SPHERICAL DG-FUNCTORS

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Abstract. For two DG-categories $\mathcal{A}$ and $\mathcal{B}$ we define the notion of a spherical Morita quasi-functor $\mathcal{A} \to \mathcal{B}$. We construct its associated autoequivalences: the twist $T \in \text{Aut} \, D(\mathcal{B})$ and the co-twist $F \in \text{Aut} \, D(\mathcal{A})$. We give powerful sufficiency criteria for a quasi-functor to be spherical and for the twists associated to a collection of spherical quasi-functors to braid. Using the framework of DG-enhanced triangulated categories, we translate all of the above to Fourier-Mukai transforms between the derived categories of algebraic varieties. This is a broad generalisation of the results on spherical objects in [ST01] and on spherical functors in [Ann07]. In fact, this paper replaces [Ann07], which has a fatal gap in the proof of its main theorem. Though conceptually correct, the proof was impossible to fix within the framework of triangulated categories.

1. Introduction

Let $X$ be a smooth projective variety over an algebraically closed field $k$ of characteristic 0. Let $D(X)$ be the bounded derived category of coherent sheaves on $X$. In [ST01] Seidel and Thomas introduced the notion of a spherical object in $D(X)$. These objects are defined in terms of certain cohomological properties and they are mirror-symmetric analogues of Lagrangian spheres on a symplectic manifold. Given a Lagrangian sphere we can associate to it a symplectic automorphism called the generalised Dehn twist. Correspondingly:

**Theorem** ([ST01]). Let $E \in D(X)$. The twist functor $T_E$ is a certain functorial cone of the natural transformation $E \otimes_k R\text{Hom}_X(E, -) \xrightarrow{\text{eval}} \text{Id}_{D(X)}$. If $E$ is spherical, then $T_E$ is an autoequivalence of $D(X)$.

Moreover, in [ST01, Theorem 2.17] Seidel and Thomas give simple criteria on a set $E_1, \ldots, E_n$ of spherical objects in $D(X)$ sufficient to ensure that the corresponding spherical twists $T_1, \ldots, T_n$ represent the braid group $B_n$. In other words, that we have:

$$T_i T_j T_i \simeq T_j T_i T_j \quad |i - j| = 1,$$

$$T_i T_j \simeq T_j T_i \quad |i - j| \geq 2.$$

Spherical objects and twists quickly became an essential tool in studying derived categories of algebraic varieties as well as more classical areas of algebraic geometry [Muk87], [Bri08], [Bri09], [IU05], [BP10]. For some time now it was understood by specialists that the notion of a spherical object should generalise to the notion of a spherical functor $D(Z) \xrightarrow{\simeq} D(X)$ where $Z$ is some other variety. Such functor should produce two auto-equivalences — the twist $t \in \text{Aut} \, D(X)$ and the co-twist $f \in \text{Aut} \, D(Z)$. More generally, there should be a notion of a spherical functor between two abstract triangulated categories. Limited special cases of this appear in [Hor05], [Rou04] [Sze04], [Tod07], [KT07], but general treatment was obstructed by well-known imperfections of the axioms of triangulated categories such as non-functoriality of the cone construction and non-uniqueness of the data supplied by the octahedral axiom.

An attempt at such general treatment was made in [Ann07]. Conceptually sound, it was brought low by the octahedral axiom. The proof of its main theorem [Ann07, Prop.1] contains a fatal gap which is impossible to fix within the axioms of triangulated categories. None the less, it was clear that its ideas could work if we had an extra level of control over what the octahedral axiom provides us with.

In this paper, we are at last able to give an ideal definition and prove an ideal statement about spherical functors and their associated auto-equivalences. We do it by passing to differentially graded (DG) categories. The axioms of triangulated categories were developed in [Ver96] to describe the derived categories of algebraic varieties, which are cohomological truncations of certain natural DG-categories. The imperfections of these axioms can now clearly be seen as artefacts of the truncation. Working in the original DG-category provides us precisely with the layer of control that was missing. This allows us not only to fix the results in [Ann07], but to significantly improve upon them. It allows us to do something more — to provide for a collection of spherical functors, as [ST01] did for spherical objects, a set of straightforward criteria sufficient for braid relations to occur between their twists. For some years now the first author was well-aware of what these criteria should be, but proving them on the level of triangulated categories was hopeless.

We first state our results in the language of triangulated categories. Let $A$ and $B$ be two Karoubi closed triangulated categories and let $s$ be an exact functor $A \to B$ which has left and right adjoints $l$ and $r$. Suppose
that we can construct a preferred functorial exact triangle for each of the four adjunction units and co-units involved. Use these triangles to define the \textit{twist} \( t \) of \( s \) by the exact triangle
\[
\begin{array}{c}
sr & \xrightarrow{\text{adj.counit}} & \text{Id}_B & \rightarrow & t, \\
\end{array}
\] (1.1)
The \textit{dual twist} \( t' \) of \( s \) by the exact triangle
\[
\begin{array}{c}
t' & \rightarrow & \text{Id}_B & \xrightarrow{\text{adj.unit}} & sl, \\
\end{array}
\] (1.2)
the \textit{cotwist} \( f \) of \( s \) by the exact triangle
\[
\begin{array}{c}
f & \rightarrow & \text{Id}_A & \xrightarrow{\text{adj.unit}} & rs, \\
\end{array}
\] (1.3)
and the \textit{dual cotwist} \( f' \) of \( s \) by the exact triangle
\[
\begin{array}{c}
l_{s} & \xrightarrow{\text{adj.counit}} & \text{Id}_A & \rightarrow & f'. \\
\end{array}
\] (1.4)
Define also two natural transformations
\[
\begin{array}{c}
lt[-1] & \xrightarrow{(1.1)} & ls & \xrightarrow{\text{adj.counit}} & r \\
\end{array}
\] (1.5)
\[
\begin{array}{c}
r & \xrightarrow{\text{adj.unit}} & rs & \xrightarrow{(1.3)} & f[l][1]. \\
\end{array}
\] (1.6)

**Definition 1.1.** The functor \( s \) is \textit{spherical} if all of the following holds:

1. \( t \) and \( t' \) are quasi-inverse autoequivalences of \( B \)
2. \( f \) and \( f' \) are quasi-inverse autoequivalences of \( A \)
3. \( l_{t}[-1] \xrightarrow{(5.11)} r \) is an isomorphism of functors (“the twist identifies the adjoints”).
4. \( r \xrightarrow{(5.12)} f[l][1] \) is an isomorphism of functors (“the co-twist identifies the adjoints”).

The main obstruction is the lack of canonical functorial exact triangles (1.1)-(1.4) defining \( t, t', f \) and \( f' \). What [Ann07] tried to do was to assume that \textit{some} functorial exact triangles as above exist, define \( s \) to be spherical if (2) and (4) hold, and then prove that for any spherical \( s \) the condition (1) also holds. In this paper, as explained in more detail below, we assume that

1. \( A \) and \( B \) admit \( DG \)-enhancements
2. \( s, r \) and \( l \) descend from \( DG \)-functors \( S, R \) and \( L \) between some enhancements of \( A \) and \( B \)

and prove that there is a canonical construction of the exact triangles (1.1)-(1.4) determined by a certain equivalence class of \( S \) such that any two of the conditions in Defn. 1.1 imply that all four of them hold and \( s \) is spherical. This is the ideal statement mentioned above.

Let us be more precise. Let \( A \) be a triangulated category. Traditionally, a \textit{DG enhancement} of \( A \) is a \( DG \)-category \( \mathcal{A} \) together with an isomorphism \( H^{0}(\mathcal{A}) \cong A \). A more useful notion for us is that of a \textit{Morita enhancement}, which is a \( DG \)-category \( \mathcal{A} \) together with an isomorphism \( D_{c}(\mathcal{A}) \cong A \). Here \( D_{c}(\mathcal{A}) \) is the full subcategory of the derived category \( D(\mathcal{A}) \) consisting of the compact objects. A \textit{Morita equivalence} is a \( DG \)-functor \( \mathcal{A} \xrightarrow{f} \mathcal{B} \) whose induced functor \( D_{c}(\mathcal{A}) \xrightarrow{f_{!}} D_{c}(\mathcal{B}) \) is an equivalence of categories. This is the right notion of equivalence for Morita enhancements. Thus we are led to work in the Morita homotopy category \( \text{Mrt}(\text{DG-Cat}) \), which is the localisation of the category \( \text{DG-Cat} \) of all \( DG \)-categories by Morita equivalences. The objects of \( \text{Mrt}(\text{DG-Cat}) \) should be thought of as enhanced Karoubi closed triangulated categories with a fixed equivalence class of enhancements. The morphisms in \( \text{Mrt}(\text{DG-Cat}) \) are called \textit{Morita quasi-functors}, each Morita quasi-functor \( \mathcal{A} \rightarrow \mathcal{B} \) induces a genuine exact functor \( D_{c}(\mathcal{A}) \rightarrow D_{c}(\mathcal{B}) \).

Let \( \mathcal{A} \) and \( \mathcal{B} \) be Morita enhancements of triangulated categories \( A \) and \( B \). A fundamental result of Toën [Toë07a, Theorem 7.2] implies that the Morita quasi-functors \( \mathcal{A} \rightarrow \mathcal{B} \) are in 1-to-1 correspondence with the isomorphism classes in \( D(\mathcal{A}-\mathcal{B}) \) of the \( \mathcal{A}-\mathcal{B} \)-bimodules which are \( B \)-perfect, i.e. \( \mathcal{A}M \in D_{c}(\mathcal{B}) \) for all \( a \in \mathcal{A} \). Given \( M \in D^{B-\text{perf}}(\mathcal{A}-\mathcal{B}) \) the derived tensor product functor
\[
(-) \otimes_{\mathcal{A}} M : D_{c}(\mathcal{A}) \rightarrow D_{c}(\mathcal{B})
\]
is the exact functor underlying the corresponding Morita quasi-functor. Thus, we think of \( D^{B-\text{perf}}(\mathcal{A}-\mathcal{B}) \) as of triangulated category structure on the set \( \text{Hom}_{\text{Mrt}(\text{DG-Cat})}(\mathcal{A}, \mathcal{B}) \) and of morphisms in it as morphisms of Morita quasi-functors. This packages up into a 2-category structure on \( \text{Mrt}(\text{DG-Cat}) \) with a functor to the 2-category of Karoubi closed triangulated categories. See Section 4 for more details on \( DG \)-enhancements.

We now describe our results. In the body of the paper they are stated in a slightly more flexible language of \( DG \)-bimodules. Here we state them in the language of Morita quasi-functors, which gives a more intuitive picture. Let \( \mathcal{A} \xrightarrow{S} \mathcal{B} \) be a Morita quasi-functor and let \( \mathcal{A} \xrightarrow{\omega} B \) be the underlying exact functor. Assume that
s has left and right adjoints $B \xrightarrow{\text{tr}} A$ which also descend from Morita quasi-functors. The derived $A$- and $B$-duals of $S$ in $D(B, A)$ are then $A$-perfect and hence define Morita quasi-functors $B \xrightarrow{\text{LR}} A$. In Section 2.2 we construct derived trace and action maps

$$SR \xrightarrow{\text{tr}} \text{Id}_S \quad \text{and} \quad LS \xrightarrow{\text{tr}} \text{Id}_A$$

$$(1.7)$$

$$\text{Id}_S \xrightarrow{\text{act}} SL \quad \text{and} \quad \text{Id}_A \xrightarrow{\text{act}} RS.$$  

$$(1.8)$$

and prove that the exact functors underlying $L$ and $R$ are left and right adjoint to $s$ and that the derived trace and action maps above induce the units and co-units of the adjunctions. Then, working in the DG-enhancements, we construct natural exact triangles of Morita quasi-functors

$$SR \xrightarrow{\text{tr}} \text{Id}_S \rightarrow T,$$

$$(1.9)$$

$$T' \rightarrow \text{Id}_B \xrightarrow{\text{act}} SL,$$

$$(1.10)$$

$$F \rightarrow \text{Id}_A \xrightarrow{\text{act}} RS,$$

$$(1.11)$$

$$LS \xrightarrow{\text{tr}} \text{Id}_A \rightarrow F',$$

$$(1.12)$$

which define the twist $T$, the dual twist $T'$, the cotwist $F$ and the dual cotwist $F'$ of $S$. Thus we obtain a natural choice of functorial exact triangles (1.1)-(1.4) defining $t$, $t'$, $f$ and $f'$. We then prove that $t'$ and $f'$ are left adjoint to $t$ and $f$, respectively. All the above constructions are readily seen to be Morita-invariant, i.e. they are preserved if we replace $A$ or $B$ by a Morita-equivalent DG-category. Hence they only depend on Morita equivalence classes of $A$ and $B$ and on $S \in \text{Hom}_{\text{Mrt}(\text{DG-Cat})}(A, B)$.

The following is the main result of this paper:

**Theorem 1.1** (see Theorem 5.1). If any two of the following conditions hold:

1. $t$ is an autoequivalence of $B$ (“the twist is an equivalence”).
2. $f$ is an equivalence of $A$ (“the cotwist is an equivalence”).
3. $lt[-1] \xrightarrow{(5.11)} r$ is an isomorphism of functors (“the twist identifies the adjoints”).
4. $r \xrightarrow{(5.12)} f[l][1]$ is an isomorphism of functors (“the cotwist identifies the adjoints”).

then all four hold and $S$ is said to be a spherical quasi-functor.

Finally, we give the braiding criteria for spherical quasi-functors. These have a natural interpretation in geometrical context that is the subject of a future paper [AL]. An example of these criteria being satisfied can be seen in a construction by Khovanov and Thomas in [KT07].

Let $A_1, \ldots, A_n, B$ be triangulated categories with Morita enhancements $A_1, \ldots, A_n, B$. Let $A_i \xrightarrow{S_i} B$ be spherical Morita quasi-functors. For any $i \neq j$ trace maps $S_iR_i \xrightarrow{\text{tr}} \text{Id}_S$ and $S_jR_j \xrightarrow{\text{tr}} \text{Id}_S$ define a map

$$S_iR_iS_jR_j \xrightarrow{S_iR_i, \text{tr} \oplus \text{tr} S_jR_j} S_iR_i \oplus S_jR_j.$$  

$$(1.13)$$

Next, for any $i \neq j$ define a Morita quasi-functor $A_i \xrightarrow{O_{ij}} A_j$ by

$$O_{ij} = F_i \text{Cone} \left( L_iS_jR_jS_i \xrightarrow{\text{tr} \circ (L_i \text{tr} S_j)} A_i \right).$$  

$$(1.14)$$

As $S_i$ is spherical we have $R_i[-1] \simeq F_iL_i$, so $S_iR_i \xrightarrow{\text{tr}} \text{Id}_S$ and $S_jR_j \xrightarrow{\text{tr}} \text{Id}_S$ define (cf. Section 6.2) a map

$$S_iO_{ij}R_i \rightarrow S_iR_iS_jR_j \oplus S_jR_jS_iR_i.$$  

$$(1.15)$$

**Theorem 1.2** (Theorems 6.1-6.2). Suppose that for all $i, j \in 1, \ldots, n$

1. if $|i - j| > 1$ there exists an isomorphism

$$S_iR_iS_jR_j \simeq S_jR_jS_iR_i$$

which commutes with the maps (1.13).
2. if $|i - j| = 1$, there exists an isomorphism

$$S_iO_{ij}R_i \simeq S_jO_{ji}R_j$$

which commutes with the maps (1.15).

Then the twists $T_1, \ldots, T_n$ generate a categorical action of the braid group $B_n$ on $B$. 

Finally, we interpret the above in the context of algebraic geometry. Let $Z$ and $X$ be separated schemes of finite type over $k$. Let $D_{qc}(Z)$ and $D_{qc}(X)$ be the derived categories of quasi-coherent sheaves and $D(Z)$ and $D(X)$ be the bounded derived categories of coherent sheaves on $Z$ and $X$. Let $\mathcal{A}$ and $\mathcal{B}$ be the standard DG-enhancements of $D(Z)$ and $D(X)$. These are given by the DG-categories of $h$-injective complexes of sheaves on $Z$ and $X$, respectively. In Example 4.3 we prove an analogue for the bounded coherent derived categories of the famous result of Toën [Toën07a, Theorem 8.9] for the unbounded quasi-coherent ones. We prove that the exact functors $D(Z) \rightarrow D(X)$ which descend from the Morita quasi-functors $\mathcal{A} \rightarrow \mathcal{B}$ are precisely the Fourier-Mukai transforms. Given an object $E \in D(Z \times X)$ the Fourier-Mukai transform $\Phi_E$ is apriori a functor $D_{qc}(Z) \rightarrow D_{qc}(X)$. In Example 4.3 we identify $\text{Hom}_{\text{Morita}}(\mathcal{A}, \mathcal{B})$ with the full subcategory of $D(Z \times X)$ consisting the objects $E$ such that $\Phi_E$ restricts to $D(Z) \rightarrow D(X)$. Under this identification, each Morita quasi-functor $\mathcal{A} \rightarrow \mathcal{B}$ goes to such object $E \in D(Z \times X)$ that $D(Z) \xrightarrow{\Phi_E} D(X)$ is the exact functor $s$ underlying $S$.

The above results for Morita quasi-functors can then all be interpreted for the Fourier-Mukai transforms. Let $E \in D(Z \times X)$ be such that $\Phi_E$ restricts to a functor $D(Z) \xrightarrow{s} D(X)$ and this restriction has a left adjoint which is also a Fourier-Mukai transform. E.g. it is sufficient to assume that $E$ is proper over $Z$ and $X$ and perfect over $Z$ and $X$. Our results for Morita quasi-functors provide natural constructions on the level of Fourier-Mukai kernels of the right and left adjoints $r$ and $l$ and of all of four adjunctions units and co-units involved. We conjecture that these coincide with the explicit formulas proved independently in [AL12] and [AL10]. Regardless of whether this holds or not, the functorial exact triangles (1.1)-(1.4) defining the twists and co-twists $t, t', f$ and $f'$ are well-defined and depend only on $E \in D(Z \times X)$. We say that $E$ is spherical over $Z$ if the four conditions of the Definition 1.1 are satisfied. Our main theorem then applies to show that, in fact, it suffices to only verify any two of these four conditions. The braiding criteria above translate similarly to the language of Fourier-Mukai kernels. It is worth noting that if we set $Z = \text{Spec } k$ then the natural isomorphism $Z \times X \simeq X$ identifies $D(Z \times X)$ with $D(X)$ and our results imply immediately the results in [ST01].

Finally, we also describe in Section 5.2 a variation on all of the above. It uses a slightly different enhancement framework which allows one to work with the unbounded derived categories $D_{qc}(Z)$ and $D_{qc}(X)$. The penalty is a strong smoothness condition. We can only work with $E \in D_{qc}(X \times Y)$ such that $\Phi_E$ has a left adjoint which is also a Fourier-Mukai transform and they both take compact objects to compact objects.

About the structure of this paper: in Section 2.1 we give an overview of the facts we need on DG-categories and DG-modules over them. In Section 2.2 we define the dualizing functors for DG-modules and DG-bimodules. We then construct and study trace and action maps and show them to be units and co-units of homotopy adjunctions between an $\mathcal{A}$-$\mathcal{B}$-bimodule $M$ and its $\mathcal{A}$- and $\mathcal{B}$-duals $M^\mathcal{A}$ and $M^\mathcal{B}$. In Section 3.1 we give an overview on twisted complexes over a DG-category and prove explicit formulas for taking a tensor product and for dualizing on the level of twisted complexes. Section 3.2 summarizes the facts we need about pre-triangulated categories. In Section 3.3 we develop a theory of twisted cubes, which acts as a “higher” octahedral axiom for the world of pretriangulated categories. In Section 4 we explain the framework of DG-enhancements of triangulated categories and its applications to algebraic geometry. In Section 5.1 we constructs twists and co-twists of a DG-bimodule, define a notion of a spherical DG-bimodule and prove our main theorem on the level of DG-bimodules. In Section 5.2 we interpret this for Fourier-Mukai transforms between the derived categories of algebraic varieties via the framework introduced in Section 4. In Section 6 we state and prove the braiding criteria for spherical DG-bimodules. Finally, the Appendix A contains some technical results we need in Section 6 on constructing homotopy equivalences between twisted complexes. There the authors have to resort to using $A_{\infty}$-categories, $A_{\infty}$-functors and the interpretation of DG quasi-functors as strictly unital $A_{\infty}$-functors between the corresponding DG-categories. It is something they quite happily avoided doing throughout the rest of the paper.

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2. Preliminaries

Notation: Throughout the paper all schemes are defined and all DG-categories are considered over the base field $k$ which is assumed to be an algebraically closed field of characteristic 0.

Let $X$ be a scheme. We denote by $D_{qc}(X)$, resp. $D(X)$, the full subcategory of the derived category of $\mathcal{O}_X$-$\text{Mod}$ consisting of complexes with quasi-coherent, resp. bounded and coherent, cohomology.
2.1. DG categories, modules and bimodules. Let $k$ be a commutative ring. A DG-category over $k$ is a category $\mathcal{A}$ whose morphism spaces $\text{Hom}_\mathcal{A}(a,b)$ are complexes of $k$-modules and whose composition maps

$$\text{Hom}_\mathcal{A}(b,c) \otimes \text{Hom}_\mathcal{A}(a,b) \rightarrow \text{Hom}_\mathcal{A}(a,c)$$

are closed degree 0 maps of complexes of $k$-modules. We denote by $C(k)$ the DG-category of complexes of $k$-modules itself. See [Kel94, §1.1-1.2] or [Toë97b] for details.

Given a DG-category $\mathcal{A}$ denote by $\mathcal{A}^{\text{opp}}$ the opposite DG-category of $\mathcal{A}$. Its objects are the same as those of $\mathcal{A}$ and for all $a,b \in \mathcal{A}^{\text{opp}}$ we have $\text{Hom}_{\mathcal{A}^{\text{opp}}}(a,b) = \text{Hom}_\mathcal{A}(b,a)$. The composition is defined by composing the standard sign-twisting isomorphism $\text{Hom}_\mathcal{A}(c,b) \otimes \text{Hom}_\mathcal{A}(b,a) \xrightarrow{\sim} \text{Hom}_\mathcal{A}(b,a) \otimes \text{Hom}_\mathcal{A}(c,b)$ with the composition map of $\mathcal{A}$. In other words we set

$$\beta \circ_{\mathcal{A}^{\text{opp}}} \alpha = (-1)^{\deg(\alpha)\deg(\beta)}\alpha \circ \beta$$

for all $\alpha \in \text{Hom}_{\mathcal{A}^{\text{opp}}}(a,b)$, $\beta \in \text{Hom}_{\mathcal{A}^{\text{opp}}}(b,c)$.

Let $\mathcal{A}$ and $\mathcal{B}$ be two DG-categories. A DG-functor $\mathcal{A} \rightarrow \mathcal{B}$ is an additive functor which preserves the grading and the differential on morphisms. The DG-category $\text{DGFun}(\mathcal{A},\mathcal{B})$ has as its objects all DG-functors $\mathcal{A} \rightarrow \mathcal{B}$ and for any two $\Phi, \Psi : \mathcal{A} \rightarrow \mathcal{B}$ the morphism complex $\text{Hom}_{\text{DGFun}(\mathcal{A},\mathcal{B})}(\Phi, \Psi)$ has as its $k$-th graded part all the graded natural transformations $\Phi \rightarrow \Psi$ of degree $k$. The composition maps are also defined levelwise in $\mathcal{B}$.

We never consider any functors between DG-categories other than DG-functors, so wherever the context permits we omit “DG-” and simply use the term “functor”.

A (right) $\mathcal{A}$-module is a functor from $\mathcal{A}^{\text{opp}}$ to $C(k)$. For the reasons of brevity and to mimic the notation used for DG-algebras, for any two $E,F \in \text{Mod-}\mathcal{A}$ we write $\text{Hom}_\mathcal{A}(E,F)$ for $\text{Hom}_{\text{Mod-}\mathcal{A}}(E,F)$. The homotopy category $\text{H}^0(\text{Mod-}\mathcal{A})$ has same objects as $\text{Mod-}\mathcal{A}$ and its morphisms spaces are 0-th cohomologies of their counterparts in $\text{Mod-}\mathcal{A}$. $\text{H}^0(\text{Mod-}\mathcal{A})$ admits natural structure of a triangulated category which is defined levelwise via the usual triangulated structure on $\text{H}^0(C(k))$, cf. [Kel94, §2.2].

