DIFFERENTIAL GRADED SHEAVES

0FQS

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1. Introduction

This chapter is a continuation of the discussion started in Differential Graded Algebra, Section 1. A survey paper is [Kel06].

2. Conventions

In this chapter we hold on to the convention that a ring means commutative ring with 1. If \( R \) is a ring, then an \( R \)-algebra \( A \) will be an \( R \)-module \( A \) endowed with an \( R \)-bilinear map \( A \times A \rightarrow A \) (multiplication) such that multiplication is associative and has an identity. In other words, these are unital associative \( R \)-algebras such that the structure map \( R \rightarrow A \) maps into the center of \( A \).

3. Sheaves of graded algebras

Please skip this section.

Definition 3.1. Let \((\mathcal{C},\mathcal{O})\) be a ringed site. A sheaf of graded \(\mathcal{O}\)-algebras or a sheaf of graded algebras on \((\mathcal{C},\mathcal{O})\) is given by a family \(A_n\) indexed by \(n \in \mathbb{Z}\) of \(\mathcal{O}\)-modules endowed with \(\mathcal{O}\)-bilinear maps
\[
A_n \times A_m \rightarrow A_{n+m}, \quad (a,b) \mapsto ab
\]
called the multiplication maps with the following properties

1. multiplication is associative, and
2. there is a global section \(1\) of \(A_0\) which is a two-sided identity for multiplication.

We often denote such a structure \(A\). A homomorphism of graded \(\mathcal{O}\)-algebras \(f : A \rightarrow B\) is a family of maps \(f^n : A^n \rightarrow B^n\) of \(\mathcal{O}\)-modules compatible with the multiplication maps.

Given a graded \(\mathcal{O}\)-algebra \(A\) and an object \(U \in \text{Ob}(\mathcal{C})\) we use the notation
\[
A(U) = \Gamma(U, A) = \bigoplus_{n \in \mathbb{Z}} A^n(U)
\]
This is a graded \(\mathcal{O}(U)\)-algebra.

Remark 3.2. Let \((f,f^*) : (\text{Sh}(\mathcal{C}),\mathcal{O}_\mathcal{C}) \rightarrow (\text{Sh}(\mathcal{D}),\mathcal{O}_\mathcal{D})\) be a morphism of ringed topoi. We have

1. Let \(A\) be a graded \(\mathcal{O}_\mathcal{C}\)-algebra. The multiplication maps of \(A\) induce multiplication maps \(f_*A^n \times f_*A^m \rightarrow f_*A^{n+m}\) and via \(f^*\) we may view these as \(\mathcal{O}_\mathcal{D}\)-bilinear maps. We will denote \(f_*A\) the graded \(\mathcal{O}_\mathcal{D}\)-algebra we so obtain.
2. Let \(B\) be a graded \(\mathcal{O}_\mathcal{D}\)-algebra. The multiplication maps of \(B\) induce multiplication maps \(f^*B^n \times f^*B^m \rightarrow f^*B^{n+m}\) and using \(f^*\) we may view these as \(\mathcal{O}_\mathcal{C}\)-bilinear maps. We will denote \(f^*B\) the graded \(\mathcal{O}_\mathcal{C}\)-algebra we so obtain.
3. The set of homomorphisms \(f^*B \rightarrow A\) of graded \(\mathcal{O}_\mathcal{C}\)-algebras is in 1-to-1 correspondence with the set of homomorphisms \(B \rightarrow f_*A\) of graded \(\mathcal{O}_\mathcal{C}\)-algebras.

Part (3) follows immediately from the usual adjunction between \(f^*\) and \(f_*\) on sheaves of modules.
4. Sheaves of graded modules

Definition 4.1. Let \((C, \mathcal{O})\) be a ringed site. Let \(A\) be a sheaf of graded algebras on \((C, \mathcal{O})\). A (right) graded \(A\)-module or (right) graded module over \(A\) is given by a family \(M^n\) indexed by \(n \in \mathbb{Z}\) of \(\mathcal{O}\)-modules endowed with \(\mathcal{O}\)-bilinear maps \(M^n \times A^m \to M^{n+m}\), \((x, a) \mapsto xa\)
called the multiplication maps with the following properties

1. multiplication satisfies \((xa)a' = x(aa')\),
2. the identity section \(1\) of \(A^0\) acts as the identity on \(M^n\) for all \(n\).

We often say “let \(M\) be a graded \(A\)-module” to indicate this situation. A homomorphism of graded \(A\)-modules \(f : M \to N\) is a family of maps \(f^n : M^n \to N^n\) of \(\mathcal{O}\)-modules compatible with the multiplication maps. The category of (right) graded \(A\)-modules is denoted \(\text{Mod}_A\).

We can define left graded modules in exactly the same manner but our default in the chapter will be right modules.

Given a graded \(A\)-module \(M\) and an object \(U \in \text{Ob}(C)\) we use the notation

\[ M(U) = \Gamma(U, M) = \bigoplus_{n \in \mathbb{Z}} M^n(U) \]

This is a (right) graded \(A(U)\)-module.

Lemma 4.2. Let \((C, \mathcal{O})\) be a ringed site. Let \(A\) be a graded \(\mathcal{O}\)-algebra. The category \(\text{Mod}_A\) is an abelian category with the following properties

1. \(\text{Mod}_A\) has arbitrary direct sums,
2. \(\text{Mod}_A\) has arbitrary colimits,
3. filtered colimit in \(\text{Mod}_A\) are exact,
4. \(\text{Mod}_A\) has arbitrary products,
5. \(\text{Mod}_A\) has arbitrary limits.

The functor

\[ \text{Mod}_A \to \text{Mod}(\mathcal{O}), \quad M \mapsto M^n \]
sending a graded \(A\)-module to its \(n\)th term commutes with all limits and colimits.

The lemma says that we may take limits and colimits termwise. It also says (or implies if you like) that the forgetful functor

\[ \text{Mod}_A \to \text{Mod}_{\mathcal{O}} \]

from graded \(A\)-modules to graded \(\mathcal{O}\)-modules (where \(\mathcal{O}\) is viewed as a graded \(\mathcal{O}\)-algebra sitting in degree 0) commutes with all limits and colimits.

Proof. Let us denote \(\text{gr}^n : \text{Mod}_A \to \text{Mod}(\mathcal{O})\) the functor in the statement of the lemma. Consider a homomorphism \(f : M \to N\) of graded \(A\)-modules. The kernel and cokernel of \(f\) as maps of graded \(\mathcal{O}\)-modules are additionally endowed with multiplication maps as in Definition 4.1. Hence these are also the kernel and cokernel in \(\text{Mod}_A\). Thus \(\text{Mod}_A\) is an abelian category and taking kernels and cokernels commutes with \(\text{gr}^n\).

To prove the existence of limits and colimits it is sufficient to prove the existence of products and direct sums, see Categories, Lemmas \([14.10]\) and \([14.11]\). The same
lemmas show that proving the commutation of limits and colimits with $\text{gr}^n$ follows if $\text{gr}^n$ commutes with direct sums and products.

Let $\mathcal{M}_t$, $t \in T$ be a set of graded $\mathcal{A}$-modules. Then we can consider the graded $\mathcal{A}$-module whose degree $n$ term is $\bigoplus_{t \in T} \mathcal{M}_t^n$ (with obvious multiplication maps). The reader easily verifies that this is a direct sum in $\text{Mod} \mathcal{A}$. Similarly for products.

Observe that $\text{gr}^n$ is an exact functor for all $n$ and that a complex $\mathcal{M}_1 \to \mathcal{M}_2 \to \mathcal{M}_3$ of $\text{Mod} \mathcal{A}$ is exact if and only if $\text{gr}^n \mathcal{M}_1 \to \text{gr}^n \mathcal{M}_2 \to \text{gr}^n \mathcal{M}_3$ is exact in $\text{Mod}(\mathcal{O})$ for all $n$. Hence we conclude that (3) holds as filtered colimits are exact in $\text{Mod}(\mathcal{O})$; it is a Grothendieck abelian category, see Cohomology on Sites, Section [19] \(\square\)

5. The graded category of sheaves of graded modules

0FR1 Please skip this section. This section is the analogue of Differential Graded Algebra, Example [25.6] For our conventions on graded categories, please see Differential Graded Algebra, Section [25].

Let $(\mathcal{C}, \mathcal{O})$ be a ringed site. Let $\mathcal{A}$ be a sheaf of graded algebras on $(\mathcal{C}, \mathcal{O})$. We will construct a graded category $\text{Mod}^g_{\mathcal{A}}$ over $R = \Gamma(\mathcal{C}, \mathcal{O})$ whose associated category $(\text{Mod}^g_{\mathcal{A}})^0$ is the category of graded $\mathcal{A}$-modules. As objects of $\text{Mod}^g_{\mathcal{A}}$ we take right graded $\mathcal{A}$-modules (see Section [4]). Given graded $\mathcal{A}$-modules $\mathcal{L}$ and $\mathcal{M}$ we set

$$\text{Hom}_{\text{Mod}^g_{\mathcal{A}}} (\mathcal{L}, \mathcal{M}) = \bigoplus_{n \in \mathbb{Z}} \text{Hom}^n(\mathcal{L}, \mathcal{M})$$

where $\text{Hom}^n(\mathcal{L}, \mathcal{M})$ is the set of right $\mathcal{A}$-module maps $f : \mathcal{L} \to \mathcal{M}$ which are homogeneous of degree $n$. More precisely, $f$ is given by a family of maps $f : \mathcal{L}^i \to \mathcal{M}^{i+n}$ for $i \in \mathbb{Z}$ compatible with the multiplication maps. In terms of components, we have that

$$\text{Hom}^n(\mathcal{L}, \mathcal{M}) \subset \prod_{p+q = n} \text{Hom}_{\mathcal{O}} (\mathcal{L}^{-q}, \mathcal{M}^p)$$

(observe reversal of indices) is the subset consisting of those $f = \langle f_{p,q} \rangle$ such that

$$f_{p,q}(ma) = f_{p-i,q+p}(m)a$$

for local sections $a$ of $\mathcal{A}^i$ and $m$ of $\mathcal{L}^{-q-i}$. For graded $\mathcal{A}$-modules $\mathcal{K}$, $\mathcal{L}$, $\mathcal{M}$ we define composition in $\text{Mod}^g_{\mathcal{A}}$ via the maps

$$\text{Hom}^m(\mathcal{L}, \mathcal{M}) \times \text{Hom}^n(\mathcal{K}, \mathcal{L}) \to \text{Hom}^{m+n}(\mathcal{K}, \mathcal{M})$$

by simple composition of right $\mathcal{A}$-module maps: $(g, f) \mapsto g \circ f$.

6. Tensor product for sheaves of graded modules

0FR2 Please skip this section. This section is the analogue of part of Differential Graded Algebra, Section [12].

Let $(\mathcal{C}, \mathcal{O})$ be a ringed site. Let $\mathcal{A}$ be a sheaf of graded algebras on $(\mathcal{C}, \mathcal{O})$. Let $\mathcal{M}$ be a right graded $\mathcal{A}$-module and let $\mathcal{N}$ be a left graded $\mathcal{A}$-module. Then we define the tensor product $\mathcal{M} \otimes_{\mathcal{A}} \mathcal{N}$ to be the graded $\mathcal{O}$-module whose degree $n$ term is

$$(\mathcal{M} \otimes_{\mathcal{A}} \mathcal{N})^n = \text{Coker} \left( \bigoplus_{r+s+t = n} \mathcal{M}^r \otimes_{\mathcal{O}} \mathcal{A}^s \otimes_{\mathcal{O}} \mathcal{N}^t \rightarrow \bigoplus_{p+q = n} \mathcal{M}^p \otimes_{\mathcal{O}} \mathcal{N}^q \right)$$

where the map sends the local section $x \otimes a \otimes y$ of $\mathcal{M}^r \otimes_{\mathcal{O}} \mathcal{A}^s \otimes_{\mathcal{O}} \mathcal{N}^t$ to $xa \otimes y - x \otimes ay$. With this definition we have that $(\mathcal{M} \otimes_{\mathcal{A}} \mathcal{N})^n$ is the sheafification of the presheaf $U \mapsto (\mathcal{M}(U) \otimes_{\mathcal{A}(U)} \mathcal{N}(U))^n$ where the tensor product of graded modules is as defined in Differential Graded Algebra, Section [12].
If we fix the left graded $A$-module $N$ we obtain a functor
\[- \otimes_A N : \text{Mod}_A \to \text{Mod}_O\]
where on the right hand side we have the category of graded $O$-modules where $O$ is viewed as a graded $O$-algebra (sitting in degree 0 to be sure). This can be upgraded to a functor of graded categories
\[- \otimes_A N : \text{Mod}^{gr}_A \to \text{Mod}^{gr}_O\]
by sending homomorphisms of degree $n$ from $M \to M'$ to the induced map of degree $n$ from $M \otimes_A N$ to $M' \otimes_A N$.

7. Internal hom for sheaves of graded modules

We urge the reader to skip this section.

We are going to need the sheafified version of the construction in Section 5. Let $(\mathcal{C}, \mathcal{O}), A, M, L$ be as in Section 5. Then we define
\[\text{Hom}^{gr}_A(M, L)\]
as the graded $O$-module whose degree $n$ term
\[\text{Hom}^n_A(M, L) \subset \prod_{p+q=n} \text{Hom}_O(L^{-q}, M^p)\]
is the subsheaf consisting of those local sections $f = (f_{p,q})$ such that
\[f_{p,q}(ma) = f_{p-i,q+i}(m)a\]
for local sections $a$ of $A^i$ and $m$ of $L^{-q-i}$. As in Section 5 there is a composition map
\[\text{Hom}^{gr}_A(L, M) \otimes_O \text{Hom}^{gr}_A(K, L) \to \text{Hom}^{gr}_A(K, M)\]
where the left hand side is the tensor product of graded $O$-modules defined in Section 6. This map is given by the composition map
\[\text{Hom}^n_A(L, M) \otimes_O \text{Hom}^m_A(K, L) \to \text{Hom}^{n+m}_A(K, M)\]
defined by simple composition (locally).

With these definitions we have
\[\text{Hom}_{\text{Mod}^{gr}_A}(L, M) = \Gamma(\mathcal{C}, \text{Hom}^{gr}_A(L, M))\]
as graded $R$-modules compatible with composition.

8. Sheaves of graded bimodules and tensor-hom adjunction

We urge the reader to skip this section.

Definition 8.1. Let $(\mathcal{C}, \mathcal{O})$ be a ringed site. Let $A$ and $B$ be a sheaves of graded algebras on $(\mathcal{C}, \mathcal{O})$. A graded $(A, B)$-bimodule is given by a family $M^n$ indexed by $n \in \mathbb{Z}$ of $O$-modules endowed with $O$-bilinear maps
\[M^n \times B^m \to M^{n+m}, \quad (x, b) \mapsto xb\]
and
\[A^n \times M^m \to M^{n+m}, \quad (a, x) \mapsto ax\]
called the multiplication maps with the following properties
1. multiplication satisfies $a(a'x) = (aa')x$ and $(xa)b' = x(ab')$,
2. $(ax)b = a(xb)$,
Let multiplication maps.

We often denote such a structure

This is a graded

Let \((C, O)\) be a sheaves of graded algebras on \((C, O)\).

Let \( \mathcal{M} \) be a right graded \( \mathcal{A} \)-module and let \( \mathcal{N} \) be a graded \( (\mathcal{A}, \mathcal{B}) \)-bimodule. In this case the graded tensor product defined in Section 6

is a right graded \( \mathcal{B} \)-module with obvious multiplication maps. This construction defines a functor and a functor of graded categories

by sending homomorphisms of degree \( n \) from \( \mathcal{M} \to \mathcal{M}' \) to the induced map of degree \( n \) from \( \mathcal{M} \otimes_{\mathcal{A}} \mathcal{N} \) to \( \mathcal{M}' \otimes_{\mathcal{A}} \mathcal{N} \).

Let \((C, O)\) be a sheaves of graded algebras on \((C, O)\).

Let \( \mathcal{N} \) be a graded \( (\mathcal{A}, \mathcal{B}) \)-bimodule. Let \( \mathcal{L} \) be a right graded \( \mathcal{B} \)-module. In this case the graded internal hom defined in Section 7

is a right graded \( \mathcal{A} \)-module with multiplication maps. This construction defines a functor and a functor of graded categories

by sending homomorphisms of degree \( n \) from \( \mathcal{M} \to \mathcal{M}' \) to the induced map of degree \( n \) from \( \mathcal{M} \otimes_{\mathcal{A}} \mathcal{N} \) to \( \mathcal{M}' \otimes_{\mathcal{A}} \mathcal{N} \).

We omit the verification that this is well defined. This construction defines a functor and a functor of graded categories

by sending homomorphisms of degree \( n \) from \( \mathcal{L} \to \mathcal{L}' \) to the induced map of degree \( n \) from \( \mathcal{M} \otimes_{\mathcal{A}} \mathcal{N} \) to \( \mathcal{M}' \otimes_{\mathcal{A}} \mathcal{N} \).

**Lemma 8.2.** Let \((C, O)\) be a sheaves of graded algebras on \((C, O)\). Let \( \mathcal{M} \) be a right graded \( \mathcal{A} \)-module. Let \( \mathcal{N} \) be a graded \( (\mathcal{A}, \mathcal{B}) \)-bimodule. Let \( \mathcal{L} \) be a right graded \( \mathcal{B} \)-module. With conventions as above we have

\[ \text{Hom}_{\mathcal{M} \otimes_{\mathcal{A}} \mathcal{N}, \mathcal{L}} = \text{Hom}_{\mathcal{M}, \text{Hom}_{\mathcal{B}}(\mathcal{N}, \mathcal{L})} \]

and

\[ \text{Hom}_{\mathcal{B}}(\mathcal{M} \otimes_{\mathcal{A}} \mathcal{N}, \mathcal{L}) = \text{Hom}_{\mathcal{A}}(\mathcal{M}, \text{Hom}_{\mathcal{B}}(\mathcal{N}, \mathcal{L})) \]

functorially in \( \mathcal{M}, \mathcal{N}, \mathcal{L} \).

Our conventions are here that this does not involve any signs.
Proof. Omitted. Hint: This follows by interpreting both sides as $\mathcal{A}$-bilinear graded maps $\psi: \mathcal{M} \times \mathcal{N} \to \mathcal{L}$ which are $\mathcal{B}$-linear on the right. □

Let $(\mathcal{C}, \mathcal{O})$ be a ringed site. Let $\mathcal{A}$ and $\mathcal{B}$ be a sheaves of graded algebras on $(\mathcal{C}, \mathcal{O})$. Let $\mathcal{A}$ and $\mathcal{B}$ be graded $\mathcal{O}$-algebras. Then we obtain a functor and a functor of graded categories

$$\otimes_{\mathcal{A}, \varphi} \mathcal{B} : \text{Mod}_\mathcal{A} \to \text{Mod}_\mathcal{B} \quad \text{and} \quad \otimes_{\mathcal{A}, \varphi} \mathcal{M} : \text{Mod}_\mathcal{A} \to \text{Mod}_\mathcal{B}$$

On the other hand, we have the restriction functors

$$\text{res}_\varphi : \text{Mod}_\mathcal{B} \to \text{Mod}_\mathcal{A} \quad \text{and} \quad \text{res}_\varphi : \text{Mod}_\mathcal{B} \to \text{Mod}_\mathcal{A}$$

We can use the lemma above to show these functors are adjoint to each other (as usual with restriction and base change). Namely, let us write $\mathcal{A}\mathcal{B}$ for $\mathcal{B}$ viewed as a graded $\mathcal{A}$-module. Then for any right graded $\mathcal{B}$-module $L$ we have

$$\text{Hom}(\mathcal{A}\mathcal{B}, L) = \text{res}_\varphi(L)$$

as right graded $\mathcal{A}$-modules. Thus Lemma 8.2 tells us that we have a functorial isomorphism

$$\text{Hom}(\mathcal{M} \otimes_{\mathcal{A}, \varphi} \mathcal{B}, L) = \text{Hom}(\mathcal{M}, \text{res}_\varphi(L))$$

We usually drop the dependence on $\varphi$ in this formula if it is clear from context. In the same manner we obtain the equality

$$\text{Hom}(\mathcal{M} \otimes_{\mathcal{A}} \mathcal{B}, L) = \text{Hom}(\mathcal{M}, L)$$

of graded $\mathcal{O}$-modules.

9. Pull and push for sheaves of graded modules

We advise the reader to skip this section.

Let $(f, f^\sharp) : (\text{Sh}(\mathcal{C}), \mathcal{O}_\mathcal{C}) \to (\text{Sh}(\mathcal{D}), \mathcal{O}_\mathcal{D})$ be a morphism of ringed topoi. Let $\mathcal{A}$ be a graded $\mathcal{O}_\mathcal{C}$-algebra. Let $\mathcal{B}$ be a graded $\mathcal{O}_\mathcal{D}$-algebra. Suppose we are given a map $\varphi : f^{-1}\mathcal{B} \to \mathcal{A}$ of graded $f^{-1}\mathcal{O}_\mathcal{D}$-algebras. By the adjunction of restriction and extension of scalars, this is the same thing as a map $\varphi : f^*\mathcal{B} \to \mathcal{A}$ of graded $\mathcal{O}_\mathcal{C}$-algebras or equivalently $\varphi$ can be viewed as a map

$$\varphi : \mathcal{B} \to f_*\mathcal{A}$$

of graded $\mathcal{O}_\mathcal{D}$-algebras. See Remark 3.2.

Let us define a functor

$$f_* : \text{Mod}_{\mathcal{A}} \to \text{Mod}_{\mathcal{B}}$$

Given a graded $\mathcal{A}$-module $\mathcal{M}$ we define $f_*\mathcal{M}$ to be the graded $\mathcal{B}$-module whose degree $n$ term is $f_*\mathcal{M}^n$. As multiplication we use

$$f_*\mathcal{M}^n \times \mathcal{B}^m \stackrel{(id, \varphi^n)}{\longrightarrow} f_*\mathcal{M}^n \times f_*\mathcal{A}^m \stackrel{f_*\mu_{n,m}}{\longrightarrow} f_*\mathcal{M}^{n+m}$$

where $\mu_{n,m} : \mathcal{M}^n \times \mathcal{A}^m \to \mathcal{M}^{n+m}$ is the multiplication map for $\mathcal{M}$ over $\mathcal{A}$. This uses that $f_*$ commutes with products. The construction is clearly functorial in $\mathcal{M}$ and we obtain our functor.

Let us define a functor

$$f^* : \text{Mod}_{\mathcal{B}} \to \text{Mod}_{\mathcal{A}}$$
We will define this functor as a composite of functors
\[ \text{Mod}_B \xrightarrow{f^{-1}} \text{Mod}_{f^{-1}B} \xrightarrow{- \otimes_{f^{-1}B} A} \text{Mod}_A \]
First, given a graded \( B \)-module \( N \) we define \( f^{-1}N \) to be the graded \( f^{-1}B \)-module whose degree \( n \) term is \( f^{-1}N^n \). As multiplication we use \( f^{-1} \nu_{n,m} : f^{-1}N^n \times f^{-1}B^m \to f^{-1}N^{n+m} \) where \( \nu_{n,m} : N^n \times B^m \to N^{n+m} \) is the multiplication map for \( N \) over \( B \). This uses that \( f^{-1} \) commutes with products. The construction is clearly functorial in \( N \) and we obtain our functor \( f^{-1} \). Having said this, we can use the tensor product discussion in Section 8 to define the functor
\[ - \otimes_{f^{-1}B} A : \text{Mod}_{f^{-1}B} \longrightarrow \text{Mod}_A \]
Finally, we set
\[ f^*N = f^{-1}N \otimes_{f^{-1}B} A \]
as already foretold above.

The functors \( f_* \) and \( f^* \) are readily enhanced to give functors of graded categories
\[ f_* : \text{Mod}_A^{gr} \longrightarrow \text{Mod}_B^{gr} \quad \text{and} \quad f^* : \text{Mod}_B^{gr} \longrightarrow \text{Mod}_A^{gr} \]
which do the same thing on underlying objects and are defined by functoriality of the constructions on homogenous morphisms of degree \( n \).

**Lemma 9.1.** In the situation above we have
\[ \text{Hom}_{\text{Mod}_B^{gr}}(N, f_* M) = \text{Hom}_{\text{Mod}_A^{gr}}(f^* N, M) \]

**Proof.** Omitted. Hints: First prove that \( f^{-1} \) and \( f_* \) are adjoint as functors between \( \text{Mod}_B \) and \( \text{Mod}_{f^{-1}B} \) using the adjunction between \( f^{-1} \) and \( f_* \) on sheaves of abelian groups. Next, use the adjunction between base change and restriction given in Section 8. \( \square \)

**10. Localization and sheaves of graded modules**

We advise the reader to skip this section.

Let \( (\mathcal{C}, \mathcal{O}) \) be a ringed site. Let \( U \in \text{Ob}(\mathcal{C}) \) and denote
\[ j : (\text{Sh}(\mathcal{C}/U), \mathcal{O}_U) \longrightarrow (\text{Sh}(\mathcal{C}), \mathcal{O}) \]
the corresponding localization morphism (Modules on Sites, Section 19). Below we will use the following fact: for \( \mathcal{O}_U \)-modules \( \mathcal{M}_i, i = 1, 2 \) and a \( \mathcal{O} \)-module \( \mathcal{A} \) there is a canonical map
\[ j_! : \text{Hom}_{\mathcal{O}_U}(\mathcal{M}_1 \otimes_{\mathcal{O}_U} \mathcal{A}|_U, \mathcal{M}_2) \longrightarrow \text{Hom}_{\mathcal{O}}(j_! \mathcal{M}_1 \otimes_{\mathcal{O}} \mathcal{A}, j_! \mathcal{M}_2) \]
Namely, we have \( j_!(\mathcal{M}_1 \otimes_{\mathcal{O}_U} \mathcal{A}|_U) = j_! \mathcal{M}_1 \otimes_{\mathcal{O}} \mathcal{A} \) by Modules on Sites, Lemma 27.7.

