{O}_{C,x}/\pi \mathcal{O}_{C,x} \simeq k$. The morphism $\mathcal{L}(-D) \rightarrow \mathcal{L}$ comes from the fact that $\mathcal{O}_C(-D)$ is a subsheaf of $\mathcal{O}_C(0) \simeq \mathcal{O}_C$ in a canonical way (just look at Definition 3.0.1). Exactness can be easily checked on stalks, using the description of the stalks of $\mathcal{O}_C(-D)$ given in the proof of Fact 1.

By additivity of the Euler–Poincaré characteristic (Claim 2.2.1),

$$\chi(C, \mathcal{L}(-D)) = \chi(C, \mathcal{L}) - \chi(C, i_* \mathcal{O}_{\text{Spec } k}) .$$

But i is a closed embedding, hence affine, so $\chi(C, i_* \mathcal{O}_{\text{Spec } k}) = \chi(\text{Spec } k, \mathcal{O}_{\text{Spec } k}) = 1$ by Corollary 1.6.1. q.e.d.

Fact 3. Equation (1) holds for all divisors $D \in \text{Div}(C)$.

Proof. For $D = 0$, this is trivial. Using induction on $\sum_{x \in C_1} |D(x)|$, the general case reduces to Fact 2. q.e.d.

Before we proceed with the proof of Theorem 7(c), we will use the group homomorphism $\deg: \text{Pic}(\mathbb{P}_k^1) \rightarrow \mathbb{Z}$ to see how line bundles $\mathcal{O}_{\mathbb{P}_k^1}(D)$ defined by divisors can be expressed in terms of the line bundles $\mathcal{O}(d)$ on \mathbb{P}_k^1 for $d \in \mathbb{Z}$. This wasn't mentioned in the lecture, but it's perhaps worthwhile to know and Franke will probably use it anyway.

Corollary 1. *Let $D \in \text{Div}(\mathbb{P}_k^1)$ be a divisor. Then $\mathcal{O}_{\mathbb{P}_k^1}(D) \simeq \mathcal{O}(\deg D)$.*

Proof. Since $\text{Pic}(\mathbb{P}_k^1)$ is generated by (the isomorphism class of) $\mathcal{O}(1)$ and \deg is clearly surjective, it must be an isomorphism. Hence $\deg \mathcal{O}(1) = \pm 1$. We will show that it is actually $+1$. Indeed, assume $\deg \mathcal{O}(1) = -1$ and let D be a divisor which vanishes at all closed points $x \in \mathbb{P}_k^1$ except for x_0 , where $D(x_0) = 1$. Then $\deg D = 1$ and $\deg(-D) = -1$, so $\mathcal{O}(1) \simeq \mathcal{O}_{\mathbb{P}_k^1}(-D)$ and $\mathcal{O}(-1) \simeq \mathcal{O}_{\mathbb{P}_k^1}(D)$ (using that \deg is an isomorphism). From Definition 3.0.1 it is clear that $\mathcal{O}_{\mathbb{P}_k^1}(-D)$ is naturally a subsheaf of $\mathcal{O}_{\mathbb{P}_k^1}(D)$. However, there is no non-zero morphism of sheaves $\mathcal{O}(1) \rightarrow \mathcal{O}(-1)$. Indeed,

$$\text{Hom}_{\mathcal{O}_{\mathbb{P}_k^1}}(\mathcal{O}(1), \mathcal{O}(-1)) \simeq \mathcal{O}(1)^{-1} \otimes_{\mathcal{O}_{\mathbb{P}_k^1}} \mathcal{O}(-1) \simeq \mathcal{O}(-2)$$

has vanishing global section by Theorem 2(a). This is a contradiction.

Now let $D \in \text{Div}(\mathbb{P}_k^1)$ be any divisor and $\mathcal{O}_{\mathbb{P}_k^1}(D) \simeq \mathcal{O}(d)$, then $\deg D = \deg \mathcal{O}(d) = d \cdot \deg \mathcal{O}(1) = d$. q.e.d.

Fact 4. Theorem 7 and Theorem 8 hold in the special case $C = \mathbb{P}_k^1$.

Proof. For Theorem 7(b), it suffices to provide an identification of Ω_C with $\mathcal{O}(-2)$ and to show that $c_1(\mathcal{O}(1))$ has a non-zero image in the one-dimensional k -vector space $H^1(C, \mathcal{O}(-2))$ (here we use Theorem 2(d)).¹

We get a derivation $d: \mathcal{O}_{\mathbb{P}_k^1} \rightarrow \mathcal{O}(-2)$ as follows. For $U \subseteq \mathbb{P}_k^1$ open and $f \in \mathcal{O}_{\mathbb{P}_k^1}(U)$ put

$$d(f) = \begin{cases} \frac{1}{Y} \cdot \frac{\partial f}{\partial X} & \text{on } U \setminus V(Y) \\ -\frac{1}{X} \cdot \frac{\partial f}{\partial Y} & \text{on } U \setminus V(X) \end{cases} .$$