For any $E \in \text{Mod-}\mathcal{A}$ and $a \in \mathcal{A}$ we write $E_a$ for the complex of $k$-modules $E(a)$. We write $v \in E$ if $v \in E_a$ for some $a \in \mathcal{A}$. The Yoneda embedding $\mathcal{A} \hookrightarrow \text{Mod-}\mathcal{A}$ is the fully faithful functor defined on the objects by

$$a \mapsto \text{Hom}_\mathcal{A}(-,a) \quad \forall a \in \mathcal{A}$$

and on the morphisms by composition. For each $a \in \mathcal{A}$ denote by $a\mathcal{A}$ its image under the Yoneda embedding, these are the representable objects of $\text{Mod-}\mathcal{A}$. Note, that for all $a,b \in \mathcal{A}$ we have $a\mathcal{A}_b = \text{Hom}_\mathcal{A}(b,a)$. For any $E \in \text{Mod-}\mathcal{A}$ trivially $\text{Hom}_\mathcal{A}(a,E) = E_a$. For each $s \in E_a$ and $\alpha \in a\mathcal{A}_b$ we write $s \cdot \alpha$ for the element $(-1)^{\deg(s)\deg(\alpha)}E(\alpha)(s) \in E_b$. We have

$$(s \cdot \alpha) \cdot \beta = s \cdot (\alpha \circ \beta).$$

In other words, we can think of the data defining an $\mathcal{A}$-module $E$ as of collection of fibers $E_a \in C(k)$ for each $a \in \mathcal{A}$ with a right action of (the Hom-spaces of) $\mathcal{A}$ on them, such that $a\mathcal{A}_b$ acts on $E_a$ and maps it to $E_b$.

A left $\mathcal{A}$-module is a functor $\mathcal{A} \rightarrow C(k)$, i.e. it is a right $\mathcal{A}^{\text{opp}}$-module. To facilitate the treatment of bimodules below, it is often useful to treat (right) $\mathcal{A}^{\text{opp}}$-modules as left $\mathcal{A}$-modules and employ for them the following notation. For any $F \in \text{Mod-}\mathcal{A}^{\text{opp}}$ and $a \in \mathcal{A}$ we write $aF$ (instead of $F_a$) for the complex $F(a)$. For each $a \in \mathcal{A}$ write $a\mathcal{A}$ for the image of $a$ under the Yoneda embedding of $\mathcal{A}^{\text{opp}}$, i.e. for the $\mathcal{A}^{\text{opp}}$-module $\text{Hom}_{\mathcal{A}^{\text{opp}}}(\cdot,a) = \text{Hom}_\mathcal{A}(a,\cdot)$. Set $a \cdot s = F(\alpha)(s)$ for each $s \in aF$ and $\alpha \in a\mathcal{A}_b$, it is a left action of $\mathcal{A}$ on $F$.

Let $E$ and $F$ be an $\mathcal{A}$- and an $\mathcal{A}^{\text{opp}}$-module. Define $E \otimes_{\mathcal{A}} F \in C(k)$ to be the quotient of

$$\bigoplus_{a \in \mathcal{A}} E_a \otimes_{a\mathcal{A}} F \subset C(k)$$

by the $\mathcal{A}$-action relations

$$(s \cdot \alpha) \otimes t = s \otimes (\alpha \cdot t) \tag{2.1}$$

for each $\alpha \in a\mathcal{A}_b$, $s \in E_a$, $t \in F_b$. We thus obtain a DG bifunctor:

$$(-) \otimes_{\mathcal{A}} (-) : \text{Mod-}\mathcal{A} \times \text{Mod-}\mathcal{A}^{\text{opp}} \rightarrow C(k).$$

A module $C \in \text{Mod-}\mathcal{A}$ is acyclic if for each $a \in \mathcal{A}$ the complex of $k$-modules $C_a$ is acyclic. A module $P \in \text{Mod-}\mathcal{A}$ is $h$-projective if $\text{Hom}_{\mathcal{H}^0(\text{Mod-}\mathcal{A})}(P,C) = 0$ for every acyclic $C \in \text{Mod-}\mathcal{A}$. Denote by $\mathcal{P}(\mathcal{A})$ the corresponding full subcategory of $\text{Mod-}\mathcal{A}$. A morphism $E \rightarrow F$ of $\mathcal{A}$-modules is a quasi-isomorphism if for each $a \in \mathcal{A}$ the induced morphism $E_a \rightarrow F_a$ is a quasi-isomorphism. The derived category $D(\mathcal{A})$ is the localisation of $\mathcal{H}^0(\text{Mod-}\mathcal{A})$ by the class of all quasi-isomorphisms. It can be understood explicitly as follows. By definition of $\mathcal{P}(\mathcal{A})$ the natural functor $\mathcal{H}^0(\mathcal{P}(\mathcal{A})) \rightarrow D(\mathcal{A})$ is fully faithful. It is, moreover, an equivalence since resolutions by $h$-projectives exist in $\text{Mod-}\mathcal{A}$, i.e. for any $\mathcal{A}$-module we can find an
$h$-projective module quasi-isomorphic to it. In practice, we can use for resolutions a smaller full subcategory $\mathcal{SF}(\mathcal{A})$ of the semifree modules in $\text{Mod-}\mathcal{A}$. These are the modules $E \in \text{Mod-}\mathcal{A}$ which admit a filtration $F_0 \subseteq F_1 \subseteq F_2 \subseteq \cdots \subseteq E$ whose quotients $F_i/F_{i-1}$ are direct sums of shifts of representable modules. Any semifree module is $h$-projective and any $\mathcal{A}$-module can be resolved by a semifree module [Dri04, §C.8]. When $k$ is a field, we have a functorial semifree resolution of $\mathcal{A}$-modules provided by the bar-resolution $\mathcal{A}$ of the diagonal $\mathcal{A}\mathcal{A}$-bimodule $\mathcal{A}$ [Kel94, §6.6].

Another way to understand $D(\mathcal{A})$ is via either of the two natural model category structures induced on $\text{Mod-}\mathcal{A}$ from $C(k)$. In particular, in the projective model category structure on $C(k)$ the weak equivalences and the fibrations are the quasi-isomorphisms and the termwise surjections of complexes. In the corresponding model category structure on $\text{Mod-}\mathcal{A}$ we define the equivalences and the fibrations levelwise in $C(k)$, i.e. a morphism $A \to B$ is an equivalence (resp. fibration) if for every $a \in \mathcal{A}$ morphism $a_{\mathcal{A}} \to a_{\mathcal{B}}$ is an equivalence (resp. fibration) in $C(k)$ [Toë07a, §3]. It follows that every $\mathcal{A}$-module is fibrant, while the cofibrant modules are precisely the direct summands of semifree modules. We denote the full subcategory of $\text{Mod-}\mathcal{A}$ consisting of cofibrant objects by $\text{Int}(\mathcal{A})$. It is the Karoubi completion of $\mathcal{SF}(\mathcal{A})$.

Summarizing, we have a chain of full subcategories
\begin{equation}
\mathcal{SF}(\mathcal{A}) \hookrightarrow \text{Int}(\mathcal{A}) \rightarrow \mathcal{P}(\mathcal{A})
\end{equation}
of $\text{Mod-}\mathcal{A}$ which, after applying $H^0$ becomes a chain of equivalent full triangulated subcategories
\begin{equation}
H^0(\mathcal{SF}(\mathcal{A})) \simeq H^0(\text{Int}(\mathcal{A})) \simeq H^0(\mathcal{P}(\mathcal{A}))
\end{equation}
of $H^0(\text{Mod-}\mathcal{A})$. The natural functor $H^0(\text{Mod-}\mathcal{A}) \to D(\mathcal{A})$ induces an equivalence of these with $D(\mathcal{A})$. In the language of Section 4, $\mathcal{SF}(\mathcal{A})$, $\text{Int}(\mathcal{A})$ and $\mathcal{P}(\mathcal{A})$ are quasi-equivalent DG-enhancements of $D(\mathcal{A})$.

An $\mathcal{A}$-module $E$ is quasi-representable if it is quasi-isomorphic to a representable module. We denote by $Qr(\mathcal{A})$ and $\mathcal{P}^{\text{perf}}(\mathcal{A})$ the corresponding full subcategories of $\text{Mod-}\mathcal{A}$ and of $\mathcal{P}(\mathcal{A})$. A semi-free $\mathcal{A}$-module $E$ is finitely-generated if the filtration $F_0 \subseteq F_1 \subseteq F_2 \subseteq \cdots \subseteq E$ can be taken to be finite with quotients $F_i/F_{i-1}$ finite direct sums of shifts of representables. Denote by $\mathcal{SF}_{fg}(\mathcal{A})$ the corresponding full subcategory of $\mathcal{SF}(\mathcal{A})$. Its homotopy category $H^0(\mathcal{SF}_{fg}(\mathcal{A}))$ is the triangulated hull of $H^0(\mathcal{A})$ in $H^0(\text{Mod-}\mathcal{A})$, i.e. it is the smallest full triangulated subcategory of $H^0(\text{Mod-}\mathcal{A})$ containing $H^0(\mathcal{A})$. An $\mathcal{A}$-module $E$ is perfect if its image in $D(\mathcal{A})$ lies in the full subcategory $D_c(\mathcal{A})$ of compact objects, i.e. if $\text{Hom}_{D(\mathcal{A})}(E, -)$ commutes with infinite direct sums. We denote the full subcategories of perfect modules in $\text{Mod-}\mathcal{A}$ and $\mathcal{P}(\mathcal{A})$ by $\mathcal{Perf}(\mathcal{A})$ and $\mathcal{P}^{\text{perf}}(\mathcal{A})$, respectively.

In any category, an object $E$ is a retract of an object $F$ if there exist morphisms $F \to E \to F$ whose composition is the identity. An $\mathcal{A}$-module $E$ is a homotopy retract of an $\mathcal{A}$-module $F$ if there exist $E \to F \to E$ whose composition is homotopic to identity. In other words, $E$ is a retract of $F$ in $H^0(\text{Mod-}\mathcal{A})$. In triangulated categories the notion of a retract is the same as that of a direct summand. The category $D_c(\mathcal{A})$ is the Karoubi completion of $H^0(\mathcal{SF}_{fg}(\mathcal{A}))$ inside $D(\mathcal{A})$ [Kel94, §5]. Thus $\mathcal{P}^{\text{perf}}(\mathcal{A})$ coincides with the full subcategory of $\text{Mod-}\mathcal{A}$ of homotopy retracts of elements of $\mathcal{SF}_{fg}(\mathcal{A})$.

Let $\mathcal{B}$ be another DG-category. An $\mathcal{A}\mathcal{B}$ bimodule is an $\mathcal{A}^{\text{opp}} \otimes \mathcal{B}$-module. Here $\mathcal{A}^{\text{opp}} \otimes \mathcal{B}$ is the DG-category whose objects are pairs $(a, b)$ with $a \in \mathcal{A}^{\text{opp}}$, $b \in \mathcal{B}$, whose morphism complexes are given by
\[\text{Hom}_{\mathcal{A}^{\text{opp}} \otimes \mathcal{B}}((a, b), (a', b')) = \text{Hom}_\mathcal{A}(a, a') \otimes \text{Hom}_\mathcal{B}(b, b')\]
and whose composition is defined by
\[\alpha' \circ (\alpha \otimes \beta) = (-1)^{\deg(\beta') \deg(\alpha)} (\alpha' \circ \alpha) \otimes (\beta' \circ \beta)\].

We write $\text{Mod-}\mathcal{A}\mathcal{B}$ for the DG category of all $\mathcal{A}\mathcal{B}$-bimodules, and similarly for $Qr(\mathcal{A}\mathcal{B})$, $\mathcal{P}(\mathcal{A}\mathcal{B})$, etc.

For any $a \in \mathcal{A}$, $b \in \mathcal{B}$ write $\alpha_{M}$ for $\alpha(a, b) \in C(k)$, write $\alpha_{M}$ for the $\mathcal{B}$-module $M(a, -)$, and write $\alpha_{M}$ for the $\mathcal{A}^{\text{opp}}$-module $M(-, b)$. The induced functor $\mathcal{A} \to \text{Mod-}\mathcal{B}$ which maps $a$ to $\alpha_{M}$ extends to the functor
\[(-) \otimes_\mathcal{A} M : \text{Mod-}\mathcal{A} \to \text{Mod-}\mathcal{B}\],
where for any $E \in \text{Mod-}\mathcal{A}$ and $b \in \mathcal{B}$ we set $(E \otimes_\mathcal{A} M)_b = E \otimes_\mathcal{A} M_b$ and have $\mathcal{B}$ act via $M_b$. This lift of the tensor bifunctor from $\mathcal{A}^{\text{opp}} \otimes \text{Mod-}\mathcal{A}$ to $\text{Mod-}\mathcal{A}\mathcal{B}$ in the second argument admits a more general description.

Let $\mathcal{A}$, $\mathcal{B}$ and $\mathcal{C}$ be any DG-categories. Since $\text{Mod-}\mathcal{C}\mathcal{A}$ and $\text{Mod-}\mathcal{C}\mathcal{B}$ are equivalent to $\text{DGFun}(\mathcal{C}, \text{Mod-}\mathcal{A})$ and $\text{DGFun}(\mathcal{C}, \text{Mod-}\mathcal{B})$, any functor $\text{Mod-}\mathcal{A} \to \text{Mod-}\mathcal{B}$ induces a functor $\text{Mod-}\mathcal{C}\mathcal{A} \to \text{Mod-}\mathcal{C}\mathcal{B}$ and similarly for morphisms of functors. This produces a functor
\[\text{DGFun}(\text{Mod-}\mathcal{A}, \text{Mod-}\mathcal{B}) \to \text{DGFun}(\text{Mod-}\mathcal{C}\mathcal{A}, \text{Mod-}\mathcal{C}\mathcal{B})\]
best described as the functor of “defining fiberwise over $\mathcal{C}$".
Applying this to both arguments of (2.2) we obtain a bifunctor

\[ (-) \otimes_A (-): \text{Mod } \mathcal{B} \times \text{Mod } \mathcal{A} \to \text{Mod } \mathcal{B}, \]

Setting either \( \mathcal{B} \), or \( \mathcal{C} \), or both of them to be \( k \) we obtain all the prior incarnations of the tensor bifunctor we have seen so far. Similarly, we define the DG bifunctor

\[ \text{Hom}_A(-, -): \text{Mod } \mathcal{C} \times \text{Mod } \mathcal{A} \to \text{Mod } \mathcal{B} \]

fiberwise over \( \mathcal{B} \) and \( \mathcal{C} \) using \( \text{Hom}_A(-, -): \text{Mod } \mathcal{A} \times \text{Mod } \mathcal{A} \to \text{C}(k) \).

Let now \( M \) be any \( \mathcal{A}-\mathcal{B} \)-bimodule. Then for any DG-category \( \mathcal{C} \)

\[ (-) \otimes_A M: \text{Mod } \mathcal{C} \times \text{Mod } \mathcal{A} \to \text{Mod } \mathcal{B} \]

is left adjoint to

\[ \text{Hom}_B(M, -): \text{Mod } \mathcal{C} \to \text{Mod } \mathcal{A}, \]

while

\[ M \otimes_B (-): \text{Mod } \mathcal{B} \to \text{Mod } \mathcal{C} \]

is left adjoint to

\[ \text{Hom}_A(-, M): \text{Mod } \mathcal{A} \to \text{Mod } \mathcal{B}, \]

Let \( (-) \otimes_A M, M \otimes_B (-), \text{RHom}_B(M, -) \) and \( \text{RHom}_A(-, M) \) be the corresponding derived functors. Whenever these functors are mentioned, unless made clear otherwise, \( \mathcal{C} \) is assumed to be \( k \).

We say that an \( \mathcal{A}-\mathcal{B} \)-bimodule \( M \) is:

- \( \mathcal{A} \)-perfect if \( M_b \) is a perfect \( \mathcal{A}^{\text{opp}} \)-module for each \( b \in \mathcal{B} \).
- \( \mathcal{B} \)-perfect if \( M_a \) is a perfect \( \mathcal{B} \)-module for each \( a \in \mathcal{A} \).

We define similarly the notions of \( \mathcal{A} \)- and \( \mathcal{B} \)- quasi-representability, \( \mathcal{h} \)-projectivity, etc.

Since acyclicity is defined levelwise in \( \mathcal{C}(k) \), it is easy to see that if \( M \) is \( \mathcal{B} \)-\( \mathcal{h} \)-projective then \( \text{Hom}_B(M, -) \) and \( M \otimes_B (-) \) preserve acyclic modules and hence compute \( \text{RHom}_B(M, -) \) and \( M \otimes_B (-) \). Similarly, if \( M \) is \( \mathcal{A} \)-\( \mathcal{h} \)-projective, then \( (-) \otimes_A M \) computes \( (-) \otimes_A M \). If \( k \) is a field\(^1\) then any \( \mathcal{h} \)-projective \( \mathcal{A}-\mathcal{B} \)-bimodule is both \( \mathcal{A} \)- and \( \mathcal{B} \)-\( \mathcal{h} \)-projective \([\text{Kel}94, \S6.1]\), and hence the derived functors above can be computed by taking an \( \mathcal{h} \)-projective resolution of \( M \).

It follows from the above, that \( M \) is

- \( \mathcal{A} \)-perfect if and only if \( (-) \otimes_A M \) restricts to \( D_c(\mathcal{A}) \to D_c(\mathcal{B}) \).
- \( \mathcal{B} \)-perfect if and only if \( M \otimes_B (-) \) restricts to \( D_c(\mathcal{B}^{\text{opp}}) \to D_c(\mathcal{A}^{\text{opp}}) \) and

If \( k \) is a field we can be more precise. Let \( M \in \mathcal{P}(\mathcal{A}-\mathcal{B}) \). The functors \( (-) \otimes_A M \) and \( M \otimes_B (-) \) restrict to \( \mathcal{A} \to \mathcal{P}(\mathcal{B}) \) and \( \mathcal{B}^{\text{opp}} \to \mathcal{P}(\mathcal{A}^{\text{opp}}) \) and

- \( \mathcal{A} \)-perfect if and only if \( M \otimes_B (-) \) restricts to a functor \( \mathcal{P}^{\text{perf}}(\mathcal{B}^{\text{opp}}) \to \mathcal{P}^{\text{perf}}(\mathcal{A}^{\text{opp}}) \) and
- \( \mathcal{B} \)-perfect if and only if \( (-) \otimes_A M \) restricts to a functor \( \mathcal{P}^{\text{perf}}(\mathcal{A}) \to \mathcal{P}^{\text{perf}}(\mathcal{B}) \).

2.2. Duals and adjoints. As before, let \( \mathcal{A} \) be a DG-category. Define the diagonal \( \mathcal{A}-\mathcal{A} \) bimodule \( \mathcal{A} \) by setting \( a \mathcal{A}_b = \text{Hom}_A(b, a) \) for any \( a, b \in \mathcal{A} \). Then \( a \mathcal{A} \) and \( \mathcal{A} a \) are precisely the representable modules \( \text{Hom}_A(-, a) \) and \( \text{Hom}_A(a, -) \) in \( \text{Mod } \mathcal{A} \) and \( \text{Mod } \mathcal{A}^{\text{opp}} \). This coincides with the notation introduced in Section 2.1.

The diagonal bimodule corresponds to the functor \( \mathcal{A} \to \text{Mod } \mathcal{A} \) which sends \( a \mapsto a \mathcal{A} \). We have natural functorial isomorphisms

\[ \text{Hom}_A(\mathcal{A}, -) \cong \text{Id}_{\text{Mod } \mathcal{A}} \cong (-) \otimes_A \mathcal{A} \]

\[(2.8)\]
given for any \( \mathcal{A} \)-module \( M \) explicitly by

\[ M \to M \otimes_A \mathcal{A}: \quad s \mapsto s \otimes \text{Id}_a \quad \forall a \in \mathcal{A}, s \in M_a \]

\[ M \otimes_A \mathcal{A} \to M : \quad s \otimes a \mapsto s a \quad \forall a, b \in \mathcal{A}, s \in M_b, a \in \mathcal{A}_b \]

\[ M \to \text{Hom}_A(\mathcal{A}, M) : \quad s \mapsto (\alpha \mapsto s \alpha) \quad \forall b \in \mathcal{A}, \alpha \in a \mathcal{A}_b \]

\[ \text{Hom}_A(\mathcal{A}, M) \to M : \quad \alpha \mapsto \alpha(\text{Id}_a) \quad a \in \mathcal{A}, \alpha \in \text{Hom}_A(a \mathcal{A}, M) . \]

We use these isomorphisms implicitly throughout the paper.

On the other hand, \( \text{Hom}_A(-, \mathcal{A}) \) is the dualizing functor

\[ (-)^\mathcal{A}: \text{Mod } \mathcal{A}^{\text{opp}} \to \text{Mod } \mathcal{A}^{\text{opp}}. \]

\(^1\)If it is not, one should take cofibrant replacements of \( \mathcal{A} \) and \( \mathcal{B} \) \([\text{To"e}07a, \text{Prop 3.3}]\).
Explicitly, for any \( C \in \text{Mod} \cdot \mathcal{A} \) its dual module \( C^A \) is the \( \mathcal{A}^{\text{opp}} \)-module \( a \mapsto \text{Hom}_A(C, a) \). For any morphism \( C \xrightarrow{\alpha} D \) in \( \text{Mod} \cdot \mathcal{A} \) the dual morphism \( \alpha^A \) is defined with a sign twist: for each \( a \in \mathcal{A} \) define the requisite morphism \( \text{Hom}_A(D, a) \to \text{Hom}_A(C, a) \) by
\[
\beta \mapsto (-1)^{\deg(\beta) \cdot \deg(a)} \beta \circ \alpha.
\]

Tautologically, \((-)^A\) restricts to \( \text{Id} \) on the Yoneda embedded subcategories \( \mathcal{A}^{\text{opp}} \hookrightarrow (\text{Mod} \cdot \mathcal{A})^{\text{opp}} \) and \( \mathcal{A}^{\text{opp}} \hookrightarrow \text{Mod} \cdot \mathcal{A}^{\text{opp}} \). Therefore it induces an equivalence
\[
\mathcal{S} \mathcal{F}_{\alpha}(\mathcal{A})^{\text{opp}} \cong \mathcal{S} \mathcal{F}_{\alpha}(\mathcal{A}^{\text{opp}})
\]
and a quasi-equivalence
\[
\mathcal{P}^{\text{ret}}(\mathcal{A})^{\text{opp}} \to \mathcal{P}^{\text{ret}}(\mathcal{A}^{\text{opp}}),
\]
whose induced maps on morphism complexes are homotopy equivalences. By abuse of notation, we also use \((-)^{A} \) to refer to the dualizing functor for \( \mathcal{A}^{\text{opp}} \). The double dualizing functor \((-)^{A^A} \colon \text{Mod} \cdot \mathcal{A} \to \text{Mod} \cdot \mathcal{A} \) is isomorphic to the identity on \( \mathcal{S} \mathcal{F}_{\alpha}(\mathcal{A}) \) and homotopic to the identity on \( \mathcal{P}^{\text{ret}}(\mathcal{A}) \). An analogous claim holds for \((-)^{A^A} \colon \text{Mod} \cdot \mathcal{A}^{\text{opp}} \to \text{Mod} \cdot \mathcal{A}^{\text{opp}} \).

Let \( C \in \text{Mod} \cdot \mathcal{B} \), \( D \in \text{Mod} \cdot \mathcal{A} \) and let \( M \) be an \( \mathcal{A} \cdot \mathcal{B} \)-bimodule. There is a natural map of DG \( k \)-modules
\[
D \otimes_{\mathcal{A}} \text{Hom}_B(C, M) \to \text{Hom}_B(C, D \otimes_{\mathcal{A}} M)
\]
defined by setting for any \( a \in \mathcal{A} \)
\[
s \otimes \gamma \mapsto (\forall t \in C, \ t \mapsto s \otimes \gamma(t)) \quad s \in D_a, \gamma \in \text{Hom}_B(C, a) \).
\]
This map is clearly an isomorphism when either \( C \) or \( D \) are representable. It follows that it is an isomorphism when either \( C \) or \( D \) lie in \( \mathcal{S} \mathcal{F}_{\alpha}(\mathcal{A}) \) and a homotopy equivalence when either \( C \) or \( D \) lie in \( \mathcal{P}^{\text{ret}}(\mathcal{A}) \).

If in (2.9) we set \( B = \mathcal{A} \) and let \( M \) be the diagonal bimodule \( \mathcal{A} \) we obtain the evaluation map
\[
D \otimes_{\mathcal{A}} C^A \to \text{Hom}_{\mathcal{A}}(C, D).
\]

It is the same map of DG \( k \)-modules as the composition map
\[
\text{Hom}_{\mathcal{A}}(A, D) \otimes_{\mathcal{A}} \text{Hom}_{\mathcal{A}}(C, \mathcal{A}) \to \text{Hom}_{\mathcal{A}}(C, D).
\]
Let \( M \) be an \( \mathcal{A} \cdot \mathcal{B} \) bimodule. We define \( M^A \), the dual of \( M \) with respect to \( \mathcal{A} \), to be the \( \mathcal{B} \cdot \mathcal{A} \)-bimodule \( \text{Hom}_{\mathcal{A}^{\text{opp}}}(M, \mathcal{A}) \). In other words, \( M^A \) corresponds to the functor \( \mathcal{B} \to \text{Mod} \cdot \mathcal{A} \) which maps \( b \mapsto (M_b)^A \). Similarly, we define \( M^B \), the dual of \( M \) with respect to \( \mathcal{B} \), to be the \( \mathcal{A} \cdot \mathcal{B} \)-bimodule \( \text{Hom}_{\mathcal{B}}(M, \mathcal{B}) \), which corresponds to the functor \( \mathcal{A}^{\text{opp}} \to \text{Mod} \cdot \mathcal{B}^{\text{opp}} \) which maps \( a \mapsto (aM)^B \).