Let \( \mathcal{A} \) be a graded \( \mathcal{O} \)-algebra. We will denote \( \mathcal{A}_U \) the restriction of \( \mathcal{A} \) to \( \mathcal{C}/U \), in other words, we have \( \mathcal{A}_U = j^* \mathcal{A} = j^{-1} \mathcal{A} \). In Section 9 we have constructed adjoint functors
\[ j_* : \text{Mod}^{gr}_{\mathcal{A}_U} \longrightarrow \text{Mod}^{gr}_B \quad \text{and} \quad j^* : \text{Mod}^{gr}_{\mathcal{A}} \longrightarrow \text{Mod}^{gr}_{\mathcal{A}_U} \]
with \( j^* \) left adjoint to \( j_* \). We claim there is in addition an exact functor
\[ j_! : \text{Mod}^{gr}_{\mathcal{A}_U} \longrightarrow \text{Mod}^{gr}_{\mathcal{A}} \]
left adjoint to \( j^* \). Namely, given a graded \( A_U \)-module \( M \) we define \( j_! M \) to be the graded \( A \)-module whose degree \( n \) term is \( j_! M^n \). As multiplication map we use

\[
\mu_{n,m} : j_! M^n \times A^m \to j_! M^{n+m}
\]

where \( \mu_{m,n} : M^n \times A^m \to M^{n+m} \) is the given multiplication map. Given a homogeneous map \( f : M \to M' \) of degree \( n \) of graded \( A_U \)-modules, we obtain a homogeneous map \( j_! f : j_! M \to j_! M' \) of degree \( n \). Thus we obtain our functor.

**Lemma 10.1.** In the situation above we have

\[
\text{Hom}_{\text{Mod}^{gr}_A}(j_! M, \mathcal{N}) = \text{Hom}_{\text{Mod}^{gr}_{A_U}}(M, j^* \mathcal{N})
\]

**Proof.** By the discussion in Modules on Sites, Section 19 the functors \( j_! \) and \( j^* \) on \( \mathcal{O} \)-modules are adjoint. Thus if we only look at the \( \mathcal{O} \)-module structures we know that

\[
\text{Hom}_{\text{Mod}^{gr}_A}(j_! M, \mathcal{N}) = \text{Hom}_{\text{Mod}^{gr}_{A_U}}(M, j^* \mathcal{N})
\]

Then one has to check that these identifications map the \( \mathcal{O} \)-module maps on the left hand side to the \( \mathcal{O} \)-module maps on the right hand side. To check this, given \( \mathcal{O}_U \)-linear maps \( f^n : M^n \to j^* \mathcal{N}^{n+d} \) corresponding to \( \mathcal{O} \)-linear maps \( g^n : j_! M^n \to \mathcal{N}^{n+d} \) it suffices to show that

\[
\begin{array}{ccc}
M^n \otimes_{\mathcal{O}_U} A^m & \xrightarrow{f^n \otimes 1} & j^* \mathcal{N}^{n+d} \otimes_{\mathcal{O}_U} A^m \\
\downarrow & & \downarrow \\
M^{n+m} & \xrightarrow{f^{n+m}} & j^* \mathcal{N}^{n+m+d}
\end{array}
\]

commutes if and only if

\[
\begin{array}{ccc}
j_! M^n \otimes_{\mathcal{O}} A^m & \xrightarrow{g^n \otimes 1} & \mathcal{N}^{n+d} \otimes_{\mathcal{O}} A^m \\
\downarrow & & \downarrow \\
j_! M^{n+m} & \xrightarrow{g^{n+m}} & \mathcal{N}^{n+m+d}
\end{array}
\]

commutes. However, we know that

\[
\text{Hom}_{\mathcal{O}_U}(\mathcal{M}^n \otimes_{\mathcal{O}_U} A^m, j^* \mathcal{N}^{n+d+m}) = \text{Hom}_{\mathcal{O}}(j_!(\mathcal{M}^n \otimes_{\mathcal{O}_U} A^m), \mathcal{N}^{n+d+m}) = \text{Hom}_{\mathcal{O}}(j_! M^n \otimes_{\mathcal{O}} A^m, \mathcal{N}^{n+d+m})
\]

by the already used Modules on Sites, Lemma 27.7. We omit the verification that shows that the obstruction to the commutativity of the first diagram in the first group maps to the obstruction to the commutativity of the second diagram in the last group.

**Lemma 10.2.** In the situation above, let \( M \) be a right graded \( A_U \)-module and let \( \mathcal{N} \) be a left graded \( A \)-module. Then

\[
j_! M \otimes_A \mathcal{N} = j_!(M \otimes_{A_U} \mathcal{N}|_U)
\]

as graded \( \mathcal{O} \)-modules functorially in \( M \) and \( \mathcal{N} \).

**Proof.** Recall that the degree \( n \) component of \( j_! M \otimes_A \mathcal{N} \) is the cokernel of the canonical map

\[
\bigoplus_{r+s+t=n} j_! M^r \otimes_{\mathcal{O}} A^s \otimes_{\mathcal{O}} \mathcal{N}^t \longrightarrow \bigoplus_{p+q=n} j_! M^p \otimes_{\mathcal{O}} \mathcal{N}^q
\]
See Section 6 by Modules on Sites, Lemma 27.7 this is the same thing as the
cokernel of
$\bigoplus_{r+s+t=n} j_!(M^n \otimes_{\mathcal{O}_U} A^s|_U \otimes_{\mathcal{O}_U} N^t|_U) \to \bigoplus_{p+q=n} j_!(M^p \otimes_{\mathcal{O}_U} N^q|_U)$
and we win. An alternative proof would be to redo the Yoneda argument given in
the proof of the lemma cited above. □

11. Shift functors on sheaves of graded modules

Let $(\mathcal{C}, \mathcal{O})$ be a ringed site. Let $\mathcal{A}$ be a sheaf of graded algebras on $(\mathcal{C}, \mathcal{O})$. Let $\mathcal{M}$
be a graded $\mathcal{A}$-module. Let $k \in \mathbb{Z}$. We define the $k$th shift of $\mathcal{M}$, denoted $\mathcal{M}[k]$, to be the graded
$\mathcal{A}$-module whose $n$th part is given by
$$(\mathcal{M}[k])^n = \mathcal{M}^{n+k}$$
is the $(n+k)$th part of $\mathcal{M}$. As multiplication maps
$$(\mathcal{M}[k])^n \times \mathcal{A}^m \to (\mathcal{M}[k])^{n+m}$$
we simply use the multiplication maps
$$\mathcal{M}^{n+k} \times \mathcal{A}^m \to \mathcal{M}^{n+m+k}$$
of $\mathcal{M}$. It is clear that we have defined a functor $[k]$, that we have $[k+l] = [k] \circ [l]$, and that we have
$$\text{Hom}_{\text{Mod}_A}(\mathcal{L}, \mathcal{M}[k]) = \text{Hom}_{\text{Mod}_A}(\mathcal{L}, \mathcal{M})[k]$$
(without the intervention of signs) functorially in $\mathcal{M}$ and $\mathcal{L}$. Thus we see indeed
that the graded category of graded $\mathcal{A}$-modules can be recovered from the ordinary
category of graded $\mathcal{A}$-modules and the shift functors as discussed in Differential
Graded Algebra, Remark 25.7.

Lemma 11.1. Let $(\mathcal{C}, \mathcal{O})$ be a ringed site. Let $\mathcal{A}$ be a graded $\mathcal{O}$-algebra. The
category $\text{Mod}_A$ is a Grothendieck abelian category.

Proof. By Lemma 4.2 and the definition of a Grothendieck abelian category (Injectives, Definition 10.1) it suffices to show that $\text{Mod}_A$ has a generator. We claim that
$$\mathcal{G} = \bigoplus_{k, U} j_{U!}\mathcal{A}_U[k]$$
is a generator where the sum is over all objects $U$ of $\mathcal{C}$ and $k \in \mathbb{Z}$. Indeed, given a
graded $\mathcal{A}$-module $\mathcal{M}$ if there are no nonzero maps from $\mathcal{G}$ to $\mathcal{M}$, then we see that
for all $k$ and $U$ we have
$$\text{Hom}_{\text{Mod}_A}(j_{U!}\mathcal{A}_U[k], \mathcal{M}) = \text{Hom}_{\text{Mod}_{\mathcal{A}_U}}(\mathcal{A}_U[k], \mathcal{M}|_U) = \Gamma(U, \mathcal{M}^{-k})$$
is equal to zero. Hence $\mathcal{M}$ is zero. □
12. Sheaves of differential graded algebras

Definition 12.1. Let \((\mathcal{C}, \mathcal{O})\) be a ringed site. A sheaf of differential graded \(\mathcal{O}\)-algebras or a sheaf of differential graded algebras on \((\mathcal{C}, \mathcal{O})\) is a cochain complex \(\mathcal{A}^\bullet\) of \(\mathcal{O}\)-modules endowed with \(\mathcal{O}\)-bilinear maps \(\mathcal{A}^n \times \mathcal{A}^m \to \mathcal{A}^{n+m}\), \((a, b) \mapsto \overrightarrow{ab}\)
called the multiplication maps with the following properties

1. multiplication is associative,
2. there is a global section \(1\) of \(\mathcal{A}^0\) which is a two-sided identity for multiplication,
3. for \(U \in \text{Ob}(\mathcal{C})\), \(a \in \mathcal{A}^n(U)\), and \(b \in \mathcal{A}^m(U)\) we have
   \[d^{n+m}(ab) = d^n(a)b + (-1)^n a d^m(b)\]

We often denote such a structure \((\mathcal{A}, d)\). A homomorphism of differential graded \(\mathcal{O}\)-algebras from \((\mathcal{A}, d)\) to \((\mathcal{B}, d)\) is a map \(f : \mathcal{A}^\bullet \to \mathcal{B}^\bullet\) of complexes of \(\mathcal{O}\)-modules compatible with the multiplication maps.

Given a differential graded \(\mathcal{O}\)-algebra \((\mathcal{A}, d)\) and an object \(U \in \text{Ob}(\mathcal{C})\) we use the notation
\[
\mathcal{A}(U) = \Gamma(U, \mathcal{A}) = \bigoplus_{n \in \mathbb{Z}} \mathcal{A}^n(U)
\]
This is a differential graded \(\mathcal{O}(U)\)-algebra.

As much as possible, we will think of a differential graded \(\mathcal{O}\)-algebra \((\mathcal{A}, d)\) as a graded \(\mathcal{O}\)-algebra \(\mathcal{A}\) endowed with the operator \(d : \mathcal{A} \to \mathcal{A}\) of degree 1 (where \(\mathcal{A}\) is viewed as a graded \(\mathcal{O}\)-module) satisfying the Leibniz rule given in the definition.

Remark 12.2. Let \((f, f^\sharp) : (\text{Sh}(\mathcal{C}), \mathcal{O}_\mathcal{C}) \to (\text{Sh}(\mathcal{D}), \mathcal{O}_\mathcal{D})\) be a morphism of ringed topoi.

1. Let \((\mathcal{A}, d)\) be a differential graded \(\mathcal{O}_\mathcal{C}\)-algebra. The pushforward will be the differential graded \(\mathcal{O}_\mathcal{D}\)-algebra \((f_* \mathcal{A}, d)\) where \(f_* \mathcal{A}\) is as in Remark 3.2 and \(d = f_* d\) as maps \(f_* \mathcal{A}^n \to f_* \mathcal{A}^{n+1}\). We omit the verification that the Leibniz rule is satisfied.
2. Let \(\mathcal{B}\) be a differential graded \(\mathcal{O}_\mathcal{D}\)-algebra. The pullback will be the differential graded \(\mathcal{O}_\mathcal{C}\)-algebra \((f^* \mathcal{B}, d)\) where \(f^* \mathcal{B}\) is as in Remark 3.2 and \(d = f^* d\) as maps \(f^* \mathcal{B}^n \to f^* \mathcal{B}^{n+1}\). We omit the verification that the Leibniz rule is satisfied.
3. The set of homomorphisms \(f^* \mathcal{B} \to \mathcal{A}\) of differential graded \(\mathcal{O}_\mathcal{C}\)-algebras is in 1-to-1 correspondence with the set of homomorphisms \(\mathcal{B} \to f_* \mathcal{A}\) of differential graded \(\mathcal{O}_\mathcal{D}\)-algebras.

Part (3) follows immediately from the usual adjunction between \(f^*\) and \(f_*\) on sheaves of modules.

13. Sheaves of differential graded modules

This section is the analogue of Differential Graded Algebra, Section 4.
Definition 13.1. Let \((\mathcal{C}, \mathcal{O})\) be a ringed site. Let \((\mathcal{A}, d)\) be a sheaf of differential graded algebras on \((\mathcal{C}, \mathcal{O})\). A (right) differential graded \(\mathcal{A}\)-module or (right) differential graded module over \(\mathcal{A}\) is a cochain complex \(\mathcal{M}^\bullet\) endowed with \(\mathcal{O}\)-bilinear maps
\[
\mathcal{M}^n \times \mathcal{A}^m \to \mathcal{M}^{n+m}, \quad (x, a) \mapsto xa
\]
called the multiplication maps with the following properties

1. multiplication satisfies \((xa)a' = x(aa')\),
2. the identity section \(1\) of \(\mathcal{A}^0\) acts as the identity on \(\mathcal{M}^n\) for all \(n\),
3. for \(U \in \text{Ob}(\mathcal{C})\), \(x \in \mathcal{M}^n(U)\), and \(a \in \mathcal{A}^m(U)\) we have
\[
d^{n+m}(xa) = d^n(x)a + (-1)^n xd^m(a)
\]

We often say “let \(\mathcal{M}\) be a differential graded \(\mathcal{A}\)-module” to indicate this situation.

A homomorphism of differential graded \(\mathcal{A}\)-modules from \(\mathcal{M}\) to \(\mathcal{N}\) is a map \(f: \mathcal{M}^\bullet \to \mathcal{N}^\bullet\) of complexes of \(\mathcal{O}\)-modules compatible with the multiplication maps.

The category of (right) differential graded \(\mathcal{A}\)-modules is denoted \(\text{Mod}(\mathcal{A}, d)\).

We can define left differential graded modules in exactly the same manner but our default in the chapter will be right modules.

Given a differential graded \(\mathcal{A}\)-module \(\mathcal{M}\) and an object \(U \in \text{Ob}(\mathcal{C})\) we use the notation
\[
\mathcal{M}(U) = \Gamma(U, \mathcal{M}) = \bigoplus_{n \in \mathbb{Z}} \mathcal{M}^n(U)
\]
This is a (right) differential graded \(\mathcal{A}(U)\)-module.

Lemma 13.2. Let \((\mathcal{C}, \mathcal{O})\) be a ringed site. Let \((\mathcal{A}, d)\) be a differential graded \(\mathcal{O}\)-algebra. The category \(\text{Mod}(\mathcal{A}, d)\) is an abelian category with the following properties

1. \(\text{Mod}(\mathcal{A}, d)\) has arbitrary direct sums,
2. \(\text{Mod}(\mathcal{A}, d)\) has arbitrary colimits,
3. filtered colimit in \(\text{Mod}(\mathcal{A}, d)\) are exact,
4. \(\text{Mod}(\mathcal{A}, d)\) has arbitrary products,
5. \(\text{Mod}(\mathcal{A}, d)\) has arbitrary limits.

The forgetful functor
\[
\text{Mod}(\mathcal{A}, d) \to \text{Mod}\mathcal{A}
\]
sending a differential graded \(\mathcal{A}\)-module to its underlying graded module commutes with all limits and colimits.

Proof. Let us denote \(F: \text{Mod}(\mathcal{A}, d) \to \text{Mod}\mathcal{A}\) the functor in the statement of the lemma. Observe that the category \(\text{Mod}\mathcal{A}\) has properties (1) – (5), see Lemma 4.2.

Consider a homomorphism \(f: \mathcal{M} \to \mathcal{N}\) of graded \(\mathcal{A}\)-modules. The kernel and cokernel of \(f\) as maps of graded \(\mathcal{A}\)-modules are additionally endowed with differentials as in Definition 13.1. Hence these are also the kernel and cokernel in \(\text{Mod}(\mathcal{A}, d)\). Thus \(\text{Mod}(\mathcal{A}, d)\) is an abelian category and taking kernels and cokernels commutes with \(F\).

To prove the existence of limits and colimits it is sufficient to prove the existence of products and direct sums, see Categories, Lemmas 14.10 and 14.11. The same lemmas show that proving the commutation of limits and colimits with \(F\) follows if \(F\) commutes with direct sums and products.

Let \(\mathcal{M}_t, t \in T\) be a set of differential graded \(\mathcal{A}\)-modules. Then we can consider the direct sum \(\bigoplus \mathcal{M}_t\) as a graded \(\mathcal{A}\)-module. Since the direct sum of graded modules
is done termwise, it is clear that $\bigoplus M_i$ comes endowed with a differential. The reader easily verifies that this is a direct sum in $\text{Mod}_{(A,d)}$. Similarly for products.

Observe that $F$ is an exact functor and that a complex $M_1 \to M_2 \to M_3$ of $\text{Mod}_{(A,d)}$ is exact if and only if $F(M_1) \to F(M_2) \to F(M_3)$ is exact in $\text{Mod}_A$. Hence we conclude that (3) holds as filtered colimits are exact in $\text{Mod}_A$. □

Combining Lemmas 13.2 and 4.2 we find that there is an exact and faithful functor $\text{Mod}_{(A,d)} \longrightarrow \text{Comp}(\mathcal{O})$ of abelian categories. For a differential graded $A$-module $\mathcal{M}$ the cohomology $\mathcal{O}$-modules, denoted $H^i(\mathcal{M})$, are defined as the cohomology of the complex of $\mathcal{O}$-modules corresponding to $\mathcal{M}$. Therefore, a short exact sequence $0 \to K \to L \to M \to 0$ of differential graded $A$-modules gives rise to a long exact sequence

$$0 \text{FRK (13.2.1)} \quad H^n(K) \to H^n(L) \to H^n(M) \to H^{n+1}(K)$$

of cohomology modules, see Homology, Lemma 13.12.

Moreover, from now on we borrow all the terminology used for complexes of modules. For example, we say that a differential graded $A$-module $\mathcal{M}$ is acyclic if $H^k(\mathcal{M}) = 0$ for all $k \in \mathbb{Z}$. We say that a homomorphism $\mathcal{M} \to \mathcal{N}$ of differential graded $A$-modules is a quasi-isomorphism if it induces isomorphisms $H^k(\mathcal{M}) \to H^k(\mathcal{N})$ for all $k \in \mathbb{Z}$. And so on and so forth.

14. The differential graded category of modules

This section is the analogue of Differential Graded Algebra, Example 26.8. For our conventions on differential graded categories, please see Differential Graded Algebra, Section 26.

Let $(\mathcal{C}, \mathcal{O})$ be a ringed site. Let $(A, d)$ be a sheaf of differential graded algebras on $(\mathcal{C}, \mathcal{O})$. We will construct a differential graded category

$$\text{Mod}_{(A,d)}$$

over $R = \Gamma(\mathcal{C}, \mathcal{O})$ whose associated category of complexes is the category of differential graded $A$-modules:

$$\text{Mod}_{(A,d)} = \text{Comp}(\text{Mod}_{(A,d)})$$

As objects of $\text{Mod}_{(A,d)}$ we take right differential graded $A$-modules, see Section 13. Given differential graded $A$-modules $\mathcal{L}$ and $\mathcal{M}$ we set

$$\text{Hom}_{\text{Mod}_{(A,d)}}(\mathcal{L}, \mathcal{M}) = \text{Hom}_{\text{Mod}_{A}}^r(\mathcal{L}, \mathcal{M}) = \bigoplus_{n \in \mathbb{Z}} \text{Hom}^n(\mathcal{L}, \mathcal{M})$$

as a graded $R$-module, see Section 5. In other words, the $n$th graded piece $\text{Hom}^n(\mathcal{L}, \mathcal{M})$ is the $R$-module of right $A$-module maps homogeneous of degree $n$. For an element $f \in \text{Hom}^n(\mathcal{L}, \mathcal{M})$ we set

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

To make sense of this we think of $d_M$ and $d_L$ as graded $\mathcal{O}$-module maps and we use composition of graded $\mathcal{O}$-module maps. It is clear that $d(f)$ is homogeneous of
degree \( n + 1 \) as a graded \( \mathcal{O} \)-module map, and it is \( \mathcal{A} \)-linear because for homogeneous local sections \( x \) and \( a \) of \( \mathcal{M} \) and \( \mathcal{A} \) we have

\[
d(f)(xa) = d_M(f(x)a) - (-1)^n f(d(L)(xa))
\]

\[
= d_M(f(x)a + (-1)^{\deg(x) + n} f(x)d(a) - (-1)^n f(d(L)(x))a - (-1)^{n + \deg(x)} f(x)d(a)
\]

\[
= d(f)(xa)
\]

as desired (observe that this calculation would not work without the sign in the differential graded modules \( \text{Hom}^n(\mathcal{L}, \mathcal{M}) \times \text{Hom}^n(\mathcal{K}, \mathcal{M}) \rightarrow \text{Hom}^{n+m}(\mathcal{K}, \mathcal{M}) \) in Section \[5\] by the usual composition of maps of sheaves. This defines a map of differential graded modules

\[
\text{Hom}_{\mathcal{M}^{dg}_{\text{Mod}}(\mathcal{A}, \mathcal{A})}(\mathcal{L}, \mathcal{M}) \otimes_R \text{Hom}_{\mathcal{M}^{dg}_{\text{Mod}}(\mathcal{A}, \mathcal{A})}(\mathcal{K}, \mathcal{L}) \rightarrow \text{Hom}_{\mathcal{M}^{dg}_{\text{Mod}}(\mathcal{A}, \mathcal{A})}(\mathcal{K}, \mathcal{M})
\]

as required in Differential Graded Algebra, Definition \[26.1\] because

\[
d(g \circ f) = d_M \circ g \circ f - (-1)^{n+m} g \circ f \circ d_K
\]

\[
= (d_M \circ g - (-1)^m g \circ d_L) \circ f + (-1)^m g \circ (d_L \circ f - (-1)^n f \circ d_K)
\]

\[
= d(g) \circ f + (-1)^m g \circ d(f)
\]

if \( f \) has degree \( n \) and \( g \) has degree \( m \) as desired.

15. Tensor product for sheaves of differential graded modules

0FRM This section is the analogue of part of Differential Graded Algebra, Section \[12\]

Let \( (\mathcal{C}, \mathcal{O}) \) be a ringed site. Let \( (\mathcal{A}, d) \) be a sheaf of differential graded algebras on \( (\mathcal{C}, \mathcal{O}) \). Let \( \mathcal{M} \) be a right differential graded \( \mathcal{A} \)-module and let \( \mathcal{N} \) be a left differential graded \( \mathcal{A} \)-module. In this situation we define the tensor product \( \mathcal{M} \otimes_{\mathcal{A}} \mathcal{N} \) as follows. As a graded \( \mathcal{O} \)-module it is given by the construction in Section \[6\]. It comes endowed with a differential

\[
d_{\mathcal{M} \otimes_{\mathcal{A}} \mathcal{N}} : (\mathcal{M} \otimes_{\mathcal{A}} \mathcal{N})^n \rightarrow (\mathcal{M} \otimes_{\mathcal{A}} \mathcal{N})^{n+1}
\]

defined by the rule that

\[
d_{\mathcal{M} \otimes_{\mathcal{A}} \mathcal{N}}(x \otimes y) = d_M(x) \otimes y + (-1)^{\deg(x)} x \otimes d_N(y)
\]

for homogeneous local sections \( x \) and \( y \) of \( \mathcal{M} \) and \( \mathcal{N} \). To see that this is well defined we have to show that \( d_{\mathcal{M} \otimes_{\mathcal{A}} \mathcal{N}} \) annihilates elements of the form \( xa \otimes y - x \otimes ay \) for homogeneous local sections \( x, a, y \) of \( \mathcal{M}, \mathcal{A}, \mathcal{N} \). We compute

\[
d_{\mathcal{M} \otimes_{\mathcal{A}} \mathcal{N}}(xa \otimes y - x \otimes ay)
\]

\[
= d_M(xa) \otimes y + (-1)^{\deg(x) + \deg(a)} xa \otimes d_N(y) - d_M(x) \otimes ay - (-1)^{\deg(x)} x \otimes d_N(ay)
\]

\[
= d_M(x) a \otimes y + (-1)^{\deg(x)} xd(a) \otimes y + (-1)^{\deg(x) + \deg(a)} xa \otimes d_N(y)
\]

\[
- d_M(x) ay - (-1)^{\deg(x)} x \otimes d(a)y - (-1)^{\deg(x) + \deg(a)} x \otimes ad_N(y)
\]

then we observe that the elements

\[
d_M(x)a \otimes y - d_M(x) \otimes ay, \ xd(a) \otimes y - x \otimes d(a)y, \text{ and } xa \otimes d_N(y) - x \otimes ad_N(y)
\]

map to zero in \( \mathcal{M} \otimes_{\mathcal{A}} \mathcal{N} \) and we conclude. We omit the verification that \( d_{\mathcal{M} \otimes_{\mathcal{A}} \mathcal{N}} \circ d_{\mathcal{M} \otimes_{\mathcal{A}} \mathcal{N}} = 0 \).
If we fix the left differential graded \(A\)-module \(\mathcal{N}\) we obtain a functor
\[ - \otimes_A \mathcal{N} : \text{Mod}_{(A,d)}(\mathcal{O}) \to \text{Comp}(\mathcal{O}) \]
where on the right hand side we have the category of complexes of \(\mathcal{O}\)-modules. This can be upgraded to a functor of differential graded categories
\[ - \otimes_A \mathcal{N} : \text{Mod}^{dg}_{(A,d)}(\mathcal{O}) \to \text{Comp}^{dg}(\mathcal{O}) \]

On underlying graded objects, we send a homomorphism \(f : \mathcal{M} \to \mathcal{M}'\) of degree \(n\) to the degree \(n\) map \(f \otimes \text{id}_\mathcal{N} : \mathcal{M} \otimes_A \mathcal{N} \to \mathcal{M}' \otimes_A \mathcal{N}\), because this is what we did in Section 6. To show that this works, we have to verify that the map
\[ \text{Hom}^\text{Mod}_{(A,d)}(\mathcal{M}, \mathcal{M}') \to \text{Hom}^\text{Comp}^{dg}(\mathcal{O})(\mathcal{M} \otimes_A \mathcal{N}, \mathcal{M}' \otimes_A \mathcal{N}) \]
is compatible with differentials. To see this for \(f\) as above we have to show that
\[ (d_{\mathcal{M}'} \circ f - (-1)^n f \circ d_{\mathcal{M}}) \otimes \text{id}_\mathcal{N} \]
is equal to
\[ d_{\mathcal{M}' \otimes_A \mathcal{N}} \circ (f \otimes \text{id}_\mathcal{N}) - (-1)^n (f \otimes \text{id}_\mathcal{N}) \circ d_{\mathcal{M} \otimes_A \mathcal{N}} \]

Let us compute the effect of these operators on a local section of the form \(x \otimes y\) with \(x\) and \(y\) homogeneous local sections of \(\mathcal{M}\) and \(\mathcal{N}\). For the first we obtain
\[ (d_{\mathcal{M}'}(f(x))) \otimes y - (-1)^n f(d_{\mathcal{M}}(x)) \otimes y \]
and for the second we obtain
\[ d_{\mathcal{M}' \otimes_A \mathcal{N}}(f(x) \otimes y) - (-1)^n (f \otimes \text{id}_\mathcal{N})(d_{\mathcal{M} \otimes_A \mathcal{N}}(x \otimes y) \]
\[ = d_{\mathcal{M}'}(f(x)) \otimes y + (-1)^{\deg(x)+n} f(x) \otimes d_{\mathcal{N}}(y) \]
\[ - (-1)^n f(d_{\mathcal{M}}(x)) \otimes y - (-1)^n (-1)^{\deg(x)} f(x) \otimes d_{\mathcal{N}}(y) \]
which is indeed the same local section.

