COHOMOLOGY OF SHEAVES

01DW

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1. Introduction

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. Cohomology of sheaves

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 $\mathcal{F}[0] \to \mathcal{I}^\bullet$. As is customary we define

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

(2.0.1)

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

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

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

(2.0.2)

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

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 $\mathcal{F}[0] \to \mathcal{I}^\bullet$. As is customary we define

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

(2.0.3)

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

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

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

(2.0.4)
3. Derived functors

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

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

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

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

where $\mathcal{I}$ is the strictly full additive subcategory of $\text{Mod}(\mathcal{O}_X)$ consisting of injective sheaves. For any left exact functor $F : \text{Mod}(\mathcal{O}_X) \rightarrow \mathcal{B}$ 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:

\[ RF = F \circ j_X' : D^+(X) \longrightarrow D^+(\mathcal{B}) \]

see Derived Categories, Lemma [25.1] for notation. Note that we may think of $RF$ as defined on $\text{Mod}(\mathcal{O}_X)$, Comp$^+$($\text{Mod}(\mathcal{O}_X))$, $K^+(X)$, or $D^+(X)$ depending on the situation. According to Derived Categories, Definition [16.2] we obtain the $i$th right derived functor

\[ R^iF = H^i \circ RF : \text{Mod}(\mathcal{O}_X) \longrightarrow \mathcal{B} \]

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

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

\[ \Gamma(U, -) : D^+(X) \longrightarrow D^+(\mathcal{O}_X(U)) \]

by the discussion above. We set $H^i(U, -) = R^i \Gamma(U, -)$. If $U = X$ we recover [2.0.3]. If $f : X \rightarrow Y$ is a morphism of ringed spaces, then we have the left exact functor $f_* : \text{Mod}(\mathcal{O}_X) \longrightarrow \text{Mod}(\mathcal{O}_Y)$ which gives rise to the derived pushforward

\[ Rf_* : D^+(X) \longrightarrow D^+(Y) \]

The $i$th cohomology sheaf of $Rf_*\mathcal{F}^\bullet$ is denoted $R^if_*\mathcal{F}^\bullet$ and called the $i$th higher direct image in accordance with [2.0.4]. 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 \( \alpha \) is represented by a morphism of complexes. If we have an actual morphism of complexes we will say so.

4. First cohomology and torsors

**Definition 4.1.** 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 \( F \) on \( X \) endowed with an action \( \mathcal{G}(U) \times F(U) \to F(U) \) such that

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

A morphism of \( \mathcal{G} \)-torsors \( F \to F' \) 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.

**Lemma 4.2.** Let \( X \) be a topological space. Let \( \mathcal{G} \) be a sheaf of (possibly non-commutative) groups on \( X \). A \( \mathcal{G} \)-torsor \( F \) is trivial if and only if \( F(X) \neq \emptyset \).

**Proof.** Omitted.

**Lemma 4.3.** 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 \( \mathcal{H}(X) \).

**Proof.** Let \( F \) be a \( \mathcal{H} \)-torsor. Consider the free abelian sheaf \( \mathbb{Z}[F] \) on \( F \). 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 \( n_i \in \mathbb{Z} \) and \( s_i \in F(U) \). There is a natural map

\[
\sigma : \mathbb{Z}[F] \to \mathbb{Z}
\]

which to a local section \( \sum n_i [s_i] \) associates \( \sum n_i \). The kernel of \( \sigma \) is generated by the local section of the form \( [s] - [s'] \). There is a canonical map \( a : \text{Ker}(\sigma) \to \mathcal{H} \) 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

\[
\begin{array}{ccc}
0 & \longrightarrow & \text{Ker}(\sigma) & \longrightarrow & \mathbb{Z}[F] & \longrightarrow & Z & \longrightarrow & 0 \\
& & & \downarrow{=} & & \downarrow{=} & & & \\
0 & \longrightarrow & \mathcal{H} & \longrightarrow & \mathcal{E} & \longrightarrow & \mathbb{Z} & \longrightarrow & 0
\end{array}
\]

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 \( \xi = \xi_F \in H^1(X, \mathcal{H}) \) by applying the boundary operator to \( 1 \in H^0(X, \mathcal{H}) \).

Conversely, given \( \xi \in H^1(X, \mathcal{H}) \) we can associate to \( \xi \) a torsor as follows. Choose an embedding \( \mathcal{H} \to \mathcal{I} \) 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 \( \xi \) 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 \( F \subset \mathcal{I} \) be the subsheaf (of sets) of sections that map to \( q \) in the sheaf \( \mathcal{Q} \). It is easy to verify that \( F \) is a torsor.
We omit the verification that the two constructions given above are mutually inverse.

5. First cohomology and extensions

**Lemma 5.1.** 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

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

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 $\text{Mod}(\mathcal{O}_X)$. Set $\mathcal{Q} = \mathcal{I}/\mathcal{F}$.

By the long exact sequence of cohomology, we see that $\xi$ is the image of a section $\tilde{\xi} \in \Gamma(X, \mathcal{Q}) = \text{Hom}_{\mathcal{O}_X}(\mathcal{O}_X, \mathcal{Q})$. Now, we just form the pullback

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

see Homology, Section [6].

6. First cohomology and invertible sheaves

**Lemma 6.1.** Let $(X, \mathcal{O}_X)$ be a locally ringed space. There is a canonical isomorphism

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

of abelian groups.

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

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

This presheaf satisfies the sheaf condition. Moreover, if $f \in \mathcal{O}_X^\ast(U)$ and $s \in \mathcal{L}^\ast(U)$, then clearly $fs \in \mathcal{L}^\ast(U)$. By the same token, if $s, s' \in \mathcal{L}^\ast(U)$ then there exists a unique $f \in \mathcal{O}_X^\ast(U)$ such that $fs = s'$. Moreover, the sheaf $\mathcal{L}^\ast$ has sections locally by Modules, Lemma 23.4. In other words we see that $\mathcal{L}^\ast$ is a $\mathcal{O}_X^\ast$-torsor. Thus we get a map

invertible sheaves on $(X, \mathcal{O}_X) \rightarrow \text{O}_X^\ast$-torsors

up to isomorphism

We omit the verification that this is a homomorphism of abelian groups. By Lemma 4.3 the right hand side is canonically bijective to $H^1(X, \mathcal{O}_X^\ast)$. Thus we have to show this map is injective and surjective.

Injective. If the torsor $\mathcal{L}^\ast$ is trivial, this means by Lemma 4.2 that $\mathcal{L}^\ast$ has a global section. Hence this means exactly that $\mathcal{L} \cong \mathcal{O}_X$ is the neutral element in $\text{Pic}(X)$. 

09NT The Picard group of a ringed space is defined in Modules, Section [23].
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 \((s, g) + (s', g') = (s + s'/s)g'\) 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 \( \mathcal{F} \). \( \square \)

### 7. Locality of cohomology

#### Lemma 7.1
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 \( H^n(U, \mathcal{F}) = H^n(U, \mathcal{F}|_U) \).

**Proof.** Denote \( j : U \to X \) 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 \( \text{[31.8]} \). Moreover, \( j_! \) is exact. Hence (1) follows from Homology, Lemma \( \text{[29.1]} \).

By definition \( H^n(U, \mathcal{F}) = H^n(\Gamma(U, \mathcal{I}^*)) \) where \( \mathcal{F} \to \mathcal{I}^* \) is an injective resolution in \( \text{Mod} (\mathcal{O}_X) \). By the above we see that \( \mathcal{F}|_U \to \mathcal{I}^*|_U \) is an injective resolution in \( \text{Mod} (\mathcal{O}_U) \). Hence \( H^n(U, \mathcal{F}|_U) \) is equal to \( H^n(\Gamma(U, \mathcal{I}^*|_U)) \). 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

\[
H^n(V, \mathcal{F}) \to H^n(U, \mathcal{F}), \quad \xi \mapsto \xi|_U
\]

functorial in \( \mathcal{F} \). Namely, choose any injective resolution \( \mathcal{F} \to \mathcal{I}^* \). The restriction mappings of the sheaves \( \mathcal{I}^p \) give a morphism of complexes

\[
\Gamma(V, \mathcal{I}^*) \to \Gamma(U, \mathcal{I}^*)
\]

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 \( H^n(\mathcal{F}) \). We will give another interpretation of this presheaf in Lemma \( \text{[11.4]} \).

#### Lemma 7.2
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 \( \mathcal{F} \to \mathcal{I}^* \) be an injective resolution. Then
\[
H^n(U, \mathcal{F}) = \frac{\text{Ker}(\mathcal{I}^n(U) \to \mathcal{I}^{n+1}(U))}{\text{Im}(\mathcal{I}^{n-1}(U) \to \mathcal{I}^n(U))}.
\]

Pick an element \( \tilde{\xi} \in \mathcal{I}^n(U) \) representing the cohomology class in the presentation above. Since \( \mathcal{I}^* \) is an injective resolution of \( \mathcal{F} \) and \( n > 0 \) we see that the complex \( \mathcal{I}^* \) is exact in degree \( n \). Hence \( \text{Im}(\mathcal{I}^{n-1} \to \mathcal{I}^n) = \text{Ker}(\mathcal{I}^n \to \mathcal{I}^{n+1}) \) as sheaves. Since \( \tilde{\xi} \) is a section of the kernel sheaf over \( U \) we conclude there exists an open covering
Let $f : X \to Y$ be a morphism of ringed spaces. Let $\mathcal{F}$ be an $\mathcal{O}_X$-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 (7.1.1). There is a similar statement for $R^i f_* \mathcal{F}$ applied to a bounded below complex $\mathcal{F}^\bullet$.\hfill □

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

$$f_* \mathcal{I}^0 \to f_* \mathcal{I}^1 \to f_* \mathcal{I}^2 \to \ldots$$

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

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

and this is obviously equal to

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

which is equal to $H^i(f^{-1}(V), \mathcal{F})$ and we win.\hfill □
(3) Let \( f : X \to Y \) 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 \( 7.3 \) 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.

8. Mayer-Vietoris

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.

**Lemma 8.1.** 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 \( \mathcal{I}(U) \to \mathcal{I}(U') \) is surjective.

**Proof.** Let \( j : U \to X \) and \( j' : U' \to X \) be the open immersions. Recall that \( j_! \mathcal{O}_U \) is the extension by zero of \( \mathcal{O}_U \) on \( U \), see Sheaves, Section \( 31 \). Since \( j_! \) is 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

\[
\text{Hom}_{\mathcal{O}_X}(j_! \mathcal{O}_U, \mathcal{I}) \to \text{Hom}_{\mathcal{O}_X}(j_! \mathcal{O}_U, \mathcal{F})
\]

which corresponds to the restriction mapping \( \mathcal{F}(U) \to \mathcal{F}(U') \) 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

\[
\text{Hom}_{\mathcal{O}_X}(j_! \mathcal{O}_U, \mathcal{I}) \to \text{Hom}_{\mathcal{O}_X}(j_! \mathcal{O}_{U'}, \mathcal{I})
\]

is surjective, see Homology, Lemma \( 27.2 \). Putting everything together we obtain the lemma. \( \square \)

**Lemma 8.2** (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

\[
0 \to H^0(X, \mathcal{F}) \to H^0(U, \mathcal{F}) \oplus H^0(V, \mathcal{F}) \to H^0(U \cap V, \mathcal{F}) \to H^1(X, \mathcal{F}) \to \ldots
\]

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

**Proof.** The sheaf condition says that the kernel of \( (1, -1) : \mathcal{F}(U) \oplus \mathcal{F}(V) \to \mathcal{F}(U \cap V) \) is equal to the image of \( \mathcal{F}(X) \) by the first map for any abelian sheaf \( \mathcal{F} \). Lemma \( 8.1 \) above implies that the map \( (1, -1) : \mathcal{I}(U) \oplus \mathcal{I}(V) \to \mathcal{I}(U \cap V) \) is surjective whenever \( \mathcal{I} \) is an injective \( \mathcal{O}_X \)-module. Hence if \( \mathcal{F} \to \mathcal{I}^\bullet \) is an injective resolution of \( \mathcal{F} \), then we get a short exact sequence of complexes

\[
0 \to \mathcal{I}^\bullet(X) \to \mathcal{I}^\bullet(U) \oplus \mathcal{I}^\bullet(V) \to \mathcal{I}^\bullet(U \cap V) \to 0.
\]

Taking cohomology gives the result (use Homology, Lemma \( 13.12 \)). We omit the proof of the functoriality of the sequence. \( \square \)
Let \( f : X \to Y \) be a morphism of ringed spaces. Suppose that \( X = U \cup V \) is a union of two open subsets. Denote \( a = f|_U : U \to Y \), \( b = f|_V : V \to Y \), and \( c = f|_{U \cap V} : U \cap V \to Y \). For every \( \mathcal{O}_X \)-module \( \mathcal{F} \) there exists a long exact sequence

\[
0 \to f_* \mathcal{F} \to a_* (\mathcal{F}|_U) \oplus b_* (\mathcal{F}|_V) \to c_* (\mathcal{F}|_{U \cap V}) \to R^1 f_* \mathcal{F} \to \ldots
\]

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

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

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

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

\[
0 \to \mathcal{I}^n(f^{-1}(W)) \to \mathcal{I}^n(U \cap f^{-1}(W)) \oplus \mathcal{I}^n(V \cap f^{-1}(W)) \to \mathcal{I}^n(U \cap V \cap f^{-1}(W)) \to 0
\]

was shown to be short exact in the proof of Lemma 8.2. 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 7.1.

**9. The Čech complex and Čech cohomology**

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 \( U_{i_0 \ldots i_p} = U_{i_0} \cap \ldots \cap U_{i_p} \) for the \((p+1)\)-fold intersection of members of \( \mathcal{U} \). Let \( \mathcal{F} \) be an abelian presheaf on \( X \). Set

\[
\check{C}^p(\mathcal{U}, \mathcal{F}) = \prod_{(i_0, \ldots, i_p) \in I_{p+1}} \mathcal{F}(U_{i_0 \ldots i_p}).
\]

This is an abelian group. For \( s \in \check{C}^p(\mathcal{U}, \mathcal{F}) \) we denote \( s_{i_0 \ldots i_p} \) its value in \( \mathcal{F}(U_{i_0 \ldots i_p}) \). 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 23). We define

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

by the formula

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

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

**Definition 9.1.** 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 \( \check{C}^*(\mathcal{U}, \mathcal{F}) \) is the Čech complex associated to \( \mathcal{F} \) and the open covering \( \mathcal{U} \). Its cohomology groups \( H^i(\check{C}^*(\mathcal{U}, \mathcal{F})) \) are called the Čech cohomology groups associated to \( \mathcal{F} \) and the covering \( \mathcal{U} \). They are denoted \( H^i(\mathcal{U}, \mathcal{F}) \).

**Lemma 9.2.** 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. \( \check{C}^*(\mathcal{U}, \mathcal{F}) \) is a sheafification of \( \mathcal{F} \).
for every open covering \( U : U = \bigcup_{i \in I} U_i \) the natural map
\[
\mathcal{F}(U) \to \check{H}^0(U, \mathcal{F})
\]
is bijective.

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

10. Čech cohomology as a functor on presheaves

**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 \( U : U = \bigcup_{i \in I} U_i \) be an open covering. Let \( \mathcal{F} \) be a presheaf of \( \mathcal{O}_X \)-modules. We have the Čech complex \( \check{C}^\bullet(U, \mathcal{F}) \) of \( \mathcal{F} \) just by thinking of \( \mathcal{F} \) as a presheaf of abelian groups. However, each term \( \check{C}^p(U, \mathcal{F}) \) has a natural structure of a \( \mathcal{O}_X \)-module and the differential is given by \( \mathcal{O}_X \)-module maps. Moreover, it is clear that the construction
\[
\mathcal{F} \mapsto \check{C}^\bullet(U, \mathcal{F})
\]
is functorial in \( \mathcal{F} \). In fact, it is a functor
\[
\check{C}^\bullet(U, -) : \text{PMod}(\mathcal{O}_X) \to \text{Comp}^+_{\mathcal{O}_X(U)}
\]
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 [13.9].

**Lemma 10.1.** The functor given by Equation (10.0.1) 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 \( \text{PMod}(\mathcal{O}_X) \) to \( \text{Mod}_{\mathcal{O}_X(U)} \). The terms \( \check{C}^p(U, \mathcal{F}) \) 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. \( \square \)

**Lemma 10.2.** Let \( X \) be a ringed space. Let \( U : U = \bigcup_{i \in I} U_i \) be an open covering. The functors \( \mathcal{F} \mapsto \check{H}^n(U, \mathcal{F}) \) form a ď-functor from the abelian category of presheaves of \( \mathcal{O}_X \)-modules to the category of \( \mathcal{O}_X(U) \)-modules (see Homology, Definition [12.7]).

**Proof.** By Lemma [10.1] a short exact sequence of presheaves of \( \mathcal{O}_X \)-modules \( 0 \to \mathcal{F}_1 \to \mathcal{F}_2 \to \mathcal{F}_3 \to 0 \) is turned into a short exact sequence of complexes of \( \mathcal{O}_X(U) \)-modules. Hence we can use Homology, Lemma [13.12] to get the boundary maps \( \delta_{\mathcal{F}_1, \mathcal{F}_2, \mathcal{F}_3} : \check{H}^n(U, \mathcal{F}_3) \to \check{H}^{n+1}(U, \mathcal{F}_1) \) 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 \( j_! \) of extension by 0 for presheaves of modules relative to an open immersion \( j : U \to X \). See Sheaves, Section 31. For any open \( W \subset X \) and any presheaf \( \mathcal{G} \) of \( \mathcal{O}_X|_U \)-modules we have
\[
(j_! \mathcal{G})(W) = \begin{cases} 
\mathcal{G}(W) & \text{if } W \subset U \\
0 & \text{else.}
\end{cases}
\]
Moreover, the functor \( j_! \) is a left adjoint to the restriction functor see Sheaves, Lemma 31.8. In particular we have the following formula
\[
\text{Hom}_{\mathcal{O}_X}(j_! \mathcal{O}_U, \mathcal{F}) = \text{Hom}_{\mathcal{O}_U}(\mathcal{O}_U, \mathcal{F}|_U) = \mathcal{F}(U).
\]
Since the functor \( \mathcal{F} \mapsto j_! \mathcal{F} \) is an exact functor on the category of presheaves we conclude that the presheaf \( j_! \mathcal{O}_U \) is a projective object in the category \( \text{PMod}(\mathcal{O}_X) \), see Homology, Lemma 28.2.

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 \( (j_U)_! j_U^* \mathcal{O}_V \to (j_V)_! j_V^* \mathcal{O}_V \). It is the identity on sections over any open \( W \subset U \) and 0 else. In terms of the identification \( \text{Hom}_{\mathcal{O}_X}(j_U)_! j_U^* \mathcal{O}_V, (j_V)_! j_V^* \mathcal{O}_V) \) (\( (j_U)_! j_U^* \mathcal{O}_V(U) = \mathcal{O}_V(U) \) it corresponds to the element \( 1 \in \mathcal{O}_V(U) \)).

**Lemma 10.3.** Let \( X \) be a ringed space. Let \( \mathcal{U} : U = \bigcup_{i \in I} U_i \) be a covering. Denote \( j_{i_0 \ldots i_p} : U_{i_0 \ldots i_p} \to X \) the open immersion. Consider the chain complex \( K(\mathcal{U})_\bullet \) of presheaves of \( \mathcal{O}_X \)-modules
\[
\cdots \to \bigoplus_{i_0 i_1 i_2} (j_{i_0 i_1 i_2})_! j_{i_0 i_1 i_2}^* \mathcal{O}_{U_{i_0 i_1 i_2}} \to \bigoplus_{i_0 i_1} (j_{i_0 i_1})_! j_{i_0 i_1}^* \mathcal{O}_{U_{i_0 i_1}} \to \bigoplus_{i_0} (j_{i_0})_! j_{i_0}^* \mathcal{O}_{U_{i_0}} \to 0 \to \cdots
\]
where the last nonzero term is placed in degree 0 and where the map
\[
(j_{i_0 \ldots i_p+1})_! j_{i_0 \ldots i_p+1}^* \mathcal{O}_{U_{i_0 \ldots i_p+1}} \to (j_{i_0 \ldots i_p})_! j_{i_0 \ldots i_p}^* \mathcal{O}_{U_{i_0 \ldots i_p}}
\]
is given by \((-1)^p\) times the canonical map. Then there is an isomorphism
\[
\text{Hom}_{\mathcal{O}_X}(K(\mathcal{U})_\bullet, \mathcal{F}) = \mathcal{C}^\bullet(\mathcal{U}, \mathcal{F})
\]
functorial in \( \mathcal{F} \in \text{Ob}(\text{PMod}(\mathcal{O}_X)) \).

**Proof.** We saw in the discussion just above the lemma that
\[
\text{Hom}_{\mathcal{O}_X}(j_{i_0 \ldots i_p}^* \mathcal{O}_{U_{i_0 \ldots i_p}}, \mathcal{F}) = \mathcal{F}(U_{i_0 \ldots i_p}).
\]
Hence we see that it is indeed the case that the direct sum
\[
\bigoplus_{i_0 \ldots i_p} (j_{i_0 \ldots i_p})_! j_{i_0 \ldots i_p}^* \mathcal{O}_{U_{i_0 \ldots i_p}}
\]
represents the functor
\[
\mathcal{F} \mapsto \prod_{i_0 \ldots i_p} \mathcal{F}(U_{i_0 \ldots i_p}).
\]
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.

**Lemma 10.4.** Let \( X \) be a ringed space. Let \( \mathcal{U} : U = \bigcup_{i \in J} U_i \) be a covering. Let \( \mathcal{O}_\mathcal{U} \subset \mathcal{O}_X \) be the image presheaf of the map \( \bigoplus_{j_!} \mathcal{O}_{U_j} \to \mathcal{O}_X \). The chain complex \( K(\mathcal{U})_\bullet \) of presheaves of Lemma 10.3 above has homology presheaves
\[
H_i(K(\mathcal{U})_\bullet) = \begin{cases} 
0 & \text{if } i \neq 0 \\
\mathcal{O}_\mathcal{U} & \text{if } i = 0
\end{cases}
\]
Let \( I \) which is equal to \( \mathbb{1} \). The sum is finite as the element \( i_0 \) of the left exact functor \( \mathcal{O}_U \) is homotopy equivalent to the zero complex. Write \( I = I_1 \cap I_2 \) where \( W \subset U_i \) if and only if \( i \in I_1 \).

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

If \( I_1 \neq \emptyset \), then \( \mathcal{O}_U(W) = \mathcal{O}_X(W) \) and
\[
K^\bullet_{\text{ext}}(W) = \bigoplus_{i_0 \ldots i_p \in I_1} \mathcal{O}_X(W).
\]
This is true because of the simple description of the presheaves \((j_{i_0 \ldots i_p})_! \mathcal{O}_{U_{i_0 \ldots i_p}}\).

Moreover, the differential of the complex \( K^\bullet_{\text{ext}}(W) \) is given by
\[
d(s)_{i_0 \ldots i_p} = \sum_{j=0, \ldots, p+1} \sum_{i \in I_1} (-1)^j s_{i_0 \ldots i_{j-1} i_j \ldots i_p}.
\]
The sum is finite as the element \( s \) has finite support. Fix an element \( i_{\text{fix}} \in I_1 \). Define a map
\[
h : K^\bullet_{\text{ext}}(W) \to K^\bullet_{p+1}(W)
\]
by the rule
\[
h(s)_{i_0 \ldots i_p} = \begin{cases} 0 & \text{if } i_0 \neq i \\ s_{i_1 \ldots i_{p+1}} & \text{if } i_0 = i_{\text{fix}} \end{cases}
\]
We will use the shorthand \( h(s)_{i_0 \ldots i_p} = (i_0 = i_{\text{fix}}) s_{i_1 \ldots i_p} \) for this. Then we compute
\[
(dh + hd)(s)_{i_0 \ldots i_p} = \sum_{i \in I_1} \sum_{j \geq 1} (-1)^j h(s)_{i_0 \ldots i_{j-1} i_i \ldots i_p} + (i = i_0) d(s)_{i_1 \ldots i_p}
\]
\[
= s_{i_0 \ldots i_p} + \sum_{j \geq 1} \sum_{i \in I_1} (-1)^j (i_0 = i_{\text{fix}}) s_{i_1 \ldots i_{j-1} i_i \ldots i_p} + (i_0 = i_{\text{fix}}) d(s)_{i_1 \ldots i_p}
\]
which is equal to \( s_{i_0 \ldots i_p} \) as desired. \( \square \)

**Lemma 10.5.** 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 \( \delta \)-functor to the right derived functors of the functor
\[
\check{H}^0(\mathcal{U}, -) : \text{PMod}(\mathcal{O}_X) \to \text{Mod}_{\mathcal{O}_X(U)}.
\]
Moreover, there is a functorial quasi-isomorphism
\[
\check{C}^\bullet(\mathcal{U}, \mathcal{F}) \to R\check{H}^0(\mathcal{U}, \mathcal{F})
\]
where the right hand side indicates the right derived functor \( R\check{H}^0(\mathcal{U}, -) : D^+(\text{PMod}(\mathcal{O}_X)) \to D^+(\mathcal{O}_X(U)) \) 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 \( I \) be an injective presheaf of \( \mathcal{O}_X \)-modules. In this case the functor \( \text{Hom}_{\mathcal{O}_X}(-, I) \) is exact on \( \mathcal{PMod}(\mathcal{O}_X) \). By Lemma 10.3 we have
\[
\text{Hom}_{\mathcal{O}_X}(K(U), I) = \check{C}(U, I).
\]

By Lemma 10.4 we have that \( K(U)_* \) is quasi-isomorphic to \( \mathcal{O}_U[0] \). Hence by the exactness of \( \text{Hom} \) into \( I \) mentioned above we see that \( \check{H}^i(U, I) = 0 \) for all \( i > 0 \). Thus the \( \delta \)-functor \( (\check{H}^n, \delta) \) (see Lemma 10.2) satisfies the assumptions of Homology, Lemma 12.4, and hence is a universal \( \delta \)-functor.

By Derived Categories, Lemma 20.4 also the sequence \( R^i \check{H}^0(U, -) \) forms a universal \( \delta \)-functor. By the uniqueness of universal \( \delta \)-functors, see Homology, Lemma 12.5 we conclude that \( R^i \check{H}^0(U, -) = \check{H}^i(U, -) \). This is enough for most applications and the reader is suggested to skip the rest of the proof.

Let \( F \) be any presheaf of \( \mathcal{O}_X \)-modules. Choose an injective resolution \( F \to I^\bullet \) in the category \( \mathcal{PMod}(\mathcal{O}_X) \). Consider the double complex \( A^{p,q} \) with terms
\[
A^{p,q} = \check{C}^p(U, I^q).
\]

Consider the simple complex \( sA^\bullet \) associated to this double complex. There is a map of complexes
\[
\check{C}^\bullet(U, F) \to sA^\bullet
\]
coming from the maps \( \check{C}^p(U, F) \to A^{p,0} = \check{C}^p(U, I^0) \) and there is a map of complexes
\[
\check{H}^0(U, I^\bullet) \to sA^\bullet
\]
coming from the maps \( \check{H}^0(U, I^q) \to A^{0,q} = \check{C}^0(U, I^q) \). Both of these maps are quasi-isomorphisms by an application of Homology, Lemma 25.4. Namely, the columns of the double complex are exact in positive degrees because the Čech complex as a functor is exact (Lemma 10.1) 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 \( I^q \) 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.

11. Čech cohomology and cohomology

**Lemma 11.1.** Let \( X \) be a ringed space. Let \( U : U = \bigcup_{i \in I} U_i \) be a covering. Let \( I \) be an injective \( \mathcal{O}_X \)-module. Then
\[
\check{H}^p(U, I) = \begin{cases} I(U) & \text{if } p = 0 \\ 0 & \text{if } p > 0 \end{cases}
\]

**Proof.** An injective \( \mathcal{O}_X \)-module is also injective as an object in the category \( \mathcal{PMod}(\mathcal{O}_X) \) (for example since sheafification is an exact left adjoint to the inclusion functor, using Homology, Lemma 29.1). Hence we can apply Lemma 10.5 (or its proof) to see the result.

**Lemma 11.2.** Let \( X \) be a ringed space. Let \( U : U = \bigcup_{i \in I} U_i \) be a covering. There is a transformation
\[
\check{C}^\bullet(U, -) \to R\Gamma(U, -)
\]

of functors \( \text{Mod}(\mathcal{O}_X) \to D^+(\mathcal{O}_X(U)) \). In particular this provides canonical maps
\[
\check{H}^p(U, F) \to H^p(U, F) \text{ for } F \text{ ranging over } \text{Mod}(\mathcal{O}_X).
\]
Proof. Let $F$ be an $O_X$-module. Choose an injective resolution $F \to \mathcal{I}^\bullet$. Consider the double complex $C^\bullet(U, \mathcal{I}^\bullet)$ with terms $C^p(U, \mathcal{I}^q)$. There is a map of complexes $\alpha : \Gamma(U, \mathcal{I}^\bullet) \to \text{Tot}(C^\bullet(U, \mathcal{I}^\bullet))$ coming from the maps $\mathcal{I}^q(U) \to H^q(U, \mathcal{I}^q)$ and a map of complexes $\beta : C^\bullet(U, F) \to \text{Tot}(C^\bullet(U, \mathcal{I}^\bullet))$ coming from the map $F \to \mathcal{I}^0$. We can apply Homology, Lemma 25.4 to see that $\alpha$ is a quasi-isomorphism. Namely, Lemma 11.1 implies that the $q^\text{th}$ row of the double complex $C^\bullet(U, \mathcal{I}^\bullet)$ is a resolution of $\Gamma(U, \mathcal{I}^q)$. Hence $\alpha$ becomes invertible in $D^+(O_X(U))$ and the transformation of the lemma is the composition of $\beta$ followed by the inverse of $\alpha$. We omit the verification that this is functorial. □

0B8R Lemma 11.3. Let $X$ be a topological space. Let $\mathcal{H}$ be an abelian sheaf on $X$. Let $U : X = \bigcup_{i \in I} U_i$ be an open covering. The map

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

is injective and identifies $\check{H}^1(U, \mathcal{H})$ via the bijection of Lemma 4.3 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 $F$ be a $\mathcal{H}$-torsor whose restriction to $U_i$ is trivial. By Lemma 11.2 this means there exists a section $s_i \in F(U_i)$. On $U_{i_0} \cap U_{i_1}$ there is a unique section $s_{i_0i_1}$ of $\mathcal{H}$ such that $s_{i_0i_1} : s_{i_0}|_{U_{i_0} \cap U_{i_1}} = s_{i_1}|_{U_{i_0} \cap U_{i_1}}$. A computation shows that $s_{i_0i_1}$ 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 $F$ to the cohomology class of the cocycle $(s_{i_0i_1})$. We omit the verification that this map is indeed an inverse. □

01ER Lemma 11.4. Let $X$ be a ringed space. Consider the functor $i : \text{Mod}(O_X) \to P\text{Mod}(O_X)$. It is a left exact functor with right derived functors given by

$$R^pi(F) = H^p(F) : U \mapsto H^p(U, F)$$

see discussion in Section 2.

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

$$\text{Ker}(\mathcal{I}^n(U) \to \mathcal{I}^{n+1}(U)) \to \text{Im}(\mathcal{I}^{n-1}(U) \to \mathcal{I}^n(U)),$$

which is the definition of $H^p(U, F)$. □

01ES Lemma 11.5. Let $X$ be a ringed space. Let $U : U = \bigcup_{i \in I} U_i$ be a covering. For any sheaf of $O_X$-modules $F$ there is a spectral sequence $(E_r, d_r)_{r \geq 0}$ with

$$E_2^{p,q} = H^p(U, H^q(F))$$

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

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

$$i : \text{Mod}(O_X) \to P\text{Mod}(O_X) \quad \text{and} \quad \check{H}^q(U, -) : P\text{Mod}(O_X) \to \text{Mod}(O_X(U)).$$
Namely, we have $\hat{H}^0(U, i(\mathcal{F})) = \mathcal{F}(U)$ by Lemma \[0.2\] We have that $i(\mathcal{I})$ is Čech acyclic by Lemma \[11.1\] And we have that $\hat{H}^p(U, -) = R^p\hat{H}^0(U, -)$ as functors on $\text{PMod}(\mathcal{O}_X)$ by Lemma \[10.5\] Putting everything together gives the lemma. □

**Lemma 11.6.** Let $X$ be a ringed space. Let $\mathcal{U} : \mathcal{U} = \bigcup_{i \in I} U_i$ be a covering. Let $\mathcal{F}$ be an $\mathcal{O}_X$-module. Assume that $\hat{H}^i(U_{i_0, \ldots, i_p}, \mathcal{F}) = 0$ for all $i > 0$, all $p \geq 0$ and all $i_0, \ldots, i_p \in I$. Then $\hat{H}^p(U, \mathcal{F}) = \hat{H}^p(U, \mathcal{F})$ as $\mathcal{O}_X(U)$-modules.

**Proof.** We will use the spectral sequence of Lemma \[11.5\] 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. □

**Lemma 11.7.** 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 $\hat{H}^1(\mathcal{U}, \mathcal{F}) = 0$, 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 $\mathcal{U} : \mathcal{U} = \bigcup_{i \in I} U_i$ such that (a) $\hat{H}^1(\mathcal{U}, \mathcal{F}) = 0$ 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

$$s_{i_0i_1} = s_{i_1}|_{U_{i_0i_1}} - s_{i_0}|_{U_{i_0i_1}}.$$

Since $s_i$ lifts $s$ we see that $s_{i_0i_1} \in \mathcal{F}(U_{i_0i_1})$. By the vanishing of $\hat{H}^1(\mathcal{U}, \mathcal{F})$ we can find sections $t_i \in \mathcal{F}(U_i)$ such that

$$s_{i_0i_1} = t_i|_{U_{i_0i_1}} - t_{i_0}|_{U_{i_0i_1}}.$$

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. □

**Lemma 11.8.** Let $X$ be a ringed space. Let $\mathcal{F}$ be an $\mathcal{O}_X$-module such that

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

for all $p > 0$ and any open covering $\mathcal{U} : \mathcal{U} = \bigcup_{i \in I} U_i$ of an open of $X$. Then $\hat{H}^p(U, \mathcal{F}) = 0$ 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 \[11.1\] $\mathcal{I}$ 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 \[11.7\] 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 \[10.2\] 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

\[
\begin{array}{ccccccc}
0 & \rightarrow & H^0(U, \mathcal{F}) & \rightarrow & H^0(U, \mathcal{I}) & \rightarrow & H^0(U, \mathcal{Q}) \\
& & \uparrow & & \uparrow & & \uparrow \\
& & H^1(U, \mathcal{F}) & \rightarrow & H^1(U, \mathcal{I}) & \rightarrow & H^1(U, \mathcal{Q}) \\
& & \downarrow & & \downarrow & & \downarrow \\
& & \vdots & & \vdots & & \vdots \\
\end{array}
\]

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. \( \square \)

**Lemma 11.9.** (Variant of Lemma \[11.8\]) 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 \( \text{Cov} \) with the following properties:

1. For every \( U \in \text{Cov} \) with \( U = \bigcup_{i \in I} U_i \) we have \( U, U_i \in \mathcal{B} \) and every \( U_{i_0 \ldots i_p} \in \mathcal{B} \).
2. For every \( U \in \mathcal{B} \) the open coverings of \( U \) occurring in \( \text{Cov} \) is a cofinal system of open coverings of \( U \).
3. For every \( U \in \text{Cov} \) we have \( H^p(U, \mathcal{F}) = 0 \) 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 \( \text{Cov} \) be as in the lemma. We will indicate this by saying “\( \mathcal{F} \) has vanishing higher Čech cohomology for any \( U \in \text{Cov} \)”. Choose an embedding \( \mathcal{F} \rightarrow \mathcal{I} \) into an injective \( \mathcal{O}_X \)-module. By Lemma \[11.1\] \( \mathcal{I} \) has vanishing higher Čech cohomology for any \( U \in \text{Cov} \). 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 \[11.7\] 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 \( U \in \text{Cov} \) we get a short exact sequence of Čech complexes

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

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 \( U \in \text{Cov} \). This implies that \( \mathcal{Q} \) is also an \( \mathcal{O}_X \)-module with vanishing higher Čech cohomology for all \( U \in \text{Cov} \).
Next, we look at the long exact cohomology sequence

\[
\begin{array}{cccc}
0 & \rightarrow & H^0(U, \mathcal{F}) & \rightarrow H^0(U, \mathcal{I}) & \rightarrow H^0(U, \mathcal{Q}) \\
& & H^1(U, \mathcal{F}) & \rightarrow H^1(U, \mathcal{I}) & \rightarrow H^1(U, \mathcal{Q}) \\
& & \vdots & \vdots & \vdots \\
\end{array}
\]

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 \ref{derived-categories-lemma}). 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. □

**Lemma 11.10.** Let \( f : X \rightarrow Y \) be a morphism of ringed spaces. Let \( \mathcal{I} \) be an injective \( \mathcal{O}_X \)-module. Then

1. \( H^p(V, f_* \mathcal{I}) = 0 \) for all \( p > 0 \) and any open covering \( V : V = \bigcup_{j \in J} V_j \) 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 \ref{derived-categories-definition}) 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

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

This is true because

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

Thus the first statement of the lemma follows from Lemma \ref{derived-categories-lemma}. The second statement follows from the first and Lemma \ref{derived-categories-lemma}.

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

**Lemma 11.11.** 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 \ref{modules-lemma}). Hence the result follows from Homology, Lemma \ref{homology-lemma}.

**Lemma 11.12.** 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

\[ H^p(U, \prod_{i \in I} \mathcal{F}_i) \rightarrow \prod_{i \in I} H^p(U, \mathcal{F}_i) \]

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 \ref{sheaves-section}. Proof for \( p = 1 \). Set \( \mathcal{F} = \prod F_i \). Let \( \xi \in H^1(U, \mathcal{F}) \) map to zero in \( \prod_i H^1(U, \mathcal{F}_i) \). By locality of cohomology, see Lemma \ref{locality-cohomology-lemma}, there exists an open covering \( \mathcal{U} : U = \bigcup U_j \) such that \( \xi|_{U_j} = 0 \) for all \( j \). By Lemma \ref{locality-cohomology-lemma} this means \( \xi \) comes from an element
$\xi \in \check{H}^1(U, \mathcal{F})$. Since the maps $\check{H}^1(U, \mathcal{F}_i) \to H^1(U, \mathcal{F}_i)$ are injective for all $i$ (by Lemma 11.3), and since the image of $\xi$ is zero in $\prod H^1(U, \mathcal{F}_i)$ we see that the image $\xi_i = 0$ in $\check{H}^1(U, \mathcal{F}_i)$. However, since $\mathcal{F} = \prod \mathcal{F}_i$ we see that $\check{C}^\bullet(U, \mathcal{F})$ is the product of the complexes $\check{C}^\bullet(U, \mathcal{F}_i)$, hence by Homology, Lemma 32.1 we conclude that $\xi = 0$ as desired. \hfill \Box

12. Flasque sheaves

\textbf{Definition 12.1.} Let $X$ be a topological space. We say a presheaf of sets $\mathcal{F}$ is \textit{flasque} or \textit{flabby} if for every $U \subset V$ open in $X$ the restriction map $\mathcal{F}(V) \to \mathcal{F}(U)$ 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 $\mathcal{F}(X) \to \mathcal{F}(U)$ is surjective for every open $U \subset X$.