For any DG-category \( \mathcal{C} \) the adjunction co-unit
\[
\text{Hom}_B(M, -) \otimes_{\mathcal{A}} M \to \text{Id}
\]
is the morphism of functors \( \text{Mod} \cdot \mathcal{C} \cdot \mathcal{B} \to \text{Mod} \cdot \mathcal{C} \cdot \mathcal{B} \) given by the composition map
\[
\text{Hom}_B(M, -) \otimes_{\mathcal{A}} \text{Hom}_B(B, M) \to \text{Hom}_B(B, -).
\]
If we set \( \mathcal{C} = \mathcal{B} \) and evaluate this co-unit at the diagonal bimodule \( \mathcal{B} \) we obtain the trace map
\[
M^B \otimes_{\mathcal{A}} M \to \mathcal{B}.
\]
We define the trace map \( M \otimes_{\mathcal{A}} M^A \to \mathcal{A} \) similarly.

On the other hand, the adjunction unit
\[
\text{Id} \to \text{Hom}_B(M, (-) \otimes_{\mathcal{A}} M)
\]
is a morphism of functors \( \text{Mod} \cdot \mathcal{C} \cdot \mathcal{A} \to \text{Mod} \cdot \mathcal{C} \cdot \mathcal{A} \). Explicitly, it is defined by
\[
s \mapsto (\forall t \in _a M, \ t \mapsto s \otimes t) \quad \forall c \in \mathcal{C}, a \in \mathcal{A}, \ s \in _a (-)_a.
\]
Setting \( \mathcal{C} = \mathcal{A} \) and evaluating at the diagonal bimodule \( \mathcal{A} \), we obtain the \( \mathcal{A} \)-action map
\[
\mathcal{A} \xrightarrow{\text{act}} \text{Hom}_B(M, M).
\]
Explicitly, it is the map of \( \mathcal{A} \)-bimodules given by the action of \( \mathcal{A} \) on \( M \):
\[
aA_b = \text{Hom}_A(b, a) \to \text{Hom}_B(aM, bM).
\]
We define the \( \mathcal{B} \)-action map \( \mathcal{B} \xrightarrow{\text{act}} \text{Hom}_{\mathcal{A}^{\text{opp}}}(M, M) \) similarly.

The evaluation map (2.10) induces a morphism of functors \( \text{Mod} \cdot \mathcal{B} \to \text{Mod} \cdot \mathcal{A} \)
\[
(-) \otimes_{\mathcal{B}} M^B \to \text{Hom}_B(M, -)
\]
It follows from the above that for any $M$ the map \((2.15)\) is an isomorphism on all of $\mathcal{S}_{\mathcal{F}_{\mathcal{B}}(\mathcal{B})}$ and a homotopy equivalence on all of $\mathcal{P}_{\mathcal{F}_{\mathcal{B}}(\mathcal{B})}$. On the other hand, if $M$ is $\mathcal{B}$-h-projective and $\mathcal{B}$-perfect, then all $\mathcal{A}$-$\mathcal{M}$ lie in $\mathcal{P}_{\mathcal{F}_{\mathcal{B}}(\mathcal{B})}$ and so \((2.15)\) is a homotopy equivalence on all of $\textbf{Mod}-\mathcal{B}$. In particular, the induced map
\[
M \otimes_{\mathcal{B}} M^B \to \text{Hom}_B(M,M)
\] (2.16)
of $\mathcal{A}$-$\mathcal{A}$-bimodules is a homotopy equivalence for any $\mathcal{B}$-h-projective, $\mathcal{B}$-perfect $M$. Similarly for
\[
M^A \otimes_{\mathcal{A}} (-) \to \text{Hom}_{\mathcal{A}^{opp}}(M,-)
\] (2.17)
and the induced map
\[
M^A \otimes_{\mathcal{A}} M \to \text{Hom}_{\mathcal{A}^{opp}}(M,M).
\] (2.18)
We say that a map $\mathcal{A} \to M \otimes_{\mathcal{B}} M^B$ is an $\mathcal{A}$-action map if it is a composition of $\mathcal{A} \xrightarrow{\text{act}} \text{Hom}_B(M,M)$ with any homotopy inverse of \((2.16)\). Similarly for $\mathcal{B}$-action maps $\mathcal{B} \to M^A \otimes_{\mathcal{A}} M$.

Finally, the right adjoint of $M \otimes_{\mathcal{B}} M^A \xrightarrow{\text{act}} \mathcal{A}$ with respect to $(-) \otimes_{\mathcal{B}} M^A$ is the map
\[
M \to M^{\text{opp}}A.
\] (2.19)
It is easy to see that if all $M_k$ are representable $\mathcal{A}^{opp}$-modules, then this map is an isomorphism. It follows that the induced morphism $\text{Id} \to (-)^{\text{opp}}A$ of functors $\textbf{Mod} \cdot \mathcal{A} \cdot \mathcal{B} \to \textbf{Mod} \cdot \mathcal{A} \cdot \mathcal{B}$ is a homotopy equivalence on any $\mathcal{A}$-h-projective $\mathcal{A}$-perfect bimodule. We define a map $M \to M^{\text{opp}}B$ similarly.

**Proposition 2.1.** Let $\mathcal{A}$ and $\mathcal{B}$ be DG-categories and $M \in \text{Mod} \cdot \mathcal{A} \cdot \mathcal{B}$.

If $M$ is $\mathcal{B}$-h-projective and $\mathcal{B}$-perfect the compositions
\[
M^B \xrightarrow{\text{Id} \otimes \text{act}} M^B \otimes_{\mathcal{A}} M \otimes_{\mathcal{B}} M^B \xrightarrow{\text{tr} \otimes \text{Id}} M^B
\] (2.20)
\[
M \xrightarrow{\text{act} \otimes \text{Id}} M \otimes_{\mathcal{B}} M^B \otimes_{\mathcal{A}} M \xrightarrow{\text{Id} \otimes \text{tr}} M
\] (2.21)
are homotopic to the identity map for any choice of $\mathcal{A} \xrightarrow{\text{act}} M \otimes_{\mathcal{B}} M^B$.

If $M$ is $\mathcal{A}$-h-projective and $\mathcal{A}$-perfect the compositions
\[
M^A \xrightarrow{\text{act} \otimes \text{Id}} M^A \otimes_{\mathcal{A}} M \otimes_{\mathcal{B}} M^A \xrightarrow{\text{tr} \otimes \text{Id}} M^A
\] (2.22)
\[
M \xrightarrow{\text{act} \otimes \text{Id}} M \otimes_{\mathcal{B}} M^A \otimes_{\mathcal{A}} M \xrightarrow{\text{tr} \otimes \text{Id}} M
\] (2.23)
are homotopic to the identity map for any choice of $\mathcal{B} \xrightarrow{\text{act}} M^A \otimes_{\mathcal{A}} M$.

**Proof.** We only prove that if $M$ is $\mathcal{B}$-h-projective and $\mathcal{B}$-perfect, then \((2.20)\) is homotopic to the identity map. The other three assertions are proved similarly.

So let $M$ be $\mathcal{B}$-h-projective and $\mathcal{B}$-perfect, let $\xi$ be a homotopy inverse of $M \otimes_{\mathcal{B}} M^B \xrightarrow{\text{ev}} \text{Hom}_B(M,M)$ and let
\[
\mathcal{A} \xrightarrow{\text{act}} \text{Hom}_B(M,M) \xrightarrow{\xi} M \otimes_{\mathcal{B}} M^B
\]
be the corresponding action map.

The isomorphisms \((2.8)\) identify the evaluation map $M \otimes_{\mathcal{B}} M^B \xrightarrow{\text{ev}} B$ with the composition map
\[
\text{Hom}_B(M,M) \otimes_{\mathcal{B}} \text{Hom}_B(M,B) \to \text{Hom}_B(M,M),
\]
let $\xi$ also denote the corresponding homotopy inverse of the latter.

The isomorphisms \((2.8)\) also identify the trace map $M^B \otimes_{\mathcal{A}} M \to B$ with the composition map
\[
\text{Hom}_B(M,B) \otimes_{\mathcal{A}} \text{Hom}_B(M,M) \xrightarrow{\text{comp} \otimes \text{Id}} \text{Hom}_B(B,B)
\]
and the isomorphism $B \otimes_{\mathcal{B}} M^B \xrightarrow{\text{comp}} M^B$ with the composition map
\[
\text{Hom}_B(B,B) \otimes_{\mathcal{B}} \text{Hom}_B(M,B) \xrightarrow{\text{comp}} \text{Hom}_B(M,B).
\]

Thus \((2.20)\) is isomorphic to
\[
\text{Hom}_B(M,B) \xrightarrow{(2.8)} \text{Hom}_B(M,B) \otimes_{\mathcal{A}} \text{Hom}_B(M,M) \xrightarrow{\text{comp} \otimes \text{Id}} \text{Hom}_B(M,B).
\]

By associativity of the composition map this is equal to
\[
\text{Hom}_B(M,B) \xrightarrow{(2.8)} \text{Hom}_B(M,B) \otimes_{\mathcal{A}} \text{Hom}_B(M,M) \xrightarrow{\text{Id} \otimes \text{comp}} \text{Hom}_B(M,B) \otimes_{\mathcal{B}} \text{Hom}_B(M,B) \xrightarrow{\text{comp}} \text{Hom}_B(M,B).
\]
Since
\[ \text{Hom}_B(M, M) \xrightarrow{\zeta} \text{Hom}_B(B, M) \otimes_B \text{Hom}_B(M, B) \xrightarrow{\text{compos}} \text{Hom}_B(M, M) \]
is homotopic to the identity map, it suffices to show that
\[ \text{Hom}_B(M, B) \xrightarrow{(\alpha)} \text{Hom}_B(M, B) \otimes_A A \xrightarrow{\text{Id} \otimes \text{act}} \text{Hom}_B(M, B) \otimes_A \text{Hom}_B(M, M) \xrightarrow{\text{compos}} \text{Hom}_B(M, B). \]
is the identity map. This is a straightforward verification. □

The functors \((-)^A\) and \((-)^B\) from \textbf{Mod-} \textbf{-} \textbf{B}^{\text{op}} \textbf{p} to \textbf{Mod-} \textbf{-} \textbf{A} induce derived functors \((-)^{\hat{A}}\) and \((-)^{\hat{B}}\) from \text{D}(\text{A-} \text{B}) to \text{D}(\text{B-} \text{A}). These can be computed by taking \text{h-projective} resolutions: if \text{M} is \text{A-\text{h-projective}} then \text{M}^{\hat{A}} \simeq (\text{M})^{A} and if \text{M} is \text{B-\text{h-projective}}, then \text{M}^{\hat{B}} \simeq (\text{M})^{B} in \text{D}(\text{B-} \text{A}). The natural maps such as (2.10) all produce natural transformations of the corresponding derived functors. In particular, we define the derived trace maps
\[ M^B \otimes_A M \xrightarrow{\text{tr}} B \]
by replacing \text{M} by any \text{A-} and \text{B-\text{h-projective}} resolution and then applying the corresponding ordinary trace map. Similarly we define the derived action maps
\[ \text{A} \xrightarrow{\text{act}} \text{R Hom}_B(M, M) \]
\[ \text{B} \xrightarrow{\text{act}} \text{R Hom}_A^{\text{op}}(M, M) \]
by taking any \text{B-\text{h-projective}} resolution and any \text{A-\text{h-projective}} resolution of \text{M}, respectively.

We also define a morphism
\[ \text{Id} \rightarrow (-)^{\hat{A}} \]
of functors \text{D}(\text{A-} \text{B}) \rightarrow \text{D}(\text{A-} \text{B}) by taking an \text{A-\text{h-projective}} resolution of \text{M}. It is an isomorphism for any \text{A-\text{perfect}} object of \text{D}(\text{A-} \text{B}). Similarly we define a morphism
\[ \text{Id} \rightarrow (-)^{\hat{B}} \]
which is an isomorphism for any \text{B-\text{perfect}} object of \text{D}(\text{A-} \text{B}).

To see that the definitions above are independent of the choice of the resolution, let \text{N} \xrightarrow{\alpha} \text{M} be any morphism in \textbf{Mod-} \textbf{-} \textbf{B} and consider e.g. the following commutative diagram in \textbf{Mod-} \textbf{-} \textbf{B-} \textbf{B}:
\[ \begin{array}{ccc}
M^B \otimes_A M & \xrightarrow{\text{tr}} & B \\
\text{Id} \otimes \alpha & & \\
M^B \otimes_A N & \xrightarrow{\text{tr}} & B \\
\alpha^B \otimes \text{Id} & & \\
N^B \otimes_A N & & \\
\end{array} \]
Suppose that \text{\alpha} is a quasi-isomorphism. If \text{M} and \text{N} are \text{A-\text{h-projective}} then \text{Id} \otimes \alpha is also a quasi-isomorphism. If \text{M} and \text{N} are \text{B-\text{h-projective}} \text{\alpha}^B is a quasi-isomorphism, and then assuming that \text{M} and \text{N} are also \text{A-\text{h-projective}}, so is \text{\alpha}^B \otimes \text{Id}. Thus if \text{M} and \text{N} are both \text{A-} and \text{B-\text{h-projective}} the trace maps in (2.30) are isomorphic in \text{D}(\text{B-} \text{B}). The other cases are treated similarly.

If \text{M} is \text{B-\text{perfect}}, then the evaluation map (2.16) induces an isomorphism in the derived category and we define the derived action map
\[ \text{A} \xrightarrow{\text{act}} M^L \otimes_B M^\hat{B} \]
to be the composition of (2.26) with the inverse of this isomorphism. We can compute it by taking any \text{B-\text{h-projective}} resolution \hat{M} of \text{M} and \text{any} action map \text{A} \rightarrow \hat{M} \otimes_B M^B. Similarly, for any \text{A-\text{perfect}} \text{M} we define the derived action map
\[ \text{B} \xrightarrow{\text{act}} M^{\hat{A}} \otimes_A M. \]
Proposition 2.1 implies immediately the following two results:
Lemma 2.2. Let \( \mathcal{A} \) and \( \mathcal{B} \) be two small DG-categories. Let \( M \) be an \( \mathcal{A}\mathcal{B} \)-bimodule which is \( \mathcal{A} \)-perfect. Then
\[
(-) \otimes_{\mathcal{A}} M : D(\mathcal{A}) \to D(\mathcal{B})
\]
has a right adjoint
\[
(-) \otimes_{\mathcal{B}} M^\mathcal{B} : D(\mathcal{B}) \to D(\mathcal{A})
\]
whose adjunction unit
\[
\text{Id}_{D(\mathcal{A})} \to (-) \otimes_{\mathcal{A}} M \otimes_{\mathcal{B}} M^\mathcal{B}
\]
is induced by the derived \( \mathcal{A} \)-action map
\[
\mathcal{A} \xrightarrow{\text{act}} M \otimes_{\mathcal{B}} M^\mathcal{B}
\]
and whose adjunction co-unit
\[
(-) \otimes_{\mathcal{B}} M^\mathcal{B} \otimes_{\mathcal{A}} M \to \text{Id}_{D(\mathcal{B})}
\]
is induced by the derived trace map
\[
M^\mathcal{B} \otimes_{\mathcal{A}} M \xrightarrow{\text{tr}} \mathcal{B}.
\]

Lemma 2.3. Let \( \mathcal{A} \) and \( \mathcal{B} \) be two small DG-categories. Let \( M \) be an \( \mathcal{A}\mathcal{B} \)-bimodule which is \( \mathcal{B} \)-perfect. Then
\[
(-) \otimes_{\mathcal{A}} M : D(\mathcal{A}) \to D(\mathcal{B})
\]
has a left adjoint
\[
(-) \otimes_{\mathcal{B}} M^\mathcal{A} : D(\mathcal{B}) \to D(\mathcal{A})
\]
whose adjunction unit
\[
\text{Id} \to (-) \otimes_{\mathcal{B}} M^\mathcal{A} \otimes_{\mathcal{A}} M
\]
is induced by the derived \( \mathcal{B} \)-action map
\[
\mathcal{B} \xrightarrow{\text{act}} M^\mathcal{A} \otimes_{\mathcal{A}} M
\]
and whose adjunction co-unit
\[
(-) \otimes_{\mathcal{A}} M \otimes_{\mathcal{B}} M^\mathcal{A} \to \text{Id}
\]
is induced by the derived trace map
\[
M \otimes_{\mathcal{B}} M^\mathcal{A} \xrightarrow{\text{tr}} \mathcal{A}.
\]

Let now \( \mathcal{A}, \mathcal{B} \) and \( \mathcal{C} \) be DG-categories and \( M \) and \( N \) be \( \mathcal{A}\mathcal{B} \)- and \( \mathcal{B}\mathcal{C} \)-bimodules. Consider the following composition of natural maps of \( \mathcal{C}\mathcal{A} \)-bimodules:
\[
N^\mathcal{C} \otimes_{\mathcal{B}} M^\mathcal{B} \xrightarrow{\text{ev}} \text{Hom}_{\mathcal{B}}(M, N^\mathcal{C}) = \text{Hom}_{\mathcal{B}}(M, \text{Hom}_{\mathcal{B}}(N, \mathcal{C})) \xrightarrow{\text{adj}} \text{Hom}_{\mathcal{B}}(M \otimes_{\mathcal{B}} N, \mathcal{C}) = (M \otimes_{\mathcal{B}} N)^\mathcal{C} \quad (2.33)
\]
The first map is the evaluation map \((2.10)\), it is a quasi-isomorphism if \( M \) is \( \mathcal{B} \)-perfect. The second map is the adjunction isomorphism for \((-) \otimes_{\mathcal{B}} N \) and \( \text{Hom}_{\mathcal{B}}(N, -) \). Similar considerations apply to
\[
N^\mathcal{B} \otimes_{\mathcal{B}} M^\mathcal{A} \xrightarrow{\text{ev}} \text{Hom}_{\mathcal{B}}(N, \text{Hom}_{\mathcal{B}}(M, \mathcal{A})) \xrightarrow{\text{adj}} (M \otimes_{\mathcal{B}} N)^\mathcal{A}. \quad (2.34)
\]
We have therefore established:

Lemma 2.4. Let \( \mathcal{A}, \mathcal{B} \) and \( \mathcal{C} \) be DG-categories. Let \( M \) and \( N \) be \( \mathcal{A}\mathcal{B} \)- and \( \mathcal{B}\mathcal{C} \)-bimodules. If \( M \) is \( \mathcal{B} \)-perfect, then \( (2.33) \) induces an isomorphism in \( D(\mathcal{C}\mathcal{A}) \):
\[
N^\mathcal{C} \otimes_{\mathcal{B}} M^\mathcal{B} \simeq (M \otimes_{\mathcal{B}} N)^\mathcal{C}. \quad (2.35)
\]
If \( N \) is \( \mathcal{B} \)-perfect, then \( (2.34) \) induces an isomorphism in \( D(\mathcal{C}\mathcal{A}) \):
\[
N^\mathcal{B} \otimes_{\mathcal{B}} M^\mathcal{A} \simeq (M \otimes_{\mathcal{B}} N)^\mathcal{A}. \quad (2.36)
\]

More is true:

Lemma 2.5. Let \( \mathcal{A} \) and \( \mathcal{B} \) be DG-categories. Let \( M \) be an \( \mathcal{A} \)- and \( \mathcal{B} \)-perfect and \( \mathcal{A} \)- and \( \mathcal{B} \)-h-projective \( \mathcal{A}\mathcal{B} \)-bimodule. Then \( \mathcal{B} \xrightarrow{\text{act}} M^\mathcal{A} \otimes_{\mathcal{A}} M \) is homotopy equivalent to
\[
(M^\mathcal{B} \otimes_{\mathcal{A}} M \xrightarrow{\text{tr}} \mathcal{B})^{\mathcal{IB}}.
\]
Similarly, \( \mathcal{A} \xrightarrow{\text{act}} M \otimes_{\mathcal{B}} M^\mathcal{B} \) is homotopy equivalent to
\[
(M \otimes_{\mathcal{B}} M^\mathcal{A} \xrightarrow{\text{tr}} \mathcal{A})^{\mathcal{rA}}.
\]
Here by \((-)^{\mathcal{IB}}\) we mean dualising an \( \mathcal{B}\mathcal{B} \)-bimodule as a left \( \mathcal{B} \)-module. Similarly for \((-)^{\mathcal{rA}}, \) etc.
Proof. We only prove the first assertion, the second assertion is proved similarly.

The action map $B \xrightarrow{\text{act}} \Hom_{B^{opp}}(B, B) = B^{B^B}$ is an isomorphism. We have a chain of homotopy equivalences

$$M^A \otimes_A M \xrightarrow{\Id \otimes (2.19)} M^A \otimes_A M^{BB} \xrightarrow{(2.34)} \left(M^B \otimes_A M\right)^{B^B}. \tag{2.37}$$

Since $B \xrightarrow{\text{act}} \Hom_{B^{opp}}(B, B)$ is an isomorphism, it suffices to prove the following diagram to be commutative:

\[
\begin{array}{ccc}
B & \xrightarrow{\text{act}} & \Hom_{A^{opp}}(M, M) \\
\downarrow & & \downarrow \Id \otimes (2.19) \\
\Hom_{A^{opp}}(M, M^{BB}) & \xrightarrow{\text{adjunction}} & \Hom_{B^{opp}}(B, B) \\
& & \xrightarrow{\text{tr}} \Hom_{B^{opp}}(M^B \otimes_A M, B).
\end{array}
\tag{2.38}
\]

It can be readily verified by the reader that both halves of (2.38) compose into the element of $\Hom_{B,B}(B, \Hom_{B^{opp}}(M^B \otimes_A M, B))$ which is adjoint to the trace map $M^B \otimes_A M \xrightarrow{\text{tr}} B$ in $\Hom_{B,B}(M^B \otimes_A M, B)$ under the adjunction of $M^B \otimes_A M \otimes_B (-)$ and $\Hom_{B^{opp}}(M^B \otimes_A M, -)$.

\begin{corollary}
Let $\mathcal{A}$ and $\mathcal{B}$ be DG-categories and $M \in D(\mathcal{A}, \mathcal{B})$ be $\mathcal{A}$- and $\mathcal{B}$-perfect. Then $B \xrightarrow{\text{act}} M^A \otimes_A M$ is isomorphic in $D(\mathcal{B}, \mathcal{B})$ to

$$(M^B \otimes_A M \xrightarrow{\text{tr}} B)^{B^B}.$$

Similarly, $A \xrightarrow{\text{act}} M \otimes_B M^B$ is isomorphic in $D(\mathcal{A}, \mathcal{A})$ to

$$(M \otimes_B M^A \xrightarrow{\text{tr}} A)^{\mathcal{A}}.$$

\end{corollary}

\begin{proof}
Once again, we only prove the first assertion. First, replace $M$ by an $h$-projective resolution. Since $k$ is a field, $M$ is then also $\mathcal{A}$- and $\mathcal{B}$-h-projective. Hence derived trace and action maps for $M$ are computed by ordinary trace and action maps. Moreover, since $B$ and $M^B \otimes_A M$ are both left-$\mathcal{B}$-h-projective, we have

$$\left(M^B \otimes_A M \xrightarrow{\text{tr}} B\right)^{B^B} \simeq \left(M^B \otimes_A M \xrightarrow{\text{tr}} B\right)^{B^B}.$$

The claim now follows from Lemma 2.5.
\end{proof}

\begin{proposition}
Let $\mathcal{A}$, $\mathcal{B}$ and $\mathcal{C}$ be DG-categories. Let $M$ be an $\mathcal{A}$-$\mathcal{B}$-bimodule and $N$ be a $\mathcal{B}$-$\mathcal{C}$-bimodule. If either of the following holds

1. $M$ is $h$-projective and $N$ is a $C$-$h$-projective.
2. $M$ is $A$-$h$-projective and $N$ is $h$-projective.

then $M \otimes_B N$ is an $h$-projective $\mathcal{A}$-$\mathcal{C}$-bimodule.

\end{proposition}

\begin{proof}
Suppose $M$ is $h$-projective and $N$ is $C$-$h$-projective and let $Q$ be any acyclic $\mathcal{A}$-$\mathcal{C}$-bimodule. By the adjunction of $(-) \otimes_B N$ and $\Hom_{\mathcal{C}}(N, -)$ done over $\mathcal{A}$ we have a natural isomorphism

$$\Hom_{\mathcal{A},\mathcal{C}}(M \otimes_B N, Q) \simeq \Hom_{\mathcal{A},\mathcal{B}}(M, \Hom_{\mathcal{C}}(N, Q)).$$

For any $a \in \mathcal{A}$ and $b \in \mathcal{B}$, $a N$ and $Q_a$ are an $h$-projective and an acyclic $\mathcal{C}$-modules. It follows that $\Hom_{\mathcal{C}}(N, Q)$ is an acyclic $\mathcal{A}$-$\mathcal{B}$-bimodule, and hence $\Hom_{\mathcal{A},\mathcal{B}}(M, \Hom_{\mathcal{C}}(N, Q))$ is acyclic. We have now shown $\Hom_{\mathcal{A},\mathcal{C}}(M \otimes_B N, Q)$ to be acyclic for any acyclic $Q$, whereby $M \otimes_B N$ is an $h$-projective $\mathcal{A}$-$\mathcal{C}$-bimodule.