### 16. Internal hom for sheaves of differential graded modules

We are going to need the sheafified version of the construction in Section 14. Let \((\mathcal{L}, \mathcal{O}), \mathcal{A}, \mathcal{M}, \mathcal{L}\) be as in Section 14. Then we define
\[ \text{Hom}_{\mathcal{A}}^{dg}(\mathcal{M}, \mathcal{L}) = \bigoplus_{n \in \mathbb{Z}} \text{Hom}_{\mathcal{A}}^{n}(\mathcal{M}, \mathcal{L}) \]
as a graded \(\mathcal{O}\)-module, see Section 7. In other words, a section \(f\) of the \(n\)th graded piece \(\text{Hom}_{\mathcal{A}}^{n}(\mathcal{L}, \mathcal{M})\) over \(U\) is a map of right \(\mathcal{A}_U\)-module map \(\mathcal{L}|_U \to \mathcal{M}|_U\) homogeneous of degree \(n\). For such \(f\) we set
\[ d(f) = d_{\mathcal{M}|_U} \circ f - (-1)^n f \circ d_{\mathcal{L}|_U} \]
To make sense of this we think of \(d_{\mathcal{M}|_U}\) and \(d_{\mathcal{L}|_U}\) as graded \(\mathcal{O}_U\)-module maps and we use composition of graded \(\mathcal{O}_U\)-module maps. It is clear that \(d(f)\) is homogeneous of degree \(n + 1\) as a graded \(\mathcal{O}_U\)-module map. Using the exact same computation as in Section 14 we see that \(d(f)\) is \(\mathcal{A}_U\)-linear.

As in Section 14 there is a composition map
\[ \text{Hom}_{\mathcal{A}}^{dg}(\mathcal{L}, \mathcal{M}) \otimes_{\mathcal{O}} \text{Hom}_{\mathcal{A}}^{dg}(\mathcal{K}, \mathcal{L}) \to \text{Hom}_{\mathcal{A}}^{dg}(\mathcal{K}, \mathcal{M}) \]
where the left hand side is the tensor product of differential graded \(\mathcal{O}\)-modules defined in Section 15. This map is given by the composition map
\[ \text{Hom}^{n}(\mathcal{L}, \mathcal{M}) \otimes_{\mathcal{O}} \text{Hom}^{n}(\mathcal{K}, \mathcal{L}) \to \text{Hom}^{n+m}(\mathcal{K}, \mathcal{M}) \]
defined by simple composition (locally). Using the exact same computation as in Section 14 on local sections we see that the composition map is a morphism of differential graded \( O \)-modules.

With these definitions we have

\[ \text{Hom}_{\text{Mod}^{dg}_A}(L, M) = \Gamma(C, \text{Hom}^{dg}_A(L, M)) \]

as graded \( R \)-modules compatible with composition.

17. Sheaves of differential graded bimodules and tensor-hom adjunction

This section is the analogue of part of Differential Graded Algebra, Section 12.

**Definition 17.1.** Let \((C, O)\) be a ringed site. Let \(A\) and \(B\) be a sheaves of differential graded algebras on \((C, O)\). A differential graded \((A, B)\)-bimodule is given by a complex \(M^\bullet\) of \(O\)-modules endowed with \(O\)-bilinear maps

\[ M^n \times B^m \to M^{n+m}, \quad (x, b) \mapsto xb \]

and

\[ A^n \times M^m \to M^{n+m}, \quad (a, x) \mapsto ax \]

called the multiplication maps with the following properties

1. multiplication satisfies \(a(a'x) = (aa')x\) and \((xb)b' = x(bb')\),
2. \((ax)b = a(xb)\),
3. \(d(ax) = d(a)x + (-1)^{\deg(a)}ad(x)\) and \(d(xb) = d(x)b + (-1)^{\deg(x)}xd(b)\),
4. the identity section 1 of \(A^0\) acts as the identity by multiplication, and
5. the identity section 1 of \(B^0\) acts as the identity by multiplication.

We often denote such a structure \(M\) and sometimes we write \(\_AM\_B\). A homomorphism of differential graded \((A, B)\)-bimodules \(f : M \to N\) is a map of complexes \(f : M^\bullet \to N^\bullet\) of \(O\)-modules compatible with the multiplication maps.

Given a differential graded \((A, B)\)-bimodule \(M\) and an object \(U \in \text{Ob}(C)\) we use the notation

\[ M(U) = \Gamma(U, M) = \bigoplus_{n \in \mathbb{Z}} M^n(U) \]

This is a differential graded \((A(U), B(U))\)-bimodule.

Observe that a differential graded \((A, B)\)-bimodule \(M\) is the same thing as a right differential graded \(B\)-module which is also a left differential graded \(A\)-module such that the grading and differentials agree and such that the \(A\)-module structure commutes with the \(B\)-module structure. Here is a precise statement.

**Lemma 17.2.** Let \((C, O)\) be a ringed site. Let \(A\) and \(B\) be a sheaves of differential graded algebras on \((C, O)\). Let \(N\) be a right differential graded \(B\)-module. There is a 1-to-1 correspondence between \((A, B)\)-bimodule structures on \(N\) compatible with the given differential graded \(B\)-module structure and homomorphisms

\[ A \to \text{Hom}^{dg}_B(N, N) \]

each differential graded \(O\)-algebra.

**Proof.** Omitted. □
Let \((C, O)\) be a ringed site. Let \(A\) and \(B\) be sheaves of differential graded algebras on \((C, O)\). Let \(M\) be a right differential graded \(A\)-module and let \(N\) be a differential graded \((A, B)\)-bimodule. In this case the differential graded tensor product defined in Section 16

\[ M \otimes_A N \]

is a right differential graded \(B\)-module with multiplication maps as in Section 8. This construction defines a functor and a functor of graded categories

\[ \otimes_A N : \text{Mod}_{(A,d)} \rightarrow \text{Mod}_{(B,d)} \]
\[ \otimes_A N : \text{Mod}^{dg}_{(A,d)} \rightarrow \text{Mod}^{dg}_{(B,d)} \]

by sending homomorphisms of degree \(n\) from \(M \rightarrow M'\) to the induced map of degree \(n\) from \(M \otimes_A N\) to \(M' \otimes_A N\).

Let \((C, O)\) be a ringed site. Let \(A\) and \(B\) be sheaves of differential graded algebras on \((C, O)\). Let \(N\) be a differential graded \((A, B)\)-bimodule. Let \(L\) be a right differential graded \(B\)-module. In this case the differential graded internal hom defined in Section 16

\[ \text{Hom}^{dg}_B(N, L) \]

is a right differential graded \(A\)-module where the right graded \(A\)-module structure is the one defined in Section 8. Another way to define the multiplication is the use the composition

\[ \text{Hom}^{dg}_B(N, L) \otimes_C A \rightarrow \text{Hom}^{dg}_B(N, L) \otimes_C \text{Hom}^{dg}_B(N, N) \rightarrow \text{Hom}^{dg}_B(N, L) \]

where the first arrow comes from Lemma 17.2 and the second arrow is the composition of Section 16. Since these arrows are both compatible with differentials, we conclude that we indeed obtain a differential graded \(A\)-module. This construction defines a functor and a functor of differential graded categories

\[ \text{Hom}^{dg}_B(N, -) : \text{Mod}_{(B,d)} \rightarrow \text{Mod}_{(A,d)} \]
\[ \text{Hom}^{dg}_B(N, -) : \text{Mod}^{dg}_{(B,d)} \rightarrow \text{Mod}^{dg}_{(A,d)} \]

by sending homomorphisms of degree \(n\) from \(L \rightarrow L'\) to the induced map of degree \(n\) from \(\text{Hom}^{dg}_B(N, L) \rightarrow \text{Hom}^{dg}_B(N, L')\).

**Lemma 17.3.** Let \((C, O)\) be a ringed site. Let \(A\) and \(B\) be sheaves of differential graded algebras on \((C, O)\). Let \(M\) be a right differential graded \(A\)-module. Let \(N\) be a differential graded \((A, B)\)-bimodule. Let \(L\) be a right differential graded \(B\)-module. With conventions as above we have

\[ \text{Hom}_{\text{Mod}^{dg}_{(B,d)}}(M \otimes_A N, L) = \text{Hom}_{\text{Mod}^{dg}_{(A,d)}}(M, \text{Hom}^{dg}_B(N, L)) \]

and

\[ \text{Hom}^{dg}_B(M \otimes_A N, L) = \text{Hom}^{dg}_A(M, \text{Hom}^{dg}_B(N, L)) \]

functorially in \(M, N, L\).

**Proof.** Omitted. Hint: On the graded level we have seen this is true in Lemma 8.2. Thus it suffices to check the isomorphisms are compatible with differentials which can be done by a computation on the level of local sections. \(\square\)

Let \((C, O)\) be a ringed site. Let \(A\) and \(B\) be sheaves of differential graded algebras on \((C, O)\). As a special case of the above, suppose we are given a homomorphism \(\varphi : A \rightarrow B\) of differential graded \(O\)-algebras. Then we obtain a functor and a functor of differential graded categories

\[ \otimes_{A, \varphi} B : \text{Mod}_{(A,d)} \rightarrow \text{Mod}_{(B,d)} \]
\[ \otimes_{A, \varphi} B : \text{Mod}^{dg}_{(A,d)} \rightarrow \text{Mod}^{dg}_{(B,d)} \]
On the other hand, we have the restriction functors
\[ \text{res}_\varphi : \text{Mod}((B, d)) \rightarrow \text{Mod}((A, d)) \quad \text{and} \quad \text{res}_\varphi : \text{Mod}^dg((B, d)) \rightarrow \text{Mod}^dg((A, d)) \]
We can use the lemma above to show these functors are adjoint to each other (as usual with restriction and base change). Namely, let us write \( \mathcal{A}B \) for \( B \) viewed as a differential graded \((\mathcal{A}, B)\)-bimodule. Then for any right differential graded \( B \)-module \( L \) we have
\[ \text{Hom}^dg_B(\mathcal{A}B, L) = \text{res}_\varphi(L) \]
as right differential graded \( A \)-modules. Thus Lemma 8.2 tells us that we have a functorial isomorphism
\[ \text{Hom}^dg_B(M \otimes_{\mathcal{A}, \varphi} B, L) = \text{Hom}^dg_B(\mathcal{M}, \text{res}_\varphi(L)) \]
We usually drop the dependence on \( \varphi \) in this formula if it is clear from context. In the same manner we obtain the equality
\[ \text{Hom}^dg_B(M \otimes_{\mathcal{A}} B, L) = \text{Hom}^dg_B(\mathcal{M}, L) \]
of graded \( O \)-modules.

18. Pull and push for sheaves of differential graded modules

Let \( (f, f^\sharp) : (\mathcal{O}(\mathcal{C}), \mathcal{O}_\mathcal{C}) \rightarrow (\mathcal{O}(\mathcal{D}), \mathcal{O}_\mathcal{D}) \) be a morphism of ringed topoi. Let \( A \) be a differential graded \( \mathcal{O}_\mathcal{C} \)-algebra. Let \( B \) be a differential graded \( \mathcal{O}_\mathcal{D} \)-algebra. Suppose we are given a map
\[ \varphi : f^{-1}B \rightarrow A \]
of differential graded \( f^{-1}\mathcal{O}_\mathcal{D} \)-algebras. By the adjunction of restriction and extension of scalars, this is the same thing as a map \( \varphi : f^*B \rightarrow A \) of differential graded \( \mathcal{O}_\mathcal{C} \)-algebras or equivalently \( \varphi \) can be viewed as a map
\[ \varphi : B \rightarrow f_*A \]
of differential graded \( \mathcal{O}_\mathcal{D} \)-algebras. See Remark 12.2

Let us define a functor
\[ f_* : \text{Mod}((A, d)) \rightarrow \text{Mod}((B, d)) \]
Given a differential graded \( A \)-module \( M \) we define \( f_*M \) to be the graded \( B \)-module constructed in Section 9 with differential given by the maps \( f_* : f_*M^n \rightarrow f_*M^{n+1} \). The construction is clearly functorial in \( M \) and we obtain our functor.

Let us define a functor
\[ f^* : \text{Mod}((B, d)) \rightarrow \text{Mod}((A, d)) \]
Given a differential graded \( B \)-module \( N \) we define \( f^*N \) to be the graded \( A \)-module constructed in Section 9. Recall that
\[ f^*N = f^{-1}N \otimes_{f^{-1}B} A \]
Since \( f^{-1}N \) comes with the differentials \( f^{-1}d : f^{-1}N^n \rightarrow f^{-1}N^{n+1} \) we can view this tensor product as an example of the tensor product discussed in Section 17 which provides us with a differential. The construction is clearly functorial in \( N \) and we obtain our functor \( f^* \).

The functors \( f_* \) and \( f^* \) are readily enhanced to give functors of differential graded categories
\[ f_* : \text{Mod}^dg((A, d)) \rightarrow \text{Mod}^dg((B, d)) \quad \text{and} \quad f^* : \text{Mod}^dg((B, d)) \rightarrow \text{Mod}^dg((A, d)) \]
which do the same thing on underlying objects and are defined by functoriality of the constructions on homogenous morphisms of degree $n$.

**Lemma 18.1.** In the situation above we have

$$\text{Hom}_{\text{Mod}^dg_{(A, d)}}(N, f_*M) = \text{Hom}_{\text{Mod}^dg_{(B, d)}}(f^*N, M)$$

**Proof.** Omitted. Hints: This is true for the underlying graded categories by Lemma 9.1. A calculation shows that these isomorphisms are compatible with differentials. □

**19. Localization and sheaves of differential graded modules**

Let $(\mathcal{C}, \mathcal{O})$ be a ringed site. Let $U \in \text{Ob}(\mathcal{C})$ and denote

$$j : (\text{Sh}(\mathcal{C}/U), \mathcal{O}_U) \longrightarrow (\text{Sh}(\mathcal{C}), \mathcal{O})$$

the corresponding localization morphism (Modules on Sites, Section 19). Below we will use the following fact: for $\mathcal{O}_U$-modules $M_i$, $i = 1, 2$ and an $\mathcal{O}$-module $A$ there is a canonical map

$$j_! : \text{Hom}_{\mathcal{O}_U}(M_1 \otimes_{\mathcal{O}_U} A|_U, M_2) \longrightarrow \text{Hom}_{\mathcal{O}}(j_!M_1 \otimes_{\mathcal{O}} A, j_!M_2)$$

Namely, we have $j_!(M_1 \otimes_{\mathcal{O}_U} A|_U) = j_!M_1 \otimes_{\mathcal{O}} A$ by Modules on Sites, Lemma 27.7.

Let $A$ be a differential graded $\mathcal{O}$-algebra. We will denote $A_U$ the restriction of $A$ to $\mathcal{C}/U$, in other words, we have $A_U = j_!A = j^{-1} A$. In Section 18 we have constructed adjoint functors

$$j_* : \text{Mod}^dg_{(A_U, d)} \longrightarrow \text{Mod}^dg_{(A, d)} \text{ and } j^* : \text{Mod}^dg_{(A, d)} \longrightarrow \text{Mod}^dg_{(A_U, d)}$$

with $j^*$ left adjoint to $j_*$. We claim there is in addition an exact functor

$$j_! : \text{Mod}^dg_{(A_U, d)} \longrightarrow \text{Mod}^dg_{(A, d)}$$

right adjoint to $j_*$. Namely, given a differential graded $A_U$-module $M$ we define $j_!M$ to be the graded $A$-module constructed in Section 10 with differentials $j_!d : j_!M^n \to j_!M^{n+1}$. Given a homogeneous map $f : M \to M'$ of degree $n$ of differential graded $A_U$-modules, we obtain a homogeneous map $j_!f : j_!M \to j_!M'$ of degree $n$ of differential graded $A$-modules. We omit the straightforward verification that this construction is compatible with differentials. Thus we obtain our functor.

**Lemma 19.1.** In the situation above we have

$$\text{Hom}_{\text{Mod}^dg_{(A, d)}}(j_!M, N) = \text{Hom}_{\text{Mod}^dg_{(A_U, d)}}(M, j^*N)$$

**Proof.** Omitted. Hint: We have seen in Lemma 10.1 that the lemma is true on graded level. Thus all that needs to be checked is that the resulting isomorphism is compatible with differentials. □

**Lemma 19.2.** In the situation above, let $M$ be a right differential graded $A_U$-module and let $N$ be a left differential graded $A$-module. Then

$$j_!M \otimes_A N = j_!(M \otimes_{A_U} N|_U)$$

as complexes of $\mathcal{O}$-modules functorially in $M$ and $N$.

**Proof.** As graded modules, this follows from Lemma 10.2. We omit the verification that this isomorphism is compatible with differentials. □
20. Shift functors on sheaves of differential graded modules

Let \((\mathcal{C}, \mathcal{O})\) be a ringed site. Let \(\mathcal{A}\) be a sheaf of differential graded algebras on \((\mathcal{C}, \mathcal{O})\). Let \(\mathcal{M}\) be a differential graded \(\mathcal{A}\)-module. Let \(k \in \mathbb{Z}\). We define the \(k\)th shift of \(\mathcal{M}\), denoted \(\mathcal{M}[k]\), as follows

1. as a graded \(\mathcal{A}\)-module we let \(\mathcal{M}[k]\) be as defined in Section \[11\]
2. the differential \(d_{\mathcal{M}[k]} : (\mathcal{M}[k])^n \to (\mathcal{M}[k])^{n+1}\) is defined to be \((-1)^k d_{\mathcal{M}} : \mathcal{M}^{n+k} \to \mathcal{M}^{n+k+1}\).

For a homomorphism \(f : \mathcal{L} \to \mathcal{M}\) of \(\mathcal{A}\)-modules homogeneous of degree \(n\), we let \(f[k] : \mathcal{L}[k] \to \mathcal{M}[k]\) be given by the same component maps as \(f\). Then \(f[k]\) is a homogeneous \(\mathcal{A}\)-module map of degree \(n\). This gives a map

\[
\text{Hom}_{\text{Mod}^{dg}_{(\mathcal{A}, d)}}(\mathcal{L}, \mathcal{M}) \to \text{Hom}_{\text{Mod}^{dg}_{(\mathcal{A}, d)}}(\mathcal{L}[k], \mathcal{M}[k])
\]

compatible with differentials (it follows from the fact that the signs of the differentials of \(\mathcal{L}\) and \(\mathcal{M}\) are changed by the same amount). These choices are compatible with the choice in Differential Graded Algebra, Definition \[4.3\]. It is clear that we have defined a functor

\[
[k] : \text{Mod}^{dg}_{(\mathcal{A}, d)} \to \text{Mod}^{dg}_{(\mathcal{A}, d)}
\]
of differential graded categories and that we have \([k + l] = [k] \circ [l]\).

We claim that the isomorphism

\[
\text{Hom}_{\text{Mod}^{dg}_{(\mathcal{A}, d)}}(\mathcal{L}, \mathcal{M}[k]) = \text{Hom}_{\text{Mod}^{dg}_{(\mathcal{A}, d)}}(\mathcal{L}, \mathcal{M})[k]
\]
defined in Section \[11\] on underlying graded modules is compatible with the differentials. To see this, suppose we have a right \(\mathcal{A}\)-module map \(f : \mathcal{L} \to \mathcal{M}[k]\) homogeneous of degree \(n\); this is an element of degree \(n\) of the LHS. Denote \(f' : \mathcal{L} \to \mathcal{M}\) the homogeneous \(\mathcal{A}\)-module map of degree \(n + k\) with the same component maps as \(f\). By our conventions, this is the corresponding element of degree \(n\) of the RHS. By definition of the differential of LHS we obtain

\[
d_{\text{LHS}}(f) = d_{\mathcal{M}[k]} \circ f - (-1)^n f \circ d_{\mathcal{L}} = (-1)^k d_{\mathcal{M}} \circ f - (-1)^n f \circ d_{\mathcal{L}}
\]
and for the differential on the RHS we obtain

\[
d_{\text{RHS}}(f') = (-1)^k (d_{\mathcal{M}} \circ f' - (-1)^{n+k} f' \circ d_{\mathcal{L}}) = (-1)^k d_{\mathcal{M}} \circ f' - (-1)^n f' \circ d_{\mathcal{L}}
\]
These maps have the same component maps and the proof is complete.

21. The homotopy category

Let \((\mathcal{C}, \mathcal{O})\) be a ringed site. Let \(\mathcal{A}\) be a sheaf of differential graded algebras on \((\mathcal{C}, \mathcal{O})\). Let \(f, g : \mathcal{M} \to \mathcal{N}\) be homomorphisms of differential graded \(\mathcal{A}\)-modules. A homotopy between \(f\) and \(g\) is a graded \(\mathcal{A}\)-module map \(h : \mathcal{M} \to \mathcal{N}\) homogeneous of degree \(-1\) such that

\[
f - g = d_{\mathcal{N}} \circ h + h \circ d_{\mathcal{M}}
\]
If a homotopy exists, then we say \(f\) and \(g\) are homotopic.
In the situation of the definition, if we have maps $a : K \to M$ and $c : N \to L$ then we see that

- $h$ is a homotopy between $f$ and $g$ \( \Rightarrow \) $c \circ h \circ a$ is a homotopy between $c \circ f \circ a$ and $c \circ g \circ a$

Thus we can define composition of homotopy classes of morphisms in $\text{Mod}_{(A,d)}$.

**Definition 21.2.** Let $(\mathcal{C}, \mathcal{O})$ be a ringed site. Let $\mathcal{A}$ be a sheaf of differential graded algebras on $(\mathcal{C}, \mathcal{O})$. The homotopy category, denoted $K(\text{Mod}_{(A,d)})$, is the category whose objects are the objects of $\text{Mod}_{(A,d)}$ and whose morphisms are homotopy classes of homomorphisms of differential graded $\mathcal{A}$-modules.

The notation $K(\text{Mod}_{(A,d)})$ is not standard but at least is consistent with the use of $K(\text{−})$ in other places of the Stacks project.

In Differential Graded Algebra, Definition 26.3 we have defined what we mean by the category of complexes $\text{Comp}(\mathcal{S})$ and the homotopy category $K(\mathcal{S})$ of a differential graded category $\mathcal{S}$. Applying this to the differential graded category $\text{Mod}_{dg}^{(A,d)}$ we obtain

\[ \text{Mod}_{(A,d)} = \text{Comp}(\text{Mod}_{dg}^{(A,d)}) \]

(see discussion in Section 14) and we obtain

\[ K(\text{Mod}_{(A,d)}) = K(\text{Mod}_{dg}^{(A,d)}) \]

To see that this last equality is true, note that we have the equality

\[ d_{\text{Hom}_{\text{Mod}_{dg}^{(A,d)}}(\mathcal{M}, \mathcal{N})}(h) = d_{\mathcal{N}} \circ h + h \circ d_{\mathcal{M}} \]

when $h$ is as in Definition 21.1. We omit the details.

**Lemma 21.3.** Let $(\mathcal{C}, \mathcal{O})$ be a ringed site. Let $\mathcal{A}$ be a sheaf of differential graded algebras on $(\mathcal{C}, \mathcal{O})$. The homotopy category $K(\text{Mod}_{(A,d)})$ has direct sums and products.

**Proof.** Omitted. Hint: Just use the direct sums and products as in Lemma 13.2. This works because we saw that these functors commute with the forgetful functor to the category of graded $\mathcal{A}$-modules and because $\prod$ and $\bigoplus$ are exact functors on the category of families of abelian groups.

---

**22. Cones and triangles**

In this section we use the material from Differential Graded Algebra, Section 27 to conclude that the homotopy category of the category of differential graded $\mathcal{A}$-modules is a triangulated category.

**Lemma 22.1.** Let $(\mathcal{C}, \mathcal{O})$ be a ringed site. Let $\mathcal{A}$ be a sheaf of differential graded algebras on $(\mathcal{C}, \mathcal{O})$. The differential graded category $\text{Mod}_{dg}^{(A,d)}$ satisfies axioms (A) and (B) of Differential Graded Algebra, Section 27.

**Proof.** Suppose given differential graded $\mathcal{A}$-modules $\mathcal{M}$ and $\mathcal{N}$. Consider the differential graded $\mathcal{A}$-module $\mathcal{M} \oplus \mathcal{N}$ defined in the obvious manner. Then the coprojections $i : \mathcal{M} \to \mathcal{M} \oplus \mathcal{N}$ and $j : \mathcal{N} \to \mathcal{M} \oplus \mathcal{N}$ and the projections $p : \mathcal{M} \oplus \mathcal{N} \to \mathcal{N}$ and $q : \mathcal{M} \oplus \mathcal{N} \to \mathcal{M}$ are morphisms of differential graded $\mathcal{A}$-modules. Hence $i, j, p, q$ are homogeneous of degree 0 and closed, i.e., $d(i) = 0$, etc.
Thus this direct sum is a differential graded sum in the sense of Differential Graded Algebra, Definition 26.4. This proves axiom (A).

Axiom (B) was shown in Section 20. □

Let \((\mathcal{C}, \mathcal{O})\) be a ringed site. Let \(\mathcal{A}\) be a sheaf of differential graded algebras on \((\mathcal{C}, \mathcal{O})\). Recall that a sequence

\[0 \to K \to L \to N \to 0\]

in \(\text{Mod}_{\mathcal{A}, d}\) is called an admissible short exact sequence (in Differential Graded Algebra, Section 27) if it is split in \(\text{Mod}_\mathcal{A}\). In other words, if it is split as a sequence of graded \(\mathcal{A}\)-modules. Denote \(s : N \to L\) and \(\pi : L \to K\) graded \(\mathcal{A}\)-module splittings. Combining Lemma 22.1 and Differential Graded Algebra, Lemma 27.1 we obtain a triangle

\[K \to L \to N \to K[1]\]

where the arrow \(N \to K[1]\) in the proof of Differential Graded Algebra, Lemma 27.1 is constructed as

\[\delta = \pi \circ d_{\text{Hom}_{\text{Mod}_{\mathcal{A}, d}}(L, \mathcal{A})}(s) = \pi \circ d_L \circ s - \pi \circ s \circ d_N = \pi \circ d_L \circ s\]

with apologies for the horrendous notation. In any case, we see that in our setting the boundary map \(\delta\) as constructed in Differential Graded Algebra, Lemma 27.1 agrees on underlying complexes of \(\mathcal{O}\)-modules with the usual boundary map used throughout the Stacks project for termwise split short exact sequences of complexes, see Derived Categories, Definition 9.9.