\textbf{Lemma 12.2.} Let $(X, \mathcal{O}_X)$ be a ringed space. Then any injective $\mathcal{O}_X$-module is flasque.

\textbf{Proof.} This is a reformulation of Lemma 8.1. \hfill \Box

\textbf{Lemma 12.3.} 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 $X$.

\textbf{Proof.} We will prove this using Derived Categories, Lemma 15.6. 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

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

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 section 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 $(V_\alpha, t_\alpha)$, $\alpha \in A$ 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 $t_\alpha$ over $V_\alpha$ 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 $V \cup W = V$. Thus $x \in V$ and we are done. \hfill \Box

The following lemma does not hold for flasque presheaves.
Lemma 12.4. Let \((X, O_X)\) be a ringed space. Let \(\mathcal{F}\) be a sheaf of \(O_X\)-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 \(H^q(\mathcal{F})\) used in the statement of Lemma 12.3 are zero by Lemma 12.3. Hence \(\check{H}^p(\mathcal{U}, \mathcal{F}) = H^p(\mathcal{U}, \mathcal{F}) = 0\) by Lemma 12.3 again. \(\square\)

Lemma 12.5. Let \((X, O_X) \to (Y, O_Y)\) be a morphism of ringed spaces. Let \(\mathcal{F}\) be a sheaf of \(O_X\)-modules. If \(\mathcal{F}\) is flasque, then \(R^p f_* \mathcal{F} = 0\) for \(p > 0\).

Proof. Immediate from Lemma 12.3 and Lemma 12.3. \(\square\)

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

Lemma 12.6. 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 \(\mathcal{F}(U) \to \mathcal{F}(U')\) are surjective for \(U'\) an arbitrary union of opens of the form \(U_{i_0, \ldots, i_p}\). 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 \(A, B, C, \ldots\) 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 \(A \in V_{t_s}\) for some \(t_s \in T_s\). But since \(A\) is also minimal in \(V_s\) we conclude that \(J_{s,t_s} = J_t\).

Next we map the set of opens of \(Y\) to opens of \(X\). Namely, we send \(Y\) 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 $V : Y = \bigcup_{i \in I} V_{(i)}$ of $Y$. By construction we have an equality

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

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 12.4.

\[\square\]

13. The Leray spectral sequence

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**Lemma 13.1.** Let $f : X \to Y$ be a morphism of ringed spaces. There is a commutative diagram

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

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

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

See also Remark 13.3 for more explanation.

**Proof.** Let $\Gamma_{\text{res}} : \text{Mod}(\mathcal{O}_X) \to \text{Mod}_{\mathcal{O}_Y}(Y)$ be the functor which associates to an $\mathcal{O}_X$-module $\mathcal{F}$ the global sections of $\mathcal{F}$ viewed as an $\mathcal{O}_Y(Y)$-module via the map $f^* : \mathcal{O}_Y(Y) \to \mathcal{O}_X(X)$. Let $\text{restriction} : \text{Mod}_{\mathcal{O}_X(X)} \to \text{Mod}_{\mathcal{O}_Y(Y)}$ be the restriction functor induced by $f^* : \mathcal{O}_Y(Y) \to \mathcal{O}_X(X)$. Note that $\text{restriction}$ is exact so that its right derived functor is computed by simply applying the restriction functor, see Derived Categories, Lemma 16.9. It is clear that

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

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 11.10 which implies that injective $\mathcal{O}_X$-modules are mapped to $\Gamma(Y, -)$-acyclic sheaves on $Y$. 

\[\square\]
Remark 13.2. Here is a down-to-earth explanation of the meaning of Lemma 13.1. It says that given \( f : X \to Y \) and \( F \in \text{Mod}(\mathcal{O}_X) \) and given an injective resolution \( F \to I^\bullet \) we have
\[
R\Gamma(X,F) \quad \text{is represented by} \quad \Gamma(X,I^\bullet)
\]
\[
Rf_*F \quad \text{is represented by} \quad f_*I^\bullet
\]
the last fact coming from Leray’s acyclicity lemma (Derived Categories, Lemma 16.7) and Lemma 11.10. Finally, it combines this with the trivial observation that
\[
\Gamma(X,I^\bullet) = \Gamma(Y,f_*I^\bullet)
\]
to arrive at the commutativity of the diagram of the lemma.

Lemma 13.3. Let \( X \) be a ringed space. Let \( F \) be an \( \mathcal{O}_X \)-module.

1. The cohomology groups \( H^i(U,F) \) for \( U \subset X \) open of \( F \) computed as an \( \mathcal{O}_X \)-module, or computed as an abelian sheaf are identical.

2. Let \( f : X \to Y \) be a morphism of ringed spaces. The higher direct images \( R^i f_*F \) of \( F \) 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 \( (X,\mathcal{O}_X) \to (Y,\mathcal{O}_Y) \) given by the identity on the underlying topological space and by the unique map of sheaves of rings \( \mathcal{O}_X \to \mathcal{O}_Y \). Let \( F \) be an \( \mathcal{O}_X \)-module. Denote \( F_{ab} \) the same sheaf seen as an \( \mathcal{O}_Y \)-module, i.e., seen as a sheaf of abelian groups. Let \( F \to I^\bullet \) be an injective resolution. By Remark 13.2 we see that \( \Gamma(X,I^\bullet) \) computes both \( R\Gamma(X,F) \) and \( R\Gamma(X,F_{ab}) \). This proves (1).

To prove (2) we use (1) and Lemma 7.3. The result follows immediately. □

Lemma 13.4 (Leray spectral sequence). Let \( f : X \to Y \) be a morphism of ringed spaces. Let \( F^\bullet \) be a bounded below complex of \( \mathcal{O}_X \)-modules. There is a spectral sequence
\[
E_2^{p,q} = H^p(Y, R^q f_*(F^\bullet))
\]
converging to \( H^{p+q}(X,F^\bullet) \).

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 \( \Gamma_{res} \) is as in the proof of Lemma 13.1. To see that the assumptions of Derived Categories, Lemma 22.2 are satisfied, see the proof of Lemma 13.1 or Remark 13.2. □

Remark 13.5. The Leray spectral sequence, the way we proved it in Lemma 13.4 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 \( f' : (X,\mathcal{O}_X) \to (Y,f_*\mathcal{O}_X) \). By Lemma 13.3 the terms \( E_r^{p,q} \) of the Leray spectral sequence for an \( \mathcal{O}_X \)-module \( F \) and \( f \) are identical with those for \( F \) and \( f' \) at least for \( r \geq 2 \). Namely, they both agree with the terms of the Leray spectral sequence for \( F \) 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.

Lemma 13.6. Let \( f : X \to Y \) be a morphism of ringed spaces. Let \( F \) be an \( \mathcal{O}_X \)-module.
(1) If $R^qf_*\mathcal{F} = 0$ for $q > 0$, then $H^p(X, \mathcal{F}) = H^p(Y, f_*\mathcal{F})$ for all $p$.
(2) If $H^p(Y, R^qf_*\mathcal{F}) = 0$ for all $q$ and $p > 0$, then $H^q(X, \mathcal{F}) = H^q(Y, R^qf_*\mathcal{F})$ 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. \( \square \)

**Lemma 13.7.** Let $f : X \to Y$ and $g : Y \to Z$ be morphisms of ringed spaces. In this case $Rg_* \circ Rf_* = R(g \circ f)_*$ as functors from $D^+(X) \to D^+(Z)$.

**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 11.10 and the description of the higher direct images $R^ig_*$ in Lemma 7.3. \( \square \)

**Lemma 13.8 (Relative Leray spectral sequence).** Let $f : X \to Y$ and $g : Y \to Z$ be morphisms of ringed spaces. Let $\mathcal{F}$ be an $\mathcal{O}_X$-module. There is a spectral sequence with

$$E_2^{pq} = R^pg_*(R^qf_*\mathcal{F})$$

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 13.7 and Derived Categories, Lemma 22.2. \( \square \)

## 14. Functoriality of cohomology

**Lemma 14.1.** Let $f : X \to Y$ 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 $\varphi : \mathcal{G}^\bullet \to f_*\mathcal{F}^\bullet$ be a morphism of complexes. There is a canonical morphism

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

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

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

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

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

Let $f : X \to Y$ 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 $\varphi$ from $\mathcal{G}$ to $\mathcal{F}$ is a map $\varphi : \mathcal{G} \to f_*\mathcal{F}$, or what is the same thing, a map $\varphi : f^*\mathcal{G} \to \mathcal{F}$. See Sheaves, Definition 21.7. Such an $f$-map gives rise to a morphism of complexes

$$\varphi : R\Gamma(Y, \mathcal{G}) \to R\Gamma(X, \mathcal{F})$$

in $D^+(\mathcal{O}_Y(Y))$. Namely, we use the morphism $\mathcal{G} \to Rf_*\mathcal{F}$ in $D^+(Y)$ of Lemma 14.1 and we apply $R\Gamma(Y, -)$. By Lemma 13.1 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 14.2 below. In particular it gives rise to maps on cohomology

$$\varphi : H^i(Y, \mathcal{G}) \to H^i(X, \mathcal{F}).$$
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 \( \varphi \) 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 \( \beta \) such that the diagram commutes. Applying global section functors we see that we get a diagram

\[
\begin{array}{ccc}
\Gamma(Y, \mathcal{G}) & \longrightarrow & \Gamma(Y, f_*\mathcal{I}^\bullet) \\
\uparrow & & \uparrow \\
\Gamma(Y, \mathcal{J}^\bullet) & \longrightarrow & \Gamma(Y, (\mathcal{J}')^\bullet)
\end{array}
\]

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 13.1 which becomes invertible after applying the localization functor \( K^+(\mathcal{O}_Y(Y)) \rightarrow D^+(\mathcal{O}_Y(Y)) \). The arrow (14.1.1) is given by the composition of the horizontal map by the inverse of the vertical map.

**15. Refinements and Čech cohomology**

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

\[
\gamma : \check{\mathcal{C}}^\bullet(\mathcal{V}, \mathcal{F}) \rightarrow \check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}), \quad (\xi_{j_0 \ldots j_p}) \mapsto (\xi_{c(i_0) \ldots c(i_p)}|_{U_{i_0} \cap \ldots \cap U_{i_p}})
\]

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

\[
h(\xi)_{i_0 \ldots i_p} = \sum_{a=0}^p (-1)^a \alpha(\xi(\sigma c(i_0), \ldots c(i_a) c(i_{a+1}), \ldots c(i_p)) \in C^p(\mathcal{F})(U_{i_0} \cap \ldots \cap U_{i_p})
\]

We omit the computation showing this works; please see the discussion following (25.0.2) 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

\[
\check{\mathcal{C}}^\bullet(\mathcal{W}, \mathcal{F}) \rightarrow \check{\mathcal{C}}^\bullet(\mathcal{V}, \mathcal{F}) \rightarrow \check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F})
\]

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

\[
\check{H}^p(X, \mathcal{F}) = \text{colim}_\mathcal{U} \check{H}^p(\mathcal{U}, \mathcal{F})
\]

where the colimit is over all open coverings of \( X \) preordered by refinement.
It turns out that the maps $\gamma$ defined above are compatible with the map to cohomology, in other words, the composition
\[ \hat{H}^p(\mathcal{V}, \mathcal{F}) \to \hat{H}^p(\mathcal{U}, \mathcal{F}) \xrightarrow{\text{Lemma } 11.2} H^p(X, \mathcal{F}) \]
is the canonical map from the first group to cohomology of Lemma 11.2. In the lemma below we will prove this in a slightly more general setting. A consequence is that we obtain a well defined map
\[ \hat{H}^p(X, \mathcal{F}) = \colim_{\mathcal{U}} \hat{H}^p(\mathcal{U}, \mathcal{F}) \to H^p(X, \mathcal{F}) \]
from Cech cohomology to cohomology.

**Lemma 15.1.** Let $f : X \to Y$ be a morphism of ringed spaces. Let $\varphi : f^* \mathcal{G} \to \mathcal{F}$ be an $f$-map from an $\mathcal{O}_X$-module $\mathcal{G}$ to an $\mathcal{O}_Y$-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
\[
\begin{array}{ccc}
\check{C}^*(\mathcal{U}, \mathcal{F}) & \longrightarrow & R\Gamma(X, \mathcal{F}) \\
\gamma & & \uparrow \\
\check{C}^*(\mathcal{V}, \mathcal{G}) & \longrightarrow & R\Gamma(Y, \mathcal{G})
\end{array}
\]
in $D^+(\mathcal{O}_X(X))$ with horizontal arrows given by Lemma 11.2 and right vertical arrow by 14.1.1. In particular we get commutative diagrams of cohomology groups
\[
\begin{array}{ccc}
\check{H}^p(\mathcal{U}, \mathcal{F}) & \longrightarrow & H^p(X, \mathcal{F}) \\
\gamma & & \uparrow \\
\check{H}^p(\mathcal{V}, \mathcal{G}) & \longrightarrow & H^p(Y, \mathcal{G})
\end{array}
\]
where the right vertical arrow is 14.1.2.

**Proof.** We first define the left vertical arrow. Namely, choose a map $c : I \to J$ 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
\[ \gamma(s)_{i_0\ldots i_p} = \varphi(s)_{c(i_0)\ldots c(i_p)} \]
This makes sense because $\varphi$ does indeed induce maps $\mathcal{G}(V_{c(i_0)\ldots c(i_p)}) \to \mathcal{F}(U_{i_0\ldots i_p})$ by assumption. It is also clear that this defines a morphism of complexes. Choose injective resolutions $\mathcal{F} \to \mathcal{I}^*$ on $X$ and $\mathcal{G} \to \mathcal{J}^*$ on $Y$. According to the proof of Lemma 11.2 we introduce the double complexes $A^{p\bullet}$ and $B^{p\bullet}$ 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 14.2 above we also choose an injective resolution $f_*\mathcal{I} \to (\mathcal{J}')^*$ on $Y$ and a morphism of complexes $\beta : J \to (\mathcal{J}')^*$ making 14.2.1 commutes. We introduce some more double complexes, namely $(B')^{p\bullet}$ and $(B'')^{p\bullet}$ 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 $f_*\mathcal{I}^*$ to $\mathcal{I}^*$. Hence it is clear that the same rule as above defines a morphism of double complexes
\[ \gamma : (B'')^{p\bullet} \to A^{p\bullet}. \]
Consider the diagram of complexes

\[ \begin{array}{ccc}
\check{C}^\bullet(U, F) & \rightarrow & sA^\bullet \\
\gamma & & qis \\
\check{C}^\bullet(V, G) & \rightarrow & sB^\bullet \\
\beta & \rightarrow & s(B')^\bullet \\
\Gamma(Y, J^\bullet) & \rightarrow & s\Gamma(Y, (J')^\bullet) \\
\end{array} \]

The two horizontal arrows with targets \( sA^\bullet \) and \( sB^\bullet \) are the ones explained in Lemma 11.2. The left upper shape (a pentagon) is commutative simply because (14.2.1) 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 \( \check{C}^\bullet(U, F) \) to \( \Gamma(X, I^\bullet) \) either on top or on bottom is the same (where you have to invert any quasi-isomorphisms along the way).

\[ \square \]

16. Cohomology on Hausdorff quasi-compact spaces

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

09V1 **Lemma 16.1.** 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 (15.0.1) is an isomorphism.

**Proof.** Let \( U \) be an open covering of \( X \). By Lemma 11.5 there is an exact sequence

\[ 0 \rightarrow \check{H}^1(U, \mathcal{F}) \rightarrow H^1(U, \mathcal{F}) \rightarrow \check{H}^0(U, H^1(\mathcal{F})) \]

Thus the map is injective. To show surjectivity it suffices to show that any element of \( \check{H}^0(U, H^1(\mathcal{F})) \) maps to zero after replacing \( U \) by a refinement. This is immediate from the definitions and the fact that \( H^1(\mathcal{F}) \) is a presheaf of abelian groups whose sheafification is zero by locality of cohomology, see Lemma 7.2. \( \square \)

09V2 **Lemma 16.2.** 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 (15.0.1) is an isomorphism for all \( n \).

**Proof.** We already know that \( \check{H}^n(X, -) \rightarrow H^n(X, -) \) is an isomorphism of functors for \( n = 0, 1 \), see Lemma 16.1. The functors \( H^n(X, -) \) form a universal \( \delta \)-functor, see Derived Categories, Lemma 20.4. If we show that \( \check{H}^n(X, -) \) forms a universal \( \delta \)-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 \( \delta \)-functors, see Homology, Lemma 12.5.

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

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

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

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

\[
U_{i_0 \ldots i_n} = \bigcup W_{i_0 \ldots i_n, k}
\]

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

\[
\begin{array}{c}
0 \longrightarrow \check{C}^\bullet (U, \mathcal{F}) \longrightarrow \check{C}^\bullet (U, \mathcal{G}) \longrightarrow \check{C}^\bullet (U, \mathcal{H}) \longrightarrow 0 \\
\downarrow \quad \quad \downarrow \quad \quad \downarrow \\
0 \longrightarrow \check{C}^\bullet (\mathcal{V}, \mathcal{F}) \longrightarrow \check{C}^\bullet (\mathcal{V}, \mathcal{G}) \longrightarrow \check{C}^\bullet (\mathcal{V}, \mathcal{H}) \longrightarrow 0
\end{array}
\]

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

\[
g_{j_0 \ldots j_n} \in \mathcal{G}(V_{j_0 \ldots j_n}), \quad g_{j_0 \ldots j_n} \mapsto h_{\alpha(j_0) \ldots \alpha(j_n)}|V_{j_0 \ldots j_n}
\]

The cochain \( g = (g_{j_0 \ldots j_n}) \) 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 \( \xi \) 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 \( \mathcal{U}, \mathcal{V}, \mathcal{F}, \alpha : J \to I, g \). The class of \( d(g) \) is independent of the choice of the lifts \( g_{i_0 \ldots i_n} \) because the difference will be a coboundary. Independence of \( \alpha \) holds because a different choice of \( \alpha \) determines homotopic vertical maps of complexes in the diagram above, see Section \[\ref{15} \]. 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 \( \check{H}^n(X, -) \to H^n(X, -) \) are compatible with boundary maps. To do this we choose injective resolutions

\[
\begin{array}{c}
0 \longrightarrow \mathcal{F} \longrightarrow \mathcal{G} \longrightarrow \mathcal{H} \longrightarrow 0 \\
\downarrow \quad \quad \downarrow \quad \quad \downarrow \\
0 \longrightarrow I_1^* \longrightarrow I_2^* \longrightarrow I_3^* \longrightarrow 0
\end{array}
\]

\[\footnote{This is an important check because the nonuniqueness of \( \alpha \) 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.} \]
as in Derived Categories, Lemma \[18.9\] This will give a commutative diagram

\[
\begin{array}{cccccc}
0 & \longrightarrow & \hat{C}^\bullet(\mathcal{U}, \mathcal{F}) & \longrightarrow & \hat{C}^\bullet(\mathcal{U}, \mathcal{F}) & \longrightarrow & 0 \\
\downarrow & & \downarrow & & \downarrow & & \\
0 & \longrightarrow & \text{Tot}(\hat{C}^\bullet(\mathcal{U}, \mathcal{I}_1^*)) & \longrightarrow & \text{Tot}(\hat{C}^\bullet(\mathcal{U}, \mathcal{I}_2^*)) & \longrightarrow & 0 \\
\end{array}
\]

Here \( \mathcal{U} \) is an open covering as above and the vertical maps are those used to define the maps \( H^n(\mathcal{U}, -) \to H^n(X, -) \), see Lemma \[11.2\] 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 \[13.12\] 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 \( \delta \)-functor on Čech cohomology and why this structure is compatible with the given \( \delta \)-functor structure on usual cohomology.

Finally, we may apply Lemma \[11.1\] to see that higher Čech cohomology is trivial on injective sheaves. Hence we see that Čech cohomology is a universal \( \delta \)-functor by Homology, Lemma \[12.4\].

\[\Box\]

**Lemma 16.3.** 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

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

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 \( s|_{\mathcal{F}(U_i)} \) 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 \( s_i|_{\mathcal{F}(W_{ij})} = s_j|_{\mathcal{F}(W_{ij})} \). 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 \( s_i|_{\mathcal{F}(V_i)} \) 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 \[16.2\] the element \( \bar{\xi} \) comes from \( H^p(\mathcal{V}, \mathcal{I}|_Z) \) for some open covering \( \mathcal{V} : Z = \bigcup V_i \) of \( Z \). Say \( \bar{\xi} \) is the image of the class of a cocycle \( \xi = (\xi_{i_0...i_p}) \) in \( \hat{C}^p(\mathcal{V}, \mathcal{I}|_Z) \).

Let \( \mathcal{I}' \subset \mathcal{I}|_Z \) be the presheaf 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 \( i_0...i_p \) we can find an open covering \( V_{i_0...i_p} = \bigcup W_{i_0...i_p,k} \) such that \( \xi_{i_0...i_p}|_{W_{i_0...i_p,k}} \) is a section of \( \mathcal{I}' \). Applying Topology, Lemma \[13.5\] we may after refining \( \mathcal{V} \) assume that each \( \xi_{i_0...i_p} \) 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 12.2) and since $\xi_{i_0 \ldots i_p}$ is a section of $\mathcal{I}'$ for every $(p + 1)$-tuple $i_0 \ldots i_p$ we can choose a section $s_{i_0 \ldots i_p} \in \mathcal{I}(U_{i_0 \ldots i_p})$ which restricts to $\xi_{i_0 \ldots i_p}$ on $V_{i_0 \ldots i_p} = Z \cap U_{i_0 \ldots i_p}$. (This appeal to injectives being flasque can be avoided by an additional application of Topology, Lemma 13.7.) Let $s = (s_{i_0 \ldots i_p})$ be the corresponding cochain for the open covering $U = \bigcup U_i$. Since $d(s) = 0$ we see that the sections $d(s)_{i_0 \ldots i_p}$ restrict to zero on $Z \cap U_{i_0 \ldots i_p+1}$. Hence, by the initial remarks of the proof, there exists open subsets $W_{i_0 \ldots i_p+1} \subset U_{i_0 \ldots i_p+1}$ such that $d(s)_{i_0 \ldots i_p}|_{W_{i_0 \ldots i_p+1}} = 0$. By Topology, Lemma 13.7 we can find $U_i' \subset U_i$ such that $Z \subset \bigcup U_i'$ and such that $U_{i_0 \ldots i_p+1}' \subset W_{i_0 \ldots i_p+1}$. Then $s' = (s_{i_0 \ldots i_p}')$ 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 11.1) we conclude that $s'$ is a coboundary. It follows that the image of $\xi$ in the Čech complex for the open covering $Z = \bigcup Z \cap U_i'$ is a coboundary and we are done. \qed

17. 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 $g : X \to Y$ is a flat morphism of ringed spaces. By Modules, Lemma 19.2 the functor $g^* : \text{Mod}(\mathcal{O}_Y) \to \text{Mod}(\mathcal{O}_X)$ is exact. Hence it has a derived functor $g^* : D^+(Y) \to D^+(X)$ which is computed by simply pulling back an representative of a given object in $D^+(Y)$, see Derived Categories, Lemma 16.9. Hence as indicated we indicate this functor by $g^*$ rather than $Lg^*$.

02N7 \textbf{Lemma 17.1.} Let

\begin{tikzcd}
X' \rar{g'} \dar{f'} & X \dar{f} \\
S' \rar{g} & S
\end{tikzcd}

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

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

in $D^+(S')$.

\textbf{Proof.} Choose injective resolutions $\mathcal{F}^\bullet \to \mathcal{I}^\bullet$ and $(g')^* \mathcal{F}^\bullet \to \mathcal{J}^\bullet$. By Lemma 11.11 we see that $(g')^* \mathcal{J}^\bullet$ is a complex of injectives representing $R(g')^* (g')^\bullet \mathcal{F}^\bullet$. Hence by Derived Categories, Lemmas 18.6 and 18.7 the arrow $\beta$ in the diagram

\begin{tikzcd}
(g')^* (g')^\bullet \mathcal{F}^\bullet \ar{r} \ar{d}[description]{adjunction} & (g')^* \mathcal{J}^\bullet \ar{d}[description]{\beta} \\
\mathcal{F}^\bullet & \mathcal{I}^\bullet
\end{tikzcd}

is an isomorphism.
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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 $\beta$ and everything was done on the level of complexes. □

02N8 **Remark 17.2.** 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 28.3.

18. Proper base change in topology

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 $\mathcal{R}^pf_*$ can be computed on the fibre.

**Lemma 18.1.** 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 17.1 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 16.3 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 16.7. 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 16.3, 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. □

**Theorem 18.2 (Proper base change).** Consider a cartesian square of topological spaces, with $f$ proper and separated. Let $E$ be an object of $D^+(X)$. Then the base change map
\[ g^{-1}Rf_*E \rightarrow Rf'_*(g')^{-1}E \]
of Lemma 17.1 is an isomorphism in $D^+(Y')$. 

AGV71 Expose V bis, 4.1.1
**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 18.1 twice to see that

\[
(Rf'_{\ast}(g'_{\ast}\mathcal{E}))_{y'} = R\Gamma((f'_{\ast})^{-1}(y'), (g'_{\ast})^{-1} E|_{(f'_{\ast})^{-1}(y')})
\]

and

\[
(Rf_{\ast}\mathcal{E})_{y} = R\Gamma(f^{-1}(y), E|_{f^{-1}(y)})
\]

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

**Lemma 18.3** (Proper base change for sheaves of sets). Consider a cartesian square of topological spaces

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

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

**Proof.** We argue exactly as in the proof of Theorem 18.2 and we find it suffices to show \((f_{\ast}\mathcal{F})_{y} = \Gamma(X_{y}, \mathcal{F}|_{X_{y}})\). Then we argue as in Lemma 18.1 to reduce this to the \( p = 0 \) case of Lemma 16.3 for sheaves of sets. The first part of the proof of Lemma 16.3 works for sheaves of sets and this finishes the proof. Some details omitted. \( \square \)

### 19. Cohomology and colimits

**Lemma 19.1.** 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

\[
\colim_i H^q(U, \mathcal{F}_i) \longrightarrow H^q(U, \colim_i \mathcal{F}_i)
\]

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 $(\mathcal{F}_i, \varphi_{i'j})$ over $I$ is directed. By Injectives, Lemma 5.1 the category of $\mathcal{O}_X$-modules has functorial injective embeddings. Thus for any system $(\mathcal{F}_i, \varphi_{i'j})$ 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 $\mathcal{F}_i \to \mathcal{I}_i$. Denote $\mathcal{Q}_i$ the cokernel so that we have short exact sequences

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

We claim that the sequence

$$0 \to \text{colim}_i \mathcal{F}_i \to \text{colim}_i \mathcal{I}_i \to \text{colim}_i \mathcal{Q}_i \to 0.$$ 

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 $H^q(U, \text{colim}_i \mathcal{I}_i) = 0$ for all quasi-compact open $U \subset X$ and all $q \geq 1$. Accepting this claim for the moment consider the diagram

$$
\begin{array}{ccc}
\text{colim}_i H^q(U, \mathcal{I}_i) & \longrightarrow & \text{colim}_i H^q(U, \mathcal{Q}_i) \\
\downarrow & & \downarrow \\
H^q(U, \text{colim}_i \mathcal{I}_i) & \longrightarrow & H^q(U, \text{colim}_i \mathcal{Q}_i)
\end{array}
$$

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 11.9. 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 $\mathcal{U} : U = \bigcup_{j=1}^m U_j$ with each of $U_i, U_j$ quasi-compact open in $X$. By the result for $q = 0$ we see that for $U \in \text{Cov}$ we have

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

because all the multiple intersections $U_{i_0 \ldots i_p}$ are quasi-compact. By Lemma 11.1 each of the complexes in the colimit of Čech complexes is acyclic in degree $\geq 1$. Hence by Algebra, Lemma 8.8 we see that also the Čech complex $\check{C}^* (\mathcal{U}, \text{colim}_i \mathcal{I}_i)$ is acyclic in degrees $\geq 1$. 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 11.9 are satisfied and the claim follows. □

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 $a : j \to i$ an $f_a$-map $\varphi_a : F_i \to F_j$ of abelian sheaves (see Sheaves, Definition 21.7) such that $\varphi_c = \varphi_b \circ \varphi_a$ whenever $c = a \circ b$. Set $F = \colim p_i^{-1}F_i$ on $X$.

**Lemma 19.2.** In the situation discussed above. Let $i \in \Ob(I)$ and let $U_i \subset X_i$ be quasi-compact open. Then
\[
\colim_{a,j \to i} H^p(f_a^{-1}(U_i), F_j) = H^p(p_i^{-1}(U_i), F)
\]
for all $p \geq 0$. In particular we have $H^p(X, F) = \colim H^p(X_i, F_i)$.

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

In this paragraph we show that we can find a map of systems $(\gamma_i) : (F_i, \varphi_a) \to (G_i, \psi_a)$ with $G_i$ an injective abelian sheaf and $\gamma_i$ injective. For each $i$ we pick an injection $F_i \to I_i$ where $I_i$ is an injective abelian sheaf on $X_i$. Then we can consider the family of maps
\[
\gamma_i : F_i \longrightarrow \prod_{b,k \to i} f_{b,*}I_k = G_i
\]
where the component maps are the maps adjoint to the maps $f_b^{-1}F_i \to F_k \to I_k$. For $a : j \to i$ in $I$ there is a canonical map
\[
\psi_a : f_a^{-1}G_i \to G_j
\]
whose components are the canonical maps $f_b^{-1}f_{a,b,*}I_k \to f_{b,*}I_k$ for $b : k \to j$. Thus we find an injection $(\gamma_i) : (F_i, \varphi_a) \to (G_i, \psi_a)$ of systems of abelian sheaves.

Note that $G_i$ is an injective sheaf of abelian groups on $X_i$, see Lemma 11.11 and Homology, Lemma 27.3. This finishes the construction.

Arguing exactly as in the proof of Lemma 19.1 we see that it suffices to prove that $H^p(X, \colim f_i^{-1}G_i) = 0$ for $p > 0$.

Set $G = \colim f_i^{-1}G_i$. To show vanishing of cohomology of $G$ on every quasi-compact open of $X$, it suffices to show that the Čech cohomology of $G$ for any covering $U$ of a quasi-compact open of $X$ by finitely many quasi-compact opens is zero, see Lemma 11.9. Such a covering is the inverse by $p_i$ of such a covering $U_i$ on the space $X_i$ for some $i$ by Topology, Lemma 24.6. We have
\[
\check{C}^\bullet(U, G) = \colim_{a,j \to i} \check{C}^\bullet(f_a^{-1}(U_i), G_j)
\]
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 11.1. Thus we conclude by Algebra, Lemma 8.8.

**20. Vanishing on Noetherian topological spaces**

**Lemma 20.1.** Let $i : Z \to X$ be a closed immersion of topological spaces. For any abelian sheaf $F$ on $Z$ we have $H^p(Z, F) = H^p(X, i_*F)$.

**Proof.** This is true because $i_*$ is exact (see Modules, Lemma 6.1), and hence $R^pi_* = 0$ as a functor (Derived Categories, Lemma 16.9). Thus we may apply Lemma 13.6. 

**Lemma 20.2.** Let $X$ be an irreducible topological space. Then $H^p(X, A) = 0$ for all $p > 0$ and any abelian group $A$. 

See Gro57. 

Proof. Recall that \( A \) is the constant sheaf as defined in Sheaves, Definition 7.4. It is clear that for any nonempty open \( U \subset X \) we have \( A(U) = A \) as \( X \) is irreducible (and hence \( U \) is connected). We will show that the higher Čech cohomology groups \( H^p(U, A) \) are zero for any open covering \( U : U = \bigcup_{i \in I} U_i \) of an open \( U \subset X \). Then the lemma will follow from Lemma 14.8.

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

\[
\prod_{i_0 \in I} A \to \prod_{(i_0, i_1) \in I^2} A \to \prod_{(i_0, i_1, i_2) \in I^3} A \to \ldots
\]

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.) \( \square \)

**Lemma 20.3.** Let \( X \) be a topological space such that the intersection of any two quasi-compact opens is quasi-compact. Let \( \mathcal{F} \subset \mathbb{Z} \) be a subsheaf generated by finitely many sections over quasi-compact opens. Then there exists a finite filtration

\[
(0) = \mathcal{F}_0 \subset \mathcal{F}_1 \subset \ldots \subset \mathcal{F}_n = \mathcal{F}
\]

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

\[
0 \to j'_* \mathbb{Z}_V \to j_* \mathbb{Z}_U \to \mathcal{F}_i/\mathcal{F}_{i-1} \to 0
\]

with \( j : U \to X \) and \( j' : V \to X \) the inclusion of quasi-compact opens into \( X \).

**Proof.** Say \( \mathcal{F} \) is generated by the sections \( s_1, \ldots, s_t \) over the quasi-compact opens \( U_1, \ldots, U_t \). Since \( U_i \) is quasi-compact and \( s_i \) a locally constant function to \( \mathbb{Z} \) 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 \( s_i = n_i \in \mathbb{Z} \). 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 \( I \subset \{1, \ldots, t\} \) 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 \( \{(U_1, n_1), \ldots, (U_t, n_t)\} \) satisfies the following property: For \( x \in X \) set \( I_x = \{i \in \{1, \ldots, t\} \mid x \in U_i\} \). 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 \( U = \bigcup_{n \leq n} U_i \) and the kernel of the map \( j'_* \mathbb{Z}_V \to \mathcal{F}_n/\mathcal{F}_{n-1} \) is generated by the section \( n \) over \( V = \bigcup_{n \leq n-1} U_i \). Thus this is a short exact sequence as in the statement of the lemma. \( \square \)

**Lemma 20.4.** 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. \( H^p(X, j'_* \mathbb{Z}_V) = 0 \) for all \( p > d \) and any quasi-compact open \( j : U \to X \).

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 [Gro67, Proposition 3.6.1].
Proof. Let \( S = \prod_{U \subset X} \mathcal{F}(U) \) where \( U \) runs over the quasi-compact opens of \( X \). For any finite subset \( A = \{s_1, \ldots, s_n\} \subset S \), 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 19.1 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 \( s_1, \ldots, s_n \). Let \( \mathcal{F}' \subset \mathcal{F} \) be the subsheaf generated by \( s_1, \ldots, s_{n-1} \). Then we have a short exact sequence

\[
0 \to \mathcal{F}' \to \mathcal{F} \to \mathcal{F}/\mathcal{F}' \to 0
\]

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 \( j^! \mathbb{Z}_U \) where \( U \) is a quasi-compact open of \( X \).

Assume now that we have a short exact sequence

\[
0 \to K \to j^! \mathbb{Z}_U \to \mathcal{F} \to 0
\]

with \( U \) quasi-compact open in \( X \). It suffices to show that \( H^q(X, K) \) is zero for \( q \geq d+1 \). As above we can write \( K \) as the filtered colimit of subsheaves \( K' \) generated by finitely many sections over quasi-compact opens. Then \( \mathcal{F} \) is the filtered colimit of the sheaves \( j^! \mathbb{Z}_U/K' \). In this way we reduce to the case that \( K \) is generated by finitely many sections over quasi-compact opens. Note that \( K' \) is a subsheaf of \( \mathbb{Z}_X \).

Thus by Lemma 20.3 there exists a finite filtration of \( K \) whose successive quotients \( Q \) fit into a short exact sequence

\[
0 \to j'' \mathbb{Z}_W \to j' \mathbb{Z}_V \to Q \to 0
\]

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

Example 20.5. Let \( X = \mathbb{N} \) 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 \( H^p(X, j^! \mathbb{Z}_U) = 0 \), \( p \geq 1 \) if \( j : U = U_n \to X \) is the inclusion. Thus we see that \( X \) is an example of a space satisfying conditions (2), (3), and (4) of Lemma 20.4 for \( d = 0 \) but not the conclusion.
Let \( U \) be an irreducible topological space. Let \( H \subset Z \) be an abelian subsheaf of the constant sheaf. Then there exists a nonempty open \( U \subset X \) such that \( H|_U = dZ|_U \) for some \( d \in Z \).

**Proof.** Recall that \( Z(V) = Z \) for any nonempty open \( V \) of \( X \) (see proof of Lemma 20.2). If \( H = 0 \), then the lemma holds with \( d = 0 \). If \( H \neq 0 \), then there exists a nonempty open \( U \subset X \) such that \( H(U) \neq 0 \). Say \( H(U) = nZ \) for some \( n \geq 1 \). Hence we see that \( nZ|_U \subset H|_U \subset Z|_U \). If the first inclusion is strict we can find a nonempty \( U' \subset U \) and an integer \( 1 \leq n' < n \) such that \( n'Z|_{U'} \subset H|_{U'} \subset Z|_{U'} \). This process has to stop after a finite number of steps, and hence we get the lemma. \( \square \)

Proposition 20.7 (Grothendieck). Let \( X \) be a Noetherian topological space. If \( \dim(X) \leq d \), then \( H^p(X,F) = 0 \) for all \( p > d \) and any abelian sheaf \( F \) on \( X \).

**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 \( F \) be an abelian sheaf on \( X \). Suppose \( U \subset X \) is an open. Let \( Z \subset X \) denote the closed complement. Denote \( j : U \to X \) and \( i : Z \to X \) the inclusion maps. Then there is a short exact sequence

\[
0 \to j_! j^* F \to F \to i_* i^* F \to 0
\]

see Modules, Lemma 7.1. Note that \( j_! j^* F \) is supported on the topological closure \( Z' \) of \( U \), i.e., it is of the form \( i'_* F' \) for some abelian sheaf \( F' \) on \( Z' \), where \( i' : Z' \to X \) 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 \( H^p(X,i_* i^* F) \) and \( H^p(X,i'_* F') \) for \( p > d \). By Lemma 20.1 it suffices to prove \( H^p(Z,i^* F) \) and \( H^p(Z',F') \) 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 20.2).

Suppose \( X \) is irreducible of dimension \( d \). By Lemma 20.3 we reduce to the case where \( F = j_! Z|_U \) for some open \( U \subset X \). In this case we look at the short exact sequence

\[
0 \to j_! (Z|_U) \to Z|_X \to i_* Z|_Z \to 0
\]

where \( Z = X \setminus U \). By Lemma 20.2 we have the vanishing of \( H^p(X,Z|_X) \) for all \( p \geq 1 \). By induction we have \( H^p(X,i_* Z|_Z) = H^p(Z,Z|_Z) = 0 \) for \( p > d \). Hence we win by the long exact cohomology sequence. \( \square \)

### 21. Cohomology with support in a closed

Let \( X \) be a topological space and let \( Z \subset X \) be a closed subset. Let \( F \) be an abelian sheaf on \( X \). We let

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

$$
R\Gamma_Z(X,-) : D(X) \to D(Ab)
$$

and cohomology groups with support in $Z$ defined by $H^q_Z(X,F) = R^q\Gamma_Z(X,F)$.

Let $\mathcal{I}$ be an injective abelian sheaf on $X$. Let $U = X \setminus Z$. Then the restriction map $\mathcal{I}(X) \to \mathcal{I}(U)$ is surjective (Lemma $8.1$) with kernel $\Gamma_Z(X,\mathcal{I})$. It immediately follows that for $K \in D(X)$ there is a distinguished triangle

$$
R\Gamma_Z(X,K) \to R\Gamma(X,K) \to R\Gamma(U,K) \to R\Gamma_Z(X,K)[1]
$$
in $D(Ab)$. As a consequence we obtain a long exact cohomology sequence

$$
\ldots \to H^i_Z(X,K) \to H^i(X,K) \to H^i(U,K) \to H^{i+1}_Z(X,K) \to \ldots
$$

for any $K$ in $D(X)$.