All derivatives are considered as formal derivatives of rational functions in X and Y . Since f is a homogeneous rational function of degree 0, the two terms for $d(f)$ coincide on $U \setminus V(XY)$ (we leave it to the reader to push around X and Y until this comes out). On $\mathbb{P}_k^1 \setminus V(Y) \simeq \text{Spec } k[t]$

¹Where does $c_1(\mathcal{O}(1))$ come from? In Corollary A.2.1 we see that $\text{Pic}(\mathbb{P}_k^n) \simeq \mathbb{Z}$ with $\mathcal{O}(1)$ a generator.

(for $t = \frac{X}{Y}$) we have $f(X, Y) = \varphi(t)$ for some polynomial φ , and $d(f) = Y^{-2} \cdot \varphi'(t)$. Hence d is a universal derivation there, and similar arguments apply to $\mathbb{P}_k^1 \setminus V(X)$. Thus $\Omega_{\mathbb{P}_k^1} \simeq \mathcal{O}(-2)$, as claimed.

It remains to determine the image of $c_1(\mathcal{O}(1))$ under this identification followed by the isomorphism $H^1(\mathbb{P}_k^1, \mathcal{O}(-2)) \xrightarrow{\sim} k$ from Theorem 2(d). Let $U_0 = \mathbb{P}_k^1 \setminus V(X)$, $U_1 = \mathbb{P}_k^1 \setminus V(Y)$, then $\mathcal{O}(1)$ is trivialized by X on U_0 and by Y on U_1 . Let $\mathcal{U}: \mathbb{P}_k^1 = U_0 \cup U_1$ denote this affine open cover. Reading carefully through the construction before Proposition 1.7.1 again, we find that the element of $\check{H}_{\text{alt}}^1(\mathcal{U}, \mathcal{O}_{\mathbb{P}_k^1}^\times)$ which gives the $\mathcal{O}_{\mathbb{P}_k^1}^\times$ -torsor $\mathcal{O}(1)^\times$ is given by $\frac{X}{Y} = t \in \mathcal{O}_{\mathbb{P}_k^1}^\times(U_{0,1})$.

The image of $f = t$ under $f \mapsto d(f)f^{-1}$ equals $(XY)^{-1} \neq 0$ and this element is sent to 1 under the isomorphism $H^1(\mathbb{P}_k^1, \mathcal{O}(-2)) \xrightarrow{\sim} k$ from Theorem 2(d). Hence $c_1(\mathcal{O}(1)) = 1$. Thus Theorem 7(b) follows for $C = \mathbb{P}_k^1$, and so does Theorem 7(c) in the special case $\mathcal{V} = \mathcal{O}(k)$ by the duality assertion from Theorem 2(e). By Theorem A, any vector bundle \mathcal{V} on \mathbb{P}_k^1 is isomorphic to a direct sum of line bundles $\mathcal{O}(k)$, showing Theorem 2 (and thus Theorem 8) for $C = \mathbb{P}_k^1$ *q.e.d.*

The strategy for arbitrary C will be to use a finite separable morphism $C \xrightarrow{f} \mathbb{P}_k^1$ (that is, a morphism inducing separable extensions of fields of rational functions). Then $H^\bullet(C, \mathcal{V}) \simeq H^\bullet(\mathbb{P}_k^1, f_*\mathcal{V})$ for every vector bundle \mathcal{V} on C (by Corollary 1.6.1 – note that f is finite, thus in particular affine). Also $f_*\mathcal{V}$ is a coherent $\mathcal{O}_{\mathbb{P}_k^1}$ -module and torsion-free (because \mathcal{V} is), hence a vector bundle by the classification of modules over PIDs. Thus

$$H^1(C, \mathcal{V}) \simeq H^1(\mathbb{P}_k^1, f_*\mathcal{V}) \simeq \text{Hom}_{\mathcal{O}_{\mathbb{P}_k^1}}(f_*\mathcal{V}, \Omega_{\mathbb{P}_k^1}) \simeq \text{Hom}_{\mathcal{O}_{\mathbb{P}_k^1}}(\mathcal{V}, f^!\Omega_{\mathbb{P}_k^1})$$

(this is the Serre duality calculation from Remark 1 again), where $f^!$ is (hopefully) a right-adjoint functor for f_* . Then if (hopefully again) one has a canonical isomorphism $f^!\Omega_{\mathbb{P}_k^1} \simeq \Omega_C$, Serre duality for C follows. The fact that the resulting isomorphism $H^1(C, \Omega_C) \xrightarrow{\sim} k$ sends $c_1(\mathcal{O}_C(D))$ to the image of $\deg D$ in k has to be checked separately.