The case of $M$ being $A$-$h$-projective and $N$ being $h$-projective is treated similarly.
\end{proof}

\begin{proposition}
Let $\mathcal{A}$, $\mathcal{B}$ and $\mathcal{C}$ be DG-categories. Let $M$ be a perfect $\mathcal{A}$-$\mathcal{B}$-bimodule and $N$ be a $\mathcal{C}$-perfect $\mathcal{B}$-$\mathcal{C}$-bimodule. Then $M \otimes_B N$ is a perfect $\mathcal{A}$-$\mathcal{C}$-bimodule.

\end{proposition}
Definition 3.1. Let $\bigoplus Q_i$ be an infinite direct sum of $A$-$C$-bimodules. We have a chain of natural isomorphisms:

$$
\Hom_{D(A,C)} \left( M \underset{B}{\otimes} N, \bigoplus Q_i \right) \simeq \Hom_{D(A,B)} \left( M, R \Hom_C \left( N, \bigoplus Q_i \right) \right) 
$$

(2.39)

$$
\Hom_{D(A,B)} \left( M, R \Hom_C \left( N, \bigoplus Q_i \right) \right) \simeq \Hom_{D(A,B)} \left( M, \bigoplus \Hom_{D(A,B)} \left( M, R \Hom_C \left( N, Q_i \right) \right) \right) 
$$

(2.40)

$$
\bigoplus \Hom_{D(A,B)} \left( M, R \Hom_C \left( N, Q_i \right) \right) \simeq \bigoplus \Hom_{D(A,C)} \left( M \underset{B}{\otimes} N, Q_i \right). 
$$

(2.41)

The isomorphisms (2.39) and (2.42) are due to the adjunction of $(\cdot) \otimes_B N$ and $R \Hom_C(N, \cdot)$ done over $A$.

(2.40) is due to $N$ being $C$-perfect and (2.41) is due to $M$ being perfect.

Thus $\Hom_{D(A,C)} \left( M \underset{B}{\otimes} N, - \right)$ commutes with infinite direct sums, i.e. $M \underset{B}{\otimes} N$ is perfect.

Recall that a DG-category $A$ is called smooth if the diagonal bimodule $A$ is a perfect $A$-$A$-bimodule.

Corollary 2.9. Let $A$ be a smooth DG category and $B$ be any DG-category. Then any $B$-perfect $A$-$B$-bimodule $N$ is perfect.

Proof. By definition, $A$ being smooth means that $A$ is a perfect $A$-$A$-bimodule. We then apply Lemma 2.8 to conclude that $N = A \otimes_A N$ is perfect.

3. Twisted complexes and twisted cubes

3.1. Twisted complexes. The notion of a twisted complex was introduced in [BK90]. There exist at present two different conventions for writing down twisted complexes: the original one introduced in [BK90] and a slightly different one introduced in [BLL04] where all the objects in a twisted complex are shifted so as to ensure that all the twisted maps have degree 1. Abstractly, this latter convention is more natural as these shifts are precisely what one has to do when taking the convolution of a twisted complex.

However, all the twisted complexes we work with in this paper are lifts of genuine complexes in the homotopy category, and hence they exist naturally in the convention of [BK90]. For this reason we are going to present the material in this section, such as the formulas for dualizing and tensoring twisted complexes, in the notation of [BK90]. The authors are well aware that the signs in these formulas are much simpler in the notation of [BLL04]. However, to actually apply any formula in [BLL04] convention to the twisted complexes we work with throughout the paper, we’d first have to shift everything to make all the twisted maps have degree 1, then apply the formula, and then shift everything back to relate the answer to what we are working with. This would introduce back all the complicated signs, and it is therefore better to write down the formulas in [BK90] convention from the start.

The definitions in the published version of [BK90] contain sign errors. For reader’s convenience we give below the corrected versions of these definitions:

Definition 3.1. Let $A$ be a DG-category. A twisted complex over $A$ is a collection

$$
\{ (E_i)_{i \in \mathbb{Z}}, \alpha_{ij} : E_i \to E_j \}
$$

where $E_i$ are objects in $A$ with $E_i = 0$ for all but finite number of $i$, and $\alpha_{ij}$ are morphisms in $A$ of degree $i - j + 1$ satisfying the condition

$$
(-1)^j \partial \alpha_{ij} + \sum_k \alpha_{kj} \circ \alpha_{ik} = 0.
$$

A twisted complex is called one-sided if $\alpha_{ij} = 0$ for all $i \geq j$.

We adopt the following convention: to write down a twisted complex we write down two expressions separated by a comma. First expression is the $i$-th graded part of the twisted complex. The second expression is the twisted map from $i$th to $j$th graded parts of the twisted complex. E.g. $(E_i, \alpha_{ij})$ is a twisted complex whose $i$-th graded part is $E_i$ and whose twisted map from $E_i$ to $E_j$ is $\alpha_{ij}$.

To make twisted complexes over $A$ into a DG-category we define the Hom-complex from a twisted complex $(E_i, \alpha_{ij})$ to a twisted complex $(F_i, \beta_{ij})$ to be the complex of $k$-modules whose degree $p$ part is

$$
\prod_{p = q+1-k} \Hom^p_A(E_k, F_l)
$$
with the differential defined by setting, for each \( \gamma \in \text{Hom}^q_A(E_k, F_l) \),
\[
d\gamma = (-1)^{d_A} \gamma + \sum_{m \in \mathbb{Z}} (\beta_{tm} \circ \gamma - (-1)^{q+l-k} \gamma \circ \alpha_{mk}),
\]
where \( d_A \) is the differential on morphisms in \( A \).

The signs and indices in the definitions above are set up precisely so as to ensure that the following notion of convolution extends naturally to a fully faithful functor from the DG-category of twisted complexes over \( A \) to the DG-category \( \text{Mod} \cdot A \). But first we need to define the notion of a shift of an \( A \)-module. We do it levelwise in \( C(k) \) and, since we are dealing with right modules, we do not twist the \( A \)-action, that is:

**Definition 3.2.** Let \( M \) be an \( A \)-module. For any \( n \in \mathbb{Z} \) define the \( A \)-module \( M[n] \) by setting
\[
(M[n])_a = M_a[n] \quad \forall a \in A
\]
and having \( A \) act via its action on \( M \). That is, for any \( \alpha \in aA_b \) and any \( s \in (M[n])_a \) we set \( s \cdot M[n] \alpha \in (M[n])_b \) to be \( s \cdot M \alpha \).

**Definition 3.3.** Let \( A \) be a DG-category and let \( (E_i, \alpha_{ij}) \) be a twisted complex over \( A \). Let \( \bigoplus_i E_i[-i] \) be the \( A \)-module where we use the Yoneda embedding to embed each \( E_i \) into \( \text{Mod} \cdot A \). The convolution of \( (E_i, \alpha_{ij}) \) is the \( A \)-module obtained by taking \( \bigoplus_i E_i[-i] \) and endowing it with a new differential \( d + \sum_{i,j} \alpha_{ij} \), where \( d \) is the natural differential of \( \bigoplus_i E_i[-i] \).

We use curly brackets to denote taking the convolution of the twisted complex, e.g. \( \{E_i, \alpha_{ij}\} \).

The most time-consuming part of proving the next two results is in getting the signs to agree. Recall, once more, that we follow the sign conventions laid out in [Kel06, §2].

**Lemma 3.4.** Let \( A, B \) and \( C \) be DG-categories. Let \((E_i, \alpha_{ij})\) and \((F_i, \beta_{ij})\) be twisted complexes of \( A \cdot B \) and \( B \cdot C \) bimodules, respectively. Then
\[
\{E_i, \alpha_{ij}\} \otimes_B \{F_i, \beta_{ij}\} \simeq \bigoplus_{k+i=l} E_k \otimes_B F_l, \sum_{l+m=j} (-1)^{(k-m+1)} \alpha_{km} \otimes \text{Id}_l + \sum_{k+n=j} (-1)^k \text{Id}_k \otimes \beta_{ln}. \tag{3.1}
\]

**Proof.** A straightforward verification. We only outline the main point. The \( A \cdot C \)-bimodules on the two sides of (3.1) have a similar description. Each sends any \((a, c) \in A^{\text{opp}} \otimes C\) to the quotient of a complex of \( k \)-modules whose degree \( n \) part is
\[
\bigoplus_{b \in B, k_1+k_2+l_1+l_2=n} (a(E_{k_1})_b)_{k_2} \otimes_k (b(F_{l_1})_c)_{l_2}
\]
by \( B \)-action relations as per (2.1).

What differs on the left and on the right hand side of (3.1) are the differentials in the above complex of \( k \)-modules and the \( A \)-action relations which we have to factor out. Both of these differ by a sign only and are identified by multiplying each term \((a(E_{k_1})_b)_{k_2} \otimes_k (b(F_{l_1})_c)_{l_2}\) by \((-1)^{k_1l_1}\).

**Lemma 3.5.** Let \( A \) and \( B \) be DG-categories and let \((E_i, \alpha_{ij})\) be a twisted complex of \( A \cdot B \)-bimodules. Let \( E \) be its convolution \( \{E_i, \alpha_{ij}\} \).

1. Then
\[
E^B \simeq \{E_{-l}^B, (-1)^{2+l+j+1} \alpha_{E_{-l}^B}^B \}_{l} \tag{3.2}
\]
\[
E^A \simeq \{E_{-l}^A, (-1)^{2+l+j+1} \alpha_{E_{-l}^A}^A \}_{l} \tag{3.3}
\]
in \( \text{Mod} \cdot A \cdot B \).

2. The \( A \)-trace map \( E \otimes_B E^A \to A \) is isomorphic to the image in \( \text{Mod} \cdot A \cdot A \) of the following map of twisted complexes
\[
\left( \bigoplus_{k-i=l} E_k \otimes_A E^A_l, \sum_{m-l=j} (-1)^{(l-j)} \alpha_{km} \otimes \text{Id} + \sum_{k-n=j} (-1)^{k+n^2+n+1} \text{Id} \otimes \alpha_n \right) \to A \tag{3.4}
\]
which consists of a single map of degree 0
\[
\bigoplus_k E_k \otimes_A E^A_k \to A \tag{3.5}
\]
which is the sum of the trace maps.
Now let each $E_i$ be $B$-perfect and $B$-h-projective and fix a choice of action maps $A \xrightarrow{\alpha} E_i \otimes B E_i^B$. Then the image in $\text{Mod} \cdot A \cdot A$ of the map of twisted complexes

$$A \to \left( \bigoplus_{k-l=i} E_k \otimes_B E_k^B, \sum_{m-t=j} (-1)^{(k-m+1)} \alpha_{km} \otimes \text{Id} + \sum_{k-n=j} (-1)^{k+n^2+nl+1} \text{Id} \otimes \alpha_{nl}^B \right)$$

which consists of a single map of degree 0

$$A \xrightarrow{\sum \alpha} \bigoplus_k E_k \otimes B E_k^B$$

is isomorphic to an $A$-action map $A \xrightarrow{\text{act}} E \otimes_B E^B$.

Analogous statements hold also for $B$-trace and $A$-action maps.

Proof. (1):

We only prove the first assertion - the second one is proved identically. We first observe that on the level of underlying graded $A$-$B$-bimodules, i.e. forgetting the differentials, the left hand side of (3.2) is isomorphic to

$$\text{Hom}_B \left( \bigoplus_i E_i[-i], B \right),$$

while the right hand side is isomorphic to

$$\bigoplus_i \text{Hom}_B(E_i, B)[i].$$

Since all but finite number of $E_i$ are zero all the direct sums above are finite. Therefore the obvious natural map from the latter bimodule to the former is an isomorphism of graded $A$-$B$-bimodules.

This map itself doesn’t respect the differentials and hence doesn’t extend to an isomorphism of DG $A$-$B$-bimodules. However, one can check that it can be made to respect the differentials by composing it with an automorphism of $\bigoplus_i \text{Hom}_B(E_i, B)[i]$ which multiplies each $\text{Hom}_B^k(E_i, B)$ by $(-1)^{(k-1)}$.

(2):

For the $A$-trace map claim, the isomorphisms (3.3) and (3.1) compose to give an isomorphism from $E \otimes_B E^A$ to the convolution of the left hand side of (3.4). It remains only to check that its composition with the image of (3.6) in $\text{Mod} \cdot A \cdot A$ is precisely the trace map $E \otimes_B E^A \xrightarrow{\text{tr}} A$. This is a straightforward verification. Moreover, since when checking that two maps are equal we only care about the underlying graded $\text{Mod} \cdot A \cdot A$-modules, the verification boils down to checking that the trace map of a finite direct sum of graded modules equals the sum of the trace maps for each individual module.

Similarly, for the $A$-action map, we are reduced to checking that the canonical action map $A \to \text{Hom}_B(E, E)$ is compatible with finite direct sums and that the evaluation map $E \otimes_B E^B \to \text{Hom}_B(E, E)$ is also compatible with finite direct sums.

3.2. Pre-triangulated categories. Let $A$ and $B$ be two DG-categories. A functor $A \xrightarrow{f} B$ is a quasi-equivalence if $f$ induces quasi-isomorphisms on morphism complexes and if $H^0(A) \xrightarrow{H^0(f)} H^0(B)$ is an equivalence of categories.

A DG-category $A$ is pretriangulated if $H^0(A)$ is a triangulated subcategory of $H^0(\text{Mod} \cdot A)$ under Yoneda embedding. The pretriangulated hull $\text{Pre-Tr}(A)$ of $A$ is the category of one-sided twisted complexes in $A$, these are the twisted complexes $(E_i, q_{ij})$ where $q_{ij} = 0$ if $i \leq j$. The convolution functor gives a fully faithful embedding $\text{Pre-Tr}(A) \hookrightarrow \text{Mod} \cdot A$ whose composition with $A \to \text{Pre-Tr}(A)$ is the Yoneda embedding and whose image in $\text{Mod} \cdot A$ is equivalent to $\mathcal{SF}_{fg}(A)$ [Dri04, §2.4]. Hence $H^0(\text{Pre-Tr}(A))$ coincides with the triangulated hull of $H^0(A)$ in $H^0(\text{Mod} \cdot A)$. Therefore $A$ is pretriangulated if and only if the natural embedding $A \to \text{Pre-Tr}(A)$ is a quasi-equivalence. We say that $A$ is strongly pretriangulated if $A \hookrightarrow \text{Pre-Tr}(A)$ is, in fact, an equivalence. In other words, if it has a quasi-inverse $\text{Pre-Tr}(A) \xrightarrow{f} A$. Note, that in such case the convolution functor filters through the Yoneda embedding, i.e.

$$\text{Pre-Tr}(A) \xrightarrow{T} A \hookrightarrow \text{Mod} \cdot A$$

is the convolution functor. For strongly pre-triangulated categories, by abuse of notation, we mainly use the term convolution functor to mean $T$.

Let $A$ be any DG-category. It is known that $\text{Pre-Tr}(A)$ is strongly pretriangulated [BK90]. Also $\text{Hom}(A, C)$ is strongly pretriangulated for any strongly pretriangulated $C$ since we can define convolutions of twisted
complexes levelwise in $C$. In particular, Mod-$A$ is strongly pretriangulated since $C(k)$ is. Finally, a full subcategory of Mod-$A$ (or any other strongly pretriangulated DG-category) which is itself pretriangulated, e.g. it descends to a triangulated subcategory of $H^0(\text{Mod}-A)$, and closed under homotopy equivalences is strongly pretriangulated. Therefore $\mathcal{P}(A)$ and $\mathcal{P}_{pre}(A)$ are strongly pretriangulated and, for any other DG-category $B$, $\mathcal{P}^A_{pre}(A-B)$ and $\mathcal{P}^B_{pre}(A-B)$ are also strongly pretriangulated. If $A$ itself is pretriangulated, then $\mathcal{P}^q(A)$ and $\mathcal{P}^A_{pre}(A-B)$ are strongly pretriangulated. If, on the other hand, $B$ is pretriangulated, then $\mathcal{P}^B_{pre}(A-B)$ is strongly pretriangulated.

3.3. Twisted cubes. One of the chief technical tools we employ in this paper is a notion of a twisted cube over a pre-triangulated category. This seemingly trivial extension of a notion of a twisted complex has some far-reaching consequences that we exploit. To the authors’ knowledge, the material below is original to this paper.

We employ the following notation: let $I = \{1, \ldots, n\}$ enumerate vertices of an $n$-cube. For $i, j \in I$ with $i = (i_1, \ldots, i_n)$ and $j = (j_1, \ldots, j_n)$ we say that $j > i$ if $j_m \geq i_m$ for all $m$ and $i \neq j$. For any $i \in I$ we denote by $|i|$ its degree $\sum i_m$.

Let $C$ be a pre-triangulated category. A twisted $n$-cube over $C$ is

1. a set of objects $X_i$ of $C$ for each $i \in I$
2. a set $(q_{ij})$ of morphisms $X_i \to X_j$ of degree $|i| - |j| + 1$ in $C$ for each pair $i, j \in I$ with $|i| < |j|$, such that each $q_{ij}$ satisfies the relation

$$(-1)^{|j|}dq_{ij} + \sum_{i < k < j} q_{ik}q_{kj} = 0. \quad (3.9)$$

The total complex $\text{tot}(X_i, q_{ij})$ of a twisted $n$-cube $(X_i, q_{ij})$ is the one-sided twisted complex

$$\bigoplus_{i \in I, |i| = i} \sum_{i < j \in I, |i| = i, |j| = j} q_{ij}$$

over $C$. Its convolution is an object of $C$ which we call the convolution of the twisted cube $(X_i, q_{ij})$.

Lemma 3.6 (The Cube Lemma). Let $X = (X_i, q_{ij})$ be a twisted $n$-cube indexed by $I$ over a pre-triangulated category $C$. Choose $0 \leq m \leq n$ and choose any $m$ indices in $1, \ldots, n$ to define a splitting $I = J \times K$ with $J = \{-1, 0\}^m$, $K = \{-1, 0\}^{n-m}$. Then

1. Fix $k \in K$. Then

$$X_{(i,k)} \in J$$

and $$(\cdot)(-1)^{|k|}q_{(i,k)(j,k)}$$

form a twisted $m$-cube indexed by $J$ over $C$. We denote it by $X^{(k)}$ and call it a “sign-twisted subcube” of $X$, to stress that the morphisms in $X^{(k)}$ and in $X$ differ (possibly) by a sign.

2. Fix $k, l \in K$. For any $0 \leq i < j \leq m$ let

$$p_{ij}^{(k,l)} = \sum_{i \leq j, |i| = i, |j| = j} q_{(i,k)(j,l)}.$$

The collection $(p_{ij}^{(k,l)})_{i,j}$ defines a morphism of twisted complexes

$$\text{tot}(X^{(k)}) \to \text{tot}(X^{(l)})$$

of degree $|k| - |l| + 1$. Denote it by $p^{(k,l)}$.

3. The twisted complexes $\text{tot}(X^{(k)})$ and the morphisms $p^{(k,l)}$ form a twisted $(n-m)$-cube over $\text{Pre-Tr}(C)$ indexed by $K$. Let $Z \in \text{Pre-Tr}(\text{Pre-Tr}(C))$ be its total complex.

4. The (double) convolution of $Z$ is isomorphic in $C$ to the convolution of the original twisted cube $X$. In particular, it is independent of $m$ and of the choice of $I = J \times K$.

Proof. A straightforward verification. \qed
Given a twisted $n$-cube $\bar{X}$ over a pre-triangulated category $C$ its image in $H^0(C)$ is an ordinary $n$-cube shaped diagram $X$ which commutes (up to isomorphism). Roughly, the point of the Cube Lemma is that $X$ can be canonically extended in $H^0(C)$ to an $n$-cube $X'$ of side 2 with the following properties:

- The vertices of $X'$ are the convolutions of the faces of $X$.
- The rows and columns of $X'$ are exact triangles in $H^0(C)$.
- $X'$ commutes (up to isomorphism).

This is best understood by looking at some examples. Let $C$ be a pre-triangulated category.

1. A twisted 0-cube over $C$ is a single object of $C$.
2. A twisted 1-cube over $C$ is a pair of objects $A$ and $B$ of $C$ together with a closed morphism $A \xrightarrow{f_{AB}} B$ of degree 0. Write $a \xrightarrow{f_{ab}} b$ for its image in $H^0(C)$. Here we denote by $a$ and $b$, and $f_{ab}$ the classes of $A$, $B$ and $f_{AB}$ in $H^0(C)$.

There are no non-trivial ways to split this up as a cube of cubes, so the Cube Lemma doesn’t tell us anything new. However, the total complex of this cube is, trivially,

$$A \xrightarrow{f_{AB}} B_{\deg 0}$$

and its convolution fits into a diagram

$$A \xrightarrow{f_{AB}} B \to \left\{ A \xrightarrow{f_{AB}} B \right\} \to A[1] \quad (3.10)$$

in $C$ where the two new morphisms are induced by the canonical morphisms of twisted complexes

$$\left( \begin{array}{c} B_{\deg 0} \\ \Id_B \end{array} \right) \xrightarrow{\Id_B} \left( \begin{array}{c} A \xrightarrow{f_{AB}} B \end{array} \right)_{\deg 0} \quad (3.11)$$

and

$$\left( \begin{array}{c} A \xrightarrow{f_{AB}} B \end{array} \right)_{\deg 0} \xrightarrow{\Id_{A_{\deg -1}}} \left( \begin{array}{c} A \end{array} \right)_{\deg -1} \quad (3.12)$$

Moreover, the image of (3.10) in $H^0(C)$ is precisely the exact triangle

$$a \xrightarrow{f_{ab}} b \to \text{Cone}(f_{ab}) \to$$

which was the original point of [BK90].

Note that we can also complete $A \xrightarrow{f_{AB}} B_{\deg 0}$ to the diagram

$$A \xrightarrow{f_{AB}} B \to \left\{ A \xrightarrow{-f_{AB}} B \right\} \to A[1] \quad (3.14)$$

whose image in $H^0(C)$ is canonically isomorphic to (3.13). The two new morphisms in (3.14) are defined exactly as in (3.11) and (3.12).

Thus, convolving a twisted 1-cube produces an exact triangle in $H^0(C)$. In the language above - the image of a twisted 1-cube in $H^0(C)$ is an ordinary 1-cube and we can canonically complete it to a 1-cube of side 2 whose single row is an exact triangle. It is this, together with repeated application of the Cube Lemma, that produces the desired phenomena for twisted cubes of higher dimension.

3. A twisted 2-cube over $C$ is a diagram

$$A \xrightarrow{f_{AB}} B \xrightarrow{f_{BD}} \quad \xrightarrow{f_{CD}} \quad D$$

$$C \xrightarrow{f_{CD}}$$

of objects and morphisms in $C$, where $f_{AB}$, $f_{AC}$, $f_{BD}$, $f_{CD}$ are closed maps of degree 0 and $f_{AD}$ is a map of degree $-1$ such that

$$-df_{AD} = f_{BD}f_{AB} + f_{CD}f_{AC}. \quad (3.16)$$
The image of (3.15) in $H^0(C)$ is the diagram

$$
\begin{array}{ccc}
 a & \xrightarrow{f_{ab}} & b \\
 \downarrow{f_{ac}} & & \downarrow{f_{bd}} \\
 c & \xrightarrow{f_{cd}} & d
\end{array}
$$

(3.17)

Note that $f_{AD}$, not being necessarily closed, doesn’t apriori define a morphism in $H^0(C)$. However the condition (3.16) on $f_{AD}$ ensures that we have $f_{bd}f_{ab} + f_{cd}f_{ac} = 0$ in $H^0(C)$, i.e. the diagram (3.17) commutes up to the isomorphism $(-1)\text{id}_d$.

The Cube Lemma tells us is that

$$
\begin{array}{ccc}
 A & \xrightarrow{f_{AB}} & B \\
 \downarrow{f_{AC}} & & \downarrow{f_{BD}} \\
 C & \xrightarrow{f_{CD}} & D
\end{array}
$$

are twisted 1-cubes and that maps $(f_{AC}, f_{AD}, f_{BD})$ define a closed morphism $f_{ABCD}$ of degree 0 between their convolutions producing a twisted 1-cube:

$$
\begin{array}{ccc}
 A & \xrightarrow{f_{AB}} & B \\
 \downarrow{f_{AC}} & & \downarrow{f_{BD}} \\
 C & \xrightarrow{f_{CD}} & D
\end{array}
\xrightarrow{f_{ABCD}}
\begin{array}{ccc}
 C & \xrightarrow{f_{CD}} & D \\
 \downarrow{f_{AC}} & & \downarrow{f_{BD}} \\
 A & \xrightarrow{f_{AB}} & B
\end{array}
$$

(3.18)

Using the argument in the above section on twisted 1-cubes we complete (3.17) to

$$
\begin{array}{ccc}
 a & \xrightarrow{f_{ab}} & b \\
 \downarrow{f_{ac}} & & \downarrow{f_{cd}} \\
 c & \xrightarrow{f_{cd}} & d
\end{array}
\xrightarrow{f_{acbd}}
\begin{array}{ccc}
 \text{Cone}(f_{ab}) & & \text{Cone}(f_{cd}) \\
 \downarrow{f_{ac}} & & \downarrow{f_{bd}} \\
 \text{Cone}(f_{ac}) & & \text{Cone}(f_{bd})
\end{array}
$$

(3.19)

We then check that each of the squares (including the third ‘wrap-around’ square) in this diagram commutes (up to an isomorphism). We can do this since we have constructed (3.19) as the image $H^0(C)$ of an explicit diagram of twisted complexes in Pre-Tr$(C)$ and we can check that, in fact, that diagram itself commutes up to an isomorphism.