**Definition 22.2.** Let \((\mathcal{C}, \mathcal{O})\) be a ringed site. Let \(\mathcal{A}\) be a sheaf of differential graded algebras on \((\mathcal{C}, \mathcal{O})\). Let \(f : K \to L\) be a homomorphism of differential graded \(\mathcal{A}\)-modules. The cone of \(f\) is the differential graded \(\mathcal{A}\)-module \(C(f)\) defined as follows:

1. the underlying complex of \(\mathcal{O}\)-modules is the cone of the corresponding map
   \[f : K^\bullet \to L^\bullet\]
   of complexes of \(\mathcal{A}\)-modules, i.e., we have \(C(f)^n = L^n \oplus K^{n+1}\)
   and differential
   \[d_{C(f)} = \begin{pmatrix} d_L & f \\ 0 & -d_K \end{pmatrix}\]

2. the multiplication map
   \[C(f)^n \times \mathcal{A}^m \to C(f)^{n+m}\]
   is the direct sum of the multiplication map \(L^n \times \mathcal{A}^m \to L^{n+m}\) and the multiplication map \(K^{n+1} \times \mathcal{A}^m \to K^{n+1+m}\).

It comes equipped with canonical homomorphisms of differential graded \(\mathcal{A}\)-modules \(i : L \to C(f)\) and \(p : C(f) \to K[1]\) induced by the obvious maps.

Observe that in the situation of the definition the sequence

\[0 \to L \to C(f) \to K[1] \to 0\]

is an admissible short exact sequence.

**Lemma 22.3.** Let \((\mathcal{C}, \mathcal{O})\) be a ringed site. Let \(\mathcal{A}\) be a sheaf of differential graded algebras on \((\mathcal{C}, \mathcal{O})\). The differential graded category \(\text{Mod}_{\mathcal{A}, d}\) satisfies axiom (C) formulated in Differential Graded Algebra, Situation 27.2.
Proof. Let \( f : K \to L \) be a homomorphism of differential graded \( A \)-modules. By the above we have an admissible short exact sequence
\[
0 \to L \to C(f) \to K[1] \to 0
\]
To finish the proof we have to show that the boundary map
\[
\delta : K[1] \to L[1]
\]
associated to this (see discussion above) is equal to \( f[1] \). For the section \( s : K[1] \to C(f) \) we use in degree \( n \) the embedding \( K^{n+1} \to C(f)^n \). Then in degree \( n \) the map \( \pi \) is given by the projections \( C(f)^n \to L^n \). Then finally we have to compute
\[
\delta = \pi \circ d_{C(f)} \circ s
\]
(see discussion above). In matrix notation this is equal to
\[
(1 \ 0) \begin{pmatrix} d_{L} & f \\ 0 & -d_K \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} = f
\]
as desired. □

At this point we know that all lemmas proved in Differential Graded Algebra, Section 27 are valid for the differential graded category \( \text{Mod}_{dg}(A,d) \). In particular, we have the following.

### Proposition 22.4.
Let \((C,O)\) be a ringed site. Let \( A \) be a sheaf of differential graded algebras on \((C,O)\). The homotopy category \( K(\text{Mod}_{(A,d)}) \) is a triangulated category where

1. the shift functors are those constructed in Section 21,
2. the distinguished triangles are those triangles in \( K(\text{Mod}_{(A,d)}) \) which are isomorphic as a triangle to a triangle

\[
K \to L \to N \overset{\delta}{\to} K[1], \quad \delta = \pi \circ d_{C(f)} \circ s
\]
constructed from an admissible short exact sequence \( 0 \to K \to L \to N \to 0 \) in \( \text{Mod}_{(A,d)} \) above.

Proof. Recall that \( K(\text{Mod}_{(A,d)}) = K(\text{Mod}_{dg}(A,d)) \), see Section 21. Having said this, the proposition follows from Lemmas 22.1 and 22.3 and Differential Graded Algebra, Proposition 27.16. □

### Remark 22.5.
Let \((C,O)\) be a ringed site. Let \( A \) be a sheaf of differential graded algebras on \((C,O)\). Let \( C = C(\text{id}_A) \) be the cone on the identity map \( A \to A \) viewed as a map of differential graded \( A \)-modules. Then
\[
\text{Hom}_{\text{Mod}_{(A,d)}}(C,M) = \{(x,y) \in \Gamma(C,M^0) \times \Gamma(C,M^{-1}) \mid x = d(y)\}
\]
where the map from left to right sends \( f \) to the pair \( (x,y) \) where \( x \) is the image of the global section \( (0,1) \) of \( C^{-1} = A^{-1} \oplus A^0 \) and where \( y \) is the image of the global section \( (1,0) \) of \( C^0 = A^0 \oplus A^1 \).

### Lemma 22.6.
Let \((C,O)\) be a ringed site. Let \((A,d)\) be a differential graded \( O \)-algebra. The category \( \text{Mod}_{(A,d)} \) is a Grothendieck abelian category.
Proof. By Lemma \ref{lemma:flat} and the definition of a Grothendieck abelian category (Injectives, Definition \ref{definition:injective}) it suffices to show that \( \text{Mod}_{\mathcal{A}} \) has a generator. For every object \( U \) of \( \mathcal{C} \) we denote \( C_U \) the cone on the identity map \( A_U \to A_U \) as in Remark \ref{remark:cone}. We claim that
\[
\mathcal{G} = \bigoplus_{k, U} j_{U!} C_U[k]
\]
is a generator where the sum is over all objects \( U \) of \( \mathcal{C} \) and \( k \in \mathbb{Z} \). Indeed, given a differential graded \( \mathcal{A} \)-module \( \mathcal{M} \) if there are no nonzero maps from \( \mathcal{G} \) to \( \mathcal{M} \), then we see that for all \( k \) and \( U \) we have
\[
\text{Hom}_{\text{Mod}_{\mathcal{A}}} (j_{U!} C_U[k], \mathcal{M}) = \text{Hom}_{\text{Mod}_{\mathcal{A}}}(C_U[k], \mathcal{M}|_{U})
\]
\[
= \{(x, y) \in \mathcal{M}^{-k}(U) \times \mathcal{M}^{-k-1}(U) \mid x = d(y)\}
\]
is equal to zero. Hence \( \mathcal{M} \) is zero. \( \square \)

23. Flat resolutions

Let \( \mathcal{C} \) be a ringed site. Let \( \mathcal{A} \) be a sheaf of differential graded algebras on \( \mathcal{C} \). Let us call a right differential graded \( \mathcal{A} \)-module \( \mathcal{P} \) good if

1. the functor \( \mathcal{N} \mapsto \mathcal{P} \otimes_{\mathcal{A}} \mathcal{N} \) is exact on the category of graded left \( \mathcal{A} \)-modules,
2. if \( \mathcal{N} \) is an acyclic differential graded left \( \mathcal{A} \)-module, then \( \mathcal{P} \otimes_{\mathcal{A}} \mathcal{N} \) is acyclic,
3. for any morphism \((f, f^2) : (\text{Sh}(\mathcal{C}'), \mathcal{O}') \to (\text{Sh}(\mathcal{C}), \mathcal{O})\) of ringed topoi and any differential graded \( \mathcal{O}' \)-algebra \( \mathcal{A}' \) and any map \( \varphi : f^{-1} \mathcal{A} \to \mathcal{A}' \) of differential graded \( f^{-1} \mathcal{O}_\mathcal{D} \)-algebras we have properties (1) and (2) for the pullback \( f^* \mathcal{P} \) (Section \ref{section:pullback}) viewed as a differential graded \( \mathcal{A}' \)-module.

The first condition means that \( \mathcal{P} \) is flat as a right graded \( \mathcal{A} \)-module, the second condition means that \( \mathcal{P} \) is K-flat in the sense of Spaltenstein (see Cohomology on Sites, Section \ref{section:spaltenstein}), and the third condition is that this holds after arbitrary base change.

Perhaps surprisingly, there are many good modules.

Lemma \ref{lemma:good}. Let \( \mathcal{C} \) be a ringed site. Let \( \mathcal{A} \) be a sheaf of differential graded algebras on \( \mathcal{C} \). Let \( U \in \text{Ob}(\mathcal{C}) \). Then \( j_{U!} A_U \) is a good differential graded \( \mathcal{A} \)-module.

Proof. Let \( \mathcal{N} \) be a left graded \( \mathcal{A} \)-module. By Lemma \ref{lemma:restriction} we have
\[
j_{U!} A_U \otimes_{\mathcal{A}} \mathcal{N} = j_U(\mathcal{A}_U \otimes_{\mathcal{A}_U} \mathcal{N}|_U) = j_U(\mathcal{N}_U)
\]
as graded modules. Since both restriction to \( U \) and \( j_U \) are exact this proves condition (1). The same argument works for (2) using Lemma \ref{lemma:extension}.

Consider a morphism \((f, f^2) : (\text{Sh}(\mathcal{C}'), \mathcal{O}') \to (\text{Sh}(\mathcal{C}), \mathcal{O})\) of ringed topoi, a differential graded \( \mathcal{O}' \)-algebra \( \mathcal{A}' \), and a map \( \varphi : f^{-1} \mathcal{A} \to \mathcal{A}' \) of differential graded \( f^{-1} \mathcal{O} \)-algebras. We have to show that
\[
f^* j_{U!} A_U = f^{-1} j_U A_U \otimes_{f^{-1} \mathcal{A}} \mathcal{A}'
\]
satisfies (1) and (2) for the ringed topos \((\text{Sh}(\mathcal{C}'), \mathcal{O}')\) endowed with the sheaf of differential graded \( \mathcal{O}' \)-algebras \( \mathcal{A}' \). To prove this we may replace \((\text{Sh}(\mathcal{C}), \mathcal{O})\) and \((\text{Sh}(\mathcal{C}'), \mathcal{O}')\) by equivalent ringed topoi. Thus by Modules on Sites, Lemma \ref{lemma:replacement}. 
we may assume that \( f \) comes from a morphism of sites \( f : C \to C' \) given by the continuous functor \( u : C \to C' \). In this case, set \( U' = u(U) \) and denote \( j' : Sh(C'/U') \to Sh(C') \) the corresponding localization morphism. We obtain a commutative square of morphisms of ringed topoi

\[
\begin{array}{ccc}
(Sh(C'/U'), \mathcal{O}_{U'}) & \xrightarrow{(j', (f')^\sharp)} & (Sh(C'), \mathcal{O}') \\
\downarrow & & \downarrow (f, f^\sharp) \\
(Sh(C/U), \mathcal{O}_U) & \xrightarrow{(j, j^\sharp)} & (Sh(C), \mathcal{O}).
\end{array}
\]

and we have \( f_*'(j')^{-1} = j^{-1}f_* \). See Modules on Sites, Lemma \[20.1\] By uniqueness of adjoints we obtain \( f^{-1}j_! = j_!(f')^{-1} \). Thus we obtain

\[
f^*j_! \mathcal{A}_U = f^{-1}j_! \mathcal{A}_U \otimes_{f^{-1}\mathcal{A}} \mathcal{A}'
= j_!(f')^{-1} \mathcal{A}_U \otimes_{f^{-1}\mathcal{A}} \mathcal{A}'
= j_!(f')^{-1} \mathcal{A}_U \otimes_{f^{-1}\mathcal{A}_U, \mathcal{A}'|_{U'}} \mathcal{A}'|_{U'}
= j_! \mathcal{A}_U'.
\]

The first equation is the definition of the pullback of \( j_! \mathcal{A}_U \) to a differential graded module over \( \mathcal{A}' \). The second equation because \( f^{-1}j_! = j_!(f')^{-1} \). The third equation by Lemma \[19.2\] applied to the ringed site \( (C', f^{-1}\mathcal{O}) \) with sheaf of differential graded algebras \( f^{-1}\mathcal{A} \) and with differential graded modules \( (f')^{-1}\mathcal{A}_U \) on \( C'/U' \) and \( \mathcal{A}' \) on \( C' \). The fourth equation holds because of course we have \( (f')^{-1}\mathcal{A}_U = f^{-1}\mathcal{A}|_{U'} \). Hence we see that the pullback is another module of the same kind and we’ve proven conditions (1) and (2) for it above.

**Lemma 23.2.** et \( (C, \mathcal{O}) \) be a ringed site. Let \( \mathcal{A} \) be a sheaf of differential graded algebras on \( (C, \mathcal{O}) \). Let \( 0 \to \mathcal{P} \to \mathcal{P}' \to \mathcal{P}'' \to 0 \) be an admissible short exact sequence of differential graded \( \mathcal{A} \)-modules. If two-out-of-three of these modules are good, so is the third.

**Proof.** For condition (1) this is immediate as the sequence is a direct sum at the graded level. For condition (2) note that for any left differential graded \( \mathcal{A} \)-module, the sequence

\[
0 \to \mathcal{P} \otimes_{\mathcal{A}} \mathcal{N} \to \mathcal{P}' \otimes_{\mathcal{A}} \mathcal{N} \to \mathcal{P}'' \otimes_{\mathcal{A}} \mathcal{N} \to 0
\]

is an admissible short exact sequence of differential graded \( \mathcal{O} \)-modules (since forgetting the differential the tensor product is just taken in the category of graded modules). Hence if two out of three are exact as complexes of \( \mathcal{O} \)-modules, so is the third. Finally, the same argument shows that given a morphism \( (f, f^\sharp) : (Sh(C'), \mathcal{O}') \to (Sh(C), \mathcal{O}) \) of ringed topoi, a differential graded \( \mathcal{O}' \)-algebra \( \mathcal{A}' \), and a map \( \varphi : f^{-1}\mathcal{A} \to \mathcal{A}' \) of differential graded \( f^{-1}\mathcal{O} \)-algebras we have that

\[
0 \to f^*\mathcal{P} \to f^*\mathcal{P}' \to f^*\mathcal{P}'' \to 0
\]

is an admissible short exact sequence of differential graded \( \mathcal{A}' \)-modules and the same argument as above applies here.

**Lemma 23.3.** Let \( (C, \mathcal{O}) \) be a ringed site. Let \( \mathcal{A} \) be a sheaf of differential graded algebras on \( (C, \mathcal{O}) \). An arbitrary direct sum of good differential graded \( \mathcal{A} \)-modules is good. A filtered colimit of good differential graded \( \mathcal{A} \)-modules is good.
Proof. Omitted. Hint: direct sums and filtered colimits commute with tensor products and with pullbacks. □

Lemma 23.4. Let \((\mathcal{C}, \mathcal{O})\) be a ringed site. Let \(\mathcal{A}\) be a sheaf of differential graded algebras on \((\mathcal{C}, \mathcal{O})\). Let \(\mathcal{M}\) be a differential graded \(\mathcal{A}\)-module. There exists a homomorphism \(\mathcal{P} \to \mathcal{M}\) of differential graded \(\mathcal{A}\)-modules with the following properties

(1) \(\mathcal{P} \to \mathcal{M}\) is surjective,
(2) \(\text{Ker}(d_\mathcal{P}) \to \text{Ker}(d_\mathcal{M})\) is surjective, and
(3) \(\mathcal{P}\) is good.

Proof. Consider triples \((U, k, x)\) where \(U\) is an object of \(\mathcal{C}\), \(k \in \mathbb{Z}\), and \(x\) is a section of \(\mathcal{M}_k\) over \(U\) with \(d_\mathcal{M}(x) = 0\). Then we obtain a unique morphism of differential graded \(\mathcal{A}_U\)-modules \(\varphi_x : \mathcal{A}_U[-k] \to \mathcal{M}_U\) mapping 1 to \(x\). This is adjoint to a morphism \(\psi_x : j_U!\mathcal{A}_U[-k] \to \mathcal{M}\). Observe that 1 \(\in \mathcal{A}_U(U)\) corresponds to a section \(1 \in j_U!\mathcal{A}_U[-k](U)\) of degree \(k\) whose differential is zero and which is mapped to \(x\) by \(\psi_x\). Thus if we consider the map

\[
\bigoplus_{(U, k, x)} j_U!\mathcal{A}_U[-k] \longrightarrow \mathcal{M}
\]

then we will have conditions (2) and (3). Namely, the objects \(j_U!\mathcal{A}_U[-k]\) are good (Lemma 23.1) and any direct sum of good objects is good (Lemma 23.3).

Next, consider triples \((U, k, x)\) where \(U\) is an object of \(\mathcal{C}\), \(k \in \mathbb{Z}\), and \(x\) is a section of \(\mathcal{M}_k\) (not necessarily annihilated by the differential). Then we can consider the cone \(\mathcal{C}_U\) on the identity map \(\mathcal{A}_U \to \mathcal{A}_U\) as in Remark 22.5. The element \(x\) will determine a map \(\varphi_x : \mathcal{C}_U[-k-1] \to \mathcal{A}_U\), see Remark 22.5. Now, since we have an admissible short exact sequence

\[
0 \to \mathcal{A}_U \to \mathcal{C}_U \to \mathcal{A}_U[1] \to 0
\]

we conclude that \(j_U!\mathcal{C}_U\) is a good module by Lemma 23.2 and the already used Lemma 23.1. As above we conclude that the direct sum of the maps \(\psi_x : j_U!\mathcal{C}_U \to \mathcal{M}\) adjoint to the \(\varphi_x\)

\[
\bigoplus_{(U, k, x)} j_U!\mathcal{C}_U \longrightarrow \mathcal{M}
\]

is surjective. Taking the direct sum with the map produced in the first paragraph we conclude. □

Remark 23.5. Let \((\mathcal{C}, \mathcal{O})\) be a ringed site. A sheaf of graded sets on \(\mathcal{C}\) is a sheaf of sets \(\mathcal{S}\) endowed with a map \(\text{deg} : \mathcal{S} \to \mathbb{Z}\) of sheaves of sets. Let us denote \(\mathcal{O}[\mathcal{S}]\) the graded \(\mathcal{O}\)-module which is the free \(\mathcal{O}\)-module on the graded sheaf of sets \(\mathcal{S}\).

More precisely, the \(n\)th graded part of \(\mathcal{O}[\mathcal{S}]\) is the sheafification of the rule

\[
U \mapsto \bigoplus_{s \in \mathcal{S}(U), \text{deg}(s) = n} s \cdot \mathcal{O}(U)
\]

With zero differential we also may consider this as a differential graded \(\mathcal{O}\)-module.

Let \(\mathcal{A}\) be a sheaf of graded \(\mathcal{O}\)-algebras. Then we similarly define \(\mathcal{A}[\mathcal{S}]\) to be the graded \(\mathcal{A}\)-module whose \(n\)th graded part is the sheafification of the rule

\[
U \mapsto \bigoplus_{s \in \mathcal{S}(U), \text{deg}(s) = n} s \cdot \mathcal{A}[\mathcal{S}](U)
\]

If \(\mathcal{A}\) is a differential graded \(\mathcal{O}\)-algebra, the we turn this into a differential graded \(\mathcal{O}\)-module by setting \(d(s) = 0\) for all \(s \in \mathcal{S}(U)\) and sheafifying.
Lemma 23.6. Let $(\mathcal{C}, \mathcal{O})$ be a ringed site. Let $\mathcal{A}$ be a differential graded $\mathcal{A}$-algebra. Let $\mathcal{S}$ be a sheaf of graded sets on $\mathcal{C}$. Then the free graded module $\mathcal{A}[\mathcal{S}]$ on $\mathcal{S}$ endowed with differential as in Remark 23.5 is a good differential graded $\mathcal{A}$-module.

Proof. Let $\mathcal{N}$ be a left graded $\mathcal{A}$-module. Then we have
$$\mathcal{A}[\mathcal{S}] \otimes_{\mathcal{A}} \mathcal{N} = \mathcal{O}[\mathcal{S}] \otimes_{\mathcal{O}} \mathcal{N} = \mathcal{N}[\mathcal{S}]$$
where $\mathcal{N}[\mathcal{S}]$ is the graded $\mathcal{O}$-module whose degree $n$ part is the sheaf associated to the presheaf
$$U \mapsto \bigoplus_{s \in \mathcal{S}(U)} s \cdot \mathcal{N}^{n-\deg(s)}(U)$$
It is clear that $\mathcal{N} \to \mathcal{N}[\mathcal{S}]$ is an exact functor, hence $\mathcal{A}[\mathcal{S}]$ is flat as a graded $\mathcal{A}$-module. Next, suppose that $\mathcal{N}$ is a differential graded left $\mathcal{A}$-module. Then we have
$$H^*(\mathcal{A}[\mathcal{S}] \otimes_{\mathcal{A}} \mathcal{N}) = H^*(\mathcal{O}[\mathcal{S}] \otimes_{\mathcal{O}} \mathcal{N})$$
as graded sheaves of $\mathcal{O}$-modules, which by the flatness (over $\mathcal{O}$) is equal to
$$H^*(\mathcal{N})[\mathcal{S}]$$
as a graded $\mathcal{O}$-module. Hence if $\mathcal{N}$ is acyclic, then $\mathcal{A}[\mathcal{S}]$ is acyclic.

Finally, consider a morphism $(f, f^\#: (\mathcal{C}', \mathcal{O}') \to (\mathcal{C}, \mathcal{O})$ of ringed topoi, a differential graded $\mathcal{O}'$-algebra $\mathcal{A}'$, and a map $\phi : f^\# \mathcal{A} \to \mathcal{A}'$ of differential graded $f^\# \mathcal{O}$-algebras. Then it is straightforward to see that
$$f^* \mathcal{A}[\mathcal{S}] = \mathcal{A}'[f^{-1} \mathcal{S}]$$
which finishes the proof that our module is good. □

Lemma 23.7. Let $(\mathcal{C}, \mathcal{O})$ be a ringed site. Let $\mathcal{A}$ be a sheaf of differential graded algebras on $(\mathcal{C}, \mathcal{O})$. Let $\mathcal{M}$ be a differential graded $\mathcal{A}$-module. There exists a homomorphism $P \to \mathcal{M}$ of differential graded $\mathcal{A}$-modules with the following properties

1. $P \to \mathcal{M}$ is a quasi-isomorphism, and
2. $P$ is good.

First proof. Let $\mathcal{S}_0$ be the sheaf of graded sets (Remark 23.5) whose degree $n$ part is $\text{Ker}(d^n_{\mathcal{A}})$. Consider the homomorphism of differential graded modules
$$P_0 = \mathcal{A}[\mathcal{S}_0] \to \mathcal{M}$$
where the left hand side is as in Remark 23.5 and the map sends a local section $s$ of $\mathcal{S}_0$ to the corresponding local section of $\mathcal{M}^{\text{deg}(s)}$ (which is in the kernel of the differential, so our map is a map of differential graded modules indeed). By construction the induced maps on cohomology sheaves $H^n(P_0) \to H^n(\mathcal{M})$ are surjective. We are going to inductively construct maps
$$P_0 \to P_1 \to P_2 \to \ldots \to \mathcal{M}$$
Observe that of course $H^*(P_i) \to H^*(\mathcal{M})$ will be surjective for all $i$. Given $P_i \to \mathcal{M}$ denote $\mathcal{S}_{i+1}$ the sheaf of graded sets whose degree $n$ part is
$$\text{Ker}(d^{n+1}_{P_i}) \times_{\mathcal{M}_i} \mathcal{M}_i$$
Then we set
$$P_{i+1} = P_i \oplus \mathcal{A}[\mathcal{S}_{i+1}]$$
as graded $\mathcal{A}$-module with differential and map to $\mathcal{M}$ defined as follows

1. for local sections of $P_i$ use the differential on $P_i$ and the given map to $\mathcal{M}$,
(2) for a local section \( s = (p, m) \) of \( S_{i+1} \) we set \( d(s) \) equal to \( p \) viewed as a section of \( P_i \) of degree \( \deg(s) + 1 \) and we map \( s \) to \( m \) in \( M \), and

(3) extend the differential uniquely so that the Leibniz rule holds.

This makes sense because \( d(m) \) is the image of \( p \) and \( d(p) = 0 \). Finally, we set \( P = \colim P_i \) with the induced map to \( M \).

The map \( P \to M \) is a quasi-isomorphism: we have \( H^n(P) = \colim H^n(P_i) \) and for each \( i \) the map \( H^n(P_i) \to H^n(M) \) is surjective with kernel annihilated by the map \( H^n(P_i) \to H^n(P_{i+1}) \) by construction. Each \( P_i \) is good because \( P_0 \) is good by Lemma 23.6 and each \( P_{i+1} \) is in the middle of the admissible short exact sequence

\[ 0 \to P_i \to P_{i+1} \to A[S_{i+1}] \to 0 \]

whose outer terms are good by induction. Hence \( P_{i+1} \) is good by Lemma 23.2. Finally, we conclude that \( P \) is good by Lemma 23.3.

\[ \square \]

Second proof. We urge the reader to read the proof of Differential Graded Algebra, Lemma 20.4 before reading this proof. Set \( M = M_0 \). We inductively choose short exact sequences

\[ 0 \to M_{i+1} \to P_i \to M_i \to 0 \]

where the maps \( P_i \to M_i \) are chosen as in Lemma 23.4. This gives a “resolution”

\[ \ldots \to P_2 \xrightarrow{f_2} P_1 \xrightarrow{f_1} P_0 \to M \to 0 \]

Then we let \( P \) be the differential graded \( A \)-module defined as follows

(1) as a graded \( A \)-module we set \( P = \bigoplus_{a \leq 0} P_{-a} \), i.e., the degree \( n \) part is given by \( P_n = \bigoplus_{a+b=n} P_{-a}^b \);

(2) the differential on \( P \) is as in the construction of the total complex associated to a double complex given by

\[ d_P(x) = f_{-a}(x) + (-1)^a d_{P_{-a}}(x) \]

for \( x \) a local section of \( P_{-a}^b \).

With these conventions \( P \) is indeed a differential graded \( A \)-module; we omit the details. There is a map \( P \to M \) of differential graded \( A \)-modules which is zero on the summands \( P_{-a}[-a] \) for \( a < 0 \) and the given map \( P_0 \to M \) for \( a = 0 \). Observe that we have

\[ P = \colim_i F_i P \]

where \( F_i P \subset P \) is the differential graded \( A \)-submodule whose underlying graded \( A \)-module is

\[ F_i P = \bigoplus_{i \geq -a \geq 0} P_{-a} [-a] \]

It is immediate that the maps

\[ 0 \to F_i P \to F_{i+1} P \to F_{i+2} P \to \ldots \to P \]

are all admissible monomorphisms and we have admissible short exact sequences

\[ 0 \to F_i P \to F_{i+1} P \to P_{i+1}[i + 1] \to 0 \]

By induction and Lemma 23.2 we find that \( F_i P \) is a good differential graded \( A \)-module. Since \( P = \colim F_i P \) we find that \( P \) is good by Lemma 23.3.

