

COHOMOLOGY OF SHEAVES

01DW

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1. Introduction

01DX In this document we work out some topics on cohomology of sheaves on topological spaces. We mostly work in the generality of modules over a sheaf of rings and we work with morphisms of ringed spaces. To see what happens for sheaves on sites take a look at the chapter Cohomology on Sites, Section 1. Basic references are [God73] and [Ive86].

2. Topics

01DY Here are some topics that should be discussed in this chapter, and have not yet been written.

- (1) Ext-groups.
- (2) Ext sheaves.
- (3) Tor functors.
- (4) Derived pullback for morphisms between ringed spaces.
- (5) Cup-product.
- (6) Etc, etc, etc.

3. Cohomology of sheaves

01DZ Let X be a topological space. Let \mathcal{F} be an abelian sheaf. We know that the category of abelian sheaves on X has enough injectives, see Injectives, Lemma 4.1. Hence we can choose an injective resolution $\mathcal{F}[0] \rightarrow \mathcal{I}^\bullet$. As is customary we define

$$0712 \quad (3.0.1) \quad H^i(X, \mathcal{F}) = H^i(\Gamma(X, \mathcal{I}^\bullet))$$

to be the *ith cohomology group of the abelian sheaf* \mathcal{F} . The family of functors $H^i((X, -))$ forms a universal δ -functor from $Ab(X) \rightarrow Ab$.

Let $f : X \rightarrow Y$ be a continuous map of topological spaces. With $\mathcal{F}[0] \rightarrow \mathcal{I}^\bullet$ as above we define

$$0713 \quad (3.0.2) \quad R^i f_* \mathcal{F} = H^i(f_* \mathcal{I}^\bullet)$$

to be the *ith higher direct image of* \mathcal{F} . The family of functors $R^i f_*$ forms a universal δ -functor from $Ab(X) \rightarrow Ab(Y)$.

Let (X, \mathcal{O}_X) be a ringed space. Let \mathcal{F} be an \mathcal{O}_X -module. We know that the category of \mathcal{O}_X -modules on X has enough injectives, see Injectives, Lemma 5.1. Hence we can choose an injective resolution $\mathcal{F}[0] \rightarrow \mathcal{I}^\bullet$. As is customary we define

$$0714 \quad (3.0.3) \quad H^i(X, \mathcal{F}) = H^i(\Gamma(X, \mathcal{I}^\bullet))$$

to be the i th cohomology group of \mathcal{F} . The family of functors $H^i((X, -))$ forms a universal δ -functor from $Mod(\mathcal{O}_X) \rightarrow Mod_{\mathcal{O}_X(X)}$.

Let $f : (X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$ be a morphism of ringed spaces. With $\mathcal{F}[0] \rightarrow \mathcal{I}^\bullet$ as above we define

$$0715 \quad (3.0.4) \quad R^i f_* \mathcal{F} = H^i(f_* \mathcal{I}^\bullet)$$

to be the i th higher direct image of \mathcal{F} . The family of functors $R^i f_*$ forms a universal δ -functor from $Mod(\mathcal{O}_X) \rightarrow Mod(\mathcal{O}_Y)$.

4. Derived functors

0716 We briefly explain an approach to right derived functors using resolution functors. Let (X, \mathcal{O}_X) be a ringed space. The category $Mod(\mathcal{O}_X)$ is abelian, see Modules, Lemma 3.1. In this chapter we will write

$$K(X) = K(\mathcal{O}_X) = K(Mod(\mathcal{O}_X)) \quad \text{and} \quad D(X) = D(\mathcal{O}_X) = D(Mod(\mathcal{O}_X)).$$

and similarly for the bounded versions for the triangulated categories introduced in Derived Categories, Definition 8.1 and Definition 11.3. By Derived Categories, Remark 24.3 there exists a resolution functor

$$j = j_X : K^+(Mod(\mathcal{O}_X)) \longrightarrow K^+(\mathcal{I})$$

where \mathcal{I} is the strictly full additive subcategory of $Mod(\mathcal{O}_X)$ consisting of injective sheaves. For any left exact functor $F : Mod(\mathcal{O}_X) \rightarrow \mathcal{B}$ into any abelian category \mathcal{B} we will denote RF the right derived functor described in Derived Categories, Section 20 and constructed using the resolution functor j_X just described:

$$05U3 \quad (4.0.1) \quad RF = F \circ j'_X : D^+(X) \longrightarrow D^+(\mathcal{B})$$

see Derived Categories, Lemma 25.1 for notation. Note that we may think of RF as defined on $Mod(\mathcal{O}_X)$, $Comp^+(Mod(\mathcal{O}_X))$, $K^+(X)$, or $D^+(X)$ depending on the situation. According to Derived Categories, Definition 17.2 we obtain the i th right derived functor

$$05U4 \quad (4.0.2) \quad R^i F = H^i \circ RF : Mod(\mathcal{O}_X) \longrightarrow \mathcal{B}$$

so that $R^0 F = F$ and $\{R^i F, \delta\}_{i \geq 0}$ is universal δ -functor, see Derived Categories, Lemma 20.4.

Here are two special cases of this construction. Given a ring R we write $K(R) = K(Mod_R)$ and $D(R) = D(Mod_R)$ and similarly for bounded versions. For any open $U \subset X$ we have a left exact functor $\Gamma(U, -) : Mod(\mathcal{O}_X) \longrightarrow Mod_{\mathcal{O}_X(U)}$ which gives rise to

$$0717 \quad (4.0.3) \quad R\Gamma(U, -) : D^+(X) \longrightarrow D^+(\mathcal{O}_X(U))$$

by the discussion above. We set $H^i(U, -) = R^i \Gamma(U, -)$. If $U = X$ we recover (3.0.3). If $f : X \rightarrow Y$ is a morphism of ringed spaces, then we have the left exact functor $f_* : Mod(\mathcal{O}_X) \longrightarrow Mod(\mathcal{O}_Y)$ which gives rise to the *derived pushforward*

$$0718 \quad (4.0.4) \quad Rf_* : D^+(X) \longrightarrow D^+(Y)$$

The i th cohomology sheaf of $Rf_* \mathcal{F}^\bullet$ is denoted $R^i f_* \mathcal{F}^\bullet$ and called the i th higher direct image in accordance with (3.0.4). The two displayed functors above are exact functors of derived categories.

Abuse of notation: When the functor Rf_* , or any other derived functor, is applied to a sheaf \mathcal{F} on X or a complex of sheaves it is understood that \mathcal{F} has been replaced by a suitable resolution of \mathcal{F} . To facilitate this kind of operation we will say, given an object $\mathcal{F}^\bullet \in D(X)$, that a bounded below complex \mathcal{I}^\bullet of injectives of $\text{Mod}(\mathcal{O}_X)$ represents \mathcal{F}^\bullet in the derived category if there exists a quasi-isomorphism $\mathcal{F}^\bullet \rightarrow \mathcal{I}^\bullet$. In the same vein the phrase “let $\alpha : \mathcal{F}^\bullet \rightarrow \mathcal{G}^\bullet$ be a morphism of $D(X)$ ” does not mean that α is represented by a morphism of complexes. If we have an actual morphism of complexes we will say so.

5. First cohomology and torsors

02FN

02FO **Definition 5.1.** Let X be a topological space. Let \mathcal{G} be a sheaf of (possibly non-commutative) groups on X . A *torsor*, or more precisely a \mathcal{G} -torsor, is a sheaf of sets \mathcal{F} on X endowed with an action $\mathcal{G} \times \mathcal{F} \rightarrow \mathcal{F}$ such that

- (1) whenever $\mathcal{F}(U)$ is nonempty the action $\mathcal{G}(U) \times \mathcal{F}(U) \rightarrow \mathcal{F}(U)$ is simply transitive, and
- (2) for every $x \in X$ the stalk \mathcal{F}_x is nonempty.

A *morphism of \mathcal{G} -torsors* $\mathcal{F} \rightarrow \mathcal{F}'$ is simply a morphism of sheaves of sets compatible with the \mathcal{G} -actions. The *trivial \mathcal{G} -torsor* is the sheaf \mathcal{G} endowed with the obvious left \mathcal{G} -action.

It is clear that a morphism of torsors is automatically an isomorphism.

02FP **Lemma 5.2.** Let X be a topological space. Let \mathcal{G} be a sheaf of (possibly non-commutative) groups on X . A \mathcal{G} -torsor \mathcal{F} is trivial if and only if $\mathcal{F}(X) \neq \emptyset$.

Proof. Omitted. □

02FQ **Lemma 5.3.** Let X be a topological space. Let \mathcal{H} be an abelian sheaf on X . There is a canonical bijection between the set of isomorphism classes of \mathcal{H} -torsors and $H^1(X, \mathcal{H})$.

Proof. Let \mathcal{F} be a \mathcal{H} -torsor. Consider the free abelian sheaf $\mathbf{Z}[\mathcal{F}]$ on \mathcal{F} . It is the sheafification of the rule which associates to $U \subset X$ open the collection of finite formal sums $\sum n_i[s_i]$ with $n_i \in \mathbf{Z}$ and $s_i \in \mathcal{F}(U)$. There is a natural map

$$\sigma : \mathbf{Z}[\mathcal{F}] \longrightarrow \underline{\mathbf{Z}}$$

which to a local section $\sum n_i[s_i]$ associates $\sum n_i$. The kernel of σ is generated by the local section of the form $[s] - [s']$. There is a canonical map $a : \text{Ker}(\sigma) \rightarrow \mathcal{H}$ which maps $[s] - [s'] \mapsto h$ where h is the local section of \mathcal{H} such that $h \cdot s = s'$. Consider the pushout diagram

$$\begin{array}{ccccccc} 0 & \longrightarrow & \text{Ker}(\sigma) & \longrightarrow & \mathbf{Z}[\mathcal{F}] & \longrightarrow & \underline{\mathbf{Z}} \longrightarrow 0 \\ & & \downarrow a & & \downarrow & & \downarrow \\ 0 & \longrightarrow & \mathcal{H} & \longrightarrow & \mathcal{E} & \longrightarrow & \underline{\mathbf{Z}} \longrightarrow 0 \end{array}$$

Here \mathcal{E} is the extension obtained by pushout. From the long exact cohomology sequence associated to the lower short exact sequence we obtain an element $\xi = \xi_{\mathcal{F}} \in H^1(X, \mathcal{H})$ by applying the boundary operator to $1 \in H^0(X, \underline{\mathbf{Z}})$.

Conversely, given $\xi \in H^1(X, \mathcal{H})$ we can associate to ξ a torsor as follows. Choose an embedding $\mathcal{H} \rightarrow \mathcal{I}$ of \mathcal{H} into an injective abelian sheaf \mathcal{I} . We set $\mathcal{Q} = \mathcal{I}/\mathcal{H}$ so that we have a short exact sequence

$$0 \longrightarrow \mathcal{H} \longrightarrow \mathcal{I} \longrightarrow \mathcal{Q} \longrightarrow 0$$

The element ξ is the image of a global section $q \in H^0(X, \mathcal{Q})$ because $H^1(X, \mathcal{I}) = 0$ (see Derived Categories, Lemma 20.4). Let $\mathcal{F} \subset \mathcal{I}$ be the subsheaf (of sets) of sections that map to q in the sheaf \mathcal{Q} . It is easy to verify that \mathcal{F} is a torsor.

We omit the verification that the two constructions given above are mutually inverse. \square

6. First cohomology and extensions

0B39

0B3A **Lemma 6.1.** *Let (X, \mathcal{O}_X) be a ringed space. Let \mathcal{F} be a sheaf of \mathcal{O}_X -modules. There is a canonical bijection*

$$\mathrm{Ext}_{\mathrm{Mod}(\mathcal{O}_X)}^1(\mathcal{O}_X, \mathcal{F}) \longrightarrow H^1(X, \mathcal{F})$$

which associates to the extension

$$0 \rightarrow \mathcal{F} \rightarrow \mathcal{E} \rightarrow \mathcal{O}_X \rightarrow 0$$

the image of $1 \in \Gamma(X, \mathcal{O}_X)$ in $H^1(X, \mathcal{F})$.

Proof. Let us construct the inverse of the map given in the lemma. Let $\xi \in H^1(X, \mathcal{F})$. Choose an injection $\mathcal{F} \subset \mathcal{I}$ with \mathcal{I} injective in $\mathrm{Mod}(\mathcal{O}_X)$. Set $\mathcal{Q} = \mathcal{I}/\mathcal{F}$. By the long exact sequence of cohomology, we see that ξ is the image of a section $\tilde{\xi} \in \Gamma(X, \mathcal{Q}) = \mathrm{Hom}_{\mathcal{O}_X}(\mathcal{O}_X, \mathcal{Q})$. Now, we just form the pullback

$$\begin{array}{ccccccc} 0 & \longrightarrow & \mathcal{F} & \longrightarrow & \mathcal{E} & \longrightarrow & \mathcal{O}_X \longrightarrow 0 \\ & & \parallel & & \downarrow & & \downarrow \tilde{\xi} \\ 0 & \longrightarrow & \mathcal{F} & \longrightarrow & \mathcal{I} & \longrightarrow & \mathcal{Q} \longrightarrow 0 \end{array}$$

see Homology, Section 6. \square

7. First cohomology and invertible sheaves

09NT The Picard group of a ringed space is defined in Modules, Section 22.

09NU **Lemma 7.1.** *Let (X, \mathcal{O}_X) be a locally ringed space. There is a canonical isomorphism*

$$H^1(X, \mathcal{O}_X^*) = \mathrm{Pic}(X).$$

of abelian groups.

Proof. Let \mathcal{L} be an invertible \mathcal{O}_X -module. Consider the presheaf \mathcal{L}^* defined by the rule

$$U \longmapsto \{s \in \mathcal{L}(U) \text{ such that } \mathcal{O}_U \xrightarrow{s \cdot} \mathcal{L}_U \text{ is an isomorphism}\}$$

This presheaf satisfies the sheaf condition. Moreover, if $f \in \mathcal{O}_X^*(U)$ and $s \in \mathcal{L}^*(U)$, then clearly $fs \in \mathcal{L}^*(U)$. By the same token, if $s, s' \in \mathcal{L}^*(U)$ then there exists a unique $f \in \mathcal{O}_X^*(U)$ such that $fs = s'$. Moreover, the sheaf \mathcal{L}^* has sections locally

by Modules, Lemma 22.4. In other words we see that \mathcal{L}^* is a \mathcal{O}_X^* -torsor. Thus we get a map

$$\begin{array}{ccc} \text{invertible sheaves on } (X, \mathcal{O}_X) & \longrightarrow & \mathcal{O}_X^*\text{-torsors} \\ \text{up to isomorphism} & & \text{up to isomorphism} \end{array}$$

We omit the verification that this is a homomorphism of abelian groups. By Lemma 5.3 the right hand side is canonically bijective to $H^1(X, \mathcal{O}_X^*)$. Thus we have to show this map is injective and surjective.

Injective. If the torsor \mathcal{L}^* is trivial, this means by Lemma 5.2 that \mathcal{L}^* has a global section. Hence this means exactly that $\mathcal{L} \cong \mathcal{O}_X$ is the neutral element in $\text{Pic}(X)$.

Surjective. Let \mathcal{F} be an \mathcal{O}_X^* -torsor. Consider the presheaf of sets

$$\mathcal{L}_1 : U \mapsto (\mathcal{F}(U) \times \mathcal{O}_X(U)) / \mathcal{O}_X^*(U)$$

where the action of $f \in \mathcal{O}_X^*(U)$ on (s, g) is $(fs, f^{-1}g)$. Then \mathcal{L}_1 is a presheaf of \mathcal{O}_X -modules by setting $(s, g) + (s', g') = (s, g + (s'/s)g')$ where s'/s is the local section f of \mathcal{O}_X^* such that $fs = s'$, and $h(s, g) = (s, hg)$ for h a local section of \mathcal{O}_X .

We omit the verification that the sheafification $\mathcal{L} = \mathcal{L}_1^\#$ is an invertible \mathcal{O}_X -module whose associated \mathcal{O}_X^* -torsor \mathcal{L}^* is isomorphic to \mathcal{F} . \square

8. Locality of cohomology

01E0 The following lemma says there is no ambiguity in defining the cohomology of a sheaf \mathcal{F} over an open.

01E1 **Lemma 8.1.** *Let X be a ringed space. Let $U \subset X$ be an open subspace.*

- (1) *If \mathcal{I} is an injective \mathcal{O}_X -module then $\mathcal{I}|_U$ is an injective \mathcal{O}_U -module.*
- (2) *For any sheaf of \mathcal{O}_X -modules \mathcal{F} we have $H^p(U, \mathcal{F}) = H^p(U, \mathcal{F}|_U)$.*

Proof. Denote $j : U \rightarrow X$ the open immersion. Recall that the functor j^{-1} of restriction to U is a right adjoint to the functor $j_!$ of extension by 0, see Sheaves, Lemma 31.8. Moreover, $j_!$ is exact. Hence (1) follows from Homology, Lemma 25.1.

By definition $H^p(U, \mathcal{F}) = H^p(\Gamma(U, \mathcal{I}^\bullet))$ where $\mathcal{F} \rightarrow \mathcal{I}^\bullet$ is an injective resolution in $\text{Mod}(\mathcal{O}_X)$. By the above we see that $\mathcal{F}|_U \rightarrow \mathcal{I}^\bullet|_U$ is an injective resolution in $\text{Mod}(\mathcal{O}_U)$. Hence $H^p(U, \mathcal{F}|_U)$ is equal to $H^p(\Gamma(U, \mathcal{I}^\bullet|_U))$. Of course $\Gamma(U, \mathcal{F}) = \Gamma(U, \mathcal{F}|_U)$ for any sheaf \mathcal{F} on X . Hence the equality in (2). \square

Let X be a ringed space. Let \mathcal{F} be a sheaf of \mathcal{O}_X -modules. Let $U \subset V \subset X$ be open subsets. Then there is a canonical *restriction mapping*

01E2 (8.1.1)
$$H^n(V, \mathcal{F}) \longrightarrow H^n(U, \mathcal{F}), \quad \xi \mapsto \xi|_U$$

functorial in \mathcal{F} . Namely, choose any injective resolution $\mathcal{F} \rightarrow \mathcal{I}^\bullet$. The restriction mappings of the sheaves \mathcal{I}^p give a morphism of complexes

$$\Gamma(V, \mathcal{I}^\bullet) \longrightarrow \Gamma(U, \mathcal{I}^\bullet)$$

The LHS is a complex representing $R\Gamma(V, \mathcal{F})$ and the RHS is a complex representing $R\Gamma(U, \mathcal{F})$. We get the map on cohomology groups by applying the functor H^n . As indicated we will use the notation $\xi \mapsto \xi|_U$ to denote this map. Thus the rule $U \mapsto H^n(U, \mathcal{F})$ is a presheaf of \mathcal{O}_X -modules. This presheaf is customarily denoted $\underline{H}^n(\mathcal{F})$. We will give another interpretation of this presheaf in Lemma 12.4.

01E3 **Lemma 8.2.** *Let X be a ringed space. Let \mathcal{F} be a sheaf of \mathcal{O}_X -modules. Let $U \subset X$ be an open subspace. Let $n > 0$ and let $\xi \in H^n(U, \mathcal{F})$. Then there exists an open covering $U = \bigcup_{i \in I} U_i$ such that $\xi|_{U_i} = 0$ for all $i \in I$.*

Proof. Let $\mathcal{F} \rightarrow \mathcal{I}^\bullet$ be an injective resolution. Then

$$H^n(U, \mathcal{F}) = \frac{\text{Ker}(\mathcal{I}^n(U) \rightarrow \mathcal{I}^{n+1}(U))}{\text{Im}(\mathcal{I}^{n-1}(U) \rightarrow \mathcal{I}^n(U))}.$$

Pick an element $\tilde{\xi} \in \mathcal{I}^n(U)$ representing the cohomology class in the presentation above. Since \mathcal{I}^\bullet is an injective resolution of \mathcal{F} and $n > 0$ we see that the complex \mathcal{I}^\bullet is exact in degree n . Hence $\text{Im}(\mathcal{I}^{n-1} \rightarrow \mathcal{I}^n) = \text{Ker}(\mathcal{I}^n \rightarrow \mathcal{I}^{n+1})$ as sheaves. Since $\tilde{\xi}$ is a section of the kernel sheaf over U we conclude there exists an open covering $U = \bigcup_{i \in I} U_i$ such that $\tilde{\xi}|_{U_i}$ is the image under d of a section $\xi_i \in \mathcal{I}^{n-1}(U_i)$. By our definition of the restriction $\xi|_{U_i}$ as corresponding to the class of $\tilde{\xi}|_{U_i}$ we conclude. \square

01E4 **Lemma 8.3.** *Let $f : X \rightarrow Y$ be a morphism of ringed spaces. Let \mathcal{F} be a \mathcal{O}_X -module. The sheaves $R^i f_* \mathcal{F}$ are the sheaves associated to the presheaves*

$$V \mapsto H^i(f^{-1}(V), \mathcal{F})$$

with restriction mappings as in Equation (8.1.1). There is a similar statement for $R^i f_$ applied to a bounded below complex \mathcal{F}^\bullet .*

Proof. Let $\mathcal{F} \rightarrow \mathcal{I}^\bullet$ be an injective resolution. Then $R^i f_* \mathcal{F}$ is by definition the i th cohomology sheaf of the complex

$$f_* \mathcal{I}^0 \rightarrow f_* \mathcal{I}^1 \rightarrow f_* \mathcal{I}^2 \rightarrow \dots$$

By definition of the abelian category structure on \mathcal{O}_Y -modules this cohomology sheaf is the sheaf associated to the presheaf

$$V \mapsto \frac{\text{Ker}(f_* \mathcal{I}^i(V) \rightarrow f_* \mathcal{I}^{i+1}(V))}{\text{Im}(f_* \mathcal{I}^{i-1}(V) \rightarrow f_* \mathcal{I}^i(V))}$$

and this is obviously equal to

$$\frac{\text{Ker}(\mathcal{I}^i(f^{-1}(V)) \rightarrow \mathcal{I}^{i+1}(f^{-1}(V)))}{\text{Im}(\mathcal{I}^{i-1}(f^{-1}(V)) \rightarrow \mathcal{I}^i(f^{-1}(V)))}$$

which is equal to $H^i(f^{-1}(V), \mathcal{F})$ and we win. \square

01E5 **Lemma 8.4.** *Let $f : X \rightarrow Y$ be a morphism of ringed spaces. Let \mathcal{F} be an \mathcal{O}_X -module. Let $V \subset Y$ be an open subspace. Denote $g : f^{-1}(V) \rightarrow V$ the restriction of f . Then we have*

$$R^p g_*(\mathcal{F}|_{f^{-1}(V)}) = (R^p f_* \mathcal{F})|_V$$

There is a similar statement for the derived image $Rf_ \mathcal{F}^\bullet$ where \mathcal{F}^\bullet is a bounded below complex of \mathcal{O}_X -modules.*

Proof. First proof. Apply Lemmas 8.3 and 8.1 to see the displayed equality. Second proof. Choose an injective resolution $\mathcal{F} \rightarrow \mathcal{I}^\bullet$ and use that $\mathcal{F}|_{f^{-1}(V)} \rightarrow \mathcal{I}^\bullet|_{f^{-1}(V)}$ is an injective resolution also. \square

03BA **Remark 8.5.** Here is a different approach to the proofs of Lemmas 8.2 and 8.3 above. Let (X, \mathcal{O}_X) be a ringed space. Let $i_X : \text{Mod}(\mathcal{O}_X) \rightarrow \text{PMod}(\mathcal{O}_X)$ be the inclusion functor and let $\#$ be the sheafification functor. Recall that i_X is left exact and $\#$ is exact.

- (1) First prove Lemma 12.4 below which says that the right derived functors of i_X are given by $R^p i_X \mathcal{F} = \underline{H}^p(\mathcal{F})$. Here is another proof: The equality is clear for $p = 0$. Both $(R^p i_X)_{p \geq 0}$ and $(\underline{H}^p)_{p \geq 0}$ are delta functors vanishing on injectives, hence both are universal, hence they are isomorphic. See Homology, Section 11.
- (2) A restatement of Lemma 8.2 is that $(\underline{H}^p(\mathcal{F}))^\# = 0$, $p > 0$ for any sheaf of \mathcal{O}_X -modules \mathcal{F} . To see this is true, use that $\#$ is exact so

$$(\underline{H}^p(\mathcal{F}))^\# = (R^p i_X \mathcal{F})^\# = R^p(\# \circ i_X)(\mathcal{F}) = 0$$

because $\# \circ i_X$ is the identity functor.

- (3) Let $f : X \rightarrow Y$ be a morphism of ringed spaces. Let \mathcal{F} be an \mathcal{O}_X -module. The presheaf $V \mapsto H^p(f^{-1}V, \mathcal{F})$ is equal to $R^p(i_Y \circ f_*)\mathcal{F}$. You can prove this by noticing that both give universal delta functors as in the argument of (1) above. Hence Lemma 8.3 says that $R^p f_* \mathcal{F} = (R^p(i_Y \circ f_*)\mathcal{F})^\#$. Again using that $\#$ is exact a that $\# \circ i_Y$ is the identity functor we see that

$$R^p f_* \mathcal{F} = R^p(\# \circ i_Y \circ f_*)\mathcal{F} = (R^p(i_Y \circ f_*)\mathcal{F})^\#$$

as desired.

9. Mayer-Vietoris

01E9 Below will construct the Čech-to-cohomology spectral sequence, see Lemma 12.5. A special case of that spectral sequence is the Mayer-Vietoris long exact sequence. Since it is such a basic, useful and easy to understand variant of the spectral sequence we treat it here separately.

01EA **Lemma 9.1.** *Let X be a ringed space. Let $U' \subset U \subset X$ be open subspaces. For any injective \mathcal{O}_X -module \mathcal{I} the restriction mapping $\mathcal{I}(U) \rightarrow \mathcal{I}(U')$ is surjective.*

Proof. Let $j : U \rightarrow X$ and $j' : U' \rightarrow X$ be the open immersions. Recall that $j_! \mathcal{O}_U$ is the extension by zero of $\mathcal{O}_U = \mathcal{O}_X|_U$, see Sheaves, Section 31. Since $j_!$ is a left adjoint to restriction we see that for any sheaf \mathcal{F} of \mathcal{O}_X -modules

$$\text{Hom}_{\mathcal{O}_X}(j_! \mathcal{O}_U, \mathcal{F}) = \text{Hom}_{\mathcal{O}_U}(\mathcal{O}_U, \mathcal{F}|_U) = \mathcal{F}(U)$$

see Sheaves, Lemma 31.8. Similarly, the sheaf $j'_! \mathcal{O}_{U'}$ represents the functor $\mathcal{F} \mapsto \mathcal{F}(U')$. Moreover there is an obvious canonical map of \mathcal{O}_X -modules

$$j'_! \mathcal{O}_{U'} \longrightarrow j_! \mathcal{O}_U$$

which corresponds to the restriction mapping $\mathcal{F}(U) \rightarrow \mathcal{F}(U')$ via Yoneda's lemma (Categories, Lemma 3.5). By the description of the stalks of the sheaves $j'_! \mathcal{O}_{U'}$, $j_! \mathcal{O}_U$ we see that the displayed map above is injective (see lemma cited above). Hence if \mathcal{I} is an injective \mathcal{O}_X -module, then the map

$$\text{Hom}_{\mathcal{O}_X}(j_! \mathcal{O}_U, \mathcal{I}) \longrightarrow \text{Hom}_{\mathcal{O}_X}(j'_! \mathcal{O}_{U'}, \mathcal{I})$$

is surjective, see Homology, Lemma 23.2. Putting everything together we obtain the lemma. \square

01EB **Lemma 9.2** (Mayer-Vietoris). *Let X be a ringed space. Suppose that $X = U \cup V$ is a union of two open subsets. For every \mathcal{O}_X -module \mathcal{F} there exists a long exact cohomology sequence*

$$0 \rightarrow H^0(X, \mathcal{F}) \rightarrow H^0(U, \mathcal{F}) \oplus H^0(V, \mathcal{F}) \rightarrow H^0(U \cap V, \mathcal{F}) \rightarrow H^1(X, \mathcal{F}) \rightarrow \dots$$

This long exact sequence is functorial in \mathcal{F} .

Proof. The sheaf condition says that the kernel of $(1, -1) : \mathcal{F}(U) \oplus \mathcal{F}(V) \rightarrow \mathcal{F}(U \cap V)$ is equal to the image of $\mathcal{F}(X)$ by the first map for any abelian sheaf \mathcal{F} . Lemma 9.1 above implies that the map $(1, -1) : \mathcal{I}(U) \oplus \mathcal{I}(V) \rightarrow \mathcal{I}(U \cap V)$ is surjective whenever \mathcal{I} is an injective \mathcal{O}_X -module. Hence if $\mathcal{F} \rightarrow \mathcal{I}^\bullet$ is an injective resolution of \mathcal{F} , then we get a short exact sequence of complexes

$$0 \rightarrow \mathcal{I}^\bullet(X) \rightarrow \mathcal{I}^\bullet(U) \oplus \mathcal{I}^\bullet(V) \rightarrow \mathcal{I}^\bullet(U \cap V) \rightarrow 0.$$

Taking cohomology gives the result (use Homology, Lemma 12.12). We omit the proof of the functoriality of the sequence. \square

01EC **Lemma 9.3** (Relative Mayer-Vietoris). *Let $f : X \rightarrow Y$ be a morphism of ringed spaces. Suppose that $X = U \cup V$ is a union of two open subsets. Denote $a = f|_U : U \rightarrow Y$, $b = f|_V : V \rightarrow Y$, and $c = f|_{U \cap V} : U \cap V \rightarrow Y$. For every \mathcal{O}_X -module \mathcal{F} there exists a long exact sequence*

$$0 \rightarrow f_*\mathcal{F} \rightarrow a_*(\mathcal{F}|_U) \oplus b_*(\mathcal{F}|_V) \rightarrow c_*(\mathcal{F}|_{U \cap V}) \rightarrow R^1 f_*\mathcal{F} \rightarrow \dots$$

This long exact sequence is functorial in \mathcal{F} .

Proof. Let $\mathcal{F} \rightarrow \mathcal{I}^\bullet$ be an injective resolution of \mathcal{F} . We claim that we get a short exact sequence of complexes

$$0 \rightarrow f_*\mathcal{I}^\bullet \rightarrow a_*\mathcal{I}^\bullet|_U \oplus b_*\mathcal{I}^\bullet|_V \rightarrow c_*\mathcal{I}^\bullet|_{U \cap V} \rightarrow 0.$$

Namely, for any open $W \subset Y$, and for any $n \geq 0$ the corresponding sequence of groups of sections over W

$$0 \rightarrow \mathcal{I}^n(f^{-1}(W)) \rightarrow \mathcal{I}^n(U \cap f^{-1}(W)) \oplus \mathcal{I}^n(V \cap f^{-1}(W)) \rightarrow \mathcal{I}^n(U \cap V \cap f^{-1}(W)) \rightarrow 0$$

was shown to be short exact in the proof of Lemma 9.2. The lemma follows by taking cohomology sheaves and using the fact that $\mathcal{I}^\bullet|_U$ is an injective resolution of $\mathcal{F}|_U$ and similarly for $\mathcal{I}^\bullet|_V$, $\mathcal{I}^\bullet|_{U \cap V}$ see Lemma 8.1. \square

10. The Čech complex and Čech cohomology

01ED Let X be a topological space. Let $\mathcal{U} : U = \bigcup_{i \in I} U_i$ be an open covering, see Topology, Basic notion (13). As is customary we denote $U_{i_0 \dots i_p} = U_{i_0} \cap \dots \cap U_{i_p}$ for the $(p+1)$ -fold intersection of members of \mathcal{U} . Let \mathcal{F} be an abelian presheaf on X . Set

$$\check{C}^p(\mathcal{U}, \mathcal{F}) = \prod_{(i_0, \dots, i_p) \in I^{p+1}} \mathcal{F}(U_{i_0 \dots i_p}).$$

This is an abelian group. For $s \in \check{C}^p(\mathcal{U}, \mathcal{F})$ we denote $s_{i_0 \dots i_p}$ its value in $\mathcal{F}(U_{i_0 \dots i_p})$. Note that if $s \in \check{C}^1(\mathcal{U}, \mathcal{F})$ and $i, j \in I$ then s_{ij} and s_{ji} are both elements of $\mathcal{F}(U_i \cap U_j)$ but there is no imposed relation between s_{ij} and s_{ji} . In other words, we are *not* working with alternating cochains (these will be defined in Section 24). We define

$$d : \check{C}^p(\mathcal{U}, \mathcal{F}) \longrightarrow \check{C}^{p+1}(\mathcal{U}, \mathcal{F})$$

by the formula

$$01EE \quad (10.0.1) \quad d(s)_{i_0 \dots i_{p+1}} = \sum_{j=0}^{p+1} (-1)^j s_{i_0 \dots \hat{i}_j \dots i_{p+1}}|_{U_{i_0 \dots i_{p+1}}}$$

It is straightforward to see that $d \circ d = 0$. In other words $\check{C}^\bullet(\mathcal{U}, \mathcal{F})$ is a complex.

01EF **Definition 10.1.** Let X be a topological space. Let $\mathcal{U} : U = \bigcup_{i \in I} U_i$ be an open covering. Let \mathcal{F} be an abelian presheaf on X . The complex $\check{C}^\bullet(\mathcal{U}, \mathcal{F})$ is the Čech complex associated to \mathcal{F} and the open covering \mathcal{U} . Its cohomology groups $H^i(\check{C}^\bullet(\mathcal{U}, \mathcal{F}))$ are called the Čech cohomology groups associated to \mathcal{F} and the covering \mathcal{U} . They are denoted $\check{H}^i(\mathcal{U}, \mathcal{F})$.

01EG **Lemma 10.2.** Let X be a topological space. Let \mathcal{F} be an abelian presheaf on X . The following are equivalent

- (1) \mathcal{F} is an abelian sheaf and
- (2) for every open covering $\mathcal{U} : U = \bigcup_{i \in I} U_i$ the natural map

$$\mathcal{F}(U) \rightarrow \check{H}^0(\mathcal{U}, \mathcal{F})$$

is bijective.

Proof. This is true since the sheaf condition is exactly that $\mathcal{F}(U) \rightarrow \check{H}^0(\mathcal{U}, \mathcal{F})$ is bijective for every open covering. \square

11. Čech cohomology as a functor on presheaves

01EH **Warning:** In this section we work almost exclusively with presheaves and categories of presheaves and the results are completely wrong in the setting of sheaves and categories of sheaves!

Let X be a ringed space. Let $\mathcal{U} : U = \bigcup_{i \in I} U_i$ be an open covering. Let \mathcal{F} be a presheaf of \mathcal{O}_X -modules. We have the Čech complex $\check{C}^\bullet(\mathcal{U}, \mathcal{F})$ of \mathcal{F} just by thinking of \mathcal{F} as a presheaf of abelian groups. However, each term $\check{C}^p(\mathcal{U}, \mathcal{F})$ has a natural structure of a $\mathcal{O}_X(U)$ -module and the differential is given by $\mathcal{O}_X(U)$ -module maps. Moreover, it is clear that the construction

$$\mathcal{F} \mapsto \check{C}^\bullet(\mathcal{U}, \mathcal{F})$$

is functorial in \mathcal{F} . In fact, it is a functor

$$01EI \quad (11.0.1) \quad \check{C}^\bullet(\mathcal{U}, -) : PMod(\mathcal{O}_X) \longrightarrow \text{Comp}^+(\text{Mod}_{\mathcal{O}_X(U)})$$

see Derived Categories, Definition 8.1 for notation. Recall that the category of bounded below complexes in an abelian category is an abelian category, see Homology, Lemma 12.9.

01EJ **Lemma 11.1.** The functor given by Equation (11.0.1) is an exact functor (see Homology, Lemma 7.2).

Proof. For any open $W \subset U$ the functor $\mathcal{F} \mapsto \mathcal{F}(W)$ is an additive exact functor from $PMod(\mathcal{O}_X)$ to $\text{Mod}_{\mathcal{O}_X(U)}$. The terms $\check{C}^p(\mathcal{U}, \mathcal{F})$ of the complex are products of these exact functors and hence exact. Moreover a sequence of complexes is exact if and only if the sequence of terms in a given degree is exact. Hence the lemma follows. \square

01EK **Lemma 11.2.** *Let X be a ringed space. Let $\mathcal{U} : U = \bigcup_{i \in I} U_i$ be an open covering. The functors $\mathcal{F} \mapsto \check{H}^n(\mathcal{U}, \mathcal{F})$ form a δ -functor from the abelian category of presheaves of \mathcal{O}_X -modules to the category of $\mathcal{O}_X(U)$ -modules (see Homology, Definition 11.1).*

Proof. By Lemma 11.1 a short exact sequence of presheaves of \mathcal{O}_X -modules $0 \rightarrow \mathcal{F}_1 \rightarrow \mathcal{F}_2 \rightarrow \mathcal{F}_3 \rightarrow 0$ is turned into a short exact sequence of complexes of $\mathcal{O}_X(U)$ -modules. Hence we can use Homology, Lemma 12.12 to get the boundary maps $\delta_{\mathcal{F}_1 \rightarrow \mathcal{F}_2 \rightarrow \mathcal{F}_3} : \check{H}^n(\mathcal{U}, \mathcal{F}_3) \rightarrow \check{H}^{n+1}(\mathcal{U}, \mathcal{F}_1)$ and a corresponding long exact sequence. We omit the verification that these maps are compatible with maps between short exact sequences of presheaves. \square

In the formulation of the following lemma we use the functor $j_{p!}$ of extension by 0 for presheaves of modules relative to an open immersion $j : U \rightarrow X$. See Sheaves, Section 31. For any open $W \subset X$ and any presheaf \mathcal{G} of $\mathcal{O}_X|_U$ -modules we have

$$(j_{p!}\mathcal{G})(W) = \begin{cases} \mathcal{G}(W) & \text{if } W \subset U \\ 0 & \text{else.} \end{cases}$$

Moreover, the functor $j_{p!}$ is a left adjoint to the restriction functor see Sheaves, Lemma 31.8. In particular we have the following formula

$$\mathrm{Hom}_{\mathcal{O}_X}(j_{p!}\mathcal{O}_U, \mathcal{F}) = \mathrm{Hom}_{\mathcal{O}_U}(\mathcal{O}_U, \mathcal{F}|_U) = \mathcal{F}(U).$$

Since the functor $\mathcal{F} \mapsto \mathcal{F}(U)$ is an exact functor on the category of presheaves we conclude that the presheaf $j_{p!}\mathcal{O}_U$ is a projective object in the category $PMod(\mathcal{O}_X)$, see Homology, Lemma 24.2.

Note that if we are given open subsets $U \subset V \subset X$ with associated open immersions j_U, j_V , then we have a canonical map $(j_U)_{p!}\mathcal{O}_U \rightarrow (j_V)_{p!}\mathcal{O}_V$. It is the identity on sections over any open $W \subset U$ and 0 else. In terms of the identification $\mathrm{Hom}_{\mathcal{O}_X}((j_U)_{p!}\mathcal{O}_U, (j_V)_{p!}\mathcal{O}_V) = (j_V)_{p!}\mathcal{O}_V(U) = \mathcal{O}_V(U)$ it corresponds to the element $1 \in \mathcal{O}_V(U)$.

01EL **Lemma 11.3.** *Let X be a ringed space. Let $\mathcal{U} : U = \bigcup_{i \in I} U_i$ be a covering. Denote $j_{i_0 \dots i_p} : U_{i_0 \dots i_p} \rightarrow X$ the open immersion. Consider the chain complex $K(\mathcal{U})_\bullet$ of presheaves of \mathcal{O}_X -modules*

$$\dots \rightarrow \bigoplus_{i_0 i_1 i_2} (j_{i_0 i_1 i_2})_{p!}\mathcal{O}_{U_{i_0 i_1 i_2}} \rightarrow \bigoplus_{i_0 i_1} (j_{i_0 i_1})_{p!}\mathcal{O}_{U_{i_0 i_1}} \rightarrow \bigoplus_{i_0} (j_{i_0})_{p!}\mathcal{O}_{U_{i_0}} \rightarrow 0 \rightarrow \dots$$

where the last nonzero term is placed in degree 0 and where the map

$$(j_{i_0 \dots i_{p+1}})_{p!}\mathcal{O}_{U_{i_0 \dots i_{p+1}}} \longrightarrow (j_{i_0 \dots \hat{i}_j \dots i_{p+1}})_{p!}\mathcal{O}_{U_{i_0 \dots \hat{i}_j \dots i_{p+1}}}$$

is given by $(-1)^j$ times the canonical map. Then there is an isomorphism

$$\mathrm{Hom}_{\mathcal{O}_X}(K(\mathcal{U})_\bullet, \mathcal{F}) = \check{C}^\bullet(\mathcal{U}, \mathcal{F})$$

functorial in $\mathcal{F} \in \mathrm{Ob}(PMod(\mathcal{O}_X))$.

Proof. We saw in the discussion just above the lemma that

$$\mathrm{Hom}_{\mathcal{O}_X}((j_{i_0 \dots i_p})_{p!}\mathcal{O}_{U_{i_0 \dots i_p}}, \mathcal{F}) = \mathcal{F}(U_{i_0 \dots i_p}).$$

Hence we see that it is indeed the case that the direct sum

$$\bigoplus_{i_0 \dots i_p} (j_{i_0 \dots i_p})_{p!}\mathcal{O}_{U_{i_0 \dots i_p}}$$

represents the functor

$$\mathcal{F} \mapsto \prod_{i_0 \dots i_p} \mathcal{F}(U_{i_0 \dots i_p}).$$

Hence by Categories, Yoneda Lemma 3.5 we see that there is a complex $K(\mathcal{U})_\bullet$ with terms as given. It is a simple matter to see that the maps are as given in the lemma. \square

01EM **Lemma 11.4.** *Let X be a ringed space. Let $\mathcal{U} : U = \bigcup_{i \in I} U_i$ be a covering. Let $\mathcal{O}_{\mathcal{U}} \subset \mathcal{O}_X$ be the image presheaf of the map $\bigoplus_{j_p!} \mathcal{O}_{U_i} \rightarrow \mathcal{O}_X$. The chain complex $K(\mathcal{U})_\bullet$ of presheaves of Lemma 11.3 above has homology presheaves*

$$H_i(K(\mathcal{U})_\bullet) = \begin{cases} 0 & \text{if } i \neq 0 \\ \mathcal{O}_{\mathcal{U}} & \text{if } i = 0 \end{cases}$$

Proof. Consider the extended complex K_\bullet^{ext} one gets by putting $\mathcal{O}_{\mathcal{U}}$ in degree -1 with the obvious map $K(\mathcal{U})_0 = \bigoplus_{i_0} (j_{i_0})_{p!} \mathcal{O}_{U_{i_0}} \rightarrow \mathcal{O}_{\mathcal{U}}$. It suffices to show that taking sections of this extended complex over any open $W \subset X$ leads to an acyclic complex. In fact, we claim that for every $W \subset X$ the complex $K_\bullet^{ext}(W)$ is homotopy equivalent to the zero complex. Write $I = I_1 \amalg I_2$ where $W \subset U_i$ if and only if $i \in I_1$.

If $I_1 = \emptyset$, then the complex $K_\bullet^{ext}(W) = 0$ so there is nothing to prove.

If $I_1 \neq \emptyset$, then $\mathcal{O}_{\mathcal{U}}(W) = \mathcal{O}_X(W)$ and

$$K_p^{ext}(W) = \bigoplus_{i_0 \dots i_p \in I_1} \mathcal{O}_X(W).$$

This is true because of the simple description of the presheaves $(j_{i_0 \dots i_p})_{p!} \mathcal{O}_{U_{i_0 \dots i_p}}$. Moreover, the differential of the complex $K_\bullet^{ext}(W)$ is given by

$$d(s)_{i_0 \dots i_p} = \sum_{j=0, \dots, p+1} \sum_{i \in I_1} (-1)^j s_{i_0 \dots i_{j-1} i i_j \dots i_p}.$$

The sum is finite as the element s has finite support. Fix an element $i_{\text{fix}} \in I_1$. Define a map

$$h : K_p^{ext}(W) \longrightarrow K_{p+1}^{ext}(W)$$

by the rule

$$h(s)_{i_0 \dots i_{p+1}} = \begin{cases} 0 & \text{if } i_0 \neq i \\ s_{i_1 \dots i_{p+1}} & \text{if } i_0 = i_{\text{fix}} \end{cases}$$

We will use the shorthand $h(s)_{i_0 \dots i_{p+1}} = (i_0 = i_{\text{fix}}) s_{i_1 \dots i_p}$ for this. Then we compute

$$\begin{aligned} & (dh + hd)(s)_{i_0 \dots i_p} \\ &= \sum_j \sum_{i \in I_1} (-1)^j h(s)_{i_0 \dots i_{j-1} i i_j \dots i_p} + (i = i_0) d(s)_{i_1 \dots i_p} \\ &= s_{i_0 \dots i_p} + \sum_{j \geq 1} \sum_{i \in I_1} (-1)^j (i_0 = i_{\text{fix}}) s_{i_1 \dots i_{j-1} i i_j \dots i_p} + (i_0 = i_{\text{fix}}) d(s)_{i_1 \dots i_p} \end{aligned}$$

which is equal to $s_{i_0 \dots i_p}$ as desired. \square

01EN **Lemma 11.5.** *Let X be a ringed space. Let $\mathcal{U} : U = \bigcup_{i \in I} U_i$ be an open covering of $U \subset X$. The Čech cohomology functors $\check{H}^p(\mathcal{U}, -)$ are canonically isomorphic as a δ -functor to the right derived functors of the functor*

$$\check{H}^0(\mathcal{U}, -) : P\text{Mod}(\mathcal{O}_X) \longrightarrow \text{Mod}_{\mathcal{O}_X(U)}.$$

Moreover, there is a functorial quasi-isomorphism

$$\check{C}^\bullet(\mathcal{U}, \mathcal{F}) \longrightarrow R\check{H}^0(\mathcal{U}, \mathcal{F})$$

where the right hand side indicates the right derived functor

$$R\check{H}^0(\mathcal{U}, -) : D^+(PMod(\mathcal{O}_X)) \longrightarrow D^+(\mathcal{O}_X(U))$$

of the left exact functor $\check{H}^0(\mathcal{U}, -)$.

Proof. Note that the category of presheaves of \mathcal{O}_X -modules has enough injectives, see Injectives, Proposition 8.5. Note that $\check{H}^0(\mathcal{U}, -)$ is a left exact functor from the category of presheaves of \mathcal{O}_X -modules to the category of $\mathcal{O}_X(U)$ -modules. Hence the derived functor and the right derived functor exist, see Derived Categories, Section 20.

Let \mathcal{I} be an injective presheaf of \mathcal{O}_X -modules. In this case the functor $\text{Hom}_{\mathcal{O}_X}(-, \mathcal{I})$ is exact on $PMod(\mathcal{O}_X)$. By Lemma 11.3 we have

$$\text{Hom}_{\mathcal{O}_X}(K(\mathcal{U})_\bullet, \mathcal{I}) = \check{C}^\bullet(\mathcal{U}, \mathcal{I}).$$

By Lemma 11.4 we have that $K(\mathcal{U})_\bullet$ is quasi-isomorphic to $\mathcal{O}_U[0]$. Hence by the exactness of Hom into \mathcal{I} mentioned above we see that $\check{H}^i(\mathcal{U}, \mathcal{I}) = 0$ for all $i > 0$. Thus the δ -functor (\check{H}^n, δ) (see Lemma 11.2) satisfies the assumptions of Homology, Lemma 11.4, and hence is a universal δ -functor.

By Derived Categories, Lemma 20.4 also the sequence $R^i\check{H}^0(\mathcal{U}, -)$ forms a universal δ -functor. By the uniqueness of universal δ -functors, see Homology, Lemma 11.5 we conclude that $R^i\check{H}^0(\mathcal{U}, -) = \check{H}^i(\mathcal{U}, -)$. This is enough for most applications and the reader is suggested to skip the rest of the proof.

Let \mathcal{F} be any presheaf of \mathcal{O}_X -modules. Choose an injective resolution $\mathcal{F} \rightarrow \mathcal{I}^\bullet$ in the category $PMod(\mathcal{O}_X)$. Consider the double complex $A^{\bullet, \bullet}$ with terms

$$A^{p,q} = \check{C}^p(\mathcal{U}, \mathcal{I}^q).$$

Consider the simple complex sA^\bullet associated to this double complex. There is a map of complexes

$$\check{C}^\bullet(\mathcal{U}, \mathcal{F}) \longrightarrow sA^\bullet$$

coming from the maps $\check{C}^p(\mathcal{U}, \mathcal{F}) \rightarrow A^{p,0} = \check{C}^p(\mathcal{U}, \mathcal{I}^0)$ and there is a map of complexes

$$\check{H}^0(\mathcal{U}, \mathcal{I}^\bullet) \longrightarrow sA^\bullet$$

coming from the maps $\check{H}^0(\mathcal{U}, \mathcal{I}^q) \rightarrow A^{0,q} = \check{C}^0(\mathcal{U}, \mathcal{I}^q)$. Both of these maps are quasi-isomorphisms by an application of Homology, Lemma 22.7. Namely, the columns of the double complex are exact in positive degrees because the Čech complex as a functor is exact (Lemma 11.1) and the rows of the double complex are exact in positive degrees since as we just saw the higher Čech cohomology groups of the injective presheaves \mathcal{I}^q are zero. Since quasi-isomorphisms become invertible in $D^+(\mathcal{O}_X(U))$ this gives the last displayed morphism of the lemma. We omit the verification that this morphism is functorial. \square

12. Čech cohomology and cohomology

01EO

01EP **Lemma 12.1.** *Let X be a ringed space. Let $\mathcal{U} : U = \bigcup_{i \in I} U_i$ be a covering. Let \mathcal{I} be an injective \mathcal{O}_X -module. Then*

$$\check{H}^p(\mathcal{U}, \mathcal{I}) = \begin{cases} \mathcal{I}(U) & \text{if } p = 0 \\ 0 & \text{if } p > 0 \end{cases}$$

Proof. An injective \mathcal{O}_X -module is also injective as an object in the category $PMod(\mathcal{O}_X)$ (for example since sheafification is an exact left adjoint to the inclusion functor, using Homology, Lemma 25.1). Hence we can apply Lemma 11.5 (or its proof) to see the result. \square

01EQ **Lemma 12.2.** *Let X be a ringed space. Let $\mathcal{U} : U = \bigcup_{i \in I} U_i$ be a covering. There is a transformation*

$$\check{C}^\bullet(\mathcal{U}, -) \longrightarrow R\Gamma(U, -)$$

of functors $Mod(\mathcal{O}_X) \rightarrow D^+(\mathcal{O}_X(U))$. In particular this provides canonical maps $\check{H}^p(\mathcal{U}, \mathcal{F}) \rightarrow H^p(U, \mathcal{F})$ for \mathcal{F} ranging over $Mod(\mathcal{O}_X)$.