Similarly, the Cube Lemma tells us is that

$$
\begin{array}{ccc}
 A & \xrightarrow{f_{AC}} & C \\
 \downarrow{f_{AC}} & & \downarrow{f_{BD}} \\
 B & \xrightarrow{f_{BD}} & D
\end{array}
$$

are twisted 1-cubes and that maps $(f_{AB}, f_{AD}, f_{CD})$ define a closed morphism $f_{ACBD}$ of degree 0 between their convolutions producing a twisted 1-cube:

$$
\begin{array}{ccc}
 A & \xrightarrow{f_{AC}} & C \\
 \downarrow{f_{AC}} & & \downarrow{f_{BD}} \\
 B & \xrightarrow{f_{BD}} & D
\end{array}
\xrightarrow{f_{ACBD}}
\begin{array}{ccc}
 C & \xrightarrow{f_{CD}} & D \\
 \downarrow{f_{AC}} & & \downarrow{f_{BD}} \\
 A & \xrightarrow{f_{AB}} & B
\end{array}
$$

(3.20)

We can therefore complete (3.17) to

$$
\begin{array}{ccc}
 a & \xrightarrow{f_{ab}} & b \\
 \downarrow{f_{ac}} & & \downarrow{f_{bd}} \\
 c & \xrightarrow{f_{cd}} & d
\end{array}
\xrightarrow{f_{acbd}}
\begin{array}{ccc}
 \text{Cone}(f_{ac}) & \xrightarrow{f_{acbd}} & \text{Cone}(f_{bd}) \\
 \downarrow{f_{ac}} & & \downarrow{f_{bd}} \\
 \text{Cone}(f_{ac}) & & \text{Cone}(f_{bd})
\end{array}
$$

(3.21)

and check that each of the squares in it commutes.

Finally, the Cube Lemma tells us the the convolutions of the twisted 1-cubes (3.18) and (3.20) are both isomorphic to the convolution $T$ of the original twisted 2-cube (3.15). We can therefore fit
Lemma 3.7 (The Cube Completion Lemma). Let $I = \{ -1,0 \}^n$ and let $X = (X_i, q_{ij})$ be a twisted $n$-cube over $C$ indexed by $I$. There exists a uniquely defined “$n$-cube of side $2^n$” — a diagram $Z = \{ Z_m, r_{mn} \}$ in $C$ indexed by $M = \{ -1,0,1 \}^n$ with the following properties:

1. **Objects of $Z$.** Let $\tilde{m}$ be any vertex of $M$. Define the splitting $I = J \times K$ by choosing for $J$ all the indices where $\tilde{m}$ equals 1. Let $m'$ be the restriction of $\tilde{m}$ to $K$.

   The object $Z_m$ is isomorphic to the convolution of the sign-twisted subcube $Y^{m'}$ of $X$ constructed by the Cube Lemma with respect to the vertex $\tilde{m}$ of $K$. This cube consists of all the objects $X_i$ such that $i$ restricts to $m'$ in $K$ and all the morphisms between these vertices in $X$ multiplied by $(-1)^{|\bar{m}'|}$.

   Since $\tilde{m}$ uniquely determines the twisted cube $Y^{m'}$ we also refer to this cube simply as $Y^m$.

2. **Morphisms of $Z$.** Let $l \to \tilde{m} \to \bar{n}$ be any row of $M$, i.e. for some $k \in \{ 1, \ldots, n \}$ we have

   $$\begin{cases}
   l_i = -1, \quad \tilde{m}_i = 0, \quad \bar{n}_i = 1 & i = k \\
   l_i = \tilde{m}_i = \bar{n}_i & i \neq k
   \end{cases}$$

   Take the sign-twisted subcube $Y^\bar{n}$ of $X$ and split its index set into $J' \times K'$ where we choose for $J'$ all the indices where $\bar{l}$ and $\tilde{m}$ equal 1 and for $K'$ the single remaining index $k$. Apply the Cube Lemma to $Y^\bar{n}$ with respect to this splitting to construct the twisted 1-cube

   $$\{ Y_{i'}^l \} \overset{\alpha}{\to} \{ Y_m \}_{deg.0}$$

   whose convolution is $\{ Y^n \}$.

   Then

   $$Z_l \overset{r_{lm}}{\to} Z_m \overset{r_{mn}}{\to} Z_{\bar{n}} \overset{r_{n1}}{\to} Z_l[1]$$

   is the image in $C$ of the diagram

   $$Y^l_i \overset{\alpha}{\to} Y^\bar{m} \to \left( Y^l_i \overset{\alpha}{\to} Y^n \right) \to Y^l_i[1]$$

   constructed as explained in the section on the completion for twisted 1-cubes, cf. (3.10).

3. Any morphism in $Z$ which doesn’t occur in (3.23) for some row $l \to \tilde{m} \to \bar{n}$ of $M$ is 0.

4. **Recursivity.** Let $I = J \times K$ be a splitting as in the Cube Lemma and let $Y$ be the twisted cube of sign-twisted subcubes of $X$ constructed by the Cube Lemma with respect to this splitting. Then the cube $Z_Y$ of side 2 in $C$ defined by $Y$ is naturally a subcube of $Z$.

5. **Commutativity.** The image of the diagram $Z$ in $H^0(C)$ commutes (up to isomorphism).

Proof. The first three properties uniquely define the diagram $Z = \{ Z_m, r_{mn} \}$. The recursivity is a straightforward verification. To prove the commutativity of $Z$ it suffices to prove that every 2-face of $Z$ commutes. This reduces via the recursivity to the case of $X$ being a 2-cube, where it is again a straightforward verification. See the section on the completion for twisted 2-cubes. \qed
4. DG enhancements

4.1. On DG-enhancements of triangulated categories. Let $T$ be a triangulated category. An enhancement of $T$ is a pretriangulated DG-category $A$ and an exact equivalence $H^0(A) \xrightarrow{\sim} T$. Two enhancements $(A,\epsilon)$ and $(A',\epsilon')$ are equivalent if there exists a quasi-equivalence $A \xrightarrow{f} A'$. If we want to use DG-categories as enhancements of triangulated ones, we are led to work in the localisation of DG-Cat, the category of all small DG-categories, by quasi-equivalences. We denote this localisation by $\text{Ho}(\text{DG-Cat})$. For any two small DG-categories $A$ and $B$ denote by $[A, B]$ the set of morphisms between $A$ and $B$ in $\text{Ho}(\text{DG-Cat})$. The elements of $[A, B]$ are called quasi-functors.

Any category quasi-equivalent to a pretriangulated category is itself pretriangulated. We denote the full subcategory of $\text{Ho}(\text{DG-Cat})$ consisting of classes of pretriangulated categories by $\text{Ho}(\text{DG-Cat}')$. We call the elements of $\text{Ho}(\text{DG-Cat}')$ enhanced triangulated categories and think of them as of small triangulated categories with a fixed quasi-equivalence class of DG-enhancements. Similarly, we can think of a quasi-functor between two enhanced triangulated categories as of an exact functor between the triangulated categories and a fixed choice of a certain equivalence class of DG-functors between their enhancements which all descend to this exact functor. In this sense, exact functors and quasi-functors are precisely analogous to morphisms between cohomologies of two complexes and morphisms between their classes in the derived category.

One way to understand the morphism set $[A, B]$ in $\text{Ho}(\text{DG-Cat})$ is via the model category structure on $\text{DG-Cat}$ constructed in [Tab05]. The weak equivalences are the quasi-equivalences, and the fibrations are defined in such a way that every object is fibrant. Therefore, the elements of $[A, B]$ can be identified with the functors from a fixed cofibrant replacement of $A$ into $B$, up to homotopy relation. Moreover, there exists a cofibrant replacement functor $Q\colon \text{DG-Cat} \to \text{DG-Cat}'$ equipped with a natural transformation $Q \to \text{id}$ such that $QA \to A$ is a quasi-equivalence which is an identity on the sets of objects [Toë07a, Prop. 2.3].

The set $[A, B]$ can be naturally endowed with a structure of an element of $\text{Ho}(\text{DG-Cat})$ as follows. The tensor product $\otimes = \otimes_k$ of elements of $\text{DG-Cat}$ can be derived into a bifunctor

$$\otimes: \text{Ho}(\text{DG-Cat}) \times \text{Ho}(\text{DG-Cat}) \to \text{Ho}(\text{DG-Cat})$$

giving a symmetric monoidal structure for $\text{Ho}(\text{DG-Cat})$. We compute $A \otimes B$ as either $QA \otimes B$ or $A \otimes QB$. If $k$ is a field, every small DG-category is $k$-flat and $A \otimes B = A \otimes B$. The monoidal structure defined by $\otimes$ on $\text{Ho}(\text{DG-Cat})$ is closed [Toë07a, §4.2], i.e. for any $A, B \in \text{Ho}(\text{DG-Cat})$ the functor $((-) \otimes A, B]$ is representable by an object of $\text{Ho}(\text{DG-Cat})$, defined up to unique isomorphism. Denoted by $\mathbf{R} \text{Hom}(A, B)$, it is constructed as the class in $\text{Ho}(\text{DG-Cat})$ of $\mathcal{P}^{B\text{-}qr}(QA, B)$ [Toë07a, Thrm 6.1]. These are the $h$-projective $QA, B$-bimodules $M$ where for all $a \in QA$ the $B$-module $\alpha M$ is quasi-isomorphic (and hence homotopic as $\alpha M$ is $h$-projective [Kel94, Lemma 6.1(c)]) to a representable. By [Toë07a, Cor 4.8] the isomorphism classes of $H^0(\mathcal{P}^{B\text{-}qr}(QA, B))$ are in natural bijection with the elements of $[A, B]$. Explicitly, any element of $[A, B]$ can be represented by a functor $QA \to B$. Composing this with the Yoneda embedding $B \to \text{Mod-}B$ defines a $QA, B$-bimodule which is even $B$-representable. Any $h$-projective resolution of it defines the desired isomorphism class in $H^0(\mathcal{P}^{B\text{-}qr}(QA, B))$. Getting from $M \in \mathcal{P}^{B\text{-}qr}(QA, B)$ to the corresponding quasi-functor $f \in [A, B]$ is more subtle, but it is easy to pin down the underlying functor $H^0(A) \to H^0(B)$. Indeed, $M$ defines a functor $QA \to \text{Mod-}B$ which maps every element of $QA$ to something homotopic to a representable element of $\text{Mod-}B$. This defines, up to an isomorphism, the requisite functor $H^0(QA) = H^0(A) \to H^0(B)$. Indeed, this also shows that any morphism between two elements of $H^0(\mathcal{P}^{B\text{-}qr}(QA, B))$ induces a natural transformation between the underlying functors of the corresponding quasi-functors in a way which is compatible with compositions.

In other words, $R\text{Hom}(A, B) = \mathcal{P}^{B\text{-}qr}(QA, B)$ is, in a sense, a DG-enhancement of the set $[A, B]$. Let us therefore enrich $\text{Ho}(\text{DG-Cat})$ to a 2-category by setting the category of morphisms from $A$ to $B$ to be $H^0(\mathbf{R}\text{Hom}(A, B))$. By above, each 1-morphism in $\text{Ho}(\text{DG-Cat})$ corresponds naturally to a quasi-functor from $A$ to $B$. By abuse of notation, we now refer to the elements of $H^0(\mathbf{R}\text{Hom}(A, B))$ also as “quasi-functors”. There is a natural functor

$$\Phi: H^0(\mathbf{R}\text{Hom}(A, B)) \to \text{Fun}(H^0(A), H^0(B))$$

(4.1)

which sends each quasi-functor to its underlying functor. Defining $\Phi$ depends on a choice for each quasi-representable object in $\text{Mod-}B$ of a homotopy to a representable one. A different choice would produce a different functor canonically isomorphic to $\Phi$. We therefore make a particular choice for each $B$ and consider

---

3 If $k$ is a field, then $\mathcal{P}^{B\text{-}qr}(QA, B)$ is quasi-equivalent to $\mathcal{P}^{B\text{-}qr}(A, B)$ and we use the latter instead.
all functors $\Phi$ fixed. Our functors $\Phi$ package up into a 2-functor

$$\Phi: \text{Ho}(\text{DG-Cat}) \rightarrow \text{Cat}$$

(4.2)

into a 2-category $\text{Cat}$ whose objects are small categories, whose 1-morphisms are functors and whose 2-morphisms are natural transformations.

By above, if $A$ and $B$ lie in $\text{Ho}(\text{DG-Cat}_{\text{pretr}}^\text{pretr})$ then so does $R\text{Hom}(A,B)$. Therefore, in the 2-category $\text{Ho}(\text{DG-Cat}_{\text{pretr}}^\text{pretr})$ the morphism categories are themselves enhanced triangulated categories. The 2-functor $\Phi$ sends the triangulated category $H^0(R\text{Hom}(A,B))$ of quasi-functors to the full subcategory in $\text{Fun}(H^0(A,B))$ consisting of exact functors. Moreover, for any morphism of quasi-functors $\Phi$ sends its cone to a functorial cone of the underlying morphism of exact functors. This is exactly the situation we want to be in. This paper adheres to the currently prevalent philosophy that instead of working with triangulated categories $A$ and $B$ and the (non-triangulated) category $\text{ExFun}(A,B)$ of exact functors between them, one should work with enhancements of $A$ and $B$ of $A$ and $B$ in $\text{Ho}(\text{DG-Cat})$ (which are often unique up to isomorphism, cf. [LO10]), the enhanced triangulated category $R\text{Hom}(A,B)$ and the functor $H^0(R\text{Hom}(A,B)) \xrightarrow{\Phi} \text{ExFun}(A,B)$. For years now, this has been practiced implicitly by all who work with Fourier-Mukai kernels of the derived functors between algebraic varieties, cf. Examples 4.2 and 4.3.

4.2. Morita enhancements. The triangulated categories we want to enhance are the derived categories of quasi-coherent sheaves and the bounded derived categories of coherent sheaves of separated schemes of finite type over $k$. All these categories are Karoubi closed. It turns out that the full subcategory of $\text{Ho}(\text{DG-Cat}_{\text{pretr}}^\text{pretr})$ consisting of those enhanced triangulated categories whose underlying triangulated categories are Karoubi closed admits a more natural description.

Define a $\text{DG}$-category $A$ to be $kc$-triangulated if it is pre-triangulated and $H^0(A)$ is Karoubi closed. It follows that $A$ is $kc$-triangulated if and only if the Yoneda embedding $A \hookrightarrow \text{P}^\text{pretr}(A)$ is a quasi-equivalence. Denote by $\text{Ho}(\text{DG-Cat}_{\text{kc}})$ the full subcategory of $\text{Ho}(\text{DG-Cat})$ consisting of $kc$-triangulated categories. The following is explained in detail in [Toë07b, §4.4]. A functor $A \xrightarrow{f} B$ between two $\text{DG}$-categories is a Morita equivalence if the induced functor $f_*: D(B) \rightarrow D(A)$ is an exact equivalence. Equivalently, $A \xrightarrow{f} B$ is a Morita equivalence if the induced functor $f^*: \text{P}^\text{pretr}(A) \rightarrow \text{P}^\text{pretr}(B)$ is a quasi-equivalence. The functor

$$\text{P}^\text{pretr}(-): \text{Ho}(\text{DG-Cat}) \rightarrow \text{Ho}(\text{DG-Cat}_{\text{kc}})$$

is the left adjoint of the natural inclusion $\text{Ho}(\text{DG-Cat}_{\text{kc}}) \hookrightarrow \text{Ho}(\text{DG-Cat})$ [Toë07b, Prop. 6]. It follows that $\text{P}^\text{pretr}(-)$ induces an equivalence $\text{Mrt}(\text{DG-Cat}) \xrightarrow{\sim} \text{Ho}(\text{DG-Cat}_{\text{kc}})$, where $\text{Mrt}(\text{DG-Cat})$ is the localisation of $\text{DG-Cat}$ by Morita equivalences. We use this to identify Morita equivalence classes of small $\text{DG}$ categories with the elements of $\text{Ho}(\text{DG-Cat}_{\text{kc}})$. In other words, when speaking of the class of a small $\text{DG}$-category $A$ in $\text{Ho}(\text{DG-Cat}_{\text{kc}})$ we mean $\text{P}^\text{pretr}(A)$.

We call the morphisms in $\text{Mrt}(\text{DG-Cat})$ Morita quasi-functors. By above Morita quasi-functors $A \rightarrow B$ correspond to the ordinary quasi-functors $\text{P}^\text{pretr}(A) \rightarrow \text{P}^\text{pretr}(B)$. It follows from [Toë07a, Theorem 7.2] that $R\text{Hom}(\text{P}^\text{pretr}(A), \text{P}^\text{pretr}(B))$ is quasi-equivalent to $\text{P}\text{B}^\text{pretr}(A,B)$. This gives a more natural DG-enhancement of the set $\text{Hom}_{\text{Mrt}(\text{DG-Cat})}(A,B)$. In particular, we think of the elements of $\text{B}^\text{pretr}(A,B)$ as of Morita quasi-functors $A \rightarrow B$. Note that given $M \in \text{B}^\text{pretr}(A,B)$, the exact functor underlying the corresponding Morita quasi-functor is $(\xrightarrow{L} \otimes A)_M$.

This leads to a slightly different notion of DG-enhancement. Define a Morita enhancement of a small triangulated category $A$ to be a small $\text{DG}$-category $A$ together with an isomorphism $D_e(A) \xrightarrow{\sim} A$. Since $D_e(A) = H^0(\text{P}^\text{pretr}(A))$, $A$ is a Morita enhancement of $A$ if and only if its class in $\text{Ho}(\text{DG-Cat}_{\text{kc}})$ is the usual enhancement of $A$. Moreover, we can similarly use small $\text{DG}$ categories to enhance non-small triangulated categories (i.e. unbounded derived categories of quasi-coherent sheaves). Define a large Morita enhancement of a triangulated category $A$ to be a small $\text{DG}$-category $A$ together with an isomorphism $D(A) \xrightarrow{\sim} A$. An advantage of this Morita point of view is that we use much smaller $\text{DG}$ categories to define our enhancements. In fact, the derived categories of schemes can be Morita enhanced by $\text{DG}$-algebras, cf. Examples 4.2 and 4.3.

4.3. Examples. The following examples illustrate the notions in introduced in the previous section and explain the framework to which the main definitions of Section 5 rightfully belong. First is the usual framework of DG-enhancements:

---

4Here “kc” stands for “Karoubi closed”. These are simply called “triangulated DG-categories” in papers of Toën, however we feel that it didn’t reflect well their main difference from the established notion of pretriangulated DG categories.
Example 4.1. Let $A$ and $B$ be two elements of $\text{Ho}(\text{DG-Cat})$. As described in Section 4, $R\text{Hom}(A,B)$ is represented in $\text{Ho}(\text{DG-Cat})$ by the full subcategory $P^{B,qr}(A\dashv B)$ of $P(A\dashv B)$ consisting of $B$-quasi-representable bimodules. Such bimodules, in particular are $B$-perfect.

Let $M \in P^{B,qr}(A\dashv B)$. The functor $H^0(A) \to H^0(B)$ defined by the corresponding quasi-functor is the restriction of $(\_) \otimes_A M$ from $D(A) \to D(B)$ to $H^0(A) \to H^0(B)$. It follows from Section 2.2 that if $M$ is also $A$-perfect, then $(\_) \otimes_A M$, as a functor $D(A) \to D(B)$, has left and right adjoints $(\_) \otimes_B M^A$ and $(\_) \otimes_B M^B$. If moreover $M^A$ and $M^B$ are $A$-quasi-representable, then these adjoints restrict to functors $H^0(B) \to H^0(A)$. In other words, $M^A$ and $M^B$ define quasi-functors $B 	o A$ whose induced functors $H^0(B) \to H^0(A)$ are left and right adjoint to the functor $H^0(A) \to H^0(B)$ defined by $M$.

Next we illustrate Morita enhancements. In the two examples below we explain how derived categories of algebraic varieties are Morita enhanced by DG algebras and how the quasi-functors between these enhancements may be represented as DG-bimodules for these algebras:

Example 4.2. Let $X$ and $Y$ be two quasi-compact, separated schemes. By [BvdB03, Theorem 3.1.1] there exist compact generators $E_X$ and $E_Y$ of $D_q(X)$ and $D_q(Y)$. We choose $h$-injective resolutions of $E_X$ and $E_Y$ and define $A$ and $B$ to be their DG-End-algebras. Then $A$ and $B$ are the standard large Morita enhancements of $D_q(X)$ and $D_q(Y)$, i.e. $P(A)$ and $P(B)$ are their standard enhancements in the usual sense.

By [Toë07a, Theorem 7.2] the pullback along the Yoneda embedding $A \to \text{Mod} \dashv A$ induces an isomorphism

$$R\text{Hom}_{cts}(P(A), P(B)) \cong R\text{Hom}(A, P(B))$$

in $\text{Ho}(\text{DG-Cat})$. The universal properties of $R\text{Hom}$ and [Toë07a, Lemma 6.2] imply that $R\text{Hom}(A, P(B))$ is represented in $\text{Ho}(\text{DG-Cat})$ by $P(A\dashv B)$. Explicitly, after replacing $A$ by its cofibrant resolution any quasi-functor in $H^0(R\text{Hom}(A, P(B)))$ can be represented by an actual functor $A \to P(B)$. Taking an $h$-projective resolution of the corresponding $A-B$-bimodule gives the desired homotopy class in $P(A\dashv B)$.

Thus every continuous quasi-functor $P(A) \to P(B)$ can be represented by an element $M \in P(A\dashv B)$. The underlying functor $D_q(X) \to D_q(Y)$ is then precisely $(\_) \otimes_A M$. It follows from Section 2.2 that if $M$ is $A$- and $B$-perfect, then $M^A$ and $M^B$ define quasi-functors $P(B) \to P(A)$ such that $(\_) \otimes_B M^A$ and $(\_) \otimes_B M^B$ are the left and right adjoints of $(\_) \otimes_A M$.

It is also shown in [Toë07a, Section 8.3] that $A^{opp} \otimes B$ is the standard large Morita enhancement of $D(X \times_k Y)$, and the induced identification of $D(X \times_k Y)$ with $D(A\dashv B)$ identifies each object $E \in D(X \times Y)$ with a quasi-functor $P(A) \to P(B)$ whose underlying functor $D_q(X) \to D_q(Y)$ is isomorphic to the Fourier-Mukai transform defined by $E$.

Example 4.3. Let $X$ and $Y$ be separated schemes of finite type over $k$. By [Ron08, Theorem 7.39] there exist strong generators $F_X$ and $F_Y$ of $D(X)$. Choose $h$-injective resolutions of $F_X$ and $F_Y$ and let $A$ and $B$ be their DG-End-algebras. Then $A$ and $B$ are the standard Morita enhancements of $D(X)$ and $D(Y)$, i.e. $P^{qr}(A)$ and $P^{qr}(B)$ are their standard enhancements in the usual sense. It was, moreover, proved in [Lun10, Theorem 6.3] that for any choice of generators $F_X$ and $F_Y$ the DG-algebras $A$ and $B$ are smooth.

By [Toë07a, Theorem 7.2] the pullback along the Yoneda embedding $A \to P^{qr}(A)$ induces an isomorphism

$$R\text{Hom}(P^{qr}(A), P^{qr}(B)) \cong R\text{Hom}(A, P^{qr}(B))$$

in $\text{Ho}(\text{DG-Cat})$. Once again, the universal properties of $R\text{Hom}$ and [Toë07a, Lemma 6.2] imply that $R\text{Hom}(A, P^{qr}(B))$ is represented in $\text{Ho}(\text{DG-Cat})$ by $P^{B,qr}(A\dashv B)$, the full subcategory of $P(A\dashv B)$ consisting of $B$-perfect bimodules. Explicitly, after replacing $A$ by its cofibrant resolution any quasi-functor in $H^0(R\text{Hom}(A, P^{qr}(B)))$ can be represented by an actual functor $A \to P^{qr}(B)$. Taking an $h$-projective resolution of the corresponding $B$-perfect $A-B$-bimodule we obtain desired homotopy class in $P^{B,qr}(A\dashv B)$.