Finally, we have to show that \( P \to M \) is a quasi-isomorphism. If \( C \) has enough points, then this follows from the elementary Homology, Lemma 26.2 by checking on stalks. In general, we can argue as follows (this proof is far too long — there is an alternative argument by working with local sections as in the elementary proof but
it is also rather long). Since filtered colimits are exact on the category of abelian sheaves, we have

\[ H^d(\mathcal{P}) = \text{colim} \ H^d(F_i \mathcal{P}) \]

We claim that for each \( i \geq 0 \) and \( d \in \mathbb{Z} \) we have (a) a short exact sequence

\[ 0 \to H^d(\mathcal{M}_{i+1}[i]) \to H^d(F_i \mathcal{P}) \to H^d(\mathcal{M}) \to 0 \]

where the second arrow comes from \( F_i \mathcal{P} \to \mathcal{P} \to \mathcal{M} \) and (b) the composition

\[ H^d(\mathcal{M}_{i+1}[i]) \to H^d(F_i \mathcal{P}) \to H^d(F_{i+1} \mathcal{P}) \]

is zero. It is clear that the claim suffices to finish the proof.

Proof of the claim. For any \( i \geq 0 \) there is a map \( \mathcal{M}_{i+1}[i] \to F_i \mathcal{P} \) coming from the inclusion of \( \mathcal{M}_{i+1} \) into \( \mathcal{P}_i \) as the kernel of \( f_i \). Consider the short exact sequence

\[ 0 \to \mathcal{M}_{i+1}[i] \to F_i \mathcal{P} \to C_i \to 0 \]

of complexes of \( \mathcal{O} \)-modules defining \( C_i \). Observe that \( C_0 = \mathcal{M}_0 = \mathcal{M} \). Also, observe that \( C_i \) is the total complex associated to the double complex \( C_{i}^{\bullet \bullet} \) with columns

\[ \mathcal{M}_i = \mathcal{P}_i/\mathcal{M}_{i+1}, \mathcal{P}_{i-1}, \ldots, \mathcal{P}_0 \]

in degree \(-i, -i+1, \ldots, 0\). There is a map of double complexes \( C_{i}^{\bullet \bullet} \to C_i^{\bullet \bullet} \) which is zero on the column in degree \(-i\), is the surjection \( \mathcal{P}_{i-1} \to \mathcal{M}_{i-1} \) in degree \(-i+1\), and is the identity on the other columns. Hence there are maps of complexes

\[ C_i \to C_{i-1} \]

These maps are surjective quasi-isomorphisms because the kernel is the total complex on the double complex with columns \( \mathcal{M}_i, \mathcal{M}_i \) in degrees \(-i, -i+1\) and the identity map between these two columns. Using the resulting identifications \( H^d(C_i) = H^d(C_{i-1}) = \ldots = H^d(\mathcal{M}) \) this already shows we get a long exact sequence

\[ H^d(\mathcal{M}_{i+1}[i]) \to H^d(F_i \mathcal{P}) \to H^d(\mathcal{M}) \to H^{d+1}(\mathcal{M}_{i+1}[i]) \]

from the short exact sequence of complexes above. However, we also have the commutative diagram

\[
\begin{array}{ccc}
\mathcal{M}_{i+2}[i+1] & \xrightarrow{a} & T_{i+1} \\
\downarrow{b} & & \downarrow{a} \\
\mathcal{M}_{i+1}[i] & \xrightarrow{F_i} & C_i
\end{array}
\]

where \( T_{i+1} \) is the total complex on the double complex with columns \( \mathcal{P}_{i+1}, \mathcal{M}_{i+1} \) placed in degrees \(-i-1\) and \(-i\). In other words, \( T_{i+1} \) is a shift of the cone on the map \( \mathcal{P}_{i+1} \to \mathcal{M}_{i+1} \) and we find that \( a \) is a quasi-isomorphism and the map \( a^{-1} \circ b \) is a shift of the third map of the distinguished triangle in \( D(\mathcal{O}) \) associated to the short exact sequence

\[ 0 \to \mathcal{M}_{i+2} \to \mathcal{P}_{i+1} \to \mathcal{M}_{i+1} \to 0 \]

The map \( H^d(\mathcal{P}_{i+1}) \to H^d(\mathcal{M}_{i+1}) \) is surjective because we chose our maps such that \( \text{Ker}(d_{\mathcal{P}_{i+1}}) \to \text{Ker}(d_{\mathcal{M}_{i+1}}) \) is surjective. Thus we see that \( a^{-1} \circ b \) is zero on cohomology sheaves. This proves part (b) of the claim. Since \( T_{i+1} \) is the kernel
of the surjective map of complexes $F_{i+1}P \to C_i$ we find a map of long exact cohomology sequences

$$
\begin{array}{cccccc}
H^d(T_{i+1}) & \longrightarrow & H^d(F_{i+1}P) & \longrightarrow & H^d(M) & \longrightarrow & H^{d+1}(T_{i+1}) \\
\uparrow & & \uparrow & & \uparrow & & \uparrow \\
H^d(M_{i+1}[i]) & \longrightarrow & H^d(F_iP) & \longrightarrow & H^d(M) & \longrightarrow & H^{d+1}(M_{i+1}[i]) 
\end{array}
$$

Here we know, by the discussion above, that the vertical maps on the outside are zero. Hence the maps $H^d(F_{i+1}P) \to H^d(M)$ are surjective and part (a) of the claim follows. More precisely, the claim follows for $i > 0$ and we leave the claim for $i = 0$ to the reader (actually it suffices to prove the claim for all $i \gg 0$ in order to get the lemma). \[\square\]

**Lemma 23.8.** Let $(\mathcal{C}, \mathcal{O})$ be a ringed site. Let $\mathcal{A}$ be a sheaf of differential graded algebras on $(\mathcal{C}, \mathcal{O})$. Let $\mathcal{P}$ be a good acyclic right differential graded $\mathcal{A}$-module.

1. for any differential graded left $\mathcal{A}$-module $\mathcal{N}$ the tensor product $\mathcal{P} \otimes_{\mathcal{A}} \mathcal{N}$ is acyclic,

2. for any morphism $(f, f^\sharp) : (\mathcal{O}', \mathcal{O}) \to (\mathcal{O}(\mathcal{C}), \mathcal{O})$ of ringed topoi and any differential graded $\mathcal{O}'$-algebra $\mathcal{A}'$ and any map $\varphi : f^{-1}\mathcal{A} \to \mathcal{A}'$ of differential graded $f^{-1}\mathcal{O}$-algebras the pullback $f^*\mathcal{P}$ is acyclic and good.

**Proof.** Proof of (1). By Lemma 23.7 we can choose a good left differential graded $\mathcal{Q}$ and a quasi-isomorphism $\mathcal{Q} \to \mathcal{N}$. Then $\mathcal{P} \otimes_{\mathcal{A}} \mathcal{Q}$ is acyclic because $\mathcal{Q}$ is good. Let $\mathcal{N}'$ be the cone on the map $\mathcal{Q} \to \mathcal{N}$. Then $\mathcal{P} \otimes_{\mathcal{A}} \mathcal{N}'$ is acyclic because $\mathcal{P}$ is good and because $\mathcal{N}'$ is acyclic (as the cone on a quasi-isomorphism). We have a distinguished triangle

$$\mathcal{Q} \to \mathcal{N} \to \mathcal{N}' \to \mathcal{Q}[1]$$

in $K(\text{Mod}_{(\mathcal{A}, d)})$ by our construction of the triangulated structure. Since $\mathcal{P} \otimes_{\mathcal{A}} -$ sends distinguished triangles to distinguished triangles, we obtain a distinguished triangle

$$\mathcal{P} \otimes_{\mathcal{A}} \mathcal{Q} \to \mathcal{P} \otimes_{\mathcal{A}} \mathcal{N} \to \mathcal{P} \otimes_{\mathcal{A}} \mathcal{N}' \to \mathcal{P} \otimes_{\mathcal{A}} \mathcal{Q}[1]$$

in $K(\text{Mod}(\mathcal{O}))$. Thus we conclude.

Proof of (2). Observe that $f^*\mathcal{P}$ is good by our definition of good modules. Recall that $f^*\mathcal{P} = f^{-1}\mathcal{P} \otimes_{f^{-1}\mathcal{A}} \mathcal{A}'$. Then $f^{-1}\mathcal{P}$ is a good acyclic (because $f^{-1}$ is exact) differential graded $f^{-1}\mathcal{A}$-module. Hence we see that $f^*\mathcal{P}$ is acyclic by part (1). \[\square\]

24. The differential graded hull of a graded module

The differential graded hull of a graded module $\mathcal{N}$ is the result of applying the functor $G$ in the following lemma.

**Lemma 24.1.** Let $(\mathcal{C}, \mathcal{O})$ be a ringed site. Let $\mathcal{A}$ be a sheaf of differential graded algebras on $(\mathcal{C}, \mathcal{O})$. The forgetful functor $F : \text{Mod}_{(\mathcal{A}, d)} \to \text{Mod}_{\mathcal{A}}$ has a left adjoint $G : \text{Mod}_{\mathcal{A}} \to \text{Mod}_{(\mathcal{A}, d)}$.

**Proof.** To prove the existence of $G$ we can use the adjoint functor theorem, see Categories, Theorem 25.3 (observe that we have switched the roles of $F$ and $G$). The exactness conditions on $F$ are satisfied by Lemma 13.2. The set theoretic
condition can be seen as follows: suppose given a graded \(A\)-module \(N\). Then for any map
\[
\varphi : N \to F(M)
\]
we can consider the smallest differential graded \(A\)-submodule \(M' \subset M\) with \(\text{Im}(\varphi) \subset F(M')\). It is clear that \(M'\) is the image of the map of graded \(A\)-modules
\[
N \oplus N[-1] \otimes O \to M
\]
defined by
\[
(n, \sum n_i \otimes a_i) \mapsto \varphi(n) + \sum d(\varphi(n_i))a_i
\]
because the image of this map is easily seen to be a differential graded submodule of \(M\). Thus the number of possible isomorphism classes of these \(M'\) is bounded and we conclude. □

Let \((\mathcal{C}, \mathcal{O})\) be a ringed site. Let \(\mathcal{A}\) be a sheaf of differential graded algebras on \((\mathcal{C}, \mathcal{O})\). Let \(M\) be a differential graded \(\mathcal{A}\)-module and suppose we have a short exact sequence
\[
0 \to N \to F(M) \to N' \to 0
\]
in \(\text{Mod}_\mathcal{A}\). Then we obtain a canonical graded \(\mathcal{A}\)-module homomorphism
\[
\mathfrak{f} : N \to N'[1]
\]
as follows: given a local section \(x\) of \(N\) denote \(\mathfrak{f}(x)\) the image in \(N'\) of \(d_M(x)\) when \(x\) is viewed as a local section of \(M\).

0FSL. **Lemma 24.2.** The functors \(F, G\) of Lemma 24.1 have the following properties. Given a graded \(\mathcal{A}\)-module \(N\) we have

1. the counit \(N \to F(G(N))\) is injective,
2. the map \(\mathfrak{f} : N \to \text{Coker}(N \to F(G(N)))[1]\) is an isomorphism, and
3. \(G(N)\) is an acyclic differential graded \(\mathcal{A}\)-module.

**Proof.** We observe that property (3) is a consequence of properties (1) and (2). Namely, if \(s\) is a nonzero local section of \(F(G(N))\) with \(d(s) = 0\), then \(s\) cannot be in the image of \(N \to F(G(N))\). Hence we can write the image \(\overline{s}\) of \(s\) in the cokernel as \(\mathfrak{f}(s')\) for some local section \(s'\) of \(N\). Then we see that \(s = d(s')\) because the difference \(s - d(s')\) is still in the kernel of \(d\) and is contained in the image of the counit.

Let us write temporarily \(\mathcal{A}_{gr}\), respectively \(\mathcal{A}_{dg}\) the sheaf \(\mathcal{A}\) viewed as a (right) graded module over itself, respectively as a (right) differential graded module over itself. The most important case of the lemma is to understand what is \(G(\mathcal{A}_{gr})\). Of course \(G(\mathcal{A}_{gr})\) is the object of \(\text{Mod}_{(\mathcal{A}, d)}\) representing the functor
\[
\mathcal{M} \mapsto \text{Hom}_{\text{Mod}_\mathcal{A}}(\mathcal{A}_{gr}, F(\mathcal{M})) = \Gamma(\mathcal{C}, \mathcal{M})
\]
By Remark 22.5 we see that this functor represented by \(C[-1]\) where \(C\) is the cone on the identity of \(\mathcal{A}_{dg}\). We have a short exact sequence
\[
0 \to \mathcal{A}_{dg}[-1] \to C[-1] \to \mathcal{A}_{dg} \to 0
\]
in \(\text{Mod}_{(\mathcal{A}, d)}\) which is split by the counit \(\mathcal{A}_{gr} \to F(C[-1])\) in \(\text{Mod}_\mathcal{A}\). Thus \(G(\mathcal{A}_{gr})\) satisfies properties (1) and (2).

Let \(U\) be an object of \(\mathcal{C}\). Denote \(j_U : \mathcal{C}/U \to \mathcal{C}\) the localization morphism. Denote \(\mathcal{A}_U\) the restriction of \(\mathcal{A}\) to \(U\). We will use the notation \(\mathcal{A}_{U, gr}\) to denote \(\mathcal{A}_U\) viewed...
as a graded \( A \)-module. Denote \( F_U : \text{Mod}_{(A_U,d)} \to \text{Mod}_{A_U} \) the forgetful functor and denote \( G_U \) its adjoint. Then we have the commutative diagrams

\[
\begin{array}{ccc}
\text{Mod}_{(A,d)} & \xrightarrow{F_U} & \text{Mod}_A \\
\downarrow j_U & & \downarrow j_U^* \\
\text{Mod}_{(A_U,d)} & \xrightarrow{F_U} & \text{Mod}_{A_U}
\end{array}
\quad \text{and} \quad
\begin{array}{ccc}
\text{Mod}_{(A_d)} & \xrightarrow{F_U} & \text{Mod}_{A}\ \\
\downarrow j_U & & \downarrow j_U^* \\
\text{Mod}_{(A_U,d)} & \xrightarrow{F_U} & \text{Mod}_{A_U}
\end{array}
\]

by the construction of \( j_U^* \) and \( j_U^! \) in Sections 9, 18, 10, and 19. By uniqueness of adjoints we obtain \( j_U^! \circ G_U = G \circ j_U^! \). Since \( j_U^! \) is an exact functor, we see that the properties (1) and (2) for the counit \( A_{U,gr} \to F_U(G_U(A_{U,gr})) \) which we’ve seen in the previous part of the proof imply properties (1) and (2) for the counit \( j_U^! : A_{U,gr} \to F_U(G_U(A_{U,gr})) \).

In the proof of Lemma 11.1 we have seen that any object of \( \text{Mod}_A \) is a quotient of a direct sum of copies of \( j_U^! A_{U,gr} \). Since \( G \) is a left adjoint, we see that \( G \) commutes with direct sums. Thus properties (1) and (2) hold for direct sums of objects for which they hold. Thus we see that every object \( N \) of \( \text{Mod}_A \) fits into an exact sequence

\[ N_1 \to N_0 \to N \to 0 \]

such that (1) and (2) hold for \( N_1 \) and \( N_0 \). We leave it to the reader to deduce (1) and (2) for \( N \) using that \( G \) is right exact.

25. K-injective differential graded modules

This section is the analogue of Injectives, Section 12 in the setting of sheaves of differential graded modules over a sheaf of differential graded algebras.

**Lemma 25.1.** Let \((\mathcal{C}, \mathcal{O})\) be a ringed site. Let \( A \) be a sheaf of graded algebras on \((\mathcal{C}, \mathcal{O})\). There exists a set \( T \) and for each \( t \in T \) an injective map \( N_t \to N'_t \) of graded \( A \)-modules such that an object \( I \) of \( \text{Mod}_A \) is injective if and only if for every solid diagram

\[
\begin{array}{ccc}
N_t & \xrightarrow{=} & I \\
\downarrow & & \downarrow \text{dotted arrow} \\
N'_t & \xrightarrow{=} & I
\end{array}
\]

a dotted arrow exists in \( \text{Mod}_A \) making the diagram commute.

**Proof.** This is true in any Grothendieck abelian category, see Injectives, Lemma 11.6. By Lemma 11.1 the category \( \text{Mod}_A \) is a Grothendieck abelian category. □

**Definition 25.2.** Let \((\mathcal{C}, \mathcal{O})\) be a ringed site. Let \((A, d)\) be a sheaf of differential graded algebras on \((\mathcal{C}, \mathcal{O})\). A differential graded \( A \)-module \( I \) is said to be graded injective\(^2\) if \( M \) viewed as a graded \( A \)-module is an injective object of the category \( \text{Mod}_A \) of graded \( A \)-modules.

**Remark 25.3.** Let \((\mathcal{C}, \mathcal{O})\) be a ringed site. Let \((A, d)\) be a sheaf of differential graded algebras on \((\mathcal{C}, \mathcal{O})\). Let \( I \) be a graded injective differential graded \( A \)-module. Let

\[ 0 \to M_1 \to M_2 \to M_3 \to 0 \]

\(^2\)This may be nonstandard terminology.
be a short exact sequence of differential graded \( A \)-modules. Since \( I \) is graded injective we obtain a short exact sequence of complexes

\[
0 \to \text{Hom}_{\text{Mod}_{dg}(A,d)}(M_3,I) \to \text{Hom}_{\text{Mod}_{dg}(A,d)}(M_2,I) \to \text{Hom}_{\text{Mod}_{dg}(A,d)}(M_1,I) \to 0
\]

of \( \Gamma(C,O) \)-modules. Taking cohomology we obtain a long exact sequence

\[
\text{Hom}_{K(\text{Mod}(A,d))}(M_3,I) \quad \text{Hom}_{K(\text{Mod}(A,d))}(M_3,I)[1] \quad \text{Hom}_{K(\text{Mod}(A,d))}(M_2,I) \quad \text{Hom}_{K(\text{Mod}(A,d))}(M_2,I)[1] \quad \text{Hom}_{K(\text{Mod}(A,d))}(M_1,I) \quad \text{Hom}_{K(\text{Mod}(A,d))}(M_1,I)[1]
\]

of groups of homomorphisms in the homotopy category. The point is that we get this even though we didn’t assume that our short exact sequence is admissible (so the short exact sequence in general does not define a distinguished triangle in the homotopy category).

\textbf{Lemma 25.4.} \( 0\text{FSR} \) Let \((C,O)\) be a ringed site. Let \((A,d)\) be a sheaf of differential graded algebras on \((C,O)\). Let \( T \) be a set and for each \( t \in T \) let \( I_t \) be a graded injective differential graded \( A \)-module. Then \( \prod I_t \) is a graded injective differential graded \( A \)-module.

\textbf{Proof.} This is true because products of injectives are injectives, see Homology, Lemma 27.3, and because products in \( \text{Mod}(A,d) \) are compatible with products in \( \text{Mod}_A \) via the forgetful functor. \( \square \)

\textbf{Lemma 25.5.} \( 0\text{FSS} \) Let \((C,O)\) be a ringed site. Let \((A,d)\) be a sheaf of differential graded algebras on \((C,O)\). There exists a set \( T \) and for each \( t \in T \) an injective differential graded \( A \)-module \( M_t \) such that for an object \( I \) of \( \text{Mod}_{(A,d)} \) the following are equivalent

1. \( I \) is graded injective, and
2. for every solid diagram

\[
\begin{array}{ccc}
M_t & \longrightarrow & I \\
\downarrow & & \uparrow \\
M_t' & \quad & \\
\end{array}
\]

a dotted arrow exists in \( \text{Mod}_{(A,d)} \) making the diagram commute.

\textbf{Proof.} Let \( T \) and \( N_t \to N_t' \) be as in Lemma 25.1 Denote \( F : \text{Mod}_{(A,d)} \to \text{Mod}_A \) the forgetful functor. Let \( G \) be the left adjoint functor to \( F \) as in Lemma 24.1 Set

\[
M_t = G(N_t) \to G(N_t') = M_t'
\]

This is an injective map of acyclic differential graded \( A \)-modules by Lemma 24.2 Since \( G \) is the left adjoint to \( F \) we see that there exists a dotted arrow in the
Differential graded algebras on $(\mathcal{C}, \mathcal{O})$. There exists a set $S$ and for each $s$ an acyclic differential graded $\mathcal{A}$-module $\mathcal{M}_s$ such that for every nonzero acyclic differential graded $\mathcal{A}$-module $\mathcal{M}$ there is an $s \in S$ and an injective map $\mathcal{M}_s \to \mathcal{M}$ in $\text{Mod}(\mathcal{A}, d)$.

**Proof.** Before we start recall that our conventions guarantee the site $\mathcal{C}$ has a set of objects and morphisms and a set $\text{Cov}(\mathcal{C})$ of coverings. If $\mathcal{F}$ is a differential graded $\mathcal{A}$-module, let us define $|\mathcal{F}|$ to be the sum of the cardinality of

$$\prod_{(U, n)} \mathcal{F}^n(U)$$

as $U$ ranges over the objects of $\mathcal{C}$ and $n \in \mathbb{Z}$. Choose an infinite cardinal $\kappa$ bigger than the cardinals $|\text{Ob}(\mathcal{C})|$, $|\text{Arrows}(\mathcal{C})|$, $|\text{Cov}(\mathcal{C})|$, $\sup |I|$ for $\{U_i \to U\}_{i \in I} \in \text{Cov}(\mathcal{C})$, and $|\mathcal{A}|$.

Let $\mathcal{F} \subset \mathcal{M}$ be an inclusion of differential graded $\mathcal{A}$-modules. Suppose given a set $K$ and for each $k \in K$ a triple $(U_k, n_k, x_k)$ consisting of an object $U_k$ of $\mathcal{C}$, integer $n_k$, and a section $x_k \in \mathcal{M}^{n_k}(U_k)$. Then we can consider the smallest differential graded $\mathcal{A}$-submodule $\mathcal{F}' \subset \mathcal{M}$ containing $\mathcal{F}$ and the sections $x_k$ for $k \in K$. We can describe

$$(\mathcal{F}')^n(U) \subset \mathcal{M}^n(U)$$

as the set of elements $x \in \mathcal{M}^n(U)$ such that there exists $\{f_i : U_i \to U\}_{i \in I} \in \text{Cov}(\mathcal{C})$ such that for each $i \in I$ there is a finite set $T_i$ and morphisms $g_i : U_i \to U_{k_i}$

$$f_i^* x = y_i + \sum_{t \in T_i} a_{it} g_i^* x_{k_t} + b_{it} g_i^* \delta(x_{k_t})$$

for some section $y_i \in \mathcal{F}^n(U)$ and sections $a_{it} \in \mathcal{A}^{n-n_{k_t}}(U_i)$ and $b_{it} \in \mathcal{A}^{n-n_{k_t}-1}(U_i)$. (Details omitted: hints: these sections are certainly in $\mathcal{F}'$ and you show conversely that this rule defines a differential graded $\mathcal{A}$-submodule.) It follows from this description that $|\mathcal{F}'| \leq \max(|\mathcal{F}|, |K|, \kappa)$.

Let $\mathcal{M}$ be a nonzero acyclic differential graded $\mathcal{A}$-module. Then we can find an integer $n$ and a nonzero section $x$ of $\mathcal{M}^n$ over some object $U$ of $\mathcal{C}$. Let

$$\mathcal{F}_0 \subset \mathcal{M}$$

be the smallest differential graded $\mathcal{A}$-submodule containing $x$. By the previous paragraph we have $|\mathcal{F}_0| \leq \kappa$. By induction, given $\mathcal{F}_0, \ldots, \mathcal{F}_n$ define $\mathcal{F}_{n+1}$ as follows. Consider the set

$$L = \{(U, n, x) | \{U_i \to U\}_{i \in I}, (x_i)_{i \in I}\}$$

If and only if there exists a dotted arrow in the diagram

$$\xymatrix{ \mathcal{M}_i \ar[r] \ar[d] & \mathcal{I} \ar[d] \\
\mathcal{M}'_i \ar@{.>}[ur] }$$

Hence the result follows from the choice of our collection of arrows $\mathcal{N}_i \to \mathcal{N}'_i$. \qed
of triples where $U$ is an object of $\mathcal{C}$, $n \in \mathbb{Z}$, and $x \in \mathcal{F}_n(U)$ with $d(x) = 0$. Since $\mathcal{M}$ is acyclic for each triple $l = (U_l, n_l, x_l) \in L$ we can choose $\{(U_l, n_l, x_l) \in \text{Cov}(\mathcal{C}) \text{ and } x_l \in \mathcal{M}^{n_l-1}(U_l,i) \text{ such that } d(x_l) = x|_{U_l,i} \}$. Then we set

$$K = \{(U_l, n_l - 1, x_{l,i}) \ | \ l \in L, i \in I_l \}$$

and we let $\mathcal{F}_{n+1}$ be the smallest differential graded $\mathcal{A}$-submodule of $\mathcal{M}$ containing $\mathcal{F}_n$ and the sections $x_{l,i}$. Since $|K| = \max(\kappa, |\mathcal{F}_n|)$ we conclude that $|\mathcal{F}_{n+1}| \leq \kappa$ by induction.

By construction the inclusion $\mathcal{F}_n \to \mathcal{F}_{n+1}$ induces the zero map on cohomology sheaves. Hence we see that $\mathcal{F} = \bigcup \mathcal{F}_n$ is a nonzero acyclic submodule with $|\mathcal{F}| \leq \kappa$. Since there is only a set of isomorphism classes of differential graded $\mathcal{A}$-modules $\mathcal{F}$ with $|\mathcal{F}|$ bounded, we conclude. \hfill $\square$

**Definition 25.7.** Let $(\mathcal{C}, \mathcal{O})$ be a ringed site. Let $(\mathcal{A}, d)$ be a sheaf of differential graded algebras on $(\mathcal{C}, \mathcal{O})$. A differential graded $\mathcal{A}$-module $\mathcal{I}$ is $K$-injective if for every acyclic differential graded $\mathcal{A}$-module $\mathcal{M}$ we have

$$\text{Hom}_{\text{Mod}(\mathcal{A}, d)}(\mathcal{M}, \mathcal{I}) = 0$$

Please note the similarity with Derived Categories, Definition 31.1.