3.3. The functor $f^!$

Let $C \xrightarrow{f} D$ be a finite separable morphism of regular connected curves over the algebraically closed field k . We want to construct a *right-adjoint* $f^!: \mathcal{O}_D\text{-Mod} \rightarrow \mathcal{O}_C\text{-Mod}$ to the functor f_* . For this, Professor Franke assumes familiarity with extensions of Dedekind domains, *differents*, and the *trace form*. We refer to [Nk, Ch. II, §2] for an introduction.

Let R be a Dedekind domain with field of fractions K , L/K a finite separable field extension, S the algebraic closure of R in L and $\text{Tr}_{L/K}: L \rightarrow K$ the *trace*. Put

$$S^* = \left\{ \sigma \in L \mid \text{Tr}_{L/K}(\sigma s) \in R \text{ for all } s \in S \right\}.$$

Then S^* is a fractional ideal of S and thus has an inverse, the **Dedekind different** $\mathfrak{D}_{S/R} := (S^*)^{-1}$. The construction of $\mathfrak{D}_{S/R}$ commutes with localization, hence we obtain

Fact 1. If f is a morphism as above, there is a unique sheaf of ideals $\mathfrak{D}_f \subseteq \mathcal{O}_C$ such that

$$\mathfrak{D}_f(f^{-1}U) = \mathfrak{D}_{\mathcal{O}_C(f^{-1}U)/\mathcal{O}_D(U)}$$

for all affine open $U \subseteq D$.

We may view \mathfrak{D}_f^{-1} (the inverse of the line bundle \mathfrak{D}_f) as a subsheaf of \mathcal{K}_C , the (constant) sheaf of rational functions on C . Define \mathcal{K}_D in a similar way and let L, K be the fields of rational functions on C, D respectively. By definition, $\mathrm{Tr}_{L/K}: L \rightarrow K$ defines morphisms

$$\mathrm{Tr}: f_*\mathcal{K}_C \longrightarrow \mathcal{K}_D \quad \text{and} \quad \mathrm{Tr}_{C/D}: f_*\mathfrak{D}_f^{-1} \longrightarrow \mathcal{O}_D.$$

If \mathcal{M} is a quasi-coherent \mathcal{O}_D -module, we denote the composition

$$f_* \left(f^*\mathcal{M} \otimes_{\mathcal{O}_C} \mathfrak{D}_f^{-1} \right) \simeq \mathcal{M} \otimes_{\mathcal{O}_D} f_*\mathfrak{D}_f^{-1} \xrightarrow{\mathrm{id}_{\mathcal{M}} \otimes \mathrm{Tr}_{C/D}} \mathcal{M} \otimes_{\mathcal{O}_D} \mathcal{O}_D \simeq \mathcal{M}$$

by $\mathrm{Tr}_f = \mathrm{Tr}_{C/D}$ as well. As $\mathrm{Tr}_{L/K}: S \times S^* \rightarrow R$ is a perfect duality pairing in the above situation of Dedekind domains, one obtains

Proposition 1. *For every quasi-coherent \mathcal{O}_C -module \mathcal{N} , the map*

$$\mathrm{Hom}_{\mathcal{O}_C}(\mathcal{N}, f^*\mathcal{M} \otimes_{\mathcal{O}_C} \mathfrak{D}_f^{-1}) \longrightarrow \mathrm{Hom}_{\mathcal{O}_D}(f_*\mathcal{N}, \mathcal{M}) \quad (1)$$

$$\varphi \longmapsto \mathrm{Tr}_f \circ f_*(\varphi) \quad (2)$$

is bijective. Thus, the functor $f^!: \mathrm{QCoh}(D) \rightarrow \mathrm{QCoh}(C)$ given by $f^!\mathcal{M} = f^*\mathcal{M} \otimes_{\mathcal{O}_C} \mathfrak{D}_f^{-1}$ is right-adjoint to f_* .

To prove this, we will formulate a lemma first, and to do this, we need to justify that with f as above, a point $d \in D$ has only finitely many preimages in C . Indeed, on an affine open neighbourhood $U \subseteq D$ of d the situation looks like a finite extension of Dedekind domains² $R = \mathcal{O}_D(U)$ and $S = \mathcal{O}_C(f^{-1}U)$, where d corresponds to a prime ideal $\mathfrak{p} \in \mathrm{Spec} R$. The preimages of d correspond to the prime ideals of S lying above \mathfrak{p} , and it's well-known that there is a finite number $\mathfrak{P}_1, \dots, \mathfrak{P}_N$ of them (the finitely many prime ideal factors of $\mathfrak{p}S$, cf. [Nk, Ch. I, §8]).