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

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

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

$$
Ab(X) \to Ab(Z), \quad F \mapsto \mathcal{H}_Z(F)
$$

viewed as a sheaf on $Z$ which is left exact, but in general not exact.

**Lemma 21.1.** Let $i : Z \to X$ 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

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

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 $Z$. □

Denote

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

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

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

**Lemma 21.2.** Let $i : Z \to X$ be the inclusion of a closed subset. Let $\mathcal{G}$ be an injective abelian sheaf on $Z$. Then $\mathcal{H}^p_Z(i_* \mathcal{G}) = 0$ for $p > 0$.

**Proof.** This is true because the functor $i_*$ is exact and transforms injective abelian sheaves into injective abelian sheaves by Lemma $11.11$. □

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 $Z$. 
Let $i : Z \to X$ be the inclusion of a closed subset of a topological space $X$. The map $Ri_* = i_* : D(Z) \to D(X)$ induces an equivalence $D(Z) \to D_Z(X)$ with quasi-inverse
\[
i^{-1}|_{D_Z(X)} = RH_Z|_{D_Z(X)}
\]

**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, Lemma 6.3 and 6.1. Thus $i_* : D(Z) \to D_Z(X)$ 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 $K \to i_*i^{-1}K$. Using exactness of $i_*$ and $i^{-1}$ this induces the adjunction maps $H^n(K) \to i_*i^{-1}H^n(K)$ on cohomology sheaves. Since these cohomology sheaves are supported on $Z$ we see these adjunction maps are isomorphisms and we conclude that $D(Z) \to D_Z(X)$ is an equivalence.

To finish the proof we have to show that $RH_Z(K) = i^{-1}K$ 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 $I*$ for $i^{-1}K$. Since $i_*$ is the right adjoint to the exact functor $i^{-1}$, the complex $i_*I*$ is $K$-injective (Derived Categories, Lemma 31.9). We see that $RH_Z(K)$ is computed by $H_Z(i_*I*) = I*$ as desired.

### 22. Cohomology on spectral spaces

A key result on the cohomology of spectral spaces is Lemma 19.2, 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 16.3 and 18.1 as follows.

**Lemma 22.1.** Let $X$ be a spectral space. Let $F$ 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. $H^p(W, F|_W) = \colim H^p(U, F)$ where the colimit is over quasi-compact open neighbourhoods of $E$.
2. $H^p(W \setminus E, F|_{W \setminus E}) = \colim H^p(U \setminus E, F|_{U \setminus E})$ 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 19.2 to conclude that (1) holds. The same proof works for part (2) except we use Topology, Lemma 24.8.

**Lemma 22.2.** Let $f : X \to Y$ be a spectral map of spectral spaces. Let $y \in Y$. Let $E \subset Y$ be the set of points specializing to $y$. Let $F$ be an abelian sheaf on $X$. Then $(R^p f_* F)_y = H^p(f^{-1}(E), F|_{f^{-1}(E)})$.

**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 $H^p(f^{-1}(E), F|_{f^{-1}(E)}) = \colim H^p(f^{-1}(V), F)$ by Lemma 19.2. On the other hand, the stalk of $R^p f_* F$ at $y$ is given by the colimit on the right.
Lemma 22.3. Let $X$ be a profinite topological space. Then $H^q(X, F) = 0$ for all $q > 0$ and all abelian sheaves $F$.

Proof. Any open covering of $X$ can be refined by a finite disjoint union decomposition with open parts, see Topology, Lemma 22.4. Hence if $F \to G$ is a surjection of abelian sheaves on $X$, then $F(X) \to G(X)$ is surjective. In other words, the global sections functor is an exact functor. Therefore its higher derived functors are zero, see Derived Categories, Lemma 16.9. □

The following result on cohomological vanishing improves Grothendieck’s result (Proposition 20.7) and can be found in [Sch92].

Proposition 22.4. Let $X$ be a spectral space of Krull dimension $d$. Let $F$ be an abelian sheaf on $X$.

(1) $H^q(X, F) = 0$ for $q > d$,
(2) $H^d(X, F) \to H^d(U, F)$ is surjective for every quasi-compact open $U \subset X$,
(3) $H^q_Z(X, F) = 0$ 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 22.3. If $U \subset X$ is quasi-compact open, then $U$ is also closed as a quasi-compact subset of a Hausdorff space. Hence $X = U \sqcup (X \setminus U)$ as a topological space and we see that (2) holds. Given $Z$ as in (3) we consider the long exact sequence

$$H^{q-1}(X, F) \to H^{q-1}(X \setminus Z, F) \to H^q_Z(X, F) \to H^q(X, F)$$

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 $\xi \in H^d(U, F)$. Set $Z = X \setminus U$. Let $W \subset X$ be the set of points specializing to $Z$. By Lemma 22.1 we have

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

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 $\xi$ in $H^d(W \setminus Z, F|_{W \setminus Z})$ 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 8.2) for the covering $X = U \cap V$ that there exists a $\xi \in H^d(X, F)$ which restricts to $\xi$ on $U$ and to zero on $V$. In other words, part (2) is true.

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

$$G = \text{Im}(I^{d-1} \to I^d) = \text{Ker}(I^d \to I^{d+1})$$

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

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

and $s_{i_0...i_m...i_n...i_p} = -s_{i_0...i_m...i_n...i_p}$ in any case.

We omit the verification that the differential $d$ of Equation (9.0.1) maps $\tilde{C}_{alt}^p(\mathcal{U}, \mathcal{F})$ into $\tilde{C}^{p+1}_{alt}(\mathcal{U}, \mathcal{F})$.

**Definition 23.1.** 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 $\tilde{C}_{alt}^*(\mathcal{U}, \mathcal{F})$ is the alternating Čech complex associated to $\mathcal{F}$ and the open covering $\mathcal{U}$.

Hence there is a canonical morphism of complexes

$$
\tilde{C}_{alt}^*(\mathcal{U}, \mathcal{F}) \to \tilde{C}^*(\mathcal{U}, \mathcal{F})
$$

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

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

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

$$
d : \tilde{C}_{ord}^p(\mathcal{U}, \mathcal{F}) \to \tilde{C}_{ord}^{p+1}(\mathcal{U}, \mathcal{F})
$$
by the formula
\[ d(s)_{i_0 \ldots i_{p+1}} = \sum_{j=0}^{p+1} (-1)^j s_{i_0 \ldots i_j \ldots i_{p+1}} |_{U_{i_0 \ldots i_{p+1}}} \]
for any \( i_0 < \ldots < i_{p+1} \). Note that this formula is identical to Equation (9.0.1). It is straightforward to see that \( d \circ d = 0 \). In other words \( \check{C}^{\bullet}_{ord}(U, F) \) is a complex.

**Definition 23.2.** Let \( X \) be a topological space. Let \( U : U = \bigcup_{i \in I} U_i \) be an open covering. Assume given a total ordering on \( I \). Let \( F \) be an abelian presheaf on \( X \). The complex \( \check{C}^{\bullet}_{ord}(U, F) \) is the **ordered Čech complex** associated to \( F \), the open covering \( U \) 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
\[ c : \check{C}^{\bullet}_{ord}(U, F) \longrightarrow \check{C}^{\bullet}(U, F) \]
given by the rule
\[ c(s)_{i_0 \ldots i_p} = \begin{cases} 0 & \text{if } i_n = i_m \text{ for some } n \neq m \\ \text{sgn}(\sigma)s_{i_{\sigma(0)} \ldots i_{\sigma(p)}} & \text{if } i_{\sigma(0)} < i_{\sigma(1)} < \ldots < i_{\sigma(p)} \end{cases} \]
Here \( \sigma \) denotes a permutation of \( \{0, \ldots, p\} \) 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.

**Lemma 23.3.** Let \( X \) be a topological space. Let \( U : U = \bigcup_{i \in I} U_i \) be an open covering. Assume \( I \) comes equipped with a total ordering. The map \( c : \check{C}^{\bullet}_{ord}(U, F) \rightarrow \check{C}^{\bullet}_{ord}(U, F) \) is a morphism of complexes. It induces an isomorphism
\[ c : \check{C}^{\bullet}_{ord}(U, F) \rightarrow \check{C}^{\bullet}_{alt}(U, F) \]
of complexes.

**Proof.** Omitted. \( \square \)

There is also a map
\[ \pi : \check{C}^{\bullet}(U, F) \longrightarrow \check{C}^{\bullet}_{ord}(U, F) \]
which is described by the rule
\[ \pi(s)_{i_0 \ldots i_p} = s_{i_0 \ldots i_p} \]
whenever \( i_0 < i_1 < \ldots < i_p \).

**Lemma 23.4.** Let \( X \) be a topological space. Let \( U : U = \bigcup_{i \in I} U_i \) be an open covering. Assume \( I \) comes equipped with a total ordering. The map \( \pi : \check{C}^{\bullet}(U, F) \rightarrow \check{C}^{\bullet}_{ord}(U, F) \) is a morphism of complexes. It induces an isomorphism
\[ \pi : \check{C}^{\bullet}_{alt}(U, F) \rightarrow \check{C}^{\bullet}_{ord}(U, F) \]
of complexes which is a left inverse to the morphism \( c \).

**Proof.** Omitted. \( \square \)
Lemma 23.6. 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 $\check{C}^\bullet(\mathcal{U}, F)$. In particular the inclusion map $\check{C}^\bullet_{\text{fil}}(\mathcal{U}, F) \to \check{C}^\bullet(\mathcal{U}, F)$ is a homotopy equivalence.

**Proof.** For any multi-index $(i_0, \ldots, i_p) \in I_p$ there exists a unique permutation $\sigma : \{0, \ldots, p\} \to \{0, \ldots, p\}$ such that

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

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

For any permutation $\sigma : \{0, \ldots, p\} \to \{0, \ldots, p\}$ and any $a$, $0 \leq a \leq p$ we denote $\sigma_a$ the permutation of $\{0, \ldots, p\}$ such that

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

So if $p = 3$ and $\sigma, \tau$ are given by

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

then we have

$$\begin{array}{cccc} \text{id} & 0 & 1 & 2 \\ \sigma_0 & 0 & 1 & 2 \\ \sigma_1 & 3 & 0 & 1 \\ \sigma_2 & 3 & 2 & 0 \\ \sigma_3 & 3 & 2 & 1 \end{array}$$

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

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

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

where $\sigma = \sigma^{i_0 \cdots i_p}$. The index $i_{\sigma(a)}$ occurs twice in $i_{\sigma(0)} \cdots i_{\sigma(a)} i_{\sigma_a(0)} \cdots i_{\sigma_a(p)}$ 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 $\sigma_a$. Hence the sum makes sense since each of the elements $s_{i_{\sigma(0)} \cdots i_{\sigma(a)} i_{\sigma_a(0)} \cdots i_{\sigma_a(p)}}$ is defined over the open $U_{i_0 \cdots i_p}$.

Note also that for $a = 0$ we get $s_{i_0 \cdots i_p}$ and for $a = p$ we get $(-1)^p \text{sign}(\sigma) s_{i_{\sigma(0)} \cdots i_{\sigma(p)}}$.

We claim that

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

where $\sigma = \sigma^{i_0 \cdots i_p}$. 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
\[ \kappa : \check{C}^\bullet(\mathcal{U}, \mathcal{F}) \rightarrow \check{C}^\bullet(\mathcal{U}, \mathcal{F}) \]
for the operator given by the rule
\[ \kappa(s)_{i_0 \ldots i_p} = \text{sign}(\sigma_{i_0 \ldots i_p}) s_{i_{\sigma(0)} \ldots i_{\sigma(p)}}. \]

The claim above implies that \( \kappa \) is a morphism of complexes and that \( \kappa \) is homotopic to the identity map of the Čech complex. This does not immediately imply the lemma since the image of the operator \( \kappa \) is not the alternating subcomplex. Namely, the image of \( \kappa \) is the “semi-alternating” complex \( \check{C}^p_{\text{semi-alt}}(\mathcal{U}, \mathcal{F}) \) where \( s \) is a \( p \)-cochain of this complex if and only if
\[ s_{i_0 \ldots i_p} = \text{sign}(\sigma) s_{i_{\sigma(0)} \ldots i_{\sigma(p)}} \]
for any \((i_0, \ldots, i_p) \in I^{p+1}\) with \( \sigma = \sigma^0 \ldots i_p \). We introduce yet another variant Čech complex, namely the semi-ordered Čech complex defined by
\[ \check{C}^p_{\text{semi-ord}}(\mathcal{U}, \mathcal{F}) = \prod_{i_0 \leq i_1 \leq \ldots \leq i_p} \mathcal{F}(U_{i_0 \ldots i_p}) \]
It is easy to see that Equation (9.0.1) also defines a differential and hence that we get a complex. It is also clear (analogous to Lemma 23.4) that the projection map
\[ \check{C}^\bullet_{\text{semi-alt}}(\mathcal{U}, \mathcal{F}) \rightarrow \check{C}^\bullet_{\text{semi-ord}}(\mathcal{U}, \mathcal{F}) \]
is an isomorphism of complexes.

Hence the Lemma follows if we can show that the obvious inclusion map
\[ \check{C}^p_{\text{ord}}(\mathcal{U}, \mathcal{F}) \rightarrow \check{C}^p_{\text{semi-ord}}(\mathcal{U}, \mathcal{F}) \]
is a homotopy equivalence. To see this we use the homotopy (23.6.2)
\[ h(s)_{i_0 \ldots i_p} = \left\{ \begin{array}{ll} 0 & \text{if } i_0 < i_1 < \ldots < i_p \\ (-1)^a s_{i_0 \ldots i_a - i_{a+1} i_{a+1} \ldots i_p} & \text{if } i_0 < i_1 < \ldots < i_{a-1} < i_a = i_{a+1} \end{array} \right. \]
We claim that
\[ (dh + hd)(s)_{i_0 \ldots i_p} = \left\{ \begin{array}{ll} 0 & \text{if } i_0 < i_1 < \ldots < i_p \\ s_{i_0 \ldots i_p} & \text{else} \end{array} \right. \]
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
\[ \check{C}^\bullet_{\text{semi-ord}}(\mathcal{U}, \mathcal{F}) \rightarrow \check{C}^\bullet_{\text{ord}}(\mathcal{U}, \mathcal{F}) \rightarrow \check{C}^\bullet_{\text{semi-ord}}(\mathcal{U}, \mathcal{F}) \]
of the projection with the natural inclusion is homotopic to the identity map as desired. \( \Box \)
24. Alternative view of the Čech complex

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

**Lemma 24.1.** Let \( X \) be a ringed space. Let \( U : X = \bigcup_{i \in I} U_i \) be an open covering of \( X \). Let \( F \) be an \( \mathcal{O}_X \)-module. Denote \( F_{i_0 \ldots i_p} \) the restriction of \( F \) to \( U_{i_0 \ldots i_p} \). There exists a complex \( \mathcal{C}^\bullet(U, F) \) of \( \mathcal{O}_X \)-modules with

\[
\mathcal{C}^p(U, F) = \prod_{i_0 \ldots i_p} (j_{i_0 \ldots i_p})_* F_{i_0 \ldots i_p},
\]

and differential \( d : \mathcal{C}^p(U, F) \to \mathcal{C}^{p+1}(U, F) \) as in Equation [9.0.1]. Moreover, there exists a canonical map

\[
F \to \mathcal{C}^\bullet(U, F)
\]

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

**Proof.** We check

\[
0 \to F \to \mathcal{C}^0(U, F) \to \mathcal{C}^1(U, F) \to \ldots
\]

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

\[
h : \mathcal{C}^p(U, F)_x \to \mathcal{C}^{p-1}(U, F)_x
\]

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

\[
\tilde{s} \in \mathcal{C}^p(U, F)(V) = \prod_{i_0 \ldots i_p} F(V \cap U_{i_0} \cap \ldots \cap U_{i_p})
\]

defined on some neighborhood \( V \) of \( x \), and set

\[
h(s)_{i_0 \ldots i_{p-1}} = \tilde{s}_{i_{\text{fix}}i_0 \ldots i_{p-1}} \cdot x.
\]

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

\[
(dh + hd)(s)_{i_0 \ldots i_p} = \sum_{j=0}^p (-1)^j h(s)_{i_0 \ldots \hat{i}_j \ldots i_p} + d(s)_{i_{\text{fix}}i_0 \ldots i_{p-1}}
\]

\[
= \sum_{j=0}^p (-1)^j s_{i_{\text{fix}}i_0 \ldots \hat{i}_j \ldots i_p} + s_{i_0 \ldots i_{p-1}} + \sum_{j=0}^p (-1)^{j+1} s_{i_{\text{fix}}i_0 \ldots \hat{i}_j \ldots i_p}
\]

\[
= s_{i_0 \ldots i_p}
\]

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

\[
0 \to F_x \to \mathcal{C}^0(U, F)_x \to \mathcal{C}^1(U, F)_x \to \ldots
\]

to zero and we conclude. \( \square \)

With this lemma it is easy to reprove the Čech to cohomology spectral sequence of Lemma [11.5]. Namely, let \( X, \mathcal{U}, F \) as in Lemma [24.1] and let \( F \to \mathcal{I}^\bullet \) be an injective resolution. Then we may consider the double complex

\[
A_{\bullet \bullet} = \Gamma(X, \mathcal{C}^\bullet(U, \mathcal{I}^\bullet)).
\]

By construction we have

\[
A^{p,q} = \prod_{i_0 \ldots i_p} \mathcal{I}^q(U_{i_0 \ldots i_p})
\]

Consider the two spectral sequences of Homology, Section [25] associated to this double complex, see especially Homology, Lemma [25.1]. For the spectral sequence \( (E_r, d_r)_{r \geq 0} \) we get \( E_2^{p,q} = \tilde{H}^p(U, \mathcal{H}^q(F)) \) because taking products is exact (Homology, Lemma [32.1]). For the spectral sequence \( (E_r, d_r)_{r \geq 0} \) we get \( E_2^{p,q} = 0 \)
for sheaves of abelian groups $\mathcal{C}^\bullet(\mathcal{U}, T^q)$ is a resolution (Lemma \[24.1\]) of the injective sheaf $I^q$ by injective sheaves (by Lemmas \[7.1\] and \[11.11\] and Homology, Lemma \[27.3\]). Hence the cohomology of $\Gamma(X, \mathcal{C}^\bullet(\mathcal{U}, T^q))$ is zero in positive degrees and equal to $\Gamma(X, T^q)$ in degree 0. Taking cohomology of the next differential we get our claim about the spectral sequence $('^nE_r, '{d_r})_{r \geq 0}$. Hence the result since both spectral sequences converge to the cohomology of the associated total complex of $A^\bullet$.  

**Definition 24.2.** 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.

**Remark 24.3.** Let $X = \bigcup_{i \in I} U_i$ be a locally finite open covering. Denote $j_i : U_i \to X$ 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 \[24.1\] has terms

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

which is sometimes useful.

### 25. Čech cohomology of complexes

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

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

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 $\check{\mathcal{C}}(\mathcal{U}, \mathcal{F})$ (Definition \[9.1\]) is functorial in the presheaf $\mathcal{F}$ we obtain a double complex $\check{\mathcal{C}}(\mathcal{U}, \mathcal{F}^\bullet)$. The associated total complex to $\check{\mathcal{C}}(\mathcal{U}, \mathcal{F}^\bullet)$ is the complex with degree $n$ term

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

see Homology, Definition \[18.3\]. A typical element in $\text{Tot}^n$ will be denoted $\alpha = \{\alpha_{i_0 \ldots i_p}\}$ where $\alpha_{i_0 \ldots i_p} \in \mathcal{F}^q(U_{i_0 \ldots i_p})$. In other words the $\mathcal{F}$-degree of $\alpha_{i_0 \ldots i_p}$ is $q = n - p$. This notation requires us to be aware of the degree $\alpha$ lives in at all times. We indicate this situation by the formula $\text{deg}_\mathcal{F}(\alpha_{i_0 \ldots i_p}) = q$. According to
our conventions in Homology, Definition 1.8.3] the differential of an element \( \alpha \) of degree \( n \) is given by

\[
d(\alpha)_{i_0\ldots i_{p+1}} = \sum_{j=0}^{p+1} (-1)^j \alpha_{i_0\ldots i_j\ldots i_{p+1}} + (-1)^{p+1} d_F(\alpha_{i_0\ldots i_{p+1}})
\]

where \( d_F \) denotes the differential on the complex \( F^* \). The expression \( \alpha_{i_0\ldots i_j\ldots i_{p+1}} \) means the restriction of \( \alpha \) to \( U_{i_0\ldots i_j\ldots i_{p+1}} \).

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

\[
\text{Tot}(\tilde{C}^* (\mathcal{U}, F^*)) \longrightarrow \text{Tot}(\tilde{C}^* (\mathcal{U}, F^*))
\]

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

\[
T_t : \text{Tot}(\tilde{C}^* (\mathcal{U}, F^*)) \longrightarrow \text{Tot}(\tilde{C}^* (\mathcal{V}, F^*)�)
\]

defined by the rule

\[
T_t(\alpha)_{j_0\ldots j_p} = \alpha_{t(j_0)\ldots t(j_p)}|_{V_{j_0\ldots j_p}}.
\]

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

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

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

\[
(d(h(\alpha)) + h(d(\alpha)))_{j_0\ldots j_p} = \sum_{k=0}^{p} (-1)^k h(\alpha)_{j_0\ldots j_k\ldots j_p} + (-1)^p d_F(h(\alpha)_{j_0\ldots j_p}) + \\
\sum_{a=0}^{p} (-1)^a d(\alpha)_{t(j_0)\ldots t(j_a)\ldots t'(j_a)\ldots t'(j_p)} + \\
\sum_{k=0}^{p} \sum_{a=0}^{k-1} (-1)^{k+a} \alpha_{t(j_0)\ldots t(j_a)\ldots t'(j_a)\ldots t'(j_k)\ldots t'(j_p)} + \\
\sum_{k=0}^{p} \sum_{a=k+1}^{p} (-1)^{k+a-1} \alpha_{t(j_0)\ldots t(j_k)\ldots t(j_a)\ldots t'(j_a)\ldots t'(j_p)} + \\
\sum_{a=0}^{p} (-1)^{p+a} d_F(\alpha_{t(j_0)\ldots t(j_a)\ldots t'(j_a)\ldots t'(j_p)}) + \\
\sum_{a=0}^{p} \sum_{k=0}^{a} (-1)^{a+k} \alpha_{t(j_0)\ldots t(j_k)\ldots t(j_a)\ldots t'(j_a)\ldots t'(j_p)} + \\
\sum_{a=0}^{p} \sum_{k=0}^{a} (-1)^{a+k+1} \alpha_{t(j_0)\ldots t(j_k)\ldots t'(j_a)\ldots t'(j_a)\ldots t'(j_p)} + \\
\sum_{a=0}^{p} (-1)^{a+p+1} d_F(\alpha_{t(j_0)\ldots t(j_a)\ldots t'(j_a)\ldots t'(j_p)})
\]

\[
= \alpha_{t'(j_0)\ldots t'(j_p)} + (-1)^{2p+1} \alpha_{t(j_0)\ldots t(j_p)}
\]

\[
= T_{t'}(\alpha)_{j_0\ldots j_p} - T_t(\alpha)_{j_0\ldots j_p}
\]

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
Let $H^n(T_i) : H^n(\text{Tot}(\check{C}^\bullet(U, F^\bullet))) \to H^n(\text{Tot}(\check{C}^\bullet(V, F^\bullet)))$

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 $H^\bullet$. For a bounded below complex $\text{Tot}(\check{C}^\bullet(U, F^\bullet))$ is an isomorphism.

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.

**Lemma 25.1.** Let $(X, \mathcal{O}_X)$ be a ringed space. Let $U : X = \bigcup_{i \in I} U_i$ be an open covering. For a bounded below complex $F^\bullet$ of $\mathcal{O}_X$-modules there is a canonical map

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

functorial in $F^\bullet$ and compatible with (25.0.1) and (25.0.2). There is a spectral sequence (associated to $F^\bullet$) as follows from Homology, Lemma 25.4 applied to the double complex $\check{C}^\bullet(U)$ using the same remark we can view it as the total complex associated to the triple complex $\check{C}^\bullet(U, I^\bullet)$ using Lemma 11.1. Suppose $F^\bullet$ is a quasi-isomorphism of $\check{C}^\bullet(U, I^\bullet)$ using Lemma 11.1. In this case $R\Gamma(X, F^\bullet)$ is represented by the complex $\Gamma(X, F^\bullet)$.

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

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

computes $R\Gamma(X, F^\bullet)$ as we’ve seen above. By Homology, Remark 18.4 we can view this as the total complex associated to the triple complex $\check{C}^\bullet(U, I^\bullet)$. Hence, using the same remark we can view it as the total complex associated to the double complex $A^\bullet$ with terms

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

Since $I^\bullet$ is an injective resolution of $F^0$ we can apply the first spectral sequence associated to $A^\bullet$ (Homology, Lemma 25.1) to get a spectral sequence with

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

which is the $n$th term of the complex $\text{Tot}(\check{C}^\bullet(U, H^m(F^\bullet)))$. Hence we obtain $E_2$ terms as described in the lemma. Convergence by Homology, Lemma 25.3. □

**Lemma 25.2.** Let $(X, \mathcal{O}_X)$ be a ringed space. Let $U : X = \bigcup_{i \in I} U_i$ be an open covering. Let $F^\bullet$ be a bounded below complex of $\mathcal{O}_X$-modules. If $H^i(U_{i_0,...,i_p}, F^q) = 0$ for all $i \geq 0$ and all $p, i_0, \ldots, i_p, q$, then the map $\text{Tot}(\check{C}^\bullet(U, F^\bullet)) \to R\Gamma(X, F^\bullet)$ of Lemma 25.1 is an isomorphism.
Proof. Immediate from the spectral sequence of Lemma 25.1. \qed

Remark 25.3. Let \((X, \mathcal{O}_X)\) be a ringed space. Let \(\mathcal{U} : X = \bigcup_{i \in I} U_i\) be an open covering. Let \(\mathcal{F}^*\) be a bounded below complex of \(\mathcal{O}_X\)-modules. Let \(b\) be an integer. We claim there is a commutative diagram

\[
\begin{array}{ccc}
\text{Tot}(\check{\mathcal{C}}^*(\mathcal{U}, \mathcal{F}^*))[b] & \longrightarrow & R\Gamma(X, \mathcal{F}^*)[b] \\
\downarrow \gamma & & \downarrow \\
\text{Tot}(\check{\mathcal{C}}^*(\mathcal{U}, \mathcal{F}^*[b])) & \longrightarrow & R\Gamma(X, \mathcal{F}^*[b])
\end{array}
\]

in the derived category where the map \(\gamma\) is the map on complexes constructed in Homology, Remark 18.5. This makes sense because the double complex \(\check{\mathcal{C}}^*(\mathcal{U}, \mathcal{F}^*[b])\) is clearly the same as the double complex \(\check{\mathcal{C}}^*(\mathcal{U}, \mathcal{F}^*)[0, b]\) introduced in Homology, Remark 18.5. To check that the diagram commutes, we may choose an injective resolution \(\mathcal{F}^* \to \mathcal{I}^*\) as in the proof of Lemma 25.1. Chasing diagrams, we see that it suffices to check the diagram commutes when we replace \(\mathcal{F}^*\) by \(\mathcal{I}^*\). Then we consider the extended diagram

\[
\begin{array}{ccc}
\Gamma(X, \mathcal{I}^*)[b] & \longrightarrow & \text{Tot}(\check{\mathcal{C}}^*(\mathcal{U}, \mathcal{I}^*))[b] \\
\downarrow \gamma & & \downarrow \\
\Gamma(X, \mathcal{I}^*[b]) & \longrightarrow & \text{Tot}(\check{\mathcal{C}}^*(\mathcal{U}, \mathcal{I}^*[b])) \\
& & \downarrow \\
& & R\Gamma(X, \mathcal{I}^*[b])
\end{array}
\]

where the left horizontal arrows are 25.0.1. Since in this case the horizontal arrows are isomorphisms in the derived category (see proof of Lemma 25.1) it suffices to show that the left square commutes. This is true because the map \(\gamma\) uses the sign 1 on the summands \(C^0(\mathcal{U}, \mathcal{I}^*[b])\), see formula in Homology, Remark 18.5.

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

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

Then we have for an element \(\alpha\) of degree \(n\) that

\[
d(\tau(\alpha))_{i_0 \ldots i_{p+1}}
= \sum_{j=0}^{p+1} (-1)^j \tau(\alpha)_{i_0 \ldots i_j \ldots i_{p+1}} + (-1)^p d_\tau(\alpha)_{i_0 \ldots i_{p+1}}
= \sum_{j=0}^{p+1} (-1)^j + \frac{p(p+1)}{2} \alpha_{i_{p+1} \ldots i_j \ldots i_0} + (-1)^{p+1} \frac{p(p+1)(p+2)}{2} d_\tau(\alpha_{i_{p+1} \ldots i_0})
\]

On the other hand we have

\[
\tau(d(\alpha))_{i_0 \ldots i_{p+1}}
= (-1)^{\frac{(p+1)(p+2)}{2}} d(\alpha)_{i_{p+1} \ldots i_0}
= (-1)^{\frac{(p+1)(p+2)}{2}} \left( \sum_{j=0}^{p+1} (-1)^j \alpha_{i_{p+1} \ldots i_{p+1-j} \ldots i_0} + (-1)^{p+1} d_\tau(\alpha_{i_{p+1} \ldots i_0}) \right)
\]

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

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

commutes. In addition \( \tau \) is clearly compatible with refinements. This suggests that \( \tau \) 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 \( \tau \) actually is homotopic to the identity on the total Čech complex \( \text{Tot}(\check{\mathcal{C}}^*(\mathcal{U}, \mathcal{F}^*)) \). To prove this, we use as homotopy

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

for \( \alpha \) of degree \( n \). As usual we omit writing \( |\mathcal{U}|_{i_0, \ldots, i_p} \). This works because of the following computation, again with \( \alpha \) an element of degree \( n \):

\[
(d(h(\alpha)) + h(d(\alpha)))_{i_0, \ldots, i_p} = \sum_{k=0}^p (-1)^k h(\alpha)_{i_0, \ldots, i_{k+1}} + (-1)^p d_x(h(\alpha))_{i_0, \ldots, i_p} + \\
\sum_{a=0}^p \epsilon_p(a)d(\alpha)_{i_0, \ldots, i_a, \ldots, i_p} + \\
\sum_{k=0}^p \sum_{a=0}^{k-1} (-1)^k \epsilon_{p-1}(a)\alpha_{i_0, \ldots, i_k, \ldots, i_p} + \\
\sum_{k=0}^p \sum_{a=k+1}^p (-1)^k \epsilon_{p-1}(a-1)\alpha_{i_0, \ldots, i_{k-1}, \ldots, i_p} + \\
\sum_{a=0}^p (-1)^p \epsilon_p(a)d_x(\alpha)_{i_0, \ldots, i_p} + \\
\sum_{a=0}^p \sum_{k=0}^a \epsilon_p(a)(-1)^k\alpha_{i_0, \ldots, i_k, \ldots, i_p} + \\
\sum_{a=0}^p \sum_{k=0}^p \epsilon_p(a)(-1)^{p+a-1-k}\alpha_{i_0, \ldots, i_k, \ldots, i_p} + \\
\sum_{a=0}^p \epsilon_p(a)(-1)^{p+1}d_x(\alpha)_{i_0, \ldots, i_a, \ldots, i_p}
\]

= \epsilon_p(0)\alpha_{i_0, \ldots, i_p} + \epsilon_p(p)(-1)^{p+1}\alpha_{i_0, \ldots, i_p}

= (-1)^{p+1}\alpha_{i_0, \ldots, i_p}

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 \( \mathcal{F}^* \) and \( \mathcal{G}^* \). We define the complex \( \text{Tot}(\mathcal{F}^* \otimes^\mathbb{L} \mathcal{G}^*) \) to be to complex with terms \( \bigoplus_{p+q=n} \mathcal{F}^p \otimes \mathcal{G}^q \) and differential according to the rule

\[
d(\alpha \otimes \beta) = d(\alpha) \otimes \beta + (-1)^{\deg(\alpha)} \alpha \otimes d(\beta)
\]

when \( \alpha \) and \( \beta \) are homogeneous, see Homology, Definition \[25.3\].

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

\[
H^i(M^*) \times H^j(N^*) \longrightarrow H^{i+j}(\text{Tot}(M^* \otimes N^*)).
\]

This is discussed also in More on Algebra, Section \[61\].
So the construction of the cup product in hypercohomology of complexes rests on a construction of a map of complexes

\[ 07MB \quad (25.3.2) \quad \text{Tot} \left( \text{Tot}(\mathcal{C}^\bullet(\mathcal{U}, F^\bullet)) \otimes_{\mathbb{Z}} \text{Tot}(\mathcal{C}^\bullet(\mathcal{U}, G^\bullet)) \right) \rightarrow \text{Tot}(\mathcal{C}^\bullet(\mathcal{U}, \text{Tot}(F^\bullet \otimes G^\bullet))) \]

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

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

where \( \alpha \) has degree \( n \) and \( \beta \) 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 \( F^\bullet = F[0] \) is the complex consisting in a single abelian sheaf \( F \) placed in degree 0, then there no signs in the formula for \( \cup \) (as in that case \( \alpha_{i_0 \ldots i_r} = 0 \) unless \( r = n \)). For an explanation of why there has to be a sign and how to compute it see [AGV71, Expose XVII] by Deligne. To check (25.3.2) 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 \( \text{Tot}(\mathcal{C}^\bullet(\mathcal{U}, F^\bullet)) \otimes_{\mathbb{Z}} \text{Tot}(\mathcal{C}^\bullet(\mathcal{U}, G^\bullet)) \) as given in Homology, Definition [18.3]. We compute first

\[ d(\alpha \cup \beta)_{i_0 \ldots i_{p+1}} = \sum_{j=0}^{p+1} (-1)^j (\alpha \cup \beta)_{i_0 \ldots i_j \ldots i_{p+1}} + (-1)^{p+1} d_F \otimes_G ((\alpha \cup \beta)_{i_0 \ldots i_{p+1}}) \]

\[ = \sum_{j=0}^{p+1} (-1)^j \epsilon(n,m,p,r)\alpha_{i_0 \ldots i_r} \otimes \beta_{i_r \ldots i_{p+1}} + \]

\[ \sum_{j=0}^{p+1} \epsilon(n,m,p,r-1)\alpha_{i_0 \ldots i_j \ldots i_{p+1}} + \]

\[ \sum_{j=0}^{p+1} (-1)^{p+1} \epsilon(n,m,p+1,r)\alpha_{i_0 \ldots i_j \ldots i_{p+1}} \]

and note that the summands in the last term equal

\[ (-1)^{p+1} \epsilon(n,m,p+1,r) \left( d_F(\alpha_{i_0 \ldots i_r}) \otimes \beta_{i_r \ldots i_{p+1}} + (-1)^{n-r} \alpha_{i_0 \ldots i_r} \otimes d_G(\beta_{i_r \ldots i_{p+1}}) \right). \]

because \( \deg_F(\alpha_{i_0 \ldots i_r}) = n - r \). On the other hand

\[ d(\alpha \cup \beta)_{i_0 \ldots i_{p+1}} = \sum_{r=0}^{p+1} \epsilon(n+1,m,p+1,r)\alpha_{i_0 \ldots i_r} \otimes \beta_{i_r \ldots i_{p+1}} \]

\[ = \sum_{r=0}^{p+1} \sum_{j=0}^{r} \epsilon(n+1,m,p+1,r)(-1)^j \alpha_{i_0 \ldots i_j \ldots i_r} \otimes \beta_{i_r \ldots i_{p+1}} + \]

\[ \sum_{r=0}^{p+1} \epsilon(n+1,m,p+1,r)(-1)^r d_F(\alpha_{i_0 \ldots i_r}) \otimes \beta_{i_r \ldots i_{p+1}} \]

and

\[ (\alpha \cup d(\beta))_{i_0 \ldots i_{p+1}} = \sum_{r=0}^{p+1} \epsilon(n,m+1,p+1,r)\alpha_{i_0 \ldots i_r} \otimes d(\beta)_{i_r \ldots i_{p+1}} \]

\[ = \sum_{r=0}^{p+1} \sum_{j=0}^{p+1} \epsilon(n,m+1,p+1,r)(-1)^j \alpha_{i_0 \ldots i_j \ldots i_r} \otimes \beta_{i_r \ldots i_{p+1}} + \]

\[ \sum_{r=0}^{p+1} \epsilon(n,m+1,p+1,r)(-1)^{p+1-r} \alpha_{i_0 \ldots i_r} \otimes d_G(\beta_{i_r \ldots i_{p+1}}) \]
The desired equality holds if we have

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

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

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

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

$$(-1)^j \epsilon(n, m, p, r - 1) = \epsilon(n + 1, m, p + 1, r)(-1)^j$$

(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 \(F^\bullet\), \(G^\bullet\) and \(H^\bullet\) are bounded below complexes of abelian groups on \(X\). The obvious map (without the intervention of signs) is an isomorphism of complexes

$$\text{Tot}(\text{Tot}(F^\bullet \otimes_Z G^\bullet) \otimes_Z H^\bullet) \longrightarrow \text{Tot}(F^\bullet \otimes_Z \text{Tot}(G^\bullet \otimes_Z H^\bullet)).$$

Another way to say this is that the triple complex \(F^\bullet \otimes_Z G^\bullet \otimes_Z H^\bullet\) gives rise to a well defined total complex with differential satisfying

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

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

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

namely, if \(\alpha\) has degree \(a\), \(\beta\) has degree \(b\) and \(\gamma\) has degree \(c\), then

$$(\alpha \cup \beta) \cup \gamma = \sum_{r=0}^{p} \epsilon(a + b, c, p, r)(\alpha \cup \beta)_{i_0, \ldots, i_p} \otimes \gamma_{i_r, \ldots, i_p}$$

and

$$(\alpha \cup (\beta \cup \gamma) = \sum_{s=0}^{p} \epsilon(a, b + c, p, s)\alpha_{i_0, \ldots, i_s} \otimes (\beta \cup \gamma)_{i_s, \ldots, i_p}$$

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 \(\tau\) introduced above. Let \(F^\bullet\) be a bounded below complexes of abelian groups, and assume we are given a graded commutative multiplication

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

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

$$\text{Tot}(\text{Tot}(\mathcal{C}^\bullet(U, F^\bullet))) \otimes \text{Tot}(\mathcal{C}^\bullet(U, F^\bullet))) \longrightarrow \text{Tot}(\mathcal{C}^\bullet(U, \text{Tot}(F^\bullet \otimes_Z F^\bullet))) \longrightarrow \text{Tot}(\mathcal{C}^\bullet(U, F^\bullet))$$
induces a cup product on cohomology

\[ H^n(\Tot(\check{\mathcal{C}}(\mathcal{U}, \mathcal{F}^\bullet))) \times H^m(\Tot(\check{\mathcal{C}}(\mathcal{U}, \mathcal{F}^\bullet))) \to H^{n+m}(\Tot(\check{\mathcal{C}}(\mathcal{U}, \mathcal{F}^\bullet))) \]

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 \( \alpha \) of degree \( n \) in \( \Tot(\check{\mathcal{C}}(\mathcal{U}, \mathcal{F}^\bullet)) \) and an element \( \beta \) of degree \( m \) in \( \Tot(\check{\mathcal{C}}(\mathcal{U}, \mathcal{F}^\bullet)) \) and we compute

\[ \wedge^\bullet(\alpha \cup \beta)_{i_0 \ldots i_p} = \sum_{r=0}^{p} \epsilon(n, m, p, r) \alpha_{i_0 \ldots i_r} \wedge \beta_{i_r \ldots i_p} \]

\[ = \sum_{r=0}^{p} \epsilon(n, m, p, r)(-1)^{\deg(\alpha_{i_0 \ldots i_r}) \deg(\beta_{i_r \ldots i_p})} \beta_{i_r \ldots i_p} \wedge \alpha_{i_0 \ldots i_r} \]

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

\[ \tau(\wedge^\bullet(\tau(\beta) \cup \tau(\alpha)))_{i_0 \ldots i_p} = \chi(p) \sum_{r=0}^{p} \epsilon(m, n, p, r) \tau(\beta)_{i_p \ldots i_{p-r}} \wedge \tau(\alpha)_{i_{p-r} \ldots i_0} \]

\[ = \chi(p) \sum_{r=0}^{p} \epsilon(m, n, p, r) \chi(r) \chi(p-r) \beta_{i_{p-r} \ldots i_p} \wedge \alpha_{i_0 \ldots i_{p-r}} \]

\[ = \chi(p) \sum_{r=0}^{p} \epsilon(m, n, p, p-r) \chi(r) \chi(p-r) \beta_{i_r \ldots i_p} \wedge \alpha_{i_0 \ldots i_r} \]

where \( \chi(t) = (-1)^{\frac{(t+1)t}{2}} \). Since we proved earlier that \( \tau \) 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.jp in the scripts subdirectory of the Stacks project.)