Proof. Let \mathcal{F} be an \mathcal{O}_X -module. Choose an injective resolution $\mathcal{F} \rightarrow \mathcal{I}^\bullet$. Consider the double complex $\check{C}^\bullet(\mathcal{U}, \mathcal{I}^\bullet)$ with terms $\check{C}^p(\mathcal{U}, \mathcal{I}^q)$. There is a map of complexes

$$\alpha : \Gamma(U, \mathcal{I}^\bullet) \longrightarrow \text{Tot}(\check{C}^\bullet(\mathcal{U}, \mathcal{I}^\bullet))$$

coming from the maps $\mathcal{I}^q(U) \rightarrow \check{H}^0(\mathcal{U}, \mathcal{I}^q)$ and a map of complexes

$$\beta : \check{C}^\bullet(\mathcal{U}, \mathcal{F}) \longrightarrow \text{Tot}(\check{C}^\bullet(\mathcal{U}, \mathcal{I}^\bullet))$$

coming from the map $\mathcal{F} \rightarrow \mathcal{I}^0$. We can apply Homology, Lemma 22.7 to see that α is a quasi-isomorphism. Namely, Lemma 12.1 implies that the q th row of the double complex $\check{C}^\bullet(\mathcal{U}, \mathcal{I}^\bullet)$ is a resolution of $\Gamma(U, \mathcal{I}^q)$. Hence α becomes invertible in $D^+(\mathcal{O}_X(U))$ and the transformation of the lemma is the composition of β followed by the inverse of α . We omit the verification that this is functorial. \square

0B8R **Lemma 12.3.** *Let X be a topological space. Let \mathcal{H} be an abelian sheaf on X . Let $\mathcal{U} : X = \bigcup_{i \in I} U_i$ be an open covering. The map*

$$\check{H}^1(\mathcal{U}, \mathcal{H}) \longrightarrow H^1(X, \mathcal{H})$$

is injective and identifies $\check{H}^1(\mathcal{U}, \mathcal{H})$ via the bijection of Lemma 5.3 with the set of isomorphism classes of \mathcal{H} -torsors which restrict to trivial torsors over each U_i .

Proof. To see this we construct an inverse map. Namely, let \mathcal{F} be a \mathcal{H} -torsor whose restriction to U_i is trivial. By Lemma 5.2 this means there exists a section $s_i \in \mathcal{F}(U_i)$. On $U_{i_0} \cap U_{i_1}$ there is a unique section $s_{i_0 i_1}$ of \mathcal{H} such that $s_{i_0 i_1} \cdot s_{i_0}|_{U_{i_0} \cap U_{i_1}} = s_{i_1}|_{U_{i_0} \cap U_{i_1}}$. A computation shows that $s_{i_0 i_1}$ is a Čech cocycle and that its class is well defined (i.e., does not depend on the choice of the sections s_i). The inverse maps the isomorphism class of \mathcal{F} to the cohomology class of the cocycle $(s_{i_0 i_1})$. We omit the verification that this map is indeed an inverse. \square

01ER **Lemma 12.4.** *Let X be a ringed space. Consider the functor $i : Mod(\mathcal{O}_X) \rightarrow PMod(\mathcal{O}_X)$. It is a left exact functor with right derived functors given by*

$$R^p i(\mathcal{F}) = \underline{H}^p(\mathcal{F}) : U \longmapsto H^p(U, \mathcal{F})$$

see discussion in Section 8.

Proof. It is clear that i is left exact. Choose an injective resolution $\mathcal{F} \rightarrow \mathcal{I}^\bullet$. By definition $R^p i$ is the p th cohomology presheaf of the complex \mathcal{I}^\bullet . In other words, the sections of $R^p i(\mathcal{F})$ over an open U are given by

$$\frac{\text{Ker}(\mathcal{I}^n(U) \rightarrow \mathcal{I}^{n+1}(U))}{\text{Im}(\mathcal{I}^{n-1}(U) \rightarrow \mathcal{I}^n(U))}.$$

which is the definition of $H^p(U, \mathcal{F})$. \square

01ES **Lemma 12.5.** *Let X be a ringed space. Let $\mathcal{U} : U = \bigcup_{i \in I} U_i$ be a covering. For any sheaf of \mathcal{O}_X -modules \mathcal{F} there is a spectral sequence $(E_r, d_r)_{r \geq 0}$ with*

$$E_2^{p,q} = \check{H}^p(\mathcal{U}, \underline{H}^q(\mathcal{F}))$$

converging to $H^{p+q}(U, \mathcal{F})$. This spectral sequence is functorial in \mathcal{F} .

Proof. This is a Grothendieck spectral sequence (see Derived Categories, Lemma 22.2) for the functors

$$i : \text{Mod}(\mathcal{O}_X) \rightarrow \text{PMod}(\mathcal{O}_X) \quad \text{and} \quad \check{H}^0(\mathcal{U}, -) : \text{PMod}(\mathcal{O}_X) \rightarrow \text{Mod}_{\mathcal{O}_X(U)}.$$

Namely, we have $\check{H}^0(\mathcal{U}, i(\mathcal{F})) = \mathcal{F}(U)$ by Lemma 10.2. We have that $i(\mathcal{I})$ is Čech acyclic by Lemma 12.1. And we have that $\check{H}^p(\mathcal{U}, -) = R^p \check{H}^0(\mathcal{U}, -)$ as functors on $\text{PMod}(\mathcal{O}_X)$ by Lemma 11.5. Putting everything together gives the lemma. \square

01ET **Lemma 12.6.** *Let X be a ringed space. Let $\mathcal{U} : U = \bigcup_{i \in I} U_i$ be a covering. Let \mathcal{F} be an \mathcal{O}_X -module. Assume that $H^i(U_{i_0, \dots, i_p}, \mathcal{F}) = 0$ for all $i > 0$, all $p \geq 0$ and all $i_0, \dots, i_p \in I$. Then $\check{H}^p(\mathcal{U}, \mathcal{F}) = H^p(U, \mathcal{F})$ as $\mathcal{O}_X(U)$ -modules.*

Proof. We will use the spectral sequence of Lemma 12.5. The assumptions mean that $E_2^{p,q} = 0$ for all (p, q) with $q \neq 0$. Hence the spectral sequence degenerates at E_2 and the result follows. \square

01EU **Lemma 12.7.** *Let X be a ringed space. Let*

$$0 \rightarrow \mathcal{F} \rightarrow \mathcal{G} \rightarrow \mathcal{H} \rightarrow 0$$

be a short exact sequence of \mathcal{O}_X -modules. Let $U \subset X$ be an open subset. If there exists a cofinal system of open coverings \mathcal{U} of U such that $\check{H}^1(\mathcal{U}, \mathcal{F}) = 0$, then the map $\mathcal{G}(U) \rightarrow \mathcal{H}(U)$ is surjective.

Proof. Take an element $s \in \mathcal{H}(U)$. Choose an open covering $\mathcal{U} : U = \bigcup_{i \in I} U_i$ such that (a) $\check{H}^1(\mathcal{U}, \mathcal{F}) = 0$ and (b) $s|_{U_i}$ is the image of a section $s_i \in \mathcal{G}(U_i)$. Since we can certainly find a covering such that (b) holds it follows from the assumptions of the lemma that we can find a covering such that (a) and (b) both hold. Consider the sections

$$s_{i_0 i_1} = s_{i_1}|_{U_{i_0 i_1}} - s_{i_0}|_{U_{i_0 i_1}}.$$

Since s_i lifts s we see that $s_{i_0 i_1} \in \mathcal{F}(U_{i_0 i_1})$. By the vanishing of $\check{H}^1(\mathcal{U}, \mathcal{F})$ we can find sections $t_i \in \mathcal{F}(U_i)$ such that

$$s_{i_0 i_1} = t_{i_1}|_{U_{i_0 i_1}} - t_{i_0}|_{U_{i_0 i_1}}.$$

Then clearly the sections $s_i - t_i$ satisfy the sheaf condition and glue to a section of \mathcal{G} over U which maps to s . Hence we win. \square

01EV **Lemma 12.8.** *Let X be a ringed space. Let \mathcal{F} be an \mathcal{O}_X -module such that*

$$\check{H}^p(\mathcal{U}, \mathcal{F}) = 0$$

for all $p > 0$ and any open covering $\mathcal{U} : U = \bigcup_{i \in I} U_i$ of an open of X . Then $H^p(U, \mathcal{F}) = 0$ for all $p > 0$ and any open $U \subset X$.

Proof. Let \mathcal{F} be a sheaf satisfying the assumption of the lemma. We will indicate this by saying “ \mathcal{F} has vanishing higher Čech cohomology for any open covering”. Choose an embedding $\mathcal{F} \rightarrow \mathcal{I}$ into an injective \mathcal{O}_X -module. By Lemma 12.1 \mathcal{I} has vanishing higher Čech cohomology for any open covering. Let $\mathcal{Q} = \mathcal{I}/\mathcal{F}$ so that we have a short exact sequence

$$0 \rightarrow \mathcal{F} \rightarrow \mathcal{I} \rightarrow \mathcal{Q} \rightarrow 0.$$

By Lemma 12.7 and our assumptions this sequence is actually exact as a sequence of presheaves! In particular we have a long exact sequence of Čech cohomology groups for any open covering \mathcal{U} , see Lemma 11.2 for example. This implies that \mathcal{Q} is also an \mathcal{O}_X -module with vanishing higher Čech cohomology for all open coverings.

Next, we look at the long exact cohomology sequence

$$\begin{array}{ccccccc} 0 & \longrightarrow & H^0(U, \mathcal{F}) & \longrightarrow & H^0(U, \mathcal{I}) & \longrightarrow & H^0(U, \mathcal{Q}) \\ & & & & & \swarrow & \\ & & & & & & H^1(U, \mathcal{Q}) \\ & & & & & \swarrow & \\ & & & & & & H^2(U, \mathcal{Q}) \\ & & & & & \swarrow & \\ & & & & & & \dots \end{array}$$

for any open $U \subset X$. Since \mathcal{I} is injective we have $H^n(U, \mathcal{I}) = 0$ for $n > 0$ (see Derived Categories, Lemma 20.4). By the above we see that $H^0(U, \mathcal{I}) \rightarrow H^0(U, \mathcal{Q})$ is surjective and hence $H^1(U, \mathcal{F}) = 0$. Since \mathcal{F} was an arbitrary \mathcal{O}_X -module with vanishing higher Čech cohomology we conclude that also $H^1(U, \mathcal{Q}) = 0$ since \mathcal{Q} is another of these sheaves (see above). By the long exact sequence this in turn implies that $H^2(U, \mathcal{F}) = 0$. And so on and so forth. \square

01EW **Lemma 12.9.** *(Variant of Lemma 12.8.) Let X be a ringed space. Let \mathcal{B} be a basis for the topology on X . Let \mathcal{F} be an \mathcal{O}_X -module. Assume there exists a set of open coverings Cov with the following properties:*

- (1) *For every $\mathcal{U} \in \text{Cov}$ with $\mathcal{U} : U = \bigcup_{i \in I} U_i$ we have $U, U_i \in \mathcal{B}$ and every $U_{i_0 \dots i_p} \in \mathcal{B}$.*
- (2) *For every $U \in \mathcal{B}$ the open coverings of U occurring in Cov is a cofinal system of open coverings of U .*
- (3) *For every $\mathcal{U} \in \text{Cov}$ we have $\check{H}^p(\mathcal{U}, \mathcal{F}) = 0$ for all $p > 0$.*

Then $H^p(U, \mathcal{F}) = 0$ for all $p > 0$ and any $U \in \mathcal{B}$.

Proof. Let \mathcal{F} and Cov be as in the lemma. We will indicate this by saying “ \mathcal{F} has vanishing higher Čech cohomology for any $\mathcal{U} \in \text{Cov}$ ”. Choose an embedding $\mathcal{F} \rightarrow \mathcal{I}$ into an injective \mathcal{O}_X -module. By Lemma 12.1 \mathcal{I} has vanishing higher Čech cohomology for any $\mathcal{U} \in \text{Cov}$. Let $\mathcal{Q} = \mathcal{I}/\mathcal{F}$ so that we have a short exact sequence

$$0 \rightarrow \mathcal{F} \rightarrow \mathcal{I} \rightarrow \mathcal{Q} \rightarrow 0.$$

By Lemma 12.7 and our assumption (2) this sequence gives rise to an exact sequence

$$0 \rightarrow \mathcal{F}(U) \rightarrow \mathcal{I}(U) \rightarrow \mathcal{Q}(U) \rightarrow 0.$$

for every $U \in \mathcal{B}$. Hence for any $\mathcal{U} \in \text{Cov}$ we get a short exact sequence of Čech complexes

$$0 \rightarrow \check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}) \rightarrow \check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{I}) \rightarrow \check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{Q}) \rightarrow 0$$

since each term in the Čech complex is made up out of a product of values over elements of \mathcal{B} by assumption (1). In particular we have a long exact sequence of Čech cohomology groups for any open covering $\mathcal{U} \in \text{Cov}$. This implies that \mathcal{Q} is also an \mathcal{O}_X -module with vanishing higher Čech cohomology for all $\mathcal{U} \in \text{Cov}$.

Next, we look at the long exact cohomology sequence

$$\begin{array}{ccccccc} 0 & \longrightarrow & H^0(U, \mathcal{F}) & \longrightarrow & H^0(U, \mathcal{I}) & \longrightarrow & H^0(U, \mathcal{Q}) \\ & & & & & \swarrow & \\ & & H^1(U, \mathcal{F}) & \longrightarrow & H^1(U, \mathcal{I}) & \longrightarrow & H^1(U, \mathcal{Q}) \\ & & & & & \swarrow & \\ & & \dots & & \dots & & \dots \end{array}$$

for any $U \in \mathcal{B}$. Since \mathcal{I} is injective we have $H^n(U, \mathcal{I}) = 0$ for $n > 0$ (see Derived Categories, Lemma 20.4). By the above we see that $H^0(U, \mathcal{I}) \rightarrow H^0(U, \mathcal{Q})$ is surjective and hence $H^1(U, \mathcal{F}) = 0$. Since \mathcal{F} was an arbitrary \mathcal{O}_X -module with vanishing higher Čech cohomology for all $\mathcal{U} \in \text{Cov}$ we conclude that also $H^1(U, \mathcal{Q}) = 0$ since \mathcal{Q} is another of these sheaves (see above). By the long exact sequence this in turn implies that $H^2(U, \mathcal{F}) = 0$. And so on and so forth. \square

01EX **Lemma 12.10.** *Let $f : X \rightarrow Y$ be a morphism of ringed spaces. Let \mathcal{I} be an injective \mathcal{O}_X -module. Then*

- (1) $\check{H}^p(\mathcal{V}, f_*\mathcal{I}) = 0$ for all $p > 0$ and any open covering $\mathcal{V} : V = \bigcup_{j \in J} V_j$ of Y .
- (2) $H^p(V, f_*\mathcal{I}) = 0$ for all $p > 0$ and every open $V \subset Y$.

In other words, $f_\mathcal{I}$ is right acyclic for $\Gamma(V, -)$ (see Derived Categories, Definition 16.3) for any $V \subset Y$ open.*

Proof. Set $\mathcal{U} : f^{-1}(V) = \bigcup_{j \in J} f^{-1}(V_j)$. It is an open covering of X and

$$\check{\mathcal{C}}^\bullet(\mathcal{V}, f_*\mathcal{I}) = \check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{I}).$$

This is true because

$$f_*\mathcal{I}(V_{j_0 \dots j_p}) = \mathcal{I}(f^{-1}(V_{j_0 \dots j_p})) = \mathcal{I}(f^{-1}(V_{j_0}) \cap \dots \cap f^{-1}(V_{j_p})) = \mathcal{I}(U_{j_0 \dots j_p}).$$

Thus the first statement of the lemma follows from Lemma 12.1. The second statement follows from the first and Lemma 12.8. \square

The following lemma implies in particular that $f_* : \text{Ab}(X) \rightarrow \text{Ab}(Y)$ transforms injective abelian sheaves into injective abelian sheaves.

02N5 **Lemma 12.11.** *Let $f : X \rightarrow Y$ be a morphism of ringed spaces. Assume f is flat. Then $f_*\mathcal{I}$ is an injective \mathcal{O}_Y -module for any injective \mathcal{O}_X -module \mathcal{I} .*

Proof. In this case the functor f^* transforms injections into injections (Modules, Lemma 18.2). Hence the result follows from Homology, Lemma 25.1. \square

0D0A **Lemma 12.12.** *Let (X, \mathcal{O}_X) be a ringed space. Let I be a set. For $i \in I$ let \mathcal{F}_i be an \mathcal{O}_X -module. Let $U \subset X$ be open. The canonical map*

$$H^p(U, \prod_{i \in I} \mathcal{F}_i) \longrightarrow \prod_{i \in I} H^p(U, \mathcal{F}_i)$$

is an isomorphism for $p = 0$ and injective for $p = 1$.

Proof. The statement for $p = 0$ is true because the product of sheaves is equal to the product of the underlying presheaves, see Sheaves, Section 29. Proof for $p = 1$. Set $\mathcal{F} = \prod \mathcal{F}_i$. Let $\xi \in H^1(U, \mathcal{F})$ map to zero in $\prod H^1(U, \mathcal{F}_i)$. By locality of cohomology, see Lemma 8.2, there exists an open covering $\mathcal{U} : U = \bigcup U_j$ such that $\xi|_{U_j} = 0$ for all j . By Lemma 12.3 this means ξ comes from an element $\check{\xi} \in \check{H}^1(\mathcal{U}, \mathcal{F})$. Since the maps $\check{H}^1(\mathcal{U}, \mathcal{F}_i) \rightarrow H^1(U, \mathcal{F}_i)$ are injective for all i (by Lemma 12.3), and since the image of ξ is zero in $\prod H^1(U, \mathcal{F}_i)$ we see that the image $\check{\xi}_i = 0$ in $\check{H}^1(\mathcal{U}, \mathcal{F}_i)$. However, since $\mathcal{F} = \prod \mathcal{F}_i$ we see that $\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F})$ is the product of the complexes $\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}_i)$, hence by Homology, Lemma 28.1 we conclude that $\check{\xi} = 0$ as desired. \square

13. Flasque sheaves

09SV Here is the definition.

09SW **Definition 13.1.** Let X be a topological space. We say a presheaf of sets \mathcal{F} is *flasque* or *flabby* if for every $U \subset V$ open in X the restriction map $\mathcal{F}(V) \rightarrow \mathcal{F}(U)$ is surjective.

We will use this terminology also for abelian sheaves and sheaves of modules if X is a ringed space. Clearly it suffices to assume the restriction maps $\mathcal{F}(X) \rightarrow \mathcal{F}(U)$ is surjective for every open $U \subset X$.

09SX **Lemma 13.2.** *Let (X, \mathcal{O}_X) be a ringed space. Then any injective \mathcal{O}_X -module is flasque.*

Proof. This is a reformulation of Lemma 9.1. \square

09SY **Lemma 13.3.** *Let (X, \mathcal{O}_X) be a ringed space. Any flasque \mathcal{O}_X -module is acyclic for $R\Gamma(X, -)$ as well as $R\Gamma(U, -)$ for any open U of X .*

Proof. We will prove this using Derived Categories, Lemma 16.6. Since every injective module is flasque we see that we can embed every \mathcal{O}_X -module into a flasque module, see Injectives, Lemma 4.1. Thus it suffices to show that given a short exact sequence

$$0 \rightarrow \mathcal{F} \rightarrow \mathcal{G} \rightarrow \mathcal{H} \rightarrow 0$$

with \mathcal{F}, \mathcal{G} flasque, then \mathcal{H} is flasque and the sequence remains short exact after taking sections on any open of X . In fact, the second statement implies the first. Thus, let $U \subset X$ be an open subspace. Let $s \in \mathcal{H}(U)$. We will show that we can lift s to a sequence of \mathcal{G} over U . To do this consider the set T of pairs (V, t) where $V \subset U$ is open and $t \in \mathcal{G}(V)$ is a section mapping to $s|_V$ in \mathcal{H} . We put a partial ordering on T by setting $(V, t) \leq (V', t')$ if and only if $V \subset V'$ and $t'|_V = t$. If (V_α, t_α) , $\alpha \in A$ is a totally ordered subset of T , then $V = \bigcup V_\alpha$ is open and there is a unique section $t \in \mathcal{G}(V)$ restricting to t_α over V_α by the sheaf condition on \mathcal{G} . Thus by Zorn's lemma there exists a maximal element (V, t) in T . We will show that $V = U$ thereby finishing the proof. Namely, pick any $x \in U$. We can find a

small open neighbourhood $W \subset U$ of x and $t' \in \mathcal{G}(W)$ mapping to $s|_W$ in \mathcal{H} . Then $t'|_{W \cap V} - t|_{W \cap V}$ maps to zero in \mathcal{H} , hence comes from some section $r' \in \mathcal{F}(W \cap V)$. Using that \mathcal{F} is flasque we find a section $r \in \mathcal{F}(W)$ restricting to r' over $W \cap V$. Modifying t' by the image of r we may assume that t and t' restrict to the same section over $W \cap V$. By the sheaf condition of \mathcal{G} we can find a section \tilde{t} of \mathcal{G} over $W \cup V$ restricting to t and t' . By maximality of (V, t) we see that $V \cap W = V$. Thus $x \in V$ and we are done. \square

The following lemma does not hold for flasque presheaves.

09SZ **Lemma 13.4.** *Let (X, \mathcal{O}_X) be a ringed space. Let \mathcal{F} be a sheaf of \mathcal{O}_X -modules. Let $\mathcal{U} : U = \bigcup U_i$ be an open covering. If \mathcal{F} is flasque, then $\check{H}^p(\mathcal{U}, \mathcal{F}) = 0$ for $p > 0$.*

Proof. The presheaves $\underline{H}^q(\mathcal{F})$ used in the statement of Lemma 12.5 are zero by Lemma 13.3. Hence $\check{H}^p(U, \mathcal{F}) = H^p(U, \mathcal{F}) = 0$ by Lemma 13.3 again. \square

09T0 **Lemma 13.5.** *Let $(X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$ be a morphism of ringed spaces. Let \mathcal{F} be a sheaf of \mathcal{O}_X -modules. If \mathcal{F} is flasque, then $R^p f_* \mathcal{F} = 0$ for $p > 0$.*

Proof. Immediate from Lemma 8.3 and Lemma 13.3. \square

The following lemma can be proved by an elementary induction argument for finite coverings, compare with the discussion of Čech cohomology in [Vak].

0A36 **Lemma 13.6.** *Let X be a topological space. Let \mathcal{F} be an abelian sheaf on X . Let $\mathcal{U} : U = \bigcup_{i \in I} U_i$ be an open covering. Assume the restriction mappings $\mathcal{F}(U) \rightarrow \mathcal{F}(U')$ are surjective for U' an arbitrary union of opens of the form $U_{i_0 \dots i_p}$. Then $\check{H}^p(\mathcal{U}, \mathcal{F})$ vanishes for $p > 0$.*

Proof. Let Y be the set of nonempty subsets of I . We will use the letters A, B, C, \dots to denote elements of Y , i.e., nonempty subsets of I . For a finite nonempty subset $J \subset I$ let

$$V_J = \{A \in Y \mid J \subset A\}$$

This means that $V_{\{i\}} = \{A \in Y \mid i \in A\}$ and $V_J = \bigcap_{j \in J} V_{\{j\}}$. Then $V_J \subset V_K$ if and only if $J \supset K$. There is a unique topology on Y such that the collection of subsets V_J is a basis for the topology on Y . Any open is of the form

$$V = \bigcup_{t \in T} V_{J_t}$$

for some family of finite subsets J_t . If $J_t \subset J_{t'}$ then we may remove $J_{t'}$ from the family without changing V . Thus we may assume there are no inclusions among the J_t . In this case the minimal elements of V are the sets $A = J_t$. Hence we can read off the family $(J_t)_{t \in T}$ from the open V .

We can completely understand open coverings in Y . First, because the elements $A \in Y$ are nonempty subsets of I we have

$$Y = \bigcup_{i \in I} V_{\{i\}}$$

To understand other coverings, let V be as above and let $V_s \subset Y$ be an open corresponding to the family $(J_{s,t})_{t \in T_s}$. Then

$$V = \bigcup_{s \in S} V_s$$

if and only if for each $t \in T$ there exists an $s \in S$ and $t_s \in T_s$ such that $J_t = J_{s,t_s}$. Namely, as the family $(J_t)_{t \in T}$ is minimal, the minimal element $A = J_t$ has to be in V_s for some s , hence $A \in V_{J_{t_s}}$ for some $t_s \in T_s$. But since A is also minimal in V_s we conclude that $J_{t_s} = J_t$.

Next we map the set of opens of Y to opens of X . Namely, we send V to U , we use the rule

$$V_J \mapsto U_J = \bigcap_{i \in J} U_i$$

on the opens V_J , and we extend it to arbitrary opens V by the rule

$$V = \bigcup_{t \in T} V_{J_t} \mapsto \bigcup_{t \in T} U_{J_t}$$

The classification of open coverings of Y given above shows that this rule transforms open coverings into open coverings. Thus we obtain an abelian sheaf \mathcal{G} on Y by setting $\mathcal{G}(Y) = \mathcal{F}(U)$ and for $V = \bigcup_{t \in T} V_{J_t}$ setting

$$\mathcal{G}(V) = \mathcal{F}\left(\bigcup_{t \in T} U_{J_t}\right)$$

and using the restriction maps of \mathcal{F} .

With these preliminaries out of the way we can prove our lemma as follows. We have an open covering $\mathcal{V} : Y = \bigcup_{i \in I} V_{\{i\}}$ of Y . By construction we have an equality

$$\check{C}^\bullet(\mathcal{V}, \mathcal{G}) = \check{C}^\bullet(\mathcal{U}, \mathcal{F})$$

of Čech complexes. Since the sheaf \mathcal{G} is flasque on Y (by our assumption on \mathcal{F} in the statement of the lemma) the vanishing follows from Lemma 13.4. \square

14. The Leray spectral sequence

01EY

01EZ **Lemma 14.1.** *Let $f : X \rightarrow Y$ be a morphism of ringed spaces. There is a commutative diagram*

$$\begin{array}{ccc} D^+(X) & \xrightarrow{R\Gamma(X,-)} & D^+(\mathcal{O}_X(X)) \\ Rf_* \downarrow & & \downarrow \text{restriction} \\ D^+(Y) & \xrightarrow{R\Gamma(Y,-)} & D^+(\mathcal{O}_Y(Y)) \end{array}$$

More generally for any $V \subset Y$ open and $U = f^{-1}(V)$ there is a commutative diagram

$$\begin{array}{ccc} D^+(X) & \xrightarrow{R\Gamma(U,-)} & D^+(\mathcal{O}_X(U)) \\ Rf_* \downarrow & & \downarrow \text{restriction} \\ D^+(Y) & \xrightarrow{R\Gamma(V,-)} & D^+(\mathcal{O}_Y(V)) \end{array}$$

See also Remark 14.2 for more explanation.

Proof. Let $\Gamma_{res} : \text{Mod}(\mathcal{O}_X) \rightarrow \text{Mod}_{\mathcal{O}_Y(Y)}$ be the functor which associates to an \mathcal{O}_X -module \mathcal{F} the global sections of \mathcal{F} viewed as a $\mathcal{O}_Y(Y)$ -module via the map $f^\# : \mathcal{O}_Y(Y) \rightarrow \mathcal{O}_X(X)$. Let $\text{restriction} : \text{Mod}_{\mathcal{O}_X(X)} \rightarrow \text{Mod}_{\mathcal{O}_Y(Y)}$ be the restriction functor induced by $f^\# : \mathcal{O}_Y(Y) \rightarrow \mathcal{O}_X(X)$. Note that restriction is exact so that

its right derived functor is computed by simply applying the restriction functor, see Derived Categories, Lemma 17.9. It is clear that

$$\Gamma_{res} = \text{restriction} \circ \Gamma(X, -) = \Gamma(Y, -) \circ f_*$$

We claim that Derived Categories, Lemma 22.1 applies to both compositions. For the first this is clear by our remarks above. For the second, it follows from Lemma 12.10 which implies that injective \mathcal{O}_X -modules are mapped to $\Gamma(Y, -)$ -acyclic sheaves on Y . \square

01F0 **Remark 14.2.** Here is a down-to-earth explanation of the meaning of Lemma 14.1. It says that given $f : X \rightarrow Y$ and $\mathcal{F} \in \text{Mod}(\mathcal{O}_X)$ and given an injective resolution $\mathcal{F} \rightarrow \mathcal{I}^\bullet$ we have

$$\begin{array}{lll} R\Gamma(X, \mathcal{F}) & \text{is represented by} & \Gamma(X, \mathcal{I}^\bullet) \\ Rf_*\mathcal{F} & \text{is represented by} & f_*\mathcal{I}^\bullet \\ R\Gamma(Y, Rf_*\mathcal{F}) & \text{is represented by} & \Gamma(Y, f_*\mathcal{I}^\bullet) \end{array}$$

the last fact coming from Leray's acyclicity lemma (Derived Categories, Lemma 17.7) and Lemma 12.10. Finally, it combines this with the trivial observation that

$$\Gamma(X, \mathcal{I}^\bullet) = \Gamma(Y, f_*\mathcal{I}^\bullet).$$

to arrive at the commutativity of the diagram of the lemma.

01F1 **Lemma 14.3.** *Let X be a ringed space. Let \mathcal{F} be an \mathcal{O}_X -module.*

- (1) *The cohomology groups $H^i(U, \mathcal{F})$ for $U \subset X$ open of \mathcal{F} computed as an \mathcal{O}_X -module, or computed as an abelian sheaf are identical.*
- (2) *Let $f : X \rightarrow Y$ be a morphism of ringed spaces. The higher direct images $R^i f_*\mathcal{F}$ of \mathcal{F} computed as an \mathcal{O}_X -module, or computed as an abelian sheaf are identical.*

There are similar statements in the case of bounded below complexes of \mathcal{O}_X -modules.

Proof. Consider the morphism of ringed spaces $(X, \mathcal{O}_X) \rightarrow (X, \underline{\mathbf{Z}}_X)$ given by the identity on the underlying topological space and by the unique map of sheaves of rings $\underline{\mathbf{Z}}_X \rightarrow \mathcal{O}_X$. Let \mathcal{F} be an \mathcal{O}_X -module. Denote \mathcal{F}_{ab} the same sheaf seen as an $\underline{\mathbf{Z}}_X$ -module, i.e., seen as a sheaf of abelian groups. Let $\mathcal{F} \rightarrow \mathcal{I}^\bullet$ be an injective resolution. By Remark 14.2 we see that $\Gamma(X, \mathcal{I}^\bullet)$ computes both $R\Gamma(X, \mathcal{F})$ and $R\Gamma(X, \mathcal{F}_{ab})$. This proves (1).

To prove (2) we use (1) and Lemma 8.3. The result follows immediately. \square

01F2 **Lemma 14.4** (Leray spectral sequence). *Let $f : X \rightarrow Y$ be a morphism of ringed spaces. Let \mathcal{F}^\bullet be a bounded below complex of \mathcal{O}_X -modules. There is a spectral sequence*

$$E_2^{p,q} = H^p(Y, R^q f_*(\mathcal{F}^\bullet))$$

converging to $H^{p+q}(X, \mathcal{F}^\bullet)$.

Proof. This is just the Grothendieck spectral sequence Derived Categories, Lemma 22.2 coming from the composition of functors $\Gamma_{res} = \Gamma(Y, -) \circ f_*$ where Γ_{res} is as in the proof of Lemma 14.1. To see that the assumptions of Derived Categories, Lemma 22.2 are satisfied, see the proof of Lemma 14.1 or Remark 14.2. \square

01F3 **Remark 14.5.** The Leray spectral sequence, the way we proved it in Lemma 14.4 is a spectral sequence of $\Gamma(Y, \mathcal{O}_Y)$ -modules. However, it is quite easy to see that it is in fact a spectral sequence of $\Gamma(X, \mathcal{O}_X)$ -modules. For example f gives rise to a morphism of ringed spaces $f' : (X, \mathcal{O}_X) \rightarrow (Y, f_*\mathcal{O}_X)$. By Lemma 14.3 the terms $E_r^{p,q}$ of the Leray spectral sequence for an \mathcal{O}_X -module \mathcal{F} and f are identical with those for \mathcal{F} and f' at least for $r \geq 2$. Namely, they both agree with the terms of the Leray spectral sequence for \mathcal{F} as an abelian sheaf. And since $(f_*\mathcal{O}_X)(Y) = \mathcal{O}_X(X)$ we see the result. It is often the case that the Leray spectral sequence carries additional structure.

01F4 **Lemma 14.6.** *Let $f : X \rightarrow Y$ be a morphism of ringed spaces. Let \mathcal{F} be an \mathcal{O}_X -module.*

- (1) *If $R^q f_*\mathcal{F} = 0$ for $q > 0$, then $H^p(X, \mathcal{F}) = H^p(Y, f_*\mathcal{F})$ for all p .*
- (2) *If $H^p(Y, R^q f_*\mathcal{F}) = 0$ for all q and $p > 0$, then $H^q(X, \mathcal{F}) = H^0(Y, R^q f_*\mathcal{F})$ for all q .*

Proof. These are two simple conditions that force the Leray spectral sequence to degenerate at E_2 . You can also prove these facts directly (without using the spectral sequence) which is a good exercise in cohomology of sheaves. \square

01F5 **Lemma 14.7.** *Let $f : X \rightarrow Y$ and $g : Y \rightarrow Z$ be morphisms of ringed spaces. In this case $Rg_* \circ Rf_* = R(g \circ f)_*$ as functors from $D^+(X) \rightarrow D^+(Z)$.*

Proof. We are going to apply Derived Categories, Lemma 22.1. It is clear that $g_* \circ f_* = (g \circ f)_*$, see Sheaves, Lemma 21.2. It remains to show that $f_*\mathcal{I}$ is g_* -acyclic. This follows from Lemma 12.10 and the description of the higher direct images $R^i g_*$ in Lemma 8.3. \square

01F6 **Lemma 14.8** (Relative Leray spectral sequence). *Let $f : X \rightarrow Y$ and $g : Y \rightarrow Z$ be morphisms of ringed spaces. Let \mathcal{F} be an \mathcal{O}_X -module. There is a spectral sequence with*

$$E_2^{p,q} = R^p g_*(R^q f_*\mathcal{F})$$

converging to $R^{p+q}(g \circ f)_\mathcal{F}$. This spectral sequence is functorial in \mathcal{F} , and there is a version for bounded below complexes of \mathcal{O}_X -modules.*

Proof. This is a Grothendieck spectral sequence for composition of functors and follows from Lemma 14.7 and Derived Categories, Lemma 22.2. \square

15. Functoriality of cohomology

01F7

01F8 **Lemma 15.1.** *Let $f : X \rightarrow Y$ be a morphism of ringed spaces. Let \mathcal{G}^\bullet , resp. \mathcal{F}^\bullet be a bounded below complex of \mathcal{O}_Y -modules, resp. \mathcal{O}_X -modules. Let $\varphi : \mathcal{G}^\bullet \rightarrow f_*\mathcal{F}^\bullet$ be a morphism of complexes. There is a canonical morphism*

$$\mathcal{G}^\bullet \longrightarrow Rf_*(\mathcal{F}^\bullet)$$

in $D^+(Y)$. Moreover this construction is functorial in the triple $(\mathcal{G}^\bullet, \mathcal{F}^\bullet, \varphi)$.

Proof. Choose an injective resolution $\mathcal{F}^\bullet \rightarrow \mathcal{I}^\bullet$. By definition $Rf_*(\mathcal{F}^\bullet)$ is represented by $f_*\mathcal{I}^\bullet$ in $K^+(\mathcal{O}_Y)$. The composition

$$\mathcal{G}^\bullet \rightarrow f_*\mathcal{F}^\bullet \rightarrow f_*\mathcal{I}^\bullet$$

is a morphism in $K^+(Y)$ which turns into the morphism of the lemma upon applying the localization functor $j_Y : K^+(Y) \rightarrow D^+(Y)$. \square

Let $f : X \rightarrow Y$ be a morphism of ringed spaces. Let \mathcal{G} be an \mathcal{O}_Y -module and let \mathcal{F} be an \mathcal{O}_X -module. Recall that an f -map φ from \mathcal{G} to \mathcal{F} is a map $\varphi : \mathcal{G} \rightarrow f_*\mathcal{F}$, or what is the same thing, a map $\varphi : f^*\mathcal{G} \rightarrow \mathcal{F}$. See Sheaves, Definition 21.7. Such an f -map gives rise to a morphism of complexes

$$01F9 \quad (15.1.1) \quad \varphi : R\Gamma(Y, \mathcal{G}) \longrightarrow R\Gamma(X, \mathcal{F})$$

in $D^+(\mathcal{O}_Y(Y))$. Namely, we use the morphism $\mathcal{G} \rightarrow Rf_*\mathcal{F}$ in $D^+(Y)$ of Lemma 15.1, and we apply $R\Gamma(Y, -)$. By Lemma 14.1 we see that $R\Gamma(X, \mathcal{F}) = R\Gamma(Y, Rf_*\mathcal{F})$ and we get the displayed arrow. We spell this out completely in Remark 15.2 below. In particular it gives rise to maps on cohomology

$$01FA \quad (15.1.2) \quad \varphi : H^i(Y, \mathcal{G}) \longrightarrow H^i(X, \mathcal{F}).$$

01FB **Remark 15.2.** Let $f : X \rightarrow Y$ be a morphism of ringed spaces. Let \mathcal{G} be an \mathcal{O}_Y -module. Let \mathcal{F} be an \mathcal{O}_X -module. Let φ be an f -map from \mathcal{G} to \mathcal{F} . Choose a resolution $\mathcal{F} \rightarrow \mathcal{I}^\bullet$ by a complex of injective \mathcal{O}_X -modules. Choose resolutions $\mathcal{G} \rightarrow \mathcal{J}^\bullet$ and $f_*\mathcal{I}^\bullet \rightarrow (\mathcal{J}')^\bullet$ by complexes of injective \mathcal{O}_Y -modules. By Derived Categories, Lemma 18.6 there exists a map of complexes β such that the diagram

$$01FC \quad (15.2.1) \quad \begin{array}{ccccc} \mathcal{G} & \longrightarrow & f_*\mathcal{F} & \longrightarrow & f_*\mathcal{I}^\bullet \\ \downarrow & & & & \downarrow \\ \mathcal{J}^\bullet & \xrightarrow{\beta} & & \longrightarrow & (\mathcal{J}')^\bullet \end{array}$$

commutes. Applying global section functors we see that we get a diagram

$$\begin{array}{ccc} & & \Gamma(Y, f_*\mathcal{I}^\bullet) \xlongequal{\quad} \Gamma(X, \mathcal{I}^\bullet) \\ & & \downarrow \text{qis} \\ \Gamma(Y, \mathcal{J}^\bullet) & \xrightarrow{\beta} & \Gamma(Y, (\mathcal{J}')^\bullet) \end{array}$$

The complex on the bottom left represents $R\Gamma(Y, \mathcal{G})$ and the complex on the top right represents $R\Gamma(X, \mathcal{F})$. The vertical arrow is a quasi-isomorphism by Lemma 14.1 which becomes invertible after applying the localization functor $K^+(\mathcal{O}_Y(Y)) \rightarrow D^+(\mathcal{O}_Y(Y))$. The arrow (15.1.1) is given by the composition of the horizontal map by the inverse of the vertical map.

16. Refinements and Čech cohomology

09UY Let (X, \mathcal{O}_X) be a ringed space. Let $\mathcal{U} : X = \bigcup_{i \in I} U_i$ and $\mathcal{V} : X = \bigcup_{j \in J} V_j$ be open coverings. Assume that \mathcal{U} is a refinement of \mathcal{V} . Choose a map $c : I \rightarrow J$ such that $U_i \subset V_{c(i)}$ for all $i \in I$. This induces a map of Čech complexes

$$\gamma : \check{C}^\bullet(\mathcal{V}, \mathcal{F}) \longrightarrow \check{C}^\bullet(\mathcal{U}, \mathcal{F}), \quad (\xi_{j_0 \dots j_p}) \longmapsto (\xi_{c(i_0) \dots c(i_p)}|_{U_{i_0 \dots i_p}})$$

functorial in the sheaf of \mathcal{O}_X -modules \mathcal{F} . Suppose that $c' : I \rightarrow J$ is a second map such that $U_i \subset V_{c'(i)}$ for all $i \in I$. Then the corresponding maps γ and γ' are homotopic. Namely, $\gamma - \gamma' = d \circ h + h \circ d$ with $h : \check{C}^{p+1}(\mathcal{V}, \mathcal{F}) \rightarrow \check{C}^p(\mathcal{U}, \mathcal{F})$ given by the rule

$$h(\xi)_{i_0 \dots i_p} = \sum_{a=0}^p (-1)^a \alpha_{c(i_0) \dots c(i_a) c'(i_a) \dots c'(i_p)}$$

We omit the computation showing this works; please see the discussion following (26.0.2) for the proof in a more general case. In particular, the map on Čech cohomology groups is independent of the choice of c . Moreover, it is clear that if $\mathcal{W} : X = \bigcup_{k \in K} W_k$ is a third open covering and \mathcal{V} is a refinement of \mathcal{W} , then the composition of the maps

$$\check{C}^\bullet(\mathcal{W}, \mathcal{F}) \longrightarrow \check{C}^\bullet(\mathcal{V}, \mathcal{F}) \longrightarrow \check{C}^\bullet(\mathcal{U}, \mathcal{F})$$

associated to maps $I \rightarrow J$ and $J \rightarrow K$ is the map associated to the composition $I \rightarrow K$. In particular, we can define the Čech cohomology groups

$$\check{H}^p(X, \mathcal{F}) = \operatorname{colim}_{\mathcal{U}} \check{H}^p(\mathcal{U}, \mathcal{F})$$

where the colimit is over all open coverings of X preordered by refinement.

It turns out that the maps γ defined above are compatible with the map to cohomology, in other words, the composition

$$\check{H}^p(\mathcal{V}, \mathcal{F}) \rightarrow \check{H}^p(\mathcal{U}, \mathcal{F}) \xrightarrow{\text{Lemma 12.2}} H^p(X, \mathcal{F})$$

is the canonical map from the first group to cohomology of Lemma 12.2. In the lemma below we will prove this in a slightly more general setting. A consequence is that we obtain a well defined map

$$09UZ \quad (16.0.1) \quad \check{H}^p(X, \mathcal{F}) = \operatorname{colim}_{\mathcal{U}} \check{H}^p(\mathcal{U}, \mathcal{F}) \longrightarrow H^p(X, \mathcal{F})$$

from Čech cohomology to cohomology.

01FD **Lemma 16.1.** *Let $f : X \rightarrow Y$ be a morphism of ringed spaces. Let $\varphi : f^*\mathcal{G} \rightarrow \mathcal{F}$ be an f -map from an \mathcal{O}_Y -module \mathcal{G} to an \mathcal{O}_X -module \mathcal{F} . Let $\mathcal{U} : X = \bigcup_{i \in I} U_i$ and $\mathcal{V} : Y = \bigcup_{j \in J} V_j$ be open coverings. Assume that \mathcal{U} is a refinement of $f^{-1}\mathcal{V} : X = \bigcup_{j \in J} f^{-1}(V_j)$. In this case there exists a commutative diagram*

$$\begin{array}{ccc} \check{C}^\bullet(\mathcal{U}, \mathcal{F}) & \longrightarrow & R\Gamma(X, \mathcal{F}) \\ \uparrow \gamma & & \uparrow \\ \check{C}^\bullet(\mathcal{V}, \mathcal{G}) & \longrightarrow & R\Gamma(Y, \mathcal{G}) \end{array}$$

in $D^+(\mathcal{O}_X(X))$ with horizontal arrows given by Lemma 12.2 and right vertical arrow by (15.1.1). In particular we get commutative diagrams of cohomology groups

$$\begin{array}{ccc} \check{H}^p(\mathcal{U}, \mathcal{F}) & \longrightarrow & H^p(X, \mathcal{F}) \\ \uparrow \gamma & & \uparrow \\ \check{H}^p(\mathcal{V}, \mathcal{G}) & \longrightarrow & H^p(Y, \mathcal{G}) \end{array}$$

where the right vertical arrow is (15.1.2)

Proof. We first define the left vertical arrow. Namely, choose a map $c : I \rightarrow J$ such that $U_i \subset f^{-1}(V_{c(i)})$ for all $i \in I$. In degree p we define the map by the rule

$$\gamma(s)_{i_0 \dots i_p} = \varphi(s)_{c(i_0) \dots c(i_p)}$$

This makes sense because φ does indeed induce maps $\mathcal{G}(V_{c(i_0) \dots c(i_p)}) \rightarrow \mathcal{F}(U_{i_0 \dots i_p})$ by assumption. It is also clear that this defines a morphism of complexes. Choose

injective resolutions $\mathcal{F} \rightarrow \mathcal{I}^\bullet$ on X and $\mathcal{G} \rightarrow \mathcal{J}^\bullet$ on Y . According to the proof of Lemma 12.2 we introduce the double complexes $A^{\bullet,\bullet}$ and $B^{\bullet,\bullet}$ with terms

$$B^{p,q} = \check{C}^p(\mathcal{V}, \mathcal{J}^q) \quad \text{and} \quad A^{p,q} = \check{C}^p(\mathcal{U}, \mathcal{I}^q).$$

As in Remark 15.2 above we also choose an injective resolution $f_*\mathcal{I} \rightarrow (\mathcal{J}')^\bullet$ on Y and a morphism of complexes $\beta : \mathcal{J} \rightarrow (\mathcal{J}')^\bullet$ making (15.2.1) commutes. We introduce some more double complexes, namely $(B')^{\bullet,\bullet}$ and $(B'')^{\bullet,\bullet}$ with

$$(B')^{p,q} = \check{C}^p(\mathcal{V}, (\mathcal{J}')^q) \quad \text{and} \quad (B'')^{p,q} = \check{C}^p(\mathcal{V}, f_*\mathcal{I}^q).$$

Note that there is an f -map of complexes from $f_*\mathcal{I}^\bullet$ to \mathcal{I}^\bullet . Hence it is clear that the same rule as above defines a morphism of double complexes

$$\gamma : (B'')^{\bullet,\bullet} \longrightarrow A^{\bullet,\bullet}.$$

Consider the diagram of complexes

$$\begin{array}{ccccc} \check{C}^\bullet(\mathcal{U}, \mathcal{F}) & \longrightarrow & sA^\bullet & \xleftarrow{qis} & \Gamma(X, \mathcal{I}^\bullet) \\ \uparrow \gamma & & & \swarrow s\gamma & \parallel \\ \check{C}^\bullet(\mathcal{V}, \mathcal{G}) & \longrightarrow & sB^\bullet & \xrightarrow{\beta} & s(B')^\bullet \xleftarrow{\beta} s(B'')^\bullet \\ & & \uparrow qis & & \uparrow \\ & & \Gamma(Y, \mathcal{J}^\bullet) & \xrightarrow{\beta} & \Gamma(Y, (\mathcal{J}')^\bullet) \xleftarrow{qis} \Gamma(Y, f_*\mathcal{I}^\bullet) \end{array}$$

The two horizontal arrows with targets sA^\bullet and sB^\bullet are the ones explained in Lemma 12.2. The left upper shape (a pentagon) is commutative simply because (15.2.1) is commutative. The two lower squares are trivially commutative. It is also immediate from the definitions that the right upper shape (a square) is commutative. The result of the lemma now follows from the definitions and the fact that going around the diagram on the outer sides from $\check{C}^\bullet(\mathcal{V}, \mathcal{G})$ to $\Gamma(X, \mathcal{I}^\bullet)$ either on top or on bottom is the same (where you have to invert any quasi-isomorphisms along the way). \square

17. Cohomology on Hausdorff quasi-compact spaces

09V0 For such a space Čech cohomology agrees with cohomology.

09V1 **Lemma 17.1.** *Let X be a topological space. Let \mathcal{F} be an abelian sheaf. Then the map $\check{H}^1(X, \mathcal{F}) \rightarrow H^1(X, \mathcal{F})$ defined in (16.0.1) is an isomorphism.*

Proof. Let \mathcal{U} be an open covering of X . By Lemma 12.5 there is an exact sequence

$$0 \rightarrow \check{H}^1(\mathcal{U}, \mathcal{F}) \rightarrow H^1(X, \mathcal{F}) \rightarrow \check{H}^0(\mathcal{U}, \underline{H}^1(\mathcal{F}))$$

Thus the map is injective. To show surjectivity it suffices to show that any element of $\check{H}^0(\mathcal{U}, \underline{H}^1(\mathcal{F}))$ maps to zero after replacing \mathcal{U} by a refinement. This is immediate from the definitions and the fact that $\underline{H}^1(\mathcal{F})$ is a presheaf of abelian groups whose sheafification is zero by locality of cohomology, see Lemma 8.2. \square

09V2 **Lemma 17.2.** *Let X be a Hausdorff and quasi-compact topological space. Let \mathcal{F} be an abelian sheaf on X . Then the map $\check{H}^n(X, \mathcal{F}) \rightarrow H^n(X, \mathcal{F})$ defined in (16.0.1) is an isomorphism for all n .*

Proof. We already know that $\check{H}^n(X, -) \rightarrow H^p(X, -)$ is an isomorphism of functors for $n = 0, 1$, see Lemma 17.1. The functors $H^n(X, -)$ form a universal δ -functor, see Derived Categories, Lemma 20.4. If we show that $\check{H}^n(X, -)$ forms a universal δ -functor and that $\check{H}^n(X, -) \rightarrow H^n(X, -)$ is compatible with boundary maps, then the map will automatically be an isomorphism by uniqueness of universal δ -functors, see Homology, Lemma 11.5.