Also, for $f \in \mathcal{O}_C(V)$ for some open $V \subseteq C$ let $f(c)$ denote the image of f in the residue field $\mathfrak{K}(c)$ of $\mathcal{O}_{C,c}$. Note that all rings we are considering here are k -algebras. In particular, there is an embedding $k \hookrightarrow \mathcal{O}_{C,c}$ for every $c \in C$ and $k \hookrightarrow \mathfrak{K}(c)$ is even an isomorphism by Hilbert's Nullstellensatz and algebraic closedness of k .

Lemma 1. *Let f be as above, $d \in D$ any closed point and c_1, \dots, c_N its preimages in C .*

- (a) *There are an affine open neighbourhood U of D and $\xi \in \mathcal{O}_C(f^{-1}U)$ such that $\xi(c_i) \neq \xi(c_j)$ and such that $\xi - \xi(c_i) \notin \mathfrak{m}_{C,c_i}^2 \subseteq \mathcal{O}_{C,c_i}$ for $i = 1, \dots, N$.*
- (b) *If ξ has this property, after shrinking U to some smaller affine open neighbourhood of d we may assume that $\mathcal{O}_C(f^{-1}U)$ is generated by ξ as an $\mathcal{O}_D(U)$ -algebra.*

² R and S are one-dimensional regular Noetherian rings, hence Dedekind domains.

Proof. The existence of ξ is easy. There are $\varphi_i \in \mathcal{O}_C(f^{-1}U)$ such that $\varphi_i(c_j) = 1$ if $i = j$ and $= 0$ else (this is just the Chinese remainder theorem). Also, for all i let $\pi_i \in \mathcal{O}_C(f^{-1}U)$ be an element whose image in \mathcal{O}_{C,c_i} is a uniformizer. Let $\varepsilon_i \in \mathcal{O}_{C,c_i}$ such that $\varphi_i^2 \equiv 1 + \varepsilon_i \pi_i \pmod{\pi_i^2}$. We put

$$\xi = \sum_{i=1}^N \varphi_i^2(\alpha_i + \beta_i \pi_i),$$

with yet-to-define parameters α_i, β_i . When we consider the image of the above sum in \mathcal{O}_{C,c_i} , all summands except the i^{th} are $\equiv 0 \pmod{\pi_i^2}$, while $\varphi_i^2(\alpha_i + \beta_i \pi_i) \simeq \alpha_i + \alpha_i \varepsilon_i \pi_i + \beta_i \pi_i$. We then may choose $\alpha_1, \dots, \alpha_N$ such that $\xi(c_1), \dots, \xi(c_N)$ are distinct. Choosing β_1, \dots, β_N appropriately, we can moreover achieve $\xi \not\equiv \xi(c_i) \pmod{\pi_i^2}$ for all i . This shows (a).

For (b), let $R = \mathcal{O}_D(U)$ and $S = \mathcal{O}_C(f^{-1}U)$. Let \mathfrak{p} and $\mathfrak{P}_1, \dots, \mathfrak{P}_N$ be the prime ideals corresponding to d and c_1, \dots, c_N . It suffices to show that $S_{\mathfrak{p}}$ is generated by the powers of ξ as an $R_{\mathfrak{p}}$ -module. Indeed, [Alg2, Lemma 1.5.1] shows that there is a $\lambda \in R \setminus \mathfrak{p}$ such that S_{λ} is already generated by the powers of ξ as an R_{λ} -module, and replacing U by $U \setminus V(\lambda)$ does the required shrinking.

Let L and K be the fraction fields of S, R respectively. Then L/K is separable by assumption on f . Let $n = [L : K]$. Since $R_{\mathfrak{p}}$ is a DVR (and thus a PID), $S_{\mathfrak{p}}$ is a free $R_{\mathfrak{p}}$ -module of rank n by [Nk, Ch. I, (2.10)]. Let $\mathfrak{p}S = \mathfrak{P}_1^{e_1} \cdots \mathfrak{P}_N^{e_N}$ be the prime factorization of $\mathfrak{p}S$ (the e_i are called *ramification indices*). By [Nk, Ch. I, (8.2)] we have $\sum_{i=1}^N e_i = n$ (note that all *inertia degrees* equal 1 since $[\mathfrak{K}(\mathfrak{P}_i) : \mathfrak{K}(\mathfrak{p})] = [k : k] = 1$).

Claim 1. The $\sum_{i=1}^N e_i = n$ elements

$$\psi_{i,r} := \prod_{j \neq i} (\xi - \xi(c_j))^{e_j} \cdot (\xi - \xi(c_i))^r$$

for $i = 1, \dots, N$ and $r = 0, \dots, e_i - 1$ are k -linearly independent in $S_{\mathfrak{p}}/\mathfrak{p}S_{\mathfrak{p}}$.

Believing this for the moment, a comparison of dimension and Nakayama's lemma show that the $\psi_{i,r}$ actually generate $S_{\mathfrak{p}}$ as an $R_{\mathfrak{p}}$ -module. Since they are polynomials in ξ (with some coefficients from k coming from the $\xi(c_i)$), we are done.