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

\[ 0 \to \mathcal{F}^\bullet_1 \to \mathcal{F}^\bullet_2 \to \mathcal{F}^\bullet_3 \to 0 \quad \text{and} \quad 0 \leftarrow \mathcal{G}^\bullet_1 \leftarrow \mathcal{G}^\bullet_2 \leftarrow \mathcal{G}^\bullet_3 \leftarrow 0 \]

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

\[ \gamma_i : \Tot(\mathcal{F}_i^\bullet \otimes_{\mathcal{O}} \mathcal{G}_i^\bullet) \to \mathcal{H}^\bullet \]

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

\[ \begin{array}{ccc}
\Tot(\mathcal{F}_1^\bullet \otimes_{\mathcal{O}} \mathcal{G}_1^\bullet) & \xto{\gamma_1} & \Tot(\mathcal{F}_1^\bullet \otimes_{\mathcal{O}} \mathcal{G}_2^\bullet) \\
\downarrow & & \downarrow \\
\mathcal{H}^\bullet & \xto{\gamma_2} & \Tot(\mathcal{F}_2^\bullet \otimes_{\mathcal{O}} \mathcal{G}_2^\bullet) \\
\gamma_3 & & \\
\downarrow & & \downarrow \\
\Tot(\mathcal{F}_3^\bullet \otimes_{\mathcal{O}} \mathcal{G}_3^\bullet) & \xto{\gamma_3} & \mathcal{H}^\bullet 
\end{array} \]

are commutative.
Lemma 25.4. In the situation above, assume Čech cohomology agrees with cohomology for the sheaves $\mathcal{F}^p_1$ and $\mathcal{G}^q_3$. Let $a_3 \in H^n(X, \mathcal{F}^p_3)$ and $b_1 \in H^m(X, \mathcal{G}^q_3)$. 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 $\partial$ 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 $\mathcal{F}^p_1$ as a subsheaf of $\mathcal{F}^p_2$ and we think of $\mathcal{G}^q_3$ as a subsheaf of $\mathcal{G}^q_2$. Hence if $s$ is a local section of $\mathcal{F}^p_1$ we use $\bar{s}$ to denote the corresponding section of $\mathcal{F}^p_2$ as well. Similarly for local sections of $\mathcal{G}^q_3$. Furthermore, if $s$ is a local section of $\mathcal{F}^p_2$ then we denote $\bar{s}$ its image in $\mathcal{F}^p_3$. Similarly for the map $\mathcal{G}^q_3 \rightarrow \mathcal{G}^q_1$. In particular if $s$ is a local section of $\mathcal{F}^p_2$ and $\bar{s} = 0$ then $s$ is a local section of $\mathcal{F}^p_1$. The commutativity of the diagrams above implies, for local sections $s$ of $\mathcal{F}^p_2$ and $t$ of $\mathcal{G}^q_3$ that $\gamma_2(s \otimes t) = \gamma_3(\bar{s} \otimes t)$ as sections of $\mathcal{H}^{n+q}$.

Let $\mathcal{U} : X = \bigcup_{i \in I} U_i$ be an open covering of $X$. Suppose that $\alpha_3$, resp. $\beta_1$ is a degree $n$, resp. $m$ cocycle of $\text{Tot}(\mathcal{C}^\bullet(\mathcal{U}, \mathcal{F}^p_1))$, resp. $\text{Tot}(\mathcal{C}^\bullet(\mathcal{U}, \mathcal{G}^q_3))$ representing $a_3$, resp. $b_1$. After refining $\mathcal{U}$ if necessary, we can find cochains $\alpha_2$, resp. $\beta_2$ of degree $n$, resp. $m$ in $\text{Tot}(\mathcal{C}^\bullet(\mathcal{U}, \mathcal{F}^p_2))$, resp. $\text{Tot}(\mathcal{C}^\bullet(\mathcal{U}, \mathcal{G}^q_2))$ mapping to $\alpha_3$, resp. $\beta_1$. Then we see that

$$d(\alpha_2) = d(\alpha_3) = 0 \quad \text{and} \quad d(\beta_2) = d(\beta_1) = 0.$$  

This means that $\alpha_1 = d(\alpha_2)$ is a degree $n+1$ cocycle in $\text{Tot}(\mathcal{C}^\bullet(\mathcal{U}, \mathcal{F}^p_2))$ representing $\partial a_3$. Similarly, $\beta_3 = d(\beta_2)$ is a degree $m+1$ cocycle in $\text{Tot}(\mathcal{C}^\bullet(\mathcal{U}, \mathcal{G}^q_2))$ representing $\partial b_1$. Thus we may compute

$$d(\gamma_2(\alpha_2 \cup \beta_2)) = \gamma_2(d(\alpha_2 \cup \beta_2)) = \gamma_2(d(\alpha_2) \cup (\beta_2 + (-1)^n \alpha_2 \cup d(\beta_2))) = \gamma_2(\alpha_1 \cup \beta_3) + (-1)^n \gamma_2(\alpha_2 \cup \beta_3) = \gamma_1(\alpha_1 \cup \beta_1) + (-1)^n \gamma_3(\alpha_3 \cup \beta_3).$$

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

Lemma 25.5. 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 $\mathcal{O}' \rightarrow \text{Hom}(\mathcal{I}, \mathcal{I})$ 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 $\partial(f)$

\footnote{The 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 exact sequence are given by the maps in the snake lemma without the intervention of signs. See Derived Categories, Section 10.}
corresponds to the Čech cohomology class of the 1-cocycle \( \alpha \) with \( \alpha_{i_0i_1} = f_{i_0} - f_{i_1} \).

(Observe that by Lemma \[11.3\] 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 \( \beta \) with \( \beta_{i_0i_1} = g_{i_0} - g_{i_1} \). Since \( f_ig_i \in \mathcal{O}(U_i) \) lifts \( fg_i \), we see that \( \partial(fg) \) is given by the cocycle \( \gamma \) with

\[
\gamma_{i_0i_1} = f_{i_0}g_{i_0} - f_{i_1}g_{i_1} = (f_{i_0} - f_{i_1})g_{i_0} + f_{i_1}(g_{i_0} - g_{i_1}) = \alpha_{i_0i_1}g + f\beta_{i_0i_1}
\]

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

26. 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 \[15.4\] 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 \underline{Lemma 26.1}. 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.

\underline{Proof}. Omitted. Hint: See More on Algebra, Lemmas \[57.1\] and \[57.2\]. \( \square \)

06Y9 \underline{Definition 26.2}. 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 \underline{Lemma 26.3}. 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.

\underline{Proof}. Follows from Lemma \[26.1\] and the fact that quasi-isomorphisms are characterized by having acyclic cones. \( \square \)

06YB \underline{Lemma 26.4}. 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 \[57.3\]).

\underline{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 \( x \in X \) \( \mathcal{M}^\bullet \) be an acyclic complex of \( \mathcal{O}_{X,x} \)-modules. Then \( i_{x,*}\mathcal{M}^\bullet \) is an acyclic complex of \( \mathcal{O}_X \)-modules. Thus \( \text{Tot}(i_{x,*}\mathcal{M}^\bullet \otimes_{\mathcal{O}_X} \mathcal{K}^\bullet) \) is acyclic. Taking stalks at \( x \) shows that \( \text{Tot}(\mathcal{M}^\bullet \otimes_{\mathcal{O}_{X,x}} \mathcal{K}_x^\bullet) \) is acyclic. \( \square \)

079R \underline{Lemma 26.5}. 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
\[
\text{Tot}(M^\bullet \otimes_{O_X} \text{Tot}(K^\bullet \otimes_{O_X} L^\bullet)) = \text{Tot}(\text{Tot}(M^\bullet \otimes_{O_X} K^\bullet) \otimes_{O_X} L^\bullet)
\]
and the definition. \[\square\]

**Lemma 26.6.** Let \((X, O_X)\) be a ringed space. Let \((K_1^\bullet, K_2^\bullet, K_3^\bullet)\) be a distinguished triangle in \(K(\text{Mod}(O_X))\). If two out of three of \(K_i^\bullet\) are \(K\)-flat, so is the third.

**Proof.** Follows from Lemma 26.1 and the fact that in a distinguished triangle in \(K(\text{Mod}(O_X))\) if two out of three are acyclic, so is the third. \[\square\]

**Lemma 26.7.** Let \((X, O_X)\) be a ringed space. Let \((K_1^\bullet, K_2^\bullet, K_3^\bullet)\) be a distinguished triangle in \(K(\text{Mod}(O_X))\). If two out of three of \(K_i^\bullet\) are \(K\)-flat, so is the third.

**Proof.** Follows from Lemma 26.1 and the fact that in a distinguished triangle in \(K(\text{Mod}(O_X))\) if two out of three are acyclic, so is the third. \[\square\]

**Lemma 26.8.** Let \((X, O_X)\) be a ringed space. A bounded above complex of flat \(O_X\)-modules is \(K\)-flat.

**Proof.** We can check this on stalks, see Lemma 26.4. Hence this follows from Sheaves, Lemma 26.4 and More on Algebra, Lemma 57.5. \[\square\]

**Lemma 26.9.** Let \((X, O_X)\) be a ringed space. Let \(K_1^\bullet \rightarrow K_2^\bullet \rightarrow \cdots\) be a system of \(K\)-flat complexes. Then \(\text{colim}_i K_i^\bullet\) is \(K\)-flat.

**Proof.** Because we are taking termwise colimits it is clear that
\[
\text{colim}_i \text{Tot}(F^\bullet \otimes_{O_X} K_i^\bullet) = \text{Tot}(F^\bullet \otimes_{O_X} \text{colim}_i K_i^\bullet)
\]
Hence the lemma follows from the fact that filtered colimits are exact. \[\square\]

**Lemma 26.10.** Let \((X, O_X)\) be a ringed space. For any complex \(G^\bullet\) of \(O_X\)-modules there exists a commutative diagram of complexes of \(O_X\)-modules

\[
\begin{array}{ccc}
K_1^\bullet & \rightarrow & K_2^\bullet & \rightarrow & \cdots \\
\downarrow & & \downarrow & & \downarrow \\
\tau_{\leq 1} G^\bullet & \rightarrow & \tau_{\leq 2} G^\bullet & \rightarrow & \cdots
\end{array}
\]

with the following properties: (1) the vertical arrows are quasi-isomorphisms, (2) each \(K_i^\bullet\) is a bounded above complex whose terms are direct sums of \(O_X\)-modules of the form \(j_U^* O_U\), and (3) the maps \(K_n^\bullet \rightarrow K_{n+1}^\bullet\) are termwise split injections whose cokernels are direct sums of \(O_X\)-modules of the form \(j_U^* O_U\). Moreover, the map \(\text{colim}_i K_i^\bullet \rightarrow G^\bullet\) 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 29.1. The induced map \(\text{colim}_i K_i^\bullet \rightarrow G^\bullet\) is a quasi-isomorphism because filtered colimits are exact. \[\square\]

**Lemma 26.11.** Let \((X, O_X)\) be a ringed space. For any complex \(G^\bullet\) there exists a \(K\)-flat complex \(K^\bullet\) and a quasi-isomorphism \(K^\bullet \rightarrow G^\bullet\). Moreover, each \(K^n\) is a flat \(O_X\)-module.
Proof. Choose a diagram as in Lemma \ref{lem-26.10}. Each complex $K^*_n$ is a bounded above complex of flat modules, see Modules, Lemma \ref{modules-lemma-flat-1.5.5}. Hence $K^*_n$ is K-flat by Lemma \ref{lem-26.8}. The induced map $\colim K^*_n \to G^*$ is a quasi-isomorphism by construction. Thus $\colim K^*_n$ is K-flat by Lemma \ref{lem-26.9} Property (3) of Lemma \ref{lem-26.10} shows that $\colim K^*_m$ is a direct sum of flat modules and hence flat which proves the final assertion. \hfill \qed

Lemma \ref{lem-26.12}. \(\text{(X, } \mathcal{O}_X)\) be a ringed space. Let $\alpha : P^* \to Q^*$ be a quasi-isomorphism of K-flat complexes of $O_X$-modules. For every complex $F^*$ of $O_X$-modules the induced map
\[ \Tot(id_{F^*} \otimes \alpha) : \Tot(F^* \otimes_{O_X} P^*) \to \Tot(F^* \otimes_{O_X} Q^*) \]
is a quasi-isomorphism.

Proof. Choose a quasi-isomorphism $K^* \to F^*$ with $K^*$ a K-flat complex, see Lemma \ref{lem-26.11} Consider the commutative diagram
\[
\begin{array}{ccc}
\Tot(K^* \otimes_{O_X} P^*) & \to & \Tot(K^* \otimes_{O_X} Q^*) \\
\downarrow & & \downarrow \\
\Tot(F^* \otimes_{O_X} P^*) & \to & \Tot(F^* \otimes_{O_X} Q^*)
\end{array}
\]
The result follows as by Lemma \ref{lem-26.3} the vertical arrows and the top horizontal arrow are quasi-isomorphisms. \hfill \qed

Let $(X, \mathcal{O}_X)$ be a ringed space. Let $F^*$ be an object of $D(O_X)$. Choose a K-flat resolution $K^* \to F^*$, see Lemma \ref{lem-26.11} By Lemma \ref{lem-26.1} we obtain an exact functor of triangulated categories
\[ K(O_X) \to K(O_X), \quad G^* \mapsto \Tot(G^* \otimes_{O_X} K^*) \]
By Lemma \ref{lem-26.3} this functor induces a functor $D(O_X) \to D(O_X)$ simply because $D(O_X)$ is the localization of $K(O_X)$ at quasi-isomorphisms. By Lemma \ref{lem-26.12} the resulting functor (up to isomorphism) does not depend on the choice of the K-flat resolution.

Definition \ref{def-26.13}. Let $(X, \mathcal{O}_X)$ be a ringed space. Let $F^*$ be an object of $D(O_X)$. The \textit{derived tensor product}
\[ - \otimes^L_{O_X} F^* : D(O_X) \to D(O_X) \]
is the exact functor of triangulated categories described above.

It is clear from our explicit constructions that there is a canonical isomorphism
\[ F^* \otimes^L_{O_X} G^* \cong G^* \otimes^L_{O_X} F^* \]
for $G^*$ and $F^*$ in $D(O_X)$. Hence when we write $F^* \otimes^L_{O_X} G^*$ we will usually be agnostic about which variable we are using to define the derived tensor product with.

Definition \ref{def-26.14}. Let $(X, \mathcal{O}_X)$ be a ringed space. Let $F, G$ be $O_X$-modules. The \textit{Tor's} of $F$ and $G$ are define by the formula
\[ \Tor^p_{O_X}(F, G) = H^{-p}(F \otimes^L_{O_X} G) \]
with derived tensor product as defined above.
This definition implies that for every short exact sequence of \( \mathcal{O}_X \)-modules 0 \( \to \mathcal{F}_1 \to \mathcal{F}_2 \to \mathcal{F}_3 \to 0 \) we have a long exact cohomology sequence

\[
\begin{align*}
\mathcal{F}_1 \otimes_{\mathcal{O}_X} \mathcal{G} & \longrightarrow \mathcal{F}_2 \otimes_{\mathcal{O}_X} \mathcal{G} \longrightarrow \mathcal{F}_3 \otimes_{\mathcal{O}_X} \mathcal{G} \longrightarrow 0 \\
\text{Tor}_1^{\mathcal{O}_X}(\mathcal{F}_1, \mathcal{G}) & \longrightarrow \text{Tor}_1^{\mathcal{O}_X}(\mathcal{F}_2, \mathcal{G}) \longrightarrow \text{Tor}_1^{\mathcal{O}_X}(\mathcal{F}_3, \mathcal{G})
\end{align*}
\]

for every \( \mathcal{O}_X \)-module \( \mathcal{G} \). This will be called the long exact sequence of Tor associated to the situation.

**Lemma 26.15.** 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) \( \text{Tor}_1^{\mathcal{O}_X}(\mathcal{F}, \mathcal{G}) = 0 \) 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 \( \mathcal{G} \to \mathcal{H} \) is injective with cokernel \( \mathcal{Q} \), the long exact sequence of Tor shows that the kernel of \( \mathcal{F} \otimes_{\mathcal{O}_X} \mathcal{G} \to \mathcal{F} \otimes_{\mathcal{O}_X} \mathcal{H} \) is a quotient of \( \text{Tor}_1^{\mathcal{O}_X}(\mathcal{F}, \mathcal{Q}) \) which is zero by assumption. Hence \( \mathcal{F} \) is flat. \( \square \)

### 27. Derived pullback

**Lemma 27.1.** The construction above is independent of choices and defines an exact functor of triangulated categories \( LF^* : D(\mathcal{O}_Y) \to D(\mathcal{O}_X) \).

**Proof.** To see this we use the general theory developed in Derived Categories, Section 14.1. Set \( \mathcal{D} = K(\mathcal{O}_Y) \) and \( \mathcal{D}' = D(\mathcal{O}_X) \). Let us write \( \mathcal{F} : \mathcal{D} \to \mathcal{D}' \) the exact functor of triangulated categories defined by the rule \( \mathcal{F}(\mathcal{G}^*) = f^* \mathcal{G}^* \). 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 14.1 so that Derived Categories, Definition 14.2 applies. We claim that \( LF \) is everywhere defined. This follows from Derived Categories, Lemma 14.15 with \( \mathcal{P} \subset \text{Ob}(\mathcal{D}) \) the collection of \( K \)-flat complexes: (1) follows from Lemma 26.11 and to see (2) we have to show that for a quasi-isomorphism \( \mathcal{K}_1^* \to \mathcal{K}_2^* \) between \( K \)-flat complexes of \( \mathcal{O}_Y \)-modules the map \( f^* \mathcal{K}_1^* \to f^* \mathcal{K}_2^* \) is a quasi-isomorphism. To see this write this as

\[
f^{-1} \mathcal{K}_1^* \otimes_{f^{-1} \mathcal{O}_Y} \mathcal{O}_X \longrightarrow f^{-1} \mathcal{K}_2^* \otimes_{f^{-1} \mathcal{O}_Y} \mathcal{O}_X
\]

The functor \( f^{-1} \) is exact, hence the map \( f^{-1} \mathcal{K}_1^* \to f^{-1} \mathcal{K}_2^* \) is a quasi-isomorphism. By Lemma 26.7 applied to the morphism \( (X, f^{-1} \mathcal{O}_Y) \to (Y, \mathcal{O}_Y) \) the complexes \( f^{-1} \mathcal{K}_1^* \) and \( f^{-1} \mathcal{K}_2^* \) are \( K \)-flat complexes of \( f^{-1} \mathcal{O}_Y \)-modules. Hence Lemma 26.12 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 (14.9.1). Finally, Derived Categories, Lemma 14.15 also guarantees that $LF(K^\bullet) = F(K^\bullet) = f^*K^\bullet$ when $K^\bullet$ is K-flat, i.e., $Lf^* = LF$ is indeed computed in the way described above.

\textbf{Lemma 27.2.} Let $f : X \to Y$ and $g : Y \to Z$ be morphisms of ringed spaces. Then $L(fg)^* = Lf^*gL^* = L(g \circ f)^*$ as functors $D(O_Z) \to D(O_X)$.

\textbf{Proof.} Let $E$ be an object of $D(O_Z)$. By construction $Lg^*E$ is computed by choosing a K-flat complex $K^\bullet$ representing $E$ on $Z$ and setting $Lg^*E = g^*K^\bullet$. By Lemma 26.7 we see that $g^*K^\bullet$ is K-flat on $Y$. Then $Lf^*Lg^*E$ is given by $(g \circ f)^*K^\bullet$ which also represents $L(g \circ f)^*E$.

\textbf{Lemma 27.3.} Let $f : (X, O_X) \to (Y, O_Y)$ be a morphism of ringed spaces. There is a canonical bifunctorial isomorphism

$$Lf^*(F^\bullet \otimes_{O_Y} G^\bullet) = Lf^*F^\bullet \otimes_{O_X} Lf^*G^\bullet$$

for $F^\bullet, G^\bullet \in \text{Ob}(D(X))$.

\textbf{Proof.} We may assume that $F^\bullet$ and $G^\bullet$ are K-flat complexes. In this case $F^\bullet \otimes_{O_Y} G^\bullet$ is just the total complex associated to the double complex $F^\bullet \otimes_{O_Y} G^\bullet$. By Lemma 26.5 Tot$(F^\bullet \otimes_{O_Y} G^\bullet)$ is K-flat also. Hence the isomorphism of the lemma comes from the isomorphism

$$\text{Tot}(f^*F^\bullet \otimes_{O_X} f^*G^\bullet) \to f^*\text{Tot}(F^\bullet \otimes_{O_Y} G^\bullet)$$

whose constituents are the isomorphisms $f^*F^p \otimes_{O_X} f^qG^q \to f^*(F^p \otimes_{O_Y} G^q)$ of Modules, Lemma 15.4.

\textbf{Lemma 27.4.} Let $f : (X, O_X) \to (Y, O_Y)$ be a morphism of ringed spaces. There is a canonical bifunctorial isomorphism

$$F^\bullet \otimes_{O_X} Lf^*G^\bullet = F^\bullet \otimes_{f^{-1}O_Y} f^{-1}G^\bullet$$

for $F^\bullet \in D(X)$ and $G^\bullet \in D(Y)$.

\textbf{Proof.} Let $F$ be an $O_X$-module and let $G$ be an $O_Y$-module. Then $F \otimes_{O_X} f^*G = F \otimes_{f^{-1}O_Y} f^{-1}G$ because $f^*G = O_X \otimes_{f^{-1}O_Y} f^{-1}G$. The lemma follows from this and the definitions.

\textbf{Lemma 27.5.} Let $f : (X, O_X) \to (Y, O_Y)$ be a morphism of ringed spaces. Let $K^\bullet$ and $M^\bullet$ be complexes of $O_Y$-modules. The diagram

$$Lf^*(K^\bullet \otimes_{O_Y} M^\bullet) \to Lf^*\text{Tot}(K^\bullet \otimes_{O_Y} M^\bullet)$$

$$Lf^*K^\bullet \otimes_{O_X} Lf^*M^\bullet \to f^*\text{Tot}(K^\bullet \otimes_{O_Y} M^\bullet)$$

$$f^*K^\bullet \otimes_{O_X} f^*M^\bullet \to \text{Tot}(f^*K^\bullet \otimes_{O_X} f^*M^\bullet)$$

commutes.
Proof. We will use the existence of K-flat resolutions as in Lemma 26.7. If we choose such resolutions $P^\bullet \to K^\bullet$ and $Q^\bullet \to M^\bullet$, then we see that

\[
\begin{array}{rcccccc}
L f^* \text{Tot}(P^\bullet \otimes_{O_Y} Q^\bullet) & \longrightarrow & L f^* \text{Tot}(K^\bullet \otimes_{O_Y} M^\bullet) \\
\downarrow & & \downarrow \\
f^* \text{Tot}(P^\bullet \otimes_{O_Y} Q^\bullet) & \longrightarrow & f^* \text{Tot}(K^\bullet \otimes_{O_Y} M^\bullet) \\
\downarrow & & \downarrow \\
\text{Tot}(f^*P^\bullet \otimes_{O_X} f^*Q^\bullet) & \longrightarrow & \text{Tot}(f^*K^\bullet \otimes_{O_X} f^*M^\bullet)
\end{array}
\]

commutes. However, now the left hand side of the diagram is the left hand side of the diagram by our choice of $P^\bullet$ and $Q^\bullet$ and Lemma 26.5. □

28. Cohomology of unbounded complexes

Let $(X, O_X)$ be a ringed space. The category $\text{Mod}(O_X)$ is a Grothendieck abelian category: it has all colimits, filtered colimits are exact, and it has a generator, namely

$$\bigoplus_{U \subset X \text{ open}} j_{U!} O_U,$$

see Modules, Section 3 and Lemmas 16.5 and 16.6. By Injectives, Theorem 12.6 for every complex $F^\bullet$ of $O_X$-modules there exists an injective quasi-isomorphism $F^\bullet \to I^\bullet$ to a K-injective complex of $O_X$-modules. Hence we can define

$$R \Gamma(X, F^\bullet) = \Gamma(X, I^\bullet)$$

and similarly for any left exact functor, see Derived Categories, Lemma 31.7. For any morphism of ringed spaces $f : (X, O_X) \to (Y, O_Y)$ we obtain

$$Rf_* : D(X) \longrightarrow D(Y)$$
on the unbounded derived categories.

Lemma 28.1. Let $f : (X, O_X) \to (Y, O_Y)$ be a morphism of ringed spaces. The functor $Rf_*$ defined above and the functor $L f^*$ defined in Lemma 27.7 are adjoint:

$$\text{Hom}_{D(X)}(Lf^* G^\bullet, F^\bullet) = \text{Hom}_{D(Y)}(G^\bullet, Rf_* F^\bullet)$$

bifunctorially in $F^\bullet \in \text{Ob}(D(X))$ and $G^\bullet \in \text{Ob}(D(Y))$.

Proof. This follows formally from the fact that $Rf_*$ and $L f^*$ exist, see Derived Categories, Lemma 30.3. □

Lemma 28.2. Let $f : X \to Y$ and $g : Y \to Z$ be morphisms of ringed spaces. Then $Rg_* \circ Rf_* = R(g \circ f)_*$ as functors $D(O_X) \to D(O_Z)$.

Proof. By Lemma 28.1 we see that $Rg_* \circ Rf_*$ is adjoint to $L f^* \circ L g^*$. We have $L f^* \circ L g^* = L(g \circ f)^*$ by Lemma 27.2 and hence by uniqueness of adjoint functors we have $R g_* \circ R f_* = R(g \circ f)_*$. □

Remark 28.3. The construction of unbounded derived functor $L f^*$ and $Rf_*$ allows one to construct the base change map in full generality. Namely, suppose
that

\[
\begin{array}{ccc}
X' & \xrightarrow{f'} & X \\
\downarrow{g'} & & \downarrow{f} \\
S' & \xrightarrow{g} & S
\end{array}
\]

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

\[
Lg^* Rf_* K \to R(f')_* L(g')^* K
\]

in \( D(\mathcal{O}_S) \). Namely, this map is adjoint to a map \( L(f')^* Lg^* Rf_* K \to L(g')^* K \) since \( L(f')^* Lg^* = L(g')^* Lf^* \) we see this is the same as a map \( L(g')^* Lf^* Rf_* K \to L(g')^* K \) which we can take to be \( L(g')^* \) of the adjunction map \( Lf^* Rf_* K \to K \).

**Remark 28.4.** Consider a commutative diagram

\[
\begin{array}{ccc}
X' & \xrightarrow{k} & X \\
\downarrow{f'} & & \downarrow{f} \\
Y' & \xrightarrow{i} & Y \\
\downarrow{g'} & & \downarrow{g} \\
Z' & \xrightarrow{m} & Z
\end{array}
\]

of ringed spaces. Then the base change maps of Remark 28.3 for the two squares compose to give the base change map for the outer rectangle. More precisely, the composition

\[
Lm^* \circ R(g \circ f)_* = Lm^* \circ Rg_* \circ Rf_* \\
\to Rg'_* \circ Rf'_* \circ Lk^* \\
= R(g' \circ f')_* \circ Lk^*
\]

is the base change map for the rectangle. We omit the verification.

**Remark 28.5.** Consider a commutative diagram

\[
\begin{array}{ccc}
X'' & \xrightarrow{g'} & X' \\
\downarrow{f''} & & \downarrow{f} \\
Y'' & \xrightarrow{h'} & Y' \\
\downarrow{h} & & \downarrow{h} \\
\end{array}
\]

of ringed spaces. Then the base change maps of Remark 28.3 for the two squares compose to give the base change map for the outer rectangle. More precisely, the composition

\[
L(h \circ h')^* \circ Rf_* = L(h')^* \circ Lh_* \circ Rf_* \\
\to L(h')^* \circ Rf'_* \circ Lg^* \\
\to Rf''_* \circ L(g')^* \circ Lg^* \\
= Rf''_* \circ L(g \circ g')^*
\]

is the base change map for the rectangle. We omit the verification.
Lemma 28.6. Let $f : (X, \mathcal{O}_X) \to (Y, \mathcal{O}_Y)$ be a morphism of ringed spaces. Let $K^\bullet$ be a complex of $\mathcal{O}_X$-modules. The diagram
\[
\begin{array}{ccc}
Lf^*f_*K^\bullet & \xrightarrow{f^*} & f^*f_*K^\bullet \\
\downarrow & & \downarrow \\
Lf^*Rf_*K^\bullet & \xrightarrow{} & K^\bullet
\end{array}
\]
coming from $Lf^* \to f^*$ on complexes, $f_* \to Rf_*$ on complexes, and adjunction $Lf^* \circ Rf_* \to id$ commutes in $D(\mathcal{O}_X)$.

Proof. We will use the existence of K-flat resolutions and K-injective resolutions, see Lemma 26.7 and the discussion above. Choose a quasi-isomorphism $K^\bullet \to I^\bullet$ where $I^\bullet$ is K-injective as a complex of $\mathcal{O}_X$-modules. Choose a quasi-isomorphism $Q^\bullet \to f_*I^\bullet$ where $Q^\bullet$ is K-flat as a complex of $\mathcal{O}_Y$-modules. We can choose a K-flat complex of $\mathcal{O}_Y$-modules $P^\bullet$ and a diagram of morphisms of complexes
\[
\begin{array}{ccc}
P^\bullet & \xrightarrow{f_*} & f_*K^\bullet \\
\downarrow & & \downarrow \\
Q^\bullet & \xrightarrow{f_*} & f_*I^\bullet
\end{array}
\]
commutative up to homotopy where the top horizontal arrow is a quasi-isomorphism. Namely, we can first choose such a diagram for some complex $P^\bullet$ because the quasi-isomorphisms form a multiplicative system in the homotopy category of complexes and then we can replace $P^\bullet$ by a K-flat complex. Taking pullbacks we obtain a diagram of morphisms of complexes
\[
\begin{array}{ccc}
f^*P^\bullet & \xrightarrow{f^*} & f^*f_*K^\bullet \\
\downarrow & & \downarrow \\
f^*Q^\bullet & \xrightarrow{f^*} & f^*f_*I^\bullet
\end{array}
\]
commutative up to homotopy. The outer rectangle witnesses the truth of the statement in the lemma. □

Remark 28.7. Let $f : (X, \mathcal{O}_X) \to (Y, \mathcal{O}_Y)$ be a morphism of ringed spaces. The adjointness of $Lf^*$ and $Rf_*$ allows us to construct a relative cup product
\[
Rf_*K \otimes_{\mathcal{O}_Y}^L Rf_*L \to Rf_*(K \otimes_{\mathcal{O}_X}^L L)
\]
in $D(\mathcal{O}_Y)$ for all $K, L$ in $D(\mathcal{O}_X)$. Namely, this map is adjoint to a map $Lf^*(Rf_*K \otimes_{\mathcal{O}_Y}^L Rf_*L) \to K \otimes_{\mathcal{O}_Y}^L L$ for which we can take the composition of the isomorphism $Lf^*(Rf_*K \otimes_{\mathcal{O}_Y}^L Rf_*L) = Lf^*Rf_*K \otimes_{\mathcal{O}_X}^L Lf^*Rf_*L$ (Lemma 27.3) with the map $Lf^*Rf_*K \otimes_{\mathcal{O}_X}^L Lf^*Rf_*L \to K \otimes_{\mathcal{O}_X}^L L$ coming from the counit $Lf^* \circ Rf_* \to id$.

29. Cohomology of filtered complexes

Filtered complexes of sheaves frequently come up in a natural fashion when studying cohomology of algebraic varieties, for example the de Rham complex comes with its Hodge filtration. In this section we use the very general Injectives, Lemma 13.7 to find construct spectral sequences on cohomology and we relate these to previously constructed spectral sequences.
Lemma 29.1. Let $(X, O_X)$ be a ringed space. Let $\mathcal{F}^\bullet$ be a filtered complex of $O_X$-modules. There exists a canonical spectral sequence $(E_r, d_r)_{r \geq 1}$ of bigraded $\Gamma(X, O_X)$-modules with $d_r$ of bidegree $(r, -r + 1)$ and

$$E_1^{p,q} = H^{p+q}(X, \text{gr}^p \mathcal{F}^\bullet)$$

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 $j : \mathcal{F}^\bullet \to \mathcal{J}^\bullet$ as in Injectives, Lemma 13.7. The spectral sequence is the spectral sequence of Homology, Section 24 associated to the filtered complex $\Gamma(X, \mathcal{J}^\bullet)$ with $F^p \Gamma(X, \mathcal{J}^\bullet) = \Gamma(X, F^p \mathcal{J}^\bullet)$

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 24.13.

Remark 29.2. Let $(X, O_X)$ be a ringed space. Let $\mathcal{F}^\bullet$ be a filtered complex of $O_X$-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 29.1 avoiding Injectives, Lemma 13.7. Namely, by Derived Categories, Lemma 26.9 there is a filtered quasi-isomorphism $i : \mathcal{F}^\bullet \to \mathcal{I}^\bullet$ 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 $O_X$-module. Then we take the spectral sequence associated to $\Gamma(X, \mathcal{I}^\bullet)$ with $F^p \Gamma(X, \mathcal{I}^\bullet) = \Gamma(X, F^p \mathcal{I}^\bullet)$

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 24.11. In fact, this is a special case of the spectral sequence in Derived Categories, Lemma 26.14.

Example 29.3. Let $(X, O_X)$ be a ringed space. Let $\mathcal{F}^\bullet$ be a complex of $O_X$-modules. We can apply Lemma 29.1 with $F^p \mathcal{F}^\bullet = \tau_{\leq -p} \mathcal{F}^\bullet$. (If $\mathcal{F}^\bullet$ is bounded below we can use Remark 29.2.) 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 $K \in D(O_X)$ 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).
Example 29.4. 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 29.1 with \(F^p\mathcal{F}^\bullet = \sigma_{\geq p}\mathcal{F}^\bullet\). Then we get a spectral sequence

\[ E_1^{p,q} = H^{p+q}(X, \mathcal{F}^p[-p]) = H^q(X, \mathcal{F}^p) \]

If \(\mathcal{F}^\bullet\) is bounded below, then

1. we can use Remark 29.2 to construct this spectral sequence,
2. the spectral sequence is bounded and converges to \(H^{i+j}(X, \mathcal{F}^\bullet)\),
3. the spectral sequence is equal to the first spectral sequence of Derived Categories, Lemma 21.3 (constructed using Cartan-Eilenberg resolutions).

Lemma 29.5. Let \(f : (X, \mathcal{O}_X) \to (Y, \mathcal{O}_Y)\) be a morphism of ringed spaces. 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 \(\mathcal{O}_Y\)-modules with \(d_r\) of bidegree \((r, -r + 1)\) and

\[ E_1^{p,q} = R^{p+q}f_*g^p\mathcal{F}^\bullet \]

If for every \(n\) we have

\[ R^n f_*F^p\mathcal{F}^\bullet = 0 \text{ for } p \gg 0 \quad \text{and} \quad R^n f_*F^p\mathcal{F}^\bullet = R^n f_*\mathcal{F}^\bullet \text{ for } p \ll 0 \]

then the spectral sequence is bounded and converges to \(Rf_*\mathcal{F}^\bullet\).

Proof. The proof is exactly the same as the proof of Lemma 29.1.

30. Godement resolution

A reference is Godement, Chapter 73.

Let \((X, \mathcal{O}_X)\) be a ringed space. Denote \(X_{\text{disc}}\) the discrete topological space with the same points as \(X\). Denote \(f : X_{\text{disc}} \to X\) the obvious continuous map. Set \(\mathcal{O}_{X_{\text{disc}}} = f^{-1}\mathcal{O}_X\). Then \(f : (X_{\text{disc}}, \mathcal{O}_{X_{\text{disc}}}) \to (X, \mathcal{O}_X)\) is a flat morphism of ringed spaces. We can apply the dual of the material in Simplicial, Section 33 to the adjoint pair of functors \(f^*, f_*\) on sheaves of modules. Thus we obtain an augmented cosimplicial object

\[
\begin{align*}
\text{id} & \longrightarrow f_*f^* \longrightarrow f_*f^*f_*f^* \longrightarrow f_*f^*f_*f^*f_*f^* \longrightarrow \cdots \\
& \quad \longrightarrow f_*f^*f_*f^*f_*f^*f_*f^*f_*f^*f_*f^*f_*f^*
\end{align*}
\]

in the category of functors from \(\text{Mod}(\mathcal{O}_X)\) to itself, see Simplicial, Lemma 33.4. Moreover, the augmentation

\[
\begin{align*}
f^* & \longrightarrow f^*f_*f^* \longrightarrow f^*f_*f^*f_*f^* \longrightarrow f^*f_*f^*f_*f^*f_*f^*f_*f^*f_*f^*f_*f^*f_*f^*
\end{align*}
\]

is a homotopy equivalence, see Simplicial, Lemma 33.5.

Lemma 30.1. Let \((X, \mathcal{O}_X)\) be a ringed space. For every sheaf of \(\mathcal{O}_X\)-modules \(\mathcal{F}\) there is a resolution

\[ 0 \to \mathcal{F} \to f_*f^*\mathcal{F} \to f_*f^*f_*f^*\mathcal{F} \to f_*f^*f_*f^*f_*f^*\mathcal{F} \to \cdots \]

functorial in \(\mathcal{F}\) such that each term \(f_*f^*\cdots f_*f^*\mathcal{F}\) is a flasque \(\mathcal{O}_X\)-module and such that for all \(x \in X\) the map

\[
\mathcal{F}_x[0] \to \left( (f_*f^*\mathcal{F})_x \to (f_*f^*f_*f^*\mathcal{F})_x \to (f_*f^*f_*f_*f^*\mathcal{F})_x \to \cdots \right)
\]

is a homotopy equivalence in the category of complexes of \(\mathcal{O}_{X,x}\)-modules.
Proof. The complex \( f_! f^* F \to f_! f^* f_! f^* F \to f_! f^* f_! f^* f_! f^* F \to \ldots \) is the complex associated to the cosimplicial object with terms \( f_! f^* F, f_! f^* f_! f^* F, f_! f^* f_! f^* f_! f^* F, \ldots \) described above, see Simplicial, Section \( \text{[28]} \). The augmentation gives rise to the map \( F \to f_! f^* F \) as indicated. For any abelian sheaf \( \mathcal{H} \) on \( X_{\text{disc}} \) the pushforward \( f_! \mathcal{H} \) is flasque because \( X_{\text{disc}} \) is a discrete space and the pushforward of a flasque sheaf is flasque. Hence the terms of the complex are flasque \( \mathcal{O}_X \)-modules.