Let $0 \rightarrow \mathcal{F} \rightarrow \mathcal{G} \rightarrow \mathcal{H} \rightarrow 0$ be a short exact sequence of abelian sheaves on X . Let $\mathcal{U} : X = \bigcup_{i \in I} U_i$ be an open covering. This gives a complex of complexes

$$0 \rightarrow \check{C}^\bullet(\mathcal{U}, \mathcal{F}) \rightarrow \check{C}^\bullet(\mathcal{U}, \mathcal{G}) \rightarrow \check{C}^\bullet(\mathcal{U}, \mathcal{H}) \rightarrow 0$$

which is in general not exact on the right. The sequence defines the maps

$$\check{H}^n(\mathcal{U}, \mathcal{F}) \rightarrow \check{H}^n(\mathcal{U}, \mathcal{G}) \rightarrow \check{H}^n(\mathcal{U}, \mathcal{H})$$

but isn't good enough to define a boundary operator $\delta : \check{H}^n(\mathcal{U}, \mathcal{H}) \rightarrow \check{H}^{n+1}(\mathcal{U}, \mathcal{F})$. Indeed such a thing will not exist in general. However, given an element $\bar{h} \in \check{H}^n(\mathcal{U}, \mathcal{H})$ which is the cohomology class of a cocycle $h = (h_{i_0 \dots i_n})$ we can choose open coverings

$$U_{i_0 \dots i_n} = \bigcup W_{i_0 \dots i_n, k}$$

such that $h_{i_0 \dots i_n}|_{W_{i_0 \dots i_n, k}}$ lifts to a section of \mathcal{G} over $W_{i_0 \dots i_n, k}$. By Topology, Lemma 13.5 we can choose an open covering $\mathcal{V} : X = \bigcup_{j \in J} V_j$ and $\alpha : J \rightarrow I$ such that $V_j \subset U_{\alpha(j)}$ (it is a refinement) and such that for all $j_0, \dots, j_n \in J$ there is a k such that $V_{j_0 \dots j_n} \subset W_{\alpha(j_0) \dots \alpha(j_n), k}$. We obtain maps of complexes

$$\begin{array}{ccccccc} 0 & \longrightarrow & \check{C}^\bullet(\mathcal{U}, \mathcal{F}) & \longrightarrow & \check{C}^\bullet(\mathcal{U}, \mathcal{G}) & \longrightarrow & \check{C}^\bullet(\mathcal{U}, \mathcal{H}) \longrightarrow 0 \\ & & \downarrow & & \downarrow & & \downarrow \\ 0 & \longrightarrow & \check{C}^\bullet(\mathcal{V}, \mathcal{F}) & \longrightarrow & \check{C}^\bullet(\mathcal{V}, \mathcal{G}) & \longrightarrow & \check{C}^\bullet(\mathcal{V}, \mathcal{H}) \longrightarrow 0 \end{array}$$

In fact, the vertical arrows are the maps of complexes used to define the transition maps between the Čech cohomology groups. Our choice of refinement shows that we may choose

$$g_{j_0 \dots j_n} \in \mathcal{G}(V_{j_0 \dots j_n}), \quad g_{j_0 \dots j_n} \mapsto h_{\alpha(j_0) \dots \alpha(j_n)}|_{V_{j_0 \dots j_n}}$$

The cochain $g = (g_{j_0 \dots j_n})$ is not a cocycle in general but we know that its Čech boundary $d(g)$ maps to zero in $\check{C}^{n+1}(\mathcal{V}, \mathcal{H})$ (by the commutative diagram above and the fact that h is a cocycle). Hence $d(g)$ is a cocycle in $\check{C}^\bullet(\mathcal{V}, \mathcal{F})$. This allows us to define

$$\delta(\bar{h}) = \text{class of } d(g) \text{ in } \check{H}^{n+1}(\mathcal{V}, \mathcal{F})$$

Now, given an element $\xi \in \check{H}^n(X, \mathcal{G})$ we choose an open covering \mathcal{U} and an element $\bar{h} \in \check{H}^n(\mathcal{U}, \mathcal{G})$ mapping to ξ in the colimit defining Čech cohomology. Then we choose \mathcal{V} and g as above and set $\delta(\xi)$ equal to the image of $\delta(\bar{h})$ in $\check{H}^n(X, \mathcal{F})$. At this point a lot of properties have to be checked, all of which are straightforward. For example, we need to check that our construction is independent of the choice of $\mathcal{U}, \bar{h}, \mathcal{V}, \alpha : J \rightarrow I, g$. The class of $d(g)$ is independent of the choice of the lifts $g_{i_0 \dots i_n}$ because the difference will be a coboundary. Independence of α holds¹

¹This is an important check because the nonuniqueness of α is the only thing preventing us from taking the colimit of Čech complexes over all open coverings of X to get a short exact sequence of complexes computing Čech cohomology.

because a different choice of α determines homotopic vertical maps of complexes in the diagram above, see Section 16. For the other choices we use that given a finite collection of coverings of X we can always find a covering refining all of them. We also need to check additivity which is shown in the same manner. Finally, we need to check that the maps $\check{H}^n(X, -) \rightarrow H^n(X, -)$ are compatible with boundary maps. To do this we choose injective resolutions

$$\begin{array}{ccccccc} 0 & \longrightarrow & \mathcal{F} & \longrightarrow & \mathcal{G} & \longrightarrow & \mathcal{H} \longrightarrow 0 \\ & & \downarrow & & \downarrow & & \downarrow \\ 0 & \longrightarrow & \mathcal{I}_1^\bullet & \longrightarrow & \mathcal{I}_2^\bullet & \longrightarrow & \mathcal{I}_3^\bullet \longrightarrow 0 \end{array}$$

as in Derived Categories, Lemma 18.9. This will give a commutative diagram

$$\begin{array}{ccccccc} 0 & \longrightarrow & \check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}) & \longrightarrow & \check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{G}) & \longrightarrow & \check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{H}) \longrightarrow 0 \\ & & \downarrow & & \downarrow & & \downarrow \\ 0 & \longrightarrow & \text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{I}_1^\bullet)) & \longrightarrow & \text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{I}_2^\bullet)) & \longrightarrow & \text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{I}_3^\bullet)) \longrightarrow 0 \end{array}$$

Here \mathcal{U} is an open covering as above and the vertical maps are those used to define the maps $\check{H}^n(\mathcal{U}, -) \rightarrow H^n(X, -)$, see Lemma 12.2. The bottom complex is exact as the sequence of complexes of injectives is termwise split exact. Hence the boundary map in cohomology is computed by the usual procedure for this lower exact sequence, see Homology, Lemma 12.12. The same will be true after passing to the refinement \mathcal{V} where the boundary map for Čech cohomology was defined. Hence the boundary maps agree because they use the same construction (whenever the first one is defined on an element in Čech cohomology on a given covering). This finishes our discussion of the construction of the structure of a δ -functor on Čech cohomology and why this structure is compatible with the given δ -functor structure on usual cohomology.

Finally, we may apply Lemma 12.1 to see that higher Čech cohomology is trivial on injective sheaves. Hence we see that Čech cohomology is a universal δ -functor by Homology, Lemma 11.4. \square

09V3 **Lemma 17.3.** *Let X be a topological space. Let $Z \subset X$ be a quasi-compact subset such that any two points of Z have disjoint open neighbourhoods in X . For every abelian sheaf \mathcal{F} on X the canonical map* [AGV71, Expose V bis, 4.1.3]

$$\text{colim } H^p(U, \mathcal{F}) \longrightarrow H^p(Z, \mathcal{F}|_Z)$$

where the colimit is over open neighbourhoods U of Z in X is an isomorphism.

Proof. We first prove this for $p = 0$. Injectivity follows from the definition of $\mathcal{F}|_Z$ and holds in general (for any subset of any topological space X). Next, suppose that $s \in H^0(Z, \mathcal{F}|_Z)$. Then we can find opens $U_i \subset X$ such that $Z \subset \bigcup U_i$ and such that $s|_{Z \cap U_i}$ comes from $s_i \in \mathcal{F}(U_i)$. It follows that there exist opens $W_{ij} \subset U_i \cap U_j$ with $W_{ij} \cap Z = U_i \cap U_j \cap Z$ such that $s_i|_{W_{ij}} = s_j|_{W_{ij}}$. Applying Topology, Lemma 13.7 we find opens V_i of X such that $V_i \subset U_i$ and such that $V_i \cap V_j \subset W_{ij}$. Hence we see that $s_i|_{V_i}$ glue to a section of \mathcal{F} over the open neighbourhood $\bigcup V_i$ of Z .

To finish the proof, it suffices to show that if \mathcal{I} is an injective abelian sheaf on X , then $H^p(Z, \mathcal{I}|_Z) = 0$ for $p > 0$. This follows using short exact sequences and

dimension shifting; details omitted. Thus, suppose $\bar{\xi}$ is an element of $H^p(Z, \mathcal{I}|_Z)$ for some $p > 0$. By Lemma 17.2 the element $\bar{\xi}$ comes from $\check{H}^p(\mathcal{V}, \mathcal{I}|_Z)$ for some open covering $\mathcal{V} : Z = \bigcup V_i$ of Z . Say $\bar{\xi}$ is the image of the class of a cocycle $\xi = (\xi_{i_0 \dots i_p})$ in $\check{C}^p(\mathcal{V}, \mathcal{I}|_Z)$.

Let $\mathcal{I}' \subset \mathcal{I}|_Z$ be the subsheaf defined by the rule

$$\mathcal{I}'(V) = \{s \in \mathcal{I}|_Z(V) \mid \exists (U, t), U \subset X \text{ open}, t \in \mathcal{I}(U), V = Z \cap U, s = t|_{Z \cap U}\}$$

Then $\mathcal{I}|_Z$ is the sheafification of \mathcal{I}' . Thus for every $(p+1)$ -tuple $i_0 \dots i_p$ we can find an open covering $V_{i_0 \dots i_p} = \bigcup W_{i_0 \dots i_p, k}$ such that $\xi_{i_0 \dots i_p}|_{W_{i_0 \dots i_p, k}}$ is a section of \mathcal{I}' . Applying Topology, Lemma 13.5 we may after refining \mathcal{V} assume that each $\xi_{i_0 \dots i_p}$ is a section of the presheaf \mathcal{I}' .

Write $V_i = Z \cap U_i$ for some opens $U_i \subset X$. Since \mathcal{I} is flasque (Lemma 13.2) and since $\xi_{i_0 \dots i_p}$ is a section of \mathcal{I}' for every $(p+1)$ -tuple $i_0 \dots i_p$ we can choose a section $s_{i_0 \dots i_p} \in \mathcal{I}(U_{i_0 \dots i_p})$ which restricts to $\xi_{i_0 \dots i_p}$ on $V_{i_0 \dots i_p} = Z \cap U_{i_0 \dots i_p}$. (This appeal to injectives being flasque can be avoided by an additional application of Topology, Lemma 13.7.) Let $s = (s_{i_0 \dots i_p})$ be the corresponding cochain for the open covering $U = \bigcup U_i$. Since $d(\xi) = 0$ we see that the sections $d(s)_{i_0 \dots i_{p+1}}$ restrict to zero on $Z \cap U_{i_0 \dots i_{p+1}}$. Hence, by the initial remarks of the proof, there exists open subsets $W_{i_0 \dots i_{p+1}} \subset U_{i_0 \dots i_{p+1}}$ with $Z \cap W_{i_0 \dots i_{p+1}} = Z \cap U_{i_0 \dots i_{p+1}}$ such that $d(s)_{i_0 \dots i_{p+1}}|_{W_{i_0 \dots i_{p+1}}} = 0$. By Topology, Lemma 13.7 we can find $U'_i \subset U_i$ such that $Z \subset \bigcup U'_i$ and such that $U'_{i_0 \dots i_{p+1}} \subset W_{i_0 \dots i_{p+1}}$. Then $s' = (s'_{i_0 \dots i_p})$ with $s'_{i_0 \dots i_p} = s_{i_0 \dots i_p}|_{U'_{i_0 \dots i_p}}$ is a cocycle for \mathcal{I} for the open covering $U' = \bigcup U'_i$ of an open neighbourhood of Z . Since \mathcal{I} has trivial higher Čech cohomology groups (Lemma 12.1) we conclude that s' is a coboundary. It follows that the image of ξ in the Čech complex for the open covering $Z = \bigcup Z \cap U'_i$ is a coboundary and we are done. \square

18. The base change map

02N6 We will need to know how to construct the base change map in some cases. Since we have not yet discussed derived pullback we only discuss this in the case of a base change by a flat morphism of ringed spaces. Before we state the result, let us discuss flat pullback on the derived category. Namely, suppose that $g : X \rightarrow Y$ is a flat morphism of ringed spaces. By Modules, Lemma 18.2 the functor $g^* : \text{Mod}(\mathcal{O}_Y) \rightarrow \text{Mod}(\mathcal{O}_X)$ is exact. Hence it has a derived functor

$$g^* : D^+(Y) \rightarrow D^+(X)$$

which is computed by simply pulling back an representative of a given object in $D^+(Y)$, see Derived Categories, Lemma 17.9. Hence as indicated we indicate this functor by g^* rather than Lg^* .

02N7 **Lemma 18.1.** *Let*

$$\begin{array}{ccc} X' & \xrightarrow{\quad} & X \\ f' \downarrow & g' \searrow & \downarrow f \\ S' & \xrightarrow{\quad g \quad} & S \end{array}$$

be a commutative diagram of ringed spaces. Let \mathcal{F}^\bullet be a bounded below complex of \mathcal{O}_X -modules. Assume both g and g' are flat. Then there exists a canonical base change map

$$g^* Rf_* \mathcal{F}^\bullet \longrightarrow R(f')_*(g')^* \mathcal{F}^\bullet$$

in $D^+(S')$.

Proof. Choose injective resolutions $\mathcal{F}^\bullet \rightarrow \mathcal{I}^\bullet$ and $(g')^*\mathcal{F}^\bullet \rightarrow \mathcal{J}^\bullet$. By Lemma 12.11 we see that $(g')_*\mathcal{J}^\bullet$ is a complex of injectives representing $R(g')_*(g')^*\mathcal{F}^\bullet$. Hence by Derived Categories, Lemmas 18.6 and 18.7 the arrow β in the diagram

$$\begin{array}{ccc} (g')_*(g')^*\mathcal{F}^\bullet & \longrightarrow & (g')_*\mathcal{J}^\bullet \\ \text{adjunction} \uparrow & & \uparrow \beta \\ \mathcal{F}^\bullet & \longrightarrow & \mathcal{I}^\bullet \end{array}$$

exists and is unique up to homotopy. Pushing down to S we get

$$f_*\beta : f_*\mathcal{I}^\bullet \longrightarrow f_*(g')_*\mathcal{J}^\bullet = g_*(f')_*\mathcal{J}^\bullet$$

By adjunction of g^* and g_* we get a map of complexes $g^*f_*\mathcal{I}^\bullet \rightarrow (f')_*\mathcal{J}^\bullet$. Note that this map is unique up to homotopy since the only choice in the whole process was the choice of the map β and everything was done on the level of complexes. \square

02N8 **Remark 18.2.** The “correct” version of the base change map is map

$$Lg^*Rf_*\mathcal{F}^\bullet \longrightarrow R(f')_*L(g')^*\mathcal{F}^\bullet.$$

The construction of this map involves unbounded complexes, see Remark 29.3.

19. Proper base change in topology

09V4 In this section we prove a very general version of the proper base change theorem in topology. It tells us that the stalks of the higher direct images $R^p f_*$ can be computed on the fibre.

09V5 **Lemma 19.1.** *Let $f : (X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$ be a morphism of ringed spaces. Let $y \in Y$. Assume that*

- (1) f is closed,
- (2) f is separated, and
- (3) $f^{-1}(y)$ is quasi-compact.

*Then for E in $D^+(\mathcal{O}_X)$ we have $(Rf_*E)_y = R\Gamma(f^{-1}(y), E|_{f^{-1}(y)})$ in $D^+(\mathcal{O}_{Y,y})$.*

Proof. The base change map of Lemma 18.1 gives a canonical map $(Rf_*E)_y \rightarrow R\Gamma(f^{-1}(y), E|_{f^{-1}(y)})$. To prove this map is an isomorphism, we represent E by a bounded below complex of injectives \mathcal{I}^\bullet . Set $Z = f^{-1}(\{y\})$. The assumptions of Lemma 17.3 are satisfied, see Topology, Lemma 4.2. Hence the restrictions $\mathcal{I}^n|_Z$ are acyclic for $\Gamma(Z, -)$. Thus $R\Gamma(Z, E|_Z)$ is represented by the complex $\Gamma(Z, \mathcal{I}^\bullet|_Z)$, see Derived Categories, Lemma 17.7. In other words, we have to show the map

$$\text{colim}_V \mathcal{I}^\bullet(f^{-1}(V)) \longrightarrow \Gamma(Z, \mathcal{I}^\bullet|_Z)$$

is an isomorphism. Using Lemma 17.3 we see that it suffices to show that the collection of open neighbourhoods $f^{-1}(V)$ of $Z = f^{-1}(\{y\})$ is cofinal in the system of all open neighbourhoods. If $f^{-1}(\{y\}) \subset U$ is an open neighbourhood, then as f is closed the set $V = Y \setminus f(X \setminus U)$ is an open neighbourhood of y with $f^{-1}(V) \subset U$. This proves the lemma. \square

09V6 **Theorem 19.2** (Proper base change). *Consider a cartesian square of topological spaces* [AGV71, Expose V bis, 4.1.1]

$$\begin{array}{ccc} X' = Y' \times_Y X & \xrightarrow{g'} & X \\ f' \downarrow & & \downarrow f \\ Y' & \xrightarrow{g} & Y \end{array}$$

Assume that f is proper and separated. Let E be an object of $D^+(X)$. Then the base change map

$$g^{-1}Rf_*E \longrightarrow Rf'_*(g')^{-1}E$$

of Lemma 18.1 is an isomorphism in $D^+(Y')$.

Proof. Let $y' \in Y'$ be a point with image $y \in Y$. It suffices to show that the base change map induces an isomorphism on stalks at y' . As f is proper it follows that f' is proper, the fibres of f and f' are quasi-compact and f and f' are closed, see Topology, Theorem 17.5. Moreover f' is separated by Topology, Lemma 4.4. Thus we can apply Lemma 19.1 twice to see that

$$(Rf'_*(g')^{-1}E)_{y'} = R\Gamma((f')^{-1}(y'), (g')^{-1}E|_{(f')^{-1}(y')})$$

and

$$(Rf_*E)_y = R\Gamma(f^{-1}(y), E|_{f^{-1}(y)})$$

The induced map of fibres $(f')^{-1}(y') \rightarrow f^{-1}(y)$ is a homeomorphism of topological spaces and the pull back of $E|_{f^{-1}(y)}$ is $(g')^{-1}E|_{(f')^{-1}(y')}$. The desired result follows. \square

0D90 **Lemma 19.3** (Proper base change for sheaves of sets). *Consider a cartesian square of topological spaces*

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

Assume that f is proper and separated. Then $g^{-1}f_*\mathcal{F} = f'_*(g')^{-1}\mathcal{F}$ for any sheaf of sets \mathcal{F} on X .

Proof. We argue exactly as in the proof of Theorem 19.2 and we find it suffices to show $(f_*\mathcal{F})_y = \Gamma(X_y, \mathcal{F}|_{X_y})$. Then we argue as in Lemma 19.1 to reduce this to the $p = 0$ case of Lemma 17.3 for sheaves of sets. The first part of the proof of Lemma 17.3 works for sheaves of sets and this finishes the proof. Some details omitted. \square

20. Cohomology and colimits

01FE Let X be a ringed space. Let $(\mathcal{F}_i, \varphi_{ii'})$ be a system of sheaves of \mathcal{O}_X -modules over the directed set I , see Categories, Section 21. Since for each i there is a canonical map $\mathcal{F}_i \rightarrow \text{colim}_i \mathcal{F}_i$ we get a canonical map

$$\text{colim}_i H^p(X, \mathcal{F}_i) \longrightarrow H^p(X, \text{colim}_i \mathcal{F}_i)$$

for every $p \geq 0$. Of course there is a similar map for every open $U \subset X$. These maps are in general not isomorphisms, even for $p = 0$. In this section we generalize the results of Sheaves, Lemma 29.1. See also Modules, Lemma 11.6 (in the special case $\mathcal{G} = \mathcal{O}_X$).

01FF **Lemma 20.1.** *Let X be a ringed space. Assume that the underlying topological space of X has the following properties:*

- (1) *there exists a basis of quasi-compact open subsets, and*
- (2) *the intersection of any two quasi-compact opens is quasi-compact.*

Then for any directed system $(\mathcal{F}_i, \varphi_{ii'})$ of sheaves of \mathcal{O}_X -modules and for any quasi-compact open $U \subset X$ the canonical map

$$\operatorname{colim}_i H^q(U, \mathcal{F}_i) \longrightarrow H^q(U, \operatorname{colim}_i \mathcal{F}_i)$$

is an isomorphism for every $q \geq 0$.

Proof. It is important in this proof to argue for all quasi-compact opens $U \subset X$ at the same time. The result is true for $i = 0$ and any quasi-compact open $U \subset X$ by Sheaves, Lemma 29.1 (combined with Topology, Lemma 27.1). Assume that we have proved the result for all $q \leq q_0$ and let us prove the result for $q = q_0 + 1$.

By our conventions on directed systems the index set I is directed, and any system of \mathcal{O}_X -modules $(\mathcal{F}_i, \varphi_{ii'})$ over I is directed. By Injectives, Lemma 5.1 the category of \mathcal{O}_X -modules has functorial injective embeddings. Thus for any system $(\mathcal{F}_i, \varphi_{ii'})$ there exists a system $(\mathcal{I}_i, \varphi_{ii'})$ with each \mathcal{I}_i an injective \mathcal{O}_X -module and a morphism of systems given by injective \mathcal{O}_X -module maps $\mathcal{F}_i \rightarrow \mathcal{I}_i$. Denote \mathcal{Q}_i the cokernel so that we have short exact sequences

$$0 \rightarrow \mathcal{F}_i \rightarrow \mathcal{I}_i \rightarrow \mathcal{Q}_i \rightarrow 0.$$

We claim that the sequence

$$0 \rightarrow \operatorname{colim}_i \mathcal{F}_i \rightarrow \operatorname{colim}_i \mathcal{I}_i \rightarrow \operatorname{colim}_i \mathcal{Q}_i \rightarrow 0.$$

is also a short exact sequence of \mathcal{O}_X -modules. We may check this on stalks. By Sheaves, Sections 28 and 29 taking stalks commutes with colimits. Since a directed colimit of short exact sequences of abelian groups is short exact (see Algebra, Lemma 8.8) we deduce the result. We claim that $H^q(U, \operatorname{colim}_i \mathcal{I}_i) = 0$ for all quasi-compact open $U \subset X$ and all $q \geq 1$. Accepting this claim for the moment consider the diagram

$$\begin{array}{ccccccc} \operatorname{colim}_i H^{q_0}(U, \mathcal{I}_i) & \longrightarrow & \operatorname{colim}_i H^{q_0}(U, \mathcal{Q}_i) & \longrightarrow & \operatorname{colim}_i H^{q_0+1}(U, \mathcal{F}_i) & \longrightarrow & 0 \\ \downarrow & & \downarrow & & \downarrow & & \downarrow \\ H^{q_0}(U, \operatorname{colim}_i \mathcal{I}_i) & \longrightarrow & H^{q_0}(U, \operatorname{colim}_i \mathcal{Q}_i) & \longrightarrow & H^{q_0+1}(U, \operatorname{colim}_i \mathcal{F}_i) & \longrightarrow & 0 \end{array}$$

The zero at the lower right corner comes from the claim and the zero at the upper right corner comes from the fact that the sheaves \mathcal{I}_i are injective. The top row is exact by an application of Algebra, Lemma 8.8. Hence by the snake lemma we deduce the result for $q = q_0 + 1$.

It remains to show that the claim is true. We will use Lemma 12.9. Let \mathcal{B} be the collection of all quasi-compact open subsets of X . This is a basis for the topology on X by assumption. Let Cov be the collection of finite open coverings $\mathcal{U} : U = \bigcup_{j=1, \dots, m} U_j$ with each of U, U_j quasi-compact open in X . By the result for $q = 0$ we see that for $\mathcal{U} \in \operatorname{Cov}$ we have

$$\check{C}^\bullet(\mathcal{U}, \operatorname{colim}_i \mathcal{I}_i) = \operatorname{colim}_i \check{C}^\bullet(\mathcal{U}, \mathcal{I}_i)$$

because all the multiple intersections U_{j_0, \dots, j_p} are quasi-compact. By Lemma 12.1 each of the complexes in the colimit of Čech complexes is acyclic in degree ≥ 1 .

Hence by Algebra, Lemma 8.8 we see that also the Čech complex $\check{C}^\bullet(\mathcal{U}, \text{colim}_i \mathcal{I}_i)$ is acyclic in degrees ≥ 1 . In other words we see that $\check{H}^p(\mathcal{U}, \text{colim}_i \mathcal{I}_i) = 0$ for all $p \geq 1$. Thus the assumptions of Lemma 12.9 are satisfied and the claim follows. \square

Next we formulate the analogy of Sheaves, Lemma 29.4 for cohomology. Let X be a spectral space which is written as a cofiltered limit of spectral spaces X_i for a diagram with spectral transition morphisms as in Topology, Lemma 24.5. Assume given

- (1) an abelian sheaf \mathcal{F}_i on X_i for all $i \in \text{Ob}(\mathcal{I})$,
- (2) for $a : j \rightarrow i$ an f_a -map $\varphi_a : \mathcal{F}_i \rightarrow \mathcal{F}_j$ of abelian sheaves (see Sheaves, Definition 21.7)

such that $\varphi_c = \varphi_b \circ \varphi_a$ whenever $c = a \circ b$. Set $\mathcal{F} = \text{colim } p_i^{-1} \mathcal{F}_i$ on X .

0A37 **Lemma 20.2.** *In the situation discussed above. Let $i \in \text{Ob}(\mathcal{I})$ and let $U_i \subset X_i$ be quasi-compact open. Then*

$$\text{colim}_{a:j \rightarrow i} H^p(f_a^{-1}(U_i), \mathcal{F}_j) = H^p(p_i^{-1}(U_i), \mathcal{F})$$

for all $p \geq 0$. In particular we have $H^p(X, \mathcal{F}) = \text{colim } H^p(X_i, \mathcal{F}_i)$.

Proof. The case $p = 0$ is Sheaves, Lemma 29.4.

In this paragraph we show that we can find a map of systems $(\gamma_i) : (\mathcal{F}_i, \varphi_a) \rightarrow (\mathcal{G}_i, \psi_a)$ with \mathcal{G}_i an injective abelian sheaf and γ_i injective. For each i we pick an injection $\mathcal{F}_i \rightarrow \mathcal{I}_i$ where \mathcal{I}_i is an injective abelian sheaf on X_i . Then we can consider the family of maps

$$\gamma_i : \mathcal{F}_i \longrightarrow \prod_{b:k \rightarrow i} f_{b,*} \mathcal{I}_k = \mathcal{G}_i$$

where the component maps are the maps adjoint to the maps $f_b^{-1} \mathcal{F}_i \rightarrow \mathcal{F}_k \rightarrow \mathcal{I}_k$. For $a : j \rightarrow i$ in \mathcal{I} there is a canonical map

$$\psi_a : f_a^{-1} \mathcal{G}_i \rightarrow \mathcal{G}_j$$

whose components are the canonical maps $f_b^{-1} f_{a \circ b,*} \mathcal{I}_k \rightarrow f_{b,*} \mathcal{I}_k$ for $b : k \rightarrow j$. Thus we find an injection $\{\gamma_i\} : \{\mathcal{F}_i, \varphi_a\} \rightarrow (\mathcal{G}_i, \psi_a)$ of systems of abelian sheaves. Note that \mathcal{G}_i is an injective sheaf of abelian groups on \mathcal{C}_i , see Lemma 12.11 and Homology, Lemma 23.3. This finishes the construction.

Arguing exactly as in the proof of Lemma 20.1 we see that it suffices to prove that $H^p(X, \text{colim } f_i^{-1} \mathcal{G}_i) = 0$ for $p > 0$.

Set $\mathcal{G} = \text{colim } f_i^{-1} \mathcal{G}_i$. To show vanishing of cohomology of \mathcal{G} on every quasi-compact open of X , it suffices to show that the Čech cohomology of \mathcal{G} for any covering \mathcal{U} of a quasi-compact open of X by finitely many quasi-compact opens is zero, see Lemma 12.9. Such a covering is the inverse by p_i of such a covering \mathcal{U}_i on the space X_i for some i by Topology, Lemma 24.6. We have

$$\check{C}^\bullet(\mathcal{U}, \mathcal{G}) = \text{colim}_{a:j \rightarrow i} \check{C}^\bullet(f_a^{-1}(\mathcal{U}_i), \mathcal{G}_j)$$

by the case $p = 0$. The right hand side is a filtered colimit of complexes each of which is acyclic in positive degrees by Lemma 12.1. Thus we conclude by Algebra, Lemma 8.8. \square

21. Vanishing on Noetherian topological spaces

02UU The aim is to prove a theorem of Grothendieck namely Proposition 21.7. See [Gro57].

02UV **Lemma 21.1.** *Let $i : Z \rightarrow X$ be a closed immersion of topological spaces. For any abelian sheaf \mathcal{F} on Z we have $H^p(Z, \mathcal{F}) = H^p(X, i_*\mathcal{F})$.*

Proof. This is true because i_* is exact (see Modules, Lemma 6.1), and hence $R^pi_* = 0$ as a functor (Derived Categories, Lemma 17.9). Thus we may apply Lemma 14.6. \square

02UW **Lemma 21.2.** *Let X be an irreducible topological space. Then $H^p(X, \underline{A}) = 0$ for all $p > 0$ and any abelian group A .*

Proof. Recall that \underline{A} is the constant sheaf as defined in Sheaves, Definition 7.4. It is clear that for any nonempty open $U \subset X$ we have $\underline{A}(U) = A$ as X is irreducible (and hence U is connected). We will show that the higher Čech cohomology groups $\check{H}^p(\mathcal{U}, \underline{A})$ are zero for any open covering $\mathcal{U} : U = \bigcup_{i \in I} U_i$ of an open $U \subset X$. Then the lemma will follow from Lemma 12.8.

Recall that the value of an abelian sheaf on the empty open set is 0. Hence we may clearly assume $U_i \neq \emptyset$ for all $i \in I$. In this case we see that $U_i \cap U_{i'} \neq \emptyset$ for all $i, i' \in I$. Hence we see that the Čech complex is simply the complex

$$\prod_{i_0 \in I} A \rightarrow \prod_{(i_0, i_1) \in I^2} A \rightarrow \prod_{(i_0, i_1, i_2) \in I^3} A \rightarrow \dots$$

We have to see this has trivial higher cohomology groups. We can see this for example because this is the Čech complex for the covering of a 1-point space and Čech cohomology agrees with cohomology on such a space. (You can also directly verify it by writing an explicit homotopy.) \square

0A38 **Lemma 21.3.** *Let X be a topological space such that the intersection of any two quasi-compact opens is quasi-compact. Let $\mathcal{F} \subset \underline{\mathbf{Z}}$ be a subsheaf generated by finitely many sections over quasi-compact opens. Then there exists a finite filtration* [Gro57, Page 168].

$$(0) = \mathcal{F}_0 \subset \mathcal{F}_1 \subset \dots \subset \mathcal{F}_n = \mathcal{F}$$

by abelian subsheaves such that for each $0 < i \leq n$ there exists a short exact sequence

$$0 \rightarrow j'_i \underline{\mathbf{Z}}_V \rightarrow j_i \underline{\mathbf{Z}}_U \rightarrow \mathcal{F}_i / \mathcal{F}_{i-1} \rightarrow 0$$

with $j : U \rightarrow X$ and $j' : V \rightarrow X$ the inclusion of quasi-compact opens into X .

Proof. Say \mathcal{F} is generated by the sections s_1, \dots, s_t over the quasi-compact opens U_1, \dots, U_t . Since U_i is quasi-compact and s_i a locally constant function to \mathbf{Z} we may assume, after possibly replacing U_i by the parts of a finite decomposition into open and closed subsets, that s_i is a constant section. Say $s_i = n_i$ with $n_i \in \mathbf{Z}$. Of course we can remove (U_i, n_i) from the list if $n_i = 0$. Flipping signs if necessary we may also assume $n_i > 0$. Next, for any subset $I \subset \{1, \dots, t\}$ we may add $\bigcup_{i \in I} U_i$ and $\gcd(n_i, i \in I)$ to the list. After doing this we see that our list $(U_1, n_1), \dots, (U_t, n_t)$ satisfies the following property: For $x \in X$ set $I_x = \{i \in \{1, \dots, t\} \mid x \in U_i\}$. Then $\gcd(n_i, i \in I_x)$ is attained by n_i for some $i \in I_x$.

As our filtration we take $\mathcal{F}_0 = (0)$ and \mathcal{F}_n generated by the sections n_i over U_i for those i such that $n_i \leq n$. It is clear that $\mathcal{F}_n = \mathcal{F}$ for $n \gg 0$. Moreover, the quotient

$\mathcal{F}_n/\mathcal{F}_{n-1}$ is generated by the section n over $U = \bigcup_{n_i \leq n} U_i$ and the kernel of the map $j_! \underline{\mathbf{Z}}_U \rightarrow \mathcal{F}_n/\mathcal{F}_{n-1}$ is generated by the section n over $V = \bigcup_{n_i \leq n-1} U_i$. Thus a short exact sequence as in the statement of the lemma. \square

02UX **Lemma 21.4.** *Let X be a topological space. Let $d \geq 0$ be an integer. Assume*

- (1) X is quasi-compact,
- (2) the quasi-compact opens form a basis for X , and
- (3) the intersection of two quasi-compact opens is quasi-compact.
- (4) $H^p(X, j_! \underline{\mathbf{Z}}_U) = 0$ for all $p > d$ and any quasi-compact open $j : U \rightarrow X$.

Then $H^p(X, \mathcal{F}) = 0$ for all $p > d$ and any abelian sheaf \mathcal{F} on X .

This is a special case of [Gro57, Proposition 3.6.1].

Proof. Let $S = \coprod_{U \subset X} \mathcal{F}(U)$ where U runs over the quasi-compact opens of X . For any finite subset $A = \{s_1, \dots, s_n\} \subset S$, let \mathcal{F}_A be the subsheaf of \mathcal{F} generated by all s_i (see Modules, Definition 4.5). Note that if $A \subset A'$, then $\mathcal{F}_A \subset \mathcal{F}_{A'}$. Hence $\{\mathcal{F}_A\}$ forms a system over the directed partially ordered set of finite subsets of S . By Modules, Lemma 4.6 it is clear that

$$\operatorname{colim}_A \mathcal{F}_A = \mathcal{F}$$

by looking at stalks. By Lemma 20.1 we have

$$H^p(X, \mathcal{F}) = \operatorname{colim}_A H^p(X, \mathcal{F}_A)$$

Hence it suffices to prove the vanishing for the abelian sheaves \mathcal{F}_A . In other words, it suffices to prove the result when \mathcal{F} is generated by finitely many local sections over quasi-compact opens of X .

Suppose that \mathcal{F} is generated by the local sections s_1, \dots, s_n . Let $\mathcal{F}' \subset \mathcal{F}$ be the subsheaf generated by s_1, \dots, s_{n-1} . Then we have a short exact sequence

$$0 \rightarrow \mathcal{F}' \rightarrow \mathcal{F} \rightarrow \mathcal{F}/\mathcal{F}' \rightarrow 0$$

From the long exact sequence of cohomology we see that it suffices to prove the vanishing for the abelian sheaves \mathcal{F}' and \mathcal{F}/\mathcal{F}' which are generated by fewer than n local sections. Hence it suffices to prove the vanishing for sheaves generated by at most one local section. These sheaves are exactly the quotients of the sheaves $j_! \underline{\mathbf{Z}}_U$ where U is a quasi-compact open of X .

Assume now that we have a short exact sequence

$$0 \rightarrow \mathcal{K} \rightarrow j_! \underline{\mathbf{Z}}_U \rightarrow \mathcal{F} \rightarrow 0$$

with U quasi-compact open in X . It suffices to show that $H^q(X, \mathcal{K})$ is zero for $q \geq d+1$. As above we can write \mathcal{K} as the filtered colimit of subsheaves \mathcal{K}' generated by finitely many sections over quasi-compact opens. Then \mathcal{F} is the filtered colimit of the sheaves $j_! \underline{\mathbf{Z}}_U/\mathcal{K}'$. In this way we reduce to the case that \mathcal{K} is generated by finitely many sections over quasi-compact opens. Note that \mathcal{K} is a subsheaf of $\underline{\mathbf{Z}}_X$. Thus by Lemma 21.3 there exists a finite filtration of \mathcal{K} whose successive quotients \mathcal{Q} fit into a short exact sequence

$$0 \rightarrow j_!'' \underline{\mathbf{Z}}_W \rightarrow j_!'' \underline{\mathbf{Z}}_V \rightarrow \mathcal{Q} \rightarrow 0$$

with $j'' : W \rightarrow X$ and $j' : V \rightarrow X$ the inclusions of quasi-compact opens. Hence the vanishing of $H^p(X, \mathcal{Q})$ for $p > d$ follows from our assumption (in the lemma) on the vanishing of the cohomology groups of $j_!'' \underline{\mathbf{Z}}_W$ and $j_!'' \underline{\mathbf{Z}}_V$. Returning to \mathcal{K} this, via an induction argument using the long exact cohomology sequence, implies the desired vanishing for it as well. \square

0BX0 **Example 21.5.** Let $X = \mathbf{N}$ endowed with the topology whose opens are \emptyset , X , and $U_n = \{i \mid i \leq n\}$ for $n \geq 1$. An abelian sheaf \mathcal{F} on X is the same as an inverse system of abelian groups $A_n = \mathcal{F}(U_n)$ and $\Gamma(X, \mathcal{F}) = \lim A_n$. Since the inverse limit functor is not an exact functor on the category of inverse systems, we see that there is an abelian sheaf with nonzero H^1 . Finally, the reader can check that $H^p(X, j_*\mathbf{Z}_U) = 0$, $p \geq 1$ if $j : U = U_n \rightarrow X$ is the inclusion. Thus we see that X is an example of a space satisfying conditions (2), (3), and (4) of Lemma 21.4 for $d = 0$ but not the conclusion.

02UY **Lemma 21.6.** *Let X be an irreducible topological space. Let $\mathcal{H} \subset \mathbf{Z}$ be an abelian subsheaf of the constant sheaf. Then there exists a nonempty open $U \subset X$ such that $\mathcal{H}|_U = d\mathbf{Z}_U$ for some $d \in \mathbf{Z}$.*

Proof. Recall that $\mathbf{Z}(V) = \mathbf{Z}$ for any nonempty open V of X (see proof of Lemma 21.2). If $\mathcal{H} = 0$, then the lemma holds with $d = 0$. If $\mathcal{H} \neq 0$, then there exists a nonempty open $U \subset X$ such that $\mathcal{H}(U) \neq 0$. Say $\mathcal{H}(U) = n\mathbf{Z}$ for some $n \geq 1$. Hence we see that $n\mathbf{Z}_U \subset \mathcal{H}|_U \subset \mathbf{Z}_U$. If the first inclusion is strict we can find a nonempty $U' \subset U$ and an integer $1 \leq n' < n$ such that $n'\mathbf{Z}_{U'} \subset \mathcal{H}|_{U'} \subset \mathbf{Z}_{U'}$. This process has to stop after a finite number of steps, and hence we get the lemma. \square

02UZ **Proposition 21.7** (Grothendieck). *Let X be a Noetherian topological space. If $\dim(X) \leq d$, then $H^p(X, \mathcal{F}) = 0$ for all $p > d$ and any abelian sheaf \mathcal{F} on X .* [Gro57, Theorem 3.6.5].

Proof. We prove this lemma by induction on d . So fix d and assume the lemma holds for all Noetherian topological spaces of dimension $< d$.

Let \mathcal{F} be an abelian sheaf on X . Suppose $U \subset X$ is an open. Let $Z \subset X$ denote the closed complement. Denote $j : U \rightarrow X$ and $i : Z \rightarrow X$ the inclusion maps. Then there is a short exact sequence

$$0 \rightarrow j_*j^*\mathcal{F} \rightarrow \mathcal{F} \rightarrow i_*i^*\mathcal{F} \rightarrow 0$$

see Modules, Lemma 7.1. Note that $j_*j^*\mathcal{F}$ is supported on the topological closure Z' of U , i.e., it is of the form $i'_*\mathcal{F}'$ for some abelian sheaf \mathcal{F}' on Z' , where $i' : Z' \rightarrow X$ is the inclusion.

We can use this to reduce to the case where X is irreducible. Namely, according to Topology, Lemma 9.2 X has finitely many irreducible components. If X has more than one irreducible component, then let $Z \subset X$ be an irreducible component of X and set $U = X \setminus Z$. By the above, and the long exact sequence of cohomology, it suffices to prove the vanishing of $H^p(X, i_*i^*\mathcal{F})$ and $H^p(X, i'_*\mathcal{F}')$ for $p > d$. By Lemma 21.1 it suffices to prove $H^p(Z, i^*\mathcal{F})$ and $H^p(Z', \mathcal{F}')$ vanish for $p > d$. Since Z' and Z have fewer irreducible components we indeed reduce to the case of an irreducible X .

If $d = 0$ and $X = \{*\}$, then every sheaf is constant and higher cohomology groups vanish (for example by Lemma 21.2).

Suppose X is irreducible of dimension d . By Lemma 21.4 we reduce to the case where $\mathcal{F} = j_*\mathbf{Z}_U$ for some open $U \subset X$. In this case we look at the short exact sequence

$$0 \rightarrow j_*(\mathbf{Z}_U) \rightarrow \mathbf{Z}_X \rightarrow i_*\mathbf{Z}_Z \rightarrow 0$$

where $Z = X \setminus U$. By Lemma 21.2 we have the vanishing of $H^p(X, \mathbf{Z}_X)$ for all $p \geq 1$. By induction we have $H^p(X, i_*\mathbf{Z}_Z) = H^p(Z, \mathbf{Z}_Z) = 0$ for $p \geq d$. Hence we win by the long exact cohomology sequence. \square

22. Cohomology with support in a closed

0A39 Let X be a topological space and let $Z \subset X$ be a closed subset. Let \mathcal{F} be an abelian sheaf on X . We let

$$\Gamma_Z(X, \mathcal{F}) = \{s \in \mathcal{F}(X) \mid \text{Supp}(s) \subset Z\}$$

be the sections with support in Z (Modules, Definition 5.1). This is a left exact functor which is not exact in general. Hence we obtain a derived functor

$$R\Gamma_Z(X, -) : D(X) \longrightarrow D(\text{Ab})$$

and cohomology groups with support in Z defined by $H_Z^q(X, \mathcal{F}) = R^q\Gamma_Z(X, \mathcal{F})$.

Let \mathcal{I} be an injective abelian sheaf on X . Let $U = X \setminus Z$. Then the restriction map $\mathcal{I}(X) \rightarrow \mathcal{I}(U)$ is surjective (Lemma 9.1) with kernel $\Gamma_Z(X, \mathcal{I})$. It immediately follows that for $K \in D(X)$ there is a distinguished triangle

$$R\Gamma_Z(X, K) \rightarrow R\Gamma(X, K) \rightarrow R\Gamma(U, K) \rightarrow R\Gamma_Z(X, K)[1]$$

in $D(\text{Ab})$. As a consequence we obtain a long exact cohomology sequence

$$\dots \rightarrow H_Z^i(X, K) \rightarrow H^i(X, K) \rightarrow H^i(U, K) \rightarrow H_Z^{i+1}(X, K) \rightarrow \dots$$

for any K in $D(X)$.

For an abelian sheaf \mathcal{F} on X we can consider the *subsheaf of sections with support in Z* , denoted $\mathcal{H}_Z(\mathcal{F})$, defined by the rule

$$\mathcal{H}_Z(\mathcal{F})(U) = \{s \in \mathcal{F}(U) \mid \text{Supp}(s) \subset U \cap Z\}$$

Using the equivalence of Modules, Lemma 6.1 we may view $\mathcal{H}_Z(\mathcal{F})$ as an abelian sheaf on Z (see also Modules, Lemmas 6.2 and 6.3). Thus we obtain a functor

$$\text{Ab}(X) \longrightarrow \text{Ab}(Z), \quad \mathcal{F} \longmapsto \mathcal{H}_Z(\mathcal{F}) \text{ viewed as a sheaf on } Z$$

which is left exact, but in general not exact.

0A3A **Lemma 22.1.** *Let $i : Z \rightarrow X$ be the inclusion of a closed subset. Let \mathcal{I} be an injective abelian sheaf on X . Then $\mathcal{H}_Z(\mathcal{I})$ is an injective abelian sheaf on Z .*

Proof. Observe that for any abelian sheaf \mathcal{G} on Z we have

$$\text{Hom}_Z(\mathcal{G}, \mathcal{H}_Z(\mathcal{I})) = \text{Hom}_X(i_*\mathcal{G}, \mathcal{I})$$

because after all any section of $i_*\mathcal{G}$ has support in Z . Since i_* is exact (Modules, Lemma 6.1) and \mathcal{I} injective on X we conclude that $\mathcal{H}_Z(\mathcal{I})$ is injective on Z . \square

Denote

$$R\mathcal{H}_Z : D(X) \longrightarrow D(Z)$$

the derived functor. We set $\mathcal{H}_Z^q(\mathcal{F}) = R^q\mathcal{H}_Z(\mathcal{F})$ so that $\mathcal{H}_Z^0(\mathcal{F}) = \mathcal{H}_Z(\mathcal{F})$. By the lemma above we have a Grothendieck spectral sequence

$$E_2^{p,q} = H^p(Z, \mathcal{H}_Z^q(\mathcal{F})) \Rightarrow H_Z^{p+q}(X, \mathcal{F})$$

0A3B **Lemma 22.2.** *Let $i : Z \rightarrow X$ be the inclusion of a closed subset. Let \mathcal{G} be an injective abelian sheaf on Z . Then $\mathcal{H}_Z^p(i_*\mathcal{G}) = 0$ for $p > 0$.*

Proof. This is true because the functor i_* is exact and transforms injective abelian sheaves into injective abelian sheaves by Lemma 12.11. \square

Let X be a topological space and let $Z \subset X$ be a closed subset. We denote $D_Z(X)$ the strictly full saturated triangulated subcategory of $D(X)$ consisting of complexes whose cohomology sheaves are supported on Z .

0AEF **Lemma 22.3.** *Let $i : Z \rightarrow X$ be the inclusion of a closed subset of a topological space X . The map $Ri_* = i_* : D(Z) \rightarrow D(X)$ induces an equivalence $D(Z) \rightarrow D_Z(X)$ with quasi-inverse*

$$i^{-1}|_{D_Z(X)} = R\mathcal{H}_Z|_{D_Z(X)}$$

Proof. Recall that i^{-1} and i_* is an adjoint pair of exact functors such that $i^{-1}i_*$ is isomorphic to the identity functor on abelian sheaves. See Modules, Lemmas 3.3 and 6.1. Thus $i_* : D(Z) \rightarrow D_Z(X)$ is fully faithful and i^{-1} determines a left inverse. On the other hand, suppose that K is an object of $D_Z(X)$ and consider the adjunction map $K \rightarrow i_*i^{-1}K$. Using exactness of i_* and i^{-1} this induces the adjunction maps $H^n(K) \rightarrow i_*i^{-1}H^n(K)$ on cohomology sheaves. Since these cohomology sheaves are supported on Z we see these adjunction maps are isomorphisms and we conclude that $D(Z) \rightarrow D_Z(X)$ is an equivalence.

To finish the proof we have to show that $R\mathcal{H}_Z(K) = i^{-1}K$ if K is an object of $D_Z(X)$. To do this we can use that $K = i_*i^{-1}K$ as we've just proved this is the case. Then we can choose a K-injective representative \mathcal{I}^\bullet for $i^{-1}K$. Since i_* is the right adjoint to the exact functor i^{-1} , the complex $i_*\mathcal{I}^\bullet$ is K-injective (Derived Categories, Lemma 29.9). We see that $R\mathcal{H}_Z(K)$ is computed by $\mathcal{H}_Z(i_*\mathcal{I}^\bullet) = \mathcal{I}^\bullet$ as desired. \square

23. Cohomology on spectral spaces

0A3C A key result on the cohomology of spectral spaces is Lemma 20.2 which loosely speaking says that cohomology commutes with cofiltered limits in the category of spectral spaces as defined in Topology, Definition 23.1. This can be applied to give analogues of Lemmas 17.3 and 19.1 as follows.

0A3D **Lemma 23.1.** *Let X be a spectral space. Let \mathcal{F} be an abelian sheaf on X . Let $E \subset X$ be a quasi-compact subset. Let $W \subset X$ be the set of points of X which specialize to a point of E .*

- (1) $H^p(W, \mathcal{F}|_W) = \operatorname{colim} H^p(U, \mathcal{F})$ where the colimit is over quasi-compact open neighbourhoods of E ,
- (2) $H^p(W \setminus E, \mathcal{F}|_{W \setminus E}) = \operatorname{colim} H^p(U \setminus E, \mathcal{F}|_{U \setminus E})$ if E is a constructible subset.

Proof. From Topology, Lemma 24.7 we see that $W = \lim U$ where the limit is over the quasi-compact opens containing E . Each U is a spectral space by Topology, Lemma 23.4. Thus we may apply Lemma 20.2 to conclude that (1) holds. The same proof works for part (2) except we use Topology, Lemma 24.8. \square

0A3E **Lemma 23.2.** *Let $f : X \rightarrow Y$ be a spectral map of spectral spaces. Let $y \in Y$. Let $E \subset Y$ be the set of points specializing to y . Let \mathcal{F} be an abelian sheaf on X . Then $(R^p f_* \mathcal{F})_y = H^p(f^{-1}(E), \mathcal{F}|_{f^{-1}(E)})$.*

Proof. Observe that $E = \bigcap V$ where V runs over the quasi-compact open neighbourhoods of y in Y . Hence $f^{-1}(E) = \bigcap f^{-1}(V)$. This implies that $f^{-1}(E) = \lim f^{-1}(V)$ as topological spaces. Since f is spectral, each $f^{-1}(V)$ is a spectral

space too (Topology, Lemma 23.4). We conclude that $f^{-1}(E)$ is a spectral space and that

$$H^p(f^{-1}(E), \mathcal{F}|_{f^{-1}(E)}) = \operatorname{colim} H^p(f^{-1}(V), \mathcal{F})$$

by Lemma 20.2. On the other hand, the stalk of $R^p f_* \mathcal{F}$ at y is given by the colimit on the right. \square

0A3F **Lemma 23.3.** *Let X be a profinite topological space. Then $H^q(X, \mathcal{F}) = 0$ for all $q > 0$ and all abelian sheaves \mathcal{F} .*

Proof. Any open covering of X can be refined by a finite disjoint union decomposition with open parts, see Topology, Lemma 22.3. Hence if $\mathcal{F} \rightarrow \mathcal{G}$ is a surjection of abelian sheaves on X , then $\mathcal{F}(X) \rightarrow \mathcal{G}(X)$ is surjective. In other words, the global sections functor is an exact functor. Therefore its higher derived functors are zero, see Derived Categories, Lemma 17.9. \square

The following result on cohomological vanishing improves Grothendieck's result (Proposition 21.7) and can be found in [Sch92].

0A3G **Proposition 23.4.** *Let X be a spectral space of Krull dimension d . Let \mathcal{F} be an abelian sheaf on X .*

Part (1) is the main theorem of [Sch92].

- (1) $H^q(X, \mathcal{F}) = 0$ for $q > d$,
- (2) $H^d(X, \mathcal{F}) \rightarrow H^d(U, \mathcal{F})$ is surjective for every quasi-compact open $U \subset X$,
- (3) $H_Z^q(X, \mathcal{F}) = 0$ for $q > d$ and any constructible closed subset $Z \subset X$.

Proof. We prove this result by induction on d .

If $d = 0$, then X is a profinite space, see Topology, Lemma 23.7. Thus (1) holds by Lemma 23.3. If $U \subset X$ is quasi-compact open, then U is also closed as a quasi-compact subset of a Hausdorff space. Hence $X = U \amalg (X \setminus U)$ as a topological space and we see that (2) holds. Given Z as in (3) we consider the long exact sequence

$$H^{q-1}(X, \mathcal{F}) \rightarrow H^{q-1}(X \setminus Z, \mathcal{F}) \rightarrow H_Z^q(X, \mathcal{F}) \rightarrow H^q(X, \mathcal{F})$$

Since X and $U = X \setminus Z$ are profinite (namely U is quasi-compact because Z is constructible) and since we have (2) and (1) we obtain the desired vanishing of the cohomology groups with support in Z .

Induction step. Assume $d \geq 1$ and assume the proposition is valid for all spectral spaces of dimension $< d$. We first prove part (2) for X . Let U be a quasi-compact open. Let $\xi \in H^d(U, \mathcal{F})$. Set $Z = X \setminus U$. Let $W \subset X$ be the set of points specializing to Z . By Lemma 23.1 we have

$$H^d(W \setminus Z, \mathcal{F}|_{W \setminus Z}) = \operatorname{colim}_{Z \subset V} H^d(V \setminus Z, \mathcal{F})$$

where the colimit is over the quasi-compact open neighbourhoods V of Z in X . By Topology, Lemma 24.7 we see that $W \setminus Z$ is a spectral space. Since every point of W specializes to a point of Z , we see that $W \setminus Z$ is a spectral space of Krull dimension $< d$. By induction hypothesis we see that the image of ξ in $H^d(W \setminus Z, \mathcal{F}|_{W \setminus Z})$ is zero. By the displayed formula, there exists a $Z \subset V \subset X$ quasi-compact open such that $\xi|_{V \setminus Z} = 0$. Since $V \setminus Z = V \cap U$ we conclude by the Mayer-Vietoris (Lemma 9.2) for the covering $X = U \cup V$ that there exists a $\tilde{\xi} \in H^d(X, \mathcal{F})$ which restricts to ξ on U and to zero on V . In other words, part (2) is true.