It remains to prove Claim 1. Suppose that $\sum_{i,r} \lambda_{i,r} \psi_{i,r} = 0$ in $S_{\mathfrak{p}}/\mathfrak{p}S_{\mathfrak{p}}$ for some coefficients $\lambda_{i,r} \in k$. Let us localize at \mathfrak{P}_i . Then all $\psi_{j,r}$ with $j \neq i$ vanish in $S_{\mathfrak{P}_i}/\mathfrak{p}S_{\mathfrak{P}_i}$ as they contain the factor $(\xi - \xi(c_i))^{e_i}$ whose \mathfrak{P}_i -adic valuation equals e_i (and we have $\mathfrak{p}S_{\mathfrak{P}_i} = (\pi_i^{e_i})$). We thus get

$$\sum_{r=0}^{e_i-1} \lambda_{i,r} \psi_{i,r} = 0 \quad \text{in } S_{\mathfrak{P}_i}/\mathfrak{p}S_{\mathfrak{P}_i}.$$

Note that $v_{\mathfrak{P}_i}(\psi_{i,r}) = r$. Indeed, the construction from (a) was chosen in such a way to guarantee $v_{\mathfrak{P}_i}(\xi - \xi(c_j)) = 0$ for $j \neq i$ and $v_{\mathfrak{P}_i}(\xi - \xi(c_i)) = 1$. From this we deduce $\lambda_{i,r} = 0$ for $r = 0, \dots, e_i - 1$. Doing this for the other \mathfrak{P}_j as well, we obtain $\lambda_{i,r} = 0$ for all i, r . This shows the required linear independence. *q.e.d.*

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

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

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. [AG1, Definition A.3.2 and Definition A.3.4]), respectively. Indeed, we have

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

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

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

(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. [AG1, 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. [AG1, 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 [AG1, 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*.

The following approach was suggested by Willem and is conceptionally way nicer than what I came up with myself. Let \mathcal{A} be a category. A **diagram** (naively, some objects of \mathcal{A} with arrows between them such that everything that should commute actually does so) is nothing else but a functor $F: \mathcal{J} \rightarrow \mathcal{A}$ from some small category \mathcal{J} into \mathcal{A} . We can form the corresponding

diagram category which is just the functor category $\mathcal{D} = \text{Funct}(\mathcal{J}, \mathcal{A})$. Taking colimits then is a functor

$$\varinjlim_{\mathcal{J}} : \mathcal{D} \longrightarrow \mathcal{A} \quad (1)$$

(perhaps we need to restrict \mathcal{D} to the class of \mathcal{J} -indexed diagrams whose colimit exists). We also have the *diagonal functor* $\Delta : \mathcal{A} \rightarrow \mathcal{D}$ assigning to $X \in \text{Ob}(\mathcal{A})$ the diagram with all objects X and all arrows the identity id_X (and for morphisms, Δ does the obvious thing).

Lemma 4. *The functors $\varinjlim_{\mathcal{J}}$ and Δ form an adjoint pair (cf. Definition 5).*

Proof. With this new terminology at hand, look at the definition of a colimit as a colimiting cocone again and find out that this is obvious. *q.e.d.*

By Remark 4, left-adjoint functors preserve colimits. In particular, Lemma 4 gives

Corollary 1. *The functor $\varinjlim_{\mathcal{J}}$ preserves colimits.*

... and if you think about it, that's precisely the kind of commutativity of colimits with colimits we wanted to have.

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 $\tau_1 = \left(\mathcal{T} \xrightarrow{\sim} \mathcal{T}^{\text{sh}} \right) \circ \tau_2$ and τ_2 makes

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

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 ([AG1, 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).

A.2. Vector bundles on \mathbb{P}_k^1

In this section, I would like to include a proof of the Grothendieck–Birkhoff structure theorem¹ for vector bundles on \mathbb{P}_k^1 , which says the following.

Theorem A (Grothendieck–Birkhoff). *Let k be a field and \mathcal{V} be a vector bundle of rank n on $X = \mathbb{P}_k^1$. Then there is a decomposition*

$$\mathcal{V} \simeq \bigoplus_{i=1}^n \mathcal{O}(d_i)$$

for some $d_i \in \mathbb{Z}$, which are unique up to order.

For this, I’m roughly following exercise sheet #8, but nevertheless this section is fanfic rather than canon.

We start by proving the $n = 1$ case, which actually holds in more generality.