If \( x \in X_{\text{disc}} = X \) is a point, then \( (f^* \mathcal{G})_x = \mathcal{G}_x \) for any \( \mathcal{O}_X \)-module \( \mathcal{G} \). Hence \( f^* \) is an exact functor and a complex of \( \mathcal{O}_X \)-modules \( \mathcal{G}_1 \to \mathcal{G}_2 \to \mathcal{G}_3 \) is exact if and only if \( f^* \mathcal{G}_1 \to f^* \mathcal{G}_2 \to f^* \mathcal{G}_3 \) is exact (see Modules, Lemma \[3.1\]). The result mentioned in the introduction to this section proves the pullback by \( f^* \) gives a homotopy equivalence from the constant cosimplicial object \( f^* F \) to the cosimplicial object with terms \( f_! f_! f_! f^* F, f_! f_! f_! f_! f_! f^* F, \ldots \). By Simplicial, Lemma \[28.7\] we obtain that

\[
f^* F[0] \to \left( f^* f^* f^* F \to f^* f^* f_! f_! f^* F \to f^* f_! f_! f_! f^* f_! f_! f^* F \to \ldots \right)
\]

is a homotopy equivalence. This immediately implies the two remaining statements of the lemma. \( \square \)

0FKT Lemma 30.2. Let \( (X, \mathcal{O}_X) \) be a ringed space. Let \( F^\bullet \) be a bounded below complex of \( \mathcal{O}_X \)-modules. There exists a quasi-isomorphism \( F^\bullet \to G^\bullet \) where \( G^\bullet \) is a bounded below complex of flasque \( \mathcal{O}_X \)-modules and for all \( x \in X \) the map \( F^\bullet_x \to G^\bullet_x \) is a homotopy equivalence in the category of complexes of \( \mathcal{O}_{X,x} \)-modules.

Proof. Let \( A \) be the category of complexes of \( \mathcal{O}_X \)-modules and let \( B \) be the category of complexes of \( \mathcal{O}_{X,x} \)-modules. Then we can apply the discussion above to the adjoint functors \( f^* \) and \( f_! \) between \( A \) and \( B \). Arguing exactly as in the proof of Lemma \[30.1\] we get a resolution

\[
0 \to F^\bullet \to f_* f^* F^\bullet \to f_* f_* f^* f^* F^\bullet \to f_* f_* f_* f_* f^* f^* f^* F^\bullet \to \ldots
\]

in the abelian category \( A \) such that each term of each \( f_* f^* \ldots f_* f^* F^\bullet \) is a flasque \( \mathcal{O}_X \)-module and such that for all \( x \in X \) the map

\[
F^\bullet_x[0] \to \left( (f_* f^* F^\bullet)_x \to (f_* f^* f_* f^* F^\bullet)_x \to (f_* f^* f_* f_* f^* F^\bullet)_x \to \ldots \right)
\]

is a homotopy equivalence in the category of complexes of complexes of \( \mathcal{O}_{X,x} \)-modules. Since a complex of complexes is the same thing as a double complex, we can consider the induced map

\[
F^\bullet \to G^\bullet = \text{Tot}(f_* f^* F^\bullet \to f_* f^* f_* f^* F^\bullet \to f_* f^* f_* f_* f^* f^* F^\bullet \to \ldots)
\]

Since the complex \( F^\bullet \) is bounded below, the same is true for \( G^\bullet \) and in fact each term of \( G^\bullet \) is a finite direct sum of terms of the complexes \( f_* f^* \ldots f_* f^* F^\bullet \) and hence is flasque. The final assertion of the lemma now follows from Homology, Lemma \[25.5\]. Since this in particular shows that \( F^\bullet \to G^\bullet \) is a quasi-isomorphism, the proof is complete. \( \square \)

31. Cup product

0FKU Let \( (X, \mathcal{O}_X) \) be a ringed space. Let \( K, M \) be objects of \( D(\mathcal{O}_X) \). Set \( A = \Gamma(X, \mathcal{O}_X) \). The (global) cup product in this setting is a map

\[
\mu : R\Gamma(X, K) \otimes^L_A R\Gamma(X, M) \to R\Gamma(X, K \otimes^L_{\mathcal{O}_X} M)
\]
in $D(A)$. We define it as the relative cup product for the morphism of ringed spaces $f : (X, \mathcal{O}_X) \to (pt, A)$ as in Remark 28.7 via $D(pt, A) = D(A)$. This map in particular defines pairings

$$\cup : H^i(X, K) \times H^j(X, M) \to H^{i+j}(X, K \otimes^\mathbb{L}_{\mathcal{O}_X} M)$$

Namely, given $\xi \in H^i(X, K) = H^i(\Gamma(X, K))$ and $\eta \in H^j(X, M) = H^j(\Gamma(X, M))$ we can first “tensor” them to get an element $\xi \otimes \eta$ in $H^{i+j}(\Gamma(X, K) \otimes^\mathbb{L}_R \Gamma(X, M))$, see More on Algebra, Section 61. Then we can apply $\mu$ to get the desired element $\xi \cup \eta = \mu(\xi \otimes \eta)$ of $H^{i+j}(X, K \otimes^\mathbb{L}_{\mathcal{O}_X} M)$.

Here is another way to think of the cup product of $\xi$ and $\eta$. Namely, we can write

$$R\Gamma(X, K) = R\text{Hom}_X(\mathcal{O}_X, K) \text{ and } R\Gamma(X, M) = R\text{Hom}_X(\mathcal{O}_X, M)$$

because $\text{Hom}(\mathcal{O}_X, -) = \Gamma(\mathcal{O}_X, -)$. Thus $\xi$ and $\eta$ are the “same” thing as maps

$$\xi : \mathcal{O}_X[-i] \to K \text{ and } \eta : \mathcal{O}_X[-j] \to M$$

Combining this with the functoriality of the derived tensor product we obtain

$$\mathcal{O}_X[-i - j] = \mathcal{O}_X[-i] \otimes^\mathbb{L}_{\mathcal{O}_X} \mathcal{O}_X[-j] \xrightarrow{\xi \otimes \eta} K \otimes^\mathbb{L}_{\mathcal{O}_X} M$$

which by the same token as above is an element of $H^{i+j}(X, K \otimes^\mathbb{L}_{\mathcal{O}_X} M)$.

**Lemma 31.1.** This construction gives the cup product.

**Proof.** With $f : (X, \mathcal{O}_X) \to (pt, A)$ as above we have $Rf_*(-) = R\Gamma(X, -)$ and our map $\mu$ is adjoint to the map

$$Lf^*(Rf_* K \otimes^\mathbb{L}_A Rf_* M) = Lf^* Rf_* K \otimes^\mathbb{L}_{\mathcal{O}_X} Lf^* Rf_* M \xrightarrow{\epsilon_K \otimes \epsilon_M} K \otimes^\mathbb{L}_{\mathcal{O}_X} M$$

where $\epsilon$ is the counit of the adjunction between $Lf^*$ and $Rf_*$. If we think of $\xi$ and $\eta$ as maps $\xi : A[-i] \to R\Gamma(X, K)$ and $\eta : A[-j] \to R\Gamma(X, M)$, then the tensor $\xi \otimes \eta$ corresponds to the map

$$A[-i - j] = A[-i] \otimes^\mathbb{L}_A A[-j] \xrightarrow{\xi \otimes \eta} R\Gamma(X, K) \otimes^\mathbb{L}_{\mathcal{O}_X} R\Gamma(X, M)$$

By definition the cup product $\xi \cup \eta$ is the map $A[-i - j] \to R\Gamma(X, K \otimes^\mathbb{L}_{\mathcal{O}_X} M)$ which is adjoint to

$$(\epsilon_K \otimes \epsilon_M) \circ Lf^*(\xi \otimes \eta) = (\epsilon_K \circ Lf^* \xi) \otimes (\epsilon_M \circ Lf^* \eta)$$

However, it is easy to see that $\epsilon_K \circ Lf^* \xi = \tilde{\xi}$ and $\epsilon_M \circ Lf^* \eta = \tilde{\eta}$. We conclude that

$$\tilde{\xi} \cup \tilde{\eta} = \hat{\xi} \otimes \hat{\eta}$$

which means we have the desired agreement. \qed

Let us formulate and prove a natural compatibility of the relative cup product. Namely, suppose that we have a morphism $f : (X, \mathcal{O}_X) \to (Y, \mathcal{O}_Y)$ of ringed spaces. Let $\mathcal{K}^*$ and $\mathcal{M}^*$ be complexes of $\mathcal{O}_X$-modules. There is a naive cup product

$$\text{Tot}(f_* \mathcal{K}^* \otimes_{\mathcal{O}_Y} f_* \mathcal{M}^*) \to f_* \text{Tot}(\mathcal{K}^* \otimes_{\mathcal{O}_X} \mathcal{M}^*)$$

We claim that this is related to the relative cup product.

---

There is a sign hidden here, namely, the equality is defined by the composition

$$A[-i - j] \to (A \otimes^\mathbb{L}_A A)[-i - j] \to A[-i] \otimes^\mathbb{L}_A A[-j]$$

where in the second step we use the identification of More on Algebra, Item 7 which uses a sign in principle. Except, in this case the sign is $+1$ by our convention and even if it wasn’t $+1$ it wouldn’t matter since we used the same sign in the identification $\mathcal{O}_X[-i - j] = \mathcal{O}_X[-i] \otimes^\mathbb{L}_{\mathcal{O}_X} \mathcal{O}_X[-j]$. 
Lemma 31.2. In the situation above the following diagram commutes

\[
\begin{array}{ccc}
  f_*K^\bullet \otimes_{O_Y} f_*M^\bullet & \longrightarrow & Rf_*K^\bullet \otimes_{O_Y} Rf_*M^\bullet \\
  \text{naive cup product} & \downarrow & \text{Remark 28.7} \\
  \text{Tot}(f_*K^\bullet \otimes_{O_Y} f_*M^\bullet) & \longrightarrow & Rf_*\text{Tot}(K^\bullet \otimes_{O_X} M^\bullet)
\end{array}
\]

Proof. By the construction in Remark 28.7 we see that going around the diagram clockwise the map

\[
f_*K^\bullet \otimes_{O_Y} f_*M^\bullet \longrightarrow Rf_*\text{Tot}(K^\bullet \otimes_{O_X} M^\bullet)
\]

is adjoint to the map

\[
Lf^*(f_*K^\bullet \otimes_{O_Y} f_*M^\bullet) = Lf^*f_*K^\bullet \otimes_{O_Y} Lf^*f_*M^\bullet \\
\rightarrow Lf^*f_*K^\bullet \otimes_{O_Y} Lf^*Rf_*M^\bullet \\
\rightarrow K^\bullet \otimes_{O_Y} M^\bullet \\
\rightarrow \text{Tot}(K^\bullet \otimes_{O_X} M^\bullet)
\]

By Lemma 28.6 this is also equal to

\[
Lf^*(f_*K^\bullet \otimes_{O_Y} f_*M^\bullet) = Lf^*f_*K^\bullet \otimes_{O_Y} Lf^*f_*M^\bullet \\
\rightarrow Lf^*f_*K^\bullet \otimes_{O_Y} f^*f_*M^\bullet \\
\rightarrow K^\bullet \otimes_{O_Y} M^\bullet \\
\rightarrow \text{Tot}(K^\bullet \otimes_{O_X} M^\bullet)
\]

Going around anti-clockwise we obtain the map adjoint to the map

\[
Lf^*(f_*K^\bullet \otimes_{O_Y} f_*M^\bullet) \rightarrow Lf^*\text{Tot}(f_*K^\bullet \otimes_{O_Y} f_*M^\bullet) \\
\rightarrow Lf^*f_*\text{Tot}(K^\bullet \otimes_{O_X} M^\bullet) \\
\rightarrow Lf^*Rf_*\text{Tot}(K^\bullet \otimes_{O_X} M^\bullet) \\
\rightarrow \text{Tot}(K^\bullet \otimes_{O_X} M^\bullet)
\]

By Lemma 28.6 this is also equal to

\[
Lf^*(f_*K^\bullet \otimes_{O_Y} f_*M^\bullet) \rightarrow Lf^*\text{Tot}(f_*K^\bullet \otimes_{O_Y} f_*M^\bullet) \\
\rightarrow Lf^*f_*\text{Tot}(K^\bullet \otimes_{O_X} M^\bullet) \\
\rightarrow f^*f_*\text{Tot}(K^\bullet \otimes_{O_X} M^\bullet) \\
\rightarrow \text{Tot}(K^\bullet \otimes_{O_X} M^\bullet)
\]
Now the proof is finished by a contemplation of the diagram

\[
\begin{array}{ccc}
Lf^*(f_*K^\bullet \otimes_{\mathcal{O}_Y} f_*\mathcal{M}^\bullet) & \longrightarrow & Lf^*f_*K^\bullet \otimes_{\mathcal{O}_X} Lf^*f_*\mathcal{M}^\bullet \\
Lf^*\text{Tot}(f_*K^\bullet \otimes_{\mathcal{O}_Y} f_*\mathcal{M}^\bullet) & \longrightarrow & f^*\text{Tot}(f_*K^\bullet \otimes_{\mathcal{O}_Y} f_*\mathcal{M}^\bullet) \\
f^*f_*\text{Tot}(K^\bullet \otimes_{\mathcal{O}_X} \mathcal{M}^\bullet) & \longrightarrow & \text{Tot}(f^*f_*K^\bullet \otimes_{\mathcal{O}_X} f^*f_*\mathcal{M}^\bullet) \\
\text{Tot}(K^\bullet \otimes_{\mathcal{O}_X} \mathcal{M}^\bullet) & \longrightarrow & K^\bullet \otimes_{\mathcal{O}_X} \mathcal{M}^\bullet
\end{array}
\]

All of the polygons in this diagram commute. The top one commutes by Lemma \ref{27.5}. The square with the two naive cup products commutes because $Lf^* \to f^*$ is functorial in the complex of modules. Similarly with the square involving the two maps $A^\bullet \otimes B^\bullet \to \text{Tot}(A^\bullet \otimes B^\bullet)$. Finally, the commutativity of the remaining square is true on the level of complexes and may be viewed as the definition of the naive cup product (by the adjointness of $f^*$ and $f_*$). The proof is finished because going around the diagram on the outside are the two maps given above. \hfill \Box

Let $(X, \mathcal{O}_X)$ be a ring space. Let $K^\bullet$ and $\mathcal{M}^\bullet$ be complexes of $\mathcal{O}_X$-modules. Then we have a “naive” cup product

\[
\mu': \text{Tot}(\Gamma(X, K^\bullet) \otimes_A \Gamma(X, \mathcal{M}^\bullet)) \longrightarrow \Gamma(X, \text{Tot}(K^\bullet \otimes_{\mathcal{O}_X} \mathcal{M}^\bullet))
\]

By Lemma \ref{31.2} applied to the morphism $(X, \mathcal{O}_X) \to (pt, A)$ this naive cup product is related to the cup product $\mu$ defined in the first paragraph of this section by the following commutative diagram

\[
\begin{array}{ccc}
\Gamma(X, K^\bullet) \otimes_{\mathcal{O}_X} \Gamma(X, \mathcal{M}^\bullet) & \longrightarrow & RT\Gamma(X, K^\bullet) \otimes_{\mathcal{O}_X} RT\Gamma(X, \mathcal{M}^\bullet) \\
\text{Tot}(\Gamma(X, K^\bullet) \otimes_A \Gamma(X, \mathcal{M}^\bullet)) & \longrightarrow & RT\Gamma(X, K^\bullet \otimes_{\mathcal{O}_X} \mathcal{M}^\bullet) \\
\Gamma(X, \text{Tot}(K^\bullet \otimes_{\mathcal{O}_X} \mathcal{M}^\bullet)) & \longrightarrow & RT\Gamma(X, \text{Tot}(K^\bullet \otimes_{\mathcal{O}_X} \mathcal{M}^\bullet))
\end{array}
\]

in $D(A)$. On cohomology we obtain the commutative diagram

\[
\begin{array}{ccc}
H^i(\Gamma(X, K^\bullet)) \times H^j(\Gamma(X, \mathcal{M}^\bullet)) & \longrightarrow & H^{i+j}(X, \text{Tot}(K^\bullet \otimes_{\mathcal{O}_X} \mathcal{M}^\bullet)) \\
H^i(X, K^\bullet) \times H^j(X, \mathcal{M}^\bullet) & \longrightarrow & H^{i+j}(X, K^\bullet \otimes_{\mathcal{O}_X} \mathcal{M}^\bullet)
\end{array}
\]

relating the naive cup product with the actual cup product.
Let $(X, \mathcal{O}_X)$ be a ringed space. Let $\mathcal{K}^\bullet$ and $\mathcal{M}^\bullet$ be bounded below complexes of $\mathcal{O}_X$-modules. Let $\mathcal{U} : X = \textstyle{\bigcup_{i \in I} U_i}$ be an open covering. Then

$$\Gamma(X, \mathcal{K}^\bullet) \otimes_{\mathcal{O}_X} \Gamma(X, \mathcal{M}^\bullet) \to \text{Tot}((\Gamma(U, \mathcal{K}^\bullet)) \otimes_{\mathcal{A}} \text{Tot}(\mathcal{U}^\bullet, \mathcal{M}^\bullet))$$

where the horizontal arrows are the ones in Lemma 25.1 commutes in $D(A)$.  

**Proof.** Choose quasi-isomorphisms of complexes $a : \mathcal{K}^\bullet \to \mathcal{K}_1^\bullet$ and $b : \mathcal{M}^\bullet \to \mathcal{M}_1^\bullet$ as in Lemma 30.2. Since the maps $a$ and $b$ on stalks are homotopy equivalences we see that the induced map

$$\text{Tot}(\mathcal{K}^\bullet \otimes_{\mathcal{O}_X} \mathcal{M}^\bullet) \to \text{Tot}(\mathcal{K}_1^\bullet \otimes_{\mathcal{O}_X} \mathcal{M}_1^\bullet)$$

is a homotopy equivalence on stalks too (More on Algebra, Lemma 57.1) and hence a quasi-isomorphism. Thus the targets

$$R\Gamma(X, \text{Tot}(\mathcal{K}^\bullet \otimes_{\mathcal{O}_X} \mathcal{M}^\bullet)) = R\Gamma(X, \text{Tot}(\mathcal{K}_1^\bullet \otimes_{\mathcal{O}_X} \mathcal{M}_1^\bullet))$$

of the two diagrams are the same in $D(A)$.

Assume $\mathcal{K}^\bullet$ and $\mathcal{M}^\bullet$ are bounded below complexes of flasque $\mathcal{O}_X$-modules and consider the diagram relating the cup product with the cup product on Čech complexes. Then we can consider the commutative diagram

$$\Gamma(X, \mathcal{K}^\bullet) \otimes_{\mathcal{A}} \Gamma(X, \mathcal{M}^\bullet) \to \text{Tot}((\Gamma(U, \mathcal{K}^\bullet)) \otimes_{\mathcal{A}} \text{Tot}(\mathcal{U}^\bullet, \mathcal{M}^\bullet))$$

In this diagram the horizontal arrows are isomorphisms in $D(A)$ because for a bounded below complex of flasque modules such as $\mathcal{K}^\bullet$ we have

$$\Gamma(X, \mathcal{K}^\bullet) = \text{Tot}(\mathcal{K}^\bullet (U, \mathcal{K}^\bullet)) = R\Gamma(X, \mathcal{K}^\bullet)$$

in $D(A)$. This follows from Lemma 12.3, Derived Categories, Lemma 16.7, and Lemma 25.2. Hence the commutativity of the diagram of the lemma involving (25.3.2) follows from the already proven commutativity of Lemma 31.2 where $f$ is the morphism to a point (see discussion following Lemma 31.2). \qed
Lemma 31.4. Let $f : (X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$ be a morphism of ringed spaces. The relative cup product of Remark 28.7 is associative in the sense that the diagram

\[
\begin{array}{c}
Rf_*K \otimes_{\mathcal{O}_Y} Rf_*L \otimes_{\mathcal{O}_Y} Rf_*M \\
\downarrow \\
Rf_*K \otimes_{\mathcal{O}_Y} Rf_*(L \otimes_{\mathcal{O}_X} M) \to Rf_*(K \otimes_{\mathcal{O}_X} L \otimes_{\mathcal{O}_X} M)
\end{array}
\]

is commutative in $D(\mathcal{O}_Y)$ for all $K, L, M$ in $D(\mathcal{O}_X)$.

Proof. Going around either side we obtain the map adjoint to the obvious map

\[
L^f*(Rf_*K \otimes_{\mathcal{O}_Y} Rf_*L \otimes_{\mathcal{O}_Y} Rf_*M) = L^f*(Rf_*K) \otimes_{\mathcal{O}_X} L^f*(Rf_*L) \otimes_{\mathcal{O}_X} L^f*(Rf_*M)
\]

\[
\rightarrow K \otimes_{\mathcal{O}_X} L \otimes_{\mathcal{O}_X} M
\]

in $D(\mathcal{O}_X)$. □

Lemma 31.5. Let $f : (X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$ be a morphism of ringed spaces. The relative cup product of Remark 28.7 is commutative in the sense that the diagram

\[
\begin{array}{c}
Rf_*K \otimes_{\mathcal{O}_Y} Rf_*L \\
\downarrow \psi \\
Rf_*L \otimes_{\mathcal{O}_Y} Rf_*K
\end{array}
\]

\[
\begin{array}{c}
Rf_*L \otimes_{\mathcal{O}_Y} Rf_*K \to Rf_*(L \otimes_{\mathcal{O}_X} K)
\end{array}
\]

is commutative in $D(\mathcal{O}_Y)$ for all $K, L$ in $D(\mathcal{O}_X)$. Here $\psi$ is the commutativity constraint on the derived category (Lemma 46.5).

Proof. Omitted. □

Lemma 31.6. Let $f : (X, \mathcal{O}_X) \rightarrow (Y, \mathcal{O}_Y)$ and $g : (Y, \mathcal{O}_Y) \rightarrow (Z, \mathcal{O}_Z)$ be morphisms of ringed spaces. The relative cup product of Remark 28.7 is compatible with compositions in the sense that the diagram

\[
\begin{array}{c}
R(g \circ f)_*K \otimes_{\mathcal{O}_Z} R(g \circ f)_*L \\
\downarrow \\
R(g \circ f)_*(K \otimes_{\mathcal{O}_Y} L) \to Rg_*Rf_*K \otimes_{\mathcal{O}_Z} Rg_*Rf_*L
\end{array}
\]

is commutative in $D(\mathcal{O}_Z)$ for all $K, L$ in $D(\mathcal{O}_X)$.

Proof. This is true because going around the diagram either way we obtain the map adjoint to the map

\[
L(g \circ f)^*(R(g \circ f)_*K \otimes_{\mathcal{O}_Z} R(g \circ f)_*L)
\]

\[
= L(g \circ f)^*(R(g \circ f)_*K \otimes_{\mathcal{O}_X} L(g \circ f)^*R(g \circ f)_*L)
\]

\[
\rightarrow K \otimes_{\mathcal{O}_X} L
\]

in $D(\mathcal{O}_X)$. To see this one uses that the composition of the counits like so

\[
L(g \circ f)^*R(g \circ f)_* = Lf^*Lg^*Rg_*Rf_* \to Lf^*Rf_* \to \text{id}
\]

is the counit for $L(g \circ f)^*$ and $R(g \circ f)_*$. See Categories, Lemma 24.8. □
32. Some properties of K-injective complexes

Let $(X, \mathcal{O}_X)$ be a ringed space. Let $U \subset X$ be an open subset. Denote $j : (U, \mathcal{O}_U) \to (X, \mathcal{O}_X)$ 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

$$D(\mathcal{O}_X) \to D(\mathcal{O}_U), \quad E \mapsto j^* E = E|_U$$

Similarly, extension by zero $j_! : \text{Mod}(\mathcal{O}_U) \to \text{Mod}(\mathcal{O}_X)$ (see Sheaves, Section 31) is an exact functor (Modules, Lemma 3.4). Thus it induces a functor

$$j_! : D(\mathcal{O}_U) \to D(\mathcal{O}_X), \quad F \mapsto j_! F$$

by simply applying $j_!$ to any complex representing the object $F$.

Lemma 32.1. 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 31.9 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.

Lemma 32.2. 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

$$H^p(U, K) = H^p(\Gamma(U, \mathcal{I}^\bullet)) = H^p(\Gamma(U, \mathcal{I}^\bullet|_U))$$

by construction of cohomology. By Lemma 32.1 the complex $\mathcal{I}^\bullet|_U$ is a K-injective complex representing $K|_U$ and the lemma follows.

Lemma 32.3. 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 32.2. Choose a K-injective complex $\mathcal{I}^\bullet$ representing $K$. Then

$$H^q(U, K) = \frac{\text{Ker}(\mathcal{I}^q(U) \to \mathcal{I}^{q+1}(U))}{\text{Im}(\mathcal{I}^q(U) \to \mathcal{I}^q(U))}$$

by our construction of cohomology. Since $H^q(K) = \text{Ker}(\mathcal{I}^q \to \mathcal{I}^{q+1})/\text{Im}(\mathcal{I}^{q-1} \to \mathcal{I}^q)$ the result is clear.

Lemma 32.4. Let $f : (X, \mathcal{O}_X) \to (Y, \mathcal{O}_Y)$ be a morphism of ringed spaces. Given an open subspace $V \subset Y$, set $U = f^{-1}(V)$ and denote $g : U \to V$ 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 32.1. Since it is clear that $(f_* F)|_V = g_*(F|_U)$ for any sheaf $F$ on $X$ the result follows.
Lemma 32.5. Let \( f : X \to Y \) be a morphism of ringed spaces. Then \( R \Gamma(Y, -) \circ R f_* = R \Gamma(X, -) \) as functors \( D(O_X) \to D(\Gamma(Y, O_Y)) \). More generally for \( V \subset Y \) open and \( U = f^{-1}(V) \) we have \( R \Gamma(U, -) = R \Gamma(V, -) \circ R f_* \).

Proof. Let \( Z \) be the ringed space consisting of a singleton space with \( \Gamma(Z, O_Z) = \Gamma(Y, O_Y) \). There is a canonical morphism \( Y \to Z \) of ringed spaces inducing the identification on global sections of structure sheaves. Then \( D(O_Z) = D(\Gamma(Y, O_Y)) \). Hence the assertion \( R \Gamma(Y, -) \circ R f_* = R \Gamma(X, -) \) follows from Lemma 28.2 applied to \( X \to Y \to Z \).

The second (more general) statement follows from the first statement after applying Lemma 32.3.

Lemma 32.6. Let \( f : (X, \mathcal{O}_X) \to (Y, \mathcal{O}_Y) \) be a morphism of ringed spaces. Let \( K \) be in \( D(\mathcal{O}_X) \). Then \( H^i(R f_* K) \) is the sheaf associated to the presheaf
\[
V \mapsto H^i(f^{-1}(V), K) = H^i(V, R f_* K)
\]

Proof. The equality \( H^i(f^{-1}(V), K) = H^i(V, R f_* K) \) follows upon taking cohomology from the second statement in Lemma 32.5. Then the statement on sheafification follows from Lemma 32.3.

Lemma 32.7. Let \( X \) be a ringed space. Let \( K \) be an object of \( D(\mathcal{O}_X) \) and denote \( K_{ab} \) its image in \( D(\mathbb{Z}_X) \).

1. For any open \( U \subset X \) there is a canonical map \( R \Gamma(U, K) \to R \Gamma(U, K_{ab}) \) which is an isomorphism in \( D(Ab) \).

2. Let \( f : X \to Y \) be a morphism of ringed spaces. There is a canonical map \( R f_* K \to R f_* (K_{ab}) \) which is an isomorphism in \( D(\mathbb{Z}_Y) \).

Proof. The map is constructed as follows. Choose a \( K \)-injective complex \( I^* \) representing \( K \). Choose a quasi-isomorphism \( I^* \to J^* \) where \( J^* \) is a \( K \)-injective complex of abelian groups. Then the map in (1) is given by \( \Gamma(U, I^*) \to \Gamma(U, J^*) \) and the map in (2) is given by \( f_* I^* \to f_* J^* \). To show that these maps are isomorphisms, it suffices to prove they induce isomorphisms on cohomology groups and group sheaves. By Lemmas 32.2 and 32.6 it suffices to show that the map
\[
H^0(X, K) \to H^0(X, K_{ab})
\]
is an isomorphism. Observe that
\[
H^0(X, K) = \text{Hom}_{D(O_X)}(\mathcal{O}_X, K)
\]
and similarly for the other group. Choose any complex \( \mathcal{K}^* \) of \( \mathcal{O}_X \)-modules representing \( K \). By construction of the derived category as a localization we have
\[
\text{Hom}_{D(O_X)}(\mathcal{O}_X, K) = \text{colim}_{s: F^* \to O_X} \text{Hom}_{K(O_X)}(F^*, \mathcal{K}^*)
\]
where the colimit is over quasi-isomorphisms \( s \) of complexes of \( \mathcal{O}_X \)-modules. Similarly, we have
\[
\text{Hom}_{D(\mathbb{Z}_X)}(\mathbb{Z}_X, K) = \text{colim}_{s: G^* \to \mathbb{Z}_X} \text{Hom}_{K(\mathbb{Z}_X)}(G^*, \mathcal{K}^*)
\]
Next, we observe that the quasi-isomorphisms \( s : G^* \to \mathbb{Z}_X \) with \( G^* \) bounded above complex of flat \( \mathbb{Z}_X \)-modules is cofinal in the system. (This follows from Modules, Lemma 16.6 and Derived Categories, Lemma 15.4; see discussion in Section 26.)
Hence we can construct an inverse to the map $H^0(X, K) \to H^0(X, K_{ab})$ by representing an element $\xi \in H^0(X, K_{ab})$ by a pair
\[(s : G^\bullet \to \mathbb{Z}_X, a : G^\bullet \to K^\bullet)\]
with $G^\bullet$ a bounded above complex of flat $\mathbb{Z}_X$-modules and sending this to
\[(G^\bullet \otimes_{\mathbb{Z}_X} \mathcal{O}_X \to \mathcal{O}_X, G^\bullet \otimes_{\mathbb{Z}_X} \mathcal{O}_X \to K^\bullet)\]
The only thing to note here is that the first arrow is a quasi-isomorphism by Lemmas 26.12 and 26.8. We omit the detailed verification that this construction is indeed an inverse. □

**Lemma 32.8.** Let $(X, \mathcal{O}_X)$ be a ringed space. Let $U \subset X$ be an open subset. Denote $j_!: (U, \mathcal{O}_U) \to (X, \mathcal{O}_X)$ the corresponding open immersion. The restriction functor $D(\mathcal{O}_X) \to D(\mathcal{O}_U)$ is a right adjoint to extension by zero $j_! : D(\mathcal{O}_U) \to D(\mathcal{O}_X)$.

**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 30.3. □

**Lemma 32.9.** Let $f : X \to Y$ be a flat morphism of ringed spaces. If $I^\bullet$ is a $K$-injective complex of $\mathcal{O}_X$-modules, then $f_*I^\bullet$ is $K$-injective as a complex of $\mathcal{O}_Y$-modules.

**Proof.** This is true because
\[\text{Hom}_{K(\mathcal{O}_Y)}(\mathcal{F}^\bullet, f_*I^\bullet) = \text{Hom}_{K(\mathcal{O}_X)}(f^*\mathcal{F}^\bullet, I^\bullet)\]
by Sheaves, Lemma 26.2 and the fact that $f^*$ is exact as $f$ is assumed to be flat. □

### 33. Unbounded Mayer-Vietoris

There is a Mayer-Vietoris sequence for unbounded cohomology as well.

**Lemma 33.2.** 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
\[E \to Rj_{U\cap V}^*E|_{U\cap V} \to j_{U!}E|_U \oplus j_{V!}E|_V \to j_{U\cap V}!E|_{U\cap V}[1] \to E\]
in $D(\mathcal{O}_X)$.

**Proof.** We have seen in Section 32 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
\[0 \to j_{U\cap V}^!\mathcal{E}^\bullet|_{U\cap V} \to j_{U!}\mathcal{E}^\bullet|_U \oplus j_{V!}\mathcal{E}^\bullet|_V \to \mathcal{E}^\bullet \to 0\]
To see this sequence is exact one checks on stalks using Sheaves, Lemma 31.8 (computation omitted). □
Lemma 33.3. 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

$$\ldots \rightarrow \text{Ext}^1(E_U \cap F_U, F_U)$$

where the subscripts denote restrictions to the relevant opens and the Ext’s are taken in the relevant derived categories.

Proof. Use the distinguished triangle of Lemma 33.1 to obtain a long exact sequence of hom’s (from Derived Categories, Lemma 4.2) and use that $\text{Hom}_{D(\mathcal{O}_X)}(j_U E_U, F_U) = \text{Hom}_{D(\mathcal{O}_U)}(E_U, F_U)$ by Lemma 32.8.

Lemma 33.4. 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

$$\ldots \rightarrow H^n(X, E) \rightarrow H^n(U, E) \oplus H^n(V, E) \rightarrow H^n(U \cap V, E) \rightarrow H^{n+1}(X, E) \rightarrow \ldots$$

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 32.1. 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

$$0 \rightarrow \mathcal{I}^\bullet(X) \rightarrow \mathcal{I}^\bullet(U) \oplus \mathcal{I}^\bullet(V) \rightarrow \mathcal{I}^\bullet(U \cap V) \rightarrow 0.$$
**Lemma 33.5.** Let \( f : X \to Y \) be a morphism of ringed spaces. Suppose that \( X = U \cup V \) is a union of two open subsets. Denote \( a = f|_U : U \to Y \), \( b = f|_V : V \to Y \), and \( c = f|_{U \cap V} : U \cap V \to Y \). For every object \( E \) of \( D(O_X) \) there exists a distinguished triangle

\[
Rf_*E \to Ra_* (E|_U) \oplus Rb_* (E|_V) \to Rc_* (E|_{U \cap V}) \to Rf_*E[1]
\]

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 \( \text{Mod}(O_X) \) for all \( n \), see Injectives, Theorem [12.6]. Then \( Rf_*E \) is computed by \( f_* \mathcal{I}^\bullet \). Similarly for \( V, U \), and \( U \cap V \) by Lemma [32.1]. 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

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

This is a short exact sequence of complexes by Lemma [8.3] and the fact that \( R^1 f_* \mathcal{I} = 0 \) for an injective object \( \mathcal{I} \) of \( \text{Mod}(O_X) \). The final statement follows from the functoriality of the construction in Injectives, Theorem [12.6]. \qed

**Lemma 33.6.** Let \( (X, O_X) \) be a ringed space. Let \( j : U \to X \) be an open subspace. Let \( T \subset X \) be a closed subset contained in \( U \).

1. If \( E \) is an object of \( D(O_X) \) whose cohomology sheaves are supported on \( T \), then \( E \to Rj_* (E|_U) \) is an isomorphism.

2. If \( F \) is an object of \( D(O_U) \) whose cohomology sheaves are supported on \( T \), then \( j_* F \to Rj_* F \) 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 \( j_W : W \to V \) the open immersion. Let \( E \) be an object of \( D(O_X) \) whose cohomology sheaves are supported on \( T \). By Lemma [32.4] we have \( (Rj_* E|_U)|_V = Rj_{W*} (E|_W) = 0 \) because \( E|_W = 0 \) by our assumption. On the other hand, \( Rj_* (E|_U)|_V = E|_U \). Thus (1) is clear. Let \( F \) be an object of \( D(O_U) \) whose cohomology sheaves are supported on \( T \). By Lemma [32.4] 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. \qed

### 34. Derived limits

**Lemma 34.1.** Let \( (X, O_X) \) be a ringed space. For \( U \subset X \) open the functor \( Rf!(U, -) \) commutes with \( R\text{lim} \). Moreover, there are short exact sequences

\[
0 \to R^1 \text{lim} H^{m-1}(U, K_n) \to H^m(U, R\text{lim} K_n) \to \text{lim} H^m(U, K_n) \to 0
\]

for any inverse system \( (K_n) \) in \( D(O_X) \) and any \( m \in \mathbb{Z} \).
Proof. The first statement follows from Injectives, Lemma \[13.6\]. Then we may apply More on Algebra, Remark \[79.9\] to \[R \lim R\Gamma(U, K_n) = R\Gamma(U, R\lim K_n)\] to get the short exact sequences. \[\square\]

**Lemma 34.2.** Let \( f : (X, \mathcal{O}_X) \to (Y, \mathcal{O}_Y) \) 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

\[ R\lim K_n \to \prod K_n \to \prod K_n \]

in \( D(\mathcal{O}_X) \). Applying the exact functor \( Rf_* \) we obtain the distinguished triangle

\[ Rf_*(R\lim K_n) \to Rf_* \left( \prod K_n \right) \to Rf_* \left( \prod K_n \right) \]

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 \[28.1\] this follows formally (see Categories, Lemma \[24.5\]). Caution: Note that we cannot apply Categories, Lemma \[24.5\] directly as \( R\lim K_n \) is not a limit in \( D(\mathcal{O}_X) \).

\[\square\]

**Remark 34.3.** 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 \( H_m^n = H_m(K_n) \) be the \( m \)th cohomology sheaf of \( K_n \) and similarly set \( H^m = H^m(K) \). Let us denote \( H^m_n \) the presheaf

\[ U \mapsto H^m_n(U) = H^m(U, K_n) \]

Similarly we set \( H^m(U) = H^m(U, K) \). By Lemma \[32.3\] we see that \( H^m_n \) is the sheafification of \( H^m_n \) and \( H^m \) is the sheafification of \( H^m_n \). Here is a diagram

\[ \begin{array}{ccc}
K & \longrightarrow & H^m \\
\downarrow & & \downarrow \\
R\lim K_n & \longrightarrow & \lim H^m_n \\
\end{array} \]

In general it may not be the case that \( \lim H^m_n \) is the sheafification of \( \lim H^m_n \). If \( U \subset X \) is an open, then we have short exact sequences

\[ 0 \to R^1 \lim H^m_n(U) \to H^m(U) \to \lim H^m_n(U) \to 0 \]

by Lemma \[34.1\].

The following lemma applies to an inverse system of quasi-coherent modules with surjective transition maps on a scheme.

**Lemma 34.4.** 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 $K = \lim \lim \mathcal{F}_n$. Using the notation of Remark 34.3 and assumption (2) we see that for $U \in \mathcal{B}$ we have $H^m_n(U) = 0$ when $m \neq 0$ and $H^0_n(U) = \mathcal{F}_n(U)$ From Equations 34.3 and assumption (3) we see that $H^m(U) = 0$ when $m \neq 0$ and equal to $\lim \lim \mathcal{F}_n(U)$ when $m = 0$. Sheafifying using (1) we find that $H^m = 0$ when $m \neq 0$ and equal to $\lim \lim \mathcal{F}_n$ when $m = 0$. Hence $K = \lim \lim \mathcal{F}_n$. Since $H^m(K, U) = H^m(U) = 0$ for $m > 0$ (see above) we see that the second assertion holds.