Thus any quasi-functor $P^{qr}(A) \to P^{qr}(B)$ can be represented by $M \in P^{B,qr}(A\dashv B)$ and the underlying functor $D(X) \to D(Y)$ is then $(\_) \otimes_A M$. It follows again from Section 2.2 that if $M$ is also $B$-perfect, then $M^A$ and $M^B$ define quasi-functors $P^{qr}(B) \to P^{qr}(A)$ such that $(\_) \otimes_B M^A$ and $(\_) \otimes_B M^B$ are the left and right adjoints of $(\_) \otimes_A M$.

It also follows from [Lun10, Prop. 6.14] that $A^{opp} \otimes B$ is the standard Morita enhancement of $D(X \times Y)$. Since $A$ is smooth, we have by Cor. 2.9 a natural inclusion $P^{B,qr}(A\dashv B) \subset P^{qr}(A\dashv B)$. This identifies each quasi-functor $P^{qr}(A) \to P^{qr}(B)$ with an object $E \in D(X \times Y)$ in such a way that the underlying functor $D(X) \to D(Y)$ is isomorphic to the Fourier-Mukai transform defined by $E$. 

Definition 5.1. Define:

- the twist $T$ of $S$ is $\text{Cone} \left( SR \xrightarrow{sr} B \right)$ in $D(B-B)$.
- the dual twist $T'$ of $S$ is $\text{Cone} \left( B \xrightarrow{act} SL \right) [-1]$ in $D(B-B)$.
- the cotwist $F$ of $S$ is $\text{Cone} \left( A \xrightarrow{act} RS \right) [-1]$ in $D(A-A)$.
- the dual cotwist $F'$ of $S$ is $\text{Cone} \left( LS \xrightarrow{sl} A \right)$ in $D(A-A)$.

Thus we have the following natural exact triangles in $D(B-B)$ and $D(A-A)$

$$SR \xrightarrow{sr} \text{Id}_{D(B)} \rightarrow T, \quad (5.1)$$

$$T' \xrightarrow{sl} \text{Id}_{D(B)} \rightarrow F, \quad (5.2)$$

$$F \xrightarrow{rs} \text{Id}_{D(A)} \rightarrow F', \quad (5.3)$$

$$LS \xrightarrow{sl} \text{Id}_{D(A)} \rightarrow F', \quad (5.4)$$

Let $t, t' : D(B) \rightarrow D(B)$ and $f, f' : D(A) \rightarrow D(A)$ be the corresponding exact functors. By Lemmas 2.2-2.3 the functorial exact triangles of functors $D(B) \rightarrow D(B)$ and $D(A) \rightarrow D(A)$ induced by (5.1)-(5.4) are

$$sr \xrightarrow{adj.unit} \text{Id}_{D(B)} \rightarrow t, \quad (5.5)$$

$$t' \xrightarrow{sl} \text{Id}_{D(B)} \rightarrow sl, \quad (5.6)$$

$$f \xrightarrow{rs} \text{Id}_{D(A)} \rightarrow rs, \quad (5.7)$$

$$ls \xrightarrow{adj.unit} \text{Id}_{D(A)} \rightarrow f', \quad (5.8)$$

i.e. $t$ and $f[1]$ are functorial cones of the counit and the unit of the adjoint pair $(s, r)$, while $t'[1]$ and $f'$ are functorial cones of the unit and the counit of the adjoint pair $(l, s)$.

Finally, consider the compositions

$$LT[-1] \xrightarrow{(5.1)} LSR \xrightarrow{tr R} R, \quad (5.9)$$

$$R \xrightarrow{Ract} RSL \xrightarrow{(5.3)} FL[1]., \quad (5.10)$$

and the induced natural transformations

$$lt[-1] \xrightarrow{(5.5)} lsr \xrightarrow{adj.commut} r, \quad (5.11)$$

$$r \xrightarrow{(5.7)} fl[1]. \quad (5.12)$$

Definition 5.2. An object $S \in D(A-B)$ is spherical if it is $A$- and $B$-perfect and the following holds:

1. $t$ and $t'$ are quasi-inverse autoequivalences of $D(B)$
2. $f$ and $f'$ are quasi-inverse autoequivalences of $D(A)$
3. $lt[-1] \xrightarrow{(5.11)} r$ is an isomorphism of functors (“the twist identifies the adjoints”).
4. $r \xrightarrow{(5.12)} fl[1]$ is an isomorphism of functors (“the co-twist identifies the adjoints”).
An \( \mathcal{A}\mathcal{B} \)-bimodule is **spherical** if its image in \( D(\mathcal{A}\mathcal{B}) \) is spherical.

Recall now that \( \mathbf{R}\text{Hom}_{\mathsf{cts}}(\mathcal{P}(\mathcal{A}), \mathcal{P}(\mathcal{B})) \) is represented in \( \text{Ho}(\mathsf{DG-Cat}_\mathcal{V}) \) by \( \mathcal{P}(\mathcal{A}\mathcal{B}) \), cf. Example 4.2.

Define a quasi-functor \( \mathcal{P}(\mathcal{A}) \to \mathcal{P}(\mathcal{B}) \) to be **spherical** if it is continuous and the corresponding element of \( D(\mathcal{A}\mathcal{B}) \) is spherical.

A Morita quasi-functor \( \mathcal{A} \to \mathcal{B} \) is a morphism from \( \mathcal{A} \) to \( \mathcal{B} \) in \( \text{Mrt}(\mathsf{DG-Cat}) \), the localisation of \( \mathsf{DG-Cat} \) by Morita equivalences. Morita quasi-functors \( \mathcal{A} \to \mathcal{B} \) are in 1-to-1 correspondence with ordinary quasi-functors \( \mathcal{P}^{\text{proj}}(\mathcal{A}) \to \mathcal{P}^{\text{proj}}(\mathcal{B}) \). Recall that \( \mathbf{R}\text{Hom}(\mathcal{P}^{\text{proj}}(\mathcal{A}), \mathcal{P}^{\text{proj}}(\mathcal{B})) \) is represented in \( \text{Ho}(\mathsf{DG-Cat}) \) by \( \mathcal{P}^{\mathcal{A}\mathcal{B}} \), cf. Example 4.3.

Define a Morita quasi-functor \( \mathcal{A} \to \mathcal{B} \) or a quasi-functor \( \mathcal{P}^{\text{proj}}(\mathcal{A}) \to \mathcal{P}^{\text{proj}}(\mathcal{B}) \) to be **spherical** if the corresponding element of \( D(\mathcal{A}\mathcal{B}) \) is spherical.

The following is the main theorem of this section:

**Theorem 5.1.** Let \( S \) be an \( \mathcal{A} \)- and \( \mathcal{B} \)-perfect object of \( D(\mathcal{A}\mathcal{B}) \). If any two of the following conditions hold:

1. \( t \) is an autoequivalence of \( D(\mathcal{B}) \) (“the twist is an equivalence”).
2. \( f \) is an equivalence of \( D(\mathcal{B}) \) (“the cotwist is an equivalence”).
3. \( \Delta t[1] \xrightarrow{(5.11)} r \) is an isomorphism of functors (“the twist identifies the adjoints”).
4. \( r \xrightarrow{(5.12)} f t[1] \) is an isomorphism of functors (“the cotwist identifies the adjoints”).

Then all four hold and \( S \) is spherical.

To prove this result we lift everything to twisted complexes in \( \mathsf{Mod-\mathcal{A}} \), \( \mathsf{Mod-\mathcal{B}} \), \( \mathsf{Mod-\mathcal{A}\mathcal{B}} \) and \( \mathsf{Mod-\mathcal{B}} \) and work there. As these \( \mathsf{DG} \)-categories are strongly pre-triangulated, we have in them the notion of the convolution of a twisted complex. We therefore write down a number of diagrams of natural morphisms of twisted complexes which descend via convolutions to the desired exact triangles in \( D(\mathcal{A}\mathcal{B}) \), \( D(\mathcal{A}) \) and \( D(\mathcal{B}) \). Given a twisted complex \( E_0 \to \cdots \to E_n \) we denote its convolution by \( \{E_0 \to \cdots \to E_n\} \).

Philosophically, it would be more fitting to work in the enhancements \( \mathcal{P}(\mathcal{A}\mathcal{B}) \), \( \mathcal{P}(\mathcal{B}\mathcal{A}) \), \( \mathcal{P}(\mathcal{A}\mathcal{A}) \) and \( \mathcal{P}(\mathcal{A}\mathcal{B}) \). The problem is that the diagonal bimodules \( \mathcal{A} \) and \( \mathcal{B} \) are usually not \( \mathsf{h} \)-projective. However, as we have assumed \( k \) to be a field, we have a natural functorial semi-free resolution provided by the bar-complex, see cf. [Kel94, §6.6]. An aesthetically minded reader should apply it to the whole of the argument below to lift it to the \( \mathsf{h} \)-projective (even semifree) enhancements. We choose instead to write down the natural morphisms we work with in their simplest form.

So let \( M \) be any \( \mathsf{h} \)-projective \( \mathcal{A}\mathcal{B} \)-bimodule which is isomorphic to \( S \) in \( D(\mathcal{A}\mathcal{B}) \). Derived dualizing functors can be computed by taking \( \mathsf{h} \)-projective resolutions, we therefore have

\[
R \simeq M^B \quad \text{in} \quad D(\mathcal{B}\mathcal{A})
\]
\[
L \simeq M^A \quad \text{in} \quad D(\mathcal{A}\mathcal{B})
\]

Next, recall that derived tensor product can be computed by taking an \( \mathsf{h} \)-projective resolution of either of its two arguments. Moreover, if \( N \xrightarrow{f} M \) is any morphism of bimodules then \( \{N \xrightarrow{f} M\}_{\deg.0} \simeq \text{Cone}(f) \) in \( D(\mathcal{B}\mathcal{B}) \). We therefore have

\[
T \simeq \{M^B \otimes_A M \xrightarrow{\alpha} B\}_{\deg.0} \quad \text{in} \quad D(\mathcal{B}\mathcal{B}),
\]
\[
T' \simeq \{B \xrightarrow{\alpha} M^A \otimes_A M\}_{\deg.0} \quad \text{in} \quad D(\mathcal{B}\mathcal{B}),
\]
\[
F \simeq \{A \xrightarrow{\alpha} M \otimes_B M^B\}_{\deg.0} \quad \text{in} \quad D(\mathcal{A}\mathcal{A}),
\]
\[
F' \simeq \{M \otimes_B M^A \xrightarrow{\alpha} A\}_{\deg.0} \quad \text{in} \quad D(\mathcal{A}\mathcal{A}),
\]

where we fix a choice of homotopy inverses of \( (2.16) \) and compose them with the canonical action maps \( (2.14) \) to obtain the action maps above.

**Proposition 5.3.** We have

\[
T'^{\mathcal{B}} \simeq T' \quad \text{in} \quad D(\mathcal{B}\mathcal{B})
\]
\[
(F')^{\mathcal{A}} \simeq F \quad \text{in} \quad D(\mathcal{A}\mathcal{A}).
\]

Consequently, \( t' \) is the left adjoint of \( t \): \( D(\mathcal{B}) \to D(\mathcal{B}) \) and \( f' \) is the left adjoint of \( f \): \( D(\mathcal{A}) \to D(\mathcal{A}) \).
Proof. Since $M^B \otimes_A M$ and $B$ are both left-$B$-$h$-projective, so is $\left\{ M^B \otimes_A M \xrightarrow{\tr} B \right\}_{\deg.0}$. Hence

$$T^B \simeq \left\{ M^B \otimes_A M \xrightarrow{\tr} B \right\}_{\deg.0}^{IB}$$

and by Lemma 3.5(1)

$$\left\{ M^B \otimes_A M \xrightarrow{\tr} B \right\}_{\deg.0}^{IB} \simeq \left\{ B \xrightarrow{-\tr} (M^B \otimes_A M)^{IB} \right\}.$$ 

Lemma 2.5 produces a homotopy equivalence $(M^B \otimes_A M)^{IB} \sim M^A \otimes_A M$ which identifies $B \xrightarrow{\tr} (M^B \otimes_A M)^{IB}$ with $B \xrightarrow{\act} M^A \otimes_A M$. Multiplied by $-1$ it induces a homotopy equivalence of twisted complexes

$$\left( B \xrightarrow{-\tr} (M^B \otimes_A M)^{IB} \right) \sim \left( B \xrightarrow{\act} M^A \otimes_A M \right)$$

which descends to an isomorphism $T^B \simeq T'$ in $D(B\cdot B)$. Identical argument shows that $(F')^\sim \simeq F$ in $D(A\cdot A)$. The final assertion of this proposition follows from Lemmas 2.2 and 2.3.

Thus, if $t$ is an auto-equivalence of $D(B)$ then $t'$ is always its quasi-inverse, and similarly for $f$ and $f'$.

**Proposition 5.4.** The unit and the counit of the $(t', t)$ adjunction are induced by the maps

$$B_{\deg.0} \to \left( M^B \otimes_A M \xrightarrow{\tr \circ (\act \otimes \Id)} B \oplus \left( M^A \otimes_A M \otimes_B M^B \otimes_A M \right) \xrightarrow{\act \oplus (-\Id \otimes \tr)} M^A \otimes_A M \right)$$

for twisted complexes over $\text{Mod} \cdot B \cdot B$ given by

$$B \xrightarrow{\Id \circ \act} B \oplus \left( M^A \otimes_A M \right) \xrightarrow{\Id \oplus (-\Id \otimes \act \otimes \Id)} B \oplus \left( M^A \otimes_A M \otimes B M^B \otimes_A M \right)$$

$$B \oplus \left( M^B \otimes_A M \otimes B M^B \otimes_A M \right) \xrightarrow{\Id \oplus (-\Id \circ \tr \otimes \Id)} B \oplus \left( M^B \otimes_A M \right) \xrightarrow{\Id \circ \tr} B$$

respectively. The twisted maps between degrees $-1, 1$ in the long twisted complexes in (5.13) and (5.14) are both zero.

**Proof.** We treat the case of the adjunction unit, the case of the counit is treated identically.

By Lemma 2.3 the functor $(-) \otimes L^T \overline{B}$ is the left adjoint of $t$ whose adjunction unit is the derived action map $B \xrightarrow{\act} TT^B \overline{B}$. We use the isomorphism $T^B \simeq T'$ constructed in Prop. 5.3 to identify $t'$ with $(-) \otimes T^B$, so the unit of the $(t', t)$ adjunction is induced by

$$B \xrightarrow{\act} TT^B \simeq \text{Prop. 5.3} \to TT'.$$

Since $M^B \otimes_A M$ and $B$ are left $B$-perfect and left $B$-$h$-projective, so is $\left\{ M^B \otimes_A M \xrightarrow{\tr} B \right\}_{\deg.0}^{IB}$. Hence any action map

$$B \xrightarrow{\act} \left\{ M^B \otimes_A M \xrightarrow{\tr} B \right\}_{\deg.0}^{IB}$$

gives the derived action map $B \xrightarrow{\act} TT^B$. Applying Lemma 3.5(2) to the twisted complex $(M^B \otimes_A M \xrightarrow{\tr} B_{\deg.0})$ we obtain the map of twisted complexes

$$B_{\deg.0} \to \left( M^B \otimes_A M \xrightarrow{\tr \oplus (-\tr \otimes \Id)} B \oplus \left( (M^B \otimes_A M)^{IB} \otimes_B (M^B \otimes_A M) \right) \xrightarrow{-\tr \oplus (-\Id \otimes \tr)} (M^B \otimes_A M)^{IB} \right)$$

given by

$$B \xrightarrow{\Id \oplus \act} B \oplus \left( (M^B \otimes_A M)^{IB} \otimes_B (M^B \otimes_A M) \right)$$

whose image in $D(B\cdot B)$ is the action map $B \xrightarrow{\act} TT^B$.

Finally, recall that the isomorphism $T^B \simeq T'$ was constructed in Prop. 5.3 via the homotopy equivalence $(M^B \otimes_A M)^{IB} \sim M^A \otimes_A M$ which identifies $B \xrightarrow{-\tr} (M^B \otimes_A M)^{IB}$ with $B \xrightarrow{\act} M^A \otimes_A M$. Applying this
homotopy equivalence to the RHS of (5.18) we obtain the RHS of (5.13). To show that (5.13) descends to (5.17), and hence to the adjunction counit of \((t', t)\), it remains to show that \((M^B \otimes_A M)^{tr} \sim M^A \otimes_A M\) identifies the map (5.19) with the map (5.15). This is a straightforward verification in the spirit of the proof of Lemma 2.5, boiling down to a commutative diagram very similar to (2.38).

The following proposition is proved in the same way:

**Proposition 5.5.** The unit and the counit of the \((f', f)\) adjunction are induced by the maps

\[
\begin{align*}
A_{\deg.0} & \to (M \otimes_B M^A \xrightarrow{\tr \otimes (-1 \otimes \act)} A \oplus (M \otimes_B M^A \otimes_A M \otimes_B M^B) \xrightarrow{\act \otimes (\tr \otimes \Id)} M \otimes_B M^B) \quad (5.20) \\
(M \otimes_B M^A \xrightarrow{\tr \otimes (\act \otimes \Id)} A \oplus (M \otimes_B M^B \otimes_A M \otimes_B M^A) \xrightarrow{\act \otimes (-1 \otimes \tr)} M \otimes_B M^B) & \to A_{\deg.0} \quad (5.21)
\end{align*}
\]

of twisted complexes over \(\text{Mod} - A\cdot A\) given by

\[
\begin{align*}
A \xrightarrow{\Id \otimes \act} A \oplus (M \otimes_B M^B) \xrightarrow{\Id \otimes (\Id \otimes \act \otimes \Id)} A \oplus (M \otimes_B M^A \otimes_A M \otimes_B M^B) \quad (5.22) \\
A \oplus (M \otimes_B M^B \otimes_A M \otimes_B M^A) \xrightarrow{\Id \otimes (\Id \otimes \tr \otimes \Id)} B \oplus (M \otimes_B M^A) \xrightarrow{\Id \otimes \tr} B \quad (5.23)
\end{align*}
\]

respectively. The twisted maps between degrees \(-1, 1\) in the long twisted complexes in (5.20) and (5.21) are both zero.

Consider the twisted 2-cube over \(\text{Mod} - B\cdot A\)

\[
\begin{array}{c}
\begin{array}{c}
A_{\deg.0} \to M^A \\
(M^B \otimes \Id) \xrightarrow{\Id \otimes \act} M^A \otimes_A M \otimes_B M^B \\
(M^B \otimes \Id) \xrightarrow{\Id \otimes \act} M^A \otimes_A M \otimes_B M^B \\
\end{array}
\end{array}
\]

whose diagonal degree \(-1\) morphism is zero.

By the Cube Lemma (Lemma 3.6) the convolutions of the rows of (5.24) fit into a 1-cube (i.e. a single morphism) whose convolution is the convolution of the total complex of the 2-cube. And similarly for the convolutions of the columns of (5.24). This is formalised in the Cube Completion Lemma (Lemma 3.7) which constructs for us the diagram

\[
\begin{array}{c}
\begin{array}{c}
O \to M^A \\
(M^B \otimes \Id) \xrightarrow{\Id \otimes \act} M^A \otimes_A M \otimes_B M^B \\
(M^B \otimes \Id) \xrightarrow{\Id \otimes \act} M^A \otimes_A M \otimes_B M^B \\
\end{array}
\end{array}
\]

in \(\text{Mod} - B\cdot A\) which descends to the commutative 3 × 3-diagram

\[
\begin{array}{c}
\begin{array}{c}
O \to L \\
R \xrightarrow{\Id} L \xrightarrow{\Id} L \\
R \xrightarrow{\Id} RSL \xrightarrow{\Id} RT'[1] \xrightarrow{\Id} RT'[1] \\
R \xrightarrow{\Id} FL[1] \xrightarrow{\Id} Q[1].
\end{array}
\end{array}
\]

in \(D(B\cdot A)\) whose rows and columns are exact triangles. The morphisms marked \([1]\) are morphisms of degree 1 which “wrap around” to the beginning of the corresponding row or column.
The precise formulas for each twisted complex and each morphism in (5.25) can be found in the Cube Completion Lemma (Lemma 3.7). In particular, $Q$ denotes in (5.26) the convolution of the 2-cube (5.24) shifted by one to the right, that is

$$Q = \left\{ M^A \oplus M^B \xrightarrow{-\text{Id} \otimes \text{act} \otimes \text{Id}} M^A \otimes M \otimes M^B \right\} \text{ in } D(B-A).$$

The connecting morphisms for the exact triangles are the images of the morphisms labeled [1] in (5.25).

**Lemma 5.6.** The following are equivalent:

- $r \xrightarrow{(5.12)} fl[1]$ is an isomorphism (the condition (4) of Theorem 5.1).
- $Q \simeq 0$ in $D(B-A)$.
- $\alpha$ is an isomorphism in $D(B-A)$.
- $\alpha'$ is an isomorphism in $D(B-A)$.

**Proof.** Denote by $q$ the functor $(-) \otimes Q$ from $D(B)$ to $D(A)$. By Lemmas 2.2 and 2.3 morphisms $R \to RSL$ and $L \to RSL$ in (5.26) induce the natural transformations $r \xrightarrow{r(\text{adj. unit})} rsl$ and $l \xrightarrow{l(\text{adj. unit})} rsl$. Hence $R \xrightarrow{r} FL[1]$ induces the natural transformation (5.12). From the functorial exact triangle $r \xrightarrow{(5.12)} fl[1] \to q[1]$ induced by the bottom row of (5.26) we deduce that $r \xrightarrow{(5.12)} fl[1]$ is an isomorphism if and only if $q$ is the zero functor. That is equivalent to $Q$ being an acyclic $A$-module for all $b \in B$, and hence to $Q_a$ being acyclic for all $a \in A$ and $b \in B$. Thus $r \xrightarrow{(5.12)} fl[1]$ is an isomorphism if and only if $Q \simeq 0$ in $D(B-A)$. On the other hand, by exactness of the bottom row of the diagram (5.26) $Q \simeq 0$ is equivalent to $\alpha$ being an isomorphism. Similarly, by exactness of the right column of (5.26) $Q \simeq 0$ is also equivalent to $\alpha'$ being an isomorphism. □

In a similar way, the twisted 2-cube

$$M^B \otimes_B M \otimes_B M^A \xrightarrow{\text{tr} \otimes \text{Id}} M^A$$

whose diagonal degree $-1$ morphism is zero produces the $3 \times 3$-diagram

$$\begin{array}{ccc}
Q'[1] & \xrightarrow{\beta'} & F' \xrightarrow{\beta} R[1] \\
\downarrow & & \downarrow \\
LT[-1] & \xrightarrow{\beta} & LSR \\
\downarrow & & \downarrow \\
R & \xrightarrow{\text{Id}} & R & \rightarrow & 0.
\end{array}$$

(5.28)

in $D(B-A)$ with exact rows and columns. Here $Q'$ is the convolution of the total complex of the 2-cube (5.27) shifted by one to the left, that is

$$Q' = \left\{ M^B \otimes_B M \otimes_B M^A \xrightarrow{-\text{tr} \otimes \text{Id} \otimes \text{tr} \otimes \text{Id}} M^A \otimes M \otimes M^B \right\} \text{ in } D(B-A).$$

Arguing as in the proof of Lemma 5.6 we obtain:

**Lemma 5.7.** The following are equivalent:

- $\operatorname{lt}[-1] \xrightarrow{(5.11)} r$ is an isomorphism (the condition (3) of Theorem 5.1).
- $Q' \simeq 0$ in $D(B-A)$.
- $\beta$ is an isomorphism in $D(B-A)$.
- $\beta'$ is an isomorphism in $D(B-A)$. 

Consider now the twisted 2-cube

\[
\begin{array}{c}
M^A \otimes_A M \\
\text{deg.1: } \text{Id} \\
\end{array} \xrightarrow{\text{Id}} \begin{array}{c}
M^A \otimes_A M \\
\text{deg.1: } \text{Id} \\
\end{array} & \begin{array}{c}
M^B \otimes_A M \\
\text{deg.0: } -\text{tr} \otimes \text{Id} \\
\end{array} \xrightarrow{\text{tr} \otimes \text{Id}} \begin{array}{c}
\text{deg.0: } \text{Id} \\
\end{array} \quad (5.29)
\end{array}
\]

over Pre-Tr(\text{Mod-}B^{-}B) and with the diagonal degree \(-1\) morphism being zero.

The left column of (5.29) is the part of the diagram (5.25) which descends to the morphism \(\alpha' \rightarrow RT'[1]\) in (5.26) shifted by 1 to the right and tensored on the right with \(M\). Thus, or by direct inspection, the convolution of the total complex of the left column of (5.29) is isomorphic to \(SQ\) in \(D(B^{-}B)\).

Note that, by definition, the total complex of a face of a twisted cube over Pre-Tr(\text{Mod-}B^{-}B) implicitly use this equivalence wherever possible, e.g. by the total complex of a face of a twisted cube over Pre-Tr(\text{Mod-}B^{-}B) the Cube Completion Lemma constructs from (5.29) to (5.31) with the equivalences identify the map which the Cube Completion Lemma constructs from (5.29) to (5.31) with the established in Prps. 5.4 to convolve to \(TT'\).