Proposition 1. *Let \mathcal{L} be a line bundle on \mathbb{P}_k^m . Then $\mathcal{L} \simeq \mathcal{O}(d)$ for some $d \in \mathbb{Z}$.*

Proof. Let $R = k[X_0, \dots, X_m]$ and $U_i = \mathbb{P}_k^m \setminus V(X_i)$ the standard affine opens. On U_i , \mathcal{L} is given by \tilde{L}_i for some $(R_{X_i})_0$ -module L_i . Giving a line bundle, L_i is invertible and it can be shown that any invertible module over a UFD is trivial, cf. [Stacks, Tag 0BCH]. Hence $L_i \simeq (R_{X_i})_0$. Let $\ell_i \in L_i$ be a generator. Then both ℓ_i and ℓ_j are generators of $\mathcal{L}|_{U_{i,j}}$, hence they differ by a unit in $\mathcal{O}_{\mathbb{P}_k^m}(U_{i,j}) = (R_{X_i X_j})_0$. That is, there are $d_{i,j} \in \mathbb{Z}$ and $\alpha_{i,j} \in k$ such that

$$\ell_i = \alpha_{i,j} \left(\frac{X_j}{X_i} \right)^{d_{i,j}} \ell_j.$$

Multiplying all ℓ_i except for ℓ_0 by suitable factors from k , we may assume $\alpha_{i,j} = 1$ for all i, j . Also, we have

$$\left(\frac{X_l}{X_i} \right)^{d_{i,l}} \ell_l = \ell_i = \left(\frac{X_j}{X_i} \right)^{d_{i,j}} \ell_j = \left(\frac{X_j}{X_i} \right)^{d_{i,j}} \left(\frac{X_j}{X_l} \right)^{d_{l,j}} \ell_l$$

in $(R_{X_i X_j X_l})_0$ for distinct i, j, l . This implies $d_{i,j} = d_{j,l}$ and we see that actually all the $d_{i,j}$ equal d for some $d \in \mathbb{Z}$. Then it’s easy to give an isomorphism $\mathcal{L} \xrightarrow{\sim} \mathcal{O}(d)$. *q.e.d.*

Corollary 1. *We have $\text{Pic}(\mathbb{P}_k^m) \simeq \mathbb{Z}$.*

Proof. By Proposition 1, $\mathcal{O}(1)$ is a generator of $\text{Pic}(\mathbb{P}_k^m)$, so it suffices to show that there is no torsion. But in Theorem 2(a) we proved that $\mathcal{O}(d)$ has a global section iff $d \geq 0$, hence the powers of $\mathcal{O}(1)$ can’t become periodic. *q.e.d.*

Now we prove a pretty useful lemma, enabling us to do all kinds of induction on the rank.

¹Though Franke likes to attribute it to Dedekind/Weber and Plemelj as well.

Lemma 1. *Let X be a regular one-dimensional connected Noetherian scheme, η its generic point, and $K = \mathcal{O}_{X,\eta}$ the stalk of the structure sheaf there.² Let \mathcal{V} be a vector bundle on X , let V be the K -vector space \mathcal{V}_η and $W \subseteq V$ a subspace. Let \mathcal{W} be the sheaf defined by*

$$\mathcal{W}(U) = \{v \in \mathcal{V}(U) \mid \text{the image of } v \text{ in } V = \mathcal{V}_\eta \text{ lands in } W\}.$$

Then \mathcal{W} and \mathcal{V}/\mathcal{W} are vector bundles.

Sketch of a proof. Since X is integral, regular and one-dimensional Noetherian, it is locally Dedekind. But finitely generated modules over Dedekind domains are projective (and that's what we need for a vector bundle) iff they are torsion-free (we proved this, e.g., in [Hom, Corollary 1.1.6]). Torsion-freeness for \mathcal{W} and \mathcal{V}/\mathcal{W} is easily checked. *q.e.d.*

Lemma 2. *Let X be a regular connected one-dimensional Noetherian scheme, \mathcal{L} a line bundle on X and \mathcal{V} a vector bundle. If $\mathcal{L} \xrightarrow{f} \mathcal{V}$ is a non-zero morphism of \mathcal{O}_X -modules, then f is a monomorphism.*

Proof. Let $K = \mathcal{O}_{X,\eta}$ be the stalk at the generic point η of X . As $f \neq 0$, $\mathcal{L}_\eta \rightarrow \mathcal{V}_\eta$ is non-zero and thus a monomorphism, since \mathcal{L}_η is a one-dimensional K -vector space. Now if $x \in X$ is any point, consider the diagram

$$\begin{array}{ccc} \mathcal{L}_x & \hookrightarrow & \mathcal{L}_\eta \\ f \downarrow & & \downarrow f \\ \mathcal{V}_x & \hookrightarrow & \mathcal{V}_\eta \end{array}$$

The right vertical arrow is injective, hence so is the left one. Therefore f induces injections on stalks, hence it is a monomorphism. *q.e.d.*

Lemma 3. *Let \mathcal{V} be a vector bundle on $X = \mathbb{P}_k^1$. Then the set $\mathfrak{L}_\mathcal{V}$ of integers $d \in \mathbb{Z}$ for which there is a non-zero morphism $\mathcal{O}(d) \rightarrow \mathcal{V}$ is bounded from above.*