Proof of part (1) assuming (2). Choose an injective resolution $\mathcal{F} \rightarrow \mathcal{I}^\bullet$. Set

$$\mathcal{G} = \operatorname{Im}(\mathcal{I}^{d-1} \rightarrow \mathcal{I}^d) = \operatorname{Ker}(\mathcal{I}^d \rightarrow \mathcal{I}^{d+1})$$

For $U \subset X$ quasi-compact open we have a map of exact sequences as follows

$$\begin{array}{ccccccc} \mathcal{I}^{d-1}(X) & \longrightarrow & \mathcal{G}(X) & \longrightarrow & H^d(X, \mathcal{F}) & \longrightarrow & 0 \\ \downarrow & & \downarrow & & \downarrow & & \\ \mathcal{I}^{d-1}(U) & \longrightarrow & \mathcal{G}(U) & \longrightarrow & H^d(U, \mathcal{F}) & \longrightarrow & 0 \end{array}$$

The sheaf \mathcal{I}^{d-1} is flasque by Lemma 13.2 and the fact that $d \geq 1$. By part (2) we see that the right vertical arrow is surjective. We conclude by a diagram chase that the map $\mathcal{G}(X) \rightarrow \mathcal{G}(U)$ is surjective. By Lemma 13.6 we conclude that $\check{H}^q(\mathcal{U}, \mathcal{G}) = 0$ for $q > 0$ and any finite covering $\mathcal{U} : U = U_1 \cup \dots \cup U_n$ of a quasi-compact open by quasi-compact opens. Applying Lemma 12.9 we find that $H^q(U, \mathcal{G}) = 0$ for all $q > 0$ and all quasi-compact opens U of X . By Leray's acyclicity lemma (Derived Categories, Lemma 17.7) we conclude that

$$H^q(X, \mathcal{F}) = H^q(\Gamma(X, \mathcal{I}^0) \rightarrow \dots \rightarrow \Gamma(X, \mathcal{I}^{d-1}) \rightarrow \Gamma(X, \mathcal{G}))$$

In particular the cohomology group vanishes if $q > d$.

Proof of (3). Given Z as in (3) we consider the long exact sequence

$$H^{q-1}(X, \mathcal{F}) \rightarrow H^{q-1}(X \setminus Z, \mathcal{F}) \rightarrow H_Z^q(X, \mathcal{F}) \rightarrow H^q(X, \mathcal{F})$$

Since X and $U = X \setminus Z$ are spectral spaces (Topology, Lemma 23.4) of dimension $\leq d$ and since we have (2) and (1) we obtain the desired vanishing. \square

24. The alternating Čech complex

01FG This section compares the Čech complex with the alternating Čech complex and some related complexes.

Let X be a topological space. Let $\mathcal{U} : U = \bigcup_{i \in I} U_i$ be an open covering. For $p \geq 0$ set

$$\check{C}_{alt}^p(\mathcal{U}, \mathcal{F}) = \left\{ s \in \check{C}^p(\mathcal{U}, \mathcal{F}) \text{ such that } s_{i_0 \dots i_p} = 0 \text{ if } i_n = i_m \text{ for some } n \neq m \right. \\ \left. \text{and } s_{i_0 \dots i_n \dots i_m \dots i_p} = -s_{i_0 \dots i_m \dots i_n \dots i_p} \text{ in any case.} \right\}$$

We omit the verification that the differential d of Equation (10.0.1) maps $\check{C}_{alt}^p(\mathcal{U}, \mathcal{F})$ into $\check{C}_{alt}^{p+1}(\mathcal{U}, \mathcal{F})$.

01FH **Definition 24.1.** Let X be a topological space. Let $\mathcal{U} : U = \bigcup_{i \in I} U_i$ be an open covering. Let \mathcal{F} be an abelian presheaf on X . The complex $\check{C}_{alt}^\bullet(\mathcal{U}, \mathcal{F})$ is the *alternating Čech complex* associated to \mathcal{F} and the open covering \mathcal{U} .

Hence there is a canonical morphism of complexes

$$\check{C}_{alt}^\bullet(\mathcal{U}, \mathcal{F}) \longrightarrow \check{C}^\bullet(\mathcal{U}, \mathcal{F})$$

namely the inclusion of the alternating Čech complex into the usual Čech complex.

Suppose our covering $\mathcal{U} : U = \bigcup_{i \in I} U_i$ comes equipped with a total ordering $<$ on I . In this case, set

$$\check{C}_{ord}^p(\mathcal{U}, \mathcal{F}) = \prod_{(i_0, \dots, i_p) \in I^{p+1}, i_0 < \dots < i_p} \mathcal{F}(U_{i_0 \dots i_p}).$$

This is an abelian group. For $s \in \check{C}_{ord}^p(\mathcal{U}, \mathcal{F})$ we denote $s_{i_0 \dots i_p}$ its value in $\mathcal{F}(U_{i_0 \dots i_p})$. We define

$$d : \check{C}_{ord}^p(\mathcal{U}, \mathcal{F}) \longrightarrow \check{C}_{ord}^{p+1}(\mathcal{U}, \mathcal{F})$$

by the formula

$$d(s)_{i_0 \dots i_{p+1}} = \sum_{j=0}^{p+1} (-1)^j s_{i_0 \dots \hat{i}_j \dots i_p} |_{U_{i_0 \dots i_{p+1}}}$$

for any $i_0 < \dots < i_{p+1}$. Note that this formula is identical to Equation (10.0.1). It is straightforward to see that $d \circ d = 0$. In other words $\check{C}_{ord}^\bullet(\mathcal{U}, \mathcal{F})$ is a complex.

01FI **Definition 24.2.** Let X be a topological space. Let $\mathcal{U} : U = \bigcup_{i \in I} U_i$ be an open covering. Assume given a total ordering on I . Let \mathcal{F} be an abelian presheaf on X . The complex $\check{C}_{ord}^\bullet(\mathcal{U}, \mathcal{F})$ is the *ordered Čech complex* associated to \mathcal{F} , the open covering \mathcal{U} and the given total ordering on I .

This complex is sometimes called the alternating Čech complex. The reason is that there is an obvious comparison map between the ordered Čech complex and the alternating Čech complex. Namely, consider the map

$$c : \check{C}_{ord}^\bullet(\mathcal{U}, \mathcal{F}) \longrightarrow \check{C}^\bullet(\mathcal{U}, \mathcal{F})$$

given by the rule

$$c(s)_{i_0 \dots i_p} = \begin{cases} 0 & \text{if } i_n = i_m \text{ for some } n \neq m \\ \text{sgn}(\sigma) s_{i_{\sigma(0)} \dots i_{\sigma(p)}} & \text{if } i_{\sigma(0)} < i_{\sigma(1)} < \dots < i_{\sigma(p)} \end{cases}$$

Here σ denotes a permutation of $\{0, \dots, p\}$ and $\text{sgn}(\sigma)$ denotes its sign. The alternating and ordered Čech complexes are often identified in the literature via the map c . Namely we have the following easy lemma.

01FJ **Lemma 24.3.** *Let X be a topological space. Let $\mathcal{U} : U = \bigcup_{i \in I} U_i$ be an open covering. Assume I comes equipped with a total ordering. The map c is a morphism of complexes. In fact it induces an isomorphism*

$$c : \check{C}_{ord}^\bullet(\mathcal{U}, \mathcal{F}) \rightarrow \check{C}_{alt}^\bullet(\mathcal{U}, \mathcal{F})$$

of complexes.

Proof. Omitted. □

There is also a map

$$\pi : \check{C}^\bullet(\mathcal{U}, \mathcal{F}) \longrightarrow \check{C}_{ord}^\bullet(\mathcal{U}, \mathcal{F})$$

which is described by the rule

$$\pi(s)_{i_0 \dots i_p} = s_{i_0 \dots i_p}$$

whenever $i_0 < i_1 < \dots < i_p$.

01FK **Lemma 24.4.** *Let X be a topological space. Let $\mathcal{U} : U = \bigcup_{i \in I} U_i$ be an open covering. Assume I comes equipped with a total ordering. The map $\pi : \check{C}^\bullet(\mathcal{U}, \mathcal{F}) \rightarrow \check{C}_{ord}^\bullet(\mathcal{U}, \mathcal{F})$ is a morphism of complexes. It induces an isomorphism*

$$\pi : \check{C}_{alt}^\bullet(\mathcal{U}, \mathcal{F}) \rightarrow \check{C}_{ord}^\bullet(\mathcal{U}, \mathcal{F})$$

of complexes which is a left inverse to the morphism c .

Proof. Omitted. □

01FL **Remark 24.5.** This means that if we have two total orderings $<_1$ and $<_2$ on the index set I , then we get an isomorphism of complexes $\tau = \pi_2 \circ c_1 : \check{C}_{ord-1}(\mathcal{U}, \mathcal{F}) \rightarrow \check{C}_{ord-2}(\mathcal{U}, \mathcal{F})$. It is clear that

$$\tau(s)_{i_0 \dots i_p} = \text{sign}(\sigma) s_{i_{\sigma(0)} \dots i_{\sigma(p)}}$$

where $i_0 <_1 i_1 <_1 \dots <_1 i_p$ and $i_{\sigma(0)} <_2 i_{\sigma(1)} <_2 \dots <_2 i_{\sigma(p)}$. This is the sense in which the ordered Čech complex is independent of the chosen total ordering.

01FM **Lemma 24.6.** *Let X be a topological space. Let $\mathcal{U} : U = \bigcup_{i \in I} U_i$ be an open covering. Assume I comes equipped with a total ordering. The map $c \circ \pi$ is homotopic to the identity on $\check{C}^\bullet(\mathcal{U}, \mathcal{F})$. In particular the inclusion map $\check{C}_{alt}^\bullet(\mathcal{U}, \mathcal{F}) \rightarrow \check{C}^\bullet(\mathcal{U}, \mathcal{F})$ is a homotopy equivalence.*

Proof. For any multi-index $(i_0, \dots, i_p) \in I^{p+1}$ there exists a unique permutation $\sigma : \{0, \dots, p\} \rightarrow \{0, \dots, p\}$ such that

$$i_{\sigma(0)} \leq i_{\sigma(1)} \leq \dots \leq i_{\sigma(p)} \quad \text{and} \quad \sigma(j) < \sigma(j+1) \quad \text{if} \quad i_{\sigma(j)} = i_{\sigma(j+1)}.$$

We denote this permutation $\sigma = \sigma^{i_0 \dots i_p}$.

For any permutation $\sigma : \{0, \dots, p\} \rightarrow \{0, \dots, p\}$ and any a , $0 \leq a \leq p$ we denote σ_a the permutation of $\{0, \dots, p\}$ such that

$$\sigma_a(j) = \begin{cases} \sigma(j) & \text{if } 0 \leq j < a, \\ \min\{j' \mid j' > \sigma_a(j-1), j' \neq \sigma(k), \forall k < a\} & \text{if } a \leq j \end{cases}$$

So if $p = 3$ and σ, τ are given by

$$\begin{array}{cccccc} \text{id} & 0 & 1 & 2 & 3 & \text{and} & \text{id} & 0 & 1 & 2 & 3 \\ \sigma & 3 & 2 & 1 & 0 & & \tau & 3 & 0 & 2 & 1 \end{array}$$

then we have

$$\begin{array}{cccccc} \text{id} & 0 & 1 & 2 & 3 & & \text{id} & 0 & 1 & 2 & 3 \\ \sigma_0 & 0 & 1 & 2 & 3 & & \tau_0 & 0 & 1 & 2 & 3 \\ \sigma_1 & 3 & 0 & 1 & 2 & \text{and} & \tau_1 & 3 & 0 & 1 & 2 \\ \sigma_2 & 3 & 2 & 0 & 1 & & \tau_2 & 3 & 0 & 1 & 2 \\ \sigma_3 & 3 & 2 & 1 & 0 & & \tau_3 & 3 & 0 & 2 & 1 \end{array}$$

It is clear that always $\sigma_0 = \text{id}$ and $\sigma_p = \sigma$.

Having introduced this notation we define for $s \in \check{C}^{p+1}(\mathcal{U}, \mathcal{F})$ the element $h(s) \in \check{C}^p(\mathcal{U}, \mathcal{F})$ to be the element with components

01FN (24.6.1)
$$h(s)_{i_0 \dots i_p} = \sum_{0 \leq a \leq p} (-1)^a \text{sign}(\sigma_a) s_{i_{\sigma(0)} \dots i_{\sigma(a)} i_{\sigma_a(a)} \dots i_{\sigma_a(p)}}$$

where $\sigma = \sigma^{i_0 \dots i_p}$. The index $i_{\sigma(a)}$ occurs twice in $i_{\sigma(0)} \dots i_{\sigma(a)} i_{\sigma_a(a)} \dots i_{\sigma_a(p)}$ once in the first group of $a+1$ indices and once in the second group of $p-a+1$ indices since $\sigma_a(j) = \sigma(a)$ for some $j \geq a$ by definition of σ_a . Hence the sum makes sense since each of the elements $s_{i_{\sigma(0)} \dots i_{\sigma(a)} i_{\sigma_a(a)} \dots i_{\sigma_a(p)}}$ is defined over the open $U_{i_0 \dots i_p}$. Note also that for $a = 0$ we get $s_{i_0 \dots i_p}$ and for $a = p$ we get $(-1)^p \text{sign}(\sigma) s_{i_{\sigma(0)} \dots i_{\sigma(p)}}$.

We claim that

$$(dh + hd)(s)_{i_0 \dots i_p} = s_{i_0 \dots i_p} - \text{sign}(\sigma) s_{i_{\sigma(0)} \dots i_{\sigma(p)}}$$

where $\sigma = \sigma^{i_0 \dots i_p}$. We omit the verification of this claim. (There is a PARI/gp script called first-homotopy.gp in the stacks-project subdirectory scripts which can

be used to check finitely many instances of this claim. We wrote this script to make sure the signs are correct.) Write

$$\kappa : \check{C}^\bullet(\mathcal{U}, \mathcal{F}) \longrightarrow \check{C}^\bullet(\mathcal{U}, \mathcal{F})$$

for the operator given by the rule

$$\kappa(s)_{i_0 \dots i_p} = \text{sign}(\sigma^{i_0 \dots i_p}) s_{i_{\sigma(0)} \dots i_{\sigma(p)}}.$$

The claim above implies that κ is a morphism of complexes and that κ is homotopic to the identity map of the Čech complex. This does not immediately imply the lemma since the image of the operator κ is not the alternating subcomplex. Namely, the image of κ is the “semi-alternating” complex $\check{C}_{semi-alt}^p(\mathcal{U}, \mathcal{F})$ where s is a p -cochain of this complex if and only if

$$s_{i_0 \dots i_p} = \text{sign}(\sigma) s_{i_{\sigma(0)} \dots i_{\sigma(p)}}$$

for any $(i_0, \dots, i_p) \in I^{p+1}$ with $\sigma = \sigma^{i_0 \dots i_p}$. We introduce yet another variant Čech complex, namely the semi-ordered Čech complex defined by

$$\check{C}_{semi-ord}^p(\mathcal{U}, \mathcal{F}) = \prod_{i_0 \leq i_1 \leq \dots \leq i_p} \mathcal{F}(U_{i_0 \dots i_p})$$

It is easy to see that Equation (10.0.1) also defines a differential and hence that we get a complex. It is also clear (analogous to Lemma 24.4) that the projection map

$$\check{C}_{semi-alt}^\bullet(\mathcal{U}, \mathcal{F}) \longrightarrow \check{C}_{semi-ord}^\bullet(\mathcal{U}, \mathcal{F})$$

is an isomorphism of complexes.

Hence the Lemma follows if we can show that the obvious inclusion map

$$\check{C}_{ord}^p(\mathcal{U}, \mathcal{F}) \longrightarrow \check{C}_{semi-ord}^p(\mathcal{U}, \mathcal{F})$$

is a homotopy equivalence. To see this we use the homotopy (24.6.2)

$$01FO \quad h(s)_{i_0 \dots i_p} = \begin{cases} 0 & \text{if } i_0 < i_1 < \dots < i_p \\ (-1)^a s_{i_0 \dots i_{a-1} i_a i_{a+1} \dots i_p} & \text{if } i_0 < i_1 < \dots < i_{a-1} < i_a = i_{a+1} \end{cases}$$

We claim that

$$(dh + hd)(s)_{i_0 \dots i_p} = \begin{cases} 0 & \text{if } i_0 < i_1 < \dots < i_p \\ s_{i_0 \dots i_p} & \text{else} \end{cases}$$

We omit the verification. (There is a PARI/gp script called second-homotopy.gp in the stacks-project subdirectory scripts which can be used to check finitely many instances of this claim. We wrote this script to make sure the signs are correct.) The claim clearly shows that the composition

$$\check{C}_{semi-ord}^\bullet(\mathcal{U}, \mathcal{F}) \longrightarrow \check{C}_{ord}^\bullet(\mathcal{U}, \mathcal{F}) \longrightarrow \check{C}_{semi-ord}^\bullet(\mathcal{U}, \mathcal{F})$$

of the projection with the natural inclusion is homotopic to the identity map as desired. \square

25. Alternative view of the Čech complex

02FR In this section we discuss an alternative way to establish the relationship between the Čech complex and cohomology.

02FU **Lemma 25.1.** *Let X be a ringed space. Let $\mathcal{U} : X = \bigcup_{i \in I} U_i$ be an open covering of X . Let \mathcal{F} be an \mathcal{O}_X -module. Denote $\mathcal{F}_{i_0 \dots i_p}$ the restriction of \mathcal{F} to $U_{i_0 \dots i_p}$. There exists a complex $\mathfrak{C}^\bullet(\mathcal{U}, \mathcal{F})$ of \mathcal{O}_X -modules with*

$$\mathfrak{C}^p(\mathcal{U}, \mathcal{F}) = \prod_{i_0 \dots i_p} (j_{i_0 \dots i_p})_* \mathcal{F}_{i_0 \dots i_p}$$

and differential $d : \mathfrak{C}^p(\mathcal{U}, \mathcal{F}) \rightarrow \mathfrak{C}^{p+1}(\mathcal{U}, \mathcal{F})$ as in Equation (10.0.1). Moreover, there exists a canonical map

$$\mathcal{F} \rightarrow \mathfrak{C}^\bullet(\mathcal{U}, \mathcal{F})$$

which is a quasi-isomorphism, i.e., $\mathfrak{C}^\bullet(\mathcal{U}, \mathcal{F})$ is a resolution of \mathcal{F} .

Proof. We check

$$0 \rightarrow \mathcal{F} \rightarrow \mathfrak{C}^0(\mathcal{U}, \mathcal{F}) \rightarrow \mathfrak{C}^1(\mathcal{U}, \mathcal{F}) \rightarrow \dots$$

is exact on stalks. Let $x \in X$ and choose $i_{\text{fix}} \in I$ such that $x \in U_{i_{\text{fix}}}$. Then define

$$h : \mathfrak{C}^p(\mathcal{U}, \mathcal{F})_x \rightarrow \mathfrak{C}^{p-1}(\mathcal{U}, \mathcal{F})_x$$

as follows: If $s \in \mathfrak{C}^p(\mathcal{U}, \mathcal{F})_x$, take a representative

$$\tilde{s} \in \mathfrak{C}^p(\mathcal{U}, \mathcal{F})(V) = \prod_{i_0 \dots i_p} \mathcal{F}(V \cap U_{i_0} \cap \dots \cap U_{i_p})$$

defined on some neighborhood V of x , and set

$$h(s)_{i_0 \dots i_{p-1}} = \tilde{s}_{i_{\text{fix}} i_0 \dots i_{p-1}, x}.$$

By the same formula (for $p = 0$) we get a map $\mathfrak{C}^0(\mathcal{U}, \mathcal{F})_x \rightarrow \mathcal{F}_x$. We compute formally as follows:

$$\begin{aligned} (dh + hd)(s)_{i_0 \dots i_p} &= \sum_{j=0}^p (-1)^j h(s)_{i_0 \dots \hat{i}_j \dots i_p} + d(s)_{i_{\text{fix}} i_0 \dots i_p} \\ &= \sum_{j=0}^p (-1)^j s_{i_{\text{fix}} i_0 \dots \hat{i}_j \dots i_p} + s_{i_0 \dots i_p} + \sum_{j=0}^p (-1)^{j+1} s_{i_{\text{fix}} i_0 \dots \hat{i}_j \dots i_p} \\ &= s_{i_0 \dots i_p} \end{aligned}$$

This shows h is a homotopy from the identity map of the extended complex

$$0 \rightarrow \mathcal{F}_x \rightarrow \mathfrak{C}^0(\mathcal{U}, \mathcal{F})_x \rightarrow \mathfrak{C}^1(\mathcal{U}, \mathcal{F})_x \rightarrow \dots$$

to zero and we conclude. \square

With this lemma it is easy to reprove the Čech to cohomology spectral sequence of Lemma 12.5. Namely, let $X, \mathcal{U}, \mathcal{F}$ as in Lemma 25.1 and let $\mathcal{F} \rightarrow \mathcal{I}^\bullet$ be an injective resolution. Then we may consider the double complex

$$A^{\bullet, \bullet} = \Gamma(X, \mathfrak{C}^\bullet(\mathcal{U}, \mathcal{I}^\bullet)).$$

By construction we have

$$A^{p, q} = \prod_{i_0 \dots i_p} \mathcal{I}^q(U_{i_0 \dots i_p})$$

Consider the two spectral sequences of Homology, Section 22 associated to this double complex, see especially Homology, Lemma 22.4. For the spectral sequence $({}'E_r, {}'d_r)_{r \geq 0}$ we get $'E_2^{p, q} = \check{H}^p(\mathcal{U}, \underline{H}^q(\mathcal{F}))$ because taking products is exact (Homology, Lemma 28.1). For the spectral sequence $({}''E_r, {}''d_r)_{r \geq 0}$ we get $''E_2^{p, q} = 0$

if $p > 0$ and ${}''E_2^{0,q} = H^q(X, \mathcal{F})$. Namely, for fixed q the complex of sheaves $\mathfrak{C}^\bullet(\mathcal{U}, \mathcal{I}^q)$ is a resolution (Lemma 25.1) of the injective sheaf \mathcal{I}^q by injective sheaves (by Lemmas 8.1 and 12.11 and Homology, Lemma 23.3). Hence the cohomology of $\Gamma(X, \mathfrak{C}^\bullet(\mathcal{U}, \mathcal{I}^q))$ is zero in positive degrees and equal to $\Gamma(X, \mathcal{I}^q)$ in degree 0. Taking cohomology of the next differential we get our claim about the spectral sequence $({}''E_r, {}''d_r)_{r \geq 0}$. Whence the result since both spectral sequences converge to the cohomology of the associated total complex of $A^{\bullet, \bullet}$.

02FS **Definition 25.2.** Let X be a topological space. An open covering $X = \bigcup_{i \in I} U_i$ is said to be *locally finite* if for every $x \in X$ there exists an open neighbourhood W of x such that $\{i \in I \mid W \cap U_i \neq \emptyset\}$ is finite.

02FT **Remark 25.3.** Let $X = \bigcup_{i \in I} U_i$ be a locally finite open covering. Denote $j_i : U_i \rightarrow X$ the inclusion map. Suppose that for each i we are given an abelian sheaf \mathcal{F}_i on U_i . Consider the abelian sheaf $\mathcal{G} = \bigoplus_{i \in I} (j_i)_* \mathcal{F}_i$. Then for $V \subset X$ open we actually have

$$\Gamma(V, \mathcal{G}) = \prod_{i \in I} \mathcal{F}_i(V \cap U_i).$$

In other words we have

$$\bigoplus_{i \in I} (j_i)_* \mathcal{F}_i = \prod_{i \in I} (j_i)_* \mathcal{F}_i$$

This seems strange until you realize that the direct sum of a collection of sheaves is the sheafification of what you think it should be. See discussion in Modules, Section 3. Thus we conclude that in this case the complex of Lemma 25.1 has terms

$$\mathfrak{C}^p(\mathcal{U}, \mathcal{F}) = \bigoplus_{i_0 \dots i_p} (j_{i_0 \dots i_p})_* \mathcal{F}_{i_0 \dots i_p}$$

which is sometimes useful.

26. Čech cohomology of complexes

01FP In general for sheaves of abelian groups \mathcal{F} and \mathcal{G} on X there is a cup product map

$$H^i(X, \mathcal{F}) \times H^j(X, \mathcal{G}) \longrightarrow H^{i+j}(X, \mathcal{F} \otimes_{\mathbf{Z}} \mathcal{G}).$$

In this section we define it using Čech cocycles by an explicit formula for the cup product. If you are worried about the fact that cohomology may not equal Čech cohomology, then you can use hypercoverings and still use the cocycle notation. This also has the advantage that it works to define the cup product for hypercohomology on any topos (insert future reference here).

Let \mathcal{F}^\bullet be a bounded below complex of presheaves of abelian groups on X . We can often compute $H^n(X, \mathcal{F}^\bullet)$ using Čech cocycles. Namely, let $\mathcal{U} : X = \bigcup_{i \in I} U_i$ be an open covering of X . Since the Čech complex $\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F})$ (Definition 10.1) is functorial in the presheaf \mathcal{F} we obtain a double complex $\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}^\bullet)$. The associated total complex to $\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}^\bullet)$ is the complex with degree n term

$$\text{Tot}^n(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}^\bullet)) = \bigoplus_{p+q=n} \prod_{i_0 \dots i_p} \mathcal{F}^q(U_{i_0 \dots i_p})$$

see Homology, Definition 22.3. A typical element in Tot^n will be denoted $\alpha = \{\alpha_{i_0 \dots i_p}\}$ where $\alpha_{i_0 \dots i_p} \in \mathcal{F}^q(U_{i_0 \dots i_p})$. In other words the \mathcal{F} -degree of $\alpha_{i_0 \dots i_p}$ is $q = n - p$. This notation requires us to be aware of the degree α lives in at all times. We indicate this situation by the formula $\text{deg}_{\mathcal{F}}(\alpha_{i_0 \dots i_p}) = q$. According to

our conventions in Homology, Definition 22.3 the differential of an element α of degree n is given by

$$d(\alpha)_{i_0 \dots i_{p+1}} = \sum_{j=0}^{p+1} (-1)^j \alpha_{i_0 \dots \hat{i}_j \dots i_{p+1}} + (-1)^{p+1} d_{\mathcal{F}}(\alpha_{i_0 \dots i_{p+1}})$$

where $d_{\mathcal{F}}$ denotes the differential on the complex \mathcal{F}^\bullet . The expression $\alpha_{i_0 \dots \hat{i}_j \dots i_{p+1}}$ means the restriction of $\alpha_{i_0 \dots \hat{i}_j \dots i_{p+1}} \in \mathcal{F}(U_{i_0 \dots \hat{i}_j \dots i_{p+1}})$ to $U_{i_0 \dots i_{p+1}}$.

The construction of $\text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}^\bullet))$ is functorial in \mathcal{F}^\bullet . As well there is a functorial transformation

$$07M9 \quad (26.0.1) \quad \Gamma(X, \mathcal{F}^\bullet) \longrightarrow \text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}^\bullet))$$

of complexes defined by the following rule: The section $s \in \Gamma(X, \mathcal{F}^n)$ is mapped to the element $\alpha = \{\alpha_{i_0 \dots i_p}\}$ with $\alpha_{i_0} = s|_{U_{i_0}}$ and $\alpha_{i_0 \dots i_p} = 0$ for $p > 0$.

Refinements. Let $\mathcal{V} = \{V_j\}_{j \in J}$ be a refinement of \mathcal{U} . This means there is a map $t : J \rightarrow I$ such that $V_j \subset U_{t(j)}$ for all $j \in J$. This gives rise to a functorial transformation

$$08BM \quad (26.0.2) \quad T_t : \text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}^\bullet)) \longrightarrow \text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{V}, \mathcal{F}^\bullet)).$$

defined by the rule

$$T_t(\alpha)_{j_0 \dots j_p} = \alpha_{t(j_0) \dots t(j_p)}|_{V_{j_0 \dots j_p}}.$$

Given two maps $t, t' : J \rightarrow I$ as above the maps T_t and $T_{t'}$ constructed above are homotopic. The homotopy is given by

$$h(\alpha)_{j_0 \dots j_p} = \sum_{a=0}^p (-1)^a \alpha_{t(j_0) \dots t(j_a) t'(j_a) \dots t'(j_p)}$$

for an element α of degree n . This works because of the following computation, again with α an element of degree n (so $d(\alpha)$ has degree $n+1$ and $h(\alpha)$ has degree $n-1$):

$$\begin{aligned} (d(h(\alpha)) + h(d(\alpha)))_{j_0 \dots j_p} &= \sum_{k=0}^p (-1)^k h(\alpha)_{j_0 \dots \hat{j}_k \dots j_p} + \\ &\quad (-1)^p d_{\mathcal{F}}(h(\alpha)_{j_0 \dots j_p}) + \\ &\quad \sum_{a=0}^p (-1)^a d(\alpha)_{t(j_0) \dots t(j_a) t'(j_a) \dots t'(j_p)} \\ &= \sum_{k=0}^p \sum_{a=0}^{k-1} (-1)^{k+a} \alpha_{t(j_0) \dots t(j_a) t'(j_a) \dots t'(\hat{j}_k) \dots t'(j_p)} + \\ &\quad \sum_{k=0}^p \sum_{a=k+1}^p (-1)^{k+a-1} \alpha_{t(j_0) \dots t(\hat{j}_k) \dots t(j_a) t'(j_a) \dots t'(j_p)} + \\ &\quad \sum_{a=0}^p (-1)^{p+a} d_{\mathcal{F}}(\alpha_{t(j_0) \dots t(j_a) t'(j_a) \dots t'(j_p)}) + \\ &\quad \sum_{a=0}^p \sum_{k=0}^a (-1)^{a+k} \alpha_{t(j_0) \dots t(\hat{j}_k) \dots t(j_a) t'(j_a) \dots t'(j_p)} + \\ &\quad \sum_{a=0}^p \sum_{k=a}^p (-1)^{a+k+1} \alpha_{t(j_0) \dots t(j_a) t'(j_a) \dots t'(\hat{j}_k) \dots t'(j_p)} + \\ &\quad \sum_{a=0}^p (-1)^{a+p+1} d_{\mathcal{F}}(\alpha_{t(j_0) \dots t(j_a) t'(j_a) \dots t'(j_p)}) \\ &= \alpha_{t'(j_0) \dots t'(j_p)} + (-1)^{2p+1} \alpha_{t(j_0) \dots t(j_p)} \\ &= T_{t'}(\alpha)_{j_0 \dots j_p} - T_t(\alpha)_{j_0 \dots j_p} \end{aligned}$$

We leave it to the reader to verify the cancellations. (Note that the terms having both k and a in the 1st, 2nd and 4th, 5th summands cancel, except the ones where

$a = k$ which only occur in the 4th and 5th and these cancel against each other except for the two desired terms.) It follows that the induced map

$$H^n(T_t) : H^n(\text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}^\bullet))) \rightarrow H^n(\text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{V}, \mathcal{F}^\bullet)))$$

is independent of the choice of t . We define *Čech hypercohomology* as the limit of the Čech cohomology groups over all refinements via the maps $H^\bullet(T_t)$.

In the limit (over all open coverings of X) the following lemma provides a map of Čech hypercohomology into cohomology, which is often an isomorphism and is always an isomorphism if we use hypercoverings.

08BN **Lemma 26.1.** *Let (X, \mathcal{O}_X) be a ringed space. Let $\mathcal{U} : X = \bigcup_{i \in I} U_i$ be an open covering. For a bounded below complex \mathcal{F}^\bullet of \mathcal{O}_X -modules there is a canonical map*

$$\text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}^\bullet)) \longrightarrow R\Gamma(X, \mathcal{F}^\bullet)$$

functorial in \mathcal{F}^\bullet and compatible with (26.0.1) and (26.0.2). There is a spectral sequence $(E_r, d_r)_{r \geq 0}$ with

$$E_2^{p,q} = H^p(\text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \underline{H}^q(\mathcal{F}^\bullet))))$$

converging to $H^{p+q}(X, \mathcal{F}^\bullet)$.

Proof. Let \mathcal{I}^\bullet be a bounded below complex of injectives. The map (26.0.1) for \mathcal{I}^\bullet is a map $\Gamma(X, \mathcal{I}^\bullet) \rightarrow \text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{I}^\bullet))$. This is a quasi-isomorphism of complexes of abelian groups as follows from Homology, Lemma 22.7 applied to the double complex $\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{I}^\bullet)$ using Lemma 12.1. Suppose $\mathcal{F}^\bullet \rightarrow \mathcal{I}^\bullet$ is a quasi-isomorphism of \mathcal{F}^\bullet into a bounded below complex of injectives. Since $R\Gamma(X, \mathcal{F}^\bullet)$ is represented by the complex $\Gamma(X, \mathcal{I}^\bullet)$ we obtain the map of the lemma using

$$\text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}^\bullet)) \longrightarrow \text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{I}^\bullet)).$$

We omit the verification of functoriality and compatibilities. To construct the spectral sequence of the lemma, choose a Cartan-Eilenberg resolution $\mathcal{F}^\bullet \rightarrow \mathcal{I}^{\bullet, \bullet}$, see Derived Categories, Lemma 21.2. In this case $\mathcal{F}^\bullet \rightarrow \text{Tot}(\mathcal{I}^{\bullet, \bullet})$ is an injective resolution and hence

$$\text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \text{Tot}(\mathcal{I}^{\bullet, \bullet})))$$

computes $R\Gamma(X, \mathcal{F}^\bullet)$ as we've seen above. By Homology, Remark 22.8 we can view this as the total complex associated to the triple complex $\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{I}^{\bullet, \bullet})$ hence, using the same remark we can view it as the total complex associate to the double complex $A^{\bullet, \bullet}$ with terms

$$A^{n,m} = \bigoplus_{p+q=n} \check{\mathcal{C}}^p(\mathcal{U}, \mathcal{I}^{q,m})$$

Since $\mathcal{I}^{q, \bullet}$ is an injective resolution of \mathcal{F}^q we can apply the first spectral sequence associated to $A^{\bullet, \bullet}$ (Homology, Lemma 22.4) to get a spectral sequence with

$$E_1^{n,m} = \bigoplus_{p+q=n} \check{\mathcal{C}}^p(\mathcal{U}, \underline{H}^m(\mathcal{F}^q))$$

which is the n th term of the complex $\text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \underline{H}^\bullet(\mathcal{F}^\bullet)))$. Hence we obtain E_2 terms as described in the lemma. Convergence by Homology, Lemma 22.6. \square

Let X be a topological space, let $\mathcal{U} : X = \bigcup_{i \in I} U_i$ be an open covering, and let \mathcal{F}^\bullet be a bounded below complex of presheaves of abelian groups. Consider the map $\tau : \text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}^\bullet)) \rightarrow \text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}^\bullet))$ defined by

$$\tau(\alpha)_{i_0 \dots i_p} = (-1)^{p(p+1)/2} \alpha_{i_p \dots i_0}.$$

Then we have for an element α of degree n that

$$\begin{aligned} & d(\tau(\alpha))_{i_0 \dots i_{p+1}} \\ &= \sum_{j=0}^{p+1} (-1)^j \tau(\alpha)_{i_0 \dots \hat{i}_j \dots i_{p+1}} + (-1)^{p+1} d_{\mathcal{F}}(\tau(\alpha))_{i_0 \dots i_{p+1}} \\ &= \sum_{j=0}^{p+1} (-1)^{j + \frac{p(p+1)}{2}} \alpha_{i_{p+1} \dots \hat{i}_j \dots i_0} + (-1)^{p+1 + \frac{(p+1)(p+2)}{2}} d_{\mathcal{F}}(\alpha_{i_{p+1} \dots i_0}) \end{aligned}$$

On the other hand we have

$$\begin{aligned} & \tau(d(\alpha))_{i_0 \dots i_{p+1}} \\ &= (-1)^{\frac{(p+1)(p+2)}{2}} d(\alpha)_{i_{p+1} \dots i_0} \\ &= (-1)^{\frac{(p+1)(p+2)}{2}} \left(\sum_{j=0}^{p+1} (-1)^j \alpha_{i_{p+1} \dots \hat{i}_{p+1-j} \dots i_0} + (-1)^{p+1} d_{\mathcal{F}}(\alpha_{i_{p+1} \dots i_0}) \right) \end{aligned}$$

Thus we conclude that $d(\tau(\alpha)) = \tau(d(\alpha))$ because $p(p+1)/2 \equiv (p+1)(p+2)/2 + p + 1 \pmod{2}$. In other words τ is an endomorphism of the complex $\text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}^\bullet))$. Note that the diagram

$$\begin{array}{ccc} \Gamma(X, \mathcal{F}^\bullet) & \longrightarrow & \text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}^\bullet)) \\ \downarrow \text{id} & & \downarrow \tau \\ \Gamma(X, \mathcal{F}^\bullet) & \longrightarrow & \text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}^\bullet)) \end{array}$$

commutes. In addition τ is clearly compatible with refinements. This suggests that τ acts as the identity on Čech cohomology (i.e., in the limit – provided Čech hypercohomology agrees with hypercohomology, which is always the case if we use hypercoverings). We claim that τ actually is homotopic to the identity on the total Čech complex $\text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}^\bullet))$. To prove this, we use as homotopy

$$h(\alpha)_{i_0 \dots i_p} = \sum_{a=0}^p \epsilon_p(a) \alpha_{i_0 \dots i_a i_p \dots i_a} \quad \text{with} \quad \epsilon_p(a) = (-1)^{\frac{(p-a)(p-a-1)}{2} + p}$$

for α of degree n . As usual we omit writing $|U_{i_0 \dots i_p}$. This works because of the following computation, again with α an element of degree n :

$$\begin{aligned} (d(h(\alpha)) + h(d(\alpha)))_{i_0 \dots i_p} &= \sum_{k=0}^p (-1)^k h(\alpha)_{i_0 \dots \hat{i}_k \dots i_p} + \\ & \quad (-1)^p d_{\mathcal{F}}(h(\alpha)_{i_0 \dots i_p}) + \\ & \quad \sum_{a=0}^p \epsilon_p(a) d(\alpha)_{i_0 \dots i_a i_p \dots i_a} \\ &= \sum_{k=0}^p \sum_{a=0}^{k-1} (-1)^k \epsilon_{p-1}(a) \alpha_{i_0 \dots i_a i_p \dots \hat{i}_k \dots i_a} + \\ & \quad \sum_{k=0}^p \sum_{a=k+1}^p (-1)^k \epsilon_{p-1}(a-1) \alpha_{i_0 \dots \hat{i}_k \dots i_a i_p \dots i_a} + \\ & \quad \sum_{a=0}^p (-1)^p \epsilon_p(a) d_{\mathcal{F}}(\alpha_{i_0 \dots i_a i_p \dots i_a}) + \\ & \quad \sum_{a=0}^p \sum_{k=0}^a \epsilon_p(a) (-1)^k \alpha_{i_0 \dots \hat{i}_k \dots i_a i_p \dots i_a} + \\ & \quad \sum_{a=0}^p \sum_{k=a}^p \epsilon_p(a) (-1)^{p+a+1-k} \alpha_{i_0 \dots i_a i_p \dots \hat{i}_k \dots i_a} + \\ & \quad \sum_{a=0}^p \epsilon_p(a) (-1)^{p+1} d_{\mathcal{F}}(\alpha_{i_0 \dots i_a i_p \dots i_a}) \\ &= \epsilon_p(0) \alpha_{i_p \dots i_0} + \epsilon_p(p) (-1)^{p+1} \alpha_{i_0 \dots i_p} \\ &= (-1)^{\frac{p(p+1)}{2}} \alpha_{i_p \dots i_0} - \alpha_{i_0 \dots i_p} \end{aligned}$$

The cancellations follow because

$$(-1)^k \epsilon_{p-1}(a) + \epsilon_p(a)(-1)^{p+a+1-k} = 0 \quad \text{and} \quad (-1)^k \epsilon_{p-1}(a-1) + \epsilon_p(a)(-1)^k = 0$$

We leave it to the reader to verify the cancellations.

Suppose we have two bounded below complexes of abelian sheaves \mathcal{F}^\bullet and \mathcal{G}^\bullet . We define the complex $\text{Tot}(\mathcal{F}^\bullet \otimes_{\mathbf{Z}} \mathcal{G}^\bullet)$ to be the complex with terms $\bigoplus_{p+q=n} \mathcal{F}^p \otimes \mathcal{G}^q$ and differential according to the rule

$$07\text{MA} \quad (26.1.1) \quad d(\alpha \otimes \beta) = d(\alpha) \otimes \beta + (-1)^{\deg(\alpha)} \alpha \otimes d(\beta)$$

when α and β are homogeneous, see Homology, Definition 22.3.

Suppose that M^\bullet and N^\bullet are two bounded below complexes of abelian groups. Then if m , resp. n is a cocycle for M^\bullet , resp. N^\bullet , it is immediate that $m \otimes n$ is a cocycle for $\text{Tot}(M^\bullet \otimes N^\bullet)$. Hence a cup product

$$H^i(M^\bullet) \times H^j(N^\bullet) \longrightarrow H^{i+j}(\text{Tot}(M^\bullet \otimes N^\bullet)).$$

This is discussed also in More on Algebra, Section 59.

So the construction of the cup product in hypercohomology of complexes rests on a construction of a map of complexes

$$07\text{MB} \quad (26.1.2) \quad \text{Tot}(\text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}^\bullet)) \otimes_{\mathbf{Z}} \text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{G}^\bullet))) \longrightarrow \text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \text{Tot}(\mathcal{F}^\bullet \otimes \mathcal{G}^\bullet)))$$

This map is denoted \cup and is given by the rule

$$(\alpha \cup \beta)_{i_0 \dots i_p} = \sum_{r=0}^p \epsilon(n, m, p, r) \alpha_{i_0 \dots i_r} \otimes \beta_{i_r \dots i_p}.$$

where α has degree n and β has degree m and with

$$\epsilon(n, m, p, r) = (-1)^{(p+r)n+rp+r}.$$

Note that $\epsilon(n, m, p, n) = 1$. Hence if $\mathcal{F}^\bullet = \mathcal{F}[0]$ is the complex consisting in a single abelian sheaf \mathcal{F} placed in degree 0, then there no signs in the formula for \cup (as in that case $\alpha_{i_0 \dots i_r} = 0$ unless $r = n$). For an explanation of why there has to be a sign and how to compute it see [AGV71, Exposee XVII] by Deligne. To check (26.1.2) is a map of complexes we have to show that

$$d(\alpha \cup \beta) = d(\alpha) \cup \beta + (-1)^{\deg(\alpha)} \alpha \cup d(\beta)$$

by the definition of the differential on $\text{Tot}(\text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}^\bullet)) \otimes_{\mathbf{Z}} \text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{G}^\bullet)))$ as given in Homology, Definition 22.3. We compute first

$$\begin{aligned} d(\alpha \cup \beta)_{i_0 \dots i_{p+1}} &= \sum_{j=0}^{p+1} (-1)^j (\alpha \cup \beta)_{i_0 \dots \hat{i}_j \dots i_{p+1}} + (-1)^{p+1} d_{\mathcal{F} \otimes \mathcal{G}}((\alpha \cup \beta)_{i_0 \dots i_{p+1}}) \\ &= \sum_{j=0}^{p+1} \sum_{r=0}^{j-1} (-1)^j \epsilon(n, m, p, r) \alpha_{i_0 \dots i_r} \otimes \beta_{i_r \dots \hat{i}_j \dots i_{p+1}} + \\ &\quad \sum_{j=0}^{p+1} \sum_{r=j+1}^{p+1} (-1)^j \epsilon(n, m, p, r-1) \alpha_{i_0 \dots \hat{i}_j \dots i_r} \otimes \beta_{i_r \dots i_{p+1}} + \\ &\quad \sum_{r=0}^{p+1} (-1)^{p+1} \epsilon(n, m, p+1, r) d_{\mathcal{F} \otimes \mathcal{G}}(\alpha_{i_0 \dots i_r} \otimes \beta_{i_r \dots i_{p+1}}) \end{aligned}$$

and note that the summands in the last term equal

$$(-1)^{p+1} \epsilon(n, m, p+1, r) (d_{\mathcal{F}}(\alpha_{i_0 \dots i_r}) \otimes \beta_{i_r \dots i_{p+1}} + (-1)^{n-r} \alpha_{i_0 \dots i_r} \otimes d_{\mathcal{G}}(\beta_{i_r \dots i_{p+1}})).$$

because $\deg_{\mathcal{F}}(\alpha_{i_0 \dots i_r}) = n - r$. On the other hand

$$\begin{aligned} (d(\alpha) \cup \beta)_{i_0 \dots i_{p+1}} &= \sum_{r=0}^{p+1} \epsilon(n+1, m, p+1, r) d(\alpha)_{i_0 \dots i_r} \otimes \beta_{i_r \dots i_{p+1}} \\ &= \sum_{r=0}^{p+1} \sum_{j=0}^r \epsilon(n+1, m, p+1, r) (-1)^j \alpha_{i_0 \dots \hat{i}_j \dots i_r} \otimes \beta_{i_r \dots i_{p+1}} + \\ &\quad \sum_{r=0}^{p+1} \epsilon(n+1, m, p+1, r) (-1)^r d_{\mathcal{F}}(\alpha_{i_0 \dots i_r}) \otimes \beta_{i_r \dots i_{p+1}} \end{aligned}$$

and

$$\begin{aligned} (\alpha \cup d(\beta))_{i_0 \dots i_{p+1}} &= \sum_{r=0}^{p+1} \epsilon(n, m+1, p+1, r) \alpha_{i_0 \dots i_r} \otimes d(\beta)_{i_r \dots i_{p+1}} \\ &= \sum_{r=0}^{p+1} \sum_{j=r}^{p+1} \epsilon(n, m+1, p+1, r) (-1)^{j-r} \alpha_{i_0 \dots i_r} \otimes \beta_{i_r \dots \hat{i}_j \dots i_{p+1}} + \\ &\quad \sum_{r=0}^{p+1} \epsilon(n, m+1, p+1, r) (-1)^{p+1-r} \alpha_{i_0 \dots i_r} \otimes d_{\mathcal{G}}(\beta_{i_r \dots i_{p+1}}) \end{aligned}$$

The desired equality holds if we have

$$\begin{aligned} (-1)^{p+1} \epsilon(n, m, p+1, r) &= \epsilon(n+1, m, p+1, r) (-1)^r \\ (-1)^{p+1} \epsilon(n, m, p+1, r) (-1)^{n-r} &= (-1)^n \epsilon(n, m+1, p+1, r) (-1)^{p+1-r} \\ \epsilon(n+1, m, p+1, r) (-1)^r &= (-1)^{1+n} \epsilon(n, m+1, p+1, r-1) \\ (-1)^j \epsilon(n, m, p, r) &= (-1)^n \epsilon(n, m+1, p+1, r) (-1)^{j-r} \\ (-1)^j \epsilon(n, m, p, r-1) &= \epsilon(n+1, m, p+1, r) (-1)^j \end{aligned}$$

(The third equality is necessary to get the terms with $r = j$ from $d(\alpha) \cup \beta$ and $(-1)^n \alpha \cup d(\beta)$ to cancel each other.) We leave the verifications to the reader. (Alternatively, check the script signs.gp in the scripts subdirectory of the Stacks project.)

Associativity of the cup product. Suppose that \mathcal{F}^\bullet , \mathcal{G}^\bullet and \mathcal{H}^\bullet are bounded below complexes of abelian groups on X . The obvious map (without the intervention of signs) is an isomorphism of complexes

$$\text{Tot}(\text{Tot}(\mathcal{F}^\bullet \otimes_{\mathbf{Z}} \mathcal{G}^\bullet) \otimes_{\mathbf{Z}} \mathcal{H}^\bullet) \longrightarrow \text{Tot}(\mathcal{F}^\bullet \otimes_{\mathbf{Z}} \text{Tot}(\mathcal{G}^\bullet \otimes_{\mathbf{Z}} \mathcal{H}^\bullet)).$$

Another way to say this is that the triple complex $\mathcal{F}^\bullet \otimes_{\mathbf{Z}} \mathcal{G}^\bullet \otimes_{\mathbf{Z}} \mathcal{H}^\bullet$ gives rise to a well defined total complex with differential satisfying

$$d(\alpha \otimes \beta \otimes \gamma) = d(\alpha) \otimes \beta \otimes \gamma + (-1)^{\deg(\alpha)} \alpha \otimes d(\beta) \otimes \gamma + (-1)^{\deg(\alpha) + \deg(\beta)} \alpha \otimes \beta \otimes d(\gamma)$$

for homogeneous elements. Using this map it is easy to verify that

$$(\alpha \cup \beta) \cup \gamma = \alpha \cup (\beta \cup \gamma)$$

namely, if α has degree a , β has degree b and γ has degree c , then

$$\begin{aligned} ((\alpha \cup \beta) \cup \gamma)_{i_0 \dots i_p} &= \sum_{r=0}^p \epsilon(a+b, c, p, r) (\alpha \cup \beta)_{i_0 \dots i_r} \otimes \gamma_{i_r \dots i_p} \\ &= \sum_{r=0}^p \sum_{s=0}^r \epsilon(a+b, c, p, r) \epsilon(a, b, r, s) \alpha_{i_0 \dots i_s} \otimes \beta_{i_s \dots i_r} \otimes \gamma_{i_r \dots i_p} \end{aligned}$$

and

$$\begin{aligned} (\alpha \cup (\beta \cup \gamma))_{i_0 \dots i_p} &= \sum_{s=0}^p \epsilon(a, b+c, p, s) \alpha_{i_0 \dots i_s} \otimes (\beta \cup \gamma)_{i_s \dots i_p} \\ &= \sum_{s=0}^p \sum_{r=s}^p \epsilon(a, b+c, p, s) \epsilon(b, c, p-s, r-s) \alpha_{i_0 \dots i_s} \otimes \beta_{i_s \dots i_r} \otimes \gamma_{i_r \dots i_p} \end{aligned}$$

and a trivial mod 2 calculation shows the signs match up. (Alternatively, check the script signs.gp in the scripts subdirectory of the Stacks project.)