Thus, the total complex of the right column of (5.29) is

\[
\mathcal{B} \oplus M^A \otimes_A M \rightarrow M^A \otimes_A M. \quad (5.30)
\]

The projection from it to the diagonal bimodule \(\mathcal{B}\) considered as a twisted complex concentrated in degree 0 is a homotopy equivalence. The total complex of the whole 2-cube is

\[
(M^A \otimes_A M) \oplus (M^B \otimes_A M) \rightarrow \mathcal{B} \oplus (M^A \otimes_A M) \oplus (M^A \otimes_A M \otimes_B M^B \otimes_A M) \rightarrow M^A \otimes_A M \quad (5.31)
\]

and the projection from it to the twisted complex

\[
M^B \otimes_A M \xrightarrow{\text{tr} \otimes (\text{act} \otimes \text{Id})} \mathcal{B} \oplus (M^A \otimes_A M \otimes_B M^B \otimes_A M) \xrightarrow{\text{act} \otimes (-\text{Id} \otimes \text{tr})} M^A \otimes_A M \quad (5.32)
\]

established in Prps. 5.4 to convolve to \(TT'\) is also a homotopy equivalence. Moreover, these two homotopy equivalences identify the map which the Cube Completion Lemma constructs from (5.29) to (5.31) with the map (5.13) from \(\mathcal{B}\) to (5.32) which was proved in Prps. 5.4 to descend to the adjunction unit \(\text{Id}_{D(B^{-}B)} \rightarrow TT'\).

Thus, applying the Cube Completion Lemma to the 2-cube (5.29) produces a commutative \(3 \times 3\) diagram

\[
\begin{array}{c}
SL[-1] \\
\text{Id} \\
\end{array} \xrightarrow{\text{Id}} \begin{array}{c}
SL[-1] \\
\text{Id} \\
\end{array} \xrightarrow{\text{Id}} \begin{array}{c}
0 \\
\end{array} \quad (5.33)
\end{array}
\]

in \(D(B^{-}B)\) with exact rows and columns.

Similarly, the twisted 2-cube

\[
\begin{array}{c}
M^B \otimes_A M \\
\text{deg.0: } \text{Id} \\
\end{array} \xrightarrow{\text{deg.1: } \text{Id} \otimes \text{act} \otimes \text{Id}} \begin{array}{c}
M^B \otimes_A M \\
\text{deg.0: } \text{act} \\
\end{array} \xrightarrow{\text{deg.1: } \text{Id} \otimes \text{tr} \otimes \text{Id}} \begin{array}{c}
M^B \otimes_A M \\
\text{deg.1: } \text{Id} \\
\end{array} \quad (5.34)
\end{array}
\]
over Pre-Tr(Mod -B -B) whose diagonal degree −1 morphism is zero produces the diagram

\[
\begin{array}{c}
TT \xrightarrow{(5.14)} B \xrightarrow{\text{Id}} SQ' \\
TT \xrightarrow{} T \xrightarrow{} S\beta T \\
0 \xrightarrow{} SR[1] \xrightarrow{\text{Id}} SR[1]
\end{array}
\]

(5.35)

in D(B-B) with exact rows and columns.

Similarly, we incorporate the morphisms (5.20) and (5.21) which descend to the unit and the counit of the adjoint pair (f', f) into the following two 3×3 diagrams in D(A-A) with exact rows and columns:

\[
\begin{array}{c}
RS[-1] \xrightarrow{\text{Id}} RS[-1] \xrightarrow{} 0 \\
F \downarrow \downarrow F \downarrow \downarrow F' \\
QS \xrightarrow{} A \xrightarrow{(5.20)} FF'
\end{array}
\]

(5.36)

\[
\begin{array}{c}
F'F \xrightarrow{(5.21)} A \xrightarrow{} Q'S \\
F' \downarrow \downarrow F' \downarrow \downarrow F'RS \\
0 \xrightarrow{} LS[1] \xrightarrow{\text{Id}} LS[1].
\end{array}
\]

(5.37)

We obtain immediately:

**Proposition 5.8.**

1. If the natural transformation \(lt[-1] \xrightarrow{(5.11)} r\) is an isomorphism (the condition (3) of Theorem 5.1) then the adjunction counits \(t' \rightarrow \text{Id}\) and \(f' \rightarrow \text{Id}\) are isomorphisms.

2. If the natural transformation \(r \xrightarrow{(5.12)} fl[-1]\) is an isomorphism (the condition (4) of Theorem 5.1) then the adjunction units \(\text{Id} \rightarrow tt'\) and \(\text{Id} \rightarrow ff'\) are isomorphisms.

**Proof.** We have established that the condition (3) of Theorem 5.1 is equivalent to \(Q \simeq 0\) in D(B-A). Therefore \(SQ \simeq 0\) in D(B-B) and since the bottom row of (5.33) is exact it follows that \(B \xrightarrow{(5.13)} TT'\) is an isomorphism.

By Prps. 5.4 the natural transformation \((-) \otimes B \xrightarrow{(5.13)} (-) \otimes TT'\) is isomorphic to the adjunction unit \(\text{Id} \rightarrow tt'\) and hence the latter is a functorial isomorphism. Similarly, \(QS \simeq 0\) in D(A-A) and by the exactness of the bottom row of (5.36) the morphism \(A \xrightarrow{(5.20)} FF'\) is an isomorphism. Hence the adjunction unit \(\text{Id} \rightarrow ff'\) is a functorial isomorphism.

The second claim is proved similarly.

**Lemma 5.9.** Let \(\alpha, \alpha', \beta\) and \(\beta'\) be as in diagrams (5.26) and (5.28). Then

1. The composition \(R \xrightarrow{(5.20)} FFR \xrightarrow{F\beta'} FL[1]\) is the map \(\alpha\).

2. The composition \(LT[-1] \xrightarrow{\alpha'T} RT'T \xrightarrow{R(5.14)} R\) is the map \(\beta\).

3. The composition \(L \xrightarrow{(5.13)} LTT' \xrightarrow{\beta'T} RT'[1]\) is the map \(\alpha'\).

4. The composition \(F'R[-1] \xrightarrow{F'\alpha} F'FL \xrightarrow{(5.21)} L\) is the map \(\beta'\).

**Proof.** We only prove the first claim, the other three are proved analogously.
By construction of the diagram (5.26) the map \( R \xrightarrow{\otimes} FL[1] \) descends from the map of twisted complexes\(^{20}\)\(^{20}\)
\[
M^B_{\deg.0} \xrightarrow{\text{Id} \otimes \text{Id}} M^A \otimes_A M \otimes_B M^B
\]

(5.38)

On the other hand, the morphism \( R \xrightarrow{(5.26)R} FF'R \) descends from the map of twisted complexes\(^{20}\)^{20}\)
\[
M^B_{\deg.0} \xrightarrow{\text{Id} \otimes (\text{Id} \otimes \text{act})} M^B \oplus \left( M^B \otimes_A M \otimes_B M^B \right)_{\deg.0} \xrightarrow{(5.40) \otimes \text{Id}} M^A \otimes_A M \otimes_B M^B
\]

(5.39)

The map \( FF'R \xrightarrow{F\beta'} FL[1] \) is slightly trickier to get at. The map of twisted complexes
\[
\begin{align*}
\left\{ M^B \otimes_A M \otimes_B M^A \xrightarrow{\text{Id} \otimes \text{tr}} M^B \right\}_{\deg.0} & \xrightarrow{\text{Id} \otimes \text{Id}} M^A_{\deg.-1} \\
\end{align*}
\]

(5.40)

given by
\[
M^B \otimes_A M \otimes_B M^A \xrightarrow{\text{tr} \otimes \text{Id}} M^A
\]
descends to \( F'R \xrightarrow{\beta'} L[1] \), while the twisted complex \( \left\{ A \xrightarrow{\text{act}} M \otimes_B M^B \right\}_{\deg.0} \) convolves to \( F \). Therefore what we want is the map of twisted complexes which convolves to the map
\[
\begin{align*}
\left\{ M^B \otimes_A M \otimes_B M^A \xrightarrow{\text{Id} \otimes \text{tr}} M^B \right\}_{\deg.0} \otimes \left\{ A \xrightarrow{\text{act}} M \otimes_B M^B \right\}_{\deg.0} \xrightarrow{(5.40) \otimes \text{Id}} M^A \otimes_A M \otimes_B M^B
\end{align*}
\]

(5.41)

The Lemma 3.4 tells us how to take tensor product of twisted complexes in a way compatible with convolutions. It follows from it that the desired map of twisted complexes which descends to \( FF'R \xrightarrow{F\beta'} FL[1] \) is the map
\[
\begin{align*}
M^B \otimes_A M \otimes_B M^A \xrightarrow{(\text{Id} \otimes \text{tr}) \otimes (-\text{Id} \otimes \text{act})} M^B \oplus \left( M^B \otimes_A M \otimes_B M^A \otimes_A M \otimes_B M^B \right)_{\deg.0} \xrightarrow{(\text{Id} \otimes \text{act}) \otimes (-\text{Id} \otimes \text{tr} \otimes \text{Id})} M^B \otimes_A M \otimes_B M^B
\end{align*}
\]

(5.41)

To prove the desired claim, it now suffices to prove that the composition of (5.39) and (5.41) is homotopic to (5.38). This amounts to commutativity of the diagram
\[
\begin{align*}
M^B \xrightarrow{\text{Id} \otimes \text{act}} (M^B \otimes_A M) \otimes_B M^B \xrightarrow{\text{Id} \otimes \text{act} \otimes \text{Id}} (M^B \otimes_A M) \otimes_B (M^A \otimes_A M) \otimes_B M^B \\
M^B \xrightarrow{\text{tr} \otimes \text{Id} \otimes \text{act}} M^B \xrightarrow{\text{tr} \otimes \text{Id} \otimes \text{act} \otimes \text{Id}} (M^B \otimes_A M) \otimes_B M^B \\
M^B \xrightarrow{\text{Id} \otimes \text{act}} (M^B \otimes_A M) \otimes_B M^B \xrightarrow{\text{Id} \otimes \text{act} \otimes \text{Id}} (M^B \otimes_A M) \otimes_B (M^A \otimes_A M) \otimes_B M^B \\
\end{align*}
\]

(5.42)

up to homotopy. It can be readily seen: the square in (5.42) commutes by the functoriality of the tensor product, while the triangle commutes up to homotopy by Prop. 2.1. 
\( \square \)
Let $\gamma : F^\ell L[-1] \to LT^\ell[1]$ be the map induced by the following morphism of twisted complexes
\[
(M^A \otimes_A M \otimes_B M^A) \xrightarrow{\text{deg.0}} (M^A \otimes_A M \otimes_B M^A).
\] (5.43)

\[
(M^A \otimes_A M \otimes_B M^A) \xrightarrow{\text{deg.0}} (M^A \otimes_A M \otimes_B M^A).
\]

**Lemma 5.10.** The morphism (5.43) is a homotopy equivalence. Consequently, the map $\gamma$ is an isomorphism.

**Proof.** We claim that the homotopy inverse of (5.43) is the morphism
\[
(M^A \otimes_A M \otimes_B M^A) \xrightarrow{\text{deg.0}} (M^A \otimes_A M \otimes_B M^A).
\] (5.44)

Indeed, the composition of (5.43) with (5.44) is the morphism of twisted complexes
\[
(M^A \otimes_A M \otimes_B M^A) \xrightarrow{\text{deg.0}} (M^A \otimes_A M \otimes_B M^A)
\]

which differs from the identity morphism by
\[
(M^A \otimes_A M \otimes_B M^A) \xrightarrow{\text{deg.0}} (M^A \otimes_A M \otimes_B M^A)
\]

This difference is null-homotopic because it is homotopic to the image under the differential of the following morphism of twisted complexes of degree $-1$
\[
(M^A \otimes_A M \otimes_B M^A) \xrightarrow{\text{deg.0}} (M^A \otimes_A M \otimes_B M^A)
\]

Thus the composition of (5.43) with (5.44) is homotopic to Id.

The composition of (5.44) and (5.43) being homotopic to Id is proved similarly. \qed

**Lemma 5.11.** The composition $F^\ell L[-1] \xrightarrow{F^\ell g} F^\ell RT^\ell \xrightarrow{\beta^\ell T^\ell} LT^\ell[1]$ equals the map $\gamma$.

**Proof.** Computing as in the proof of the (5.9), we see that on the level of twisted complexes the map $F^\ell L[-1] \xrightarrow{F^\ell g} F^\ell RT^\ell$ is given by
\[
(M^A \otimes_A M \otimes_B M^A) \xrightarrow{\text{deg.0}} (M^A \otimes_A M \otimes_B M^A)
\]

Thus the composition of (5.43) with (5.44) is homotopic to Id.

The composition of (5.44) and (5.43) being homotopic to Id is proved similarly. \qed
where we omit marking up the internal twisted maps inside twisted complexes, since they are not relevant to our argument. Similarly, the map \( F'RT' \xrightarrow{\beta'T'} LT'[1] \) is given on the level of twisted complexes by

\[
\begin{array}{rcl}
M^B \otimes_A M \otimes_B M^A & \xrightarrow{\text{tr} \otimes \text{Id}} & M^B \oplus (M^A \otimes_A M \otimes_B M^B \otimes_A M \otimes_B M^A) \\
\end{array}
\]

Hence the composition \( F'L[-1] \xrightarrow{F'\alpha'} F'RT' \xrightarrow{\beta'T'} LT'[1] \) is given on the level of twisted complexes by

\[
\begin{array}{rcl}
M^A \otimes_A M \otimes_B M^A & \xrightarrow{\text{Id} \otimes \text{tr} \otimes \text{Id}} & M^A \\
\end{array}
\]

The asserted claim is thus reduced to showing that

\[
M \xrightarrow{\text{act} \otimes \text{Id}} M \otimes_B M^B \otimes_A M \xrightarrow{\text{Id} \otimes \text{tr}} M
\]
is homotopic to \( \text{Id} \), which was established in Prop. 2.1.

\[\square\]

**Lemma 5.12.** The following maps are equal:

1. \( LT[-1] \xrightarrow{\alpha_{\beta \beta}^\circ} FL[1] \)
2. \( LT[-1] \xrightarrow{\text{(5.20)}LT} FF'LT[-1] \xrightarrow{F\gamma T} FLT'[1] \xrightarrow{FL(5.14)} FL[1] \)

**Proof.** By Lemma 5.9 the composition \( LT[-1] \xrightarrow{\alpha_{\beta \beta}^\circ} FL[1] \) equals the composition

\[
LT[-1] \xrightarrow{\alpha_{\beta}^T} RT'T \xrightarrow{R(5.14)} R \xrightarrow{\text{(5.20)}R} FF'R \xrightarrow{\beta'} FL[1].
\]

By functoriality of tensor product \( (5.48) \) equals the composition

\[
LT[-1] \xrightarrow{\alpha_{\beta}^T} RT'T \xrightarrow{\text{(5.20)}RT'T} FF'RT'T \xrightarrow{FF'R(5.14)} FF'R \xrightarrow{\beta'} FL[1],
\]

which by functoriality of tensor product again equals the composition

\[
LT[-1] \xrightarrow{\text{(5.20)}LT} FF'LT[-1] \xrightarrow{FF'\alpha^T} FF'RT'T \xrightarrow{F\beta'T'T} FLT'[1] \xrightarrow{FL(5.14)} FL[1].
\]

The claim now follows by applying Lemma 5.11 to the two maps in the middle of \( (5.50) \).

\[\square\]

Similarly, let \( \gamma' : RT[-1] \to FR[1] \) be the map induced by the following morphism of twisted complexes

\[
\begin{array}{rcl}
(M^B \otimes_A M \otimes_B M^A) & \xrightarrow{\text{tr} \otimes \text{Id}} & M^B \\
\end{array}
\]

The following two results are proved identically to Lemmas 5.10 and 5.12:

**Lemma 5.13.** The morphism \( (5.51) \) is a homotopy equivalence. Consequently, the map \( \gamma' \) is an isomorphism.

**Lemma 5.14.** The following maps are equal:

1. \( F'R[-1] \xrightarrow{\alpha'_{\beta'}^\circ} RT'[1] \)
2. \( F'R[-1] \xrightarrow{F'R(5.13)} F'RT'T[-1] \xrightarrow{F'\gamma'T'} F'FRT'[1] \xrightarrow{(5.21)RT'} RT'[1] \)
Thus, if the adjunction maps (5.20) and (5.14) are isomorphisms, the composition \( \alpha \circ \beta \) is an isomorphism, and it filters through the canonical map \( \text{RSL} \xrightarrow{\delta_0} \text{FL}[1] \).

We are now in a position to prove the main theorem. Before we begin the argument, recall that in a triangulated category all retracts are split. More precisely, let \( Z \xrightarrow{\alpha} Y \) be a retract in a triangulated category, that is — there exists \( Y \xrightarrow{\beta} Z \) with \( Z \xrightarrow{\alpha} Y \xrightarrow{\beta} Z \) being the identity. Then for any completion of \( g \) to an exact triangle \( X \xrightarrow{f} Y \xrightarrow{g} Z \xrightarrow{h} Y \) is an isomorphism. Moreover, its inverse is of form \( Y \xrightarrow{g \oplus h} X \oplus Z \) for some morphism \( Y \xrightarrow{\beta} X \). This can be established using only the axioms of triangulated categories, though for enhanced triangulated categories one can see it very explicitly on the level of twisted complexes.

**Proof of Theorem 5.1.**

(3) and (4) \( \Rightarrow \) (1) and (2):

Suppose that natural transformations \( \text{Id} \xrightarrow{\delta} t'[1] \xrightarrow{(5.11)} r \) and \( r \xrightarrow{(5.12)} f[t][1] \) are functorial isomorphisms. In other words, the conditions (3) and (4) hold. Then by the Proposition 5.8 the units and counits of both adjoint pairs \((t', t)\) and \((f', f)\) are isomorphisms. Hence \((t', t)\) and \((f', f)\) are pairs of mutually inverse equivalences, that is \( \alpha \circ \beta \) is an isomorphism, as desired.

We only prove the assertion (1) and (3) \( \Rightarrow \) (4), the other three are proved similarly.

Assume that the conditions (1) and (3) hold. The condition (1) is \( (t', t) \) being mutually inverse equivalences.

In particular, the adjunction unit \( \text{Id} \xrightarrow{\delta} t'[1] \) is an isomorphism. Therefore the morphism \( B \xrightarrow{(5.13)} T'T \), which by Prop. 5.4 induces this adjunction unit, is also an isomorphism. On the other hand, by Lemma 5.7 the condition (3) is equivalent to the map \( LT \xrightarrow{\delta} R[1] \) in the diagram (5.28) being an isomorphism.

By Lemma 5.7 the condition (4) is equivalent to the map \( L \xrightarrow{\alpha} RT'[1] \) in the diagram (5.26) being an isomorphism. By Lemma 5.9 the map \( L \xrightarrow{\alpha'} RT'[1] \) decomposes as

\[
L \xrightarrow{LT''} \xrightarrow{B TT''} \xrightarrow{T''} \xrightarrow{R} \xrightarrow{TT''} \xrightarrow{L} RT'[1].
\]

By above, both the composants are isomorphisms. Hence \( L \xrightarrow{\alpha'} RT'[1] \) is also an isomorphism, as desired.

(1) and (2) \( \Rightarrow \) (4):

Assume the conditions (1) and (2) hold. Then the maps \( \text{Id} \xrightarrow{(5.20)} FF' \) and \( T'T \xrightarrow{(5.14)} \text{Id} \) are isomorphisms. By Lemma 5.10 map \( FF'[1] \xrightarrow{\delta} LT'[1] \) induced by (5.43) is always an isomorphism. By Lemma 5.12 the map \( LT[1] \xrightarrow{\delta} R \xrightarrow{T} FL[1] \) decomposes as

\[
LT[1] \xrightarrow{(5.20) \cdot LT} FF'LT[1] \xrightarrow{F\gamma T} FLT'T[1] \xrightarrow{FL(5.14)} FL[1]
\]

and is therefore an isomorphism.

This isomorphism \( \alpha \circ \beta \) filters through the canonical map \( \text{RSL} \xrightarrow{\delta_0} \text{FL}[1] \), thus \( \text{FL}[1] \) is a retract of \( \text{RSL} \).

More specifically, denote by \( \overline{\eta} \) the map \( \text{FL}[1] \xrightarrow{(\alpha \circ \beta)^{-1}} LT[1] \xrightarrow{\delta} R \xrightarrow{\text{act}} \text{RSL} \), so that

\[
\text{FL}[1] \xrightarrow{\overline{\eta}} \text{RSL} \xrightarrow{\delta_0} \text{FL}[1]
\]

is the identity map. Since all retracts in triangulated categories are split and since \( \text{L} \xrightarrow{\text{act}} \text{RSL} \xrightarrow{\delta_0} \text{FL}[1] \) is an exact triangle it follows that there exists a map \( \text{RSL} \xrightarrow{\text{act}} \text{L} \) such that

\[
\text{L} \xrightarrow{(\alpha \circ \beta)^{-1}} \text{FL}[1] \xrightarrow{\text{act}} \text{RSL} \xrightarrow{\delta_0} \text{FL}[1]
\]

are mutually inverse isomorphisms. Similarly, since \( FF' \xrightarrow{(5.21)} \text{Id} \) and \( \text{Id} \xrightarrow{(5.13)} TT' \) are isomorphisms, Lemmas 5.13 and 5.14 imply that the map \( F'R[1] \xrightarrow{\alpha \circ \beta} RT'[1] \) is an isomorphism. Let \( \overline{\zeta} \) be the map
RT'[1] \xrightarrow{(\alpha' \circ \beta')^{-1}} F' R[−1] \xrightarrow{\beta'} L \xrightarrow{\text{act}_L} RSL, \text{ then there exists a map } RSL \xrightarrow{\text{Ract}} R \text{ such that } R \oplus RT'[1] \xrightarrow{(\text{Ract}) \oplus \zeta} RSL \xrightarrow{(\text{Ract}) \oplus \zeta} R \oplus RT'[1]

are mutually inverse isomorphisms.

Since T'T' \xrightarrow{(5.14)} B \text{ is an isomorphism, it follows from the exactness of rows and columns in the diagram (5.35) that } SLT[−1] \xrightarrow{S\beta} SR \text{ is an isomorphism. So is } SLT[−1] \xrightarrow{S \circ S \beta} SFL[1], \text{ and hence so must also be } SR \xrightarrow{S \alpha} SFL[1]. \text{ Then } S(\alpha \circ \beta)^{-1} = (S \beta)^{-1} \circ (S \alpha)^{-1}, \text{ and hence the following diagram commutes}

$$SFL[1] \xrightarrow{S\eta} SRSL.$$  

Consider now the map SFL[1] \xrightarrow{\zeta} RT'[1] which is adjoint to FL[1] \xrightarrow{\zeta_\eta} RT''[1]. \text{ It filters through}

$$SFL[1] \xrightarrow{S(\zeta \eta)} SRT'[1]$$

which we can re-write as

$$SFL[1] \xrightarrow{(S \alpha)^{-1}} SR \xrightarrow{\text{Ract}} SRSL \xrightarrow{S \circ \zeta} SRT'[1]$$

and \( R \xrightarrow{\text{Ract}} RSL \xrightarrow{\zeta} RT'[1] \) is the zero map. We conclude that FL[1] \xrightarrow{\zeta_\eta} RT''[1] is adjoint to the zero map and hence itself is the zero map.

Similarly, S\alpha' and S\beta' are isomorphisms and the following diagram commutes

$$SRT'[1] \xrightarrow{S\zeta} SRSL.$$  

It follows, similarly, that SL \xrightarrow{S(Tact \circ act)} SR is the zero map and hence so is L \xrightarrow{Tact \circ act} R.

Observe now that the composition

$$L \oplus FL[1] \xrightarrow{(act_L) \oplus \eta} RSL \xrightarrow{(Tact) \oplus \zeta} R \oplus RT'[1]$$

is an isomorphism and we have shown the compositions

$$L \xrightarrow{\text{act}_L} RSL \xrightarrow{\zeta} RT'[1] \quad \text{and} \quad FL[1] \xrightarrow{\eta} RSL \xrightarrow{\zeta} RT'[1]$$

to be the zero maps. It follows that the compositions

$$L \xrightarrow{\text{act}_L} RSL \xrightarrow{\zeta} RT'[1] \quad \text{and} \quad FL[1] \xrightarrow{\eta} RSL \xrightarrow{\zeta} R$$

are isomorphisms. The former composition is, by definition, the map \( L \xrightarrow{\alpha'} RT'[1] \). It follows by Lemma 5.7 that the condition (4) holds, as desired. \( \square \)

5.2. Applications to algebraic geometry. In this section we interpret the results of Section 5.1 in the context of algebraic geometry.

Let \( Z \) and \( X \) be two separated schemes of finite type over \( k \). Recall that for any \( E \in D_{ qc}(Z \times X) \) the\ Footnote: Fourier-Mukai transform }\( \Phi_E \) is the functor \( D_{ qc}(Z) \rightarrow D_{ qc}(X) \) defined by

\[ R \pi_{X*} \left( E \otimes \pi_Z^*(-) \right), \]

where \( \pi_Z \) and \( \pi_X \) are the projections from \( Z \times X \) to \( Z \) and \( X \). Note that \( \Phi_E \) doesn’t apriori restrict to a functor \( D(Z) \rightarrow D(X) \).