Proof. Note that $\mathcal{H}\mathrm{om}_{\mathcal{O}_X}(\mathcal{O}(d), \mathcal{V}) \simeq \mathcal{O}(-d) \otimes_{\mathcal{O}_X} \mathcal{V} = \mathcal{V}(-d)$, so we need to show that $\mathcal{V}(-d)$ has vanishing global section for $d \gg 0$. We use induction on the rank of \mathcal{V} . If the rank is 0, there is nothing to show and when $\dim \mathcal{V} = 1$, then $\mathcal{V} \simeq \mathcal{O}(\ell)$ for some $\ell \in \mathbb{Z}$ by Proposition 1 and $\mathcal{O}(\ell - d)$ has vanishing global section.

Now let $\dim \mathcal{V} \geq 2$ and assume that the assertion is true for vector bundles of smaller rank. Choose a one-dimensional subspace $L \subseteq V = \mathcal{V}_\eta$ (we keep the notation from previous lemmas) and let \mathcal{L} and $\mathcal{W} = \mathcal{V}/\mathcal{L}$ be the vector bundles constructed in Lemma 1. Note that \mathcal{L} and \mathcal{W} have strictly smaller rank than \mathcal{V} (since $\dim_K L \leq \dim_K V$ and same for V/L). From the short exact sequence $0 \rightarrow \mathcal{L}(-d) \rightarrow \mathcal{V}(-d) \rightarrow \mathcal{W}(-d) \rightarrow 0$ we get

$$H^0(X, \mathcal{L}(-d)) \longrightarrow H^0(X, \mathcal{V}(-d)) \longrightarrow H^0(X, \mathcal{W}(-d))$$

in which the outer terms vanish for sufficiently large d by the induction assumption, hence $0 = H^0(X, \mathcal{V}(-d)) = \mathcal{V}(-d)(C)$ for $d \gg 0$. *q.e.d.*

²As Professor Franke points out, K is a zero-dimensional regular local ring, hence a field. Also, X is automatically integral; compare the argument at the beginning of Section 3.2.

Lemma 4. *Let \mathcal{V} be a vector bundle on $X = \mathbb{P}_k^1$ for which -1 is the largest element of $\mathfrak{L}_{\mathcal{V}}$. Let $\mathcal{O}(-1) \rightarrow \mathcal{V}$ be a non-zero morphism.*

(a) *Its image \mathcal{L} is a line bundle and $\mathcal{W} = \mathcal{V}/\mathcal{L}$ is a vector bundle.*

(b) *$\mathfrak{L}_{\mathcal{W}}$ is bounded from above by -1 as well.*

Proof. Part (a). Note that $\mathcal{O}(-1) \rightarrow \mathcal{V}$ is a monomorphism by Lemma 2, so \mathcal{L} is indeed a line bundle. As in the proof of Lemma 1, all we need to check is torsion-freeness of $\mathcal{W} = \mathcal{V}/\mathcal{L}$. Let $R = k[X_0, X_1]$ and $U_i = X \setminus V(X_i)$ for $i = 0, 1$. Let $\mathcal{V}|_{U_i} = \tilde{V}_i$ and $\mathcal{V}|_{U_{0,1}} = \tilde{V}_{0,1}$. For \mathcal{L} and \mathcal{W} we will use the analogous notation. Assume that $V_0/L_0 \simeq W_0$ has torsion at a prime $p_0 \in \text{Spec } k[t]$ (for $t = \frac{X_1}{X_0}$) and let $x \in X$ be the corresponding point (by a linear transformation, we may achieve that x corresponds to neither of the homogeneous prime ideals $(X_0), (X_1) \subseteq R$). Since L_0 is a free $k[t]$ -module of rank 1, we must have $L_0 \subseteq p_0 V_0$.

Also $V_{0,1}/L_{0,1} \simeq W_{0,1}$ has torsion at x as well, hence so has $V_1/L_1 \simeq W_1$ (all of this is easy to see by the classification of finitely generated modules over PIDs). Then $L_1 \subseteq p_1 V_1$ where $p_1 \in \text{Spec } k[t^{-1}]$ is the prime corresponding to x .

Thus, the image \mathcal{L} of $\mathcal{O}(-1)$ is actually contained in $\mathcal{O}_X(-D) \otimes_{\mathcal{O}_X} \mathcal{V}$, where $D \in \text{Div}(X)$ is the divisor satisfying $D(x) = 1$ and $D(y) = 0$ for all $y \neq x$ and we regard $\mathcal{O}_X(-D) \otimes_{\mathcal{O}_X} \mathcal{V}$ as a subsheaf of \mathcal{V} via the natural inclusion $\mathcal{O}_X(-D) \subseteq \mathcal{O}_X$. Tensoring with $\mathcal{O}_X(D)$ gives a non-zero morphism $\mathcal{O}_X(D) \otimes_{\mathcal{O}_X} \mathcal{O}(-1) \rightarrow \mathcal{V}$. But $\mathcal{O}_X(D) \simeq \mathcal{O}(\deg D) = \mathcal{O}(1)$ by Corollary 3.2.1 and we get a non-zero morphism $\mathcal{O}(0) \rightarrow \mathcal{V}$, contradiction!