Finally, we indicate why the cup product preserves a graded commutative structure, at least on a cohomological level. For this we use the operator τ introduced above. Let \mathcal{F}^\bullet be a bounded below complexes of abelian groups, and assume we are given a graded commutative multiplication

$$\wedge^\bullet : \text{Tot}(\mathcal{F}^\bullet \otimes \mathcal{F}^\bullet) \longrightarrow \mathcal{F}^\bullet.$$

This means the following: For s a local section of \mathcal{F}^a , and t a local section of \mathcal{F}^b we have $s \wedge t$ a local section of \mathcal{F}^{a+b} . Graded commutative means we have $s \wedge t = (-1)^{ab} t \wedge s$. Since \wedge is a map of complexes we have $d(s \wedge t) = d(s) \wedge t + (-1)^a s \wedge d(t)$. The composition

$$\text{Tot}(\text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}^\bullet)) \otimes \text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}^\bullet))) \rightarrow \text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \text{Tot}(\mathcal{F}^\bullet \otimes_{\mathbf{Z}} \mathcal{F}^\bullet))) \rightarrow \text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}^\bullet))$$

induces a cup product on cohomology

$$H^n(\text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}^\bullet))) \times H^m(\text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}^\bullet))) \longrightarrow H^{n+m}(\text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}^\bullet)))$$

and so in the limit also a product on Čech cohomology and therefore (using hypercoverings if needed) a product in cohomology of \mathcal{F}^\bullet . We claim this product (on cohomology) is graded commutative as well. To prove this we first consider an element α of degree n in $\text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}^\bullet))$ and an element β of degree m in $\text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}^\bullet))$ and we compute

$$\begin{aligned} \wedge^\bullet(\alpha \cup \beta)_{i_0 \dots i_p} &= \sum_{r=0}^p \epsilon(n, m, p, r) \alpha_{i_0 \dots i_r} \wedge \beta_{i_r \dots i_p} \\ &= \sum_{r=0}^p \epsilon(n, m, p, r) (-1)^{\deg(\alpha_{i_0 \dots i_r}) \deg(\beta_{i_r \dots i_p})} \beta_{i_r \dots i_p} \wedge \alpha_{i_0 \dots i_r} \end{aligned}$$

because \wedge is graded commutative. On the other hand we have

$$\begin{aligned} \tau(\wedge^\bullet(\tau(\beta) \cup \tau(\alpha)))_{i_0 \dots i_p} &= \chi(p) \sum_{r=0}^p \epsilon(m, n, p, r) \tau(\beta)_{i_p \dots i_{p-r}} \wedge \tau(\alpha)_{i_{p-r} \dots i_0} \\ &= \chi(p) \sum_{r=0}^p \epsilon(m, n, p, r) \chi(r) \chi(p-r) \beta_{i_p \dots i_{p-r}} \wedge \alpha_{i_0 \dots i_{p-r}} \\ &= \chi(p) \sum_{r=0}^p \epsilon(m, n, p, p-r) \chi(r) \chi(p-r) \beta_{i_r \dots i_p} \wedge \alpha_{i_0 \dots i_r} \end{aligned}$$

where $\chi(t) = (-1)^{\frac{t(t+1)}{2}}$. Since we proved earlier that τ acts as the identity on cohomology we have to verify that

$$\epsilon(n, m, p, r) (-1)^{(n-r)(m-(p-r))} = (-1)^{nm} \chi(p) \epsilon(m, n, p, p-r) \chi(r) \chi(p-r)$$

A trivial mod 2 calculation shows these signs match up. (Alternatively, check the script signs.gp in the scripts subdirectory of the Stacks project.)

Finally, we study the compatibility of cup product with boundary maps. Suppose that

$$0 \rightarrow \mathcal{F}_1^\bullet \rightarrow \mathcal{F}_2^\bullet \rightarrow \mathcal{F}_3^\bullet \rightarrow 0 \quad \text{and} \quad 0 \leftarrow \mathcal{G}_1^\bullet \leftarrow \mathcal{G}_2^\bullet \leftarrow \mathcal{G}_3^\bullet \leftarrow 0$$

are short exact sequences of bounded below complexes of abelian sheaves on X . Let \mathcal{H}^\bullet be another bounded below complex of abelian sheaves, and suppose we have maps of complexes

$$\gamma_i : \text{Tot}(\mathcal{F}_i^\bullet \otimes_{\mathbf{Z}} \mathcal{G}_i^\bullet) \longrightarrow \mathcal{H}^\bullet$$

which are compatible with the maps between the complexes, namely such that the diagrams

$$\begin{array}{ccc} \mathrm{Tot}(\mathcal{F}_1^\bullet \otimes_{\mathbf{Z}} \mathcal{G}_1^\bullet) & \longleftarrow & \mathrm{Tot}(\mathcal{F}_1^\bullet \otimes_{\mathbf{Z}} \mathcal{G}_2^\bullet) \\ \gamma_1 \downarrow & & \downarrow \\ \mathcal{H}^\bullet & \xleftarrow{\gamma_2} & \mathrm{Tot}(\mathcal{F}_2^\bullet \otimes_{\mathbf{Z}} \mathcal{G}_2^\bullet) \end{array}$$

and

$$\begin{array}{ccc} \mathrm{Tot}(\mathcal{F}_2^\bullet \otimes_{\mathbf{Z}} \mathcal{G}_2^\bullet) & \longleftarrow & \mathrm{Tot}(\mathcal{F}_2^\bullet \otimes_{\mathbf{Z}} \mathcal{G}_3^\bullet) \\ \gamma_2 \downarrow & & \downarrow \\ \mathcal{H}^\bullet & \xleftarrow{\gamma_3} & \mathrm{Tot}(\mathcal{F}_3^\bullet \otimes_{\mathbf{Z}} \mathcal{G}_3^\bullet) \end{array}$$

are commutative.

07MC **Lemma 26.2.** *In the situation above, assume Čech cohomology agrees with cohomology for the sheaves \mathcal{F}_i^p and \mathcal{G}_j^q . Let $a_3 \in H^n(X, \mathcal{F}_3^\bullet)$ and $b_1 \in H^m(X, \mathcal{G}_1^\bullet)$. Then we have*

$$\gamma_1(\partial a_3 \cup b_1) = (-1)^{n+1} \gamma_3(a_3 \cup \partial b_1)$$

in $H^{n+m}(X, \mathcal{H}^\bullet)$ where ∂ indicates the boundary map on cohomology associated to the short exact sequences of complexes above.

Proof. We will use the following conventions and notation. We think of \mathcal{F}_1^p as a subsheaf of \mathcal{F}_2^p and we think of \mathcal{G}_3^q as a subsheaf of \mathcal{G}_2^q . Hence if s is a local section of \mathcal{F}_1^p we use s to denote the corresponding section of \mathcal{F}_2^p as well. Similarly for local sections of \mathcal{G}_3^q . Furthermore, if s is a local section of \mathcal{F}_2^p then we denote \bar{s} its image in \mathcal{F}_3^p . Similarly for the map $\mathcal{G}_2^q \rightarrow \mathcal{G}_3^q$. In particular if s is a local section of \mathcal{F}_2^p and $\bar{s} = 0$ then s is a local section of \mathcal{F}_1^p . The commutativity of the diagrams above implies, for local sections s of \mathcal{F}_2^p and t of \mathcal{G}_3^q that $\gamma_2(s \otimes t) = \gamma_3(\bar{s} \otimes t)$ as sections of \mathcal{H}^{p+q} .

Let $\mathcal{U} : X = \bigcup_{i \in I} U_i$ be an open covering of X . Suppose that α_3 , resp. β_1 is a degree n , resp. m cocycle of $\mathrm{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}_3^\bullet))$, resp. $\mathrm{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{G}_1^\bullet))$ representing a_3 , resp. b_1 . After refining \mathcal{U} if necessary, we can find cochains α_2 , resp. β_2 of degree n , resp. m in $\mathrm{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}_2^\bullet))$, resp. $\mathrm{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{G}_2^\bullet))$ mapping to α_3 , resp. β_1 . Then we see that

$$\overline{d(\alpha_2)} = d(\bar{\alpha}_2) = 0 \quad \text{and} \quad \overline{d(\beta_2)} = d(\bar{\beta}_2) = 0.$$

This means that $\alpha_1 = d(\alpha_2)$ is a degree $n+1$ cocycle in $\mathrm{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}_1^\bullet))$ representing ∂a_3 . Similarly, $\beta_3 = d(\beta_2)$ is a degree $m+1$ cocycle in $\mathrm{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{G}_3^\bullet))$ representing ∂b_1 . Thus we may compute

$$\begin{aligned} d(\gamma_2(\alpha_2 \cup \beta_2)) &= \gamma_2(d(\alpha_2 \cup \beta_2)) \\ &= \gamma_2(d(\alpha_2) \cup \beta_2 + (-1)^n \alpha_2 \cup d(\beta_2)) \\ &= \gamma_2(\alpha_1 \cup \beta_2) + (-1)^n \gamma_2(\alpha_2 \cup \beta_3) \\ &= \gamma_1(\alpha_1 \cup \beta_1) + (-1)^n \gamma_3(\alpha_3 \cup \beta_3) \end{aligned}$$

So this even tells us that the sign is $(-1)^{n+1}$ as indicated in the lemma². \square

²The sign depends on the convention for the signs in the long exact sequence in cohomology associated to a triangle in $D(X)$. The conventions in the Stacks project are (a) distinguished triangles correspond to termwise split exact sequences and (b) the boundary maps in the long

0B8S **Lemma 26.3.** *Let X be a topological space. Let $\mathcal{O}' \rightarrow \mathcal{O}$ be a surjection of sheaves of rings whose kernel $\mathcal{I} \subset \mathcal{O}'$ has square zero. Then $M = H^1(X, \mathcal{I})$ is a $R = H^0(X, \mathcal{O})$ -module and the boundary map $\partial : R \rightarrow M$ associated to the short exact sequence*

$$0 \rightarrow \mathcal{I} \rightarrow \mathcal{O}' \rightarrow \mathcal{O} \rightarrow 0$$

is a derivation (Algebra, Definition 130.1).

Proof. The map $\mathcal{O}' \rightarrow \mathcal{H}om(\mathcal{I}, \mathcal{I})$ factors through \mathcal{O} as $\mathcal{I} \cdot \mathcal{I} = 0$ by assumption. Hence \mathcal{I} is a sheaf of \mathcal{O} -modules and this defines the R -module structure on M . The boundary map is additive hence it suffices to prove the Leibniz rule. Let $f \in R$. Choose an open covering $\mathcal{U} : X = \bigcup U_i$ such that there exist $f_i \in \mathcal{O}'(U_i)$ lifting $f|_{U_i} \in \mathcal{O}(U_i)$. Observe that $f_i - f_j$ is an element of $\mathcal{I}(U_i \cap U_j)$. Then $\partial(f)$ corresponds to the Čech cohomology class of the 1-cocycle α with $\alpha_{i_0 i_1} = f_{i_0} - f_{i_1}$. (Observe that by Lemma 12.3 the first Čech cohomology group with respect to \mathcal{U} is a submodule of M .) Next, let $g \in R$ be a second element and assume (after possibly refining the open covering) that $g_i \in \mathcal{O}'(U_i)$ lifts $g|_{U_i} \in \mathcal{O}(U_i)$. Then we see that $\partial(g)$ is given by the cocycle β with $\beta_{i_0 i_1} = g_{i_0} - g_{i_1}$. Since $f_i g_i \in \mathcal{O}'(U_i)$ lifts $fg|_{U_i}$ we see that $\partial(fg)$ is given by the cocycle γ with

$$\gamma_{i_0 i_1} = f_{i_0} g_{i_0} - f_{i_1} g_{i_1} = (f_{i_0} - f_{i_1}) g_{i_0} + f_{i_1} (g_{i_0} - g_{i_1}) = \alpha_{i_0 i_1} g + f \beta_{i_0 i_1}$$

by our definition of the \mathcal{O} -module structure on \mathcal{I} . This proves the Leibniz rule and the proof is complete. \square

27. Flat resolutions

06Y7 A reference for the material in this section is [Spa88]. Let (X, \mathcal{O}_X) be a ringed space. By Modules, Lemma 16.6 any \mathcal{O}_X -module is a quotient of a flat \mathcal{O}_X -module. By Derived Categories, Lemma 16.5 any bounded above complex of \mathcal{O}_X -modules has a left resolution by a bounded above complex of flat \mathcal{O}_X -modules. However, for unbounded complexes, it turns out that flat resolutions aren't good enough.

06Y8 **Lemma 27.1.** *Let (X, \mathcal{O}_X) be a ringed space. Let \mathcal{G}^\bullet be a complex of \mathcal{O}_X -modules. The functor*

$$K(\text{Mod}(\mathcal{O}_X)) \longrightarrow K(\text{Mod}(\mathcal{O}_X)), \quad \mathcal{F}^\bullet \longmapsto \text{Tot}(\mathcal{F}^\bullet \otimes_{\mathcal{O}_X} \mathcal{G}^\bullet)$$

is an exact functor of triangulated categories.

Proof. Omitted. Hint: See More on Algebra, Lemmas 55.1 and 55.2. \square

06Y9 **Definition 27.2.** Let (X, \mathcal{O}_X) be a ringed space. A complex \mathcal{K}^\bullet of \mathcal{O}_X -modules is called *K-flat* if for every acyclic complex \mathcal{F}^\bullet of \mathcal{O}_X -modules the complex

$$\text{Tot}(\mathcal{F}^\bullet \otimes_{\mathcal{O}_X} \mathcal{K}^\bullet)$$

is acyclic.

06YA **Lemma 27.3.** *Let (X, \mathcal{O}_X) be a ringed space. Let \mathcal{K}^\bullet be a K-flat complex. Then the functor*

$$K(\text{Mod}(\mathcal{O}_X)) \longrightarrow K(\text{Mod}(\mathcal{O}_X)), \quad \mathcal{F}^\bullet \longmapsto \text{Tot}(\mathcal{F}^\bullet \otimes_{\mathcal{O}_X} \mathcal{K}^\bullet)$$

transforms quasi-isomorphisms into quasi-isomorphisms.

exact sequence are given by the maps in the snake lemma without the intervention of signs. See Derived Categories, Section 10.

Proof. Follows from Lemma 27.1 and the fact that quasi-isomorphisms are characterized by having acyclic cones. \square

06YB **Lemma 27.4.** *Let (X, \mathcal{O}_X) be a ringed space. Let \mathcal{K}^\bullet be a complex of \mathcal{O}_X -modules. Then \mathcal{K}^\bullet is K-flat if and only if for all $x \in X$ the complex \mathcal{K}_x^\bullet of $\mathcal{O}_{X,x}$ -modules is K-flat (More on Algebra, Definition 55.3).*

Proof. If \mathcal{K}_x^\bullet is K-flat for all $x \in X$ then we see that \mathcal{K}^\bullet is K-flat because \otimes and direct sums commute with taking stalks and because we can check exactness at stalks, see Modules, Lemma 3.1. Conversely, assume \mathcal{K}^\bullet is K-flat. Pick $x \in X$. Let M^\bullet be an acyclic complex of $\mathcal{O}_{X,x}$ -modules. Then $i_{x,*}M^\bullet$ is an acyclic complex of \mathcal{O}_X -modules. Thus $\text{Tot}(i_{x,*}M^\bullet \otimes_{\mathcal{O}_X} \mathcal{K}^\bullet)$ is acyclic. Taking stalks at x shows that $\text{Tot}(M^\bullet \otimes_{\mathcal{O}_{X,x}} \mathcal{K}_x^\bullet)$ is acyclic. \square

079R **Lemma 27.5.** *Let (X, \mathcal{O}_X) be a ringed space. If $\mathcal{K}^\bullet, \mathcal{L}^\bullet$ are K-flat complexes of \mathcal{O}_X -modules, then $\text{Tot}(\mathcal{K}^\bullet \otimes_{\mathcal{O}_X} \mathcal{L}^\bullet)$ is a K-flat complex of \mathcal{O}_X -modules.*

Proof. Follows from the isomorphism

$$\text{Tot}(\mathcal{M}^\bullet \otimes_{\mathcal{O}_X} \text{Tot}(\mathcal{K}^\bullet \otimes_{\mathcal{O}_X} \mathcal{L}^\bullet)) = \text{Tot}(\text{Tot}(\mathcal{M}^\bullet \otimes_{\mathcal{O}_X} \mathcal{K}^\bullet) \otimes_{\mathcal{O}_X} \mathcal{L}^\bullet)$$

and the definition. \square

079S **Lemma 27.6.** *Let (X, \mathcal{O}_X) be a ringed space. Let $(\mathcal{K}_1^\bullet, \mathcal{K}_2^\bullet, \mathcal{K}_3^\bullet)$ be a distinguished triangle in $K(\text{Mod}(\mathcal{O}_X))$. If two out of three of \mathcal{K}_i^\bullet are K-flat, so is the third.*

Proof. Follows from Lemma 27.1 and the fact that in a distinguished triangle in $K(\text{Mod}(\mathcal{O}_X))$ if two out of three are acyclic, so is the third. \square

06YC **Lemma 27.7.** *Let $f : (X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$ be a morphism of ringed spaces. The pullback of a K-flat complex of \mathcal{O}_Y -modules is a K-flat complex of \mathcal{O}_X -modules.*

Proof. We can check this on stalks, see Lemma 27.4. Hence this follows from Sheaves, Lemma 26.4 and More on Algebra, Lemma 55.5. \square

06YD **Lemma 27.8.** *Let (X, \mathcal{O}_X) be a ringed space. A bounded above complex of flat \mathcal{O}_X -modules is K-flat.*

Proof. We can check this on stalks, see Lemma 27.4. Thus this lemma follows from Modules, Lemma 16.2 and More on Algebra, Lemma 55.9. \square

In the following lemma by a colimit of a system of complexes we mean the termwise colimit.

06YE **Lemma 27.9.** *Let (X, \mathcal{O}_X) be a ringed space. Let $\mathcal{K}_1^\bullet \rightarrow \mathcal{K}_2^\bullet \rightarrow \dots$ be a system of K-flat complexes. Then $\text{colim}_i \mathcal{K}_i^\bullet$ is K-flat.*

Proof. Because we are taking termwise colimits it is clear that

$$\text{colim}_i \text{Tot}(\mathcal{F}^\bullet \otimes_{\mathcal{O}_X} \mathcal{K}_i^\bullet) = \text{Tot}(\mathcal{F}^\bullet \otimes_{\mathcal{O}_X} \text{colim}_i \mathcal{K}_i^\bullet)$$

Hence the lemma follows from the fact that filtered colimits are exact. \square

079T **Lemma 27.10.** *Let (X, \mathcal{O}_X) be a ringed space. For any complex \mathcal{G}^\bullet of \mathcal{O}_X -modules there exists a commutative diagram of complexes of \mathcal{O}_X -modules*

$$\begin{array}{ccccccc} \mathcal{K}_1^\bullet & \longrightarrow & \mathcal{K}_2^\bullet & \longrightarrow & \dots & & \\ \downarrow & & \downarrow & & & & \\ \tau_{\leq 1} \mathcal{G}^\bullet & \longrightarrow & \tau_{\leq 2} \mathcal{G}^\bullet & \longrightarrow & \dots & & \end{array}$$

with the following properties: (1) the vertical arrows are quasi-isomorphisms, (2) each \mathcal{K}_n^\bullet is a bounded above complex whose terms are direct sums of \mathcal{O}_X -modules of the form $j_{U!} \mathcal{O}_U$, and (3) the maps $\mathcal{K}_n^\bullet \rightarrow \mathcal{K}_{n+1}^\bullet$ are termwise split injections whose cokernels are direct sums of \mathcal{O}_X -modules of the form $j_{U!} \mathcal{O}_U$. Moreover, the map $\text{colim } \mathcal{K}_n^\bullet \rightarrow \mathcal{G}^\bullet$ is a quasi-isomorphism.

Proof. The existence of the diagram and properties (1), (2), (3) follows immediately from Modules, Lemma 16.6 and Derived Categories, Lemma 28.1. The induced map $\text{colim } \mathcal{K}_n^\bullet \rightarrow \mathcal{G}^\bullet$ is a quasi-isomorphism because filtered colimits are exact. \square

06YF **Lemma 27.11.** *Let (X, \mathcal{O}_X) be a ringed space. For any complex \mathcal{G}^\bullet there exists a K-flat complex \mathcal{K}^\bullet and a quasi-isomorphism $\mathcal{K}^\bullet \rightarrow \mathcal{G}^\bullet$.*

Proof. Choose a diagram as in Lemma 27.10. Each complex \mathcal{K}_n^\bullet is a bounded above complex of flat modules, see Modules, Lemma 16.5. Hence \mathcal{K}_n^\bullet is K-flat by Lemma 27.8. The induced map $\text{colim } \mathcal{K}_n^\bullet \rightarrow \mathcal{G}^\bullet$ is a quasi-isomorphism by construction. Since $\text{colim } \mathcal{K}_n^\bullet$ is K-flat by Lemma 27.9 we win. \square

06YG **Lemma 27.12.** *Let (X, \mathcal{O}_X) be a ringed space. Let $\alpha : \mathcal{P}^\bullet \rightarrow \mathcal{Q}^\bullet$ be a quasi-isomorphism of K-flat complexes of \mathcal{O}_X -modules. For every complex \mathcal{F}^\bullet of \mathcal{O}_X -modules the induced map*

$$\text{Tot}(\text{id}_{\mathcal{F}^\bullet} \otimes \alpha) : \text{Tot}(\mathcal{F}^\bullet \otimes_{\mathcal{O}_X} \mathcal{P}^\bullet) \longrightarrow \text{Tot}(\mathcal{F}^\bullet \otimes_{\mathcal{O}_X} \mathcal{Q}^\bullet)$$

is a quasi-isomorphism.

Proof. Choose a quasi-isomorphism $\mathcal{K}^\bullet \rightarrow \mathcal{F}^\bullet$ with \mathcal{K}^\bullet a K-flat complex, see Lemma 27.11. Consider the commutative diagram

$$\begin{array}{ccc} \text{Tot}(\mathcal{K}^\bullet \otimes_{\mathcal{O}_X} \mathcal{P}^\bullet) & \longrightarrow & \text{Tot}(\mathcal{K}^\bullet \otimes_{\mathcal{O}_X} \mathcal{Q}^\bullet) \\ \downarrow & & \downarrow \\ \text{Tot}(\mathcal{F}^\bullet \otimes_{\mathcal{O}_X} \mathcal{P}^\bullet) & \longrightarrow & \text{Tot}(\mathcal{F}^\bullet \otimes_{\mathcal{O}_X} \mathcal{Q}^\bullet) \end{array}$$

The result follows as by Lemma 27.3 the vertical arrows and the top horizontal arrow are quasi-isomorphisms. \square

Let (X, \mathcal{O}_X) be a ringed space. Let \mathcal{F}^\bullet be an object of $D(\mathcal{O}_X)$. Choose a K-flat resolution $\mathcal{K}^\bullet \rightarrow \mathcal{F}^\bullet$, see Lemma 27.11. By Lemma 27.1 we obtain an exact functor of triangulated categories

$$K(\mathcal{O}_X) \longrightarrow K(\mathcal{O}_X), \quad \mathcal{G}^\bullet \longmapsto \text{Tot}(\mathcal{G}^\bullet \otimes_{\mathcal{O}_X} \mathcal{K}^\bullet)$$

By Lemma 27.3 this functor induces a functor $D(\mathcal{O}_X) \rightarrow D(\mathcal{O}_X)$ simply because $D(\mathcal{O}_X)$ is the localization of $K(\mathcal{O}_X)$ at quasi-isomorphisms. By Lemma 27.12 the resulting functor (up to isomorphism) does not depend on the choice of the K-flat resolution.

06YH **Definition 27.13.** Let (X, \mathcal{O}_X) be a ringed space. Let \mathcal{F}^\bullet be an object of $D(\mathcal{O}_X)$. The *derived tensor product*

$$- \otimes_{\mathcal{O}_X}^{\mathbf{L}} \mathcal{F}^\bullet : D(\mathcal{O}_X) \longrightarrow D(\mathcal{O}_X)$$

is the exact functor of triangulated categories described above.

It is clear from our explicit constructions that there is a canonical isomorphism

$$\mathcal{F}^\bullet \otimes_{\mathcal{O}_X}^{\mathbf{L}} \mathcal{G}^\bullet \cong \mathcal{G}^\bullet \otimes_{\mathcal{O}_X}^{\mathbf{L}} \mathcal{F}^\bullet$$

for \mathcal{G}^\bullet and \mathcal{F}^\bullet in $D(\mathcal{O}_X)$. Hence when we write $\mathcal{F}^\bullet \otimes_{\mathcal{O}_X}^{\mathbf{L}} \mathcal{G}^\bullet$ we will usually be agnostic about which variable we are using to define the derived tensor product with.

08BP **Definition 27.14.** Let (X, \mathcal{O}_X) be a ringed space. Let \mathcal{F}, \mathcal{G} be \mathcal{O}_X -modules. The *Tor's* of \mathcal{F} and \mathcal{G} are define by the formula

$$\mathrm{Tor}_p^{\mathcal{O}_X}(\mathcal{F}, \mathcal{G}) = H^{-p}(\mathcal{F} \otimes_{\mathcal{O}_X}^{\mathbf{L}} \mathcal{G})$$

with derived tensor product as defined above.

This definition implies that for every short exact sequence of \mathcal{O}_X -modules $0 \rightarrow \mathcal{F}_1 \rightarrow \mathcal{F}_2 \rightarrow \mathcal{F}_3 \rightarrow 0$ we have a long exact cohomology sequence

$$\begin{array}{ccccccc} \mathcal{F}_1 \otimes_{\mathcal{O}_X} \mathcal{G} & \longrightarrow & \mathcal{F}_2 \otimes_{\mathcal{O}_X} \mathcal{G} & \longrightarrow & \mathcal{F}_3 \otimes_{\mathcal{O}_X} \mathcal{G} & \longrightarrow & 0 \\ & & & & \swarrow & & \\ \mathrm{Tor}_1^{\mathcal{O}_X}(\mathcal{F}_1, \mathcal{G}) & \longrightarrow & \mathrm{Tor}_1^{\mathcal{O}_X}(\mathcal{F}_2, \mathcal{G}) & \longrightarrow & \mathrm{Tor}_1^{\mathcal{O}_X}(\mathcal{F}_3, \mathcal{G}) & & \end{array}$$

for every \mathcal{O}_X -module \mathcal{G} . This will be called the long exact sequence of Tor associated to the situation.

08BQ **Lemma 27.15.** Let (X, \mathcal{O}_X) be a ringed space. Let \mathcal{F} be an \mathcal{O}_X -module. The following are equivalent

- (1) \mathcal{F} is a flat \mathcal{O}_X -module, and
- (2) $\mathrm{Tor}_1^{\mathcal{O}_X}(\mathcal{F}, \mathcal{G}) = 0$ for every \mathcal{O}_X -module \mathcal{G} .

Proof. If \mathcal{F} is flat, then $\mathcal{F} \otimes_{\mathcal{O}_X} -$ is an exact functor and the satellites vanish. Conversely assume (2) holds. Then if $\mathcal{G} \rightarrow \mathcal{H}$ is injective with cokernel \mathcal{Q} , the long exact sequence of Tor shows that the kernel of $\mathcal{F} \otimes_{\mathcal{O}_X} \mathcal{G} \rightarrow \mathcal{F} \otimes_{\mathcal{O}_X} \mathcal{H}$ is a quotient of $\mathrm{Tor}_1^{\mathcal{O}_X}(\mathcal{F}, \mathcal{Q})$ which is zero by assumption. Hence \mathcal{F} is flat. \square

28. Derived pullback

06YI Let $f : (X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$ be a morphism of ringed spaces. We can use K-flat resolutions to define a derived pullback functor

$$Lf^* : D(\mathcal{O}_Y) \rightarrow D(\mathcal{O}_X)$$

Namely, for every complex of \mathcal{O}_Y -modules \mathcal{G}^\bullet we can choose a K-flat resolution $\mathcal{K}^\bullet \rightarrow \mathcal{G}^\bullet$ and set $Lf^*\mathcal{G}^\bullet = f^*\mathcal{K}^\bullet$. You can use Lemmas 27.7, 27.11, and 27.12 to see that this is well defined. However, to cross all the t's and dot all the i's it is perhaps more convenient to use some general theory.

06YJ **Lemma 28.1.** The construction above is independent of choices and defines an exact functor of triangulated categories $Lf^* : D(\mathcal{O}_Y) \rightarrow D(\mathcal{O}_X)$.

Proof. To see this we use the general theory developed in Derived Categories, Section 15. Set $\mathcal{D} = K(\mathcal{O}_Y)$ and $\mathcal{D}' = D(\mathcal{O}_X)$. Let us write $F : \mathcal{D} \rightarrow \mathcal{D}'$ the exact functor of triangulated categories defined by the rule $F(\mathcal{G}^\bullet) = f^*\mathcal{G}^\bullet$. We let S be the set of quasi-isomorphisms in $\mathcal{D} = K(\mathcal{O}_Y)$. This gives a situation as in Derived Categories, Situation 15.1 so that Derived Categories, Definition 15.2 applies. We claim that LF is everywhere defined. This follows from Derived Categories, Lemma 15.15 with $\mathcal{P} \subset \text{Ob}(\mathcal{D})$ the collection of K -flat complexes: (1) follows from Lemma 27.11 and to see (2) we have to show that for a quasi-isomorphism $\mathcal{K}_1^\bullet \rightarrow \mathcal{K}_2^\bullet$ between K -flat complexes of \mathcal{O}_Y -modules the map $f^*\mathcal{K}_1^\bullet \rightarrow f^*\mathcal{K}_2^\bullet$ is a quasi-isomorphism. To see this write this as

$$f^{-1}\mathcal{K}_1^\bullet \otimes_{f^{-1}\mathcal{O}_Y} \mathcal{O}_X \longrightarrow f^{-1}\mathcal{K}_2^\bullet \otimes_{f^{-1}\mathcal{O}_Y} \mathcal{O}_X$$

The functor f^{-1} is exact, hence the map $f^{-1}\mathcal{K}_1^\bullet \rightarrow f^{-1}\mathcal{K}_2^\bullet$ is a quasi-isomorphism. By Lemma 27.7 applied to the morphism $(X, f^{-1}\mathcal{O}_Y) \rightarrow (Y, \mathcal{O}_Y)$ the complexes $f^{-1}\mathcal{K}_1^\bullet$ and $f^{-1}\mathcal{K}_2^\bullet$ are K -flat complexes of $f^{-1}\mathcal{O}_Y$ -modules. Hence Lemma 27.12 guarantees that the displayed map is a quasi-isomorphism. Thus we obtain a derived functor

$$LF : D(\mathcal{O}_Y) = S^{-1}\mathcal{D} \longrightarrow \mathcal{D}' = D(\mathcal{O}_X)$$

see Derived Categories, Equation (15.9.1). Finally, Derived Categories, Lemma 15.15 also guarantees that $LF(\mathcal{K}^\bullet) = F(\mathcal{K}^\bullet) = f^*\mathcal{K}^\bullet$ when \mathcal{K}^\bullet is K -flat, i.e., $Lf^* = LF$ is indeed computed in the way described above. \square

0D5S **Lemma 28.2.** *Let $f : X \rightarrow Y$ and $g : Y \rightarrow Z$ be morphisms of ringed spaces. Then $Lf^* \circ Lg^* = L(g \circ f)^*$ as functors $D(\mathcal{O}_Z) \rightarrow D(\mathcal{O}_X)$.*

Proof. Let E be an object of $D(\mathcal{O}_Z)$. By construction Lg^*E is computed by choosing a K -flat complex \mathcal{K}^\bullet representing E on Z and setting $Lg^*E = g^*\mathcal{K}^\bullet$. By Lemma 27.7 we see that $g^*\mathcal{K}^\bullet$ is K -flat on Y . Then Lf^*Lg^*E is given by $f^*g^*\mathcal{K}^\bullet = (g \circ f)^*\mathcal{K}^\bullet$ which also represents $L(g \circ f)^*E$. \square

079U **Lemma 28.3.** *Let $f : (X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$ be a morphism of ringed spaces. There is a canonical bifunctorial isomorphism*

$$Lf^*(\mathcal{F}^\bullet \otimes_{\mathcal{O}_Y}^{\mathbf{L}} \mathcal{G}^\bullet) = Lf^*\mathcal{F}^\bullet \otimes_{\mathcal{O}_X}^{\mathbf{L}} Lf^*\mathcal{G}^\bullet$$

for $\mathcal{F}^\bullet, \mathcal{G}^\bullet \in \text{Ob}(D(X))$.

Proof. We may assume that \mathcal{F}^\bullet and \mathcal{G}^\bullet are K -flat complexes. In this case $\mathcal{F}^\bullet \otimes_{\mathcal{O}_Y}^{\mathbf{L}} \mathcal{G}^\bullet$ is just the total complex associated to the double complex $\mathcal{F}^\bullet \otimes_{\mathcal{O}_Y} \mathcal{G}^\bullet$. By Lemma 27.5 $\text{Tot}(\mathcal{F}^\bullet \otimes_{\mathcal{O}_Y} \mathcal{G}^\bullet)$ is K -flat also. Hence the isomorphism of the lemma comes from the isomorphism

$$\text{Tot}(f^*\mathcal{F}^\bullet \otimes_{\mathcal{O}_X} f^*\mathcal{G}^\bullet) \longrightarrow f^*\text{Tot}(\mathcal{F}^\bullet \otimes_{\mathcal{O}_Y} \mathcal{G}^\bullet)$$

whose constituents are the isomorphisms $f^*\mathcal{F}^p \otimes_{\mathcal{O}_X} f^*\mathcal{G}^q \rightarrow f^*(\mathcal{F}^p \otimes_{\mathcal{O}_Y} \mathcal{G}^q)$ of Modules, Lemma 15.4. \square

08DE **Lemma 28.4.** *Let $f : (X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$ be a morphism of ringed spaces. There is a canonical bifunctorial isomorphism*

$$\mathcal{F}^\bullet \otimes_{\mathcal{O}_X}^{\mathbf{L}} Lf^*\mathcal{G}^\bullet = \mathcal{F}^\bullet \otimes_{f^{-1}\mathcal{O}_Y}^{\mathbf{L}} f^{-1}\mathcal{G}^\bullet$$

for \mathcal{F}^\bullet in $D(X)$ and \mathcal{G}^\bullet in $D(Y)$.

Proof. Let \mathcal{F} be an \mathcal{O}_X -module and let \mathcal{G} be an \mathcal{O}_Y -module. Then $\mathcal{F} \otimes_{\mathcal{O}_X} f^* \mathcal{G} = \mathcal{F} \otimes_{f^{-1}\mathcal{O}_Y} f^{-1}\mathcal{G}$ because $f^* \mathcal{G} = \mathcal{O}_X \otimes_{f^{-1}\mathcal{O}_Y} f^{-1}\mathcal{G}$. The lemma follows from this and the definitions. \square

29. Cohomology of unbounded complexes

079V Let (X, \mathcal{O}_X) be a ringed space. The category $\text{Mod}(\mathcal{O}_X)$ is a Grothendieck abelian category: it has all colimits, filtered colimits are exact, and it has a generator, namely

$$\bigoplus_{U \subset X \text{ open}} j_{U!} \mathcal{O}_U,$$

see Modules, Section 3 and Lemmas 16.5 and 16.6. By Injectives, Theorem 12.6 for every complex \mathcal{F}^\bullet of \mathcal{O}_X -modules there exists an injective quasi-isomorphism $\mathcal{F}^\bullet \rightarrow \mathcal{I}^\bullet$ to a K-injective complex of \mathcal{O}_X -modules. Hence we can define

$$R\Gamma(X, \mathcal{F}^\bullet) = \Gamma(X, \mathcal{I}^\bullet)$$

and similarly for any left exact functor, see Derived Categories, Lemma 29.7. For any morphism of ringed spaces $f : (X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$ we obtain

$$Rf_* : D(X) \longrightarrow D(Y)$$

on the unbounded derived categories.

079W **Lemma 29.1.** *Let $f : (X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$ be a morphism of ringed spaces. The functor Rf_* defined above and the functor Lf^* defined in Lemma 28.1 are adjoint:*

$$\text{Hom}_{D(X)}(Lf^* \mathcal{G}^\bullet, \mathcal{F}^\bullet) = \text{Hom}_{D(Y)}(\mathcal{G}^\bullet, Rf_* \mathcal{F}^\bullet)$$

bifunctorially in $\mathcal{F}^\bullet \in \text{Ob}(D(X))$ and $\mathcal{G}^\bullet \in \text{Ob}(D(Y))$.

Proof. This follows formally from the fact that Rf_* and Lf^* exist, see Derived Categories, Lemma 28.5. \square

0D5T **Lemma 29.2.** *Let $f : X \rightarrow Y$ and $g : Y \rightarrow Z$ be morphisms of ringed spaces. Then $Rg_* \circ Rf_* = R(g \circ f)_*$ as functors $D(\mathcal{O}_X) \rightarrow D(\mathcal{O}_Z)$.*

Proof. By Lemma 29.1 we see that $Rg_* \circ Rf_*$ is adjoint to $Lf^* \circ Lg^*$. We have $Lf^* \circ Lg^* = L(g \circ f)^*$ by Lemma 28.2 and hence by uniqueness of adjoint functors we have $Rg_* \circ Rf_* = R(g \circ f)_*$. \square

08HY **Remark 29.3.** The construction of unbounded derived functor Lf^* and Rf_* allows one to construct the base change map in full generality. Namely, suppose that

$$\begin{array}{ccc} X' & \xrightarrow{\quad} & X \\ f' \downarrow & & \downarrow f \\ S' & \xrightarrow{\quad g \quad} & S \end{array}$$

is a commutative diagram of ringed spaces. Let K be an object of $D(\mathcal{O}_X)$. Then there exists a canonical base change map

$$Lg^* Rf_* K \longrightarrow R(f')_* L(g')^* K$$

in $D(\mathcal{O}_{S'})$. Namely, this map is adjoint to a map $L(f')^* Lg^* Rf_* K \rightarrow L(g')^* K$. Since $L(f')^* Lg^* = L(g')^* Lf^*$ we see this is the same as a map $L(g')^* Lf^* Rf_* K \rightarrow L(g')^* K$ which we can take to be $L(g')^*$ of the adjunction map $Lf^* Rf_* K \rightarrow K$.

0ATL **Remark 29.4.** Consider a commutative diagram

$$\begin{array}{ccc} X' & \xrightarrow{\quad} & X \\ f' \downarrow & & \downarrow f \\ Y' & \xrightarrow{\quad} & Y \\ g' \downarrow & & \downarrow g \\ Z' & \xrightarrow{\quad} & Z \end{array}$$

of ringed spaces. Then the base change maps of Remark 29.3 for the two squares compose to give the base change map for the outer rectangle. More precisely, the composition

$$\begin{aligned} Lm^* \circ R(g \circ f)_* &= Lm^* \circ Rg_* \circ Rf_* \\ &\rightarrow Rg'_* \circ Ll^* \circ Rf_* \\ &\rightarrow Rg'_* \circ Rf'_* \circ Lk^* \\ &= R(g' \circ f')_* \circ Lk^* \end{aligned}$$

is the base change map for the rectangle. We omit the verification.

0ATM **Remark 29.5.** Consider a commutative diagram

$$\begin{array}{ccccc} X'' & \xrightarrow{\quad} & X' & \xrightarrow{\quad} & X \\ f'' \downarrow & & f' \downarrow & & \downarrow f \\ Y'' & \xrightarrow{\quad} & Y' & \xrightarrow{\quad} & Y \end{array}$$

of ringed spaces. Then the base change maps of Remark 29.3 for the two squares compose to give the base change map for the outer rectangle. More precisely, the composition

$$\begin{aligned} L(h \circ h')^* \circ Rf_* &= L(h')^* \circ Lh_* \circ Rf_* \\ &\rightarrow L(h')^* \circ Rf'_* \circ Lg^* \\ &\rightarrow Rf''_* \circ L(g')^* \circ Lg^* \\ &= Rf''_* \circ L(g \circ g')^* \end{aligned}$$

is the base change map for the rectangle. We omit the verification.

0B68 **Remark 29.6.** Let $f : (X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$ be a morphism of ringed spaces. The adjointness of Lf^* and Rf_* allows us to construct a relative cup product

$$Rf_* K \otimes_{\mathcal{O}_Y}^{\mathbf{L}} Rf_* L \longrightarrow Rf_*(K \otimes_{\mathcal{O}_X}^{\mathbf{L}} L)$$

in $D(\mathcal{O}_Y)$ for all K, L in $D(\mathcal{O}_X)$. Namely, this map is adjoint to a map $Lf^*(Rf_* K \otimes_{\mathcal{O}_Y}^{\mathbf{L}} Rf_* L) \rightarrow K \otimes_{\mathcal{O}_X}^{\mathbf{L}} L$ for which we can take the composition of the isomorphism $Lf^*(Rf_* K \otimes_{\mathcal{O}_Y}^{\mathbf{L}} Rf_* L) = Lf^* Rf_* K \otimes_{\mathcal{O}_X}^{\mathbf{L}} Lf^* Rf_* L$ (Lemma 28.3) with the map $Lf^* Rf_* K \otimes_{\mathcal{O}_X}^{\mathbf{L}} Lf^* Rf_* L \rightarrow K \otimes_{\mathcal{O}_X}^{\mathbf{L}} L$ coming from the counit $Lf^* \circ Rf_* \rightarrow \text{id}$.

0BKK **Lemma 29.7.** Let (X, \mathcal{O}_X) be a ringed space. Let \mathcal{F}^\bullet be a filtered complex of \mathcal{O}_X -modules. There exists a canonical spectral sequence $(E_r, d_r)_{r \geq 1}$ of bigraded $\Gamma(X, \mathcal{O}_X)$ -modules with d_r of bidegree $(r, -r + 1)$ and

$$E_1^{p,q} = H^{p+q}(X, gr^p \mathcal{F}^\bullet)$$

If for every n we have

$$H^n(X, F^p \mathcal{F}^\bullet) = 0 \text{ for } p \gg 0 \quad \text{and} \quad H^n(X, F^p \mathcal{F}^\bullet) = H^n(X, \mathcal{F}^\bullet) \text{ for } p \ll 0$$

then the spectral sequence is bounded and converges to $H^*(X, \mathcal{F}^\bullet)$.

Proof. (For a proof in case the complex is a bounded below complex of modules with finite filtrations, see the remark below.) Choose an map of filtered complexes $j : \mathcal{F}^\bullet \rightarrow \mathcal{J}^\bullet$ as in Injectives, Lemma 13.7. The spectral sequence is the spectral sequence of Homology, Section 21 associated to the filtered complex

$$\Gamma(X, \mathcal{J}^\bullet) \quad \text{with} \quad F^p \Gamma(X, \mathcal{J}^\bullet) = \Gamma(X, F^p \mathcal{J}^\bullet)$$

Since cohomology is computed by evaluating on K-injective representatives we see that the E_1 page is as stated in the lemma. The convergence and boundedness under the stated conditions follows from Homology, Lemma 21.13. \square

0BKL **Remark 29.8.** Let (X, \mathcal{O}_X) be a ringed space. Let \mathcal{F}^\bullet be a filtered complex of \mathcal{O}_X -modules. If \mathcal{F}^\bullet is bounded from below and for each n the filtration on \mathcal{F}^n is finite, then there is a construction of the spectral sequence in Lemma 29.7 avoiding Injectives, Lemma 13.7. Namely, by Derived Categories, Lemma 26.9 there is a filtered quasi-isomorphism $i : \mathcal{F}^\bullet \rightarrow \mathcal{I}^\bullet$ of filtered complexes with \mathcal{I}^\bullet bounded below, the filtration on \mathcal{I}^n is finite for all n , and with each $\text{gr}^p \mathcal{I}^n$ an injective \mathcal{O}_X -module. Then we take the spectral sequence associated to

$$\Gamma(X, \mathcal{I}^\bullet) \quad \text{with} \quad F^p \Gamma(X, \mathcal{I}^\bullet) = \Gamma(X, F^p \mathcal{I}^\bullet)$$

Since cohomology can be computed by evaluating on bounded below complexes of injectives we see that the E_1 page is as stated in the lemma. The convergence and boundedness under the stated conditions follows from Homology, Lemma 21.11. In fact, this is a special case of the spectral sequence in Derived Categories, Lemma 26.14.

0BKM **Example 29.9.** Let (X, \mathcal{O}_X) be a ringed space. Let \mathcal{F}^\bullet be a complex of \mathcal{O}_X -modules. We can apply Lemma 29.7 with $F^p \mathcal{F}^\bullet = \tau_{\leq -p} \mathcal{F}^\bullet$. (If \mathcal{F}^\bullet is bounded below we can use Remark 29.8.) Then we get a spectral sequence

$$E_1^{p,q} = H^{p+q}(X, H^{-p}(\mathcal{F}^\bullet)[p]) = H^{2p+q}(X, H^{-p}(\mathcal{F}^\bullet))$$

After renumbering $p = -j$ and $q = i + 2j$ we find that for any $K \in D(\mathcal{O}_X)$ there is a spectral sequence $(E'_r, d'_r)_{r \geq 2}$ of bigraded modules with d'_r of bidegree $(r, -r + 1)$, with

$$(E'_2)^{i,j} = H^i(X, H^j(K))$$

If K is bounded below (for example), then this spectral sequence is bounded and converges to $H^{i+j}(X, K)$. In the bounded below case this spectral sequence is an example of the second spectral sequence of Derived Categories, Lemma 21.3 (constructed using Cartan-Eilenberg resolutions).

30. Some properties of K-injective complexes

0D5U Let (X, \mathcal{O}_X) be a ringed space. Let $U \subset X$ be an open subset. Denote $j : (U, \mathcal{O}_U) \rightarrow (X, \mathcal{O}_X)$ the corresponding open immersion. The pullback functor j^* is exact as it is just the restriction functor. Thus derived pullback Lj^* is computed on any complex by simply restricting the complex. We often simply denote the corresponding functor

$$D(\mathcal{O}_X) \rightarrow D(\mathcal{O}_U), \quad E \mapsto j^* E = E|_U$$

Similarly, extension by zero $j_! : \text{Mod}(\mathcal{O}_U) \rightarrow \text{Mod}(\mathcal{O}_X)$ (see Sheaves, Section 31) is an exact functor (Modules, Lemma 3.4). Thus it induces a functor

$$j_! : D(\mathcal{O}_U) \rightarrow D(\mathcal{O}_X), \quad F \mapsto j_!F$$

by simply applying $j_!$ to any complex representing the object F .

08BS **Lemma 30.1.** *Let X be a ringed space. Let $U \subset X$ be an open subspace. The restriction of a K -injective complex of \mathcal{O}_X -modules to U is a K -injective complex of \mathcal{O}_U -modules.*

Proof. Follows from Derived Categories, Lemma 29.9 and the fact that the restriction functor has the exact left adjoint $j_!$. For the construction of $j_!$ see Sheaves, Section 31 and for exactness see Modules, Lemma 3.4. \square

0D5V **Lemma 30.2.** *Let X be a ringed space. Let $U \subset X$ be an open subspace. For K in $D(\mathcal{O}_X)$ we have $H^p(U, K) = H^p(U, K|_U)$.*

Proof. Let \mathcal{I}^\bullet be a K -injective complex of \mathcal{O}_X -modules representing K . Then

$$H^q(U, K) = H^q(\Gamma(U, \mathcal{I}^\bullet)) = H^q(\Gamma(U, \mathcal{I}^\bullet|_U))$$

by construction of cohomology. By Lemma 30.1 the complex $\mathcal{I}^\bullet|_U$ is a K -injective complex representing $K|_U$ and the lemma follows. \square

0BKJ **Lemma 30.3.** *Let (X, \mathcal{O}_X) be a ringed space. Let K be an object of $D(\mathcal{O}_X)$. The sheafification of*

$$U \mapsto H^q(U, K) = H^q(U, K|_U)$$

is the q th cohomology sheaf $H^q(K)$ of K .

Proof. The equality $H^q(U, K) = H^q(U, K|_U)$ holds by Lemma 30.2. Choose a K -injective complex \mathcal{I}^\bullet representing K . Then

$$H^q(U, K) = \frac{\text{Ker}(\mathcal{I}^q(U) \rightarrow \mathcal{I}^{q+1}(U))}{\text{Im}(\mathcal{I}^{q-1}(U) \rightarrow \mathcal{I}^q(U))}.$$

by our construction of cohomology. Since $H^q(K) = \text{Ker}(\mathcal{I}^q \rightarrow \mathcal{I}^{q+1}) / \text{Im}(\mathcal{I}^{q-1} \rightarrow \mathcal{I}^q)$ the result is clear. \square

08FE **Lemma 30.4.** *Let $f : (X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$ be a morphism of ringed spaces. Given an open subspace $V \subset Y$, set $U = f^{-1}(V)$ and denote $g : U \rightarrow V$ the induced morphism. Then $(Rf_*E)|_V = Rg_*(E|_U)$ for E in $D(\mathcal{O}_X)$.*

Proof. Represent E by a K -injective complex \mathcal{I}^\bullet of \mathcal{O}_X -modules. Then $Rf_*(E) = f_*\mathcal{I}^\bullet$ and $Rg_*(E|_U) = g_*(\mathcal{I}^\bullet|_U)$ by Lemma 30.1. Since it is clear that $(f_*\mathcal{F})|_V = g_*(\mathcal{F}|_U)$ for any sheaf \mathcal{F} on X the result follows. \square

0D5W **Lemma 30.5.** *Let $f : X \rightarrow Y$ be a morphism of ringed spaces. Then $R\Gamma(Y, -) \circ Rf_* = R\Gamma(X, -)$ as functors $D(\mathcal{O}_X) \rightarrow D(\Gamma(Y, \mathcal{O}_Y))$. More generally for $V \subset Y$ open and $U = f^{-1}(V)$ we have $R\Gamma(U, -) = R\Gamma(V, -) \circ Rf_*$.*

Proof. Let Z be the ringed space consisting of a singleton space with $\Gamma(Z, \mathcal{O}_Z) = \Gamma(Y, \mathcal{O}_Y)$. There is a canonical morphism $Y \rightarrow Z$ of ringed spaces inducing the identification on global sections of structure sheaves. Then $D(\mathcal{O}_Z) = D(\Gamma(Y, \mathcal{O}_Y))$. Hence the assertion $R\Gamma(Y, -) \circ Rf_* = R\Gamma(X, -)$ follows from Lemma 29.2 applied to $X \rightarrow Y \rightarrow Z$.