**Lemma 25.8.** Let $(\mathcal{C}, \mathcal{O})$ be a ringed site. Let $(\mathcal{A}, d)$ be a sheaf of differential graded algebras on $(\mathcal{C}, \mathcal{O})$. Let $T$ be a set and for each $t \in T$ let $\mathcal{I}_t$ be a $K$-injective differential graded $\mathcal{A}$-module. Then $\prod_{t \in T} \mathcal{I}_t$ is a $K$-injective differential graded $\mathcal{A}$-module.

**Proof.** Let $\mathcal{K}$ be an acyclic differential graded $\mathcal{A}$-module. Then we have

$$\text{Hom}_{\text{Mod}(\mathcal{A}, d)}(\mathcal{K}, \prod_{t \in T} \mathcal{I}_t) = \prod_{t \in T} \text{Hom}_{\text{Mod}(\mathcal{A}, d)}(\mathcal{K}, \mathcal{I}_t)$$

because taking products in $\text{Mod}(\mathcal{A}, d)$ commutes with the forgetful functor to graded $\mathcal{A}$-modules. Since taking products is an exact functor on the category of abelian groups we conclude. \hfill $\square$

**Lemma 25.9.** Let $(\mathcal{C}, \mathcal{O})$ be a ringed site. Let $(\mathcal{A}, d)$ be a sheaf of differential graded algebras on $(\mathcal{C}, \mathcal{O})$. Let $\mathcal{I}$ be a $K$-injective and graded injective object of $\text{Mod}(\mathcal{A}, d)$. For every solid diagram in $\text{Mod}(\mathcal{A}, d)$

$$\begin{array}{ccc}
\mathcal{M} & \xrightarrow{a} & \mathcal{I} \\
\downarrow b & & \\
\mathcal{M}' & \xrightarrow{\sigma} & \mathcal{I}
\end{array}$$

where $b$ is injective and $\mathcal{M}$ is acyclic a dotted arrow exists making the diagram commute.

**Proof.** Since $\mathcal{M}$ is acyclic and $\mathcal{I}$ is $K$-injective, there exists a graded $\mathcal{A}$-module map $h : \mathcal{M} \to \mathcal{I}$ of degree $-1$ such that $a = d(h)$. Since $\mathcal{I}$ is graded injective and $b$ is injective, there exists a graded $\mathcal{A}$-module map $h' : \mathcal{M}' \to \mathcal{I}$ of degree $-1$ such that $h = h' \circ b$. Then we can take $a' = d(h')$ as the dotted arrow. \hfill $\square$
**Lemma 25.10.** Let \((\mathcal{C}, \mathcal{O})\) be a ringed site. Let \((\mathcal{A}, d)\) be a sheaf of differential graded algebras on \((\mathcal{C}, \mathcal{O})\). Let \(\mathcal{I}\) be a K-injective and graded injective object of \(\text{Mod}_{(\mathcal{A}, d)}\). For every solid diagram in \(\text{Mod}_{(\mathcal{A}, d)}\)

\[
\begin{array}{ccc}
\mathcal{M} & \xrightarrow{a} & \mathcal{I} \\
\downarrow b & & \\
\mathcal{M}' & \nearrow & \\
\end{array}
\]

where \(b\) is a quasi-isomorphism a dotted arrow exists making the diagram commute up to homotopy.

**Proof.** After replacing \(\mathcal{M}\) by the direct sum of \(\mathcal{M}\) and the cone on the identity on \(\mathcal{M}\) (which is acyclic) we may assume \(b\) is also injective. Then the cokernel \(Q\) of \(b\) is acyclic. Thus we see that

\[
\text{Hom}_{K(\text{Mod}_{(\mathcal{A}, d)})}(Q, I) = \text{Hom}_{K(\text{Mod}_{(\mathcal{A}, d)})}(Q, I)[1] = 0
\]

as \(I\) is K-injective. As \(I\) is graded injective by Remark 25.3 we see that

\[
\text{Hom}_{K(\text{Mod}_{(\mathcal{A}, d)})}(\mathcal{M}', I) \rightarrow \text{Hom}_{K(\text{Mod}_{(\mathcal{A}, d)})}(\mathcal{M}, I)
\]

is bijective and the proof is complete. \(\square\)

**Lemma 25.11.** Let \((\mathcal{C}, \mathcal{O})\) be a ringed site. Let \((\mathcal{A}, d)\) be a sheaf of differential graded algebras on \((\mathcal{C}, \mathcal{O})\). There exists a set \(R\) and for each \(r \in R\) an injective map \(M_r \rightarrow M'_r\) of acyclic differential graded \(\mathcal{A}\)-modules such that for an object \(I\) of \(\text{Mod}_{(\mathcal{A}, d)}\) the following are equivalent

1. \(I\) is K-injective and graded injective, and
2. for every solid diagram

\[
\begin{array}{ccc}
\mathcal{M}_r & \rightarrow & \mathcal{I} \\
\downarrow & & \\
\mathcal{M}'_r & \nearrow & \\
\end{array}
\]

a dotted arrow exists in \(\text{Mod}_{(\mathcal{A}, d)}\) making the diagram commute.

**Proof.** Let \(T\) and \(M_t \rightarrow M'_t\) be as in Lemma 25.5. Let \(S\) and \(M_s\) be as in Lemma 25.6. Choose an injective map \(M_s \rightarrow M'_s\) of acyclic differential graded \(\mathcal{A}\)-modules which is homotopic to zero. This is possible because we may take \(M'_s\) to be the cone on the identity; in that case it is even true that the identity on \(M'_s\) is homotopic to zero, see Differential Graded Algebra, Lemma 27.4 which applies by the discussion in Section 22. We claim that \(R = T \coprod S\) with the given maps works.

The implication (1) \(\Rightarrow\) (2) holds by Lemma 25.9

Assume (2). First, by Lemma 25.5 we see that \(I\) is graded injective. Next, let \(\mathcal{M}\) be an acyclic differential graded \(\mathcal{A}\)-module. We have to show that

\[
\text{Hom}_{K(\text{Mod}_{(\mathcal{A}, d)})}(\mathcal{M}, I) = 0
\]

The proof will be exactly the same as the proof of Injectives, Lemma 12.3

We are going to construct by induction on the ordinal \(\alpha\) an acyclic differential graded submodule \(K_\alpha \subset \mathcal{M}\) as follows. For \(\alpha = 0\) we set \(K_0 = 0\). For \(\alpha > 0\) we proceed as follows:
(1) If $\alpha = \beta + 1$ and $K_\beta = M$ then we choose $K_\alpha = K_\beta$.
(2) If $\alpha = \beta + 1$ and $K_\beta \neq M$ then $M/K_\beta$ is a nonzero acyclic differential graded $A$-module. We choose a differential graded $A$ submodule $N_\alpha \subset M/K_\beta$ isomorphic to $M_s$ for some $s \in S$, see Lemma 25.6. Finally, we let $K_\alpha \subset M$ be the inverse image of $N_\alpha$.
(3) If $\alpha$ is a limit ordinal we set $K_\beta = \text{colim} K_\alpha$.

It is clear that $M = K_\alpha$ for a suitably large ordinal $\alpha$. We will prove that

$$\text{Hom}_{K(\text{Mod}(A,d))}(K_\alpha, I)$$

is zero by transfinite induction on $\alpha$. It holds for $\alpha = 0$ since $K_0$ is zero. Suppose it holds for $\beta$ and $\alpha = \beta + 1$. In case (1) of the list above the result is clear. In case (2) there is a short exact sequence

$$0 \rightarrow K_\beta \rightarrow K_\alpha \rightarrow N_\alpha \rightarrow 0$$

By Remark 25.3 and since we’ve seen that $I$ is graded injective, we obtain an exact sequence

$$\text{Hom}_{K(\text{Mod}(A,d))}(K_\beta, I) \rightarrow \text{Hom}_{K(\text{Mod}(A,d))}(K_\alpha, I) \rightarrow \text{Hom}_{K(\text{Mod}(A,d))}(N_\alpha, I)$$

By induction the term on the left is zero. By assumption (2) the term on the right is zero: any map $M_s \rightarrow I$ factors through $M_s'$ and hence is homotopic to zero. Thus the middle group is zero too. Finally, suppose that $\alpha$ is a limit ordinal. Because we also have $K_\alpha = \text{colim} K_\alpha$ as graded $A$-modules we see that

$$\text{Hom}_{\text{Mod}^{dg}_d(A,d)}(K_\alpha, I) = \text{lim}_{\beta < \alpha} \text{Hom}_{\text{Mod}^{dg}_d(A,d)}(K_\beta, I)$$

as complexes of abelian groups. The cohomology groups of these complexes compute morphisms in $K(\text{Mod}(A,d))$ between shifts. The transition maps in the system of complexes are surjective by Remark 25.3 because $I$ is graded injective. Moreover, for a limit ordinal $\beta \leq \alpha$ we have equality of limit and value. Thus we may apply Homology, Lemma 31.8 to conclude. □

**Lemma 25.12.** Let $(C, O)$ be a ringed site. Let $(A, d)$ be a sheaf of differential graded algebras on $(C, O)$. Let $R$ be a set and for each $r \in R$ let an injective map $M_r \rightarrow M_r'$ of acyclic differential graded $A$-modules be given. There exists a functor $M : \text{Mod}(A,d) \rightarrow \text{Mod}(A,d)$ and a natural transformation $j : \text{id} \rightarrow M$ such that

(1) $j_M : M \rightarrow M(M)$ is injective and a quasi-isomorphism,
(2) for every solid diagram

$$\begin{array}{ccc}
M_r & \rightarrow & M \\
\downarrow & & \downarrow \text{j}_M \\
M_r' & \rightarrow & M(M)
\end{array}$$

a dotted arrow exists in $\text{Mod}(A,d)$ making the diagram commute.

**Proof.** We define $M(M)$ as the pushout in the following diagram

$$\begin{array}{ccc}
\bigoplus_{(r, \varphi)} M_r & \rightarrow & M \\
\downarrow & & \downarrow \\
\bigoplus_{(r, \varphi)} M_r' & \rightarrow & M(M)
\end{array}$$
where the direct sum is over all pairs $(r, \varphi)$ with $r \in R$ and $\varphi \in \text{Hom}_{\text{Mod}(\mathcal{A}, \delta)}(\mathcal{M}_r, \mathcal{M})$. Since the pushout of an injective map is injective, we see that $\mathcal{M} \to M(\mathcal{M})$ is injective. Since the cokernel of the left vertical arrow is acyclic, we see that the (isomorphic) cokernel of $\mathcal{M} \to M(\mathcal{M})$ is acyclic, hence $\mathcal{M} \to M(\mathcal{M})$ is a quasi-isomorphism. Property (2) holds by construction. We omit the verification that this procedure can be turned into a functor. □

**Theorem 25.13.** Let $(\mathcal{C}, \mathcal{O})$ be a ringed site. Let $(\mathcal{A}, d)$ be a sheaf of differential graded algebras on $(\mathcal{C}, \mathcal{O})$. For every differential graded $\mathcal{A}$-module $\mathcal{M}$ there exists a quasi-isomorphism $\mathcal{M} \to \mathcal{I}$ where $\mathcal{I}$ is a graded injective and $K$-injective differential graded $\mathcal{A}$-module. Moreover, the construction is functorial in $\mathcal{M}$.

**Proof.** Let $R$ and $\mathcal{M}_r \to \mathcal{M}_r'$ be a set of morphisms of $\text{Mod}_{(\mathcal{A}, d)}$ found in Lemma 25.12. Let $M$ with transformation id $\to M$ be as constructed in Lemma 25.12 using $R$ and $\mathcal{M}_r \to \mathcal{M}_r'$. By transfinite induction on $\alpha$ we define a sequence of functors $\mathcal{M}_\alpha$ and natural transformations $M_\beta \to M_\alpha$ for $\alpha < \beta$ by setting

1. $M_0 = \text{id}$,
2. $M_{\alpha+1} = M \circ M_\alpha$ with natural transformation $M_\beta \to M_{\alpha+1}$ for $\beta < \alpha + 1$ coming from the already constructed $M_\beta \to M_\alpha$ and the maps $M_\alpha \to M \circ M_\alpha$ coming from id $\to M$, and
3. $M_\alpha = \text{colim}_{\beta < \alpha} M_\beta$ if $\alpha$ is a limit ordinal with the coprojections as transformations $M_\beta \to M_\alpha$ for $\alpha < \beta$.

Observe that for every differential graded $\mathcal{A}$-module the maps $\mathcal{M} \to M_\beta(\mathcal{M}) \to M_\alpha(\mathcal{M})$ are injective quasi-isomorphisms (as filtered colimits are exact).

Recall that $\text{Mod}_{(\mathcal{A}, d)}$ is a Grothendieck abelian category. Thus by Injectives, Proposition 11.5 (applied to the direct sum of $\mathcal{M}_r$ for all $r \in R$) there is a limit ordinal $\alpha$ such that $\mathcal{M}_r$ is $\alpha$-small with respect to injections for every $r \in R$. We claim that $\mathcal{M} \to M_\alpha(\mathcal{M})$ is the desired functorial embedding of $\mathcal{M}$ into a graded injective $K$-injective module.

Namely, any map $\mathcal{M}_r \to M_\alpha(\mathcal{M})$ factors through $M_\beta(\mathcal{M})$ for some $\beta < \alpha$. However, by the construction of $\mathcal{M}$ we see that this means that $\mathcal{M}_r \to M_{\beta+1}(\mathcal{M}) = M(M_\beta(\mathcal{M}))$ factors through $\mathcal{M}_r'$. Since $M_\beta(\mathcal{M}) \subset M_{\beta+1}(\mathcal{M}) \subset M_\alpha(\mathcal{M})$ we get the desired factorization into $M_\alpha(\mathcal{M})$. We conclude by our choice of $R$ and $\mathcal{M}_r \to \mathcal{M}_r'$ in Lemma 25.11. □

### 26. The derived category

This section is the analogue of Differential Graded Algebra, Section 22. Let $(\mathcal{C}, \mathcal{O})$ be a ringed site. Let $(\mathcal{A}, d)$ be a sheaf of differential graded algebras on $(\mathcal{C}, \mathcal{O})$. We will construct the derived category $D(\mathcal{A}, d)$ by inverting the quasi-isomorphisms in $K(\text{Mod}_{(\mathcal{A}, d)})$.

**Lemma 26.1.** Let $(\mathcal{C}, \mathcal{O})$ be a ringed site. Let $(\mathcal{A}, d)$ be a sheaf of differential graded algebras on $(\mathcal{C}, \mathcal{O})$. The functor $H^0 : \text{Mod}_{(\mathcal{A}, d)} \to \text{Mod}(\mathcal{O})$ of Section 13 factors through a functor

$$H^0 : K(\text{Mod}_{(\mathcal{A}, d)}) \to \text{Mod}(\mathcal{O})$$

which is homological in the sense of Derived Categories, Definition 5.6.
Proof. It follows immediately from the definitions that there is a commutative
diagram
\[
\begin{array}{ccc}
\text{Mod}(\mathcal{A}, d) & \rightarrow & K(\text{Mod}(\mathcal{A}, d)) \\
\downarrow & & \downarrow \\
\text{Comp}(\mathcal{O}) & \rightarrow & K(\text{Mod}(\mathcal{O}))
\end{array}
\]
Since $H^0(M)$ is defined as the zeroth cohomology sheaf of the underlying complex
of $\mathcal{O}$-modules of $M$ the lemma follows from the case of complexes of $\mathcal{O}$-modules
which is a special case of Derived Categories, Lemma 11.1. □

Lemma 26.2. Let $(\mathcal{C}, \mathcal{O})$ be a ringed site. Let $(\mathcal{A}, d)$ be a sheaf of differential
graded algebras on $(\mathcal{C}, \mathcal{O})$. The full subcategory $\mathcal{A}c$ of the homotopy category
$K(\text{Mod}(\mathcal{A}, d))$ consisting of acyclic modules is a strictly full saturated triangulated
subcategory of $K(\text{Mod}(\mathcal{A}, d))$.

Proof. Of course an object $M$ of $K(\text{Mod}(\mathcal{A}, d))$ is in $\mathcal{A}c$ if and only if
$H^i(M) = H^0(M[i])$ is zero for all $i$. The lemma follows from this, Lemma 26.1 and Derived
Categories, Lemma 6.3. See also Derived Categories, Definitions 6.1 and 3.4 and
Lemma 4.15. □

Lemma 26.3. Let $(\mathcal{C}, \mathcal{O})$ be a ringed site. Let $(\mathcal{A}, d)$ be a sheaf of differential
graded algebras on $(\mathcal{C}, \mathcal{O})$. Consider the subclass $\mathcal{Q}_{\text{is}} \subset \text{Arrows}(K(\text{Mod}(\mathcal{A}, d)))$
consisting of quasi-isomorphisms. This is a saturated multiplicative system compatible
with the triangulated structure on $K(\text{Mod}(\mathcal{A}, d))$.

Proof. Observe that if $f, g : M \rightarrow N$ are morphisms of $\text{Mod}(\mathcal{A}, d)$ which are homo-
topic, then $f$ is a quasi-isomorphism if and only if $H^i(M) = H^0(M[i])$ and $H^i(g) = H^0(g[i])$
are the same by Lemma 26.1. Thus it is unambiguous to say that a morphism of the homotopy
category $K(\text{Mod}(\mathcal{A}, d))$ is a quasi-isomorphism. For definitions of “multiplicative system”,
“saturated”, and “compatible with the triangulated structure” see Derived Categories, Definition 5.1

To actually prove the lemma consider the composition of exact functors of triangu-
lated categories
\[ K(\text{Mod}(\mathcal{A}, d)) \rightarrow K(\text{Mod}(\mathcal{O})) \rightarrow D(\mathcal{O}) \]
and observe that a morphism $f : M \rightarrow N$ of $K(\text{Mod}(\mathcal{A}, d))$ is in $\mathcal{Q}_{\text{is}}$ if and only if
it maps to an isomorphism in $D(\mathcal{O})$. Thus the lemma follows from Derived
Categories, Lemma 5.3. □

In the situation of Lemma 26.3 we can apply Derived Categories, Proposition 5.5
to obtain an exact functor of triangulated categories
\[ Q : K(\text{Mod}(\mathcal{A}, d)) \rightarrow \mathcal{Q}_{\text{is}}^{-1}K(\text{Mod}(\mathcal{A}, d)) \]
However, as $\text{Mod}(\mathcal{A}, d)$ is a “big” category, i.e., its objects form a proper class, it
isn’t immediately clear that given $M$ and $N$ the construction of $\mathcal{Q}_{\text{is}}^{-1}K(\text{Mod}(\mathcal{A}, d))$
produces a set
\[ \text{Mor}_{\mathcal{Q}_{\text{is}}^{-1}K(\text{Mod}(\mathcal{A}, d))}(M, N) \]
of morphisms. However, this is true thanks to our construction of K-injective
complexes. Namely, by Theorem 25.13 we can choose a quasi-isomorphism $s_0 :
\( \mathcal{N} \to \mathcal{I} \) where \( \mathcal{I} \) is a graded injective and K-injective differential graded \( \mathcal{A} \)-module. Next, recall that elements of the displayed set are equivalence classes of pairs \((f : \mathcal{M} \to \mathcal{N}^\prime, s : \mathcal{N} \to \mathcal{N}^\prime)\) where \( f \) is an arbitrary morphism of \( K(\text{Mod}(\mathcal{A},d)) \) and \( s \) is a quasi-isomorphism, see the description of the left calculus of fractions in Categories, Section \ref{sect:left-calc-fractions}. By Lemma \ref{lem:25.10} we can choose the dotted arrow making the diagram commute (in the homotopy category). Thus the pair \((f, s)\) is equivalent to the pair \((s' \circ f, s_0)\) and we find that the collection of equivalence classes forms a set.

0FT5 **Definition 26.4.** Let \((\mathcal{C}, \mathcal{O})\) be a ringed site. Let \((\mathcal{A}, d)\) be a sheaf of differential graded algebras on \((\mathcal{C}, \mathcal{O})\). Let \(\text{Qis} \) be as in Lemma \ref{lem:26.3} The *derived category of \((\mathcal{A}, d)\)* is the triangulated category

\[
D(\mathcal{A}, d) = \text{Qis}^{-1}K(\text{Mod}(\mathcal{A}, d))
\]

discussed in more detail above.

We prove some facts about this construction.

0FT6 **Lemma 26.5.** In Definition \ref{def:26.4} the kernel of the localization functor \(Q : K(\text{Mod}(\mathcal{A}, d)) \to D(\mathcal{A}, d)\) is the category \(\mathcal{A} \text{e} \) of Lemma \ref{lem:26.2}.

**Proof.** This is immediate from Derived Categories, Lemma \ref{lem:derived-categories} and the fact that \(0 \to \mathcal{M}\) is a quasi-isomorphism if and only if \(\mathcal{M}\) is acyclic. \qed

0FT7 **Lemma 26.6.** In Definition \ref{def:26.4} the functor \(H^0 : K(\text{Mod}(\mathcal{A}, d)) \to \text{Mod}(\mathcal{O})\) factors through a homological functor \(H^0 : D(\mathcal{A}, d) \to \text{Mod}(\mathcal{O})\).

**Proof.** Follows immediately from Derived Categories, Lemma \ref{lem:derived-categories} \qed

Here is the promised lemma computing morphism sets in the derived category.

0FT8 **Lemma 26.7.** Let \((\mathcal{C}, \mathcal{O})\) be a ringed site. Let \((\mathcal{A}, d)\) be a sheaf of differential graded algebras on \((\mathcal{C}, \mathcal{O})\). Let \(\mathcal{M}\) and \(\mathcal{N}\) be differential graded \(\mathcal{A}\)-modules. Let \(\mathcal{N} \to \mathcal{I}\) be a quasi-isomorphism with \(\mathcal{I}\) a graded injective and K-injective differential graded \(\mathcal{A}\)-module. Then

\[
\text{Hom}_{D(\mathcal{A}, d)}(\mathcal{M}, \mathcal{N}) = \text{Hom}_{K(\text{Mod}(\mathcal{A}, d))}(\mathcal{M}, \mathcal{I})
\]

**Proof.** Since \(\mathcal{N} \to \mathcal{I}\) is a quasi-isomorphism we see that

\[
\text{Hom}_{D(\mathcal{A}, d)}(\mathcal{M}, \mathcal{N}) = \text{Hom}_{D(\mathcal{A}, d)}(\mathcal{M}, \mathcal{I})
\]

In the discussion preceding Definition \ref{def:26.4} we found, using Lemma \ref{lem:25.10} that any morphism \(\mathcal{M} \to \mathcal{I}\) in \(D(\mathcal{A}, d)\) can be represented by a morphism \(\tilde{f} : \mathcal{M} \to \mathcal{I}\) in \(K(\text{Mod}(\mathcal{A}, d))\). Now, if \(f, f' : \mathcal{M} \to \mathcal{I}\) are two morphism in \(K(\text{Mod}(\mathcal{A}, d))\), then they define the same morphism in \(D(\mathcal{A}, d)\) if and only if there exists a quasi-isomorphism \(g : \mathcal{I} \to \mathcal{K}\) in \(K(\text{Mod}(\mathcal{A}, d))\) such that \(g \circ f = g \circ f'\), see Categories, Lemma \ref{lem:26.6}.

However, by Lemma \ref{lem:25.10} there exists a map \(h : \mathcal{K} \to \mathcal{I}\) such that \(h \circ g = \text{id}_{\mathcal{I}}\). Thus \(g \circ f = g \circ f'\) implies \(f = f'\) and the proof is complete. \qed
Lemma 26.8. Let \((\mathcal{C}, \mathcal{O})\) be a ringed site. Let \((\mathcal{A}, d)\) be a sheaf of differential graded algebras on \((\mathcal{C}, \mathcal{O})\). Then

1. \(D(\mathcal{A}, d)\) has both direct sums and products,
2. direct sums are obtained by taking direct sums of differential graded \(\mathcal{A}\)-modules,
3. products are obtained by taking products of \(K\)-injective differential graded modules.

Proof. We will use that \(\text{Mod}_{(\mathcal{A}, d)}\) is an abelian category with arbitrary direct sums and products, and that these give rise to direct sums and products in \(K(\text{Mod}_{(\mathcal{A}, d)})\). See Lemmas 13.2 and 21.3.

Let \(\mathcal{M}_j\) be a family of differential graded \(\mathcal{A}\)-modules. Consider the direct sum \(\mathcal{M} = \bigoplus \mathcal{M}_j\) as a differential graded \(\mathcal{A}\)-module. For a differential graded \(\mathcal{A}\)-module \(\mathcal{N}\) choose a quasi-isomorphism \(\mathcal{N} \to \mathcal{I}\) where \(\mathcal{I}\) is graded injective and \(K\)-injective as a differential graded \(\mathcal{A}\)-module. See Theorem 25.13. Using Lemma 26.7 we have

\[
\text{Hom}_{D(\mathcal{A}, d)}(\mathcal{M}, \mathcal{N}) = \prod \text{Hom}_{K(\mathcal{A}, d)}(\mathcal{M}_j, \mathcal{I})
\]

whence the existence of direct sums in \(D(\mathcal{A}, d)\) as given in part (2) of the lemma.