**Lemma 34.5.** 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 $m \in \mathbb{Z}$. Assume there exist an integer $n(x)$ and a fundamental system $\mathcal{U}_x$ of open neighbourhoods of $x$ such that for $U \in \mathcal{U}_x$

1. $R^1 \lim H^{m-1}(U, K_n) = 0$, and
2. $H^m(U, K_n) \to H^m(U, K_n(x))$ is injective for $n \geq n(x)$.

Then the map on stalks $H^m(R \lim K_n)_x \to H^m(K_n(x))_x$ is injective.

Proof. Let $\gamma$ 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 $U \to H^m(U, R \lim K_n)$ (by Lemma 32.3) we can choose $U \in \mathcal{U}_x$ and an element $\tilde{\gamma} \in H^m(U, R \lim K_n)$ mapping to $\gamma$. 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 $U \to H^m(U, K_n(x))$ (by Lemma 32.3 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

$$0 \to R^1 \lim H^{m-1}(U, K_n) \to H^m(U, R \lim K_n) \to \lim H^m(U, K_n) \to 0$$

of Lemma 34.1. 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.

**Lemma 34.6.** 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 $p(x, \cdot) : \mathbb{Z} \to \mathbb{Z}$ and a fundamental system $\mathcal{U}_x$ of open neighbourhoods of $x$ such that

$$H^p(U, H^{m-p}(E)) = 0 \text{ for } U \in \mathcal{U}_x \text{ and } p > p(x, m)$$

Then the canonical map $E \to R \lim \tau_{m-n} E$ is an isomorphism in $D(\mathcal{O}_X)$.

Proof. Set $K_n = \tau_{m-n} E$ and $K = R \lim K_n$. The canonical map $E \to K$ comes from the canonical maps $E \to K_n = \tau_{m-n} E$. We have to show that $E \to K$ induces an isomorphism $H^m(E) \to H^m(K)$ of cohomology sheaves. In the rest of the proof we fix $m$. If $n \geq -m$, then the map $E \to \tau_{m-n} E = K_n$ induces an isomorphism $H^m(E) \to H^m(K_n)$. 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 $H^m(K)_x \to H^m(K_{n(x)}(x))_x$ is injective. Namely, then the composition

$$H^m(E)_x \to H^m(K)_x \to H^m(K_{n(x)}(x))_x$$

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

$$H^{m-1}(U, K_{n+1}) \to H^{m-1}(U, K_n) \text{ and } H^m(U, K_{n+1}) \to H^m(U, K_n)$$

are isomorphisms.
are isomorphisms for $n \geq n(x)$ and $U \in \mathcal{U}_x$. The claim implies conditions (1) and (2) of Lemma \ref{lem:triangle} are satisfied and hence implies the desired injectivity. Recall (Derived Categories, Remark 12.4) that we have distinguished triangles
\[ H^{-n-1}(E)[n+1] \to K_{n+1} \to K_n \to H^{-n-1}(E)[n+2] \]
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 $U \in \mathcal{U}_x$. This follows from our choice of $n(x)$ and the assumption in the lemma.

\begin{lemma}
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 $\mathcal{U}_x$ of open neighbourhoods of $x$ such that
\[ H^p(U, H^q(E)) = 0 \text{ for } U \in \mathcal{U}_x, \quad p > d_x, \quad \text{and } q < 0 \]
Then the canonical map $E \to R\lim_{\tau \geq -n} E$ is an isomorphism in $D(\mathcal{O}_X)$.
\end{lemma}

\begin{proof}
This follows from Lemma \ref{lem:triangle} with $p(x, m) = d_x + \max(0, m)$. \qed
\end{proof}

\begin{lemma}
Let $(X, \mathcal{O}_X)$ be a ringed space. Let $E \in D(\mathcal{O}_X)$. Assume there exist a function $p(-) : \mathbb{Z} \to \mathbb{Z}$ 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 $E \to R\lim_{\tau \geq -n} E$ is an isomorphism in $D(\mathcal{O}_X)$.
\end{lemma}

\begin{proof}
Apply Lemma \ref{lem:triangle} with $p(x, m) = p(m)$ and $\mathcal{U}_x = \{ U \in \mathcal{B} \mid x \in U \}$. \qed
\end{proof}

\begin{lemma}
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
\[ H^p(U, H^q(E)) = 0 \text{ for } U \in \mathcal{B}, \quad p > d, \quad \text{and } q < 0 \]
Then the canonical map $E \to R\lim_{\tau \geq -n} E$ is an isomorphism in $D(\mathcal{O}_X)$.
\end{lemma}

\begin{proof}
Apply Lemma \ref{lem:triangle} with $d_x = d$ and $\mathcal{U}_x = \{ U \in \mathcal{B} \mid x \in U \}$. \qed
\end{proof}

The lemmas above can be used to compute cohomology in certain situations.

\begin{lemma}
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 $p > 0$, $q \in \mathbb{Z}$, and $U \in \mathcal{B}$.
Then $H^q(U, K) = H^q(U, H^q(K))$ for $q \in \mathbb{Z}$ and $U \in \mathcal{B}$.
\end{lemma}

\begin{proof}
Observe that $K = R\lim_{\tau \geq -n} K$ by Lemma \ref{lem:limlim} with $d = 0$. Let $U \in \mathcal{B}$. By Equation \ref{eq:limlim} we get a short exact sequence
\[ 0 \to R^1 \lim_{\tau \geq -n} H^{q-1}(U, \tau_{\geq -n} K) \to H^q(U, K) \to \lim_{\tau \geq -n} H^q(U, \tau_{\geq -n} K) \to 0 \]
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 \ref{ex:specseq}. 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. \qed
\end{proof}
Here is another case where we can describe the derived limit.

**Lemma 34.11.** Let \((X, \mathcal{O}_X)\) be a ringed space. Let \((K_n)\) be an inverse system of objects of \(D(\mathcal{O}_X)\). Let \(B\) be a set of opens of \(X\). Assume

1. every open of \(X\) has a covering whose members are elements of \(B\),
2. for all \(U \in B\) and all \(q \in \mathbb{Z}\) 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 \(q \in \mathbb{Z}\).

**Proof.** Set \(K = R \lim K_n\). We will use notation as in Remark 34.3. Let \(U \in B\).
By Lemma 34.10 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 79.9 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 \(H^q(K_n)\), which is the shaeification of the presheaf \(U \mapsto H^q(U, K)\), is equal to \(\lim H^q(K_n)\). This proves the lemma. \(\square\)

### 35. Producing K-injective resolutions

Let \((X, \mathcal{O}_X)\) be a ringed space. Let \(F^•\) 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 29.3 produce a diagram

\[
\cdots \longrightarrow \tau_{\geq -3}F^• \longrightarrow \tau_{\geq -1}F^• \longrightarrow \cdots \longrightarrow I_2^• \longrightarrow I_1^• \longrightarrow \cdots
\]

in the category of complexes of \(\mathcal{O}_X\)-modules such that

1. the vertical arrows are quasi-isomorphisms,
2. \(I_n^•\) is a bounded below complex of injectives,
3. the arrows \(I_{n+1}^• \longrightarrow I_n^•\) 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 \(I^• = \lim_n I_n^•\). By Derived Categories, Lemmas 31.4 and 31.8 this is a K-injective complex. In general the canonical map

\[
F^• \longrightarrow I^•
\]

may not be a quasi-isomorphism. In the following lemma we describe some conditions under which it is.

**Lemma 35.1.** In the situation described above. Denote \(\mathcal{H}^m = H^m(F^•)\) the \(m\)th cohomology sheaf. Let \(B\) be a set of open subsets of \(X\). Assume

1. every open in \(X\) has a covering whose members are elements of \(B\),
2. for every \(U \in B\) we have \(H^p(U, \mathcal{H}^q) = 0\) for \(p > d\) and \(q < d^\square\)

Then \(\mathcal{H}^m\) is a quasi-isomorphism.

---

\(^4\)It suffices if \(\forall m, \exists p(m), H^p(U, \mathcal{H}^{m-p}) = 0\) for \(p > p(m)\), see Lemma 34.8
Proof. By Derived Categories, Lemma [34.4] it suffices to show that the canonical map \( F^\bullet \to R\lim_{n \to -\infty} F^\bullet \) is an isomorphism. This is Lemma [34.9].

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.

**Lemma 35.2.** Let \((X, \mathcal{O}_X)\) be a ringed space. Let \((F^n)\) be an inverse system of complexes of \(\mathcal{O}_X\)-modules. Let \(m \in \mathbb{Z}\). 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 \(F_n^{m-2}(U)\) and \(F_n^{m-1}(U)\) have vanishing \(R^1\lim\) (for example these have the Mittag-Leffler condition),
   b. the system of abelian groups \(H^{m-1}(F_n^\bullet(U))\) has vanishing \(R^1\lim\) (for example it has the Mittag-Leffler condition), and
   c. we have \(H^m(F_n^\bullet(U)) = H^m(F_{n_0}^\bullet(U))\) for all \(n \geq n_0\).

Then the maps \(H^m(F^\bullet) \to \lim_n H^m(F_n^\bullet) \to H^m(F_{n_0}^\bullet)\) are isomorphisms of sheaves where \(F^\bullet = \lim_n F_n^\bullet\) is the termwise inverse limit.

**Proof.** Let \(U \in \mathcal{B}\). Note that \(H^m(F^\bullet(U))\) is the cohomology of

\[
\lim_n F_n^{m-2}(U) \to \lim_n F_n^{m-1}(U) \to \lim_n F_n^m(U) \to \lim_n F_n^{m+1}(U)
\]

in the third spot from the left. By assumptions (2)(a) and (2)(b) we may apply More on Algebra, Lemma 79.2 to conclude that

\[
H^m(F^\bullet(U)) = \lim_n H^m(F_n^\bullet(U))
\]

By assumption (2)(c) we conclude

\[
H^m(F^\bullet(U)) = H^m(F_{n_0}^\bullet(U))
\]

for all \(n \geq n_0\). By assumption (1) we conclude that the sheafification of \(U \mapsto H^m(F^\bullet(U))\) is equal to the sheafification of \(U \mapsto H^m(F_{n_0}^\bullet(U))\) for all \(n \geq n_0\). Thus the inverse system of sheaves \(H^m(F_n^\bullet)\) is constant for \(n \geq n_0\) with value \(H^m(F^\bullet)\) which proves the lemma.

36. Čech cohomology of unbounded complexes

The construction of Section 25 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 \(F^\bullet\) 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 \(\check{C}_{alt}^\bullet(\mathcal{U}, F)\) (Section 23) is functorial in the presheaf \(F\) we obtain a double complex \(\check{C}_{alt}^\bullet(\mathcal{U}, F^\bullet)\). In this section we work with the associated total complex. The construction of \(\text{Tot}(\check{C}_{alt}^\bullet(\mathcal{U}, F^\bullet))\) is functorial in \(F^\bullet\). As well there is a functorial transformation

\[
\Gamma(X, F^\bullet) \to \text{Tot}(\check{C}_{alt}^\bullet(\mathcal{U}, F^\bullet))
\]
of complexes defined by the following rule: The section \( s \in \Gamma(X, \mathcal{F}^n) \) is mapped to the element \( \alpha = \{ \alpha_{i_0 \ldots i_p} \} \) with \( \alpha_{i_0} = s|_{U_{i_0}} \) and \( \alpha_{i_0 \ldots i_p} = 0 \) for \( p > 0 \).

**Lemma 36.1.** 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

\[
\text{Tot}(\check{\mathcal{C}}^\bullet_{\text{alt}}(\mathcal{U}, \mathcal{F}^\bullet)) \rightarrow R\Gamma(X, \mathcal{F}^\bullet)
\]

functorial in \( \mathcal{F}^\bullet \) and compatible with \([36.0.1]\).

**Proof.** Let \( \mathcal{I}^\bullet \) be a K-injective complex whose terms are injective \( \mathcal{O}_X \)-modules. The map \((36.0.1)\) for \( \mathcal{I}^\bullet \) is a map \( \Gamma(X, \mathcal{I}^\bullet) \rightarrow \text{Tot}(\check{\mathcal{C}}^\bullet_{\text{alt}}(\mathcal{U}, \mathcal{I}^\bullet)) \). This is a quasi-isomorphism of complexes of abelian groups as follows from Homology, Lemma \([25.4]\). 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

\[
\text{Tot}(\check{\mathcal{C}}^\bullet_{\text{alt}}(\mathcal{U}, \mathcal{F}^\bullet)) \rightarrow \text{Tot}(\check{\mathcal{C}}^\bullet_{\text{alt}}(\mathcal{U}, \mathcal{I}^\bullet)).
\]

We omit the verification of functoriality and compatibilities. \( \square \)

**Lemma 36.2.** 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 \( U_{i_0 \ldots i_p} \in \mathcal{B} \) for all \( i_0, \ldots, i_p \in I \),
3. for every \( U \in \mathcal{B} \) and \( p > 0 \) we have
   a. \( H^p(U, \mathcal{F}^q) = 0 \),
   b. \( H^p(U, \text{Coker}(\mathcal{F}^r \rightarrow \mathcal{F}^{r-1})) = 0 \), and
   c. \( H^p(U, H^q(\mathcal{F})) = 0 \).

Then the map

\[
\text{Tot}(\check{\mathcal{C}}^\bullet_{\text{alt}}(\mathcal{U}, \mathcal{F}^\bullet)) \rightarrow R\Gamma(X, \mathcal{F}^\bullet)
\]

of Lemma \([36.1]\) is an isomorphism in \( D(\text{Ab}) \).

**Proof.** First assume \( \mathcal{F}^\bullet \) is bounded below. In this case the map

\[
\text{Tot}(\check{\mathcal{C}}^\bullet_{\text{alt}}(\mathcal{U}, \mathcal{F}^\bullet)) \rightarrow \text{Tot}(\check{\mathcal{C}}^\bullet_{\text{alt}}(\mathcal{U}, \mathcal{F}^\bullet))
\]

is a quasi-isomorphism by Lemma \([23.6]\). Namely, the map of double complexes \( \check{\mathcal{C}}^\bullet_{\text{alt}}(\mathcal{U}, \mathcal{F}^\bullet) \rightarrow \check{\mathcal{C}}^\bullet(\mathcal{U}, \mathcal{F}^\bullet) \) induces an isomorphism between the first pages of the second spectral sequences associated to these complexes (by Homology, Lemma \([25.1]\) and these spectral sequences converge (Homology, Lemma \([25.3]\)). Thus the conclusion in this case by Lemma \([25.2]\) and assumption (3)(a).

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 \([35.1]\). Then the map of the lemma becomes

\[
\lim_n \text{Tot}(\check{\mathcal{C}}^\bullet_{\text{alt}}(\mathcal{U}, \tau_{\geq -n} \mathcal{F}^\bullet)) \rightarrow \Gamma(X, \mathcal{I}^\bullet) = \lim_n \Gamma(X, \mathcal{I}_n^\bullet)
\]

Here the arrow is in the derived category, but the equality on the right holds on the level of complexes. 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

\[
\text{Tot}(\check{\mathcal{C}}^\bullet_{\text{alt}}(\mathcal{U}, \tau_{\geq -n} \mathcal{F}^\bullet)) \rightarrow \Gamma(X, \mathcal{I}_n^\bullet)
\]
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 31.7 (or the stronger More on Algebra, Lemma 79.2) and we win.

\[\square\]

### 37. Hom complexes

0A8K Let \((X, \mathcal{O}_X)\) be a ringed space. Let \(L^•\) and \(M^•\) be two complexes of \(\mathcal{O}_X\)-modules. We construct a complex of \(\mathcal{O}_X\)-modules \(\text{Hom}^•(L^•, M^•)\). Namely, for each \(n\) we set

\[\text{Hom}^n(L^•, M^•) = \prod_{p+q=n} \text{Hom}_{\mathcal{O}_X}(L^{-q}, M^p)\]

It is a good idea to think of \(\text{Hom}^n\) as the sheaf of \(\mathcal{O}_X\)-modules of all \(\mathcal{O}_X\)-linear maps from \(L^•\) to \(M^•\) (viewed as graded \(\mathcal{O}_X\)-modules) which are homogenous of degree \(n\). In this terminology, we define the differential by the rule

\[d(f) = d_M \circ f - (-1)^n f \circ d_L\]

for \(f \in \text{Hom}^n_{\mathcal{O}_X}(L^•, M^•)\). We omit the verification that \(d^2 = 0\). This construction is a special case of Differential Graded Algebra, Example 26.6. It follows immediately from the construction that we have

\[0A8L \quad (37.0.1) \quad H^n(\Gamma(U, \text{Hom}^•(L^•, M^•))) = \text{Hom}_K(\mathcal{O}_U)(L^•, M^•[n])\]

for all \(n \in \mathbb{Z}\) and every open \(U \subset X\).

0A8M **Lemma 37.1.** Let \((X, \mathcal{O}_X)\) be a ringed space. Given complexes \(K^•, L^•, M^•\) of \(\mathcal{O}_X\)-modules there is an isomorphism

\[\text{Hom}^•(K^•, \text{Hom}^•(L^•, M^•)) = \text{Hom}^•(\text{Tot}(K^• \otimes_{\mathcal{O}_X} L^•), M^•)\]

of complexes of \(\mathcal{O}_X\)-modules functorial in \(K^•, L^•, M^•\).

**Proof.** Omitted. Hint: This is proved in exactly the same way as More on Algebra, Lemma 67.1. \(\square\)

0A8N **Lemma 37.2.** Let \((X, \mathcal{O}_X)\) be a ringed space. Given complexes \(K^•, L^•, M^•\) of \(\mathcal{O}_X\)-modules there is a canonical morphism

\[\text{Tot}(\text{Hom}^•(L^•, M^•) \otimes_{\mathcal{O}_X} \text{Hom}^•(K^•, L^•)) \to \text{Hom}^•(K^•, M^•)\]

of complexes of \(\mathcal{O}_X\)-modules.

**Proof.** Omitted. Hint: This is proved in exactly the same way as More on Algebra, Lemma 67.2. \(\square\)

0BYR **Lemma 37.3.** Let \((X, \mathcal{O}_X)\) be a ringed space. Given complexes \(K^•, L^•, M^•\) of \(\mathcal{O}_X\)-modules there is a canonical morphism

\[\text{Tot}(K^• \otimes_{\mathcal{O}_X} \text{Hom}^•(M^•, L^•)) \to \text{Hom}^•(M^•, \text{Tot}(K^• \otimes_{\mathcal{O}_X} L^•))\]

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 67.3. \(\square\)
Lemma 37.4. Let $(X, \mathcal{O}_X)$ be a ringed space. Given complexes $K^\bullet, L^\bullet$ of $\mathcal{O}_X$-modules there is a canonical morphism

$$K^\bullet \longrightarrow \text{Hom}^\bullet(L^\bullet, \text{Tot}(K^\bullet \otimes_{\mathcal{O}_X} L^\bullet))$$

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 67.4.

Lemma 37.5. Let $(X, \mathcal{O}_X)$ be a ringed space. Given complexes $K^\bullet, L^\bullet, M^\bullet$ of $\mathcal{O}_X$-modules there is a canonical morphism

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

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 67.5.

Lemma 37.6. Let $(X, \mathcal{O}_X)$ be a ringed space. Let $I^\bullet$ be a K-injective complex of $\mathcal{O}_X$-modules. Let $L^\bullet$ be a complex of $\mathcal{O}_X$-modules. Then

$$H^0(\Gamma(U, \text{Hom}^\bullet(L^\bullet, I^\bullet))) = \text{Hom}_{D(\mathcal{O}_U)}(L|_U, M|_U)$$

for all $U \subset X$ open.

Proof. We have

$$H^0(\Gamma(U, \text{Hom}^\bullet(L^\bullet, I^\bullet))) = \text{Hom}_{K(\mathcal{O}_U)}(L|_U, M|_U) = \text{Hom}_{D(\mathcal{O}_U)}(L|_U, M|_U)$$

The first equality is (37.0.1). The second equality is true because $I^\bullet|_U$ is K-injective by Lemma 32.1.

Lemma 37.7. 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

$$\text{Hom}^\bullet((\mathcal{L}'^\bullet), (\mathcal{I}^\bullet)) \longrightarrow \text{Hom}^\bullet((\mathcal{L}^\bullet), (\mathcal{I}^\bullet))$$

is a quasi-isomorphism.

Proof. Let $M$ be the object of $D(\mathcal{O}_X)$ represented by $\mathcal{L}^\bullet$ and $(\mathcal{I}^\bullet)$. Let $L$ be the object of $D(\mathcal{O}_X)$ represented by $\mathcal{L}'^\bullet$ and $(\mathcal{I}^\bullet)^\bullet$. By Lemma 37.6 we see that the sheaves

$$H^0(\text{Hom}^\bullet((\mathcal{L}'^\bullet), (\mathcal{I}^\bullet))) \quad \text{and} \quad H^0(\text{Hom}^\bullet((\mathcal{L}^\bullet), (\mathcal{I}^\bullet)))$$

are both equal to the sheaf associated to the presheaf

$$U \mapsto \text{Hom}_{D(\mathcal{O}_U)}(L|_U, M|_U)$$

Thus the map is a quasi-isomorphism.

Lemma 37.8. 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 $\text{Hom}^\bullet((\mathcal{L}^\bullet), (\mathcal{I}^\bullet))$ 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
\[
\text{Hom}_{K(\mathcal{O}_X)}(\mathcal{K}^\bullet, \text{Hom}^\bullet(\mathcal{L}^\bullet, \mathcal{I}^\bullet)) = H^0(\Gamma(X, \text{Hom}^\bullet(\mathcal{K}^\bullet, \text{Hom}^\bullet(\mathcal{L}^\bullet, \mathcal{I}^\bullet)))) = H^0(\Gamma(X, \text{Hom}^\bullet(\text{Tot}(\mathcal{K}^\bullet \otimes_{\mathcal{O}_X} \mathcal{L}^\bullet), \mathcal{I}^\bullet))) = \text{Hom}_{K(\mathcal{O}_X)}(\text{Tot}(\mathcal{K}^\bullet \otimes_{\mathcal{O}_X} \mathcal{L}^\bullet), \mathcal{I}^\bullet) = 0
\]
The first equality by (37.0.1). The second equality by Lemma 37.1. The third equality because $\text{Tot}(\mathcal{K}^\bullet \otimes_{\mathcal{O}_X} \mathcal{L}^\bullet)$ is acyclic because $\mathcal{L}^\bullet$ is K-flat (Definition 26.2) and because $\mathcal{I}^\bullet$ is K-injective. \qed

38. Internal hom in the derived category

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
\[
\text{Hom}_{D(\mathcal{O}_X)}(K, R\mathcal{H}om(L, M)) = \text{Hom}_{D(\mathcal{O}_X)}(K \otimes^L_{\mathcal{O}_X} L, M)
\]
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
\[
R\mathcal{H}om(L, M) = \text{Hom}^\bullet(\mathcal{L}^\bullet, \mathcal{I}^\bullet)
\]
where the right hand side is the complex of $\mathcal{O}_X$-modules constructed in Section 37.

This is well defined by Lemma 37.7. We get a functor
\[
D(\mathcal{O}_X)^{opp} \times D(\mathcal{O}_X) \rightarrow D(\mathcal{O}_X), \quad (K, L) \mapsto R\mathcal{H}om(K, L)
\]
As a prelude to proving (38.0.1) we compute the cohomology groups of $R\mathcal{H}om(K, L)$.

Lemma 38.1. 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-flat complex $\mathcal{I}^\bullet$ of $\mathcal{O}_X$-modules representing $M$ and a K-flat complex $\mathcal{L}^\bullet$ representing $L$. Then $\text{Hom}^\bullet(\mathcal{L}^\bullet, \mathcal{I}^\bullet)$ is K-injective by Lemma 37.8.

Hence we can compute cohomology over $U$ by simply taking sections over $U$ and the result follows from Lemma 37.6. \qed

Lemma 38.2. 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
\[
R\mathcal{H}om(K, R\mathcal{H}om(L, M)) = R\mathcal{H}om(K \otimes^L_{\mathcal{O}_X} L, M)
\]
in $D(\mathcal{O}_X)$ functorial in $K, L, M$ which recovers (38.0.1) 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
\[
\text{Hom}^\bullet(\mathcal{K}^\bullet, \text{Hom}^\bullet(\mathcal{L}^\bullet, \mathcal{I}^\bullet)) = \text{Hom}^\bullet(\text{Tot}(\mathcal{K}^\bullet \otimes_{\mathcal{O}_X} \mathcal{L}^\bullet), \mathcal{I}^\bullet)
\]
by Lemma 37.1. Note that the left hand side represents $R\mathcal{H}om(K, R\mathcal{H}om(L, M))$
(use Lemma 37.8) and that the right hand side represents $R\mathcal{H}om(K \otimes^L_{\mathcal{O}_X} L, M)$. This proves the displayed formula of the lemma. Taking global sections and using Lemma 38.1, we obtain (38.0.1).

**Lemma 38.3.** 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 32.1.

**Lemma 38.4.** Let $(X, \mathcal{O}_X)$ be a ringed space. The bifunctor $R\mathcal{H}om(\cdot, \cdot)$ transforms distinguished triangles into distinguished triangles in both variables.

**Proof.** This follows from the observation that the assignment

$$(L^\bullet, M^\bullet) \mapsto \mathcal{H}om^*(L^\bullet, M^\bullet)$$

transforms a termwise split short exact sequences of complexes in either variable into a termwise split short exact sequence. Details omitted.

**Lemma 38.5.** Let $(X, \mathcal{O}_X)$ be a ringed space. Given $K, L, M$ in $D(\mathcal{O}_X)$ there is a canonical morphism

$$R\mathcal{H}om(L, M) \otimes^L_{\mathcal{O}_X} R\mathcal{H}om(K, L) \rightarrow R\mathcal{H}om(K, M)$$

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 37.2 there is a map of complexes

$$\text{Tot}(\mathcal{H}om^*(\mathcal{J}^\bullet, \mathcal{I}^\bullet) \otimes_{\mathcal{O}_X} \mathcal{H}om^*(\mathcal{K}^\bullet, \mathcal{J}^\bullet)) \rightarrow \mathcal{H}om^*(\mathcal{K}^\bullet, \mathcal{I}^\bullet)$$

The complexes of $\mathcal{O}_X$-modules $\mathcal{H}om^*(\mathcal{J}^\bullet, \mathcal{I}^\bullet)$, $\mathcal{H}om^*(\mathcal{K}^\bullet, \mathcal{J}^\bullet)$, and $\mathcal{H}om^*(\mathcal{K}^\bullet, \mathcal{I}^\bullet)$ 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 $\mathcal{H}^\bullet \rightarrow \mathcal{H}om^*(\mathcal{K}^\bullet, \mathcal{J}^\bullet)$, then there is a map

$$\text{Tot}(\mathcal{H}om^*(\mathcal{J}^\bullet, \mathcal{I}^\bullet) \otimes_{\mathcal{O}_X} \mathcal{H}^\bullet) \rightarrow \text{Tot}(\mathcal{H}om^*(\mathcal{J}^\bullet, \mathcal{I}^\bullet) \otimes_{\mathcal{O}_X} \mathcal{H}om^*(\mathcal{K}^\bullet, \mathcal{J}^\bullet))$$

whose source represents $R\mathcal{H}om(L, M) \otimes^L_{\mathcal{O}_X} R\mathcal{H}om(K, L)$. Composing the two displayed arrows gives the desired map. We omit the proof that the construction is functorial.

**Lemma 38.6.** Let $(X, \mathcal{O}_X)$ be a ringed space. Given $K, L, M$ in $D(\mathcal{O}_X)$ there is a canonical morphism

$$K \otimes^L_{\mathcal{O}_X} R\mathcal{H}om(M, L) \rightarrow R\mathcal{H}om(M, K \otimes^L_{\mathcal{O}_X} L)$$

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 $\text{Tot}(\mathcal{K}^\bullet \otimes_{\mathcal{O}_X} \mathcal{I}^\bullet) \rightarrow \mathcal{J}^\bullet$ where $\mathcal{J}^\bullet$ is $K$-injective. Then we use the map

$$\text{Tot}(\mathcal{K}^\bullet \otimes_{\mathcal{O}_X} \mathcal{H}om^*(\mathcal{M}^\bullet, \mathcal{I}^\bullet)) \rightarrow \mathcal{H}om^*(\mathcal{M}^\bullet, \text{Tot}(\mathcal{K}^\bullet \otimes_{\mathcal{O}_X} \mathcal{I}^\bullet)) \rightarrow \mathcal{H}om^*(\mathcal{M}^\bullet, \mathcal{J}^\bullet)$$

where the first map is the map from Lemma 37.3.
Lemma 38.7. Let \((X, \mathcal{O}_X)\) be a ringed space. Given \(K, L\) in \(D(\mathcal{O}_X)\) there is a canonical morphism

\[
K \to R \mathcal{H}om(L, K \otimes^L_{\mathcal{O}_X} L)
\]

in \(D(\mathcal{O}_X)\) functorial in both \(K\) and \(L\).

**Proof.** Choose a K-flat complex \(K^\bullet\) representing \(K\) and any complex of \(\mathcal{O}_X\)-modules \(L^\bullet\) representing \(L\). Choose a K-injective complex \(J^\bullet\) and a quasi-isomorphism \(\text{Tot}(K^\bullet \otimes_{\mathcal{O}_X} L^\bullet) \to J^\bullet\). Then we use

\[
K^\bullet \to \mathcal{H}om^\bullet(L^\bullet, \text{Tot}(K^\bullet \otimes_{\mathcal{O}_X} L^\bullet)) \to \mathcal{H}om^\bullet(L^\bullet, J^\bullet)
\]

where the first map comes from Lemma 38.4.

Lemma 38.8. 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

\[
M \otimes^L_{\mathcal{O}_X} L^\vee \to R \mathcal{H}om(L, M)
\]

which induces a canonical map

\[
H^0(X, M \otimes^L_{\mathcal{O}_X} L^\vee) \to \mathcal{H}om_{D(\mathcal{O}_X)}(L, M)
\]

functorial in \(M\) in \(D(\mathcal{O}_X)\).

**Proof.** The map (38.8.1) is a special case of Lemma 38.5 using the identification \(M = R \mathcal{H}om(\mathcal{O}_X, M)\).

Lemma 38.9. 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

\[
R \mathcal{H}om(L, M) \otimes^L_{\mathcal{O}_X} K \to R \mathcal{H}om(R \mathcal{H}om(K, L), M)
\]

in \(D(\mathcal{O}_X)\) functorial in \(K, L, M\).

**Proof.** Choose a K-injective complex \(I^\bullet\) representing \(M\), a K-injective complex \(J^\bullet\) representing \(L\), and a K-flat complex \(K^\bullet\) representing \(K\). The map is defined using the map

\[
\text{Tot}(\mathcal{H}om^\bullet(J^\bullet, I^\bullet) \otimes_{\mathcal{O}_X} K^\bullet) \to \mathcal{H}om^\bullet(\mathcal{H}om^\bullet(K^\bullet, J^\bullet), I^\bullet)
\]

of Lemma 38.5. By our particular choice of complexes the left hand side represents \(R \mathcal{H}om(L, M) \otimes^L_{\mathcal{O}_X} K\) 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 \(D(\mathcal{O}_X)\).

Remark 38.10. Let \(f : X \to Y\) be a morphism of ringed spaces. Let \(K, L\) be objects of \(D(\mathcal{O}_X)\). We claim there is a canonical map

\[
Rf_* R \mathcal{H}om(L, K) \to R \mathcal{H}om(Rf_* L, Rf_* K)
\]

Namely, by (38.0.1) this is the same thing as a map \(Rf_* R \mathcal{H}om(L, K) \otimes^L_{\mathcal{O}_Y} Rf_* L \to Rf_* K\). For this we can use the composition

\[
Rf_* R \mathcal{H}om(L, K) \otimes^L_{\mathcal{O}_Y} Rf_* L \to Rf_* (R \mathcal{H}om(L, K) \otimes^L_{\mathcal{O}_X} L) \to Rf_* K
\]

where the first arrow is the relative cup product (Remark 28.7) and the second arrow is \(Rf_*\) applied to the canonical map \(R \mathcal{H}om(L, K) \otimes^L_{\mathcal{O}_X} L \to K\) coming from Lemma 38.5 (with \(\mathcal{O}_X\) in one of the spots).
Remark 38.11. Let \( h : X \to Y \) be a morphism of ringed spaces. Let \( K, L \) be objects of \( D(O_Y) \). We claim there is a canonical map

\[
Lh^* R\mathcal{H}om(K, L) \longrightarrow R\mathcal{H}om(Lh^* K, Lh^* L)
\]

in \( D(O_X) \). Namely, by (38.0.1) proved in Lemma 38.2 such a map is the same thing as a map

\[
Lh^* R\mathcal{H}om(K, L) \otimes^L Lh^* K \longrightarrow Lh^* L
\]

The source of this arrow is \( Lh^*(\mathcal{H}om(K, L) \otimes^L K) \) by Lemma 27.3 hence it suffices to construct a canonical map

\[
R\mathcal{H}om(K, L) \otimes^L K \longrightarrow L.
\]

For this we take the arrow corresponding to \( \text{id} : R\mathcal{H}om(K, L) \to R\mathcal{H}om(K, L) \) via (38.0.1).

Remark 38.12. Suppose that

\[
\begin{array}{ccc}
X' & \longrightarrow & X \\
\downarrow^f & & \downarrow^f \\
S' & \longrightarrow & S
\end{array}
\]

is a commutative diagram of ringed spaces. Let \( K, L \) be objects of \( D(O_X) \). 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 \( D(O_{S'}) \). Namely, we take the map adjoint to the composition

\[
L(f')^* Lg^* Rf_* R\mathcal{H}om(K, L) = Lh^* Lf^* Rf_* R\mathcal{H}om(K, L)
\]

\[
\longrightarrow Lh^* R\mathcal{H}om(K, L)
\]

\[
\longrightarrow R\mathcal{H}om(Lh^* K, Lh^* L)
\]

where the first arrow uses the adjunction mapping \( Lf^* Rf_* \to \text{id} \) and the second arrow is the canonical map constructed in Remark 38.11.

39. Ext sheaves

Let \((X, O_X)\) be a ringed space. Let \( K, L \in D(O_X) \). Using the construction of the internal hom in the derived category we obtain a well defined sheaves of \( O_X \)-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 \( D(O_X) \). We will sometimes write \( \mathcal{E}xt^n_{O_X}(K, L) \) for this object. By Lemma 38.1 we see that this \( \mathcal{E}xt^n \)-sheaf is the sheafification of the rule

\[
U \longmapsto \mathcal{E}xt^n_{D(O_U)}(K|_U, L|_U)
\]

By Example 29.3 there is always a spectral sequence

\[
E_2^{p,q} = H^p(X, \mathcal{E}xt^q(K, L))
\]

converging to \( \mathcal{E}xt^{p+q}_{D(O_X)}(K, L) \) in favorable situations (for example if \( L \) is bounded below and \( K \) is bounded above).
40. Global derived hom

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

\[ R\text{Hom}_X(K, L) = R\Gamma(X, R\text{Hom}(K, L)) \]

in \(D(\Gamma(X, \mathcal{O}_X))\). We will sometimes write \(R\text{Hom}_{\mathcal{O}_X}(K, L)\) for this object. By Lemma 38.1 we have

\[ H^p(R\text{Hom}_X(K, L)) = \text{Hom}_{D(\mathcal{O}_X)}(K, L), \quad H^p(R\text{Hom}_X(K, L)) = \text{Ext}^p_{D(\mathcal{O}_X)}(K, L) \]

If \(f : Y \to X\) is a morphism of ringed spaces, then there is a canonical map

\[ R\text{Hom}_X(K, L) \to R\text{Hom}_Y(Lf^*K, Lf^*L) \]

in \(D(\Gamma(X, \mathcal{O}_X))\) by taking global sections of the map defined in Remark 38.1.

41. Glueing complexes

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.

**Lemma 41.1.** 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 \(c : A|_{U \cap V} \to B|_{U \cap V}\).

Then there exists an object \(F\) of \(D(\mathcal{O}_X)\) and isomorphisms \(f : F|_U \to A, g : F|_V \to B\) 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 \(a : A \to E|_U\) of \(D(\mathcal{O}_U)\),
3. a morphism \(b : B \to E|_V\) of \(D(\mathcal{O}_V)\),

such that

\[ a|_{U \cap V} = b|_{U \cap V} \circ c. \]

Then there exists a morphism \(F \to E\) 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

\[ F \to Rj_{U,*}A \oplus Rj_{V,*}B \to Rj_{U \cap V,*}(B|_{U \cap V}) \to F[1] \]

where the map \(Rj_{V,*}B \to Rj_{U \cap V,*}(B|_{U \cap V})\) is the obvious one and where \(Rj_{U,*}A \to Rj_{U \cap V,*}(A|_{U \cap V})\) is the composition of \(Rj_{U,*}A \to Rj_{U \cap V,*}(A|_{U \cap V})\) with \(Rj_{U \cap V,*}c\). Restricting to \(U\) we obtain

\[ F|_U \to A \oplus (Rj_{V,*}B)|_U \to (Rj_{U \cap V,*}(B|_{U \cap V}))|_U \to F|_U[1] \]

Denote \(j : U \cap V \to U\). 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 \(F|_U \to A\) is an isomorphism. Similarly, the
Let \( F|_V \to B \) is an isomorphism. The existence of the morphism \( F \to E \) follows from the Mayer-Vietoris sequence for \( \text{Hom} \), see Lemma 33.3.

**Lemma 41.2.** Let \( f : (X, \mathcal{O}_X) \to (Y, \mathcal{O}_Y) \) 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 \( V \mapsto H^i(f^{-1}V, K) \) 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 32.6 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 \( R\text{Hom}(K, L) \) using Lemma 38.1 to do the translation.

**Situation 41.3.** 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 \( D(\mathcal{O}_X) \),
3. for \( V \subset U \) with \( V, U \in \mathcal{B} \) an isomorphism \( \rho^U_V : K_U|_V \to K_V \) in \( D(\mathcal{O}_V) \), such that whenever we have \( W \subset V \subset U \) with \( U, V, W \in \mathcal{B} \), then \( \rho^U_W = \rho^W_V \circ \rho^U_V|_W \).

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 \( f : X \to Y \) 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 41.3 a solution will be a pair \((K, \rho_U)\) where \( K \) is an object of \( D(\mathcal{O}_X) \) and \( \rho_U : K|_U \to K_U \), \( U \in \mathcal{B} \) are isomorphisms such that we have \( \rho^U_V \circ \rho^U_V|_V = \rho_V \) for all \( V \subset U \), \( U, V \in \mathcal{B} \). In certain cases solutions are unique.

**Lemma 41.4.** In Situation 41.3 assume

1. \( X = \bigcup_{U \in \mathcal{B}} U \) and for \( U, V \in \mathcal{B} \) we have \( U \cap V = \bigcup_{W \in \mathcal{B}, W \subset U \cap V} W \),
2. for any \( U \in \mathcal{B} \) we have \( \text{Ext}^i(K_U, K_U) = 0 \) for \( i < 0 \).

If a solution \((K, \rho_U)\) exists, then it is unique up to unique isomorphism and moreover \( \text{Ext}^i(K, K) = 0 \) for \( i < 0 \).