Part (b). It suffices that there is no morphism $\mathcal{O}(0) \rightarrow \mathcal{W}$. Indeed, any nonzero morphism $\mathcal{O}(d) \rightarrow \mathcal{W}$ for $d \geq 0$ is a monomorphism by Lemma 2, hence composing it with a non-zero morphism $\mathcal{O}(0) \rightarrow \mathcal{O}(d)$ (which exists as the global section of $\mathcal{O}(-0) \otimes_{\mathcal{O}_X} \mathcal{O}(d) \simeq \mathcal{O}(d)$ doesn't vanish by Theorem 2(a)) gives a non-zero morphism $\mathcal{O}(0) \rightarrow \mathcal{W}$.

As before, we may equivalently show that the global section of \mathcal{W} vanishes, or $H^0(X, \mathcal{W}) = 0$. We already know $H^0(X, \mathcal{V}) = 0$ (since there is no non-zero $\mathcal{O}(0) \rightarrow \mathcal{V}$) and $H^1(X, \mathcal{L}) \simeq H^1(X, \mathcal{O}(-1)) = 0$ by Theorem 2(b). From the long exact cohomology sequence associated to $0 \rightarrow \mathcal{L} \rightarrow \mathcal{V} \rightarrow \mathcal{W} \rightarrow 0$ we get

$$0 = H^0(X, \mathcal{V}) \longrightarrow H^0(X, \mathcal{W}) \longrightarrow H^1(X, \mathcal{L}) = 0,$$

hence $H^0(X, \mathcal{W}) = 0$ as well.

q.e.d.

Proof of Theorem A. We show existence first. For this, we use induction on $n = \dim \mathcal{V}$ (duh!). The case $n = 0$ is trivial and $n = 1$ was done in Proposition 1. Now let $n \geq 2$ and the assertion be true for smaller ranks. We may assume that the largest element of $\mathfrak{L}_{\mathcal{V}}$ is -1 by twisting \mathcal{V} appropriately.³ By Lemma 4(a) we get a short exact sequence

$$0 \longrightarrow \mathcal{O}(-1) \longrightarrow \mathcal{V} \longrightarrow \mathcal{W} \longrightarrow 0 \quad (*)$$

of vector bundles on $X = \mathbb{P}_k^1$. By the induction hypothesis, we have $\mathcal{W} \simeq \bigoplus_{i=1}^{n-1} \mathcal{O}(d_i)$ for some $d_i \in \mathbb{Z}$. We will show that $(*)$ splits. To do this, by Proposition 1.7.2 and Proposition 1.7.1(b) it suffices to show

$$H^1(X, \text{Hom}_{\mathcal{O}_X}(\mathcal{W}, \mathcal{O}(-1))) = 0.$$

³Note that $\mathfrak{L}_{\mathcal{V}}$ is always non-empty. Indeed, the construction from Lemma 1 always gives a non-zero morphism $\mathcal{L} \rightarrow \mathcal{V}$ for some line bundle \mathcal{L} on \mathbb{P}_k^1 , and $\mathcal{L} \simeq \mathcal{O}(d)$ for some $d \in \mathbb{Z}$ by Proposition 1.

We have

$$\begin{aligned}
 \mathcal{H}om_{\mathcal{O}_X}(\mathcal{W}, \mathcal{O}(-1)) &\simeq \bigoplus_{i=1}^{n-1} \mathcal{H}om_{\mathcal{O}_X}(\mathcal{O}(d_i), \mathcal{O}(-1)) \\
 &\simeq \bigoplus_{i=1}^{n-1} \mathcal{O}(-d_i) \otimes_{\mathcal{O}_X} \mathcal{O}(-1) \\
 &\simeq \bigoplus_{i=1}^{n-1} \mathcal{O}(-d_i - 1) .
 \end{aligned}$$

Note that all d_i are ≤ -1 by Lemma 4(b). Hence

$$H^1\left(X, \bigoplus_{i=1}^{n-1} \mathcal{O}(-d_i - 1)\right) \simeq \bigoplus_{i=1}^{n-1} H^1(X, \mathcal{O}(-d_i - 1)) = 0$$

by Theorem 2(b). We are done.

It remains to show uniqueness. But for this, it suffices to compute $\dim_k H^0(X, \mathcal{V}(d))$ for $d \in \mathbb{Z}$ to filter out the $\mathcal{O}(d_i)$. *q.e.d.*

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