The second (more general) statement follows from the first statement after applying Lemma 30.4. \square

0D5X **Lemma 30.6.** *Let $f : (X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$ be a morphism of ringed spaces. Let K be in $D(\mathcal{O}_X)$. Then $H^i(Rf_*K)$ is the sheaf associated to the presheaf*

$$V \mapsto H^i(f^{-1}(V), K) = H^i(V, Rf_*K)$$

Proof. The equality $H^i(f^{-1}(V), K) = H^i(V, Rf_*K)$ follows upon taking cohomology from the second statement in Lemma 30.5. Then the statement on sheafification follows from Lemma 30.3. \square

0D5Y **Lemma 30.7.** *Let X be a ringed space. Let K be an object of $D(\mathcal{O}_X)$ and denote K_{ab} its image in $D(\mathbf{Z}_X)$.*

- (1) *For any open $U \subset X$ there is a canonical map $R\Gamma(U, K) \rightarrow R\Gamma(U, K_{ab})$ which is an isomorphism in $D(\text{Ab})$.*
- (2) *Let $f : X \rightarrow Y$ be a morphism of ringed spaces. There is a canonical map $Rf_*K \rightarrow Rf_*(K_{ab})$ which is an isomorphism in $D(\mathbf{Z}_Y)$.*

Proof. The map is constructed as follows. Choose a K-injective complex \mathcal{I}^\bullet representing K . Choose a quasi-isomorphism $\mathcal{I}^\bullet \rightarrow \mathcal{J}^\bullet$ where \mathcal{J}^\bullet is a K-injective complex of abelian groups. Then the map in (1) is given by $\Gamma(U, \mathcal{I}^\bullet) \rightarrow \Gamma(U, \mathcal{J}^\bullet)$ and the map in (2) is given by $f_*\mathcal{I}^\bullet \rightarrow f_*\mathcal{J}^\bullet$. To show that these maps are isomorphisms, it suffices to prove they induce isomorphisms on cohomology groups and cohomology sheaves. By Lemmas 30.2 and 30.6 it suffices to show that the map

$$H^0(X, K) \longrightarrow H^0(X, K_{ab})$$

is an isomorphism. Observe that

$$H^0(X, K) = \text{Hom}_{D(\mathcal{O}_X)}(\mathcal{O}_X, K)$$

and similarly for the other group. Choose any complex \mathcal{K}^\bullet of \mathcal{O}_X -modules representing K . By construction of the derived category as a localization we have

$$\text{Hom}_{D(\mathcal{O}_X)}(\mathcal{O}_X, K) = \text{colim}_{s: \mathcal{F}^\bullet \rightarrow \mathcal{O}_X} \text{Hom}_{K(\mathcal{O}_X)}(\mathcal{F}^\bullet, \mathcal{K}^\bullet)$$

where the colimit is over quasi-isomorphisms s of complexes of \mathcal{O}_X -modules. Similarly, we have

$$\text{Hom}_{D(\mathbf{Z}_X)}(\mathbf{Z}_X, K) = \text{colim}_{s: \mathcal{G}^\bullet \rightarrow \mathbf{Z}_X} \text{Hom}_{K(\mathbf{Z}_X)}(\mathcal{G}^\bullet, \mathcal{K}^\bullet)$$

Next, we observe that the quasi-isomorphisms $s : \mathcal{G}^\bullet \rightarrow \mathbf{Z}_X$ with \mathcal{G}^\bullet bounded above complex of flat \mathbf{Z}_X -modules is cofinal in the system. (This follows from Modules, Lemma 16.6 and Derived Categories, Lemma 16.5; see discussion in Section 27.) Hence we can construct an inverse to the map $H^0(X, K) \longrightarrow H^0(X, K_{ab})$ by representing an element $\xi \in H^0(X, K_{ab})$ by a pair

$$(s : \mathcal{G}^\bullet \rightarrow \mathbf{Z}_X, a : \mathcal{G}^\bullet \rightarrow \mathcal{K}^\bullet)$$

with \mathcal{G}^\bullet a bounded above complex of flat \mathbf{Z}_X -modules and sending this to

$$(\mathcal{G}^\bullet \otimes_{\mathbf{Z}_X} \mathcal{O}_X \rightarrow \mathcal{O}_X, \mathcal{G}^\bullet \otimes_{\mathbf{Z}_X} \mathcal{O}_X \rightarrow \mathcal{K}^\bullet)$$

The only thing to note here is that the first arrow is a quasi-isomorphism by Lemmas 27.12 and 27.8. We omit the detailed verification that this construction is indeed an inverse. \square

08BT **Lemma 30.8.** *Let (X, \mathcal{O}_X) be a ringed space. Let $U \subset X$ be an open subset. Denote $j : (U, \mathcal{O}_U) \rightarrow (X, \mathcal{O}_X)$ the corresponding open immersion. The restriction functor $D(\mathcal{O}_X) \rightarrow D(\mathcal{O}_U)$ is a right adjoint to extension by zero $j_! : D(\mathcal{O}_U) \rightarrow D(\mathcal{O}_X)$.*

Proof. This follows formally from the fact that $j_!$ and j^* are adjoint and exact (and hence $Lj_! = j_!$ and $Rj^* = j^*$ exist), see Derived Categories, Lemma 28.5. \square

0D5Z **Lemma 30.9.** *Let $f : X \rightarrow Y$ be a flat morphism of ringed spaces. If \mathcal{I}^\bullet is a K-injective complex of \mathcal{O}_X -modules, then $f_*\mathcal{I}^\bullet$ is K-injective as a complex of \mathcal{O}_Y -modules.*

Proof. This is true because

$$\mathrm{Hom}_{K(\mathcal{O}_Y)}(\mathcal{F}^\bullet, f_*\mathcal{I}^\bullet) = \mathrm{Hom}_{K(\mathcal{O}_X)}(f^*\mathcal{F}^\bullet, \mathcal{I}^\bullet)$$

by Sheaves, Lemma 26.2 and the fact that f^* is exact as f is assumed to be flat. \square

31. Unbounded Mayer-Vietoris

08BR There is a Mayer-Vietoris sequence for unbounded cohomology as well.

08BU **Lemma 31.1.** *Let (X, \mathcal{O}_X) be a ringed space. Let $X = U \cup V$ be the union of two open subspaces. For any object E of $D(\mathcal{O}_X)$ we have a distinguished triangle*

$$j_{U \cap V!}E|_{U \cap V} \rightarrow j_{U!}E|_U \oplus j_{V!}E|_V \rightarrow E \rightarrow j_{U \cap V!}E|_{U \cap V}[1]$$

in $D(\mathcal{O}_X)$.

Proof. We have seen in Section 30 that the restriction functors and the extension by zero functors are computed by just applying the functors to any complex. Let \mathcal{E}^\bullet be a complex of \mathcal{O}_X -modules representing E . The distinguished triangle of the lemma is the distinguished triangle associated (by Derived Categories, Section 12 and especially Lemma 12.1) to the short exact sequence of complexes of \mathcal{O}_X -modules

$$0 \rightarrow j_{U \cap V!}\mathcal{E}^\bullet|_{U \cap V} \rightarrow j_{U!}\mathcal{E}^\bullet|_U \oplus j_{V!}\mathcal{E}^\bullet|_V \rightarrow \mathcal{E}^\bullet \rightarrow 0$$

To see this sequence is exact one checks on stalks using Sheaves, Lemma 31.8 (computation omitted). \square

08BV **Lemma 31.2.** *Let (X, \mathcal{O}_X) be a ringed space. Let $X = U \cup V$ be the union of two open subspaces. For any object E of $D(\mathcal{O}_X)$ we have a distinguished triangle*

$$E \rightarrow Rj_{U,*}E|_U \oplus Rj_{V,*}E|_V \rightarrow Rj_{U \cap V,*}E|_{U \cap V} \rightarrow E[1]$$

in $D(\mathcal{O}_X)$.

Proof. Choose a K-injective complex \mathcal{I}^\bullet representing E whose terms \mathcal{I}^n are injective objects of $\mathrm{Mod}(\mathcal{O}_X)$, see Injectives, Theorem 12.6. We have seen that $\mathcal{I}^\bullet|_U$ is a K-injective complex as well (Lemma 30.1). Hence $Rj_{U,*}E|_U$ is represented by $j_{U,*}\mathcal{I}^\bullet|_U$. Similarly for V and $U \cap V$. Hence the distinguished triangle of the lemma is the distinguished triangle associated (by Derived Categories, Section 12 and especially Lemma 12.1) to the short exact sequence of complexes

$$0 \rightarrow \mathcal{I}^\bullet \rightarrow j_{U,*}\mathcal{I}^\bullet|_U \oplus j_{V,*}\mathcal{I}^\bullet|_V \rightarrow j_{U \cap V,*}\mathcal{I}^\bullet|_{U \cap V} \rightarrow 0.$$

This sequence is exact because for any $W \subset X$ open and any n the sequence

$$0 \rightarrow \mathcal{I}^n(W) \rightarrow \mathcal{I}^n(W \cap U) \oplus \mathcal{I}^n(W \cap V) \rightarrow \mathcal{I}^n(W \cap U \cap V) \rightarrow 0$$

is exact (see proof of Lemma 9.2). \square

08BW **Lemma 31.3.** *Let (X, \mathcal{O}_X) be a ringed space. Let $X = U \cup V$ be the union of two open subspaces of X . For objects E, F of $D(\mathcal{O}_X)$ we have a Mayer-Vietoris sequence*

$$\begin{array}{ccc} \dots & \longrightarrow & \text{Ext}^{-1}(E_{U \cap V}, F_{U \cap V}) \\ & \nearrow & \\ \text{Hom}(E, F) & \longleftarrow \text{Hom}(E_U, F_U) \oplus \text{Hom}(E_V, F_V) \longrightarrow & \text{Hom}(E_{U \cap V}, F_{U \cap V}) \end{array}$$

where the subscripts denote restrictions to the relevant opens and the Hom's and Ext's are taken in the relevant derived categories.

Proof. Use the distinguished triangle of Lemma 31.1 to obtain a long exact sequence of Hom's (from Derived Categories, Lemma 4.2) and use that

$$\text{Hom}_{D(\mathcal{O}_X)}(j_{U!}E|_U, F) = \text{Hom}_{D(\mathcal{O}_U)}(E|_U, F|_U)$$

by Lemma 30.8. □

08BX **Lemma 31.4.** *Let (X, \mathcal{O}_X) be a ringed space. Suppose that $X = U \cup V$ is a union of two open subsets. For an object E of $D(\mathcal{O}_X)$ we have a distinguished triangle*

$$R\Gamma(X, E) \rightarrow R\Gamma(U, E) \oplus R\Gamma(V, E) \rightarrow R\Gamma(U \cap V, E) \rightarrow R\Gamma(X, E)[1]$$

and in particular a long exact cohomology sequence

$$\dots \rightarrow H^n(X, E) \rightarrow H^n(U, E) \oplus H^n(V, E) \rightarrow H^n(U \cap V, E) \rightarrow H^{n+1}(X, E) \rightarrow \dots$$

The construction of the distinguished triangle and the long exact sequence is functorial in E .

Proof. Choose a K-injective complex \mathcal{I}^\bullet representing E . We may assume \mathcal{I}^n is an injective object of $\text{Mod}(\mathcal{O}_X)$ for all n , see Injectives, Theorem 12.6. Then $R\Gamma(X, E)$ is computed by $\Gamma(X, \mathcal{I}^\bullet)$. Similarly for U, V , and $U \cap V$ by Lemma 30.1. Hence the distinguished triangle of the lemma is the distinguished triangle associated (by Derived Categories, Section 12 and especially Lemma 12.1) to the short exact sequence of complexes

$$0 \rightarrow \mathcal{I}^\bullet(X) \rightarrow \mathcal{I}^\bullet(U) \oplus \mathcal{I}^\bullet(V) \rightarrow \mathcal{I}^\bullet(U \cap V) \rightarrow 0.$$

We have seen this is a short exact sequence in the proof of Lemma 9.2. The final statement follows from the functoriality of the construction in Injectives, Theorem 12.6. □

08HZ **Lemma 31.5.** *Let $f : X \rightarrow Y$ be a morphism of ringed spaces. Suppose that $X = U \cup V$ is a union of two open subsets. Denote $a = f|_U : U \rightarrow Y$, $b = f|_V : V \rightarrow Y$, and $c = f|_{U \cap V} : U \cap V \rightarrow Y$. For every object E of $D(\mathcal{O}_X)$ there exists a distinguished triangle*

$$Rf_*E \rightarrow Ra_*(E|_U) \oplus Rb_*(E|_V) \rightarrow Rc_*(E|_{U \cap V}) \rightarrow Rf_*E[1]$$

This triangle is functorial in E .

Proof. Choose a K-injective complex \mathcal{I}^\bullet representing E . We may assume \mathcal{I}^n is an injective object of $\text{Mod}(\mathcal{O}_X)$ for all n , see Injectives, Theorem 12.6. Then Rf_*E is computed by $f_*\mathcal{I}^\bullet$. Similarly for U, V , and $U \cap V$ by Lemma 30.1. Hence the distinguished triangle of the lemma is the distinguished triangle associated

(by Derived Categories, Section 12 and especially Lemma 12.1) to the short exact sequence of complexes

$$0 \rightarrow f_*\mathcal{I}^\bullet \rightarrow a_*\mathcal{I}^\bullet|_U \oplus b_*\mathcal{I}^\bullet|_V \rightarrow c_*\mathcal{I}^\bullet|_{U \cap V} \rightarrow 0.$$

This is a short exact sequence of complexes by Lemma 9.3 and the fact that $R^1 f_*\mathcal{I} = 0$ for an injective object \mathcal{I} of $\text{Mod}(\mathcal{O}_X)$. The final statement follows from the functoriality of the construction in Injectives, Theorem 12.6. \square

08DF **Lemma 31.6.** *Let (X, \mathcal{O}_X) be a ringed space. Let $j : U \rightarrow X$ be an open subspace. Let $T \subset X$ be a closed subset contained in U .*

- (1) *If E is an object of $D(\mathcal{O}_X)$ whose cohomology sheaves are supported on T , then $E \rightarrow Rj_*(E|_U)$ is an isomorphism.*
- (2) *If F is an object of $D(\mathcal{O}_U)$ whose cohomology sheaves are supported on T , then $j_!F \rightarrow Rj_*F$ is an isomorphism.*

Proof. Let $V = X \setminus T$ and $W = U \cap V$. Note that $X = U \cup V$ is an open covering of X . Denote $j_W : W \rightarrow V$ the open immersion. Let E be an object of $D(\mathcal{O}_X)$ whose cohomology sheaves are supported on T . By Lemma 30.4 we have $(Rj_*E|_U)|_V = Rj_{W,*}(E|_W) = 0$ because $E|_W = 0$ by our assumption. On the other hand, $Rj_*(E|_U)|_U = E|_U$. Thus (1) is clear. Let F be an object of $D(\mathcal{O}_U)$ whose cohomology sheaves are supported on T . By Lemma 30.4 we have $(Rj_*F)|_V = Rj_{W,*}(F|_W) = 0$ because $F|_W = 0$ by our assumption. We also have $(j_!F)|_V = j_{W!}(F|_W) = 0$ (the first equality is immediate from the definition of extension by zero). Since both $(Rj_*F)|_U = F$ and $(j_!F)|_U = F$ we see that (2) holds. \square

32. Derived limits

0BKN Let (X, \mathcal{O}_X) be a ringed space. Since the triangulated category $D(\mathcal{O}_X)$ has products (Injectives, Lemma 13.4) it follows that $D(\mathcal{O}_X)$ has derived limits, see Derived Categories, Definition 32.1. If (K_n) is an inverse system in $D(\mathcal{O}_X)$ then we denote $R \lim K_n$ the derived limit.

0D60 **Lemma 32.1.** *Let (X, \mathcal{O}_X) be a ringed space. For $U \subset X$ open the functor $R\Gamma(U, -)$ commutes with $R \lim$. Moreover, there are short exact sequences*

$$0 \rightarrow R^1 \lim H^{m-1}(U, K_n) \rightarrow H^m(U, R \lim K_n) \rightarrow \lim H^m(U, K_n) \rightarrow 0$$

for any inverse system (K_n) in $D(\mathcal{O}_X)$ and any $m \in \mathbf{Z}$.

Proof. The first statement follows from Injectives, Lemma 13.6. Then we may apply More on Algebra, Remark 75.9 to $R \lim R\Gamma(U, K_n) = R\Gamma(U, R \lim K_n)$ to get the short exact sequences. \square

0BKP **Lemma 32.2.** *Let $f : (X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$ be a morphism of ringed spaces. Then Rf_* commutes with $R \lim$, i.e., Rf_* commutes with derived limits.*

Proof. Let (K_n) be an inverse system in $D(\mathcal{O}_X)$. Consider the defining distinguished triangle

$$R \lim K_n \rightarrow \prod K_n \rightarrow \prod K_n$$

in $D(\mathcal{O}_X)$. Applying the exact functor Rf_* we obtain the distinguished triangle

$$Rf_*(R \lim K_n) \rightarrow Rf_*\left(\prod K_n\right) \rightarrow Rf_*\left(\prod K_n\right)$$

in $D(\mathcal{O}_Y)$. Thus we see that it suffices to prove that Rf_* commutes with products in the derived category (which are not just given by products of complexes, see Injectives, Lemma 13.4). However, since Rf_* is a right adjoint by Lemma 29.1 this follows formally (see Categories, Lemma 24.4). Caution: Note that we cannot apply Categories, Lemma 24.4 directly as $R\lim K_n$ is not a limit in $D(\mathcal{O}_X)$. \square

0BKQ **Remark 32.3.** Let (X, \mathcal{O}_X) be a ringed space. Let (K_n) be an inverse system in $D(\mathcal{O}_X)$. Set $K = R\lim K_n$. For each n and m let $\mathcal{H}_n^m = H^m(K_n)$ be the m th cohomology sheaf of K_n and similarly set $\mathcal{H}^m = H^m(K)$. Let us denote $\underline{\mathcal{H}}_n^m$ the presheaf

$$U \mapsto \underline{\mathcal{H}}_n^m(U) = H^m(U, K_n)$$

Similarly we set $\underline{\mathcal{H}}^m(U) = H^m(U, K)$. By Lemma 30.3 we see that \mathcal{H}_n^m is the sheafification of $\underline{\mathcal{H}}_n^m$ and \mathcal{H}^m is the sheafification of $\underline{\mathcal{H}}^m$. Here is a diagram

$$\begin{array}{ccc} K & & \underline{\mathcal{H}}^m \longrightarrow \mathcal{H}^m \\ \parallel & & \downarrow \qquad \qquad \downarrow \\ R\lim K_n & & \lim \underline{\mathcal{H}}_n^m \longrightarrow \lim \mathcal{H}_n^m \end{array}$$

In general it may not be the case that $\lim \mathcal{H}_n^m$ is the sheafification of $\lim \underline{\mathcal{H}}_n^m$. If $U \subset X$ is an open, then we have short exact sequences

0BKR (32.3.1) $0 \rightarrow R^1 \lim \underline{\mathcal{H}}_n^{m-1}(U) \rightarrow \underline{\mathcal{H}}^m(U) \rightarrow \lim \underline{\mathcal{H}}_n^m(U) \rightarrow 0$

by Lemma 32.1.

The following lemma applies to an inverse system of quasi-coherent modules with surjective transition maps on a scheme.

0BKS **Lemma 32.4.** Let (X, \mathcal{O}_X) be a ringed space. Let (\mathcal{F}_n) be an inverse system of \mathcal{O}_X -modules. Let \mathcal{B} be a set of opens of X . Assume

- (1) every open of X has a covering whose members are elements of \mathcal{B} ,
- (2) $H^p(U, \mathcal{F}_n) = 0$ for $p > 0$ and $U \in \mathcal{B}$,
- (3) the inverse system $\mathcal{F}_n(U)$ has vanishing $R^1 \lim$ for $U \in \mathcal{B}$.

Then $R\lim \mathcal{F}_n = \lim \mathcal{F}_n$ and we have $H^p(U, \lim \mathcal{F}_n) = 0$ for $p > 0$ and $U \in \mathcal{B}$.

Proof. Set $K_n = \mathcal{F}_n$ and $K = R\lim \mathcal{F}_n$. Using the notation of Remark 32.3 and assumption (2) we see that for $U \in \mathcal{B}$ we have $\underline{\mathcal{H}}_n^m(U) = 0$ when $m \neq 0$ and $\underline{\mathcal{H}}_n^0(U) = \mathcal{F}_n(U)$. From Equation (32.3.1) and assumption (3) we see that $\underline{\mathcal{H}}^m(U) = 0$ when $m \neq 0$ and equal to $\lim \mathcal{F}_n(U)$ when $m = 0$. Sheafifying using (1) we find that $\mathcal{H}^m = 0$ when $m \neq 0$ and equal to $\lim \mathcal{F}_n$ when $m = 0$. Hence $K = \lim \mathcal{F}_n$. Since $H^m(U, K) = \underline{\mathcal{H}}^m(U) = 0$ for $m > 0$ (see above) we see that the second assertion holds. \square

0D61 **Lemma 32.5.** Let (X, \mathcal{O}_X) be a ringed space. Let (K_n) be an inverse system in $D(\mathcal{O}_X)$. Let $x \in X$ and $m \in \mathbf{Z}$. Assume there exist an integer $n(x)$ and a fundamental system \mathfrak{U}_x of open neighbourhoods of x such that for $U \in \mathfrak{U}_x$

- (1) $R^1 \lim H^{m-1}(U, K_n) = 0$, and
- (2) $H^m(U, K_n) \rightarrow H^m(U, K_{n(x)})$ is injective for $n \geq n(x)$.

Then the map on stalks $H^m(R\lim K_n)_x \rightarrow H^m(K_{n(x)})_x$ is injective.

Proof. Let γ be an element of $H^m(R \lim K_n)_x$ which maps to zero in $H^m(K_{n(x)})_x$. Since $H^m(R \lim K_n)$ is the sheafification of $U \mapsto H^m(U, R \lim K_n)$ (by Lemma 30.3) we can choose $U \in \mathfrak{U}_x$ and an element $\tilde{\gamma} \in H^m(U, R \lim K_n)$ mapping to γ . Then $\tilde{\gamma}$ maps to $\tilde{\gamma}_{n(x)} \in H^m(U, K_{n(x)})$. Using that $H^m(K_{n(x)})$ is the sheafification of $U \mapsto H^m(U, K_{n(x)})$ (by Lemma 30.3 again) we see that after shrinking U we may assume that $\tilde{\gamma}_{n(x)} = 0$. For this U we consider the short exact sequence

$$0 \rightarrow R^1 \lim H^{m-1}(U, K_n) \rightarrow H^m(U, R \lim K_n) \rightarrow \lim H^m(U, K_n) \rightarrow 0$$

of Lemma 32.1. By assumption (1) the group on the left is zero and by assumption (2) the group on the right maps injectively into $H^m(U, K_{n(x)})$. We conclude $\tilde{\gamma} = 0$ and hence $\gamma = 0$ as desired. \square

0D62 **Lemma 32.6.** *Let (X, \mathcal{O}_X) be a ringed space. Let $E \in D(\mathcal{O}_X)$. Assume that for every $x \in X$ there exist a function $p(x, -) : \mathbf{Z} \rightarrow \mathbf{Z}$ and a fundamental system \mathfrak{U}_x of open neighbourhoods of x such that*

$$H^p(U, H^{m-p}(E)) = 0 \text{ for } U \in \mathfrak{U}_x \text{ and } p > p(x, m)$$

Then the canonical map $E \rightarrow R \lim \tau_{\geq -n} E$ is an isomorphism in $D(\mathcal{O}_X)$.

Proof. Set $K_n = \tau_{\geq -n} E$ and $K = R \lim K_n$. The canonical map $E \rightarrow K$ comes from the canonical maps $E \rightarrow K_n = \tau_{\geq -n} E$. We have to show that $E \rightarrow K$ induces an isomorphism $H^m(E) \rightarrow H^m(K)$ of cohomology sheaves. In the rest of the proof we fix m . If $n \geq -m$, then the map $E \rightarrow \tau_{\geq -n} E = K_n$ induces an isomorphism $H^m(E) \rightarrow H^m(K_n)$. To finish the proof it suffices to show that for every $x \in X$ there exists an integer $n(x) \geq -m$ such that the map $H^m(K)_x \rightarrow H^m(K_{n(x)})_x$ is injective. Namely, then the composition

$$H^m(E)_x \rightarrow H^m(K)_x \rightarrow H^m(K_{n(x)})_x$$

is a bijection and the second arrow is injective, hence the first arrow is bijective. Set

$$n(x) = 1 + \max\{-m, p(x, m-1) - m, -1 + p(x, m) - m, -2 + p(x, m+1) - m\}.$$

so that in any case $n(x) \geq -m$. Claim: the maps

$$H^{m-1}(U, K_{n+1}) \rightarrow H^{m-1}(U, K_n) \quad \text{and} \quad H^m(U, K_{n+1}) \rightarrow H^m(U, K_n)$$

are isomorphisms for $n \geq n(x)$ and $U \in \mathfrak{U}_x$. The claim implies conditions (1) and (2) of Lemma 32.5 are satisfied and hence implies the desired injectivity. Recall (Derived Categories, Remark 12.4) that we have distinguished triangles

$$H^{-n-1}(E)[n+1] \rightarrow K_{n+1} \rightarrow K_n \rightarrow H^{-n-1}(E)[n+2]$$

Looking at the associated long exact cohomology sequence the claim follows if

$$H^{m+n}(U, H^{-n-1}(E)), \quad H^{m+n+1}(U, H^{-n-1}(E)), \quad H^{m+n+2}(U, H^{-n-1}(E))$$

are zero for $n \geq n(x)$ and $U \in \mathfrak{U}_x$. This follows from our choice of $n(x)$ and the assumption in the lemma. \square

0D63 **Lemma 32.7.** *Let (X, \mathcal{O}_X) be a ringed space. Let $E \in D(\mathcal{O}_X)$. Assume that for every $x \in X$ there exist an integer $d_x \geq 0$ and a fundamental system \mathfrak{U}_x of open neighbourhoods of x such that* [Spa88, Proposition 3.13]

$$H^p(U, H^q(E)) = 0 \text{ for } U \in \mathfrak{U}_x, \quad p > d_x, \quad \text{and } q < 0$$

Then the canonical map $E \rightarrow R \lim \tau_{\geq -n} E$ is an isomorphism in $D(\mathcal{O}_X)$.

Proof. This follows from Lemma 32.6 with $p(x, m) = d_x + \max(0, m)$. \square

08U2 **Lemma 32.8.** *Let (X, \mathcal{O}_X) be a ringed space. Let $E \in D(\mathcal{O}_X)$. Assume there exist a function $p(-) : \mathbf{Z} \rightarrow \mathbf{Z}$ and a set \mathcal{B} of opens of X such that*

- (1) *every open in X has a covering whose members are elements of \mathcal{B} , and*
- (2) *$H^p(U, H^{m-p}(E)) = 0$ for $p > p(m)$ and $U \in \mathcal{B}$.*

Then the canonical map $E \rightarrow R\lim \tau_{\geq -n} E$ is an isomorphism in $D(\mathcal{O}_X)$.

Proof. Apply Lemma 32.6 with $p(x, m) = p(m)$ and $\mathfrak{U}_x = \{U \in \mathcal{B} \mid x \in U\}$. \square

0D64 **Lemma 32.9.** *Let (X, \mathcal{O}_X) be a ringed space. Let $E \in D(\mathcal{O}_X)$. Assume there exist an integer $d \geq 0$ and a basis \mathcal{B} for the topology of X such that*

$$H^p(U, H^q(E)) = 0 \text{ for } U \in \mathcal{B}, p > d, \text{ and } q < 0$$

Then the canonical map $E \rightarrow R\lim \tau_{\geq -n} E$ is an isomorphism in $D(\mathcal{O}_X)$.

Proof. Apply Lemma 32.7 with $d_x = d$ and $\mathfrak{U}_x = \{U \in \mathcal{B} \mid x \in U\}$. \square

The lemmas above can be used to compute cohomology in certain situations.

0BKT **Lemma 32.10.** *Let (X, \mathcal{O}_X) be a ringed space. Let K be an object of $D(\mathcal{O}_X)$. Let \mathcal{B} be a set of opens of X . Assume*

- (1) *every open of X has a covering whose members are elements of \mathcal{B} ,*
- (2) *$H^p(U, H^q(K)) = 0$ for all $p > 0$, $q \in \mathbf{Z}$, and $U \in \mathcal{B}$.*

Then $H^q(U, K) = H^0(U, H^q(K))$ for $q \in \mathbf{Z}$ and $U \in \mathcal{B}$.

Proof. Observe that $K = R\lim \tau_{\geq -n} K$ by Lemma 32.9 with $d = 0$. Let $U \in \mathcal{B}$. By Equation (32.3.1) we get a short exact sequence

$$0 \rightarrow R^1 \lim H^{q-1}(U, \tau_{\geq -n} K) \rightarrow H^q(U, K) \rightarrow \lim H^q(U, \tau_{\geq -n} K) \rightarrow 0$$

Condition (2) implies $H^q(U, \tau_{\geq -n} K) = H^0(U, H^q(\tau_{\geq -n} K))$ for all q by using the spectral sequence of Example 29.9. The spectral sequence converges because $\tau_{\geq -n} K$ is bounded below. If $n > -q$ then we have $H^q(\tau_{\geq -n} K) = H^q(K)$. Thus the systems on the left and the right of the displayed short exact sequence are eventually constant with values $H^0(U, H^{q-1}(K))$ and $H^0(U, H^q(K))$. The lemma follows. \square

Here is another case where we can describe the derived limit.

0BKU **Lemma 32.11.** *Let (X, \mathcal{O}_X) be a ringed space. Let (K_n) be an inverse system of objects of $D(\mathcal{O}_X)$. Let \mathcal{B} be a set of opens of X . Assume*

- (1) *every open of X has a covering whose members are elements of \mathcal{B} ,*
- (2) *for all $U \in \mathcal{B}$ and all $q \in \mathbf{Z}$ we have*
 - (a) *$H^p(U, H^q(K_n)) = 0$ for $p > 0$,*
 - (b) *the inverse system $H^0(U, H^q(K_n))$ has vanishing $R^1 \lim$.*

Then $H^q(R\lim K_n) = \lim H^q(K_n)$ for $q \in \mathbf{Z}$.

Proof. Set $K = R\lim K_n$. We will use notation as in Remark 32.3. Let $U \in \mathcal{B}$. By Lemma 32.10 and (2)(a) we have $H^q(U, K_n) = H^0(U, H^q(K_n))$. Using that the functor $R\Gamma(U, -)$ commutes with derived limits we have

$$H^q(U, K) = H^q(R\lim R\Gamma(U, K_n)) = \lim H^0(U, H^q(K_n))$$

where the final equality follows from More on Algebra, Remark 75.9 and assumption (2)(b). Thus $H^q(U, K)$ is the inverse limit the sections of the sheaves $H^q(K_n)$ over

U . Since $\lim H^q(K_n)$ is a sheaf we find using assumption (1) that $H^q(K)$, which is the sheafification of the presheaf $U \mapsto H^q(U, K)$, is equal to $\lim H^q(K_n)$. This proves the lemma. \square

33. Producing K-injective resolutions

0719 Let (X, \mathcal{O}_X) be a ringed space. Let \mathcal{F}^\bullet be a complex of \mathcal{O}_X -modules. The category $\text{Mod}(\mathcal{O}_X)$ has enough injectives, hence we can use Derived Categories, Lemma 28.3 produce a diagram

$$\begin{array}{ccccc} \dots & \longrightarrow & \tau_{\geq -2} \mathcal{F}^\bullet & \longrightarrow & \tau_{\geq -1} \mathcal{F}^\bullet \\ & & \downarrow & & \downarrow \\ \dots & \longrightarrow & \mathcal{I}_2^\bullet & \longrightarrow & \mathcal{I}_1^\bullet \end{array}$$

in the category of complexes of \mathcal{O}_X -modules such that

- (1) the vertical arrows are quasi-isomorphisms,
- (2) \mathcal{I}_n^\bullet is a bounded below complex of injectives,
- (3) the arrows $\mathcal{I}_{n+1}^\bullet \rightarrow \mathcal{I}_n^\bullet$ are termwise split surjections.

The category of \mathcal{O}_X -modules has limits (they are computed on the level of presheaves), hence we can form the termwise limit $\mathcal{I}^\bullet = \lim_n \mathcal{I}_n^\bullet$. By Derived Categories, Lemmas 29.4 and 29.8 this is a K-injective complex. In general the canonical map

071A (33.0.1)
$$\mathcal{F}^\bullet \rightarrow \mathcal{I}^\bullet$$

may not be a quasi-isomorphism. In the following lemma we describe some conditions under which it is.

071B **Lemma 33.1.** *In the situation described above. Denote $\mathcal{H}^m = H^m(\mathcal{F}^\bullet)$ the m th cohomology sheaf. Let \mathcal{B} be a set of open subsets of X . Let $d \in \mathbf{N}$. Assume*

- (1) every open in X has a covering whose members are elements of \mathcal{B} ,
- (2) for every $U \in \mathcal{B}$ we have $H^p(U, \mathcal{H}^q) = 0$ for $p > d$ and $q < 0^3$.

Then (33.0.1) is a quasi-isomorphism.

Proof. By Derived Categories, Lemma 32.4 it suffices to show that the canonical map $\mathcal{F}^\bullet \rightarrow R\lim \tau_{\geq -n} \mathcal{F}^\bullet$ is an isomorphism. This is Lemma 32.9. \square

Here is a technical lemma about the cohomology sheaves of the inverse limit of a system of complexes of sheaves. In some sense this lemma is the wrong thing to try to prove as one should take derived limits and not actual inverse limits.

08BY **Lemma 33.2.** *Let (X, \mathcal{O}_X) be a ringed space. Let (\mathcal{F}_n^\bullet) be an inverse system of complexes of \mathcal{O}_X -modules. Let $m \in \mathbf{Z}$. Assume there exist a set \mathcal{B} of open subsets of X and an integer n_0 such that*

- (1) every open in X has a covering whose members are elements of \mathcal{B} ,
- (2) for every $U \in \mathcal{B}$
 - (a) the systems of abelian groups $\mathcal{F}_n^{m-2}(U)$ and $\mathcal{F}_n^{m-1}(U)$ have vanishing $R^1 \lim$ (for example these have the Mittag-Leffler condition),
 - (b) the system of abelian groups $H^{m-1}(\mathcal{F}_n^\bullet(U))$ has vanishing $R^1 \lim$ (for example it has the Mittag-Leffler condition), and
 - (c) we have $H^m(\mathcal{F}_n^\bullet(U)) = H^m(\mathcal{F}_{n_0}^\bullet(U))$ for all $n \geq n_0$.

³It suffices if $\forall m, \exists p(m), H^p(U, \mathcal{H}^{m-p}) = 0$ for $p > p(m)$, see Lemma 32.8.

Then the maps $H^m(\mathcal{F}^\bullet) \rightarrow \lim H^m(\mathcal{F}_n^\bullet) \rightarrow H^m(\mathcal{F}_{n_0}^\bullet)$ are isomorphisms of sheaves where $\mathcal{F}^\bullet = \lim \mathcal{F}_n^\bullet$ is the termwise inverse limit.

Proof. Let $U \in \mathcal{B}$. Note that $H^m(\mathcal{F}^\bullet(U))$ is the cohomology of

$$\lim_n \mathcal{F}_n^{m-2}(U) \rightarrow \lim_n \mathcal{F}_n^{m-1}(U) \rightarrow \lim_n \mathcal{F}_n^m(U) \rightarrow \lim_n \mathcal{F}_n^{m+1}(U)$$

in the third spot from the left. By assumptions (2)(a) and (2)(b) we may apply More on Algebra, Lemma 75.2 to conclude that

$$H^m(\mathcal{F}^\bullet(U)) = \lim H^m(\mathcal{F}_n^\bullet(U))$$

By assumption (2)(c) we conclude

$$H^m(\mathcal{F}^\bullet(U)) = H^m(\mathcal{F}_n^\bullet(U))$$

for all $n \geq n_0$. By assumption (1) we conclude that the sheafification of $U \mapsto H^m(\mathcal{F}^\bullet(U))$ is equal to the sheafification of $U \mapsto H^m(\mathcal{F}_n^\bullet(U))$ for all $n \geq n_0$. Thus the inverse system of sheaves $H^m(\mathcal{F}_n^\bullet)$ is constant for $n \geq n_0$ with value $H^m(\mathcal{F}^\bullet)$ which proves the lemma. \square

34. Čech cohomology of unbounded complexes

08BZ The construction of Section 26 isn't the "correct" one for unbounded complexes. The problem is that in the Stacks project we use direct sums in the totalization of a double complex and we would have to replace this by a product. Instead of doing so in this section we assume the covering is finite and we use the alternating Čech complex.

Let (X, \mathcal{O}_X) be a ringed space. Let \mathcal{F}^\bullet be a complex of presheaves of \mathcal{O}_X -modules. Let $\mathcal{U} : X = \bigcup_{i \in I} U_i$ be a **finite** open covering of X . Since the alternating Čech complex $\check{C}_{alt}^\bullet(\mathcal{U}, \mathcal{F})$ (Section 24) is functorial in the presheaf \mathcal{F} we obtain a double complex $\check{C}_{alt}^\bullet(\mathcal{U}, \mathcal{F}^\bullet)$. In this section we work with the associated total complex. The construction of $\text{Tot}(\check{C}_{alt}^\bullet(\mathcal{U}, \mathcal{F}^\bullet))$ is functorial in \mathcal{F}^\bullet . As well there is a functorial transformation

08C0 (34.0.1)
$$\Gamma(X, \mathcal{F}^\bullet) \longrightarrow \text{Tot}(\check{C}_{alt}^\bullet(\mathcal{U}, \mathcal{F}^\bullet))$$

of complexes defined by the following rule: The section $s \in \Gamma(X, \mathcal{F}^n)$ is mapped to the element $\alpha = \{\alpha_{i_0 \dots i_p}\}$ with $\alpha_{i_0} = s|_{U_{i_0}}$ and $\alpha_{i_0 \dots i_p} = 0$ for $p > 0$.

08C1 **Lemma 34.1.** *Let (X, \mathcal{O}_X) be a ringed space. Let $\mathcal{U} : X = \bigcup_{i \in I} U_i$ be a finite open covering. For a complex \mathcal{F}^\bullet of \mathcal{O}_X -modules there is a canonical map*

$$\text{Tot}(\check{C}_{alt}^\bullet(\mathcal{U}, \mathcal{F}^\bullet)) \longrightarrow R\Gamma(X, \mathcal{F}^\bullet)$$

functorial in \mathcal{F}^\bullet and compatible with (34.0.1).

Proof. Let \mathcal{I}^\bullet be a K-injective complex whose terms are injective \mathcal{O}_X -modules. The map (34.0.1) for \mathcal{I}^\bullet is a map $\Gamma(X, \mathcal{I}^\bullet) \rightarrow \text{Tot}(\check{C}_{alt}^\bullet(\mathcal{U}, \mathcal{I}^\bullet))$. This is a quasi-isomorphism of complexes of abelian groups as follows from Homology, Lemma 22.7 applied to the double complex $\check{C}_{alt}^\bullet(\mathcal{U}, \mathcal{I}^\bullet)$ using Lemmas 12.1 and 24.6. Suppose $\mathcal{F}^\bullet \rightarrow \mathcal{I}^\bullet$ is a quasi-isomorphism of \mathcal{F}^\bullet into a K-injective complex whose terms are injectives (Injectives, Theorem 12.6). Since $R\Gamma(X, \mathcal{F}^\bullet)$ is represented by the complex $\Gamma(X, \mathcal{I}^\bullet)$ we obtain the map of the lemma using

$$\text{Tot}(\check{C}_{alt}^\bullet(\mathcal{U}, \mathcal{F}^\bullet)) \longrightarrow \text{Tot}(\check{C}_{alt}^\bullet(\mathcal{U}, \mathcal{I}^\bullet)).$$

We omit the verification of functoriality and compatibilities. \square

08C2 **Lemma 34.2.** *Let (X, \mathcal{O}_X) be a ringed space. Let $\mathcal{U} : X = \bigcup_{i \in I} U_i$ be a finite open covering. Let \mathcal{F}^\bullet be a complex of \mathcal{O}_X -modules. Let \mathcal{B} be a set of open subsets of X . Assume*

- (1) *every open in X has a covering whose members are elements of \mathcal{B} ,*
- (2) *we have $U_{i_0 \dots i_p} \in \mathcal{B}$ for all $i_0, \dots, i_p \in I$,*
- (3) *for every $U \in \mathcal{B}$ and $p > 0$ we have*
 - (a) $H^p(U, \mathcal{F}^q) = 0$,
 - (b) $H^p(U, \text{Coker}(\mathcal{F}^{q-1} \rightarrow \mathcal{F}^q)) = 0$, and
 - (c) $H^p(U, H^q(\mathcal{F})) = 0$.

Then the map

$$\text{Tot}(\check{\mathcal{C}}_{alt}^\bullet(\mathcal{U}, \mathcal{F}^\bullet)) \longrightarrow R\Gamma(X, \mathcal{F}^\bullet)$$

of Lemma 34.1 is an isomorphism in $D(\text{Ab})$.

Proof. If \mathcal{F}^\bullet is bounded below, this follows from assumption (3)(a) and the spectral sequence of Lemma 26.1 and the fact that

$$\text{Tot}(\check{\mathcal{C}}_{alt}^\bullet(\mathcal{U}, \mathcal{F}^\bullet)) \longrightarrow \text{Tot}(\check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}^\bullet))$$

is a quasi-isomorphism by Lemma 24.6 (some details omitted). In general, by assumption (3)(c) we may choose a resolution $\mathcal{F}^\bullet \rightarrow \mathcal{I}^\bullet = \lim \mathcal{I}_n^\bullet$ as in Lemma 33.1. Then the map of the lemma becomes

$$\lim_n \text{Tot}(\check{\mathcal{C}}_{alt}^\bullet(\mathcal{U}, \tau_{\geq -n} \mathcal{F}^\bullet)) \longrightarrow \lim_n \Gamma(X, \mathcal{I}_n^\bullet)$$

Note that (3)(b) shows that $\tau_{\geq -n} \mathcal{F}^\bullet$ is a bounded below complex satisfying the hypothesis of the lemma. Thus the case of bounded below complexes shows each of the maps

$$\text{Tot}(\check{\mathcal{C}}_{alt}^\bullet(\mathcal{U}, \tau_{\geq -n} \mathcal{F}^\bullet)) \longrightarrow \Gamma(X, \mathcal{I}_n^\bullet)$$

is a quasi-isomorphism. The cohomologies of the complexes on the left hand side in given degree are eventually constant (as the alternating Čech complex is finite). Hence the same is true on the right hand side. Thus the cohomology of the limit on the right hand side is this constant value by Homology, Lemma 27.7 and we win. \square

35. Hom complexes

0A8K Let (X, \mathcal{O}_X) be a ringed space. Let \mathcal{L}^\bullet and \mathcal{M}^\bullet be two complexes of \mathcal{O}_X -modules. We construct a complex of \mathcal{O}_X -modules $\mathcal{H}om^\bullet(\mathcal{L}^\bullet, \mathcal{M}^\bullet)$. Namely, for each n we set

$$\mathcal{H}om^n(\mathcal{L}^\bullet, \mathcal{M}^\bullet) = \prod_{n=p+q} \mathcal{H}om_{\mathcal{O}_X}(\mathcal{L}^{-q}, \mathcal{M}^p)$$

It is a good idea to think of $\mathcal{H}om^n$ as the sheaf of \mathcal{O}_X -modules of all \mathcal{O}_X -linear maps from \mathcal{L}^\bullet to \mathcal{M}^\bullet (viewed as graded \mathcal{O}_X -modules) which are homogenous of degree n . In this terminology, we define the differential by the rule

$$d(f) = d_{\mathcal{M}} \circ f - (-1)^n f \circ d_{\mathcal{L}}$$

for $f \in \mathcal{H}om^n_{\mathcal{O}_X}(\mathcal{L}^\bullet, \mathcal{M}^\bullet)$. We omit the verification that $d^2 = 0$. This construction is a special case of Differential Graded Algebra, Example 19.6. It follows immediately from the construction that we have

$$0A8L \quad (35.0.1) \quad H^n(\Gamma(U, \mathcal{H}om^\bullet(\mathcal{L}^\bullet, \mathcal{M}^\bullet))) = \text{Hom}_{K(\mathcal{O}_U)}(\mathcal{L}^\bullet, \mathcal{M}^\bullet[n])$$

for all $n \in \mathbf{Z}$ and every open $U \subset X$.

0A8M **Lemma 35.1.** *Let (X, \mathcal{O}_X) be a ringed space. Given complexes $\mathcal{K}^\bullet, \mathcal{L}^\bullet, \mathcal{M}^\bullet$ of \mathcal{O}_X -modules there is an isomorphism*

$$\mathcal{H}om^\bullet(\mathcal{K}^\bullet, \mathcal{H}om^\bullet(\mathcal{L}^\bullet, \mathcal{M}^\bullet)) = \mathcal{H}om^\bullet(\text{Tot}(\mathcal{K}^\bullet \otimes_{\mathcal{O}_X} \mathcal{L}^\bullet), \mathcal{M}^\bullet)$$

of complexes of \mathcal{O}_X -modules functorial in $\mathcal{K}^\bullet, \mathcal{L}^\bullet, \mathcal{M}^\bullet$.

Proof. Omitted. Hint: This is proved in exactly the same way as More on Algebra, Lemma 65.1. \square

0A8N **Lemma 35.2.** *Let (X, \mathcal{O}_X) be a ringed space. Given complexes $\mathcal{K}^\bullet, \mathcal{L}^\bullet, \mathcal{M}^\bullet$ of \mathcal{O}_X -modules there is a canonical morphism*

$$\text{Tot}(\mathcal{H}om^\bullet(\mathcal{L}^\bullet, \mathcal{M}^\bullet) \otimes_{\mathcal{O}_X} \mathcal{H}om^\bullet(\mathcal{K}^\bullet, \mathcal{L}^\bullet)) \longrightarrow \mathcal{H}om^\bullet(\mathcal{K}^\bullet, \mathcal{M}^\bullet)$$

of complexes of \mathcal{O}_X -modules.

Proof. Omitted. Hint: This is proved in exactly the same way as More on Algebra, Lemma 65.2. \square

0A8P **Lemma 35.3.** *Let (X, \mathcal{O}_X) be a ringed space. Given complexes $\mathcal{K}^\bullet, \mathcal{L}^\bullet, \mathcal{M}^\bullet$ of \mathcal{O}_X -modules there is a canonical morphism*

$$\text{Tot}(\mathcal{H}om^\bullet(\mathcal{L}^\bullet, \mathcal{M}^\bullet) \otimes_{\mathcal{O}_X} \mathcal{K}^\bullet) \longrightarrow \mathcal{H}om^\bullet(\mathcal{H}om^\bullet(\mathcal{K}^\bullet, \mathcal{L}^\bullet), \mathcal{M}^\bullet)$$

of complexes of \mathcal{O}_X -modules functorial in all three complexes.

Proof. Omitted. Hint: This is proved in exactly the same way as More on Algebra, Lemma 65.3. \square

0BYR **Lemma 35.4.** *Let (X, \mathcal{O}_X) be a ringed space. Given complexes $\mathcal{K}^\bullet, \mathcal{L}^\bullet, \mathcal{M}^\bullet$ of \mathcal{O}_X -modules there is a canonical morphism*

$$\text{Tot}(\mathcal{K}^\bullet \otimes_{\mathcal{O}_X} \mathcal{H}om^\bullet(\mathcal{M}^\bullet, \mathcal{L}^\bullet)) \longrightarrow \mathcal{H}om^\bullet(\mathcal{M}^\bullet, \text{Tot}(\mathcal{K}^\bullet \otimes_{\mathcal{O}_X} \mathcal{L}^\bullet))$$

of complexes of \mathcal{O}_X -modules functorial in all three complexes.

Proof. Omitted. Hint: This is proved in exactly the same way as More on Algebra, Lemma 65.5. \square

0A8Q **Lemma 35.5.** *Let (X, \mathcal{O}_X) be a ringed space. Given complexes $\mathcal{K}^\bullet, \mathcal{L}^\bullet$ of \mathcal{O}_X -modules there is a canonical morphism*

$$\mathcal{K}^\bullet \longrightarrow \mathcal{H}om^\bullet(\mathcal{L}^\bullet, \text{Tot}(\mathcal{K}^\bullet \otimes_{\mathcal{O}_X} \mathcal{L}^\bullet))$$

of complexes of \mathcal{O}_X -modules functorial in both complexes.

Proof. Omitted. Hint: This is proved in exactly the same way as More on Algebra, Lemma 65.6. \square

0A8R **Lemma 35.6.** *Let (X, \mathcal{O}_X) be a ringed space. Let \mathcal{I}^\bullet be a K -injective complex of \mathcal{O}_X -modules. Let \mathcal{L}^\bullet be a complex of \mathcal{O}_X -modules. Then*

$$H^0(\Gamma(U, \mathcal{H}om^\bullet(\mathcal{L}^\bullet, \mathcal{I}^\bullet))) = \text{Hom}_{D(\mathcal{O}_U)}(L|_U, M|_U)$$

for all $U \subset X$ open.

Proof. We have

$$\begin{aligned} H^0(\Gamma(U, \mathcal{H}om^\bullet(\mathcal{L}^\bullet, \mathcal{I}^\bullet))) &= \text{Hom}_{K(\mathcal{O}_U)}(L|_U, M|_U) \\ &= \text{Hom}_{D(\mathcal{O}_U)}(L|_U, M|_U) \end{aligned}$$

The first equality is (35.0.1). The second equality is true because $\mathcal{I}^\bullet|_U$ is K-injective by Lemma 30.1. \square

0A8S **Lemma 35.7.** *Let (X, \mathcal{O}_X) be a ringed space. Let $(\mathcal{I}')^\bullet \rightarrow \mathcal{I}^\bullet$ be a quasi-isomorphism of K-injective complexes of \mathcal{O}_X -modules. Let $(\mathcal{L}')^\bullet \rightarrow \mathcal{L}^\bullet$ be a quasi-isomorphism of complexes of \mathcal{O}_X -modules. Then*

$$\mathcal{H}om^\bullet(\mathcal{L}^\bullet, (\mathcal{I}')^\bullet) \longrightarrow \mathcal{H}om^\bullet((\mathcal{L}')^\bullet, \mathcal{I}^\bullet)$$

is a quasi-isomorphism.

Proof. Let M be the object of $D(\mathcal{O}_X)$ represented by \mathcal{I}^\bullet and $(\mathcal{I}')^\bullet$. Let L be the object of $D(\mathcal{O}_X)$ represented by \mathcal{L}^\bullet and $(\mathcal{L}')^\bullet$. By Lemma 35.6 we see that the sheaves

$$H^0(\mathcal{H}om^\bullet(\mathcal{L}^\bullet, (\mathcal{I}')^\bullet)) \quad \text{and} \quad H^0(\mathcal{H}om^\bullet((\mathcal{L}')^\bullet, \mathcal{I}^\bullet))$$

are both equal to the sheaf associated to the presheaf

$$U \longmapsto \text{Hom}_{D(\mathcal{O}_U)}(L|_U, M|_U)$$

Thus the map is a quasi-isomorphism. \square

0A8T **Lemma 35.8.** *Let (X, \mathcal{O}_X) be a ringed space. Let \mathcal{I}^\bullet be a K-injective complex of \mathcal{O}_X -modules. Let \mathcal{L}^\bullet be a K-flat complex of \mathcal{O}_X -modules. Then $\mathcal{H}om^\bullet(\mathcal{L}^\bullet, \mathcal{I}^\bullet)$ is a K-injective complex of \mathcal{O}_X -modules.*

Proof. Namely, if \mathcal{K}^\bullet is an acyclic complex of \mathcal{O}_X -modules, then

$$\begin{aligned} \text{Hom}_{K(\mathcal{O}_X)}(\mathcal{K}^\bullet, \mathcal{H}om^\bullet(\mathcal{L}^\bullet, \mathcal{I}^\bullet)) &= H^0(\Gamma(X, \mathcal{H}om^\bullet(\mathcal{K}^\bullet, \mathcal{H}om^\bullet(\mathcal{L}^\bullet, \mathcal{I}^\bullet)))) \\ &= H^0(\Gamma(X, \mathcal{H}om^\bullet(\text{Tot}(\mathcal{K}^\bullet \otimes_{\mathcal{O}_X} \mathcal{L}^\bullet), \mathcal{I}^\bullet))) \\ &= \text{Hom}_{K(\mathcal{O}_X)}(\text{Tot}(\mathcal{K}^\bullet \otimes_{\mathcal{O}_X} \mathcal{L}^\bullet), \mathcal{I}^\bullet) \\ &= 0 \end{aligned}$$

The first equality by (35.0.1). The second equality by Lemma 35.1. The third equality by (35.0.1). The final equality because $\text{Tot}(\mathcal{K}^\bullet \otimes_{\mathcal{O}_X} \mathcal{L}^\bullet)$ is acyclic because \mathcal{L}^\bullet is K-flat (Definition 27.2) and because \mathcal{I}^\bullet is K-injective. \square

36. Internal hom in the derived category

08DH Let (X, \mathcal{O}_X) be a ringed space. Let L, M be objects of $D(\mathcal{O}_X)$. We would like to construct an object $R\mathcal{H}om(L, M)$ of $D(\mathcal{O}_X)$ such that for every third object K of $D(\mathcal{O}_X)$ there exists a canonical bijection

$$08DI \quad (36.0.1) \quad \text{Hom}_{D(\mathcal{O}_X)}(K, R\mathcal{H}om(L, M)) = \text{Hom}_{D(\mathcal{O}_X)}(K \otimes_{\mathcal{O}_X}^{\mathbf{L}} L, M)$$

Observe that this formula defines $R\mathcal{H}om(L, M)$ up to unique isomorphism by the Yoneda lemma (Categories, Lemma 3.5).