**Proof.** Let \((K, \rho_U)\) and \((K', \rho'_U)\) be a pair of solutions. Let \( f : X \to Y \) 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 41.2 part (2). Hence we obtain the vanishing of negative exts for \( K \) and we see that the rule

\[ V \mapsto \text{Hom}(K|_{f^{-1}V}, K'|_{f^{-1}V}) \]

is a sheaf on \( Y \). As both \((K, \rho_U)\) and \((K', \rho'_U)\) are solutions the maps

\[ (\rho'_U)^{-1} \circ \rho_U : K|_U \to K'|_U \]
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 $K \to K'$ compatible with all structure available.

**Remark 41.5.** With notation and assumptions as in Lemma 41.4. Suppose that $U, V \in \mathcal{B}$. Let $\mathcal{B}'$ be the set of elements of $\mathcal{B}$ contained in $U \cap V$. Then

$$(\{K_U\}_U \in \mathcal{B}', \{\rho_U^V\}_V \subset U \text{ with } U, V \in \mathcal{B}')$$

is a system on the ringed space $U \cap V$ satisfying the assumptions of Lemma 41.4 Moreover, both $(K_U|_{U \cap V}, \rho_U^V)$ and $(K_V|_{U \cap V}, \rho_V^U)$ are solutions to this system. By the lemma we find a unique isomorphism

$$\rho_{U,V} : K_U|_{U \cap V} \to K_V|_{U \cap V}$$

such that for every $U' \subset U \cap V$, $U' \in \mathcal{B}$ the diagram

$$
\begin{array}{ccc}
K_U|_{U'} & \xrightarrow{\rho_{U,V}|_{U'}} & K_V|_{U'} \\
\rho_{U'}^V & & \rho_{V'}^U \\
K_{U'} & & K_{U'}
\end{array}
$$

commutes. Pick a third element $W \in \mathcal{B}$. We obtain isomorphisms $\rho_{U,W} : K_U|_{U \cap W} \to K_W|_{U \cap W}$ and $\rho_{V,W} : K_V|_{U \cap W} \to K_W|_{U \cap W}$ satisfying similar properties to those of $\rho_{U,V}$. Finally, we have

$$\rho_{U,W}|_{U \cap W \cap V} = \rho_{V,W}|_{U \cap W \cap V} \circ \rho_{U,V}|_{U \cap W \cap V}$$

This is true by the uniqueness in the lemma because both sides of the equality are the unique isomorphism compatible with the maps $\rho_{U''}^V$ and $\rho_{W''}^{U''}$ 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 $U : X = \bigcup_{U \in \mathcal{B}} U$ of $X$. In this language we are looking for “effectiveness of the descent datum” when we look for the existence of a solution.

**Lemma 41.6.** In Situation 41.3 assume

1. $X = U_1 \cup \ldots \cup U_n$ 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 41.4. We may prove the lemma by induction on $n$. The case $n = 1$ is immediate.

The case $n = 2$. Consider the isomorphism $\rho_{U_1,U_2} : K_{U_1}|_{U_1 \cup U_2} \to K_{U_2}|_{U_1 \cup U_2}$ constructed in Remark 41.5. By Lemma 41.1 we obtain an object $K$ in $D(\mathcal{O}_X)$ and isomorphisms $\rho_{U_1} : K|_{U_1} \to K_{U_1}$ and $\rho_{U_2} : K|_{U_2} \to K_{U_2}$ compatible with $\rho_{U_1,U_2}$. Take $U \in \mathcal{B}$. We will construct an isomorphism $\rho_U : K|_U \to K_{U}$ and we will leave it to the reader to verify that $(K, \rho_U)$ 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 $(K_U, \rho_U^V)$ is a solution for the system $(\{K_U\}_U \in \mathcal{B}', \{\rho_U^V\}_V \subset U \text{ with } U, V \in \mathcal{B}')$ 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

$$K|_{U'} \xrightarrow{\rho_{U_1}|_{U'}} K_{U_1}|_{U'} \xrightarrow{\rho_{U_1}^U} K_{U}$$
and if \( U' \subset U_2 \) then we take the composition

\[
K|_{U'} \xrightarrow{\rho_{U_2|U'}} K|_{U_2} \xrightarrow{\rho_{U_2|U'}} K_{U'}.
\]

To verify this is a solution use the property of the map \( \rho_{U_1, U_2} \) described in Remark 41.3 and the compatibility of \( \rho_{U_1} \) and \( \rho_{U_2} \) with \( \rho_{U_1, U_2} \). Having said this we apply Lemma 41.4 to see that we obtain a unique isomorphism \( K|_{U'} \to K_{U'} \) compatible with the maps \( \tau_{U'} \) and \( \rho_{U}' \), for \( U' \in \mathcal{B}' \).

The case \( n > 2 \). Consider the open subspace \( X' = U_1 \cup \ldots \cup U_{n-1} \) and let \( \mathcal{B}' \) be the set of elements of \( \mathcal{B} \) contained in \( X' \). Then we find a system \( (\{ K_U \}_{U \in \mathcal{B}'}, \{ \rho_{U}^{(i)} \}_{U, V \in \mathcal{B}'} \) on the ringed space \( X' \) to which we may apply our induction hypothesis. We find a solution \( (K_X', \rho_X') \). Then we can consider the collection \( \mathcal{B}' = \mathcal{B} \cup \{ X' \} \) of opens of \( X \) and we see that we obtain a system \( (\{ K_U \}_{U \in \mathcal{B}'}, \{ \rho_{U}^{(i)} \}_{U, V \in \mathcal{B}'} \) with \( U, V \in \mathcal{B}' \). Note that this new system also satisfies condition (3) by Lemma 41.4 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.

**Lemma 41.7.** 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 \( \alpha \) is not a successor.

Let \( K_\alpha \) be an object of \( D(O_{W_\alpha}) \) with \( \operatorname{Ext}^i(K_\alpha, K_\alpha) = 0 \) for \( i < 0 \). Assume given isomorphisms \( \rho^{(i)}_\beta : K_\beta|_{W_\alpha} \to K_\beta \) in \( D(O_{W_\alpha}) \) for all \( \beta < \alpha \) with \( \rho^{(i)}_\gamma = \rho^{(i)}_\beta \circ \rho^{(i)}_\beta \) for \( \gamma < \beta < \alpha \). Then there exists an object \( K \in D(O_X) \) and isomorphisms \( K|_{W_\alpha} \to K_\alpha \) for \( \alpha \in E \) compatible with the isomorphisms \( \rho^{(i)}_\beta \).

**Proof.** In this proof \( \alpha, \beta, \gamma, \ldots \) represent elements of \( E \). Choose a K-injective complex \( I_\bullet \) on \( W_\alpha \) representing \( K_\alpha \). For \( \beta < \alpha \) denote \( j_{\beta, \alpha} : W_\beta \to W_\alpha \) the inclusion morphism. By transfinite induction, we will construct for all \( \beta < \alpha \) a map of complexes

\[
\tau_{\beta, \alpha} : (j_{\beta, \alpha})! I_\beta^\bullet \to I_\alpha^\bullet
\]

representing the adjoint to the inverse of the isomorphism \( \rho^{(i)}_\beta : K_\alpha|_{W_\beta} \to K_\beta \). Moreover, we will do this in such a way for \( \gamma < \beta < \alpha \) we have

\[
\tau_{\gamma, \alpha} = \tau_{\beta, \alpha} \circ (j_{\gamma, \alpha})! \tau_{\gamma, \beta}
\]

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

\[
(j_{\alpha', \alpha})! I_{\alpha'}^\bullet \to I_\alpha^\bullet
\]

which is adjoint to the inverse of the isomorphism \( \rho^{(i)}_{\alpha'} : K_\alpha|_{W_{\alpha'}} \to K_{\alpha'} \) (possible because \( I_\alpha^\bullet \) is K-injective) and for any \( \beta < \alpha' \) we set

\[
\tau_{\beta, \alpha} = \tau_{\alpha', \alpha} \circ (j_{\alpha', \alpha})! \tau_{\beta, \alpha'}
\]

If \( \alpha \) is not a successor, then we can consider the complex on \( W_\alpha \) given by

\[
C^\bullet = \text{colim}_{\beta < \alpha} (j_{\beta, \alpha})! I_\beta^\bullet
\]

(terwise 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 \( K_\alpha \). Namely, for \( \beta < \alpha \) the restriction of the coprojection \( (j_{\beta, \alpha})! I_\beta^\bullet \to C^\bullet \) gives a map

\[
\sigma_\beta : I_\beta^\bullet \to C^\bullet|_{W_\beta}
\]
which is a quasi-isomorphism: if $x \in W_\beta$ then looking at stalks we get
\[(C^\bullet)_x = \colim_{\beta' < \alpha} (\mathcal{I}_{\beta'})_x = \colim_{\beta' \leq \beta' < \alpha} (\mathcal{I}_{\beta'})_x \leftarrow (\mathcal{I}_{\beta'})_x\]
which is a quasi-isomorphism. Here we used that taking stalks commutes with colimits, that filtered colimits are exact, and that the maps $(\mathcal{I}_{\beta'})_x \to (\mathcal{I}_{\beta'})_x$ are quasi-isomorphisms for $\beta \leq \beta' < \alpha$. Hence $(C^\bullet, \sigma^{-1}_\beta)$ is a solution to the system $\{(K_{\beta})_{\beta < \alpha}, \{\rho'^\beta_{\beta'}\}_{\beta' < \beta < \alpha}\}$. Since $(K_\alpha, \rho'_\alpha)$ is another solution we obtain a unique isomorphism $\sigma: K_\alpha \to C^\bullet$ in $D(\mathcal{O}_{W_\alpha})$ compatible with all our maps, see Lemma 41.6 (this is where we use the vanishing of negative ext groups). Choose a morphism $\tau: C^\bullet \to I^\bullet_\alpha$ of complexes representing $\sigma$. 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
\[K^\bullet = \colim_{\alpha \in E} (W_\alpha \to X)\mathcal{I}^\bullet_\alpha\]
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 $\alpha$ the restriction of the coprojection determines an isomorphism
\[K|_{W_\alpha} \to K_\alpha\]
compatible with the given maps $\rho_\beta^\alpha$.

Using transfinite induction we can prove the result in the general case.

**Theorem 41.8** (BBD gluing lemma). In Situation 41.3 assume

1. $X = \bigcup_{U \in B} U$, $\bigcup_{W \in B, W \subseteq U \cap V} W$,
2. for $U, V \in B$ we have $U \cap V = \bigcup_{W \in B, W \subseteq U \cap V} W$,
3. for any $U \in B$ 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 $\rho_U: K|_U \to K_U$ in $D(\mathcal{O}_U)$ for $U \in B$ such that $\rho_U|_V \circ \rho_V|_V = \rho_V$ for all $V \subseteq U$ with $U, V \in B$. The pair $(K, \rho_U)$ is unique up to unique isomorphism.

**Proof.** A pair $(K, \rho_U)$ is called a solution in the text above. The uniqueness follows from Lemma 41.4. If $X$ has a finite covering by elements of $B$ (for example if $X$ is quasi-compact), then the theorem is a consequence of Lemma 41.6. In the general case we argue in exactly the same manner, using transfinite induction and Lemma 41.7.

First we use transfinite induction to choose opens $W_\alpha \subset X$ for any ordinal $\alpha$. 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 $U_\alpha \in B$ is not contained in $W_\beta$. If $\alpha$ is a limit ordinal we set $W_\alpha = \bigcup_{\beta < \alpha} W_\beta$. Then for large enough $\alpha$ we have $W_\alpha = X$. Observe that for every $\alpha$ the open $W_\alpha$ is a union of elements of $B$. Hence if $B_\alpha = \{U \in B, U \subset W_\alpha\}$, then
\[S_\alpha = ([K_U], \rho^U_V \mid U, V \in B_\alpha, \rho^U_V \mid U, V \in B_\alpha)\]
is a system as in Lemma 41.4 on the ringed space $W_\alpha$.

We will show by transfinite induction that for every $\alpha$ the system $S_\alpha$ has a solution. This will prove the theorem as this system is the system given in the theorem for large $\alpha$. 

Special case of BBD82 Theorem 3.2.4 without boundedness assumption.
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 $U_\alpha \in B$ in this case. By induction hypothesis we have a solution $(K_{W_\beta}, \{\rho^W_U\}_{U \in B_\beta})$ for the system $S_\beta$. Then we can consider the collection $B_\alpha^* = B_\beta \cup \{W_\beta\}$ of opens of $W_\alpha$ and we see that we obtain a system $((K_U)_{U \in B_\alpha^*}, \{\rho^W_U\}_{V \subset U \text{ with } U, V \in B_\alpha^*})$. Note that this new system also satisfies condition (3) by Lemma 41.4 applied to the solution $K_{W}\beta$. For this system we have $W_\alpha = W_\beta \cup U_\alpha$. This reduces us to the case handled in Lemma 41.6.

The case where $\alpha$ is a limit ordinal. Recall that $W_\alpha = \bigcup_{\beta < \alpha} W_\beta$ in this case. For $\beta < \alpha$ let $(K_{W_\beta}, \{\rho^W_U\}_{U \in B_\beta})$ be the solution for $S_\beta$. For $\gamma < \beta < \alpha$ the restriction $K_{W_\beta}|_{W_\alpha}$ endowed with the maps $\rho^W_U$, $U \in B_\gamma$ is a solution for $S_\gamma$. By uniqueness we get unique isomorphisms $\rho^W_{W_\gamma} : K_{W_\gamma}|_{W_\alpha} \to K_{W_\alpha}$ compatible with the maps $\rho^W_U$ and $\rho^W_V$ for $U \in B_\gamma$. These maps compose in the correct manner, i.e., $\rho^W_{W_\gamma} \circ \rho^W_{W_\delta}|_{W_\alpha} = \rho^W_{W_\delta}$ for $\delta < \gamma < \beta < \alpha$. Thus we may apply Lemma 41.7 (note that the vanishing of negative exts is true for $K_{W_\beta}$ by Lemma 41.4 applied to the solution $K_{W_\beta}$) to obtain $K_{W_\alpha}$ and isomorphisms

$$\rho^W_{W_\alpha} : K_{W_\alpha}|_{W_\beta} \to K_{W_\beta}$$

compatible with the maps $\rho^W_U$ for $\gamma < \beta < \alpha$.

To show that $K_{W_\alpha}$ is a solution we still need to construct the isomorphisms $\rho^W_U : K_{W_\alpha}|_U \to K_U$ for $U \in B_\alpha$ satisfying certain compatibilities. We choose $\rho^W_U$ to be the unique map such that for any $\beta < \alpha$ and any $V \in B_\beta$ with $V \subset U$ the diagram

\[
\begin{array}{ccc}
K_{W_\alpha}|_V & \xrightarrow{\rho^W_U|_V} & K_U|_V \\
\rho^W_{W_\beta}|_V & \downarrow & \rho^V_U \\
K_{W_\beta} & \xrightarrow{\rho^V_U} & K_V
\end{array}
\]

commutes. This makes sense because

$$\{(K_V)_{V \subset U, V \in B_\beta} \text{ for some } \beta < \alpha, \{\rho^V_U|_V\}_{V \subset V'} \text{ with } V, V' \in B_\beta \text{ for some } \beta < \alpha\}$$

is a system as in Lemma 41.4 on the ringed space $U$ and because $(K_U, \rho_U)$ and $(K_{W_\alpha}|_U, \rho^W_U \circ \rho^W_{W_\beta}|_V)$ 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).

\[\square\]

42. 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** 42.1. Let $(X, O_X)$ be a ringed space. Let $E^\bullet$ be a complex of $O_X$-modules. We say $E^\bullet$ is strictly perfect if $E^i$ is zero for all but finitely many $i$ and $E^i$ is a direct summand of a finite free $O_X$-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 $O_X$-module is finite locally free.
Lemma 42.2. The cone on a morphism of strictly perfect complexes is strictly perfect.

Proof. This is immediate from the definitions. □

Lemma 42.3. The total complex associated to the tensor product of two strictly perfect complexes is strictly perfect.

Proof. Omitted. □

Lemma 42.4. Let \( f : (X, \mathcal{O}_X) \to (Y, \mathcal{O}_Y) \) be a morphism of ringed spaces. If \( F^\bullet \) is a strictly perfect complex of \( \mathcal{O}_Y \)-modules, then \( f^* F^\bullet \) 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 hence preserves direct summands. The lemma follows. □

Lemma 42.5. Let \( (X, \mathcal{O}_X) \) be a ringed space. Given a solid diagram of \( \mathcal{O}_X \)-modules

\[
\begin{array}{ccc}
\mathcal{E} & \longrightarrow & F \\
\downarrow p & & \downarrow \\
\mathcal{G} & & \\
\end{array}
\]

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 \( \Gamma(X, F) \). This is locally possible by the characterization of surjective maps of sheaves (Sheaves, Section 16). □

Lemma 42.6. Let \( (X, \mathcal{O}_X) \) be a ringed space.

1. Let \( \alpha : F^\bullet \to G^\bullet \) be a morphism of complexes of \( \mathcal{O}_X \)-modules with \( F^\bullet \) strictly perfect and \( G^\bullet \) acyclic. Then \( \alpha \) is locally on \( X \) homotopic to zero.

2. Let \( \alpha : F^\bullet \to G^\bullet \) be a morphism of complexes of \( \mathcal{O}_X \)-modules with \( F^\bullet \) strictly perfect, \( F^i = 0 \) for \( i < a \), and \( H^i(G^\bullet) = 0 \) for \( i \geq a \). Then \( \alpha \) 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 \( F^\bullet \). If \( F^\bullet \cong \mathcal{E}[-n] \) 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 42.5 and the fact that \( F^{n-1} \to \text{Ker}(F^n \to F^{n+1}) \) is surjective by the assumed vanishing of \( H^i(F^\bullet) \). If \( \mathcal{E} \) is zero except for \( i \in [a, b] \), then we have a split exact sequence of complexes

\[
0 \to \mathcal{E}^b[-b] \to \mathcal{E}^\bullet \to \sigma_{\leq b-1} \mathcal{E}^\bullet \to 0
\]

which determines a distinguished triangle in \( K(\mathcal{O}_X) \). Hence an exact sequence

\[
\text{Hom}_{K(\mathcal{O}_X)}(\sigma_{\leq b-1} \mathcal{E}^\bullet, F^\bullet) \to \text{Hom}_{K(\mathcal{O}_X)}(\mathcal{E}^\bullet, F^\bullet) \to \text{Hom}_{K(\mathcal{O}_X)}(F^b[-b], F^\bullet)
\]

by the axioms of triangulated categories. The composition \( \mathcal{E}^b[-b] \to F^\bullet \) 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. □
Lemma 42.7. Let \((X, \mathcal{O}_X)\) be a ringed space. Given a solid diagram of complexes of \(\mathcal{O}_X\)-modules

\[
\begin{array}{ccc}
\mathcal{E}^\bullet & \xrightarrow{\alpha} & \mathcal{F}^\bullet \\
\ddownarrow & & \downarrow f \\
\mathcal{G}^\bullet
\end{array}
\]

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 42.6 guarantees there is an open covering \(X = \bigcup U_i\) such that \(\alpha_{|U_i}\) is given by a morphism of complexes \(\alpha_i : \mathcal{E}^\bullet|_{U_i} \rightarrow \mathcal{F}^\bullet|_{U_i}\).

Lemma 42.8. 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 \(\text{Hom}_{D(\mathcal{O}_X)}(\mathcal{E}^\bullet, \mathcal{F}^\bullet)\) 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 42.7. We omit the proof of (2).

Lemma 42.9. 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 \(R\text{Hom}(\mathcal{E}^\bullet, \mathcal{F}^\bullet)\) is represented by the complex \(\mathcal{H}^\bullet\) with terms

\[
\mathcal{H}^n = \bigoplus_{n=p+q} \text{Hom}_{\mathcal{O}_X}(\mathcal{E}^{-q}, \mathcal{F}^p)
\]

and differential as described in Section 38.

**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

\[
(\mathcal{H}')^n = \prod_{n=p+q} \text{Hom}_{\mathcal{O}_X}(\mathcal{E}^{-q}, \mathcal{I}^p)
\]

which represents \(R\text{Hom}(\mathcal{E}^\bullet, \mathcal{F}^\bullet)\) by the construction in Section 38. It suffices to show that the map

\[
\mathcal{H}^\bullet \rightarrow (\mathcal{H}')^\bullet
\]

is a quasi-isomorphism. Given an open \(U \subset X\) we have by inspection

\[
H^0(\mathcal{H}^\bullet(U)) = \text{Hom}_{\mathcal{O}_U}(\mathcal{E}^\bullet|_U, \mathcal{K}^\bullet|_U) \rightarrow H^0((\mathcal{H}')^\bullet(U)) = \text{Hom}_{\mathcal{O}_U}(\mathcal{E}^\bullet|_U, \mathcal{K}^\bullet|_U)
\]

By Lemma 42.8 the sheafification of \(U \rightarrow H^0(\mathcal{H}^\bullet(U))\) is equal to the sheafification of \(U \rightarrow H^0((\mathcal{H}')^\bullet(U))\). 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.
Pseudo-coherent complexes

In this section we discuss pseudo-coherent complexes.

**Definition 43.1.** Let \((X, \mathcal{O}_X)\) be a ringed space. Let \(\mathcal{E}^\bullet, \mathcal{F}^\bullet\) be complexes of \(\mathcal{O}_X\)-modules. Let

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

\[
\mathcal{H}^n = \bigoplus_{p+q=n} \mathcal{H}\mathcal{O}_X(\mathcal{E}^{-q}, \mathcal{F}^p)
\]

and differential as described in Section 38.

**Proof.** Choose a quasi-isomorphism \(\mathcal{F}^\bullet \to \mathcal{I}^\bullet\) where \(\mathcal{I}^\bullet\) is a bounded below complex of injectives. Note that \(\mathcal{I}^\bullet\) is K-injective (Derived Categories, Lemma 31.4). Hence the construction in Section 38 shows that \(R\mathcal{H}om(\mathcal{E}^\bullet, \mathcal{F}^\bullet)\) is represented by the complex \((\mathcal{H}^\bullet)\) with terms

\[
(\mathcal{H}^\bullet)^n = \prod_{p+q=n} \mathcal{H}\mathcal{O}_X(\mathcal{E}^{-q}, \mathcal{I}^p) = \bigoplus_{p+q=n} \mathcal{H}\mathcal{O}_X(\mathcal{E}^{-q}, \mathcal{I}^p)
\]

(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 \(\mathcal{H}\mathcal{O}_X(\mathcal{E}^{-q}, \mathcal{I}^p)\) and similarly for \((\mathcal{H}^\bullet)\). The natural map \((\mathcal{H}^\bullet)^\bullet \to \mathcal{H}^\bullet\) 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 25.3)

\[
iE_{pq}^r = H^p(\mathcal{H}\mathcal{O}_X(\mathcal{E}^{-q}, \mathcal{F}^r))
\]

converging to \(H^{p+q}(\mathcal{H}^\bullet)\) and similarly for \((\mathcal{H}^\bullet)^\bullet\). To finish the proof of the lemma it suffices to show that \(\mathcal{F}^\bullet \to \mathcal{I}^\bullet\) induces an isomorphism

\[
H^p(\mathcal{H}\mathcal{O}_X(\mathcal{E}, \mathcal{F}^\bullet)) \to H^p(\mathcal{H}\mathcal{O}_X(\mathcal{E}, \mathcal{I}^\bullet))
\]

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. \(\square\)

**34. Pseudo-coherent modules**

In this section we discuss pseudo-coherent complexes.

**Definition 43.1.** Let \((X, \mathcal{O}_X)\) be a ringed space. Let \(\mathcal{E}^\bullet\) be a complex of \(\mathcal{O}_X\)-modules. Let \(m \in \mathbb{Z}\).

1. \(\mathcal{E}^\bullet\) is \(m\)-pseudo-coherent if there exists an open covering \(X = \bigcup U_i\) and for each \(i\) a morphism of complexes \(\alpha_i : \mathcal{E}^\bullet_i \to \mathcal{E}^\bullet|_{U_i}\) where \(\mathcal{E}^\bullet_i\) 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. \(\mathcal{E}^\bullet\) is pseudo-coherent if it is \(m\)-pseudo-coherent for all \(m\).
3. \(\mathcal{E}^\bullet\) is 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.

**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 \( X = \bigcup U_i \), strictly perfect complexes \( \mathcal{E}^*_i \) on \( U_i \), and maps \( \alpha_i : \mathcal{E}^*_i \to E_i|_{U_i} \) 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 \( \mathcal{F}^* \) be any complex representing \( E \) and let \( X = \bigcup U_i \) and \( \alpha_i : \mathcal{E}^*_i \to E_i|_{U_i} \) be as in (1). We will show that \( \mathcal{F}^* \) is \( m \)-pseudo-coherent as a complex, which will prove (1) and (2) simultaneously. By Lemma 42.8 we can after refining the open covering \( X = \bigcup U_i \) represent the maps \( \alpha_i \) by maps of complexes \( \alpha_i : \mathcal{E}^*_i \to \mathcal{F}^*|_{U_i} \).

By assumption \( H^j(\alpha_i) \) are isomorphisms for \( j > m \), and \( H^m(\alpha_i) \) is surjective whence \( \mathcal{F}^* \) is \( m \)-pseudo-coherent. □

**Lemma 43.3.** Let \( f : (X, \mathcal{O}_X) \to (Y, \mathcal{O}_Y) \) 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 \( \mathcal{E}^* \) of \( \mathcal{O}_Y \)-modules and choose an open covering \( Y = \bigcup V_i \) and \( \alpha_i : \mathcal{E}^* \to \mathcal{E}^*|_{V_i} \) as in Definition 43.1. Set \( U_i = f^{-1}(V_i) \). By Lemma 43.2 it suffices to show that \( Lf^*\mathcal{E}^*|_{U_i} \) is \( m \)-pseudo-coherent. Choose a distinguished triangle

\[ \mathcal{E}^*_i \to \mathcal{E}^*|_{V_i} \to C \to \mathcal{E}^*_i[1] \]

The assumption on \( \alpha_i \) means exactly that the cohomology sheaves \( H^j(C) \) are zero for all \( j \geq m \). Denote \( f_i : U_i \to V_i \) the restriction of \( f \). Note that \( Lf_i^*\mathcal{E}^*|_{V_i} = Lf_i^*(\mathcal{E}|_{V_i}) \). Applying \( Lf_i^* \) we obtain the distinguished triangle

\[ Lf_i^*\mathcal{E}^*_i \to Lf_i^*\mathcal{E}|_{V_i} \to Lf_i^*C \to Lf_i^*\mathcal{E}^*_i[1] \]

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 16.1). 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, \( Lf_i^*\mathcal{E}^*_i = f_i^*\mathcal{E}^*_i \) is strictly perfect by Lemma 42.4. Thus we conclude. □

**Lemma 43.4.** Let \( (X, \mathcal{O}_X) \) be a ringed space and \( m \in \mathbb{Z} \). 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 \( \alpha_i : \mathcal{K}^*_i \to K|_{U_i} \) in \( D(\mathcal{O}_{U_i}) \) with \( \mathcal{K}^*_i \) strictly perfect and \( H^j(\alpha_i) \) isomorphisms for \( j > m+1 \) and surjective for \( j = m+1 \). We may replace \( \mathcal{K}^*_i \) by \( \sigma_{m+1}\mathcal{K}^*_i \) and hence we may assume that \( \mathcal{K}^*_i = 0 \) for \( j < m+1 \). After refining the open covering we may choose maps \( \beta_i : \mathcal{L}^*_i \to L|_{U_i} \) in \( D(\mathcal{O}_{U_i}) \) with \( \mathcal{L}^*_i \) strictly perfect such that \( H^j(\beta) \) is an isomorphism for \( j > m \) and surjective for \( j = m \). By Lemma 42.7 we can, after
refining the covering, find maps of complexes \( \gamma_i : K^\bullet \rightarrow L^\bullet \) such that the diagrams

\[
\begin{array}{ccc}
K|_{U_i} & \longrightarrow & L|_{U_i} \\
\alpha_i & & \beta_i \\
\downarrow & & \downarrow \\
K_i^\bullet & \longrightarrow & L_i^\bullet
\end{array}
\]

are commutative in \( D(\mathcal{O}_{U_i}) \) (this requires representing the maps \( \alpha_i, \beta_i \) 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 42.2). The commutativity of the diagram implies that there exists a morphism of distinguished triangles

\[
(K_i^\bullet, L_i^\bullet, C(\gamma_i)^\bullet) \rightarrow (K|_{U_i}, L|_{U_i}, M|_{U_i}).
\]

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 43.2.

Assertions (2) and (3) follow from (1) by rotating the distinguished triangles. \( \square \)

**Lemma 43.6.** 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 \( K \otimes_{\mathcal{O}_X}^L L \) is \( t \)-pseudo-coherent with \( t = \max(a, n + b) \).
2. If \( K \) and \( L \) are pseudo-coherent, then \( K \otimes_{\mathcal{O}_X}^L L \) 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 \( K^\bullet \) and \( L^\bullet \) and maps \( \alpha : K^\bullet \rightarrow K \) and \( \beta : L^\bullet \rightarrow L \) 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

\[
\alpha \otimes^L \beta : \text{Tot}(K^\bullet \otimes_{\mathcal{O}_X}^L L^\bullet) \rightarrow K \otimes_{\mathcal{O}_X}^L L
\]

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). \( \square \)

**Lemma 43.6.** Let \((X, \mathcal{O}_X)\) be a ringed space. Let \( m \in \mathbb{Z} \). 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 43.4 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 \( L[n-1], L[n-2], \ldots, L \) are \( m \)-pseudo-coherent as desired.

**Lemma 43.7.** Let \((X, \mathcal{O}_X)\) be a ringed space. Let \( m \in \mathbb{Z} \). Let \( F^* \) be a (locally) bounded above complex of \( \mathcal{O}_X \)-modules such that \( F^i \) is \((m-i)\)-pseudo-coherent for all \( i \). Then \( F^* \) is \( m \)-pseudo-coherent.

**Proof.** Omitted. Hint: use Lemma 43.4 and truncations as in the proof of More on Algebra, Lemma 62.10.

**Lemma 43.8.** Let \((X, \mathcal{O}_X)\) be a ringed space. Let \( m \in \mathbb{Z} \). 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 43.4 and truncations as in the proof of More on Algebra, Lemma 62.11.

**Lemma 43.9.** Let \((X, \mathcal{O}_X)\) be a ringed space. Let \( K \) be an object of \( D(\mathcal{O}_X) \). Let \( m \in \mathbb{Z} \).

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 \( \mathcal{E}^* \) and a map \( \alpha : \mathcal{E}^* \to K \) which induces an isomorphism on cohomology in degrees \( > m \) and a surjection in degree \( m \). It suffices to prove the result for \( \mathcal{E}^* \). Let \( n \) be the largest integer such that \( \mathcal{E}^n \neq 0 \). If \( n = m \), then \( H^m(\mathcal{E}^*) \) is a quotient of \( \mathcal{E}^n \) and the result is clear. If \( n > m \), then \( \mathcal{E}^{n-1} \to \mathcal{E}^n \) is surjective as \( H^n(E^*) = 0 \). By Lemma 42.5 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 \( (\mathcal{E}')^* \) which is the same as \( \mathcal{E}^* \) 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 \( \mathcal{E}^* \) and a map \( \alpha : \mathcal{E}^* \to K \) 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 \( H^{m+1}(K) \cong H^{m+1}(\mathcal{E}^*) = \text{Coker}(\mathcal{E}^m \to \mathcal{E}^{m+1}) \) which is of finite presentation.

**Lemma 43.10.** Let \((X, \mathcal{O}_X)\) be a ringed space. Let \( F \) be a sheaf of \( \mathcal{O}_X \)-modules.

1. \( F \) viewed as an object of \( D(\mathcal{O}_X) \) is 0-pseudo-coherent if and only if \( F \) is a finite type \( \mathcal{O}_X \)-module, and
2. \( F \) viewed as an object of \( D(\mathcal{O}_X) \) is \((-1)\)-pseudo-coherent if and only if \( F \) is an \( \mathcal{O}_X \)-module of finite presentation.

**Proof.** Use Lemma 43.9 to prove the implications in one direction and Lemma 43.8 for the other.

### 44. Tor dimension

In this section we take a closer look at resolutions by flat modules.

**Definition 44.1.** Let \((X, \mathcal{O}_X)\) be a ringed space. Let \( E \) be an object of \( D(\mathcal{O}_X) \). Let \( a, b \in \mathbb{Z} \) with \( a \leq b \).
(1) We say $E$ has tor-amplitude in $[a, b]$ if $H^i(E \otimes_{O_X} F) = 0$ for all $O_X$-modules $F$ and all $i \not\in [a, b]$.

(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 $i$.

An $O_X$-module $F$ has tor dimension $\leq d$ if $F[0]$ viewed as an object of $D(O_X)$ has tor-amplitude in $[-d, 0]$.

Note that if $E$ as in the definition has finite tor dimension, then $E$ is an object of $D^b(O_X)$ as can be seen by taking $F = O_X$ in the definition above.

**Lemma 44.2.** Let $(X, O_X)$ be a ringed space. Let $E^\bullet$ be a bounded above complex of flat $O_X$-modules with tor-amplitude in $[a, b]$. Then $\text{Coker}(d_a^{a-1})$ is a flat $O_X$-module.

**Proof.** As $E^\bullet$ is a bounded above complex of flat modules we see that $E^\bullet \otimes_{O_X} F = E^\bullet \otimes_{O_X} F$ for any $O_X$-module $F$. Hence for every $O_X$-module $F$ the sequence

$$E^{a-2} \otimes_{O_X} F \to E^{a-1} \otimes_{O_X} F \to E^a \otimes_{O_X} F$$

is exact in the middle. Since $E^{a-2} \to E^{a-1} \to E^a \to \text{Coker}(d_a^{a-1}) \to 0$ is a flat resolution this implies that $\text{Tor}_1^O(X(\text{Coker}(d_a^{a-1})), F) = 0$ for all $O_X$-modules $F$. This means that $\text{Coker}(d_a^{a-1})$ is flat, see Lemma 26.15.

**Lemma 44.3.** Let $(X, O_X)$ be a ringed space. Let $E$ be an object of $D(O_X)$. Let $a, b \in \mathbb{Z}$ with $a \leq b$. The following are equivalent

1. $E$ has tor-amplitude in $[a, b]$.
2. $E$ is represented by a complex $E^\bullet$ of flat $O_X$-modules with $E^i = 0$ for $i \not\in [a, b]$.

**Proof.** If (2) holds, then we may compute $E \otimes_{O_X} F = E^\bullet \otimes_{O_X} F$ and it is clear that (1) holds.

Assume that (1) holds. We may represent $E$ by a bounded above complex of flat $O_X$-modules $K^\bullet$, see Section 20. Let $n$ be the largest integer such that $K^n \not= 0$. If $n > b$, then $K^{n-1} \to K^n$ is surjective as $H^n(K^\bullet) = 0$. As $K^n$ is flat we see that $\text{Ker}(K^{n-1} \to K^n)$ is flat (Modules, Lemma 16.8). Hence we may replace $K^\bullet$ by $\tau_{\geq n-1}K^\bullet$. Thus, by induction on $n$, we reduce to the case that $K^\bullet$ is a complex of flat $O_X$-modules with $K^i = 0$ for $i > b$.

Set $E^\bullet = \tau_{\geq a}K^\bullet$. Everything is clear except that $E^a$ is flat which follows immediately from Lemma [41.2] and the definitions.

**Lemma 44.4.** Let $f : (X, O_X) \to (Y, O_Y)$ be a morphism of ringed spaces. Let $E$ be an object of $D(O_Y)$. 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 44.3 we can represent $E$ by a complex of $E^\bullet$ of flat $O$-modules with $E^i = 0$ for $i \not\in [a, b]$. Then $Lf^*E$ is represented by $f^*E^\bullet$. By Modules, Lemma 19.2 the modules $f^*E^i$ are flat. Thus by Lemma 44.3 we conclude that $Lf^*E$ has tor amplitude in $[a, b]$.

**Lemma 44.5.** Let $(X, O_X)$ be a ringed space. Let $E$ be an object of $D(O_X)$. Let $a, b \in \mathbb{Z}$ with $a \leq b$. The following are equivalent
Let in this section we discuss properties of perfect complexes on ringed spaces.

**Proof.** Taking stalks at \( x \) is the same thing as pulling back by the morphism of ringed spaces \((x, \mathcal{O}_X, x) \to (X, \mathcal{O}_X)\). Hence the implication \((1) \Rightarrow (2)\) follows from Lemma 44.4. For the converse, note that taking stalks commutes with tensor products (Modules, Lemma 15.1). Hence

\[
H^i((E \otimes_{\mathcal{O}_X} \mathcal{F})_x) = H^i((E_x \otimes_{\mathcal{O}_{X,x}} \mathcal{F}_x)
\]

On the other hand, taking stalks is exact, so

\[
H^i(E \otimes_{\mathcal{O}_X} \mathcal{F})_x = H^i(E_x \otimes_{\mathcal{O}_{X,x}} \mathcal{F}_x)
\]

and we can check whether \( H^i(E \otimes_{\mathcal{O}_X} \mathcal{F}) \) is zero by checking whether all of its stalks are zero (Modules, Lemma 3.1). Thus \((2)\) implies \((1)\). □

**Lemma 44.6.** 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 \(a, b \in \mathbb{Z}\).

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 \(- \otimes_{\mathcal{O}_X} \mathcal{F}\) preserves distinguished triangles. The easiest one to prove is \((2)\) and the others follow from it by translation. □

**Lemma 44.7.** 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 \(K \otimes_{\mathcal{O}_X} L\) has tor amplitude in \([a + c, b + d]\).

**Proof.** Omitted. Hint: use the spectral sequence for tors. □

**Lemma 44.8.** Let \((X, \mathcal{O}_X)\) be a ringed space. Let \(a, b \in \mathbb{Z}\). For \(K, L\) objects of \(D(\mathcal{O}_X)\) if \(K \otimes L\) has tor amplitude in \([a, b]\) so do \(K\) and \(L\).

**Proof.** Clear from the fact that the Tor functors are additive. □

45. Perfect complexes

**Definition 45.1.** Let \((X, \mathcal{O}_X)\) be a ringed space. Let \(\mathcal{E}^•\) be a complex of \(\mathcal{O}_X\)-modules. We say \(\mathcal{E}^•\) is perfect if there exists an open covering \(X = \bigcup U_i\) such that for each \(i\) there exists a morphism of complexes \(\mathcal{E}_i^• \to \mathcal{E}^•|_{U_i}\) which is a quasi-isomorphism with \(\mathcal{E}_i^•\) 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.