Let \(\mathcal{M}_j\) be a family of differential graded \(\mathcal{A}\)-modules. For each \(j\) choose a quasi-isomorphism \(\mathcal{M} \to \mathcal{I}_j\) where \(\mathcal{I}_j\) is graded injective and \(K\)-injective as a differential graded \(\mathcal{A}\)-module. Consider the product \(\mathcal{I} = \prod \mathcal{I}_j\) of differential graded \(\mathcal{A}\)-modules. By Lemmas 25.8 and 25.4 we see that \(\mathcal{I}\) is graded injective and \(K\)-injective as a differential graded \(\mathcal{A}\)-module. For a differential graded \(\mathcal{A}\)-module \(\mathcal{N}\) using Lemma 26.7 we have

\[
\text{Hom}_{D(\mathcal{A}, d)}(\mathcal{N}, \mathcal{I}) = \prod \text{Hom}_{K(\mathcal{A}, d)}(\mathcal{N}, \mathcal{I}_j)
\]

whence the existence of products in \(D(\mathcal{A}, d)\) as given in part (3) of the lemma. \(\square\)

27. The canonical delta-functor

Let \((\mathcal{C}, \mathcal{O})\) be a ringed site. Let \((\mathcal{A}, d)\) be a sheaf of differential graded algebras on \((\mathcal{C}, \mathcal{O})\). Consider the functor \(\text{Mod}_{(\mathcal{A}, d)} \to K(\text{Mod}_{(\mathcal{A}, d)})\). This functor is not a \(\delta\)-functor in general. However, it turns out that the functor \(\text{Mod}_{(\mathcal{A}, d)} \to D(\mathcal{A}, d)\) is a \(\delta\)-functor. In order to see this we have to define the morphisms \(\delta\) associated to a short exact sequence

\[
0 \to \mathcal{K} \xrightarrow{a} \mathcal{L} \xrightarrow{b} \mathcal{M} \to 0
\]

in the abelian category \(\text{Mod}_{(\mathcal{A}, d)}\). Consider the cone \(C(a)\) of the morphism \(a\) together with its canonical morphisms \(i : \mathcal{L} \to C(a)\) and \(p : C(a) \to \mathcal{K}[1]\), see Definition 22.2. There is a homomorphism of differential graded \(\mathcal{A}\)-modules

\[
q : C(a) \to \mathcal{M}
\]
by Differential Graded Algebra, Lemma \[27.3\] (which we may use by the discussion in Section \[22\]) applied to the diagram

\[
\begin{array}{ccc}
\mathcal{K} & \rightarrow & \mathcal{L} \\
\downarrow & & \downarrow b \\
0 & \rightarrow & M
\end{array}
\]

The map \(q\) is a quasi-isomorphism for example because this is true in the category of morphisms of complexes of \(O\)-modules, see discussion in Derived Categories, Section \[12\]. According to Differential Graded Algebra, Lemma \[27.13\] (which we may use by the discussion in Section \[22\]) the triangle

\[
(\mathcal{K}, \mathcal{L}, C(a), a, i, -p)
\]

is a distinguished triangle in \(K(\text{Mod}(A, d))\). As the localization functor \(K(\text{Mod}(A, d)) \rightarrow D(A, d)\) is exact we see that \((\mathcal{K}, \mathcal{L}, C(a), a, i, -p)\) is a distinguished triangle in \(D(A, d)\). Since \(q\) is a quasi-isomorphism we see that \(q\) is an isomorphism in \(D(A, d)\). Hence we deduce that

\[
(\mathcal{K}, \mathcal{L}, M, a, b, -p \circ q^{-1})
\]

is a distinguished triangle of \(D(A, d)\). This suggests the following lemma.

**Lemma 27.1.** Let \((\mathcal{C}, O)\) be a ringed site. Let \((A, d)\) be a sheaf of differential graded algebras on \((\mathcal{C}, O)\). The localization functor \(\text{Mod}(A, d) \rightarrow D(A, d)\) has the natural structure of a \(\delta\)-functor, with

\[
\delta_{\mathcal{K} \rightarrow \mathcal{L} \rightarrow M} = -p \circ q^{-1}
\]

with \(p\) and \(q\) as explained above.

**Proof.** We have already seen that this choice leads to a distinguished triangle whenever given a short exact sequence of complexes. We have to show functoriality of this construction, see Derived Categories, Definition \[3.6\]. This follows from Differential Graded Algebra, Lemma \[27.3\] (which we may use by the discussion in Section \[22\]) with a bit of work. Compare with Derived Categories, Lemma \[12.1\]. \(\square\)

**Lemma 27.2.** Let \((\mathcal{C}, O)\) be a ringed site. Let \((A, d)\) be a sheaf of differential graded algebras on \((\mathcal{C}, O)\). Let \(M_n\) be a system of differential graded \(A\)-modules. Then the derived colimit \(\operatorname{hocolim} M_n\) in \(D(A, d)\) is represented by the differential graded module \(\operatorname{colim} M_n\).

**Proof.** Set \(M = \operatorname{colim} M_n\). We have an exact sequence of differential graded \(A\)-modules

\[
0 \rightarrow \bigoplus M_n \rightarrow \bigoplus M_n \rightarrow M \rightarrow 0
\]

by Derived Categories, Lemma \[33.6\] (applied the underlying complexes of \(O\)-modules). The direct sums are direct sums in \(D(A, d)\) by Lemma \[20.8\]. Thus the result follows from the definition of derived colimits in Derived Categories, Definition \[33.1\] and the fact that a short exact sequence of complexes gives a distinguished triangle (Lemma \[27.1\]). \(\square\)
28. Derived pullback

Let \((f, f^\#) : (Sh(C), O_C) \to (Sh(D), O_D)\) be a morphism of ringed topoi. Let \(A\) be a differential graded \(O_C\)-algebra. Let \(B\) be a differential graded \(O_D\)-algebra. Suppose we are given a map

\[ \varphi : f^{-1}B \to A \]

of differential graded \(f^{-1}O_D\)-algebras. By the adjunction of restriction and extension of scalars, this is the same thing as a map \(\varphi : f^*B \to A\) of differential graded \(O_C\)-algebras or equivalently \(\varphi\) can be viewed as a map

\[ \varphi : B \to f^*A \]

of differential graded \(O_D\)-algebras. See Remark \([12.2]\).

In addition to the above, let \(A'\) be a second differential graded \(O_C\)-algebra and let \(N\) be a differential graded \((A, A')\)-bimodule. In this setting we can consider the functor

\[ \text{Mod}(B, d) \to \text{Mod}(A', d), M \mapsto f^*M \otimes_A N \]

Observe that this extends to a functor

\[ \text{Mod}^{dg}(B, d) \to \text{Mod}^{dg}(A', d), M \mapsto f^*M \otimes_A N \]

of differential graded categories by the discussion in Sections \([18]\) and \([17]\). It follows formally that we also obtain an exact functor

\[ K(\text{Mod}(B, d)) \to K(\text{Mod}(A', d)), M \mapsto f^*M \otimes_A N \]

of triangulated categories.

Lemma 28.1. In the situation above, the functor \([28.0.1]\) composed with the localization functor \(K(\text{Mod}(A', d)) \to D(A', d)\) has a left derived extension \(D(B, d) \to D(A', d)\) whose value on a good right differential graded \(B\)-module \(P\) is \(f^*P \otimes_A N\).

Proof. Recall that for any (right) differential graded \(B\)-module \(M\) there exists a quasi-isomorphism \(P \to M\) with \(P\) a good differential graded \(B\)-module. See Lemma \([23.7]\). Hence by Derived Categories, Lemma \([14.13]\) it suffices to show that given a quasi-isomorphism \(P \to P'\) of good differential graded \(B\)-modules the induced map

\[ f^*P \otimes_A N \to f^*P' \otimes_A N \]

is a quasi-isomorphism. The cone \(P''\) on \(P \to P'\) is a good differential graded \(A\)-module by Lemma \([23.2]\). Since we have a distinguished triangle

\[ P \to P' \to P'' \to P[1] \]

in \(K(\text{Mod}(B, d))\) we obtain a distinguished triangle

\[ f^*P \otimes_A N \to f^*P' \otimes_A N \to f^*P'' \otimes_A N \to f^*P[1] \otimes_A N \]

in \(K(\text{Mod}(A', d))\). By Lemma \([23.8]\) the differential graded module \(f^*P'' \otimes_A N\) is acyclic and the proof is complete. \(\square\)

Definition 28.2. Derived tensor product and derived pullback.

(1) Let \((C, O)\) be a ringed site. Let \(A, B\) be differential graded \(O\)-algebras. Let \(N\) be a differential graded \((A, B)\)-bimodule. The functor \(D(A, d) \to D(B, d)\) constructed in Lemma \([28.1]\) is called the derived tensor product and denoted \(- \otimes_A^L N\).
Let \((f, f') : (Sh(C), \mathcal{O}_C) \rightarrow (Sh(D), \mathcal{O}_D)\) be a morphism of ringed topoi. Let \(\mathcal{A}\) be a differential graded \(\mathcal{O}_C\)-algebra. Let \(\mathcal{B}\) be a differential graded \(\mathcal{O}_D\)-algebra. Let \(\varphi : \mathcal{B} \rightarrow f_\ast \mathcal{A}\) be a homomorphism of differential graded \(\mathcal{O}_D\)-algebras. The functor \(D(\mathcal{B}, d) \rightarrow D(\mathcal{A}, d)\) constructed in Lemma 28.1 is called derived pullback and denote \(Lf_\ast\).

With this language in place we can express some obvious compatibilities.

**Lemma 28.3.** In Lemma 28.1 the functor \(D(\mathcal{B}, d) \rightarrow D(\mathcal{A}', d)\) is equal to \(\mathcal{M} \mapsto Lf^\ast \mathcal{M} \otimes_{\mathcal{A}} \mathcal{N}\).

**Proof.** Immediate from the fact that we can compute these functors by representing objects by good differential graded modules and because \(f^\ast \mathcal{P}\) is a good differential graded \(\mathcal{A}\)-module if \(\mathcal{P}\) is a good differential graded \(\mathcal{B}\)-module. \(\square\)

**Lemma 28.4.** Let \((f, f') : (Sh(C), \mathcal{O}) \rightarrow (Sh(C'), \mathcal{O}')\) and \((g, g') : (Sh(C'), \mathcal{O}') \rightarrow (Sh(C''), \mathcal{O}'')\) be morphisms of ringed topoi. Let \(\mathcal{A}, \mathcal{A}', \mathcal{A}''\) be a differential graded \(\mathcal{O}\)-algebra, \(\mathcal{O}'\)-algebra, and \(\mathcal{O}''\)-algebra. Let \(\varphi : \mathcal{A}' \rightarrow f_\ast \mathcal{A}\) and \(\varphi' : \mathcal{A}'' \rightarrow g_\ast \mathcal{A}'\) be a homomorphism of differential graded \(\mathcal{O}'\)-algebras and \(\mathcal{O}''\)-algebras. Then we have \(L(g \circ f)^\ast = Lf^\ast \circ Lg^\ast : D(\mathcal{A}'', d) \rightarrow D(\mathcal{A}, d)\).

**Proof.** Immediate from the fact that we can compute these functors by representing objects by good differential graded modules and because \(f^\ast \mathcal{P}\) is a good differential graded \(\mathcal{A}'\)-module if \(\mathcal{P}\) is a good differential graded \(\mathcal{A}\)-module. \(\square\)

Let \((\mathcal{C}, \mathcal{O})\) be a ringed site. Let \(\mathcal{A}, \mathcal{B}\) be differential graded \(\mathcal{O}\)-algebras. Let \(\mathcal{N} \rightarrow \mathcal{N}'\) be a homomorphism of differential graded \((\mathcal{A}, \mathcal{B})\)-bimodules. Then we obtain canonical maps

\[ t : \mathcal{M} \otimes^L_{\mathcal{A}} \mathcal{N} \longrightarrow \mathcal{M} \otimes^L_{\mathcal{A}} \mathcal{N}' \]

functorial in \(\mathcal{M}\) in \(D(\mathcal{A}, d)\) which define a natural transformation between exact functors \(D(\mathcal{A}, d) \rightarrow D(\mathcal{B}, d)\) of triangulated categories. The value of \(t\) on a good differential graded \(\mathcal{A}\)-module \(\mathcal{P}\) is the obvious map

\[ \mathcal{P} \otimes^L_{\mathcal{A}} \mathcal{N} = \mathcal{P} \otimes_{\mathcal{A}} \mathcal{N} \longrightarrow \mathcal{P} \otimes_{\mathcal{A}} \mathcal{N}' = \mathcal{P} \otimes^L_{\mathcal{A}} \mathcal{N}' \]

**Lemma 28.5.** In the situation above, if \(\mathcal{N} \rightarrow \mathcal{N}'\) is an isomorphism on cohomology sheaves, then \(t\) is an isomorphism of functors \((- \otimes^L_{\mathcal{A}} \mathcal{N}) \rightarrow (- \otimes^L_{\mathcal{A}} \mathcal{N}')\).

**Proof.** It is enough to show that \(\mathcal{P} \otimes_{\mathcal{A}} \mathcal{N} \rightarrow \mathcal{P} \otimes_{\mathcal{A}} \mathcal{N}'\) is an isomorphism on cohomology sheaves for any good differential graded \(\mathcal{A}\)-module \(\mathcal{P}\). To do this, let \(\mathcal{N}''\) be the cone on the map \(\mathcal{N} \rightarrow \mathcal{N}'\) as a left differential graded \(\mathcal{A}\)-module, see Definition 22.2. (To be sure, \(\mathcal{N}''\) is a bimodule too but we don’t need this.) By functoriality of the tensor construction (it is a functor of differential graded categories) we see that \(\mathcal{P} \otimes_{\mathcal{A}} \mathcal{N}''\) is the cone (as a complex of \(\mathcal{O}\)-modules) on the map \(\mathcal{P} \otimes_{\mathcal{A}} \mathcal{N} \rightarrow \mathcal{P} \otimes_{\mathcal{A}} \mathcal{N}'\). Hence it suffices to show that \(\mathcal{P} \otimes_{\mathcal{A}} \mathcal{N}''\) is acyclic. This follows from the fact that it is good and the fact that \(\mathcal{N}''\) is acyclic as a cone on a quasi-isomorphism. \(\square\)

**Lemma 28.6.** Let \((\mathcal{C}, \mathcal{O})\) be a ringed site. Let \(\mathcal{A}, \mathcal{B}\) be differential graded \(\mathcal{O}\)-algebras. Let \(\mathcal{N}\) be a differential graded \((\mathcal{A}, \mathcal{B})\)-bimodule. If \(\mathcal{N}\) is good as a left differential graded \(\mathcal{A}\)-module, then we have \(\mathcal{M} \otimes^L_{\mathcal{A}} \mathcal{N} = \mathcal{M} \otimes_{\mathcal{A}} \mathcal{N}\) for all differential graded \(\mathcal{A}\)-modules \(\mathcal{M}\).
Proof. Let \( P \to M \) be a quasi-isomorphism where \( P \) is a good (right) differential graded \( A \)-module. To prove the lemma we have to show that \( P \otimes_A N \to M \otimes_A N \) is a quasi-isomorphism. The cone \( C \) on the map \( P \to M \) is an acyclic right differential graded \( A \)-module. Hence \( C \otimes_A N \) is acyclic as \( N \) is assumed good as a left differential graded \( A \)-module. Since \( C \otimes_A N \) is the cone on the maps \( P \otimes_A N \to M \otimes_A N \) as a complex of \( O \)-modules we conclude. \( \square \)

Lemma 28.7. Let \((\mathcal{C},\mathcal{O})\) be a ringed site. Let \( A, A', A'' \) be differential graded \( \mathcal{O} \)-algebras. Let \( N \) and \( N' \) be a differential graded \((A,A')\)-bimodule and \((A',A'')\)-bimodule. Assume that the canonical map \( N \otimes_A N' \to N \otimes_A N' \) in \( D(A'',d) \) is a quasi-isomorphism. Then we have

\[
(M \otimes_A^L N) \otimes_{A'}^L N' = M \otimes_{A'}^L (N \otimes_{A'}^L N')
\]

as functors \( D(A,d) \to D(A'',d) \).

Proof. Choose a good differential graded \( A \)-module \( P \) and a quasi-isomorphism \( P \to M \), see Lemma 23.7. Then

\[
M \otimes_{A'}^L (N \otimes_{A'}^L N') = P \otimes_{A'}^L N \otimes_{A'}^L N'
\]

and we have

\[
(M \otimes_{A'}^L N) \otimes_{A'}^L N' = (P \otimes_{A'}^L N) \otimes_{A'}^L N'
\]

Thus we have to show the canonical map

\[
(P \otimes_{A'}^L N) \otimes_{A'}^L N' \to P \otimes_{A'}^L N \otimes_{A'}^L N'
\]

is a quasi-isomorphism. Choose a quasi-isomorphism \( Q \to N' \) where \( Q \) is a good left differential graded \( A' \)-module (Lemma 23.7). By Lemma 28.6 the map above as a map in the derived category of \( O \)-modules is the map

\[
P \otimes_{A'}^L N \otimes_{A'}^L Q \to P \otimes_{A'}^L N \otimes_{A'}^L N'
\]

Since \( N \otimes_{A'}^L Q \to N \otimes_{A'}^L N' \) is a quasi-isomorphism by assumption and \( P \) is a good differential graded \( A \)-module this map is an quasi-isomorphism by Lemma 28.5 (the left and right hand side compute \( P \otimes_{A'}^L (N \otimes_{A'}^L Q) \) and \( P \otimes_{A'}^L (N \otimes_{A'}^L N') \) or you can just repeat the argument in the proof of the lemma). \( \square \)

29. Derived pushforward

The existence of enough K-injective guarantees that we can take the right derived functor of any exact functor on the homotopy category.

Lemma 29.1. Let \((\mathcal{C},\mathcal{O})\) be a ringed site. Let \((A,d)\) be a sheaf of differential graded algebras on \((\mathcal{C},\mathcal{O})\). Then any exact functor

\[
T : K(\text{Mod}_{(A,d)}) \to D
\]

of triangulated categories has a right derived extension \( RT : D(A,d) \to D \) whose value on a graded injective and K-injective differential graded \( A \)-module \( I \) is \( T(I) \).

Proof. By Theorem 25.13 for any (right) differential graded \( A \)-module \( M \) there exists a quasi-isomorphism \( M \to I \) where \( I \) is a graded injective and K-injective differential graded \( A \)-module. Hence by Derived Categories, Lemma 14.13 it suffices to show that given a quasi-isomorphism \( I \to I' \) of differential graded \( A \)-modules
which are both graded injective and K-injective then \( T(I) \to T(I') \) is an isomorphism. This is true because the map \( I \to I' \) is an isomorphism in \( K(\text{Mod}(A,d)) \) as follows for example from Lemma 26.7 (or one can deduce it from Lemma 25.10). □

There are a number of functors we have already seen to which this applies. Here are two examples.

**Definition 29.2.** Derived internal hom and derived pushforward.

1. Let \((\mathcal{C}, \mathcal{O})\) be a ringed site. Let \( \mathcal{A}, \mathcal{B} \) be differential graded \( \mathcal{O} \)-algebras. Let \( \mathcal{N} \) be a differential graded \((\mathcal{A}, \mathcal{B})\)-bimodule. The right derived extension

\[
\mathcal{R} \mathcal{H}om_{\mathcal{B}}(\mathcal{N}, -): D(\mathcal{B}, d) \to D(\mathcal{A}, d)
\]

of the internal hom functor \( \mathcal{H}om_{\mathcal{B}}^{dg}(\mathcal{N}, -) \) is called **derived internal hom**.

2. Let \((f, f^\sharp) : (\text{Sh}(\mathcal{C}), \mathcal{O}_C) \to (\text{Sh}(\mathcal{D}), \mathcal{O}_D)\) be a morphism of ringed topoi. Let \( \mathcal{A} \) be a differential graded \( \mathcal{O}_C \)-algebra. Let \( \mathcal{B} \) be a differential graded \( \mathcal{O}_D \)-algebra. Let \( \varphi : \mathcal{B} \to f_* \mathcal{A} \) be a homomorphism of differential graded \( \mathcal{O}_D \)-algebras. The right derived extension

\[
\mathcal{R}f_*: D(\mathcal{A}, d) \to D(\mathcal{B}, d)
\]

of the pushforward \( f_* \) is called **derived pushforward**.

It turns out that \( \mathcal{R}f_*: D(\mathcal{A}, d) \to D(\mathcal{B}, d) \) agrees with derived pushforward on underlying complexes of \( \mathcal{O} \)-modules, see Lemma 29.8.

These functors are the adjoints of derived pullback and derived tensor product.

**Lemma 29.3.** Let \((\mathcal{C}, \mathcal{O})\) be a ringed site. Let \( \mathcal{A}, \mathcal{B} \) be differential graded \( \mathcal{O} \)-algebras. Let \( \mathcal{N} \) be a differential graded \((\mathcal{A}, \mathcal{B})\)-bimodule. Then

\[
\mathcal{R} \mathcal{H}om_{\mathcal{B}}(\mathcal{N}, -): D(\mathcal{B}, d) \to D(\mathcal{A}, d)
\]

is right adjoint to

\[
\mathcal{L} \mathcal{A} \mathcal{N}: D(\mathcal{A}, d) \to D(\mathcal{B}, d)
\]

**Proof.** This follows from Derived Categories, Lemma 30.1 and Lemma 17.3 □

**Lemma 29.4.** Let \((f, f^\sharp) : (\text{Sh}(\mathcal{C}), \mathcal{O}_C) \to (\text{Sh}(\mathcal{D}), \mathcal{O}_D)\) be a morphism of ringed topoi. Let \( \mathcal{A} \) be a differential graded \( \mathcal{O}_C \)-algebra. Let \( \mathcal{B} \) be a differential graded \( \mathcal{O}_D \)-algebra. Let \( \varphi : \mathcal{B} \to f_* \mathcal{A} \) be a homomorphism of differential graded \( \mathcal{O}_D \)-algebras. Then

\[
\mathcal{R}f_*: D(\mathcal{A}, d) \to D(\mathcal{B}, d)
\]

is right adjoint to

\[
\mathcal{L}f^*: D(\mathcal{B}, d) \to D(\mathcal{A}, d)
\]

**Proof.** This follows from Derived Categories, Lemma 30.1 and Lemma 18.1 □

Next, we discuss what happens in the situation considered in Section 28.

Let \((f, f^\sharp) : (\text{Sh}(\mathcal{C}), \mathcal{O}_C) \to (\text{Sh}(\mathcal{D}), \mathcal{O}_D)\) be a morphism of ringed topoi. Let \( \mathcal{A} \) be a differential graded \( \mathcal{O}_C \)-algebra. Let \( \mathcal{B} \) be a differential graded \( \mathcal{O}_D \)-algebra. Suppose we are given a map

\[
\varphi : f^{-1} \mathcal{B} \to \mathcal{A}
\]
of differential graded $f^{-1}\mathcal{O}_\mathcal{D}$-algebras. By the adjunction of restriction and extension of scalars, this is the same thing as a map $\varphi : f^*\mathcal{B} \to \mathcal{A}$ of differential graded $\mathcal{O}_\mathcal{C}$-algebras or equivalently $\varphi$ can be viewed as a map

$$\varphi : \mathcal{B} \to f_*\mathcal{A}$$

of differential graded $\mathcal{O}_\mathcal{D}$-algebras. See Remark \[12.2\]

In addition to the above, let $\mathcal{A}'$ be a second differential graded $\mathcal{O}_\mathcal{C}$-algebra and let $\mathcal{N}$ be a differential graded $(\mathcal{A}, \mathcal{A}')$-bimodule. In this setting we can consider the functor

$$\text{Mod}_{(\mathcal{A}', d)} \to \text{Mod}_{(\mathcal{B}, d)}, \quad \mathcal{M} \mapsto f_*\text{Hom}^d_{\mathcal{A}}(\mathcal{N}, \mathcal{M})$$

Observe that this extends to a functor

$$\text{Mod}^d_{(\mathcal{A}', d)} \to \text{Mod}^d_{(\mathcal{B}, d)}, \quad \mathcal{M} \mapsto f_*\text{Hom}^d_{\mathcal{A}}(\mathcal{N}, \mathcal{M})$$

of differential graded categories by the discussion in Sections \[18\] and \[17\]. It follows formally that we also obtain an exact functor

$$0\text{FTS} \quad (29.4.1) \quad K(\text{Mod}_{(\mathcal{A}', d)}) \to K(\text{Mod}_{(\mathcal{B}, d)}), \quad \mathcal{M} \mapsto f_*\text{Hom}^d_{\mathcal{A}}(\mathcal{N}, \mathcal{M})$$

of triangulated categories.

**Lemma 29.5.** In the situation above, denote $R\mathcal{T} : D(\mathcal{A}', d) \to D(\mathcal{B}, d)$ the right derived extension of \[29.4.1\]. Then we have

$$R\mathcal{T}(\mathcal{M}) = Rf_*R\text{Hom}(\mathcal{N}, \mathcal{M})$$

functorially in $\mathcal{M}$.

**Proof.** By Lemmas \[17.3\] and \[18.1\] the functor \[29.4.1\] is right adjoint to the functor \[28.0.1\]. By Derived Categories, Lemma \[30.1\] the functor $R\mathcal{T}$ is right adjoint to the functor of Lemma \[28.1\] which is equal to $Lf^*(-) \otimes^L_{\mathcal{A}}\mathcal{N}$ by Lemma \[28.3\]. By Lemmas \[29.3\] and \[29.4\] the functor $Lf^*(-) \otimes^L_{\mathcal{A}}\mathcal{N}$ is left adjoint to $Rf_*R\text{Hom}(\mathcal{N}, -)$. Thus we conclude by uniqueness of adjoints. \[\square\]

**Lemma 29.6.** Let $(f, f^2) : (\text{Sh}(\mathcal{C}), \mathcal{O}) \to (\text{Sh}(\mathcal{C}'), \mathcal{O}')$ and $(g, g^2) : (\text{Sh}(\mathcal{C}'), \mathcal{O}') \to (\text{Sh}(\mathcal{C}''), \mathcal{O}'')$ be morphisms of ringed topoi. Let $\mathcal{A}, \mathcal{A}', \mathcal{A}''$ be a differential graded $\mathcal{O}$-algebra, $\mathcal{O}'$-algebra, and $\mathcal{O}''$-algebra. Let $\varphi : \mathcal{A}' \to f_*\mathcal{A}$ and $\varphi' : \mathcal{A}'' \to g_*\mathcal{A}'$ be a homomorphism of differential graded $\mathcal{O}'$-algebras and $\mathcal{O}''$-algebras. Then we have $R(g \circ f)_* = Rg_* \circ Rf_* : D(\mathcal{A}, d) \to D(\mathcal{A}'', d)$.

**Proof.** Follows from Lemmas \[28.3\] and \[29.4\] and uniqueness of adjoints. \[\square\]

**Lemma 29.7.** Let $(\mathcal{C}, \mathcal{O})$ be a ringed site. Let $\mathcal{A}, \mathcal{A}', \mathcal{A}''$ be differential graded $\mathcal{O}$-algebras. Let $\mathcal{N}$ and $\mathcal{N}'$ be a differential graded $(\mathcal{A}, \mathcal{A}')$-bimodule and $(\mathcal{A}', \mathcal{A}'')$-bimodule. Assume that the canonical map

$$\mathcal{N} \otimes^L_{\mathcal{A}'} \mathcal{N}' \to \mathcal{N} \otimes_{\mathcal{A}'} \mathcal{N}'$$

in $D(\mathcal{A}'', d)$ is a quasi-isomorphism. Then we have

$$R\text{Hom}_{\mathcal{A}''}(\mathcal{N} \otimes_{\mathcal{A}'} \mathcal{N}', -) = R\text{Hom}_{\mathcal{A}'}(\mathcal{N}, R\text{Hom}_{\mathcal{A}''}(\mathcal{N}', -))$$

as functors $D(\mathcal{A}'', d) \to D(\mathcal{A}, d)$.