To construct such an object, choose a K-injective complex \mathcal{I}^\bullet representing M and any complex of \mathcal{O}_X -modules \mathcal{L}^\bullet representing L . Then we set

$$R\mathcal{H}om(L, M) = \mathcal{H}om^\bullet(\mathcal{L}^\bullet, \mathcal{I}^\bullet)$$

where the right hand side is the complex of \mathcal{O}_X -modules constructed in Section 35. This is well defined by Lemma 35.7. We get a functor

$$D(\mathcal{O}_X)^{opp} \times D(\mathcal{O}_X) \longrightarrow D(\mathcal{O}_X), \quad (K, L) \longmapsto R\mathcal{H}om(K, L)$$

As a prelude to proving (36.0.1) we compute the cohomology groups of $R\mathcal{H}om(K, L)$.

08DK **Lemma 36.1.** *Let (X, \mathcal{O}_X) be a ringed space. Let L, M be objects of $D(\mathcal{O}_X)$. For every open U we have*

$$H^0(U, R\mathcal{H}om(L, M)) = \text{Hom}_{D(\mathcal{O}_U)}(L|_U, M|_U)$$

and in particular $H^0(X, R\mathcal{H}om(L, M)) = \text{Hom}_{D(\mathcal{O}_X)}(L, M)$.

Proof. Choose a K-injective complex \mathcal{I}^\bullet of \mathcal{O}_X -modules representing M and a K-flat complex \mathcal{L}^\bullet representing L . Then $\mathcal{H}om^\bullet(\mathcal{L}^\bullet, \mathcal{I}^\bullet)$ is K-injective by Lemma 35.8. Hence we can compute cohomology over U by simply taking sections over U and the result follows from Lemma 35.6. \square

08DJ **Lemma 36.2.** *Let (X, \mathcal{O}_X) be a ringed space. Let K, L, M be objects of $D(\mathcal{O}_X)$. With the construction as described above there is a canonical isomorphism*

$$R\mathcal{H}om(K, R\mathcal{H}om(L, M)) = R\mathcal{H}om(K \otimes_{\mathcal{O}_X}^{\mathbf{L}} L, M)$$

in $D(\mathcal{O}_X)$ functorial in K, L, M which recovers (36.0.1) by taking $H^0(X, -)$.

Proof. Choose a K-injective complex \mathcal{I}^\bullet representing M and a K-flat complex of \mathcal{O}_X -modules \mathcal{L}^\bullet representing L . Let \mathcal{H}^\bullet be the complex described above. For any complex of \mathcal{O}_X -modules \mathcal{K}^\bullet we have

$$\mathcal{H}om^\bullet(\mathcal{K}^\bullet, \mathcal{H}om^\bullet(\mathcal{L}^\bullet, \mathcal{I}^\bullet)) = \mathcal{H}om^\bullet(\text{Tot}(\mathcal{K}^\bullet \otimes_{\mathcal{O}_X} \mathcal{L}^\bullet), \mathcal{I}^\bullet)$$

by Lemma 35.1. Note that the left hand side represents $R\mathcal{H}om(K, R\mathcal{H}om(L, M))$ (use Lemma 35.8) and that the right hand side represents $R\mathcal{H}om(K \otimes_{\mathcal{O}_X}^{\mathbf{L}} L, M)$. This proves the displayed formula of the lemma. Taking global sections and using Lemma 36.1 we obtain (36.0.1). \square

08DL **Lemma 36.3.** *Let (X, \mathcal{O}_X) be a ringed space. Let K, L be objects of $D(\mathcal{O}_X)$. The construction of $R\mathcal{H}om(K, L)$ commutes with restrictions to opens, i.e., for every open U we have $R\mathcal{H}om(K|_U, L|_U) = R\mathcal{H}om(K, L)|_U$.*

Proof. This is clear from the construction and Lemma 30.1. \square

08IO **Lemma 36.4.** *Let (X, \mathcal{O}_X) be a ringed space. The bifunctor $R\mathcal{H}om(-, -)$ transforms distinguished triangles into distinguished triangles in both variables.*

Proof. This follows from the observation that the assignment

$$(\mathcal{L}^\bullet, \mathcal{M}^\bullet) \longmapsto \mathcal{H}om^\bullet(\mathcal{L}^\bullet, \mathcal{M}^\bullet)$$

transforms a termwise split short exact sequences of complexes in either variable into a termwise split short exact sequence. Details omitted. \square

0A8U **Lemma 36.5.** *Let (X, \mathcal{O}_X) be a ringed space. Let K, L, M be objects of $D(\mathcal{O}_X)$. There is a canonical morphism*

$$R\mathcal{H}om(L, M) \otimes_{\mathcal{O}_X}^{\mathbf{L}} K \longrightarrow R\mathcal{H}om(R\mathcal{H}om(K, L), M)$$

in $D(\mathcal{O}_X)$ functorial in K, L, M .

Proof. Choose a K-injective complex \mathcal{I}^\bullet representing M , a K-injective complex \mathcal{J}^\bullet representing L , and a K-flat complex \mathcal{K}^\bullet representing K . The map is defined using the map

$$\mathrm{Tot}(\mathrm{Hom}^\bullet(\mathcal{J}^\bullet, \mathcal{I}^\bullet) \otimes_{\mathcal{O}_X} \mathcal{K}^\bullet) \longrightarrow \mathrm{Hom}^\bullet(\mathrm{Hom}^\bullet(\mathcal{K}^\bullet, \mathcal{J}^\bullet), \mathcal{I}^\bullet)$$

of Lemma 35.3. By our particular choice of complexes the left hand side represents $R\mathcal{H}om(L, M) \otimes_{\mathcal{O}_X}^{\mathbf{L}} K$ and the right hand side represents $R\mathcal{H}om(R\mathcal{H}om(K, L), M)$. We omit the proof that this is functorial in all three objects of $D(\mathcal{O}_X)$. \square

0A8V **Lemma 36.6.** *Let (X, \mathcal{O}_X) be a ringed space. Given K, L, M in $D(\mathcal{O}_X)$ there is a canonical morphism*

$$R\mathcal{H}om(L, M) \otimes_{\mathcal{O}_X}^{\mathbf{L}} R\mathcal{H}om(K, L) \longrightarrow R\mathcal{H}om(K, M)$$

in $D(\mathcal{O}_X)$ functorial in K, L, M .

Proof. Choose a K-injective complex \mathcal{I}^\bullet representing M , a K-injective complex \mathcal{J}^\bullet representing L , and any complex of \mathcal{O}_X -modules \mathcal{K}^\bullet representing K . By Lemma 35.2 there is a map of complexes

$$\mathrm{Tot}(\mathrm{Hom}^\bullet(\mathcal{J}^\bullet, \mathcal{I}^\bullet) \otimes_{\mathcal{O}_X} \mathrm{Hom}^\bullet(\mathcal{K}^\bullet, \mathcal{J}^\bullet)) \longrightarrow \mathrm{Hom}^\bullet(\mathcal{K}^\bullet, \mathcal{I}^\bullet)$$

The complexes of \mathcal{O}_X -modules $\mathrm{Hom}^\bullet(\mathcal{J}^\bullet, \mathcal{I}^\bullet)$, $\mathrm{Hom}^\bullet(\mathcal{K}^\bullet, \mathcal{J}^\bullet)$, and $\mathrm{Hom}^\bullet(\mathcal{K}^\bullet, \mathcal{I}^\bullet)$ represent $R\mathcal{H}om(L, M)$, $R\mathcal{H}om(K, L)$, and $R\mathcal{H}om(K, M)$. If we choose a K-flat complex \mathcal{H}^\bullet and a quasi-isomorphism $\mathcal{H}^\bullet \rightarrow \mathrm{Hom}^\bullet(\mathcal{K}^\bullet, \mathcal{J}^\bullet)$, then there is a map

$$\mathrm{Tot}(\mathrm{Hom}^\bullet(\mathcal{J}^\bullet, \mathcal{I}^\bullet) \otimes_{\mathcal{O}_X} \mathcal{H}^\bullet) \longrightarrow \mathrm{Tot}(\mathrm{Hom}^\bullet(\mathcal{J}^\bullet, \mathcal{I}^\bullet) \otimes_{\mathcal{O}_X} \mathrm{Hom}^\bullet(\mathcal{K}^\bullet, \mathcal{J}^\bullet))$$

whose source represents $R\mathcal{H}om(L, M) \otimes_{\mathcal{O}_X}^{\mathbf{L}} R\mathcal{H}om(K, L)$. Composing the two displayed arrows gives the desired map. We omit the proof that the construction is functorial. \square

0BYS **Lemma 36.7.** *Let (X, \mathcal{O}_X) be a ringed space. Given K, L, M in $D(\mathcal{O}_X)$ there is a canonical morphism*

$$K \otimes_{\mathcal{O}_X}^{\mathbf{L}} R\mathcal{H}om(M, L) \longrightarrow R\mathcal{H}om(M, K \otimes_{\mathcal{O}_X}^{\mathbf{L}} L)$$

in $D(\mathcal{O}_X)$ functorial in K, L, M .

Proof. Choose a K-flat complex \mathcal{K}^\bullet representing K , and a K-injective complex \mathcal{I}^\bullet representing L , and choose any complex of \mathcal{O}_X -modules \mathcal{M}^\bullet representing M . Choose a quasi-isomorphism $\mathrm{Tot}(\mathcal{K}^\bullet \otimes_{\mathcal{O}_X} \mathcal{I}^\bullet) \rightarrow \mathcal{J}^\bullet$ where \mathcal{J}^\bullet is K-injective. Then we use the map

$$\mathrm{Tot}(\mathcal{K}^\bullet \otimes_{\mathcal{O}_X} \mathrm{Hom}^\bullet(\mathcal{M}^\bullet, \mathcal{I}^\bullet)) \rightarrow \mathrm{Hom}^\bullet(\mathcal{M}^\bullet, \mathrm{Tot}(\mathcal{K}^\bullet \otimes_{\mathcal{O}_X} \mathcal{I}^\bullet)) \rightarrow \mathrm{Hom}^\bullet(\mathcal{M}^\bullet, \mathcal{J}^\bullet)$$

where the first map is the map from Lemma 35.4. \square

0A8W **Lemma 36.8.** *Let (X, \mathcal{O}_X) be a ringed space. Given K, L in $D(\mathcal{O}_X)$ there is a canonical morphism*

$$K \longrightarrow R\mathcal{H}om(L, K \otimes_{\mathcal{O}_X}^{\mathbf{L}} L)$$

in $D(\mathcal{O}_X)$ functorial in both K and L .

Proof. Choose a K-flat complex \mathcal{K}^\bullet representing K and any complex of \mathcal{O}_X -modules \mathcal{L}^\bullet representing L . Choose a K-injective complex \mathcal{J}^\bullet and a quasi-isomorphism $\mathrm{Tot}(\mathcal{K}^\bullet \otimes_{\mathcal{O}_X} \mathcal{L}^\bullet) \rightarrow \mathcal{J}^\bullet$. Then we use

$$\mathcal{K}^\bullet \rightarrow \mathrm{Hom}^\bullet(\mathcal{L}^\bullet, \mathrm{Tot}(\mathcal{K}^\bullet \otimes_{\mathcal{O}_X} \mathcal{L}^\bullet)) \rightarrow \mathrm{Hom}^\bullet(\mathcal{L}^\bullet, \mathcal{J}^\bullet)$$

where the first map comes from Lemma 35.5. \square

08I1 **Lemma 36.9.** *Let (X, \mathcal{O}_X) be a ringed space. Let L be an object of $D(\mathcal{O}_X)$. Set $L^\vee = R\mathcal{H}om(L, \mathcal{O}_X)$. For M in $D(\mathcal{O}_X)$ there is a canonical map*

$$08I2 \quad (36.9.1) \quad L^\vee \otimes_{\mathcal{O}_X}^{\mathbf{L}} M \longrightarrow R\mathcal{H}om(L, M)$$

which induces a canonical map

$$H^0(X, L^\vee \otimes_{\mathcal{O}_X}^{\mathbf{L}} M) \longrightarrow \mathrm{Hom}_{D(\mathcal{O}_X)}(L, M)$$

functorial in M in $D(\mathcal{O}_X)$.

Proof. The map (36.9.1) is a special case of Lemma 36.6 using the identification $M = R\mathcal{H}om(\mathcal{O}_X, M)$. \square

0B69 **Remark 36.10.** *Let $f : X \rightarrow Y$ be a morphism of ringed spaces. Let K, L be objects of $D(\mathcal{O}_X)$. We claim there is a canonical map*

$$Rf_* R\mathcal{H}om(L, K) \longrightarrow R\mathcal{H}om(Rf_* L, Rf_* K)$$

Namely, by (36.0.1) this is the same thing as a map $Rf_* R\mathcal{H}om(L, K) \otimes_{\mathcal{O}_Y}^{\mathbf{L}} Rf_* L \rightarrow Rf_* K$. For this we can use the composition

$$Rf_* R\mathcal{H}om(L, K) \otimes_{\mathcal{O}_Y}^{\mathbf{L}} Rf_* L \rightarrow Rf_*(R\mathcal{H}om(L, K) \otimes_{\mathcal{O}_X}^{\mathbf{L}} L) \rightarrow Rf_* K$$

where the first arrow is the relative cup product (Remark 29.6) and the second arrow is Rf_* applied to the canonical map $R\mathcal{H}om(L, K) \otimes_{\mathcal{O}_X}^{\mathbf{L}} L \rightarrow K$ coming from Lemma 36.6 (with \mathcal{O}_X in one of the spots).

08I3 **Remark 36.11.** *Let $h : X \rightarrow Y$ be a morphism of ringed spaces. Let K, L be objects of $D(\mathcal{O}_Y)$. We claim there is a canonical map*

$$Lh^* R\mathcal{H}om(K, L) \longrightarrow R\mathcal{H}om(Lh^* K, Lh^* L)$$

in $D(\mathcal{O}_X)$. Namely, by (36.0.1) proved in Lemma 36.2 such a map is the same thing as a map

$$Lh^* R\mathcal{H}om(K, L) \otimes^{\mathbf{L}} Lh^* K \longrightarrow Lh^* L$$

The source of this arrow is $Lh^*(\mathcal{H}om(K, L) \otimes^{\mathbf{L}} K)$ by Lemma 28.3 hence it suffices to construct a canonical map

$$R\mathcal{H}om(K, L) \otimes^{\mathbf{L}} K \longrightarrow L.$$

For this we take the arrow corresponding to

$$\mathrm{id} : R\mathcal{H}om(K, L) \longrightarrow R\mathcal{H}om(K, L)$$

via (36.0.1).

08I4 **Remark 36.12.** *Suppose that*

$$\begin{array}{ccc} X' & \xrightarrow{\quad h \quad} & X \\ f' \downarrow & & \downarrow f \\ S' & \xrightarrow{\quad g \quad} & S \end{array}$$

is a commutative diagram of ringed spaces. Let K, L be objects of $D(\mathcal{O}_X)$. We claim there exists a canonical base change map

$$Lg^* Rf_* R\mathcal{H}om(K, L) \longrightarrow R(f')_* R\mathcal{H}om(Lh^* K, Lh^* L)$$

in $D(\mathcal{O}_{S'})$. Namely, we take the map adjoint to the composition

$$\begin{aligned} L(f')^* Lg^* Rf_* R\mathcal{H}om(K, L) &= Lh^* Lf^* Rf_* R\mathcal{H}om(K, L) \\ &\rightarrow Lh^* R\mathcal{H}om(K, L) \\ &\rightarrow R\mathcal{H}om(Lh^* K, Lh^* L) \end{aligned}$$

where the first arrow uses the adjunction mapping $Lf^* Rf_* \rightarrow \text{id}$ and the second arrow is the canonical map constructed in Remark 36.11.

37. Ext sheaves

0BQP Let (X, \mathcal{O}_X) be a ringed space. Let $K, L \in D(\mathcal{O}_X)$. Using the construction of the internal hom in the derived category we obtain a well defined sheaves of \mathcal{O}_X -modules

$$\mathcal{E}xt^n(K, L) = H^n(R\mathcal{H}om(K, L))$$

by taking the n th cohomology sheaf of the object $R\mathcal{H}om(K, L)$ of $D(\mathcal{O}_X)$. We will sometimes write $\mathcal{E}xt_{\mathcal{O}_X}^n(K, L)$ for this object. By Lemma 36.1 we see that this $\mathcal{E}xt^n$ -sheaf is the sheafification of the rule

$$U \longmapsto \text{Ext}_{D(\mathcal{O}_U)}^n(K|_U, L|_U)$$

By Example 29.9 there is always a spectral sequence

$$E_2^{p,q} = H^p(X, \mathcal{E}xt^q(K, L))$$

converging to $\text{Ext}_{D(\mathcal{O}_X)}^{p+q}(K, L)$ in favorable situations (for example if L is bounded below and K is bounded above).

38. Global derived hom

0B6A Let (X, \mathcal{O}_X) be a ringed space. Let $K, L \in D(\mathcal{O}_X)$. Using the construction of the internal hom in the derived category we obtain a well defined object

$$R\text{Hom}(K, L) = R\Gamma(X, R\mathcal{H}om(K, L))$$

in $D(\Gamma(X, \mathcal{O}_X))$. We will sometimes write $R\text{Hom}_X(K, L)$ or $R\text{Hom}_{\mathcal{O}_X}(K, L)$ for this object. By Lemma 36.1 we have

$$H^0(R\text{Hom}(K, L)) = \text{Hom}_{D(\mathcal{O}_X)}(K, L), \quad H^p(R\text{Hom}(K, L)) = \text{Ext}_{D(\mathcal{O}_X)}^p(K, L)$$

If $f : Y \rightarrow X$ is a morphism of ringed spaces, then there is a canonical map

$$R\text{Hom}_X(K, L) \longrightarrow R\text{Hom}_Y(Lf^* K, Lf^* L)$$

in $D(\Gamma(X, \mathcal{O}_X))$ by taking global sections of the map defined in Remark 36.11.

39. Glueing complexes

0D65 We can glue complexes! More precisely, in certain circumstances we can glue locally given objects of the derived category to a global object. We first prove some easy cases and then we'll prove the very general [BBD82, Theorem 3.2.4] in the setting of topological spaces and open coverings.

08DG **Lemma 39.1.** *Let (X, \mathcal{O}_X) be a ringed space. Let $X = U \cup V$ be the union of two open subspaces of X . Suppose given*

- (1) *an object A of $D(\mathcal{O}_U)$,*
- (2) *an object B of $D(\mathcal{O}_V)$, and*
- (3) *an isomorphism $c : A|_{U \cap V} \rightarrow B|_{U \cap V}$.*

Then there exists an object F of $D(\mathcal{O}_X)$ and isomorphisms $f : F|_U \rightarrow A$, $g : F|_V \rightarrow B$ such that $c = g|_{U \cap V} \circ f^{-1}|_{U \cap V}$. Moreover, given

- (1) an object E of $D(\mathcal{O}_X)$,
- (2) a morphism $a : A \rightarrow E|_U$ of $D(\mathcal{O}_U)$,
- (3) a morphism $b : B \rightarrow E|_V$ of $D(\mathcal{O}_V)$,

such that

$$a|_{U \cap V} = b|_{U \cap V} \circ c.$$

Then there exists a morphism $F \rightarrow E$ in $D(\mathcal{O}_X)$ whose restriction to U is $a \circ f$ and whose restriction to V is $b \circ g$.

Proof. Denote $j_U, j_V, j_{U \cap V}$ the corresponding open immersions. Choose a distinguished triangle

$$F \rightarrow Rj_{U,*}A \oplus Rj_{V,*}B \rightarrow Rj_{U \cap V,*}(B|_{U \cap V}) \rightarrow F[1]$$

where the map $Rj_{V,*}B \rightarrow Rj_{U \cap V,*}(B|_{U \cap V})$ is the obvious one and where $Rj_{U,*}A \rightarrow Rj_{U \cap V,*}(B|_{U \cap V})$ is the composition of $Rj_{U,*}A \rightarrow Rj_{U \cap V,*}(A|_{U \cap V})$ with $Rj_{U \cap V,*}c$. Restricting to U we obtain

$$F|_U \rightarrow A \oplus (Rj_{V,*}B)|_U \rightarrow (Rj_{U \cap V,*}(B|_{U \cap V}))|_U \rightarrow F|_U[1]$$

Denote $j : U \cap V \rightarrow U$. Compatibility of restriction to opens and cohomology shows that both $(Rj_{V,*}B)|_U$ and $(Rj_{U \cap V,*}(B|_{U \cap V}))|_U$ are canonically isomorphic to $Rj_*(B|_{U \cap V})$. Hence the second arrow of the last displayed diagram has a section, and we conclude that the morphism $F|_U \rightarrow A$ is an isomorphism. Similarly, the morphism $F|_V \rightarrow B$ is an isomorphism. The existence of the morphism $F \rightarrow E$ follows from the Mayer-Vietoris sequence for Hom, see Lemma 31.3. \square

0D66 **Lemma 39.2.** *Let $f : (X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$ be a morphism of ringed spaces. Let \mathcal{B} be a basis for the topology on Y .*

- (1) *Assume K is in $D(\mathcal{O}_X)$ such that for $V \in \mathcal{B}$ we have $H^i(f^{-1}(V), K) = 0$ for $i < 0$. Then Rf_*K has vanishing cohomology sheaves in negative degrees, $H^i(f^{-1}(V), K) = 0$ for $i < 0$ for all opens $V \subset Y$, and the rule $V \mapsto H^0(f^{-1}V, K)$ is a sheaf on Y .*
- (2) *Assume K, L are in $D(\mathcal{O}_X)$ such that for $V \in \mathcal{B}$ we have $\text{Ext}^i(K|_{f^{-1}V}, L|_{f^{-1}V}) = 0$ for $i < 0$. Then $\text{Ext}^i(K|_{f^{-1}V}, L|_{f^{-1}V}) = 0$ for $i < 0$ for all opens $V \subset Y$ and the rule $V \mapsto \text{Hom}(K|_{f^{-1}V}, L|_{f^{-1}V})$ is a sheaf on Y .*

Proof. Lemma 30.6 tells us $H^i(Rf_*K)$ is the sheaf associated to the presheaf $V \mapsto H^i(f^{-1}(V), K) = H^i(V, Rf_*K)$. The assumptions in (1) imply that Rf_*K has vanishing cohomology sheaves in degrees < 0 . We conclude that for any open $V \subset Y$ the cohomology group $H^i(V, Rf_*K)$ is zero for $i < 0$ and is equal to $H^0(V, H^0(Rf_*K))$ for $i = 0$. This proves (1).

To prove (2) apply (1) to the complex $R\mathcal{H}om(K, L)$ using Lemma 36.1 to do the translation. \square

0D67 **Situation 39.3.** Let (X, \mathcal{O}_X) be a ringed space. We are given

- (1) a collection of opens \mathcal{B} of X ,
- (2) for $U \in \mathcal{B}$ an object K_U in $D(\mathcal{O}_U)$,
- (3) for $V \subset U$ with $V, U \in \mathcal{B}$ an isomorphism $\rho_V^U : K_U|_V \rightarrow K_V$ in $D(\mathcal{O}_V)$,

such that whenever we have $W \subset V \subset U$ with U, V, W in \mathcal{B} , then $\rho_W^U = \rho_W^V \circ \rho_V^U|_W$.

We won't be able to prove anything about this without making more assumptions. An interesting case is where \mathcal{B} is a basis for the topology on X . Another is the case where we have a morphism $f : X \rightarrow Y$ of topological spaces and the elements of \mathcal{B} are the inverse images of the elements of a basis for the topology of Y .

In Situation 39.3 a *solution* will be a pair (K, ρ_U) where K is an object of $D(\mathcal{O}_X)$ and $\rho_U : K|_U \rightarrow K_U$, $U \in \mathcal{B}$ are isomorphisms such that we have $\rho_V^U \circ \rho_U|_V = \rho_V$ for all $V \subset U$, $U, V \in \mathcal{B}$. In certain cases solutions are unique.

0D68 **Lemma 39.4.** *In Situation 39.3 assume*

$$(1) X = \bigcup_{U \in \mathcal{B}} U \text{ and for } U, V \in \mathcal{B} \text{ we have } U \cap V = \bigcup_{W \in \mathcal{B}, W \subset U \cap V} W,$$

$$(2) \text{ for any } U \in \mathcal{B} \text{ we have } \text{Ext}^i(K_U, K_U) = 0 \text{ for } i < 0.$$

If a solution (K, ρ_U) exists, then it is unique up to unique isomorphism and moreover $\text{Ext}^i(K, K) = 0$ for $i < 0$.

Proof. Let (K, ρ_U) and (K', ρ'_U) be a pair of solutions. Let $f : X \rightarrow Y$ be the continuous map constructed in Topology, Lemma 5.6. Set $\mathcal{O}_Y = f_*\mathcal{O}_X$. Then K, K' and \mathcal{B} are as in Lemma 39.2 part (2). Hence we obtain the vanishing of negative exts for K and we see that the rule

$$V \longmapsto \text{Hom}(K|_{f^{-1}V}, K'|_{f^{-1}V})$$

is a sheaf on Y . As both (K, ρ_U) and (K', ρ'_U) are solutions the maps

$$(\rho'_U)^{-1} \circ \rho_U : K|_U \longrightarrow K'|_U$$

over $U = f^{-1}(f(U))$ agree on overlaps. Hence we get a unique global section of the sheaf above which defines the desired isomorphism $K \rightarrow K'$ compatible with all structure available. \square

0D69 **Remark 39.5.** With notation and assumptions as in Lemma 39.4. Suppose that $U, V \in \mathcal{B}$. Let \mathcal{B}' be the set of elements of \mathcal{B} contained in $U \cap V$. Then

$$(\{K_{U'}\}_{U' \in \mathcal{B}'}, \{\rho_{V'}^{U'}\}_{V' \subset U' \text{ with } U', V' \in \mathcal{B}'})$$

is a system on the ringed space $U \cap V$ satisfying the assumptions of Lemma 39.4. Moreover, both $(K_U|_{U \cap V}, \rho_{U'}^U)$ and $(K_V|_{U \cap V}, \rho_{U'}^V)$ are solutions to this system. By the lemma we find a unique isomorphism

$$\rho_{U,V} : K_U|_{U \cap V} \longrightarrow K_V|_{U \cap V}$$

such that for every $U' \subset U \cap V$, $U' \in \mathcal{B}$ the diagram

$$\begin{array}{ccc} K_U|_{U'} & \xrightarrow{\rho_{U,V}|_{U'}} & K_V|_{U'} \\ & \searrow \rho_{U'}^U & \swarrow \rho_{U'}^V \\ & K_{U'} & \end{array}$$

commutes. Pick a third element $W \in \mathcal{B}$. We obtain isomorphisms $\rho_{U,W} : K_U|_{U \cap W} \rightarrow K_W|_{U \cap W}$ and $\rho_{V,W} : K_V|_{V \cap W} \rightarrow K_W|_{V \cap W}$ satisfying similar properties to those of $\rho_{U,V}$. Finally, we have

$$\rho_{U,W}|_{U \cap V \cap W} = \rho_{V,W}|_{U \cap V \cap W} \circ \rho_{U,V}|_{U \cap V \cap W}$$

This is true by the uniqueness in the lemma because both sides of the equality are the unique isomorphism compatible with the maps $\rho_{U''}^U$ and $\rho_{U''}^V$ for $U'' \subset U \cap V \cap W$, $U'' \in \mathcal{B}$. Some minor details omitted. The collection $(K_U, \rho_{U,V})$ is a descent datum

in the derived category for the open covering $\mathcal{U} : X = \bigcup_{U \in \mathcal{B}} U$ of X . In this language we are looking for “effectiveness of the descent datum” when we look for the existence of a solution.

0D6A **Lemma 39.6.** *In Situation 39.3 assume*

- (1) $X = U_1 \cup \dots \cup U_n$ with $U_i \in \mathcal{B}$,
- (2) for $U, V \in \mathcal{B}$ we have $U \cap V = \bigcup_{W \in \mathcal{B}, W \subset U \cap V} W$,
- (3) for any $U \in \mathcal{B}$ we have $\text{Ext}^i(K_U, K_U) = 0$ for $i < 0$.

Then a solution exists and is unique up to unique isomorphism.

Proof. Uniqueness was seen in Lemma 39.4. We may prove the lemma by induction on n . The case $n = 1$ is immediate.

The case $n = 2$. Consider the isomorphism $\rho_{U_1, U_2} : K_{U_1}|_{U_1 \cap U_2} \rightarrow K_{U_2}|_{U_1 \cap U_2}$ constructed in Remark 39.5. By Lemma 39.1 we obtain an object K in $D(\mathcal{O}_X)$ and isomorphisms $\rho_{U_1} : K|_{U_1} \rightarrow K_{U_1}$ and $\rho_{U_2} : K|_{U_2} \rightarrow K_{U_2}$ compatible with ρ_{U_1, U_2} . Take $U \in \mathcal{B}$. We will construct an isomorphism $\rho_U : K|_U \rightarrow K_U$ and we will leave it to the reader to verify that (K, ρ_U) is a solution. Consider the set \mathcal{B}' of elements of \mathcal{B} contained in either $U \cap U_1$ or contained in $U \cap U_2$. Then $(K_U, \rho_{U'}^U)$ is a solution for the system $(\{K_{U'}\}_{U' \in \mathcal{B}'}, \{\rho_{V'}^{U'}\}_{V' \subset U' \text{ with } U', V' \in \mathcal{B}'})$ on the ringed space U . We claim that $(K|_U, \tau_{U'})$ is another solution where $\tau_{U'}$ for $U' \in \mathcal{B}'$ is chosen as follows: if $U' \subset U_1$ then we take the composition

$$K|_{U'} \xrightarrow{\rho_{U_1}|_{U'}} K_{U_1}|_{U'} \xrightarrow{\rho_{U'}^{U_1}} K_{U'}$$

and if $U' \subset U_2$ then we take the composition

$$K|_{U'} \xrightarrow{\rho_{U_2}|_{U'}} K_{U_2}|_{U'} \xrightarrow{\rho_{U'}^{U_2}} K_{U'}.$$

To verify this is a solution use the property of the map ρ_{U_1, U_2} described in Remark 39.5 and the compatibility of ρ_{U_1} and ρ_{U_2} with ρ_{U_1, U_2} . Having said this we apply Lemma 39.4 to see that we obtain a unique isomorphism $K|_{U'} \rightarrow K_{U'}$ compatible with the maps $\tau_{U'}$ and $\rho_{U'}^U$ for $U' \in \mathcal{B}'$.

The case $n > 2$. Consider the open subspace $X' = U_1 \cup \dots \cup U_{n-1}$ and let \mathcal{B}' be the set of elements of \mathcal{B} contained in X' . Then we find a system $(\{K_{U'}\}_{U' \in \mathcal{B}'}, \{\rho_{V'}^{U'}\}_{U', V' \in \mathcal{B}'})$ on the ringed space X' to which we may apply our induction hypothesis. We find a solution $(K_{X'}, \rho_{U'}^{X'})$. Then we can consider the collection $\mathcal{B}^* = \mathcal{B} \cup \{X'\}$ of opens of X and we see that we obtain a system $(\{K_U\}_{U \in \mathcal{B}^*}, \{\rho_V^U\}_{V \subset U \text{ with } U, V \in \mathcal{B}^*})$. Note that this new system also satisfies condition (3) by Lemma 39.4 applied to the solution $K_{X'}$. For this system we have $X = X' \cup U_n$. This reduces us to the case $n = 2$ we worked out above. \square

0D6B **Lemma 39.7.** *Let X be a ringed space. Let E be a well ordered set and let*

$$X = \bigcup_{\alpha \in E} W_\alpha$$

be an open covering with $W_\alpha \subset W_{\alpha+1}$ and $W_\alpha = \bigcup_{\beta < \alpha} W_\beta$ if α is not a successor. Let K_α be an object of $D(\mathcal{O}_{W_\alpha})$ with $\text{Ext}^i(K_\alpha, K_\alpha) = 0$ for $i < 0$. Assume given isomorphisms $\rho_\beta^\alpha : K_\alpha|_{W_\beta} \rightarrow K_\beta$ in $D(\mathcal{O}_{W_\beta})$ for all $\beta < \alpha$ with $\rho_\gamma^\alpha = \rho_\gamma^\beta \circ \rho_\beta^\alpha|_{W_\gamma}$ for $\gamma < \beta < \alpha$. Then there exists an object K in $D(\mathcal{O}_X)$ and isomorphisms $K|_{W_\alpha} \rightarrow K_\alpha$ for $\alpha \in E$ compatible with the isomorphisms ρ_β^α .

Proof. In this proof $\alpha, \beta, \gamma, \dots$ represent elements of E . Choose a K-injective complex I_α^\bullet on W_α representing K_α . For $\beta < \alpha$ denote $j_{\beta, \alpha} : W_\beta \rightarrow W_\alpha$ the inclusion morphism. By transfinite induction, we will construct for all $\beta < \alpha$ a map of complexes

$$\tau_{\beta, \alpha} : (j_{\beta, \alpha})_! I_\beta^\bullet \longrightarrow I_\alpha^\bullet$$

representing the adjoint to the inverse of the isomorphism $\rho_\beta^\alpha : K_\alpha|_{W_\beta} \rightarrow K_\beta$. Moreover, we will do this in such that for $\gamma < \beta < \alpha$ we have

$$\tau_{\gamma, \alpha} = \tau_{\beta, \alpha} \circ (j_{\beta, \alpha})_! \tau_{\gamma, \beta}$$

as maps of complexes. Namely, suppose already given $\tau_{\gamma, \beta}$ composing correctly for all $\gamma < \beta < \alpha$. If $\alpha = \alpha' + 1$ is a successor, then we choose any map of complexes

$$(j_{\alpha', \alpha})_! I_{\alpha'}^\bullet \rightarrow I_\alpha^\bullet$$

which is adjoint to the inverse of the isomorphism $\rho_{\alpha'}^\alpha : K_\alpha|_{W_{\alpha'}} \rightarrow K_{\alpha'}$ (possible because I_α^\bullet is K-injective) and for any $\beta < \alpha'$ we set

$$\tau_{\beta, \alpha} = \tau_{\alpha', \alpha} \circ (j_{\alpha', \alpha})_! \tau_{\beta, \alpha'}$$

If α is not a successor, then we can consider the complex on W_α given by

$$C^\bullet = \operatorname{colim}_{\beta < \alpha} (j_{\beta, \alpha})_! I_\beta^\bullet$$

(termwise colimit) where the transition maps of the sequence are given by the maps $\tau_{\beta', \beta}$ for $\beta' < \beta < \alpha$. We claim that C^\bullet represents K_α . Namely, for $\beta < \alpha$ the restriction of the coprojection $(j_{\beta, \alpha})_! I_\beta^\bullet \rightarrow C^\bullet$ gives a map

$$\sigma_\beta : I_\beta^\bullet \longrightarrow C^\bullet|_{W_\beta}$$

which is a quasi-isomorphism: if $x \in W_\beta$ then looking at stalks we get

$$(C^\bullet)_x = \operatorname{colim}_{\beta' < \alpha} ((j_{\beta', \alpha})_! I_{\beta'}^\bullet)_x = \operatorname{colim}_{\beta \leq \beta' < \alpha} (I_{\beta'}^\bullet)_x \longleftarrow (I_\beta^\bullet)_x$$

which is a quasi-isomorphism. Here we used that taking stalks commutes with colimits, that filtered colimits are exact, and that the maps $(I_\beta^\bullet)_x \rightarrow (I_{\beta'}^\bullet)_x$ are quasi-isomorphisms for $\beta \leq \beta' < \alpha$. Hence $(C^\bullet, \sigma_\beta^{-1})$ is a solution to the system $(\{K_\beta\}_{\beta < \alpha}, \{\rho_{\beta'}^\beta\}_{\beta' < \beta < \alpha})$. Since $(K_\alpha, \rho_\beta^\alpha)$ is another solution we obtain a unique isomorphism $\sigma : K_\alpha \rightarrow C^\bullet$ in $D(\mathcal{O}_{W_\alpha})$ compatible with all our maps, see Lemma 39.6 (this is where we use the vanishing of negative ext groups). Choose a morphism $\tau : C^\bullet \rightarrow I_\alpha^\bullet$ of complexes representing σ . Then we set

$$\tau_{\beta, \alpha} = \tau|_{W_\beta} \circ \sigma_\beta$$

to get the desired maps. Finally, we take K to be the object of the derived category represented by the complex

$$K^\bullet = \operatorname{colim}_{\alpha \in E} (W_\alpha \rightarrow X)_! I_\alpha^\bullet$$

where the transition maps are given by our carefully constructed maps $\tau_{\beta, \alpha}$ for $\beta < \alpha$. Arguing exactly as above we see that for all α the restriction of the coprojection determines an isomorphism

$$K|_{W_\alpha} \longrightarrow K_\alpha$$

compatible with the given maps ρ_β^α . \square

Using transfinite induction we can prove the result in the general case.

0D6C **Theorem 39.8** (BBD gluing lemma). *In Situation 39.3 assume*

Special case of [BBD82, Theorem 3.2.4] without boundedness assumption.

- (1) $X = \bigcup_{U \in \mathcal{B}} U$,
- (2) for $U, V \in \mathcal{B}$ we have $U \cap V = \bigcup_{W \in \mathcal{B}, W \subset U \cap V} W$,
- (3) for any $U \in \mathcal{B}$ we have $\text{Ext}^i(K_U, K_U) = 0$ for $i < 0$.

Then there exists an object K of $D(\mathcal{O}_X)$ and isomorphisms $\rho_U : K|_U \rightarrow K_U$ in $D(\mathcal{O}_U)$ for $U \in \mathcal{B}$ such that $\rho_V^U \circ \rho_U|_V = \rho_V$ for all $V \subset U$ with $U, V \in \mathcal{B}$. The pair (K, ρ_U) is unique up to unique isomorphism.

Proof. A pair (K, ρ_U) is called a solution in the text above. The uniqueness follows from Lemma 39.4. If X has a finite covering by elements of \mathcal{B} (for example if X is quasi-compact), then the theorem is a consequence of Lemma 39.6. In the general case we argue in exactly the same manner, using transfinite induction and Lemma 39.7.

First we use transfinite induction to choose opens $W_\alpha \subset X$ for any ordinal α . Namely, we set $W_0 = \emptyset$. If $\alpha = \beta + 1$ is a successor, then either $W_\beta = X$ and we set $W_\alpha = X$ or $W_\beta \neq X$ and we set $W_\alpha = W_\beta \cup U_\alpha$ where $U_\alpha \in \mathcal{B}$ is not contained in W_β . If α is a limit ordinal we set $W_\alpha = \bigcup_{\beta < \alpha} W_\beta$. Then for large enough α we have $W_\alpha = X$. Observe that for every α the open W_α is a union of elements of \mathcal{B} . Hence if $\mathcal{B}_\alpha = \{U \in \mathcal{B}, U \subset W_\alpha\}$, then

$$S_\alpha = (\{K_U\}_{U \in \mathcal{B}_\alpha}, \{\rho_V^U\}_{V \subset U \text{ with } U, V \in \mathcal{B}_\alpha})$$

is a system as in Lemma 39.4 on the ringed space W_α .

We will show by transfinite induction that for every α the system S_α has a solution. This will prove the theorem as this system is the system given in the theorem for large α .

The case where $\alpha = \beta + 1$ is a successor ordinal. (This case was already treated in the proof of the lemma above but for clarity we repeat the argument.) Recall that $W_\alpha = W_\beta \cup U_\alpha$ for some $U_\alpha \in \mathcal{B}$ in this case. By induction hypothesis we have a solution $(K_{W_\beta}, \{\rho_U^{W_\beta}\}_{U \in \mathcal{B}_\beta})$ for the system S_β . Then we can consider the collection $\mathcal{B}_\alpha^* = \mathcal{B}_\alpha \cup \{W_\beta\}$ of opens of W_α and we see that we obtain a system $(\{K_U\}_{U \in \mathcal{B}_\alpha^*}, \{\rho_V^U\}_{V \subset U \text{ with } U, V \in \mathcal{B}_\alpha^*})$. Note that this new system also satisfies condition (3) by Lemma 39.4 applied to the solution K_{W_β} . For this system we have $W_\alpha = W_\beta \cup U_\alpha$. This reduces us to the case handled in Lemma 39.6.

The case where α is a limit ordinal. Recall that $W_\alpha = \bigcup_{\beta < \alpha} W_\beta$ in this case. For $\beta < \alpha$ let $(K_{W_\beta}, \{\rho_U^{W_\beta}\}_{U \in \mathcal{B}_\beta})$ be the solution for S_β . For $\gamma < \beta < \alpha$ the restriction $K_{W_\beta}|_{W_\gamma}$ endowed with the maps $\rho_U^{W_\beta}$, $U \in \mathcal{B}_\gamma$ is a solution for S_γ . By uniqueness we get unique isomorphisms $\rho_{W_\gamma}^{W_\beta} : K_{W_\beta}|_{W_\gamma} \rightarrow K_{W_\gamma}$ compatible with the maps $\rho_U^{W_\beta}$ and $\rho_U^{W_\gamma}$ for $U \in \mathcal{B}_\gamma$. These maps compose in the correct manner, i.e., $\rho_{W_\delta}^{W_\gamma} \circ \rho_{W_\gamma}^{W_\beta}|_{W_\delta} = \rho_{W_\delta}^{W_\beta}$ for $\delta < \gamma < \beta < \alpha$. Thus we may apply Lemma 39.7 (note that the vanishing of negative exts is true for K_{W_β} by Lemma 39.4 applied to the solution K_{W_β}) to obtain K_{W_α} and isomorphisms

$$\rho_{W_\beta}^{W_\alpha} : K_{W_\alpha}|_{W_\beta} \longrightarrow K_{W_\beta}$$

compatible with the maps $\rho_{W_\gamma}^{W_\beta}$ for $\gamma < \beta < \alpha$.

To show that K_{W_α} is a solution we still need to construct the isomorphisms $\rho_U^{W_\alpha} : K_{W_\alpha}|_U \rightarrow K_U$ for $U \in \mathcal{B}_\alpha$ satisfying certain compatibilities. We choose $\rho_U^{W_\alpha}$ to be

the unique map such that for any $\beta < \alpha$ and any $V \in \mathcal{B}_\beta$ with $V \subset U$ the diagram

$$\begin{array}{ccc} K_{W_\alpha}|_V & \xrightarrow{\rho_U^{W_\alpha}|_V} & K_U|_V \\ \rho_{W_\beta}^{W_\alpha}|_V \downarrow & & \downarrow \rho_U^V \\ K_{W_\beta} & \xrightarrow{\rho_V^{W_\beta}} & K_V \end{array}$$

This makes sense because

$$(\{K_V\}_{V \subset U, V \in \mathcal{B}_\beta \text{ for some } \beta < \alpha}, \{\rho_V^{V'}\}_{V \subset V' \text{ with } V, V' \subset U \text{ and } V, V' \in \mathcal{B}_\beta \text{ for some } \beta < \alpha})$$

is a system as in Lemma 39.4 on the ringed space U and because (K_U, ρ_U^U) and $(K_{W_\alpha}|_U, \rho_V^{W_\beta} \circ \rho_{W_\beta}^{W_\alpha}|_V)$ are both solutions for this system. This gives existence and uniqueness. We omit the proof that these maps satisfy the desired compatibilities (it is just bookkeeping). \square

40. Strictly perfect complexes

08C3 Strictly perfect complexes of modules are used to define the notions of pseudo-coherent and perfect complexes later on. They are defined as follows.

08C4 **Definition 40.1.** Let (X, \mathcal{O}_X) be a ringed space. Let \mathcal{E}^\bullet be a complex of \mathcal{O}_X -modules. We say \mathcal{E}^\bullet is *strictly perfect* if \mathcal{E}^i is zero for all but finitely many i and \mathcal{E}^i is a direct summand of a finite free \mathcal{O}_X -module for all i .

Warning: Since we do not assume that X is a locally ringed space, it may not be true that a direct summand of a finite free \mathcal{O}_X -module is finite locally free.

08C5 **Lemma 40.2.** *The cone on a morphism of strictly perfect complexes is strictly perfect.*

Proof. This is immediate from the definitions. \square

09J2 **Lemma 40.3.** *The total complex associated to the tensor product of two strictly perfect complexes is strictly perfect.*

Proof. Omitted. \square

09U6 **Lemma 40.4.** *Let $f : (X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$ be a morphism of ringed spaces. If \mathcal{F}^\bullet is a strictly perfect complex of \mathcal{O}_Y -modules, then $f^*\mathcal{F}^\bullet$ is a strictly perfect complex of \mathcal{O}_X -modules.*

Proof. The pullback of a finite free module is finite free. The functor f^* is additive functor hence preserves direct summands. The lemma follows. \square

08C6 **Lemma 40.5.** *Let (X, \mathcal{O}_X) be a ringed space. Given a solid diagram of \mathcal{O}_X -modules*

$$\begin{array}{ccc} \mathcal{E} & \longrightarrow & \mathcal{F} \\ & \searrow \text{dotted} & \uparrow p \\ & & \mathcal{G} \end{array}$$

with \mathcal{E} a direct summand of a finite free \mathcal{O}_X -module and p surjective, then a dotted arrow making the diagram commute exists locally on X .

Proof. We may assume $\mathcal{E} = \mathcal{O}_X^{\oplus n}$ for some n . In this case finding the dotted arrow is equivalent to lifting the images of the basis elements in $\Gamma(X, \mathcal{F})$. This is locally possible by the characterization of surjective maps of sheaves (Sheaves, Section 16). \square

08C7 **Lemma 40.6.** *Let (X, \mathcal{O}_X) be a ringed space.*

- (1) *Let $\alpha : \mathcal{E}^\bullet \rightarrow \mathcal{F}^\bullet$ be a morphism of complexes of \mathcal{O}_X -modules with \mathcal{E}^\bullet strictly perfect and \mathcal{F}^\bullet acyclic. Then α is locally on X homotopic to zero.*
- (2) *Let $\alpha : \mathcal{E}^\bullet \rightarrow \mathcal{F}^\bullet$ be a morphism of complexes of \mathcal{O}_X -modules with \mathcal{E}^\bullet strictly perfect, $\mathcal{E}^i = 0$ for $i < a$, and $H^i(\mathcal{F}^\bullet) = 0$ for $i \geq a$. Then α is locally on X homotopic to zero.*

Proof. The first statement follows from the second, hence we only prove (2). We will prove this by induction on the length of the complex \mathcal{E}^\bullet . If $\mathcal{E}^\bullet \cong \mathcal{E}[-n]$ for some direct summand \mathcal{E} of a finite free \mathcal{O}_X -module and integer $n \geq a$, then the result follows from Lemma 40.5 and the fact that $\mathcal{F}^{n-1} \rightarrow \text{Ker}(\mathcal{F}^n \rightarrow \mathcal{F}^{n+1})$ is surjective by the assumed vanishing of $H^n(\mathcal{F}^\bullet)$. If \mathcal{E}^i is zero except for $i \in [a, b]$, then we have a split exact sequence of complexes

$$0 \rightarrow \mathcal{E}^b[-b] \rightarrow \mathcal{E}^\bullet \rightarrow \sigma_{\leq b-1} \mathcal{E}^\bullet \rightarrow 0$$

which determines a distinguished triangle in $K(\mathcal{O}_X)$. Hence an exact sequence

$$\text{Hom}_{K(\mathcal{O}_X)}(\sigma_{\leq b-1} \mathcal{E}^\bullet, \mathcal{F}^\bullet) \rightarrow \text{Hom}_{K(\mathcal{O}_X)}(\mathcal{E}^\bullet, \mathcal{F}^\bullet) \rightarrow \text{Hom}_{K(\mathcal{O}_X)}(\mathcal{E}^b[-b], \mathcal{F}^\bullet)$$

by the axioms of triangulated categories. The composition $\mathcal{E}^b[-b] \rightarrow \mathcal{F}^\bullet$ is locally homotopic to zero, whence we may assume our map comes from an element in the left hand side of the displayed exact sequence above. This element is locally zero by induction hypothesis. \square

08C8 **Lemma 40.7.** *Let (X, \mathcal{O}_X) be a ringed space. Given a solid diagram of complexes of \mathcal{O}_X -modules*

$$\begin{array}{ccc} \mathcal{E}^\bullet & \xrightarrow{\alpha} & \mathcal{F}^\bullet \\ & \searrow \text{dotted} & \uparrow f \\ & & \mathcal{G}^\bullet \end{array}$$

with \mathcal{E}^\bullet strictly perfect, $\mathcal{E}^j = 0$ for $j < a$ and $H^j(f)$ an isomorphism for $j > a$ and surjective for $j = a$, then a dotted arrow making the diagram commute up to homotopy exists locally on X .

Proof. Our assumptions on f imply the cone $C(f)^\bullet$ has vanishing cohomology sheaves in degrees $\geq a$. Hence Lemma 40.6 guarantees there is an open covering $X = \bigcup U_i$ such that the composition $\mathcal{E}^\bullet \rightarrow \mathcal{F}^\bullet \rightarrow C(f)^\bullet$ is homotopic to zero over U_i . Since

$$\mathcal{G}^\bullet \rightarrow \mathcal{F}^\bullet \rightarrow C(f)^\bullet \rightarrow \mathcal{G}^\bullet[1]$$

restricts to a distinguished triangle in $K(\mathcal{O}_{U_i})$ we see that we can lift $\alpha|_{U_i}$ up to homotopy to a map $\alpha_i : \mathcal{E}^\bullet|_{U_i} \rightarrow \mathcal{G}^\bullet|_{U_i}$ as desired. \square

08C9 **Lemma 40.8.** *Let (X, \mathcal{O}_X) be a ringed space. Let $\mathcal{E}^\bullet, \mathcal{F}^\bullet$ be complexes of \mathcal{O}_X -modules with \mathcal{E}^\bullet strictly perfect.*

- (1) *For any element $\alpha \in \text{Hom}_{D(\mathcal{O}_X)}(\mathcal{E}^\bullet, \mathcal{F}^\bullet)$ there exists an open covering $X = \bigcup U_i$ such that $\alpha|_{U_i}$ is given by a morphism of complexes $\alpha_i : \mathcal{E}^\bullet|_{U_i} \rightarrow \mathcal{F}^\bullet|_{U_i}$.*

- (2) Given a morphism of complexes $\alpha : \mathcal{E}^\bullet \rightarrow \mathcal{F}^\bullet$ whose image in the group $\mathrm{Hom}_{D(\mathcal{O}_X)}(\mathcal{E}^\bullet, \mathcal{F}^\bullet)$ is zero, there exists an open covering $X = \bigcup U_i$ such that $\alpha|_{U_i}$ is homotopic to zero.