**Lemma 45.2.** 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 \(\mathcal{E}_i^•\) on \(U_i\) such that \(\mathcal{E}_i^•|_{U_i}\) 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 \ref{lemma-43.2} \hfill \square

\begin{lemma}
\label{lemma-45.3}
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

\begin{enumerate}
\item \(E\) is perfect,
\item 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
\item 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.
\end{enumerate}

Proof. This follows from Lemma \ref{lemma-45.2} and the fact that on \(X\) every direct summand of a finite free module is finite locally free. See Modules, Lemma \ref{module-14.6} \hfill \square

\begin{lemma}
\label{lemma-45.4}
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 \(\alpha : \mathcal{E}^\bullet \to E\) 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

\[\mathcal{E}^\bullet \to E \to C \to \mathcal{E}^\bullet[1]\]

From the vanishing of cohomology sheaves of \(E\) and \(\mathcal{E}^\bullet\) and the assumption on \(\alpha\) we obtain \(C \cong K[a-2]\) with \(K = \text{Ker}(\mathcal{E}^{a-1} \to \mathcal{E}^a)\). Let \(\mathcal{F}\) be an \(\mathcal{O}_X\)-module. Applying \(- \otimes^{L}_{\mathcal{O}_X} \mathcal{F}\) the assumption that \(E\) has tor amplitude in \([a, b]\) implies \(K \otimes_{\mathcal{O}_X} \mathcal{F} \to \mathcal{E}^{a-1} \otimes_{\mathcal{O}_X} \mathcal{F}\) has image \(\text{Ker}(\mathcal{E}^{a-1} \otimes_{\mathcal{O}_X} \mathcal{F} \to \mathcal{E}^a \otimes_{\mathcal{O}_X} \mathcal{F})\). It follows that \(\text{Tor}_1^{\mathcal{O}_X}(\mathcal{E}', \mathcal{F}) = 0\) where \(\mathcal{E}' = \text{Coker}(\mathcal{E}^{a-1} \to \mathcal{E}^a)\). Hence \(\mathcal{E}'\) is flat (Lemma \ref{module-26.15}). Thus \(\mathcal{E}'\) is locally a direct summand of a finite free module by Modules, Lemma \ref{module-17.3} Thus locally the complex

\[\mathcal{E}' \to \mathcal{E}^{a-1} \to \ldots \to \mathcal{E}^b\]

is quasi-isomorphic to \(E\) and \(E\) is perfect. \hfill \square

\begin{lemma}
\label{lemma-45.5}
Let \((X, \mathcal{O}_X)\) be a ringed space. Let \(E\) be an object of \(D(\mathcal{O}_X)\). The following are equivalent

\begin{enumerate}
\item \(E\) is perfect, and
\item \(E\) is pseudo-coherent and locally has finite tor dimension.
\end{enumerate}

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 \ref{lemma-43.2} Moreover, a direct summand of a finite free module is flat, hence \(E|_{U_i}\) has finite Tor dimension by Lemma \ref{lemma-44.3} 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 \ref{lemma-45.3} \hfill \square

\begin{lemma}
\label{lemma-45.6}
Let \(f : (X, \mathcal{O}_X) \to (Y, \mathcal{O}_Y)\) 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 \ref{lemma-45.5}, \ref{lemma-44.4} and \ref{lemma-43.3} (An alternative proof is to copy the proof of Lemma \ref{lemma-43.3}) \hfill \square
Lemma 45.7. 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 45.5, 43.4, and 44.6. 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 \(K^\bullet\) and \(L^\bullet\). After replacing \(X\) by the members of an open covering we may assume the map \(K \to L\) is given by a map of complexes \(\alpha : K^\bullet \to L^\bullet\), see Lemma 42.2. Then \(M\) is isomorphic to the cone of \(\alpha\) which is strictly perfect by Lemma 42.8. □

Lemma 45.8. Let \((X, \mathcal{O}_X)\) be a ringed space. If \(K, L\) are perfect objects of \(D(\mathcal{O}_X)\), then so is \(K \otimes_{\mathcal{O}_X} L\).

**Proof.** Follows from Lemmas 45.5, 43.5, and 44.7. □

Lemma 45.9. 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 45.5, 43.6, and 44.8. □

Lemma 45.10. Let \((X, \mathcal{O}_X)\) be a ringed space. Let \(j : U \to X\) 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 \(E|_{U \setminus T} = 0\). □

46. Duals

In this section we characterize the dualizable objects of the category of complexes and of the derived category. In particular, we will see that an object of \(D(\mathcal{O}_X)\) has a dual if and only if it is perfect (this follows from Example 46.6 and Lemma 46.7).

**Example 46.2.** Let \((X, \mathcal{O}_X)\) be a ringed space. Let \(F^\bullet\) be a locally bounded complex of \(\mathcal{O}_X\)-modules such that each \(F^n\) is locally a direct summand of a finite free \(\mathcal{O}_X\)-module. In other words, there is an open covering \(X = \bigcup U_i\) such that \(F^\bullet|_{U_i}\) is a strictly perfect complex. Consider the complex

\[G^\bullet = \text{Hom}^\bullet(F^\bullet, \mathcal{O}_X)\]

as in Section 37. Let

\[\eta : \mathcal{O}_X \to \text{Tot}(F^\bullet \otimes_{\mathcal{O}_X} G^\bullet)\]

and

\[\epsilon : \text{Tot}(G^\bullet \otimes_{\mathcal{O}_X} F^\bullet) \to \mathcal{O}_X\]
be \( \eta = \sum \eta_n \) and \( \epsilon = \sum \epsilon_n \) where \( \eta_n : \mathcal{O}_X \to \mathcal{F}^n \otimes_{\mathcal{O}_X} \mathcal{G}^{-n} \) and \( \epsilon_n : \mathcal{G}^{-n} \otimes_{\mathcal{O}_X} \mathcal{F}^n \to \mathcal{O}_X \) are as in Modules, Example 17.1. Then \( \mathcal{G}^\bullet, \eta, \epsilon \) is a left dual for \( \mathcal{F}^\bullet \) as in Categories, Definition 41.5. We omit the verification that \( (1 \otimes \epsilon) \circ (\eta \otimes 1) = \text{id}_{\mathcal{F}^\bullet} \) and \( (\epsilon \otimes 1) \circ (1 \otimes \eta) = \text{id}_{\mathcal{G}^\bullet} \). Please compare with More on Algebra, Lemma 68.3.

**Lemma 46.3.** Let \( (X, \mathcal{O}_X) \) be a ringed space. Let \( \mathcal{F}^\bullet \) be a complex of \( \mathcal{O}_X \)-modules. If \( \mathcal{F}^\bullet \) has a left dual in the monoidal category of complexes of \( \mathcal{O}_X \)-modules (Categories, Definition 41.5) then \( \mathcal{F}^\bullet \) is a locally bounded complex whose terms are locally direct summands of finite free \( \mathcal{O}_X \)-modules and the left dual is as constructed in Example 46.2.

**Proof.** By uniqueness of left duals (Categories, Remark 41.7) we get the final statement provided we show that \( \mathcal{F}^\bullet \) is as stated. Let \( \mathcal{G}^\bullet, \eta, \epsilon \) be a left dual. Write \( \eta = \sum \eta_n \) and \( \epsilon = \sum \epsilon_n \) where \( \eta_n : \mathcal{O}_X \to \mathcal{F}^n \otimes_{\mathcal{O}_X} \mathcal{G}^{-n} \) and \( \epsilon_n : \mathcal{G}^{-n} \otimes_{\mathcal{O}_X} \mathcal{F}^n \to \mathcal{O}_X \). Since \( (1 \otimes \epsilon) \circ (\eta \otimes 1) = \text{id}_{\mathcal{F}^\bullet} \) and \( (\epsilon \otimes 1) \circ (1 \otimes \eta) = \text{id}_{\mathcal{G}^\bullet} \) by Categories, Definition 41.5 we see immediately that we have \( (1 \otimes \epsilon_n) \circ (\eta_n \otimes 1) = \text{id}_{\mathcal{F}^n} \) and \( (\epsilon_n \otimes 1) \circ (1 \otimes \eta_n) = \text{id}_{\mathcal{G}^{-n}} \). Hence we see that \( \mathcal{F}^n \) is locally a direct summand of a finite free \( \mathcal{O}_X \)-module by Modules, Lemma 17.2. Since the sum \( \eta = \sum \eta_n \) is locally finite, we conclude that \( \mathcal{F}^\bullet \) is locally bounded. \( \square \)

**Lemma 46.4.** 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 \( (K^\vee)^\vee \cong K \). There are functorial isomorphisms

\[
M \otimes \mathcal{O}_X K^\vee = R \mathcal{H}om(K, M)
\]

and

\[
\mathcal{H}^n(X, M \otimes \mathcal{O}_X K^\vee) = \mathcal{H}om_{D(\mathcal{O}_X)}(K, M)
\]

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 38.3). We may check \( K^\vee \) is perfect locally on \( X \). There is a canonical map

\[
K = R \mathcal{H}om(\mathcal{O}_X, \mathcal{O}_X) \otimes \mathcal{O}_X K \to R \mathcal{H}om(R \mathcal{H}om(K, \mathcal{O}_X), \mathcal{O}_X) = (K^\vee)^\vee
\]

see Lemma 38.9. It suffices to prove this map is an isomorphism locally. By Lemma 38.8 to see the final statement it suffices to check that the map \( 38.8.1 \)

\[
M \otimes \mathcal{O}_X K^\vee \to R \mathcal{H}om(K, M)
\]

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 42.9 that \( \mathcal{E}^\vee \) 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 \( \mathcal{E}^\vee \) is represented by a strictly perfect complex too and we see that \( \mathcal{E}^\vee \) is perfect. The map \( K \to (\mathcal{E}^\vee)^\vee \) is an isomorphism as it is given up to sign by the evaluation maps \( \mathcal{E}^n \to ((\mathcal{E}^{-n})^\vee)^\vee \) which are isomorphisms. To see that \( 38.8.1 \) is an isomorphism, represent \( M \) by a complex \( \mathcal{F}^\bullet \). By Lemma 42.9 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, the object $M \otimes L_{O_X} K^\vee$ is represented by the complex with terms
\[
\bigoplus_{n=p+q} F^p \otimes_{O_X} (E^{-q})^\vee
\]
Thus the assertion that (38.8.1) is an isomorphism reduces to the assertion that the canonical map
\[
\mathcal{F} \otimes_{O_X} \text{Hom}_{O_X}(E, O_X) \rightarrow \text{Hom}_{O_X}(E, \mathcal{F})
\]
is an isomorphism when $E$ is a direct summand of a finite free $O_X$-module and $\mathcal{F}$ is any $O_X$-module. This follows immediately from the corresponding statement when $E$ is finite free. □

**Lemma 46.5.** Let $(X, O_X)$ be a ringed space. The derived category $D(O_X)$ is a symmetric monoidal category with tensor product given by derived tensor product with usual associativity and commutativity constraints (for sign rules, see More on Algebra, Section 68).

**Proof.** Omitted. Compare with Lemma 46.1. □

**Example 46.6.** Let $(X, O_X)$ be a ringed space. Let $K$ be a perfect object of $D(O_X)$. Set $K^\vee = R\text{Hom}(K, O_X)$ as in Lemma 46.4. Then the map
\[
K \otimes_{O_X}^L K^\vee \rightarrow R\text{Hom}(K, K)
\]
is an isomorphism (by the lemma). Denote
\[
\eta : O_X \rightarrow K \otimes_{O_X}^L K^\vee
\]
the map sending 1 to the section corresponding to $\text{id}_K$ under the isomorphism above. Denote
\[
\epsilon : K^\vee \otimes_{O_X}^L K \rightarrow O_X
\]
the evaluation map (to construct it you can use Lemma 38.5 for example). Then $K^\vee, \eta, \epsilon$ is a left dual for $K$ as in Categories, Definition 41.5. We omit the verification that $(1 \otimes \epsilon) \circ (\eta \otimes 1) = \text{id}_K$ and $(\epsilon \otimes 1) \circ (1 \otimes \eta) = \text{id}_{K^\vee}$.

**Lemma 46.7.** Let $(X, O_X)$ be a ringed space. Let $M$ be an object of $D(O_X)$. If $M$ has a left dual in the monoidal category $D(O_X)$ (Categories, Definition 41.5) then $M$ is perfect and the left dual is as constructed in Example 46.6.

**Proof.** Let $x \in X$. It suffices to find an open neighbourhood $U$ of $x$ such that $M$ restricts to a perfect complex over $U$. Hence during the proof we can (finitely often) replace $X$ by an open neighbourhood of $x$. Let $N, \eta, \epsilon$ be a left dual.

We are going to use the following argument several times. Choose any complex $\mathcal{M}^\bullet$ of $O_X$-modules representing $M$. Choose a $K$-flat complex $\mathcal{N}^\bullet$ representing $N$ whose terms are flat $O_X$-modules, see Lemma 26.11. Consider the map
\[
\eta : O_X \rightarrow \text{Tot}(\mathcal{M}^\bullet \otimes_{O_X} \mathcal{N}^\bullet)
\]
After shrinking $X$ we can find an integer $N$ and for $i = 1, \ldots , N$ integers $n_i \in \mathbb{Z}$ and sections $f_i$ and $g_i$ of $\mathcal{M}^{n_i}$ and $\mathcal{N}^{-n_i}$ such that
\[
\eta(1) = \sum_i f_i \otimes g_i
\]
Let $K^\bullet \subset M^\bullet$ be any subcomplex of $O_X$-modules containing the sections $f_i$ for $i = 1, \ldots, N$. Since $\text{Tot}(K^\bullet \otimes_{O_X} N^\bullet) \subset \text{Tot}(M^\bullet \otimes_{O_X} N^\bullet)$ by flatness of the modules $N^n$, we see that $\eta$ factors through

$$\tilde{\eta} : O_X \to \text{Tot}(K^\bullet \otimes_{O_X} N^\bullet)$$

Denoting $K$ the object of $D(O_X)$ represented by $K^\bullet$ we find a commutative diagram

$$
\begin{array}{ccc}
M & \xrightarrow{\eta \otimes 1} & M \otimes^L N \otimes^L M \\
\downarrow{\tilde{\eta} \otimes 1} & & \downarrow{1 \otimes \epsilon} \\
K \otimes^L N \otimes^L M & \xrightarrow{1 \otimes \epsilon} & K
\end{array}
$$

Since the composition of the upper row is the identity on $M$ we conclude that $M$ is a direct summand of $K$ in $D(O_X)$.

As a first use of the argument above, we can choose the subcomplex $K^\bullet = \sigma_{\geq a} \tau_{\leq b} M^\bullet$ with $a < n_i < b$ for $i = 1, \ldots, N$. Thus $M$ is a direct summand in $D(O_X)$ of a bounded complex and we conclude we may assume $M$ is in $D^b(O_X)$. (Recall that the process above involves shrinking $X$.)

Since $M$ is in $D^b(O_X)$ we may choose $M^\bullet$ to be a bounded above complex of flat modules (by Modules, Lemma 16.6 and Derived Categories, Lemma 15.4). Then we can choose $K^\bullet = \sigma_{\leq a} M^\bullet$ with $a < n_i$ for $i = 1, \ldots, N$ in the argument above. Thus we find that we may assume $M$ is a direct summand in $D(O_X)$ of a bounded complex of flat modules. In particular, $M$ has finite tor amplitude.

Say $M$ has tor amplitude in $[a, b]$. Assuming $M$ is $m$-pseudo-coherent we are going to show that (after shrinking $X$) we may assume $M$ is $(m - 1)$-pseudo-coherent. This will finish the proof by Lemma 15.4, and the fact that $M$ is $(b + 1)$-pseudo-coherent in any case. After shrinking $X$ we may assume there exists a strictly perfect complex $E^\bullet$ and a map $\alpha : E^\bullet \to M$ in $D(O_X)$ such that $H^i(\alpha)$ is an isomorphism for $i > m$ and surjective for $i = m$. We may and do assume that $E^i = 0$ for $i < m$. Choose a distinguished triangle

$$E^\bullet \to M \to L \to E^\bullet[1]$$

Observe that $H^i(L) = 0$ for $i \geq m$. Thus we may represent $L$ by a complex $L^\bullet$ with $L^i = 0$ for $i \geq m$. The map $L \to E^\bullet[1]$ is given by a map of complexes $L^\bullet \to E^\bullet[1]$ which is zero in all degrees except in degree $m - 1$ where we obtain a map $L^{m-1} \to E^m$, see Derived Categories, Lemma 27.3. Then $M$ is represented by the complex

$$M^\bullet : \cdots \to L^{m-2} \to L^{m-1} \to E^m \to E^{m+1} \to \cdots$$

Apply the discussion in the second paragraph to this complex to get sections $f_i$ of $M^{n_i}$ for $i = 1, \ldots, N$. For $n < m$ let $K^n \subset L^n$ be the $O_X$-submodule generated by the sections $f_i$ for $n_i = n$ and $d(f_i)$ for $n_i = n - 1$. For $n \geq m$ set $K^n = \mathcal{E}^n$. Clearly, we have a morphism of distinguished triangles

$$
\begin{array}{cccc}
E^\bullet & \to & M^\bullet & \to & L^\bullet & \to & E^\bullet[1] \\
\downarrow & & \downarrow & & \downarrow & & \downarrow \\
E^\bullet & \to & K^\bullet & \to & \sigma_{\leq m-1} K^\bullet & \to & E^\bullet[1]
\end{array}
$$
where all the morphisms are as indicated above. Denote $K$ the object of $D(O_X)$ corresponding to the complex $K^\bullet$. By the arguments in the second paragraph of the proof we obtain a morphism $s : M \to K$ in $D(O_X)$ such that the composition $M \to K \to M$ is the identity on $M$. We don’t know that the diagram

$$\begin{align*}
\xymatrix{
E^\bullet & K^\bullet & K \\
| & | & | \\
\mathcal{E}^\bullet & M^\bullet & M \\
\downarrow s & \downarrow s & \\
\mathcal{E}^\bullet & M^\bullet & M
}
\end{align*}$$

commutes, but we do know it commutes after composing with the map $K \to M$. By Lemma 42.8 after shrinking $X$ we may assume that $s \circ i$ is given by a map of complexes $\sigma : E^\bullet \to K^\bullet$. By the same lemma we may assume the composition of $\sigma$ with the inclusion $K^\bullet \subset M^\bullet$ is homotopic to zero by some homotopy $\{h^i : E^i \to M^i\}$. Thus, after replacing $K^{m-1}$ by $K^{m-1} + \text{Im}(h^m)$ (note that after doing this it is still the case that $K^{m-1}$ is generated by finitely many global sections), we see that $\sigma$ itself is homotopic to zero! This means that we have a commutative solid diagram

$$\begin{align*}
\xymatrix{
E^\bullet & M & L^\bullet & \mathcal{E}^\bullet[1] \\
| & | & | & | \\
\mathcal{E}^\bullet & K & \sigma_{\leq m-1}K^\bullet & \mathcal{E}^\bullet[1] \\
| & | & | & | \\
\mathcal{E}^\bullet & M & L^\bullet & \mathcal{E}^\bullet[1]
}
\end{align*}$$

By the axioms of triangulated categories we obtain a dotted arrow fitting into the diagram. Looking at cohomology sheaves in degree $m - 1$ we see that we obtain

$$\begin{align*}
H^{m-1}(M) & \to H^{m-1}(L^\bullet) & \to H^m(\mathcal{E}^\bullet) \\
H^{m-1}(K) & \to H^{m-1}(\sigma_{\leq m-1}K^\bullet) & \to H^m(\mathcal{E}^\bullet) \\
H^{m-1}(M) & \to H^{m-1}(L^\bullet) & \to H^m(\mathcal{E}^\bullet)
\end{align*}$$

Since the vertical compositions are the identity in both the left and right column, we conclude the vertical composition $H^{m-1}(\mathcal{E}^\bullet) \to H^{m-1}(\sigma_{\leq m-1}K^\bullet) \to H^{m-1}(L^\bullet)$ in the middle is surjective! In particular $H^{m-1}(\sigma_{\leq m-1}K^\bullet) \to H^{m-1}(L^\bullet)$ is surjective. Using the induced map of long exact sequences of cohomology sheaves from the morphism of triangles above, a diagram chase shows this implies $H^i(K) \to H^i(M)$ is an isomorphism for $i \geq m$ and surjective for $i = m - 1$. By construction we can choose an $r \geq 0$ and a surjection $O_X^{\oplus r} \to K^m$. Then the composition

$$(O_X^{\oplus r} \to E^m \to E^{m+1} \to \ldots) \to K \to M$$

induces an isomorphism on cohomology sheaves in degrees $\geq m$ and a surjection in degree $m - 1$ and the proof is complete. \qed
0DJI **Lemma 46.8.** Let \((X, \mathcal{O}_X)\) be a ringed space. Let \((K_n)_{n \in \mathbb{N}}\) be a system of perfect objects of \(D(\mathcal{O}_X)\). Let \(K = \text{hocolim}_n K_n\) be the derived colimit (Derived Categories, Definition 33.1). Then for any object \(E\) of \(D(\mathcal{O}_X)\) we have
\[
R\text{Hom}(K, E) = R\lim_n E \otimes_{\mathcal{O}_X} K_n^\vee
\]
where \((K_n^\vee)\) is the inverse system of dual perfect complexes.

**Proof.** By Lemma 46.4 we have \(R\lim_n E \otimes_{\mathcal{O}_X} K_n^\vee = R\lim_n R\text{Hom}(K_n, E)\) which fits into the distinguished triangle
\[
R\lim_n R\text{Hom}(K_n, E) \to \prod_n R\text{Hom}(K_n, E) \to \prod_n R\text{Hom}(K_n, E)
\]
Because \(K\) similarly fits into the distinguished triangle \(\bigoplus K_n \to \bigoplus K_n \to K\) it suffices to show that \(\prod_n R\text{Hom}(K_n, E) = R\text{Hom}(\bigoplus K_n, E)\). This is a formal consequence of (38.0.1) and the fact that derived tensor product commutes with direct sums. \(\square\)

0FPE We characterize invertible objects in the derived category of a ringed space (both in the case where the stalks of the structure sheaf are local and where not).

0FPF **Lemma 47.1.** Let \((X, \mathcal{O}_X)\) be a ringed space. Set \(R = \Gamma(X, \mathcal{O}_X)\). The category of \(\mathcal{O}_X\)-modules which are summands of finite free \(\mathcal{O}_X\)-modules is equivalent to the category of finite projective \(R\)-modules.

**Proof.** Observe that a finite projective \(R\)-module is the same thing as a summand of a finite free \(R\)-module. The equivalence is given by the functor \(\mathcal{E} \mapsto \Gamma(X, \mathcal{E})\). The inverse functor is given by the construction of Modules, Lemma 10.5. \(\square\)

0FPG **Lemma 47.2.** Let \((X, \mathcal{O}_X)\) be a ringed space. Let \(M\) be an object of \(D(\mathcal{O}_X)\). The following are equivalent
1. \(M\) is invertible in \(D(\mathcal{O}_X)\), see Categories, Definition 41.4
2. there is a locally finite direct product decomposition
\[
\mathcal{O}_X = \prod_{n \in \mathbb{Z}} \mathcal{O}_n
\]
and for each \(n\) there is an invertible \(\mathcal{O}_n\)-module \(\mathcal{H}^n\) (Modules, Definition 23.1) and \(M = \bigoplus \mathcal{H}^n[-n]\) in \(D(\mathcal{O}_X)\).

If (1) and (2) hold, then \(M\) is a perfect object of \(D(\mathcal{O}_X)\). If \(\mathcal{O}_{X,x}\) is a local ring for all \(x \in X\) these condition are also equivalent to
3. there exists an open covering \(X = \bigcup U_i\) and for each \(i\) an integer \(n_i\) such that \(M|_{U_i}\) is represented by an invertible \(\mathcal{O}_{U_i}\)-module placed in degree \(n_i\).

**Proof.** Assume (2). Consider the object \(R\text{Hom}(M, \mathcal{O}_X)\) and the composition map
\[
R\text{Hom}(M, \mathcal{O}_X) \otimes_{\mathcal{O}_X} M \to \mathcal{O}_X
\]
To prove this is an isomorphism, we may work locally. Thus we may assume \(\mathcal{O}_X = \prod_{a \leq n \leq b} \mathcal{O}_n\) and \(M = \bigoplus_{a \leq n \leq b} \mathcal{H}^n[-n]\). Then it suffices to show that
\[
R\text{Hom}(\mathcal{H}^n, \mathcal{O}_X) \otimes_{\mathcal{O}_X} \mathcal{H}^n
\]
is zero if \(n \neq m\) and equal to \(\mathcal{O}_n\) if \(n = m\). The case \(n \neq m\) follows from the fact that \(\mathcal{O}_n\) and \(\mathcal{O}_m\) are flat \(\mathcal{O}_X\)-algebras with \(\mathcal{O}_n \otimes_{\mathcal{O}_X} \mathcal{O}_m = 0\). Using the local structure of invertible \(\mathcal{O}_X\)-modules (Modules, Lemma 23.2) and working locally
the isomorphism in case $n = m$ follows in a straightforward manner; we omit the
details. Because $D(\mathcal{O}_X)$ is symmetric monoidal, we conclude that $M$ is invertible.

Assume (1). The description in (2) shows that we have a candidate for $\mathcal{O}_n$, namely, $\mathcal{H}om_{\mathcal{O}_X}(H^n(M), H^n(M))$. If this is a locally finite family of sheaves of
rings and if $\mathcal{O}_X = \prod \mathcal{O}_n$, then we immediately obtain the direct sum decomposition $M = \bigoplus H^n(M)[-n]$ using the idempotents in $\mathcal{O}_X$ coming from the product decomposition. This shows that in order to prove (2) we may work locally on $X$.

Choose an object $N$ of $D(\mathcal{O}_X)$ and an isomorphism $\mathcal{M} \otimes_{\mathcal{O}_X} \mathcal{N} \cong \mathcal{O}_X$. Let $x \in X$. Then $N$ is a left dual for $M$ in the monoidal category $D(\mathcal{O}_X)$ and we conclude that $M$ is perfect by Lemma 47.1. By symmetry we see that $N$ is perfect. After replacing $X$ by an open neighbourhood of $x$, we may assume $M$ and $N$ are represented by a strictly perfect complexes $\mathcal{E}^\bullet$ and $\mathcal{F}^\bullet$. Then $\mathcal{M} \otimes_{\mathcal{O}_X} \mathcal{N}$ is represented by $\text{Tot}(\mathcal{E}^\bullet \otimes_{\mathcal{O}_X} \mathcal{F}^\bullet)$. After another shrinking of $X$ we may assume the mutually inverse isomorphisms $\mathcal{O}_X \to \mathcal{M} \otimes_{\mathcal{O}_X} \mathcal{N}$ and $\mathcal{M} \otimes_{\mathcal{O}_X} \mathcal{N} \to \mathcal{O}_X$ are given by maps of complexes

$$\alpha : \mathcal{O}_X \to \text{Tot}(\mathcal{E}^\bullet \otimes_{\mathcal{O}_X} \mathcal{F}^\bullet) \quad \text{and} \quad \beta : \text{Tot}(\mathcal{E}^\bullet \otimes_{\mathcal{O}_X} \mathcal{F}^\bullet) \to \mathcal{O}_X.$$

See Lemma 42.8. Then $\beta \circ \alpha = 1$ as maps of complexes and $\alpha \circ \beta = 1$ as a morphism in $D(\mathcal{O}_X)$. After shrinking $X$ we may assume the composition $\alpha \circ \beta$ is homotopic to 1 by some homotopy $\theta$ with components

$$\theta^n : \text{Tot}^n(\mathcal{E}^\bullet \otimes_{\mathcal{O}_X} \mathcal{F}^\bullet) \to \text{Tot}^{n-1}(\mathcal{E}^\bullet \otimes_{\mathcal{O}_X} \mathcal{F}^\bullet)$$

by the same lemma as before. Set $R = \Gamma(X, \mathcal{O}_X)$. By Lemma 47.1 we find that we obtain

1. $M^\bullet = \Gamma(X, \mathcal{E}^\bullet)$ is a bounded complex of finite projective $R$-modules,
2. $N^\bullet = \Gamma(X, \mathcal{F}^\bullet)$ is a bounded complex of finite projective $R$-modules,
3. $\alpha$ and $\beta$ correspond to maps of complexes $a : R \to \text{Tot}(M^\bullet \otimes_R N^\bullet)$ and $b : \text{Tot}(M^\bullet \otimes_R N^\bullet) \to R$,
4. $\theta^n$ corresponds to a map $h^n : \text{Tot}^n(M^\bullet \otimes_R N^\bullet) \to \text{Tot}^{n-1}(M^\bullet \otimes_R N^\bullet)$, and
5. $b \circ a = 1$ and $b \circ a - 1 = dh +.hd$.

It follows that $M^\bullet$ and $N^\bullet$ define mutually inverse objects of $D(R)$. By More on Algebra, Lemma 114.4 we find a product decomposition $R = \prod_{a \leq n \leq b} R_n$ and invertible $R_n$-modules $H^n$ such that $M^\bullet \cong \bigoplus_{a \leq n \leq b} H^n[-n]$. This isomorphism in $D(R)$ can be lifted to an morphism

$$\bigoplus H^n[-n] \to M^\bullet$$

of complexes because each $H^n$ is projective as an $R$-module. Correspondingly, using Lemma 47.1 again, we obtain an morphism

$$\bigoplus H^n \otimes_R \mathcal{O}_X [-n] \to \mathcal{E}^\bullet$$

which is an isomorphism in $D(\mathcal{O}_X)$. Setting $\mathcal{O}_n = R_n \otimes_R \mathcal{O}_X$ we conclude (2) is true.

If all stalks of $\mathcal{O}_X$ are local, then it is straightforward to prove the equivalence of
(2) and (3). We omit the details. $\square$
48. Compact objects

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 36.1. On suitable ringed spaces the perfect objects are compact.

Lemma 48.1. Let $X$ be a ringed space. Let $j : U \to X$ be the inclusion of an open. The $\mathcal{O}_X$-module $j_! \mathcal{O}_U$ is a compact object of $D(\mathcal{O}_X)$ if there exists an integer $d$ such that

1. $H^p(U, \mathcal{F}) = 0$ for all $p > d$, and
2. the functors $\mathcal{F} \mapsto H^p(U, \mathcal{F})$ commute with direct sums.

Proof. Assume (1) and (2). Since $\text{Hom}(j_! \mathcal{O}_U, \mathcal{F}) = \mathcal{F}(U)$ by Sheaves, Lemma 31.8 we have $\text{Hom}(j_! \mathcal{O}_U, K) = R\Gamma(U, K)$ for $K$ in $D(\mathcal{O}_X)$. Thus we have to show that $R\Gamma(U, -)$ commutes with direct sums. The first assumption means that the functor $F = H^0(U, -)$ has finite cohomological dimension. Moreover, the second assumption implies any direct sum of injective modules is acyclic for $F$. Let $K_i$ be a family of objects of $D(\mathcal{O}_X)$. Choose $K$-injective representatives $I_i^*$ with injective terms representing $K_i$, see Injectives, Theorem 12.6. Since we may compute $RF$ by applying $F$ to any complex of acyclics (Derived Categories, Lemma 32.2) and since $\bigoplus K_i$ is represented by $\bigoplus I_i^*$ (Injectives, Lemma 13.4) we conclude that $R\Gamma(U, \bigoplus K_i)$ is represented by $\bigoplus H^0(U, I_i^*)$. Hence $R\Gamma(U, -)$ commutes with direct sums as desired. \hfill \Box

Lemma 48.2. 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.

Let $K$ be a perfect object of $D(\mathcal{O}_X)$. Then

(a) $K$ is a compact object of $D^+(\mathcal{O}_X)$ in the following sense: if $M = \bigoplus_{i \in I} M_i$ is bounded below, then $\text{Hom}(K, M) = \bigoplus_{i \in I} \text{Hom}(K, M_i)$.

(b) If $X$ has finite cohomological dimension, i.e., if there exists a $d$ such that $H^i(X, \mathcal{F}) = 0$ for $i > d$, then $K$ is a compact object of $D(\mathcal{O}_X)$.

Proof. Let $K^\vee$ be the dual of $K$, see Lemma 46.4. Then we have

$$\text{Hom}_{D(\mathcal{O}_X)}(K, M) = H^0(X, K^\vee \otimes_{\mathcal{O}_X}^L M)$$

functorially in $M$ in $D(\mathcal{O}_X)$. Since $K^\vee \otimes_{\mathcal{O}_X}^L$ commutes with direct sums it suffices to show that $R\Gamma(X, -)$ commutes with the relevant direct sums.

Proof of (b). Since $R\Gamma(X, K) = R\text{Hom}(\mathcal{O}_X, K)$ and since $H^p(X, -)$ commutes with direct sums by Lemma 19.1 this is a special case of Lemma 48.1.

Proof of (a). Let $\mathcal{I}_i$, $i \in I$ be a collection of injective $\mathcal{O}_X$-modules. By Lemma 19.1 we see that

$$H^p(X, \bigoplus_{i \in I} \mathcal{I}_i) = \bigoplus_{i \in I} H^p(X, \mathcal{I}_i) = 0$$

for all $p$. Now if $M = \bigoplus M_i$ is as in (a), then we see that there exists an $a \in \mathbb{Z}$ such that $H^n(M_i) = 0$ for $n < a$. Thus we can choose complexes of injective $\mathcal{O}_X$-modules $\mathcal{I}_i^*$ representing $M_i$ with $\mathcal{I}_i^n = 0$ for $n < a$, see Derived Categories,
Lemma [18.3]. By Injectives, Lemma [13.4] we see that the direct sum complex $\bigoplus I^\bullet$ represents $M$. By Leray acyclicity (Derived Categories, Lemma [16.7]) we see that $R\Gamma(X, M) = \bigoplus \Gamma(X, I^\bullet) = \bigoplus R\Gamma(X, M_i)$ as desired. □

49. Projection formula

In this section we collect variants of the projection formula. The most basic version is Lemma [49.2]. After we state and prove it, we discuss a more general version involving perfect complexes.

Lemma 49.1. Let $X$ be a ringed space. Let $I$ be an injective $\mathcal{O}_X$-module. Let $E$ be an $\mathcal{O}_X$-module. Assume $E$ is finite locally free on $X$, see Modules, Definition [14.1]. Then $E \otimes \mathcal{O}_X I$ is an injective $\mathcal{O}_X$-module.

Proof. This is true because under the assumptions of the lemma we have $\text{Hom}_{\mathcal{O}_X}(F, E \otimes \mathcal{O}_X I) = \text{Hom}_{\mathcal{O}_X}(F \otimes \mathcal{O}_X E^\vee, I)$ where $E^\vee = \text{Hom}_{\mathcal{O}_X}(E, \mathcal{O}_X)$ is the dual of $E$ which is finite locally free also. Since tensoring with a finite locally free sheaf is an exact functor we win by Homology, Lemma [27.2]. □

Lemma 49.2. Let $f : X \to Y$ be a morphism of ringed spaces. Let $F$ be an $\mathcal{O}_X$-module. Let $E$ be an $\mathcal{O}_Y$-module. Assume $E$ is finite locally free on $Y$, see Modules, Definition [14.1]. Then there exist isomorphisms

$$E \otimes_{\mathcal{O}_Y} R^q f_* F \to R^q f_*(E \otimes_{\mathcal{O}_X} f^* F)$$

for all $q \geq 0$. In fact there exists an isomorphism

$$E \otimes_{\mathcal{O}_Y} Rf_* F \to Rf_*(E \otimes_{\mathcal{O}_X} F)$$

in $D^+(Y)$ functorial in $F$.

Proof. Choose an injective resolution $F \to I^\bullet$ on $X$. Note that $f^* E$ is finite locally free also, hence we get a resolution

$$f^* E \otimes_{\mathcal{O}_X} F \to f^* E \otimes_{\mathcal{O}_X} I^\bullet$$

which is an injective resolution by Lemma [49.1]. Apply $f_*$ to see that

$$Rf_*(f^* E \otimes_{\mathcal{O}_X} F) = f_*(f^* E \otimes_{\mathcal{O}_X} I^\bullet).$$

Hence the lemma follows if we can show that $f_*(f^* E \otimes_{\mathcal{O}_X} F) = E \otimes_{\mathcal{O}_Y} f_*(F)$ functorially in the $\mathcal{O}_X$-module $F$. This is clear when $E = \mathcal{O}_Y^\oplus$, and follows in general by working locally on $Y$. Details omitted. □

Let $f : X \to Y$ 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

$$Rf_* E \otimes_{\mathcal{O}_Y} Lf^* K \to Rf_*(E \otimes_{\mathcal{O}_X} Lf^* K)$$

Namely, it is the adjoint to the canonical map

$$Lf^*(Rf_* E \otimes_{\mathcal{O}_Y} K) = Lf^* Rf_* E \otimes_{\mathcal{O}_X} Lf^* K \to E \otimes_{\mathcal{O}_X} Lf^* K$$

coming from the map $Lf^* Rf_* E \to E$ and Lemmas [27.3] and [28.1] A reasonably general version of the projection formula is the following.
Lemma 49.3. Let $f : X \to Y$ 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

$$Rf_* E \otimes_{\mathcal{O}_Y} K = Rf_*(E \otimes_{\mathcal{O}_X} Lf^* K)$$

in $D(\mathcal{O}_Y)$.

Proof. To check (49.2.1) is an isomorphism we may work locally on $Y$, i.e., we have to find a covering $\{V_j \to Y\}$ 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. \hfill \qed

Here is a case where the projection formula is true in complete generality.

Lemma 49.4. Let $f : X \to Y$ be a morphism of ringed spaces such that $f$ is a homeomorphism onto a closed subset. Then (49.2.1) 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 $K^\bullet$ of $\mathcal{O}_Y$-modules representing $K$ and choose any complex $E^\bullet$ of $\mathcal{O}_X$-modules representing $E$. Then $Lf^* K$ is represented by $f^* K^\bullet$ which is a K-flat complex of $\mathcal{O}_X$-modules (Lemma 26.7). Thus the right hand side of (49.2.1) is represented by

$$f_* \text{Tot}(E^\bullet \otimes_{\mathcal{O}_X} f^* K^\bullet)$$

By the same reasoning we see that the left hand side is represented by

$$\text{Tot}(f_* E^\bullet \otimes_{\mathcal{O}_Y} K^\bullet)$$

Since $f_*$ commutes with direct sums (Modules, Lemma 6.3) it suffices to show that

$$f_*(E \otimes_{\mathcal{O}_X} f^* K) = f_* E \otimes_{\mathcal{O}_Y} K$$

for any $\mathcal{O}_X$-module $E$ and $\mathcal{O}_Y$-module $K$. 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. \hfill \qed

Remark 49.5. The map (49.2.1) is compatible with the base change map of Remark 28.3 in the following sense. Namely, suppose that

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

then

$$Rf'_* \left( Rf_* E \otimes_{\mathcal{O}_Y} K \right) = Rf'_* \left( \text{Tot}(E \otimes_{\mathcal{O}_X} Lf^* K) \right).$$
is a commutative diagram of ringed spaces. Let \( E \in D(\mathcal{O}_X) \) and \( K \in D(\mathcal{O}_Y) \). Then the diagram

\[
\begin{align*}
Lg^*(Rf_*E \otimes_{\mathcal{O}_Y} K) \ar[r]^p \ar[d]_t & Lg^*Rf_*(E \otimes_{\mathcal{O}_X} Lf^*K) \ar[d]^b \\
Lg^*Rf_*E \otimes_{\mathcal{O}_Y} Lg^*K \ar[d]_b & Rf'_*(L(g')^*(E \otimes_{\mathcal{O}_X} Lf^*K)) \ar[d]^t \\
Rf'_*(L(g')^*E \otimes_{\mathcal{O}_Y} Lg^*K) \ar[r]^p & Rf'_*(L(g')^*E \otimes_{\mathcal{O}_Y} Lg^*K)
\end{align*}
\]

is commutative. Here arrows labeled \( t \) are gotten by an application of Lemma 27.3, arrows labeled \( b \) by an application of Remark 28.3, arrows labeled \( p \) by an application of (49.2.1), and \( c \) comes from \( L(g')^* \circ Lf^* = L(f')^* \circ Lg^* \). We omit the verification.

50. Other chapters

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