**Proof.** Follows from Lemmas \[28.7\] and \[29.3\] and uniqueness of adjoints. \[\square\]
Lemma 29.8. Let \((f, f^2) : (Sh(C), \mathcal{O}_C) \to (Sh(D), \mathcal{O}_D)\) be a morphism of ringed topoi. Let \(A\) be a differential graded \(\mathcal{O}_C\)-algebra. Let \(B\) be a differential graded \(\mathcal{O}_D\)-algebra. Let \(\varphi : B \to f_*A\) be a homomorphism of differential graded \(\mathcal{O}_D\)-algebras. The diagram

\[
\begin{array}{ccc}
D(A, d) & \xrightarrow{\text{forget}} & D(\mathcal{O}_C) \\
Rf_* & & Rf_* \\
D(B, d) & \xrightarrow{\text{forget}} & D(\mathcal{O}_D)
\end{array}
\]

commutes.

Proof. Besides identifying some categories, this lemma follows immediately from Lemma 29.6.

We may view \((\mathcal{O}_C, 0)\) as a differential graded \(\mathcal{O}_C\)-algebra by placing \(\mathcal{O}_C\) in degree 0 and endowing it with the zero differential. It is clear that we have

\[\text{Mod}(\mathcal{O}_C, 0) = \text{Comp}(\mathcal{O}_C) \quad \text{and} \quad D(\mathcal{O}_C, 0) = D(\mathcal{O}_C)\]

Via this identification the forgetful functor \(\text{Mod}(\mathcal{O}_C, d) \to \text{Comp}(\mathcal{O}_C)\) is the “push-forward” \(\text{id}_{\mathcal{C}*}\) defined in Section 18 corresponding to the identity morphism \(\text{id}_{\mathcal{C}} : (\mathcal{C}, \mathcal{O}_C) \to (\mathcal{C}, \mathcal{O}_C)\) of ringed topoi and the map \((\mathcal{O}_C, 0) \to (\mathcal{A}, d)\) of differential graded \(\mathcal{O}_C\)-algebras. Since \(\text{id}_{\mathcal{C}*}\) is exact, we immediately see that

\[\text{RId}_{\mathcal{C},*} = \text{forget} : D(\mathcal{A}, d) \to D(\mathcal{O}_C, 0) = D(\mathcal{O}_C)\]

The exact same reasoning shows that

\[\text{RId}_{\mathcal{D},*} = \text{forget} : D(\mathcal{B}, d) \to D(\mathcal{O}_D, 0) = D(\mathcal{O}_D)\]

Moreover, the construction of \(Rf_* : D(\mathcal{O}_C) \to D(\mathcal{O}_D)\) of Cohomology on Sites, Section 19 agrees with the construction of \(Rf_* : D(\mathcal{O}_C, 0) \to D(\mathcal{O}_D, 0)\) in Definition 29.2 as both functors are defined as the right derived extension of pushforward on underlying complexes of modules. By Lemma 29.6 we see that both \(Rf_* \circ \text{RId}_{\mathcal{C},*}\) and \(\text{RId}_{\mathcal{D},*} \circ Rf_*\) are the derived functors of \(f_* \circ \text{forget} = \text{forget} \circ f_*\) and hence equal by uniqueness of adjoints.

Lemma 29.9. Let \((\mathcal{C}, \mathcal{O})\) be a ringed site. Let \(\mathcal{A}\) be a differential graded \(\mathcal{O}\)-algebra. Let \(\mathcal{M}\) be a differential graded \(\mathcal{A}\)-module. Let \(n \in \mathbb{Z}\). We have

\[H^n(\mathcal{C}, \mathcal{M}) = \text{Hom}_{D(\mathcal{A}, d)}(\mathcal{A}, \mathcal{M}[n])\]

where on the left hand side we have the cohomology of \(\mathcal{M}\) viewed as a complex of \(\mathcal{O}\)-modules.

Proof. To prove the formula, observe that

\[R\Gamma(\mathcal{C}, \mathcal{M}) = \Gamma(\mathcal{C}, \mathcal{I})\]

where \(\mathcal{M} \to \mathcal{I}\) is a quasi-isomorphism to a graded injective and K-injective differential graded \(\mathcal{A}\)-module \(\mathcal{I}\) (combine Lemmas 29.1 and 29.8). By Lemma 26.7 we have

\[\text{Hom}_{D(\mathcal{A}, d)}(\mathcal{A}, \mathcal{M}[n]) = \text{Hom}_{K(\text{Mod}(\mathcal{A}, d))}(\mathcal{M}, \mathcal{I}[n]) = H^0(\Gamma(\mathcal{C}, \mathcal{I}[n])) = H^n(\Gamma(\mathcal{C}, \mathcal{I}))\]

Combining these two results we obtain our equality.

\[\Box\]
30. Equivalences of derived categories

Lemma 30.1. Let \((\mathcal{C}, \mathcal{O})\) be a ringed site. If \(\varphi : \mathcal{A} \to \mathcal{B}\) is a homomorphism of differential graded \(\mathcal{O}\)-algebras which induces an isomorphism on cohomology sheaves, then
\[
D(\mathcal{A}, d) \to D(\mathcal{B}, d), \quad \mathcal{M} \mapsto \mathcal{M} \otimes_{\mathcal{A}}^L \mathcal{B}
\]
is an equivalence of categories.

Proof. Recall that the restriction functor
\[
\text{Mod}^{dg}_{(\mathcal{B}, d)} \to \text{Mod}^{dg}_{(\mathcal{A}, d)}, \quad N \mapsto \text{res}_\varphi N
\]
is a right adjoint to
\[
\text{Mod}^{dg}_{(\mathcal{A}, d)} \to \text{Mod}^{dg}_{(\mathcal{B}, d)}, \quad \mathcal{M} \mapsto \mathcal{M} \otimes_{\mathcal{A}} \mathcal{B}
\]
See Section 17. Since restriction sends quasi-isomorphisms to quasi-isomorphisms, we see that it trivially has a left derived extension (given by restriction). This functor will be right adjoint to \(- \otimes_{\mathcal{A}}^L \mathcal{B}\) by Derived Categories, Lemma 30.1. The adjunction map
\[
\mathcal{M} \to \text{res}_\varphi(\mathcal{M} \otimes_{\mathcal{A}}^L \mathcal{B})
\]
is an isomorphism in \(D(\mathcal{A}, d)\) by our assumption that \(\mathcal{A} \to \mathcal{B}\) is a quasi-isomorphism of (left) differential graded \(\mathcal{A}\)-modules. In particular, the functor of the lemma is fully faithful, see Categories, Lemma 24.3. It is clear that the kernel of the restriction functor \(D(\mathcal{B}, d) \to D(\mathcal{A}, d)\) is zero. Thus we conclude by Derived Categories, Lemma 7.2. \(\square\)

31. Resolutions of differential graded algebras

Let \((\mathcal{C}, \mathcal{O})\) be a ringed site. As in Remark 23.5 consider a sheaf of graded sets \(S\) on \(\mathcal{C}\). Let us think of the \(r\)-fold self product \(S \times \ldots \times S\) as a sheaf of graded sets with the rule \(\deg(s_1 \cdot \ldots \cdot s_r) = \sum \deg(s_i)\). Here given local sections \(s_i \in S(U), i = 1, \ldots, r\) we use \(s_1 \cdot \ldots \cdot s_r\) to denote the corresponding section of \(S \times \ldots \times S\) over \(U\). Let us denote \(\mathcal{O}(S)\) the free graded \(\mathcal{O}\)-algebra on \(S\). More precisely, we set
\[
\mathcal{O}(S) = \mathcal{O} \oplus \bigoplus_{r \geq 1} \mathcal{O}[S \times \ldots \times S]
\]
with notation as in Remark 23.5. This becomes a sheaf of graded \(\mathcal{O}\)-algebras by concatenation
\[
(s_1 \cdot \ldots \cdot s_r)(s'_1 \cdot \ldots \cdot s'_{r'}) = s_1 \cdot \ldots \cdot s_r \cdot s'_1 \cdot \ldots \cdot s'_{r'}.
\]
We may endow \(\mathcal{O}(S)\) with a differential by setting \(d(s) = 0\) for all local sections \(s\) of \(S\) and extending uniquely using the Leibniz rule although it is important to also consider other differentials.

Indeed, suppose that we are given a system of the following kind
\begin{enumerate}
\item for \(i = 0, 1, 2, \ldots\) sheaves of graded sets \(S_i\),
\item for \(i = 0, 1, 2, \ldots\) maps
\[
\delta_{i+1} : S_{i+1} \to \mathcal{A}_i = \mathcal{O}(S_0 \amalg \ldots \amalg S_i)
\]
of sheaves of graded sets of degree 1 whose image is contained in the kernel of the inductively defined differential on the target.
More precisely, we first set \( A_0 = \mathcal{O}(S_0) \) and we endow it with the unique differential satisfying the Leibniz rule where \( d \) on \( A_0 \) suffices to prove that \( A_0 \) is K-flat as a complex of \( \mathcal{O} \)-modules. For \( i \geq 1 \) write \( S = S_0 \amalg \ldots \amalg S_i \) so that we have \( A_i = \mathcal{O}(S) \) as a graded \( \mathcal{O} \)-algebra. We are going to construct a filtration of this algebra by differential graded \( \mathcal{O} \)-submodules.

Set \( W = \mathbb{Z}_{\geq 0}^{i+1} \) considered with lexicographical ordering. Namely, given \( w = (w_0, \ldots, w_i) \) and \( w' = (w'_0, \ldots, w'_i) \) in \( W \) we say
\[
w > w' \iff \exists j, 0 \leq j \leq i : w_i = w'_i, \ w_{i-1} = w'_{i-1}, \ldots, w_{j+1} = w'_{j+1}, \ w_j < w'_j
\]
and so on. Suppose given a section \( s = s_1 \cdot \ldots \cdot s_r \) of \( S \times \ldots \times S \) over \( U \). We say that the weight of \( s \) is defined if we have \( s_a \in S_{j_a}(U) \) for a unique \( 0 \leq j_a \leq i \). In this case we define the weight
\[
w(s) = (w_0(s), \ldots, w_i(s)) \in W, \quad w_j(s) = \left\lfloor a \mid j_a = j \right\rfloor
\]
The weight of any section of \( S \times \ldots \times S \) is defined locally. The reader checks easily that we obtain a disjoint union decomposition
\[
S \times \ldots \times S = \bigsqcup_{w \in W} (S \times \ldots \times S)_w
\]
into the subsheaves of sections of a given weight. Of course only \( w \in W \) with \( \sum_{0 \leq j \leq i} w_j = r \) show up for a given \( r \). We correspondingly obtain a decomposition
\[
A_i = \mathcal{O} \oplus \bigoplus_{r \geq 1} \bigoplus_{w \in W} \mathcal{O}[(S \times \ldots \times S)_w]
\]
The rest of the proof relies on the following trivial observation: given \( r, w \) and local section \( s = s_1 \cdot \ldots \cdot s_r \) of \( (S \times \ldots \times S)_w \) we have
\[
d(s) \text{ is a local section of } \mathcal{O} \oplus \bigoplus_{r' \geq 1} \bigoplus_{w' \in W, w' < w} \mathcal{O}[(S \times \ldots \times S)_{w'}]
\]
The reason is that in each of the expressions
\[
(-1)^{\deg(s_1) + \ldots + \deg(s_{a-1})} s_1 \cdot \ldots \cdot s_{a-1} \cdot \delta(s_a) \cdot s_{a+1} \cdot \ldots \cdot s_r
\]
whose sum gives the element \( \delta(s_a) \) is locally a \( \mathcal{O} \)-linear combination of elements \( s_1' \cdots s_{r_a}' \) in \( \mathcal{S}_{j_a}' \) for some \( 0 \leq j_a' < j_a \) where \( j_a \) is such that \( s_a \) is section of \( \mathcal{S}_{j_a} \).

What this means is the following. Suppose for \( w \in W \) we set
\[
F_w \mathcal{A}_i = \mathcal{O} \oplus \bigoplus_{r \geq 1} \bigoplus_{w' \leq w} \mathcal{O}[\mathcal{S} \times \cdots \mathcal{S}]_{w'}
\]
By the observation above this is a differential graded \( \mathcal{O} \)-submodule. We get admissible short exact sequences
\[
0 \to \text{colim}_{w' < w} F_{w'} \mathcal{A}_i \to F_w \mathcal{A}_i \to \bigoplus_{r \geq 1} \mathcal{O}[\mathcal{S} \times \cdots \mathcal{S}]_{w'} \to 0
\]
of differential graded \( \mathcal{A} \)-modules where the differential on the right hand side is zero.

Now we finish the proof by transfinite induction over the ordered set \( W \). The differential graded complex \( F_0 \mathcal{A}_0 \) is the summand \( \mathcal{O} \) and this is K-flat and graded flat. For \( w \in W \) if the result is true for \( F_{w'} \mathcal{A}_i \) for \( w' < w \), then by Lemmas 23.3, 23.2, and 23.6 we obtain the result for \( w \). Finally, we have \( \mathcal{A}_i = \text{colim}_{w \in W} F_w \mathcal{A}_i \) and we conclude. \( \Box \)

**Lemma 31.2.** Let \((\mathcal{C}, \mathcal{O})\) be a ringed site. Let \((\mathcal{B}, d)\) be a differential graded \( \mathcal{O} \)-algebra. There exists a quasi-isomorphism of differential graded \( \mathcal{O} \)-algebras \((\mathcal{A}, d) \to (\mathcal{B}, d)\) such that \( \mathcal{A} \) is graded flat and K-flat as a complex of \( \mathcal{O} \)-modules and such that the same is true after pullback by any morphism of ringed topoi.

**Proof.** The proof is exactly the same as the first proof of Lemma 23.7 but now working with free graded algebras instead of free graded modules.

We will construct \( \mathcal{A} = \text{colim} \mathcal{A}_i \) as in Lemma 31.1 by constructing
\[
\mathcal{A}_0 \to \mathcal{A}_1 \to \mathcal{A}_2 \to \cdots \to \mathcal{B}
\]
Let \( \mathcal{S}_0 \) be the sheaf of graded sets (Remark 23.5) whose degree \( n \) part is \( \text{Ker}(\gamma^n_{\mathcal{B}}) \). Consider the homomorphism of differential graded modules
\[
\mathcal{A}_0 = \mathcal{O}(\mathcal{S}_0) \longrightarrow \mathcal{B}
\]
where map sends a local section \( s \) of \( \mathcal{S}_0 \) to the corresponding local section of \( \mathcal{A}^{\mathcal{O}(\mathcal{S}(s))} \) (which is in the kernel of the differential, so our map is a map of differential graded algebras indeed). By construction the induced maps on cohomology sheaves \( H^n(\mathcal{A}_0) \to H^n(\mathcal{B}) \) are surjective and hence the same will remain true for all \( i \).

Induction step of the construction. Given \( \mathcal{A}_i \to \mathcal{B} \) denote \( \mathcal{S}_{i+1} \) the sheaf of graded sets whose degree \( n \) part is
\[
\text{Ker}(\delta^{n+1}_{\mathcal{A}_i}) \times \mathcal{B}_{n+1,t} \mathcal{B}^n
\]
This comes equipped with a canonical map
\[
\delta_{i+1} : \mathcal{S}_{i+1} \longrightarrow \mathcal{A}_i
\]
whose image is contained in the kernel of \( d_{\mathcal{A}_i} \) by construction. Hence \( \mathcal{A}_{i+1} = \mathcal{O}(\mathcal{S}_0 \II \cdots \mathcal{S}_{i+1}) \) has a differential exiting the differential on \( \mathcal{A}_i \), see discussion at the start of this section. The map from \( \mathcal{A}_{i+1} \to \mathcal{B} \) is the unique map of graded algebras which restricts to the given map on \( \mathcal{A}_i \) and sends a local section \( s = (a, b) \)
of \( S_{i+1} \) to \( b \) in \( B \). This is compatible with differentials exactly because \( d(b) \) is the image of \( a \) in \( B \).

The map \( A \to B \) is a quasi-isomorphism: we have \( H^n(A) = \text{colim} H^n(A_i) \) and for each \( i \) the map \( H^n(A_i) \to H^n(B) \) is surjective with kernel annihilated by the map \( H^n(A_i) \to H^n(A_{i+1}) \) by construction. Finally, the flatness condition for \( A \) where shown in Lemma \( \ref{lem:flatness} \). \( \square \)

32. Miscellany

Let \( (f,f') : (\text{Sh}(\mathcal{C}), \mathcal{O}) \to (\text{Sh}(\mathcal{C}'), \mathcal{O}') \) be a morphism of ringed topoi. Let \( \mathcal{A} \) be a sheaf of differential graded \( \mathcal{O} \)-algebras. Using the composition

\[
\mathcal{A} \otimes L_{\mathcal{O}} \mathcal{A} \to \mathcal{A} \otimes \mathcal{O} \mathcal{A} \to \mathcal{A}
\]

and the relative cup product (see Cohomology on Sites, Remark \( \ref{rem:cup-prod} \) and Section \( \ref{sec:cup-prod} \) we obtain a multiplication

\[
\mu : Rf_* \mathcal{A} \otimes L_{\mathcal{O}'} Rf_* \mathcal{A} \to Rf_* \mathcal{A}
\]

in \( D(\mathcal{O}') \). This multiplication is associative in the sense that the diagram

\[
\begin{array}{ccc}
Rf_* \mathcal{A} \otimes L_{\mathcal{O}'} Rf_* \mathcal{A} & \to & Rf_* \mathcal{A} \\
\downarrow \mu & & \downarrow \mu \\
Rf_* \mathcal{A} & \to & Rf_* \mathcal{A}
\end{array}
\]

commutes in \( D(\mathcal{O}') \); this follows from Cohomology on Sites, Lemma \( \ref{lem:commutes} \). In exactly the same way, given a right differential graded \( \mathcal{A} \)-module \( \mathcal{M} \) we obtain a multiplication

\[
\mu_{\mathcal{M}} : Rf_* \mathcal{M} \otimes L_{\mathcal{O}'} Rf_* \mathcal{A} \to Rf_* \mathcal{M}
\]

in \( D(\mathcal{O}') \). This multiplication is compatible with \( \mu \) above in the sense that the diagram

\[
\begin{array}{ccc}
Rf_* \mathcal{M} \otimes L_{\mathcal{O}'} Rf_* \mathcal{A} & \to & Rf_* \mathcal{M} \\
\downarrow \mu_{\mathcal{M}} & & \downarrow \mu_{\mathcal{M}} \\
Rf_* \mathcal{M} & \to & Rf_* \mathcal{M}
\end{array}
\]

commutes in \( D(\mathcal{O}') \); again this follows from Cohomology on Sites, Lemma \( \ref{lem:commutes} \). A particular example of the above is when one takes \( f \) to be the morphism to the punctual topos \( \text{Sh}(pt) \). In that case \( \mu \) is just the cup product map

\[
R\Gamma(\mathcal{C}, \mathcal{A}) \otimes L_{\Gamma(\mathcal{C}, \mathcal{O})} R\Gamma(\mathcal{C}, \mathcal{A}) \to R\Gamma(\mathcal{C}, \mathcal{A}), \quad \eta \otimes \theta \mapsto \eta \cup \theta
\]

and similarly \( \mu_{\mathcal{M}} \) is the cup product map

\[
R\Gamma(\mathcal{C}, \mathcal{M}) \otimes L_{\Gamma(\mathcal{C}, \mathcal{O})} R\Gamma(\mathcal{C}, \mathcal{A}) \to R\Gamma(\mathcal{C}, \mathcal{M}), \quad \eta \otimes \theta \mapsto \eta \cup \theta
\]

3It would be more precise to write \( F(\mathcal{A}) \otimes L_{\mathcal{O}} F(\mathcal{A}) \to F(\mathcal{A} \otimes \mathcal{O} \mathcal{A}) \to F(\mathcal{A}) \) were \( F \) denotes the forgetful functor to complexes of \( \mathcal{O} \)-modules. Also, note that \( \mathcal{A} \otimes \mathcal{O} \mathcal{A} \) indicates the tensor product of Section \( \ref{sec:tensor-prod} \) so that \( F(\mathcal{A} \otimes \mathcal{O} \mathcal{A}) = \text{Tot}(F(\mathcal{A}) \otimes \mathcal{O} F(\mathcal{A})) \). The first arrow of the sequence is the canonical map from the derived tensor product of two complexes of \( \mathcal{O} \)-modules to the usual tensor product of complexes of \( \mathcal{O} \)-modules.

4Here and below \( Rf_* : D(\mathcal{O}) \to D(\mathcal{O}') \) is the derived functor studied in Cohomology on Sites, Section \( \ref{sec:derived-functors} \).
In general, via the identifications
\[ R\Gamma(C, A) = R\Gamma(C', Rf_*A) \quad \text{and} \quad R\Gamma(C, M) = R\Gamma(C', Rf_*M) \]
of Cohomology on Sites, Remark 14.4 the map \( \mu_M \) induces the cup product on cohomology. To see this use Cohomology on Sites, Lemma 32.4 where the second morphism of topoi is the morphism from \( \text{Sh}(C') \) to the punctual topos as above.

If \( M_1 \to M_2 \) is a homomorphism of right differential graded \( A \)-modules, then the diagram
\[
\begin{array}{ccc}
Rf_*M_1 \otimes_{\mathcal{O}_i} L_{\mathcal{O}_i} Rf_*A & \xrightarrow{\mu_{M_1}} & Rf_*M_1 \\
\downarrow & & \downarrow \\
Rf_*M_2 \otimes_{\mathcal{O}_i} L_{\mathcal{O}_i} Rf_*A & \xrightarrow{\mu_{M_2}} & Rf_*M_2 \\
\end{array}
\]
commutes in \( D(O') \); this follows from the fact that the relative cup product is functorial. Suppose we have a short exact sequence
\[ 0 \to M_1 \xrightarrow{a} M_2 \to M_3 \to 0 \]
of right differential graded \( A \)-modules. Then we claim that the diagram
\[
\begin{array}{ccc}
Rf_*M_3 \otimes_{\mathcal{O}_i} L_{\mathcal{O}_i} Rf_*A & \xrightarrow{\mu_{M_3}} & Rf_*M_3 \\
\downarrow \quad Rf_*\delta \otimes \text{id} & & \downarrow \quad Rf_*\delta \\
Rf_*M_1[1] \otimes_{\mathcal{O}_i} L_{\mathcal{O}_i} Rf_*A & \xrightarrow{\mu_{M_1[1]}} & Rf_*M_1[1] \\
\end{array}
\]
commutes in \( D(O') \) where \( \delta : M_3 \to M_1[1] \) is the morphism of \( D(O) \) coming from the given short exact sequence (see Derived Categories, Section 12). This is clear if our sequence is split as a sequence of graded right \( A \)-modules, because in this case \( \delta \) can be represented by a map of right \( A \)-modules and the discussion above applies. In general we argue using the cone on \( a \) and the diagram
\[
\begin{array}{ccc}
\mathcal{M}_1 & \xrightarrow{a} & \mathcal{M}_2 \\
\downarrow & & \downarrow i & \xrightarrow{C(a)} \mathcal{M}_1[1] & \xrightarrow{-p} \mathcal{M}_1[1] \\
\mathcal{M}_1 & \xrightarrow{i} & \mathcal{M}_2 & \xrightarrow{q} \mathcal{M}_3 & \xrightarrow{\delta} \mathcal{M}_1[1] \\
\end{array}
\]
where the right square is commutative in \( D(O) \) by the definition of \( \delta \) in Derived Categories, Lemma 12.1. Now the cone \( C(a) \) has the structure of a right differential graded \( A \)-module such that \( i, p, q \) are homomorphisms of right differential graded \( A \)-modules, see Definition 22.2. Hence by the above we know that the corresponding diagrams commute for the morphisms \( q \) and \( -p \). Since \( q \) is an isomorphism in \( D(O) \) we conclude the same is true for \( \delta \) as desired.

In the situation above given a right differential graded \( A \)-module \( M \) let
\[ \xi \in H^n(C, M) \]
In other words, \( \xi \) is a degree \( n \) cohomology class in the cohomology of \( M \) viewed as a complex of \( \mathcal{O} \)-modules. By Lemma 29.9 we can construct maps
\[ x : A \to M'[n] \quad \text{and} \quad s : M \to M' \]
of right differential graded \( A \)-modules where \( s \) is a quasi-isomorphism and such that \( \xi \) is the image of \( 1 \in H^0(C, A) \) via the morphism \( s[n]^{-1} \circ x \) in the derived
category $D(A,d)$ and a fortiori in the derived category $D(O)$. It follows that the corresponding map
\[ \xi' = (s[n])^{-1} \circ x : A \to M[n] \]
in $D(O)$ is uniquely characterized by the following two properties
(1) $\xi'$ can be lifted to a morphism in $D(A,d)$, and
(2) $\xi = \xi'(1)$ in $H^0(C, M[n]) = H^n(C, M)$.

Using the compatibilities of $x$ and $s$ with the relative cup product discussed above it follows that for every morphism of ringed topoi $(f, f^\#) : (Sh(C), O) \to (Sh(C'), O')$ the derived pushforward
\[ Rf_! \xi' : Rf_! A \to Rf_! M[n] \]
of $\xi'$ is compatible with the maps $\mu$ and $\mu_{M[n]}$ constructed above in the sense that the diagram
\[
\begin{array}{ccc}
Rf_! A \otimes L \Gamma(C, O) & \mu & \to & Rf_! A \\
\downarrow Rf_! \xi' \otimes \text{id} & & & \downarrow Rf_! \xi' \\
Rf_! M[n] \otimes L \Gamma(C, O) & \mu_{M[n]} & \to & Rf_! M[n]
\end{array}
\]
commutes in $D(O')$. Using this compatibility for the map to the punctual topos, we see in particular that
\[
\begin{array}{ccc}
R\Gamma(C, A) \otimes L \Gamma(C, O) & R\Gamma(C, A) \\
\downarrow \xi' \otimes \text{id} & & \downarrow \xi' \\
R\Gamma(C, M[n]) \otimes L \Gamma(C, O) & R\Gamma(C, M[n])
\end{array}
\]
commutes. Combined with $\xi'(1) = \xi$ this implies that the induced map on cohomology
\[ \xi' : R\Gamma(C, A) \to R\Gamma(C, M[n]), \quad \eta \mapsto \xi \cup \eta \]
is given by left cup product by $\xi$ as indicated.

33. Other chapters

Preliminaries

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(5) Topology
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(8) Stacks
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Schemes

\[5\] For example the identity morphism.
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| (30) | Divisors |
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| (35) | Derived Categories of Schemes |
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| (38) | Groupoid Schemes |
| (39) | More on Groupoid Schemes |
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