Proof. Proof of (1). By the construction of the derived category we can find a quasi-isomorphism $f : \mathcal{F}^\bullet \rightarrow \mathcal{G}^\bullet$ and a map of complexes $\beta : \mathcal{E}^\bullet \rightarrow \mathcal{G}^\bullet$ such that $\alpha = f^{-1}\beta$. Thus the result follows from Lemma 40.7. We omit the proof of (2). \square

08DM **Lemma 40.9.** *Let (X, \mathcal{O}_X) be a ringed space. Let $\mathcal{E}^\bullet, \mathcal{F}^\bullet$ be complexes of \mathcal{O}_X -modules with \mathcal{E}^\bullet strictly perfect. Then the internal hom $R\mathcal{H}om(\mathcal{E}^\bullet, \mathcal{F}^\bullet)$ is represented by the complex \mathcal{H}^\bullet with terms*

$$\mathcal{H}^n = \bigoplus_{n=p+q} \mathcal{H}om_{\mathcal{O}_X}(\mathcal{E}^{-q}, \mathcal{F}^p)$$

and differential as described in Section 36.

Proof. Choose a quasi-isomorphism $\mathcal{F}^\bullet \rightarrow \mathcal{I}^\bullet$ into a K-injective complex. Let $(\mathcal{H}')^\bullet$ be the complex with terms

$$(\mathcal{H}')^n = \prod_{n=p+q} \mathcal{H}om_{\mathcal{O}_X}(\mathcal{L}^{-q}, \mathcal{I}^p)$$

which represents $R\mathcal{H}om(\mathcal{E}^\bullet, \mathcal{F}^\bullet)$ by the construction in Section 36. It suffices to show that the map

$$\mathcal{H}^\bullet \longrightarrow (\mathcal{H}')^\bullet$$

is a quasi-isomorphism. Given an open $U \subset X$ we have by inspection

$$H^0(\mathcal{H}^\bullet(U)) = \mathrm{Hom}_{K(\mathcal{O}_U)}(\mathcal{E}^\bullet|_U, \mathcal{K}^\bullet|_U) \rightarrow H^0((\mathcal{H}')^\bullet(U)) = \mathrm{Hom}_{D(\mathcal{O}_U)}(\mathcal{E}^\bullet|_U, \mathcal{K}^\bullet|_U)$$

By Lemma 40.8 the sheafification of $U \mapsto H^0(\mathcal{H}^\bullet(U))$ is equal to the sheafification of $U \mapsto H^0((\mathcal{H}')^\bullet(U))$. A similar argument can be given for the other cohomology sheaves. Thus \mathcal{H}^\bullet is quasi-isomorphic to $(\mathcal{H}')^\bullet$ which proves the lemma. \square

08I5 **Lemma 40.10.** *Let (X, \mathcal{O}_X) be a ringed space. Let $\mathcal{E}^\bullet, \mathcal{F}^\bullet$ be complexes of \mathcal{O}_X -modules with*

- (1) $\mathcal{F}^n = 0$ for $n \ll 0$,
- (2) $\mathcal{E}^n = 0$ for $n \gg 0$, and
- (3) \mathcal{E}^n isomorphic to a direct summand of a finite free \mathcal{O}_X -module.

Then the internal hom $R\mathcal{H}om(\mathcal{E}^\bullet, \mathcal{F}^\bullet)$ is represented by the complex \mathcal{H}^\bullet with terms

$$\mathcal{H}^n = \bigoplus_{n=p+q} \mathcal{H}om_{\mathcal{O}_X}(\mathcal{E}^{-q}, \mathcal{F}^p)$$

and differential as described in Section 36.

Proof. Choose a quasi-isomorphism $\mathcal{F}^\bullet \rightarrow \mathcal{I}^\bullet$ where \mathcal{I}^\bullet is a bounded below complex of injectives. Note that \mathcal{I}^\bullet is K-injective (Derived Categories, Lemma 29.4). Hence the construction in Section 36 shows that $R\mathcal{H}om(\mathcal{E}^\bullet, \mathcal{F}^\bullet)$ is represented by the complex $(\mathcal{H}')^\bullet$ with terms

$$(\mathcal{H}')^n = \prod_{n=p+q} \mathcal{H}om_{\mathcal{O}_X}(\mathcal{E}^{-q}, \mathcal{I}^p) = \bigoplus_{n=p+q} \mathcal{H}om_{\mathcal{O}_X}(\mathcal{E}^{-q}, \mathcal{I}^p)$$

(equality because there are only finitely many nonzero terms). Note that \mathcal{H}^\bullet is the total complex associated to the double complex with terms $\mathcal{H}om_{\mathcal{O}_X}(\mathcal{E}^{-q}, \mathcal{F}^p)$ and similarly for $(\mathcal{H}')^\bullet$. The natural map $(\mathcal{H}')^\bullet \rightarrow \mathcal{H}^\bullet$ comes from a map of double

complexes. Thus to show this map is a quasi-isomorphism, we may use the spectral sequence of a double complex (Homology, Lemma 22.6)

$${}^l E_1^{p,q} = H^p(\mathcal{H}om_{\mathcal{O}_X}(\mathcal{E}^{-q}, \mathcal{F}^\bullet))$$

converging to $H^{p+q}(\mathcal{H}^\bullet)$ and similarly for $(\mathcal{H}')^\bullet$. To finish the proof of the lemma it suffices to show that $\mathcal{F}^\bullet \rightarrow \mathcal{I}^\bullet$ induces an isomorphism

$$H^p(\mathcal{H}om_{\mathcal{O}_X}(\mathcal{E}, \mathcal{F}^\bullet)) \longrightarrow H^p(\mathcal{H}om_{\mathcal{O}_X}(\mathcal{E}, \mathcal{I}^\bullet))$$

on cohomology sheaves whenever \mathcal{E} is a direct summand of a finite free \mathcal{O}_X -module. Since this is clear when \mathcal{E} is finite free the result follows. \square

41. Pseudo-coherent modules

08CA In this section we discuss pseudo-coherent complexes.

08CB **Definition 41.1.** Let (X, \mathcal{O}_X) be a ringed space. Let \mathcal{E}^\bullet be a complex of \mathcal{O}_X -modules. Let $m \in \mathbf{Z}$.

- (1) We say \mathcal{E}^\bullet is *m-pseudo-coherent* if there exists an open covering $X = \bigcup U_i$ and for each i a morphism of complexes $\alpha_i : \mathcal{E}_i^\bullet \rightarrow \mathcal{E}^\bullet|_{U_i}$ where \mathcal{E}_i is strictly perfect on U_i and $H^j(\alpha_i)$ is an isomorphism for $j > m$ and $H^m(\alpha_i)$ is surjective.
- (2) We say \mathcal{E}^\bullet is *pseudo-coherent* if it is *m-pseudo-coherent* for all m .
- (3) We say an object E of $D(\mathcal{O}_X)$ is *m-pseudo-coherent* (resp. *pseudo-coherent*) if and only if it can be represented by a *m-pseudo-coherent* (resp. *pseudo-coherent*) complex of \mathcal{O}_X -modules.

If X is quasi-compact, then an *m-pseudo-coherent* object of $D(\mathcal{O}_X)$ is in $D^-(\mathcal{O}_X)$. But this need not be the case if X is not quasi-compact.

08CC **Lemma 41.2.** Let (X, \mathcal{O}_X) be a ringed space. Let E be an object of $D(\mathcal{O}_X)$.

- (1) If there exists an open covering $X = \bigcup U_i$, strictly perfect complexes \mathcal{E}_i^\bullet on U_i , and maps $\alpha_i : \mathcal{E}_i^\bullet \rightarrow E|_{U_i}$ in $D(\mathcal{O}_{U_i})$ with $H^j(\alpha_i)$ an isomorphism for $j > m$ and $H^m(\alpha_i)$ surjective, then E is *m-pseudo-coherent*.
- (2) If E is *m-pseudo-coherent*, then any complex representing E is *m-pseudo-coherent*.

Proof. Let \mathcal{F}^\bullet be any complex representing E and let $X = \bigcup U_i$ and $\alpha_i : \mathcal{E}_i \rightarrow E|_{U_i}$ be as in (1). We will show that \mathcal{F}^\bullet is *m-pseudo-coherent* as a complex, which will prove (1) and (2) simultaneously. By Lemma 40.8 we can after refining the open covering $X = \bigcup U_i$ represent the maps α_i by maps of complexes $\alpha_i : \mathcal{E}_i^\bullet \rightarrow \mathcal{F}^\bullet|_{U_i}$. By assumption $H^j(\alpha_i)$ are isomorphisms for $j > m$, and $H^m(\alpha_i)$ is surjective whence \mathcal{F}^\bullet is *m-pseudo-coherent*. \square

09U7 **Lemma 41.3.** Let $f : (X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$ be a morphism of ringed spaces. Let E be an object of $D(\mathcal{O}_Y)$. If E is *m-pseudo-coherent*, then Lf^*E is *m-pseudo-coherent*.

Proof. Represent E by a complex \mathcal{E}^\bullet of \mathcal{O}_Y -modules and choose an open covering $Y = \bigcup V_i$ and $\alpha_i : \mathcal{E}_i^\bullet \rightarrow \mathcal{E}^\bullet|_{V_i}$ as in Definition 41.1. Set $U_i = f^{-1}(V_i)$. By Lemma 41.2 it suffices to show that $Lf^*\mathcal{E}^\bullet|_{U_i}$ is *m-pseudo-coherent*. Choose a distinguished triangle

$$\mathcal{E}_i^\bullet \rightarrow \mathcal{E}^\bullet|_{V_i} \rightarrow C \rightarrow \mathcal{E}_i^\bullet[1]$$

The assumption on α_i means exactly that the cohomology sheaves $H^j(C)$ are zero for all $j \geq m$. Denote $f_i : U_i \rightarrow V_i$ the restriction of f . Note that $Lf_i^*\mathcal{E}^\bullet|_{U_i} = Lf_i^*(\mathcal{E}|_{V_i})$. Applying Lf_i^* we obtain the distinguished triangle

$$Lf_i^*\mathcal{E}_i^\bullet \rightarrow Lf_i^*\mathcal{E}|_{V_i} \rightarrow Lf_i^*C \rightarrow Lf_i^*\mathcal{E}_i^\bullet[1]$$

By the construction of Lf_i^* as a left derived functor we see that $H^j(Lf_i^*C) = 0$ for $j \geq m$ (by the dual of Derived Categories, Lemma 17.1). Hence $H^j(Lf_i^*\alpha_i)$ is an isomorphism for $j > m$ and $H^m(Lf_i^*\alpha_i)$ is surjective. On the other hand, $Lf_i^*\mathcal{E}_i^\bullet = f_i^*\mathcal{E}_i^\bullet$ is strictly perfect by Lemma 40.4. Thus we conclude. \square

08CD **Lemma 41.4.** *Let (X, \mathcal{O}_X) be a ringed space and $m \in \mathbf{Z}$. Let (K, L, M, f, g, h) be a distinguished triangle in $D(\mathcal{O}_X)$.*

- (1) *If K is $(m+1)$ -pseudo-coherent and L is m -pseudo-coherent then M is m -pseudo-coherent.*
- (2) *If K and M are m -pseudo-coherent, then L is m -pseudo-coherent.*
- (3) *If L is $(m+1)$ -pseudo-coherent and M is m -pseudo-coherent, then K is $(m+1)$ -pseudo-coherent.*

Proof. Proof of (1). Choose an open covering $X = \bigcup U_i$ and maps $\alpha_i : \mathcal{K}_i^\bullet \rightarrow K|_{U_i}$ in $D(\mathcal{O}_{U_i})$ with \mathcal{K}_i^\bullet strictly perfect and $H^j(\alpha_i)$ isomorphisms for $j > m+1$ and surjective for $j = m+1$. We may replace \mathcal{K}_i^\bullet by $\sigma_{\geq m+1}\mathcal{K}_i^\bullet$ and hence we may assume that $\mathcal{K}_i^j = 0$ for $j < m+1$. After refining the open covering we may choose maps $\beta_i : \mathcal{L}_i^\bullet \rightarrow L|_{U_i}$ in $D(\mathcal{O}_{U_i})$ with \mathcal{L}_i^\bullet strictly perfect such that $H^j(\beta)$ is an isomorphism for $j > m$ and surjective for $j = m$. By Lemma 40.7 we can, after refining the covering, find maps of complexes $\gamma_i : \mathcal{K}^\bullet \rightarrow \mathcal{L}^\bullet$ such that the diagrams

$$\begin{array}{ccc} K|_{U_i} & \longrightarrow & L|_{U_i} \\ \alpha_i \uparrow & & \uparrow \beta_i \\ \mathcal{K}_i^\bullet & \xrightarrow{\gamma_i} & \mathcal{L}_i^\bullet \end{array}$$

are commutative in $D(\mathcal{O}_{U_i})$ (this requires representing the maps α_i, β_i and $K|_{U_i} \rightarrow L|_{U_i}$ by actual maps of complexes; some details omitted). The cone $C(\gamma_i)^\bullet$ is strictly perfect (Lemma 40.2). The commutativity of the diagram implies that there exists a morphism of distinguished triangles

$$(\mathcal{K}_i^\bullet, \mathcal{L}_i^\bullet, C(\gamma_i)^\bullet) \longrightarrow (K|_{U_i}, L|_{U_i}, M|_{U_i}).$$

It follows from the induced map on long exact cohomology sequences and Homology, Lemmas 5.19 and 5.20 that $C(\gamma_i)^\bullet \rightarrow M|_{U_i}$ induces an isomorphism on cohomology in degrees $> m$ and a surjection in degree m . Hence M is m -pseudo-coherent by Lemma 41.2.

Assertions (2) and (3) follow from (1) by rotating the distinguished triangle. \square

09J3 **Lemma 41.5.** *Let (X, \mathcal{O}_X) be a ringed space. Let K, L be objects of $D(\mathcal{O}_X)$.*

- (1) *If K is n -pseudo-coherent and $H^i(K) = 0$ for $i > a$ and L is m -pseudo-coherent and $H^j(L) = 0$ for $j > b$, then $K \otimes_{\mathcal{O}_X}^{\mathbf{L}} L$ is t -pseudo-coherent with $t = \max(m+a, n+b)$.*
- (2) *If K and L are pseudo-coherent, then $K \otimes_{\mathcal{O}_X}^{\mathbf{L}} L$ is pseudo-coherent.*

Proof. Proof of (1). By replacing X by the members of an open covering we may assume there exist strictly perfect complexes \mathcal{K}^\bullet and \mathcal{L}^\bullet and maps $\alpha : \mathcal{K}^\bullet \rightarrow K$ and $\beta : \mathcal{L}^\bullet \rightarrow L$ with $H^i(\alpha)$ and isomorphism for $i > n$ and surjective for $i = n$ and with $H^i(\beta)$ and isomorphism for $i > m$ and surjective for $i = m$. Then the map

$$\alpha \otimes^{\mathbf{L}} \beta : \mathrm{Tot}(\mathcal{K}^\bullet \otimes_{\mathcal{O}_X} \mathcal{L}^\bullet) \rightarrow K \otimes_{\mathcal{O}_X}^{\mathbf{L}} L$$

induces isomorphisms on cohomology sheaves in degree i for $i > t$ and a surjection for $i = t$. This follows from the spectral sequence of tors (details omitted).

Proof of (2). We may first replace X by the members of an open covering to reduce to the case that K and L are bounded above. Then the statement follows immediately from case (1). \square

08CE **Lemma 41.6.** *Let (X, \mathcal{O}_X) be a ringed space. Let $m \in \mathbf{Z}$. If $K \oplus L$ is m -pseudo-coherent (resp. pseudo-coherent) in $D(\mathcal{O}_X)$ so are K and L .*

Proof. Assume that $K \oplus L$ is m -pseudo-coherent. After replacing X by the members of an open covering we may assume $K \oplus L \in D^-(\mathcal{O}_X)$, hence $L \in D^-(\mathcal{O}_X)$. Note that there is a distinguished triangle

$$(K \oplus L, K \oplus L, L \oplus L[1]) = (K, K, 0) \oplus (L, L, L \oplus L[1])$$

see Derived Categories, Lemma 4.9. By Lemma 41.4 we see that $L \oplus L[1]$ is m -pseudo-coherent. Hence also $L[1] \oplus L[2]$ is m -pseudo-coherent. By induction $L[n] \oplus L[n+1]$ is m -pseudo-coherent. Since L is bounded above we see that $L[n]$ is m -pseudo-coherent for large n . Hence working backwards, using the distinguished triangles

$$(L[n], L[n] \oplus L[n-1], L[n-1])$$

we conclude that $L[n-1], L[n-2], \dots, L$ are m -pseudo-coherent as desired. \square

09V7 **Lemma 41.7.** *Let (X, \mathcal{O}_X) be a ringed space. Let $m \in \mathbf{Z}$. Let \mathcal{F}^\bullet be a (locally) bounded above complex of \mathcal{O}_X -modules such that \mathcal{F}^i is $(m-i)$ -pseudo-coherent for all i . Then \mathcal{F}^\bullet is m -pseudo-coherent.*

Proof. Omitted. Hint: use Lemma 41.4 and truncations as in the proof of More on Algebra, Lemma 60.10. \square

09V8 **Lemma 41.8.** *Let (X, \mathcal{O}_X) be a ringed space. Let $m \in \mathbf{Z}$. Let E be an object of $D(\mathcal{O}_X)$. If E is (locally) bounded above and $H^i(E)$ is $(m-i)$ -pseudo-coherent for all i , then E is m -pseudo-coherent.*

Proof. Omitted. Hint: use Lemma 41.4 and truncations as in the proof of More on Algebra, Lemma 60.11. \square

08DN **Lemma 41.9.** *Let (X, \mathcal{O}_X) be a ringed space. Let K be an object of $D(\mathcal{O}_X)$. Let $m \in \mathbf{Z}$.*

- (1) *If K is m -pseudo-coherent and $H^i(K) = 0$ for $i > m$, then $H^m(K)$ is a finite type \mathcal{O}_X -module.*
- (2) *If K is m -pseudo-coherent and $H^i(K) = 0$ for $i > m+1$, then $H^{m+1}(K)$ is a finitely presented \mathcal{O}_X -module.*

Proof. Proof of (1). We may work locally on X . Hence we may assume there exists a strictly perfect complex \mathcal{E}^\bullet and a map $\alpha : \mathcal{E}^\bullet \rightarrow K$ which induces an isomorphism on cohomology in degrees $> m$ and a surjection in degree m . It suffices to prove the result for \mathcal{E}^\bullet . Let n be the largest integer such that $\mathcal{E}^n \neq 0$. If $n = m$, then $H^m(\mathcal{E}^\bullet)$ is a quotient of \mathcal{E}^n and the result is clear. If $n > m$, then $\mathcal{E}^{n-1} \rightarrow \mathcal{E}^n$ is surjective as $H^n(\mathcal{E}^\bullet) = 0$. By Lemma 40.5 we can locally find a section of this surjection and write $\mathcal{E}^{n-1} = \mathcal{E}' \oplus \mathcal{E}^n$. Hence it suffices to prove the result for the complex $(\mathcal{E}')^\bullet$ which is the same as \mathcal{E}^\bullet except has \mathcal{E}' in degree $n-1$ and 0 in degree n . We win by induction on n .

Proof of (2). We may work locally on X . Hence we may assume there exists a strictly perfect complex \mathcal{E}^\bullet and a map $\alpha : \mathcal{E}^\bullet \rightarrow K$ which induces an isomorphism on cohomology in degrees $> m$ and a surjection in degree m . As in the proof of (1) we can reduce to the case that $\mathcal{E}^i = 0$ for $i > m+1$. Then we see that $H^{m+1}(K) \cong H^{m+1}(\mathcal{E}^\bullet) = \text{Coker}(\mathcal{E}^m \rightarrow \mathcal{E}^{m+1})$ which is of finite presentation. \square

09V9 **Lemma 41.10.** *Let (X, \mathcal{O}_X) be a ringed space. Let \mathcal{F} be a sheaf of \mathcal{O}_X -modules.*

- (1) *\mathcal{F} viewed as an object of $D(\mathcal{O}_X)$ is 0-pseudo-coherent if and only if \mathcal{F} is a finite type \mathcal{O}_X -module, and*
- (2) *\mathcal{F} viewed as an object of $D(\mathcal{O}_X)$ is (-1) -pseudo-coherent if and only if \mathcal{F} is an \mathcal{O}_X -module of finite presentation.*

Proof. Use Lemma 41.9 to prove the implications in one direction and Lemma 41.8 for the other. \square

42. Tor dimension

08CF In this section we take a closer look at resolutions by flat modules.

08CG **Definition 42.1.** Let (X, \mathcal{O}_X) be a ringed space. Let E be an object of $D(\mathcal{O}_X)$. Let $a, b \in \mathbf{Z}$ with $a \leq b$.

- (1) We say E has *tor-amplitude in $[a, b]$* if $H^i(E \otimes_{\mathcal{O}_X}^{\mathbf{L}} \mathcal{F}) = 0$ for all \mathcal{O}_X -modules \mathcal{F} and all $i \notin [a, b]$.
- (2) We say E has *finite tor dimension* if it has tor-amplitude in $[a, b]$ for some a, b .
- (3) We say E *locally has finite tor dimension* if there exists an open covering $X = \bigcup U_i$ such that $E|_{U_i}$ has finite tor dimension for all i .

Note that if E has finite tor dimension, then E is an object of $D^b(\mathcal{O}_X)$ as can be seen by taking $\mathcal{F} = \mathcal{O}_X$ in the definition above.

08CH **Lemma 42.2.** *Let (X, \mathcal{O}_X) be a ringed space. Let \mathcal{E}^\bullet be a bounded above complex of flat \mathcal{O}_X -modules with tor-amplitude in $[a, b]$. Then $\text{Coker}(d_{\mathcal{E}^\bullet}^{a-1})$ is a flat \mathcal{O}_X -module.*

Proof. As \mathcal{E}^\bullet is a bounded above complex of flat modules we see that $\mathcal{E}^\bullet \otimes_{\mathcal{O}_X} \mathcal{F} = \mathcal{E}^\bullet \otimes_{\mathcal{O}_X}^{\mathbf{L}} \mathcal{F}$ for any \mathcal{O}_X -module \mathcal{F} . Hence for every \mathcal{O}_X -module \mathcal{F} the sequence

$$\mathcal{E}^{a-2} \otimes_{\mathcal{O}_X} \mathcal{F} \rightarrow \mathcal{E}^{a-1} \otimes_{\mathcal{O}_X} \mathcal{F} \rightarrow \mathcal{E}^a \otimes_{\mathcal{O}_X} \mathcal{F}$$

is exact in the middle. Since $\mathcal{E}^{a-2} \rightarrow \mathcal{E}^{a-1} \rightarrow \mathcal{E}^a \rightarrow \text{Coker}(d^{a-1}) \rightarrow 0$ is a flat resolution this implies that $\text{Tor}_1^{\mathcal{O}_X}(\text{Coker}(d^{a-1}), \mathcal{F}) = 0$ for all \mathcal{O}_X -modules \mathcal{F} . This means that $\text{Coker}(d^{a-1})$ is flat, see Lemma 27.15. \square

08CI **Lemma 42.3.** *Let (X, \mathcal{O}_X) be a ringed space. Let E be an object of $D(\mathcal{O}_X)$. Let $a, b \in \mathbf{Z}$ with $a \leq b$. The following are equivalent*

- (1) *E has tor-amplitude in $[a, b]$.*
- (2) *E is represented by a complex \mathcal{E}^\bullet of flat \mathcal{O}_X -modules with $\mathcal{E}^i = 0$ for $i \notin [a, b]$.*

Proof. If (2) holds, then we may compute $E \otimes_{\mathcal{O}_X}^{\mathbf{L}} \mathcal{F} = \mathcal{E}^\bullet \otimes_{\mathcal{O}_X} \mathcal{F}$ and it is clear that (1) holds.

Assume that (1) holds. We may represent E by a bounded above complex of flat \mathcal{O}_X -modules \mathcal{K}^\bullet , see Section 27. Let n be the largest integer such that $\mathcal{K}^n \neq 0$. If $n > b$, then $\mathcal{K}^{n-1} \rightarrow \mathcal{K}^n$ is surjective as $H^n(\mathcal{K}^\bullet) = 0$. As \mathcal{K}^n is flat we see that $\text{Ker}(\mathcal{K}^{n-1} \rightarrow \mathcal{K}^n)$ is flat (Modules, Lemma 16.8). Hence we may replace \mathcal{K}^\bullet by $\tau_{\leq n-1} \mathcal{K}^\bullet$. Thus, by induction on n , we reduce to the case that \mathcal{K}^\bullet is a complex of flat \mathcal{O}_X -modules with $\mathcal{K}^i = 0$ for $i > b$.

Set $\mathcal{E}^\bullet = \tau_{\geq a} \mathcal{K}^\bullet$. Everything is clear except that \mathcal{E}^a is flat which follows immediately from Lemma 42.2 and the definitions. \square

09U8 **Lemma 42.4.** *Let $f : (X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$ be a morphism of ringed spaces. Let E be an object of $D(\mathcal{O}_Y)$. If E has tor amplitude in $[a, b]$, then Lf^*E has tor amplitude in $[a, b]$.*

Proof. Assume E has tor amplitude in $[a, b]$. By Lemma 42.3 we can represent E by a complex of \mathcal{E}^\bullet of flat \mathcal{O} -modules with $\mathcal{E}^i = 0$ for $i \notin [a, b]$. Then Lf^*E is represented by $f^*\mathcal{E}^\bullet$. By Modules, Lemma 18.2 the modules $f^*\mathcal{E}^i$ are flat. Thus by Lemma 42.3 we conclude that Lf^*E has tor amplitude in $[a, b]$. \square

09U9 **Lemma 42.5.** *Let (X, \mathcal{O}_X) be a ringed space. Let E be an object of $D(\mathcal{O}_X)$. Let $a, b \in \mathbf{Z}$ with $a \leq b$. The following are equivalent*

- (1) *E has tor-amplitude in $[a, b]$.*
- (2) *for every $x \in X$ the object E_x of $D(\mathcal{O}_{X,x})$ has tor-amplitude in $[a, b]$.*

Proof. Taking stalks at x is the same thing as pulling back by the morphism of ringed spaces $(x, \mathcal{O}_{X,x}) \rightarrow (X, \mathcal{O}_X)$. Hence the implication (1) \Rightarrow (2) follows from Lemma 42.4. For the converse, note that taking stalks commutes with tensor products (Modules, Lemma 15.1). Hence

$$(E \otimes_{\mathcal{O}_X}^{\mathbf{L}} \mathcal{F})_x = E_x \otimes_{\mathcal{O}_{X,x}}^{\mathbf{L}} \mathcal{F}_x$$

On the other hand, taking stalks is exact, so

$$H^i(E \otimes_{\mathcal{O}_X}^{\mathbf{L}} \mathcal{F})_x = H^i((E \otimes_{\mathcal{O}_X}^{\mathbf{L}} \mathcal{F})_x) = H^i(E_x \otimes_{\mathcal{O}_{X,x}}^{\mathbf{L}} \mathcal{F}_x)$$

and we can check whether $H^i(E \otimes_{\mathcal{O}_X}^{\mathbf{L}} \mathcal{F})$ is zero by checking whether all of its stalks are zero (Modules, Lemma 3.1). Thus (2) implies (1). \square

08CJ **Lemma 42.6.** *Let (X, \mathcal{O}_X) be a ringed space. Let (K, L, M, f, g, h) be a distinguished triangle in $D(\mathcal{O}_X)$. Let $a, b \in \mathbf{Z}$.*

- (1) *If K has tor-amplitude in $[a+1, b+1]$ and L has tor-amplitude in $[a, b]$ then M has tor-amplitude in $[a, b]$.*
- (2) *If K and M have tor-amplitude in $[a, b]$, then L has tor-amplitude in $[a, b]$.*
- (3) *If L has tor-amplitude in $[a+1, b+1]$ and M has tor-amplitude in $[a, b]$, then K has tor-amplitude in $[a+1, b+1]$.*

Proof. Omitted. Hint: This just follows from the long exact cohomology sequence associated to a distinguished triangle and the fact that $-\otimes_{\mathcal{O}_X}^{\mathbf{L}} \mathcal{F}$ preserves distinguished triangles. The easiest one to prove is (2) and the others follow from it by translation. \square

09J4 **Lemma 42.7.** *Let (X, \mathcal{O}_X) be a ringed space. Let K, L be objects of $D(\mathcal{O}_X)$. If K has tor-amplitude in $[a, b]$ and L has tor-amplitude in $[c, d]$ then $K \otimes_{\mathcal{O}_X}^{\mathbf{L}} L$ has tor amplitude in $[a + c, b + d]$.*

Proof. Omitted. Hint: use the spectral sequence for tors. \square

08CK **Lemma 42.8.** *Let (X, \mathcal{O}_X) be a ringed space. Let $a, b \in \mathbf{Z}$. For K, L objects of $D(\mathcal{O}_X)$ if $K \oplus L$ has tor amplitude in $[a, b]$ so do K and L .*

Proof. Clear from the fact that the Tor functors are additive. \square

43. Perfect complexes

08CL In this section we discuss properties of perfect complexes on ringed spaces.

08CM **Definition 43.1.** Let (X, \mathcal{O}_X) be a ringed space. Let \mathcal{E}^\bullet be a complex of \mathcal{O}_X -modules. We say \mathcal{E}^\bullet is *perfect* if there exists an open covering $X = \bigcup U_i$ such that for each i there exists a morphism of complexes $\mathcal{E}_i^\bullet \rightarrow \mathcal{E}^\bullet|_{U_i}$ which is a quasi-isomorphism with \mathcal{E}_i^\bullet a strictly perfect complex of \mathcal{O}_{U_i} -modules. An object E of $D(\mathcal{O}_X)$ is *perfect* if it can be represented by a perfect complex of \mathcal{O}_X -modules.

08CN **Lemma 43.2.** *Let (X, \mathcal{O}_X) be a ringed space. Let E be an object of $D(\mathcal{O}_X)$.*

- (1) *If there exists an open covering $X = \bigcup U_i$ and strictly perfect complexes \mathcal{E}_i^\bullet on U_i such that \mathcal{E}_i^\bullet represents $E|_{U_i}$ in $D(\mathcal{O}_{U_i})$, then E is perfect.*
- (2) *If E is perfect, then any complex representing E is perfect.*

Proof. Identical to the proof of Lemma 41.2. \square

0BCJ **Lemma 43.3.** *Let (X, \mathcal{O}_X) be a ringed space. Let E be an object of $D(\mathcal{O}_X)$. Assume that all stalks $\mathcal{O}_{X,x}$ are local rings. Then the following are equivalent*

- (1) *E is perfect,*
- (2) *there exists an open covering $X = \bigcup U_i$ such that $E|_{U_i}$ can be represented by a finite complex of finite locally free \mathcal{O}_{U_i} -modules, and*
- (3) *there exists an open covering $X = \bigcup U_i$ such that $E|_{U_i}$ can be represented by a finite complex of finite free \mathcal{O}_{U_i} -modules.*

Proof. This follows from Lemma 43.2 and the fact that on X every direct summand of a finite free module is finite locally free. See Modules, Lemma 14.6. \square

08CP **Lemma 43.4.** *Let (X, \mathcal{O}_X) be a ringed space. Let E be an object of $D(\mathcal{O}_X)$. Let $a \leq b$ be integers. If E has tor amplitude in $[a, b]$ and is $(a - 1)$ -pseudo-coherent, then E is perfect.*

Proof. After replacing X by the members of an open covering we may assume there exists a strictly perfect complex \mathcal{E}^\bullet and a map $\alpha : \mathcal{E}^\bullet \rightarrow E$ such that $H^i(\alpha)$ is an isomorphism for $i \geq a$. We may and do replace \mathcal{E}^\bullet by $\sigma_{\geq a-1} \mathcal{E}^\bullet$. Choose a distinguished triangle

$$\mathcal{E}^\bullet \rightarrow E \rightarrow C \rightarrow \mathcal{E}^\bullet[1]$$

From the vanishing of cohomology sheaves of E and \mathcal{E}^\bullet and the assumption on α we obtain $C \cong \mathcal{K}[a-2]$ with $\mathcal{K} = \text{Ker}(\mathcal{E}^{a-1} \rightarrow \mathcal{E}^a)$. Let \mathcal{F} be an \mathcal{O}_X -module. Applying $-\otimes_{\mathcal{O}_X}^{\mathbf{L}} \mathcal{F}$ the assumption that E has tor amplitude in $[a, b]$ implies $\mathcal{K} \otimes_{\mathcal{O}_X} \mathcal{F} \rightarrow \mathcal{E}^{a-1} \otimes_{\mathcal{O}_X} \mathcal{F}$ has image $\text{Ker}(\mathcal{E}^{a-1} \otimes_{\mathcal{O}_X} \mathcal{F} \rightarrow \mathcal{E}^a \otimes_{\mathcal{O}_X} \mathcal{F})$. It follows that $\text{Tor}_1^{\mathcal{O}_X}(\mathcal{E}', \mathcal{F}) = 0$ where $\mathcal{E}' = \text{Coker}(\mathcal{E}^{a-1} \rightarrow \mathcal{E}^a)$. Hence \mathcal{E}' is flat (Lemma 27.15). Thus \mathcal{E}' is locally a direct summand of a finite free module by Modules, Lemma 16.11. Thus locally the complex

$$\mathcal{E}' \rightarrow \mathcal{E}^{a-1} \rightarrow \dots \rightarrow \mathcal{E}^b$$

is quasi-isomorphic to E and E is perfect. \square

08CQ **Lemma 43.5.** *Let (X, \mathcal{O}_X) be a ringed space. Let E be an object of $D(\mathcal{O}_X)$. The following are equivalent*

- (1) E is perfect, and
- (2) E is pseudo-coherent and locally has finite tor dimension.

Proof. Assume (1). By definition this means there exists an open covering $X = \bigcup U_i$ such that $E|_{U_i}$ is represented by a strictly perfect complex. Thus E is pseudo-coherent (i.e., m -pseudo-coherent for all m) by Lemma 41.2. Moreover, a direct summand of a finite free module is flat, hence $E|_{U_i}$ has finite Tor dimension by Lemma 42.3. Thus (2) holds.

Assume (2). After replacing X by the members of an open covering we may assume there exist integers $a \leq b$ such that E has tor amplitude in $[a, b]$. Since E is m -pseudo-coherent for all m we conclude using Lemma 43.4. \square

09UA **Lemma 43.6.** *Let $f : (X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$ be a morphism of ringed spaces. Let E be an object of $D(\mathcal{O}_Y)$. If E is perfect in $D(\mathcal{O}_Y)$, then Lf^*E is perfect in $D(\mathcal{O}_X)$.*

Proof. This follows from Lemma 43.5, 42.4, and 41.3. (An alternative proof is to copy the proof of Lemma 41.3.) \square

08CR **Lemma 43.7.** *Let (X, \mathcal{O}_X) be a ringed space. Let (K, L, M, f, g, h) be a distinguished triangle in $D(\mathcal{O}_X)$. If two out of three of K, L, M are perfect then the third is also perfect.*

Proof. First proof: Combine Lemmas 43.5, 41.4, and 42.6. Second proof (sketch): Say K and L are perfect. After replacing X by the members of an open covering we may assume that K and L are represented by strictly perfect complexes \mathcal{K}^\bullet and \mathcal{L}^\bullet . After replacing X by the members of an open covering we may assume the map $K \rightarrow L$ is given by a map of complexes $\alpha : \mathcal{K}^\bullet \rightarrow \mathcal{L}^\bullet$, see Lemma 40.8. Then M is isomorphic to the cone of α which is strictly perfect by Lemma 40.2. \square

09J5 **Lemma 43.8.** *Let (X, \mathcal{O}_X) be a ringed space. If K, L are perfect objects of $D(\mathcal{O}_X)$, then so is $K \otimes_{\mathcal{O}_X}^{\mathbf{L}} L$.*

Proof. Follows from Lemmas 43.5, 41.5, and 42.7. \square

08CS **Lemma 43.9.** *Let (X, \mathcal{O}_X) be a ringed space. If $K \oplus L$ is a perfect object of $D(\mathcal{O}_X)$, then so are K and L .*

Proof. Follows from Lemmas 43.5, 41.6, and 42.8. \square

08DP **Lemma 43.10.** *Let (X, \mathcal{O}_X) be a ringed space. Let $j : U \rightarrow X$ be an open subspace. Let E be a perfect object of $D(\mathcal{O}_U)$ whose cohomology sheaves are supported on a closed subset $T \subset U$ with $j(T)$ closed in X . Then Rj_*E is a perfect object of $D(\mathcal{O}_X)$.*

Proof. Being a perfect complex is local on X . Thus it suffices to check that Rj_*E is perfect when restricted to U and $V = X \setminus j(T)$. We have $Rj_*E|_U = E$ which is perfect. We have $Rj_*E|_V = 0$ because $E|_{U \setminus T} = 0$. \square

08DQ **Lemma 43.11.** *Let (X, \mathcal{O}_X) be a ringed space. Let K be a perfect object of $D(\mathcal{O}_X)$. Then $K^\vee = R\mathcal{H}om(K, \mathcal{O}_X)$ is a perfect object too and $(K^\vee)^\vee = K$. There are functorial isomorphisms*

$$K^\vee \otimes_{\mathcal{O}_X}^{\mathbf{L}} M = R\mathcal{H}om(K, M)$$

and

$$H^0(X, K^\vee \otimes_{\mathcal{O}_X}^{\mathbf{L}} M) = \text{Hom}_{D(\mathcal{O}_X)}(K, M)$$

for M in $D(\mathcal{O}_X)$.

Proof. We will use without further mention that formation of internal hom commutes with restriction to opens (Lemma 36.3). In particular we may check the first two statements locally on X . By Lemma 36.9 to see the final statement it suffices to check that the map (36.9.1)

$$K^\vee \otimes_{\mathcal{O}_X}^{\mathbf{L}} M \longrightarrow R\mathcal{H}om(K, M)$$

is an isomorphism. This is local on X as well. Hence it suffices to prove the lemma when K is represented by a strictly perfect complex.

Assume K is represented by the strictly perfect complex \mathcal{E}^\bullet . Then it follows from Lemma 40.9 that K^\vee is represented by the complex whose terms are $(\mathcal{E}^{-n})^\vee = \mathcal{H}om_{\mathcal{O}_X}(\mathcal{E}^{-n}, \mathcal{O}_X)$ in degree n . Since \mathcal{E}^{-n} is a direct summand of a finite free \mathcal{O}_X -module, so is $(\mathcal{E}^{-n})^\vee$. Hence K^\vee is represented by a strictly perfect complex too. It is also clear that $(K^\vee)^\vee = K$ as we have $((\mathcal{E}^{-n})^\vee)^\vee = \mathcal{E}^{-n}$. To see that (36.9.1) is an isomorphism, represent M by a K -flat complex \mathcal{F}^\bullet . By Lemma 40.9 the complex $R\mathcal{H}om(K, M)$ is represented by the complex with terms

$$\bigoplus_{n=p+q} \mathcal{H}om_{\mathcal{O}_X}(\mathcal{E}^{-q}, \mathcal{F}^p)$$

On the other hand, then object $K^\vee \otimes_{\mathcal{O}_X}^{\mathbf{L}} M$ is represented by the complex with terms

$$\bigoplus_{n=p+q} \mathcal{F}^p \otimes_{\mathcal{O}_X} (\mathcal{E}^{-q})^\vee$$

Thus the assertion that (36.9.1) is an isomorphism reduces to the assertion that the canonical map

$$\mathcal{F} \otimes_{\mathcal{O}_X} \mathcal{H}om_{\mathcal{O}_X}(\mathcal{E}, \mathcal{O}_X) \longrightarrow \mathcal{H}om_{\mathcal{O}_X}(\mathcal{E}, \mathcal{F})$$

is an isomorphism when \mathcal{E} is a direct summand of a finite free \mathcal{O}_X -module and \mathcal{F} is any \mathcal{O}_X -module. This follows immediately from the corresponding statement when \mathcal{E} is finite free. \square

0DJ1 **Lemma 43.12.** *Let (X, \mathcal{O}_X) be a ringed space. Let $(K_n)_{n \in \mathbf{N}}$ be a system of perfect objects of $D(\mathcal{O}_X)$. Let $K = \text{hocolim} K_n$ be the derived colimit (Derived Categories, Definition 31.1). Then for any object E of $D(\mathcal{O}_X)$ we have*

$$R\mathcal{H}om(K, E) = R\lim E \otimes_{\mathcal{O}_X}^{\mathbf{L}} K_n^\vee$$

where (K_n^\vee) is the inverse system of dual perfect complexes.

Proof. By Lemma 43.11 we have $R\lim E \otimes_{\mathcal{O}_X}^{\mathbf{L}} K_n^\vee = R\lim R\mathcal{H}om(K_n, E)$ which fits into the distinguished triangle

$$R\lim R\mathcal{H}om(K_n, E) \rightarrow \prod R\mathcal{H}om(K_n, E) \rightarrow \prod R\mathcal{H}om(K_n, E)$$

Because K similarly fits into the distinguished triangle $\bigoplus K_n \rightarrow \bigoplus K_n \rightarrow K$ it suffices to show that $\prod R\mathcal{H}om(K_n, E) = R\mathcal{H}om(\bigoplus K_n, E)$. This is a formal consequence of (36.0.1) and the fact that derived tensor product commutes with direct sums. \square

44. Compact objects

09J6 In this section we study compact objects in the derived category of modules on a ringed space. We recall that compact objects are defined in Derived Categories, Definition 34.1. On suitable ringed spaces the perfect objects are compact.

09J7 **Lemma 44.1.** *Let X be a ringed space. Assume that the underlying topological space of X has the following properties:*

- (1) X is quasi-compact,
- (2) there exists a basis of quasi-compact open subsets, and
- (3) the intersection of any two quasi-compact opens is quasi-compact.

Then any perfect object of $D(\mathcal{O}_X)$ is compact.

Proof. Let K be a perfect object and let K^\vee be its dual, see Lemma 43.11. Then we have

$$\mathrm{Hom}_{D(\mathcal{O}_X)}(K, M) = H^0(X, K^\vee \otimes_{\mathcal{O}_X}^{\mathbf{L}} M)$$

functorially in M in $D(\mathcal{O}_X)$. Since $K^\vee \otimes_{\mathcal{O}_X}^{\mathbf{L}} -$ commutes with direct sums (by construction) and H^0 does by Lemma 20.1 and the construction of direct sums in Injectives, Lemma 13.4 we obtain the result of the lemma. \square

45. Projection formula

01E6 In this section we collect variants of the projection formula. The most basic version is Lemma 45.2. After we state and prove it, we discuss a more general version involving perfect complexes.

01E7 **Lemma 45.1.** *Let X be a ringed space. Let \mathcal{I} be an injective \mathcal{O}_X -module. Let \mathcal{E} be an \mathcal{O}_X -module. Assume \mathcal{E} is finite locally free on X , see Modules, Definition 14.1. Then $\mathcal{E} \otimes_{\mathcal{O}_X} \mathcal{I}$ is an injective \mathcal{O}_X -module.*

Proof. This is true because under the assumptions of the lemma we have

$$\mathrm{Hom}_{\mathcal{O}_X}(\mathcal{F}, \mathcal{E} \otimes_{\mathcal{O}_X} \mathcal{I}) = \mathrm{Hom}_{\mathcal{O}_X}(\mathcal{F} \otimes_{\mathcal{O}_X} \mathcal{E}^\vee, \mathcal{I})$$

where $\mathcal{E}^\vee = \mathcal{H}om_{\mathcal{O}_X}(\mathcal{E}, \mathcal{O}_X)$ is the dual of \mathcal{E} which is finite locally free also. Since tensoring with a finite locally free sheaf is an exact functor we win by Homology, Lemma 23.2. \square

01E8 **Lemma 45.2.** *Let $f : X \rightarrow Y$ be a morphism of ringed spaces. Let \mathcal{F} be an \mathcal{O}_X -module. Let \mathcal{E} be an \mathcal{O}_Y -module. Assume \mathcal{E} is finite locally free on Y , see Modules, Definition 14.1. Then there exist isomorphisms*

$$\mathcal{E} \otimes_{\mathcal{O}_Y} R^q f_* \mathcal{F} \longrightarrow R^q f_*(f^* \mathcal{E} \otimes_{\mathcal{O}_X} \mathcal{F})$$

for all $q \geq 0$. In fact there exists an isomorphism

$$\mathcal{E} \otimes_{\mathcal{O}_Y} Rf_* \mathcal{F} \longrightarrow Rf_*(f^* \mathcal{E} \otimes_{\mathcal{O}_X} \mathcal{F})$$

in $D^+(Y)$ functorial in \mathcal{F} .

Proof. Choose an injective resolution $\mathcal{F} \rightarrow \mathcal{I}^\bullet$ on X . Note that $f^* \mathcal{E}$ is finite locally free also, hence we get a resolution

$$f^* \mathcal{E} \otimes_{\mathcal{O}_X} \mathcal{F} \longrightarrow f^* \mathcal{E} \otimes_{\mathcal{O}_X} \mathcal{I}^\bullet$$

which is an injective resolution by Lemma 45.1. Apply f_* to see that

$$Rf_*(f^* \mathcal{E} \otimes_{\mathcal{O}_X} \mathcal{F}) = f_*(f^* \mathcal{E} \otimes_{\mathcal{O}_X} \mathcal{I}^\bullet).$$

Hence the lemma follows if we can show that $f_*(f^* \mathcal{E} \otimes_{\mathcal{O}_X} \mathcal{F}) = \mathcal{E} \otimes_{\mathcal{O}_Y} f_*(\mathcal{F})$ functorially in the \mathcal{O}_X -module \mathcal{F} . This is clear when $\mathcal{E} = \mathcal{O}_Y^{\oplus n}$, and follows in general by working locally on Y . Details omitted. \square

Let $f : X \rightarrow Y$ be a morphism of ringed spaces. Let $E \in D(\mathcal{O}_X)$ and $K \in D(\mathcal{O}_Y)$. Without any further assumptions there is a map

$$0B53 \quad (45.2.1) \quad Rf_* E \otimes_{\mathcal{O}_Y}^{\mathbf{L}} K \longrightarrow Rf_*(E \otimes_{\mathcal{O}_X}^{\mathbf{L}} Lf^* K)$$

Namely, it is the adjoint to the canonical map

$$Lf^*(Rf_* E \otimes_{\mathcal{O}_Y}^{\mathbf{L}} K) = Lf^* Rf_* E \otimes_{\mathcal{O}_X}^{\mathbf{L}} Lf^* K \longrightarrow E \otimes_{\mathcal{O}_X}^{\mathbf{L}} Lf^* K$$

coming from the map $Lf^* Rf_* E \rightarrow E$ and Lemmas 28.3 and 29.1. A reasonably general version of the projection formula is the following.

0B54 **Lemma 45.3.** *Let $f : X \rightarrow Y$ be a morphism of ringed spaces. Let $E \in D(\mathcal{O}_X)$ and $K \in D(\mathcal{O}_Y)$. If K is perfect, then*

$$Rf_* E \otimes_{\mathcal{O}_Y}^{\mathbf{L}} K = Rf_*(E \otimes_{\mathcal{O}_X}^{\mathbf{L}} Lf^* K)$$

in $D(\mathcal{O}_Y)$.

Proof. To check (45.2.1) is an isomorphism we may work locally on Y , i.e., we have to find a covering $\{V_j \rightarrow Y\}$ such that the map restricts to an isomorphism on V_j . By definition of perfect objects, this means we may assume K is represented by a strictly perfect complex of \mathcal{O}_Y -modules. Note that, completely generally, the statement is true for $K = K_1 \oplus K_2$, if and only if the statement is true for K_1 and K_2 . Hence we may assume K is a finite complex of finite free \mathcal{O}_Y -modules. In this case a simple argument involving stupid truncations reduces the statement to the case where K is represented by a finite free \mathcal{O}_Y -module. Since the statement is invariant under finite direct summands in the K variable, we conclude it suffices to prove it for $K = \mathcal{O}_Y[n]$ in which case it is trivial. \square

Here is a case where the projection formula is true in complete generality.

0B55 **Lemma 45.4.** *Let $f : X \rightarrow Y$ be a morphism of ringed spaces such that f is a homeomorphism onto a closed subset. Then (45.2.1) is an isomorphism always.*

Proof. Since f is a homeomorphism onto a closed subset, the functor f_* is exact (Modules, Lemma 6.1). Hence Rf_* is computed by applying f_* to any representative complex. Choose a K -flat complex \mathcal{K}^\bullet of \mathcal{O}_Y -modules representing K and choose any complex \mathcal{E}^\bullet of \mathcal{O}_X -modules representing E . Then $Lf^* K$ is represented by $f^* \mathcal{K}^\bullet$

which is a K-flat complex of \mathcal{O}_X -modules (Lemma 27.7). Thus the right hand side of (45.2.1) is represented by

$$f_* \text{Tot}(\mathcal{E}^\bullet \otimes_{\mathcal{O}_X} f^* \mathcal{K}^\bullet)$$

By the same reasoning we see that the left hand side is represented by

$$\text{Tot}(f_* \mathcal{E}^\bullet \otimes_{\mathcal{O}_Y} \mathcal{K}^\bullet)$$

Since f_* commutes with direct sums (Modules, Lemma 6.3) it suffices to show that

$$f_*(\mathcal{E} \otimes_{\mathcal{O}_X} f^* \mathcal{K}) = f_* \mathcal{E} \otimes_{\mathcal{O}_Y} \mathcal{K}$$

for any \mathcal{O}_X -module \mathcal{E} and \mathcal{O}_Y -module \mathcal{K} . We will check this by checking on stalks. Let $y \in Y$. If $y \notin f(X)$, then the stalks of both sides are zero. If $y = f(x)$, then we see that we have to show

$$\mathcal{E}_x \otimes_{\mathcal{O}_{X,x}} (\mathcal{O}_{X,x} \otimes_{\mathcal{O}_{Y,y}} \mathcal{F}_y) = \mathcal{E}_x \otimes_{\mathcal{O}_{Y,y}} \mathcal{F}_y$$

(using Sheaves, Lemma 32.1 and Lemma 26.4). This equality holds and therefore the lemma has been proved. \square

0B6B **Remark 45.5.** The map (45.2.1) is compatible with the base change map of Remark 29.3 in the following sense. Namely, suppose that

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

is a commutative diagram of ringed spaces. Let $E \in D(\mathcal{O}_X)$ and $K \in D(\mathcal{O}_Y)$. Then the diagram

$$\begin{array}{ccc} Lg^*(Rf_* E \otimes_{\mathcal{O}_Y}^{\mathbf{L}} K) & \xrightarrow{p} & Lg^* Rf_*(E \otimes_{\mathcal{O}_X}^{\mathbf{L}} Lf^* K) \\ \downarrow t & & \downarrow b \\ Lg^* Rf_* E \otimes_{\mathcal{O}_{Y'}}^{\mathbf{L}} Lg^* K & & Rf'_* L(g')^*(E \otimes_{\mathcal{O}_X}^{\mathbf{L}} Lf^* K) \\ \downarrow b & & \downarrow t \\ Rf'_* L(g')^* E \otimes_{\mathcal{O}_{Y'}}^{\mathbf{L}} Lg^* K & & Rf'_*(L(g')^* E \otimes_{\mathcal{O}_{Y'}}^{\mathbf{L}} L(g')^* Lf^* K) \\ & \searrow p & \downarrow c \\ & & Rf'_*(L(g')^* E \otimes_{\mathcal{O}_{Y'}}^{\mathbf{L}} L(f')^* Lg^* K) \end{array}$$

is commutative. Here arrows labeled t are gotten by an application of Lemma 28.3, arrows labeled b by an application of Remark 29.3, arrows labeled p by an application of (45.2.1), and c comes from $L(g')^* \circ Lf^* = L(f')^* \circ Lg^*$. We omit the verification.

46. Other chapters

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