As explained in Example 4.3 we can Morita enhance \( D(Z) \) and \( D(X) \) by smooth DG-algebras \( A \) and \( B \) whose classes in Ho(DG-Cat_{ketr}) are the standard enhancements of \( D(Z) \) and \( D(X) \). Moreover, DG-algebra \( A \cdot B \) Morita enhances \( D(Z \times X) \) and the following holds. Recall that Morita quasifunctors \( A \rightarrow B \) are identified naturally with the elements of \( D^{B \cdot \text{Perf}}_{B \cdot \text{Perf}}(A \cdot B) \). Since \( A \) is smooth, we have a natural inclusion \( D^{B \cdot \text{Perf}}_{B \cdot \text{Perf}}(A \cdot B) \hookrightarrow D_{c}(A \cdot B) \). Thus to each Morita quasifunctor \( A \xrightarrow{E} B \) corresponds an element in \( D_{c}(A \cdot B) \)
and so an element $E \in D(Z \times X)$. The Fourier-Mukai transform $\Phi_E$ restricts to a functor $D(Z) \xrightarrow{\Phi_E} D(X)$ and this functor is isomorphic to the exact functor $D(Z) \to D(X)$ underlying $F$.

Similarly, $\mathcal{B} \mathcal{-A}$, $\mathcal{A} \mathcal{D}$ and $\mathcal{B} \mathcal{B}$ Morita enhance $X \times Z$, $Z \times X$ and $X \times X$ with a similar correspondence between the Morita quasi-functors and the Fourier-Mukai transforms. Below we identify implicitly $X \times Z$ with $Z \times X$ using the canonical isomorphism between the two. For any object $E$ in $D_c(A)$, $D_c(B)$, $D_c(A \mathcal{-B})$, etc. we write $\mathcal{E}$ for the corresponding object in $D(Z)$, $D(X)$, $D(Z \times X)$, etc. And vice versa.

Let $\mathcal{S} \in D(Z \times X)$ be such that the corresponding $S \in D_c(A \mathcal{-B})$ is $\mathcal{A}$- and $\mathcal{B}$-perfect. In Section 5.1 we have used derived dualizing functors $(-)^{\mathcal{A}}$ and $(-)^{\mathcal{B}}$ to define objects $L = S^{\mathcal{A}}$ and $R = S^{\mathcal{B}}$ in $D(B, \mathcal{A})$. These are $\mathcal{A}$-perfect and $\mathcal{B}$-perfect, respectively. Since $\mathcal{A}$ and $\mathcal{B}$ are smooth, it follows by Cor. 2.9 that $L$ and $R$ lie in $D_c(B, \mathcal{A})$. The corresponding objects $L$ and $R$ in $D(X \times Z)$ define Fourier-Mukai transforms $D(X) \xrightarrow{\Phi_L, \Phi_R} D(Z)$ which are left and right adjoint to $D(Z) \xrightarrow{\Phi_L, \Phi_R} D(X)$. The adjunction co-units and units are the natural transformations of Fourier-Mukai transforms induced by the derived trace and action maps

$$SR \xrightarrow{\text{tr}} B \quad \text{and} \quad LS \xrightarrow{\text{tr}} A \quad (5.52)$$

$$B \xrightarrow{\text{act}} SL \quad \text{and} \quad A \xrightarrow{\text{act}} RS. \quad (5.53)$$

The co-twists $F, F' \in D(A, \mathcal{A})$ and the twists $T, T' \in D(B, \mathcal{B})$ of $S$ were defined in Section 5.1 as cones and co-cones of the derived trace and action maps above. It follows from Cor. 2.9 that they are all compact objects. Hence we can define the co-twist and the dual co-twist of $\mathcal{S}$ to be the corresponding objects $\mathcal{F}$ and $\mathcal{F}'$ in $D(Z \times X)$ and the twist and the dual twist of $\mathcal{S}$ to be $\mathcal{T}$ and $\mathcal{T}'$ in $D(X \times X)$. Finally, define

$$\Phi_R \to \Phi_R \Phi_L[1] \quad (5.54)$$

$$\Phi_L \Phi_T[-1] \to \Phi_R \quad (5.55)$$

to be the natural transformations of Fourier-Mukai transforms which correspond to the natural transformations $ll[-1] \xrightarrow{(5.11)} r$ and $r \xrightarrow{(5.12)} fl[1]$ constructed in Section 5.1.

The algebras $\mathcal{A}$ and $\mathcal{B}$ are constructed as DG-End-algebras of $h$-injective strong generators $F_Z$ and $F_X$ of $D(Z)$ and $D(X)$. The functors

$$R \text{Hom}_{D(Z)}(F_Z, -) : D(Z) \to D_c(A) \quad (5.56)$$

$$R \text{Hom}_{D(X)}(F_X, -) : D(X) \to D_c(B) \quad (5.57)$$

are the equivalences which give $\mathcal{A}$ and $\mathcal{B}$ the structure of Morita enhancements of $D(Z)$ and $D(X)$. It follows from [Lun10, Theorem 6.3] that choosing a different generator $F'_X$ of e.g. $D(X)$ produces a Morita-equivalent DG-algebra $B'$ and the Morita equivalence can be chosen so that the underlying exact equivalence $D_c(B) \simeq D_c(B')$ is compatible with enhancement equivalences (5.57) for $F_X$ and $F'_X$. More generally, it follows that a different choice of generators $F'_Z$ and $F'_X$ produces Morita-equivalent DG-algebras $\mathcal{A}'$, $B'$, $\mathcal{A}' \cdot B'$, $\mathcal{A}' \cdot \mathcal{A}'$ and $B' \cdot B'$ with Morita equivalences compatible with the enhancement equivalences as above.

All the constructions from Section 5.1 we have made use of so far were defined entirely in terms of the derived duals $R$ and $L$ of $S$ and the derived trace and action maps. One can check that the derived dualizing functors and the derived trace and action maps are preserved under Morita equivalences. Thus the objects $L, \mathcal{R}, F, F', T, T'$ and the natural transformations (5.54)-(5.55) defined above depend only on $\mathcal{S} \in D(Z \times X)$ itself, and do not depend on our choice of generators $F_X$ and $F_Y$ of $D(Z)$ and $D(X)$.

Though we have established that the above objects and maps are well-defined and determined only by $\mathcal{S} \in D(Z \times X)$, to actually compute them in any practical scenario would require explicit formulas for $L, \mathcal{R}$ in terms of $\mathcal{S}$ as well as the explicit formulas for the maps in $D(X \times X)$ and $D(Z \times Z)$ which correspond to the derived trace and action maps. To this end we offer the following:

**Conjecture 5.15.** Let $\mathcal{S} \in D(Z \times X)$ be such that the corresponding $S \in D_c(A \cdot B)$ is $\mathcal{A}$- and $\mathcal{B}$-perfect. Then

$$\mathcal{L} \simeq R \mathcal{H}om_{Z \times X} (\mathcal{S}, \pi^2_X(O_Z))$$

$$\mathcal{R} \simeq R \mathcal{H}om_{Z \times X} (\mathcal{S}, \pi^2_X(O_X))$$

and the maps in $D(Z \times X)$ and $D(X \times X)$ which correspond to the derived trace and action maps (5.52)-(5.53) are isomorphic to the explicit maps written down in [AL12] and [AL10] which lift the adjunction co-units and units of Fourier-Mukai transforms to the level of Fourier-Mukai kernels.

Finally, we need an intrinsic condition on $\mathcal{S} \in D(Z \times X)$ on the algebro-geometric side which ensures that the corresponding $S \in D_c(A \cdot B)$ is $\mathcal{A}$- and $\mathcal{B}$-perfect.
Lemma 5.16. Let \( \tilde{S} \in D(Z \times X) \). The Fourier-Mukai transform \( \Phi_S \) restricts to \( D(Z) \to D(X) \) and this restriction has a left adjoint which is also a Fourier-Mukai transform if and only if the corresponding object \( S \in D_c(\mathcal{A}-\mathcal{B}) \) is \( \mathcal{A}-\mathcal{B} \)-perfect.

Proof. As explained above, \( S \in D_c(\mathcal{A}-\mathcal{B}) \) is \( \mathcal{B} \)-perfect if and only if \( \Phi_S \) restricts to \( D(Z) \to D(X) \). In such case \( D_c(\mathcal{A}) \xrightarrow{-\otimes_\mathcal{A} S} D_c(\mathcal{B}) \) corresponds to \( D(Z) \xrightarrow{\Phi_S} D(X) \).

Suppose now \( S \) is also \( \mathcal{A} \)-perfect. By Lemma 2.2 the functor \( (-) \otimes_\mathcal{B} S^{\tilde{A}} \) is left adjoint to \( (-) \otimes_\mathcal{A} S \). Moreover, since \( S \) is \( \mathcal{A} \)-perfect, so is \( S^{\tilde{A}} \). Hence there exists an object in \( D(X \times Z) \) which defines the Fourier-Mukai transform \( D(X) \to D(Z) \) which corresponds to \( (-) \otimes_\mathcal{B} S^{\tilde{A}} \). In particular, this Fourier-Mukai transform is left adjoint to \( \Phi_S \).

Conversely, if there exists a Fourier-Mukai transform \( D(X) \to D(Z) \) which is the left adjoint to \( \Phi_S \), let \( L \) be the corresponding object of \( D^{\mathcal{A}-\mathcal{B}}(\mathcal{B}-\mathcal{A}) \). Then \( (-) \otimes_\mathcal{B} L \) is left adjoint to \( (-) \otimes_\mathcal{A} S \) as functors between \( D_c(\mathcal{A}) \) and \( D_c(\mathcal{B}) \). But since derived tensor product commutes with infinite direct sums, these are, in fact, adjoint on the whole of \( D(\mathcal{A}) \) and \( D(\mathcal{B}) \).

Since \( L \) is \( \mathcal{A} \)-perfect, by Lemma 2.2 the functor \( (-) \otimes_\mathcal{B} L \) from \( D(\mathcal{A}) \) to \( D(\mathcal{B}) \) has a right adjoint \( (-) \otimes_\mathcal{A} L^{\tilde{A}} \).

By uniqueness of adjoints we conclude that the functors \( (-) \otimes_\mathcal{A} S \) and \( (-) \otimes_\mathcal{A} L^{\tilde{A}} \) are isomorphic. Since \( L \) is \( \mathcal{A} \)-perfect, so is \( L^{\tilde{A}} \). Hence \( (-) \otimes_\mathcal{A} L^{\tilde{A}} \) takes compact objects to compact objects, and hence so does \( (-) \otimes_\mathcal{A} S \). We conclude that \( S \) is also \( \mathcal{A} \)-perfect, as desired. \( \square \)

Theorem 5.1 immediately implies the following:

**Theorem 5.2.** Let \( \tilde{S} \in D(Z \times X) \) be such that \( \Phi_S \) restricts to \( D(Z) \to D(X) \) and this restriction has a left adjoint which is also a Fourier-Mukai transform.

If any two of the following conditions hold:

1. \( \Phi_T \) is an autoequivalence of \( D(X) \) (“the twist is an equivalence”).
2. \( \Phi_F \) is an equivalence of \( D(Z) \) (“the cotwist is an equivalence”).
3. \( \Phi_R \xrightarrow{(5.54)} \Phi_F \Phi_L[1] \) is an isomorphism of functors (“the twist identifies the adjoints”).
4. \( \Phi_L \Phi_T[-1] \xrightarrow{(5.55)} \Phi_R \) is an isomorphism of functors (“the cotwist identifies the adjoints”).

then all four of them hold. If that happens, we say that \( \tilde{S} \) is spherical over \( Z \).

We can repeat all the arguments in this section using the framework of the Example 4.2 rather than the Example 4.3. Thus we would work with large Morita enhancements of \( D_{qc}(Z) \) and \( D_{qc}(X) \), rather than with Morita enhancements of \( D(Z) \) and \( D(X) \). This yields a construction of *twists* and *co-twists* as functors \( D_{qc}(X) \to D_{qc}(X) \) and \( D_{qc}(Z) \to D_{qc}(Z) \) and an analogue of Theorem 5.2. However, we would have to impose the following condition on the objects of \( \tilde{S} \in D_{qc}(Z \times X) \) which we work with: \( \Phi_S \) must have a left adjoint which is a Fourier-Mukai transform and they both must send compact objects to compact objects.

6. Braidings criteria for spherical DG-functors

Let \( \mathcal{A}_1, \mathcal{A}_2 \) and \( \mathcal{B} \) be small DG-categories and let \( S_1 \in D(\mathcal{A}_1-\mathcal{B}) \) and \( S_2 \in D(\mathcal{A}_2-\mathcal{B}) \) be two spherical objects. We keep all the notation conventions of Section 5. E.g. \( R_i \) denotes \( S_i^\mathcal{B} \), \( S_i R_i \) denotes \( R_i \otimes_\mathcal{A} S_i \), \( T_i \) denotes the cone of \( S_i R_i \xrightarrow{\text{tr}} \mathcal{B} \), etc.

6.1. Commutation. By functoriality of the derived tensor product, the following diagram commutes:

\[
\begin{array}{ccc}
S_1 R_1 S_2 R_2 & \xrightarrow{\text{Id}} & S_2 R_2 \\
\downarrow{\text{tr}} & & \downarrow{\text{Id}} \\
S_1 R_1 & \xrightarrow{\text{tr}} & S_2 R_2 \\
\end{array}
\]
The main result of this section is:

**Theorem 6.1.** Suppose there exists an isomorphism

\[ S_1 R_1 S_2 R_2 \xrightarrow{\phi} S_2 R_2 S_1 R_1 \]

which makes the diagram (6.1) commute. Then

\[ T_1 T_2 \simeq T_2 T_1. \]

**Proof.** Let \( M_1 \) and \( M_2 \) be \( h \)-projective \( A_1 \)-\( B \)- and \( A_2 \)-\( B \)-bimodules isomorphic to \( S_1 \) and \( S_2 \) in \( D(A_1 \cdot B) \) and \( D(A_2 \cdot B) \), respectively. By definition, \( T_1 T_2 \) is isomorphic in \( D(B \cdot B) \) to

\[ \left\{ M_2^R \otimes_{A_2} M_1 \overset{\gamma_1}{\rightarrow} B \right\} \otimes_{B} \left\{ M_1^B \otimes_{A_1} M_1 \overset{\gamma_2}{\rightarrow} B \right\} \]

which by Lemma 3.4 is isomorphic to the convolution of

\[ M_2^R \otimes_{A_2} M_2 \otimes_B M_1^R \otimes_{A_1} M_1 \overset{\alpha}{\rightarrow} (M_2^R \otimes_{A_2} M_2) \oplus (M_1^B \otimes_{A_1} M_1) \overset{\gamma_1}{\rightarrow} B \] \hspace{1cm} (6.2)

where \( \alpha = (\mathrm{tr} \otimes \mathrm{Id}) \oplus (\mathrm{Id} \otimes \mathrm{tr}) \) and \( \gamma_1 = \mathrm{tr} \oplus \mathrm{tr} \). Similarly, \( T_2 T_1 \) is isomorphic to the convolution of

\[ M_1^R \otimes_{A_1} M_1 \otimes_B M_2^R \otimes_{A_2} M_2 \overset{\beta}{\rightarrow} (M_1^R \otimes_{A_1} M_1) \oplus (M_2^R \otimes_{A_2} M_2) \overset{\gamma_1}{\rightarrow} B \] \hspace{1cm} (6.3)

where \( \beta = (\mathrm{tr} \otimes \mathrm{Id}) \oplus (\mathrm{Id} \otimes \mathrm{tr}) \).

By Theorem A.1 to show that (6.2) and (6.3) are homotopic in \( \mathrm{Pre-Tr}(\textbf{Mod} \cdot B \cdot B) \), and hence that \( T_1 T_2 \) and \( T_2 T_1 \) are isomorphic in \( D(B \cdot B) \), it suffices to exhibit

\[
\begin{align*}
&f \in \mathrm{Hom}_{B \cdot B} (M_2^R \otimes_{A_2} M_2 \otimes_B M_1^R \otimes_{A_1} M_1, \ M_1^R \otimes_{A_1} M_1 \otimes_B M_2^R \otimes_{A_2} M_2) \\
&s_1 \in \mathrm{Hom}_{B \cdot B}^{-1} (M_2^R \otimes_{A_2} M_2 \otimes_B M_1^R \otimes_{A_1} M_1, \ (M_1^R \otimes_{A_1} M_1) \oplus (M_2^R \otimes_{A_2} M_2)) \\
&s_2 \in \mathrm{Hom}_{B \cdot B}^{-1} (M_2^R \otimes_{A_2} M_2 \otimes_B M_1^R \otimes_{A_1} M_1, \ B)
\end{align*}
\]

such that

1. \( f \) is a homotopy equivalence
2. \( ds_1 = \alpha - \beta f \)
3. \( ds_2 = \gamma s_1 \).

Both \( M_1^R \) and \( M_2^R \) are \( B \)-\( h \)-projective. By Lemma 2.7 it follows that \( M_1^R \otimes_{A_1} M_1 \) and \( M_2^R \otimes_{A_2} M_2 \) are \( h \)-projective \( B \)-\( B \)-bimodules. So are therefore \( M_2^R \otimes_{A_2} M_2 \otimes_B M_1^R \otimes_{A_1} M_1 \) and \( M_1^R \otimes_{A_1} M_1 \otimes_B M_2^R \otimes_{A_2} M_2 \). Thus the Hom-spaces in \( \mathrm{H}^1(\textbf{Mod} \cdot B \cdot B) \) with these objects as a source are isomorphic to the corresponding \( \mathrm{Ext}^1 \)-spaces in \( D(B \cdot B) \).

In particular, we can lift the isomorphism

\[ S_1 R_1 S_2 R_2 \xrightarrow{\phi} S_2 R_2 S_1 R_1 \]

in \( D(B \cdot B) \) to some homotopy equivalence

\[ f \in \mathrm{Hom}_{D(B \cdot B)} (S_1 R_1 S_2 R_2, S_1 R_1 \oplus S_2 R_2). \]

Moreover, the fact that \( \phi \) makes (6.1) commute in \( D(B \cdot B) \) implies precisely that \( \alpha - \beta f \) vanishes in

\[ \mathrm{Hom}_{D(B \cdot B)} (S_1 R_1 S_2 R_2, S_1 R_1 \oplus S_2 R_2). \]

Hence we can find some

\[
\begin{align*}
s_1 &\in \mathrm{Hom}_{B \cdot B}^{-1} (M_2^R \otimes_{A_2} M_2 \otimes_B M_1^R \otimes_{A_1} M_1, \ (M_1^R \otimes_{A_1} M_1) \oplus (M_2^R \otimes_{A_2} M_2)) \\
ds_2 &\in \mathrm{Hom}_{B \cdot B}^{-1} (M_2^R \otimes_{A_2} M_2 \otimes_B M_1^R \otimes_{A_1} M_1, \ B)
\end{align*}
\]

with \( ds_1 = \gamma s_1 \), whence as explained above the claim of this theorem would follow.

It suffices, however, to find

\[
\begin{align*}
t_1 &\in \mathrm{Hom}_{B \cdot B}^{-1} (M_2^R \otimes_{A_2} M_2 \otimes_B M_1^R \otimes_{A_1} M_1, \ (M_1^R \otimes_{A_1} M_1) \oplus (M_2^R \otimes_{A_2} M_2))
\end{align*}
\]
with $dt_1 = 0$ and $\gamma_1 = \gamma s_1$ in $\text{Ext}^{-1}_{D(B-B)}(S_1 R_1 S_2 R_2, B)$. For if we then replace $s_1$ with $s_1 - t_1$ the condition $ds_1 = \alpha - \beta f$ would still hold, but the class of $\gamma s_1$ would now vanish in $\text{Ext}^{-1}_{D(B-B)}(S_1 R_1 S_2 R_2, B)$ as required. Thus it remains to merely show that the class $[\gamma s_1]$ in $\text{Ext}^{-1}_{D(B-B)}(S_1 R_1 S_2 R_2, B)$ lifts with respect to

$$\text{Ext}^{-1}_{D(B-B)}(S_1 R_1 S_2 R_2, S_1 R_1 \oplus S_2 R_2) \xrightarrow{\gamma(-)} \text{Ext}^{-1}_{D(B-B)}(S_1 R_1 S_2 R_2, B) \quad (6.4)$$

to some class in $\text{Ext}^{-1}_{D(B-B)}(S_1 R_1 S_2 R_2, S_1 R_1 \oplus S_2 R_2)$.

We claim that, in fact, (6.4) is surjective. Indeed, it follows from Prop. 2.1 via the usual adjunction-type argument that for any $N_1 \in D(A_2-A_1)$ and $N_2 \in D(B-B)$ the map

$$\text{Ext}^{-1}_{D(B-B)}(S_1 N_1 R_2, N_2) \rightarrow \text{Ext}^{-1}_{D(B-B)}(N_1, R_1 N_2 S_2) \quad (6.5)$$

given by

$$\alpha \rightarrow N_1 \xrightarrow{\text{act} N_1} R_1 S_1 N_1 R_2 S_2 \xrightarrow{R_1 \alpha S_2} R_1 N_2 S_2$$

is a functorial isomorphism. We thus have a commutative diagram

$$\begin{array}{c}
\text{Ext}^{-1}_{D(B-B)}(S_1 R_1 S_2 R_2, S_1 R_1 \oplus S_2 R_2) \\
\sim
\text{Ext}^{-1}_{D(B-B)}(S_1 R_1 S_2 R_2, B) \\
\sim
\text{Ext}^{-1}_{D(A_2-A_1)}(R_1 S_2, R_1 S_1 R_2 S_2 \oplus R_1 S_2 R_2 S_2) \\
\xrightarrow{(R_1 \gamma S_2)(-) \quad (6.6)} \\
\text{Ext}^{-1}_{D(A_2-A_1)}(R_1 S_2, R_1 S_2)
\end{array}$$

The map $R_1 \gamma S_2$ is the map

$$R_1 S_1 R_2 S_2 \oplus R_1 S_2 R_2 S_2 \xrightarrow{R_1 \text{tr} S_2 \oplus R_1 \text{tr} S_2} R_1 S_2$$

and by Prop 2.1 the map

$$R_1 S_2 \xrightarrow{1\text{act}} R_1 S_1 R_2 S_2 \oplus R_1 S_2 R_2 S_2$$

is its left inverse in $D(A_2-A_1)$. Therefore

$$\text{Ext}^{-1}_{D(A_2-A_1)}(R_1 S_2, R_1 S_1 R_2 S_2 \oplus R_1 S_2 R_2 S_2) \xrightarrow{(R_1 \gamma S_2)(-) \quad (6.6)} \text{Ext}^{-1}_{D(A_2-A_1)}(R_1 S_2, R_1 S_2)$$

is surjective and hence so is (6.4) as desired.

6.2. Braiding. Define

$$O_i = F_i\{L_i S_j R_j S_i \xrightarrow{\text{tr} \circ (L_i \text{tr} S_i)} A_i\} \in D(A_i-A_i) \quad (6.7)$$

where $i, j \in \{1, 2\}$, $i \neq j$. For spherical $S_1, S_2$ the natural map $R_i[-1] \xrightarrow{\alpha} F_i L_i$ is an isomorphism and it can be checked to identify the map in (6.7) with the map

$$R_i S_j R_j S_i[-1] \xrightarrow{R_i \text{tr} S_i} R_i S_i[-1] \rightarrow F_i$$

whose second composant comes from the exact triangle $F_i \rightarrow A_i \rightarrow R_i S_i$. Thus, we can identify object $O_i$ with the convolution of the twisted complex

$$\left(M_i \otimes_{B} M_j^B \otimes_{A_i} M_j \otimes_{B} M^B_{i}\right) \oplus A_i \xrightarrow{((\text{Id} \otimes \text{tr} \otimes \text{Id}) \oplus (-\text{act})) M_i \otimes M^B_{i} \quad (6.8)}$$

in Pre-Tr$(\text{Mod-} A_i-A_i)$. Denote the complex itself by $O_i$.

There are natural maps

$$S_1 O_1 R_1 \rightarrow S_1 R_1 S_2 R_2 \oplus S_2 R_2 S_1 R_1 \quad (6.9)$$

induced by the trace maps

$$M_i^B \otimes_{A_i} M_i \otimes_{B} M^B \otimes_{A_i} M_j \otimes_{B} M^B \otimes_{A_i} M_i \xrightarrow{((\text{Id} \otimes \text{tr} \otimes \text{Id} \otimes \text{Id})) M_i \otimes M^B_{i} \otimes_{A_i} M_j \otimes_{B} M^B \otimes_{A_i} M_i} \quad (6.11)$$

The main result of this section is:
**Theorem 6.2.** Suppose there exists an isomorphism

\[ S_1O_1R_1 \xrightarrow{\delta} S_2O_2R_2 \]

which commutes with the maps (6.9) and (6.10). Then

\[ T_1T_2T_1 \simeq T_2T_1T_2. \]

**Proof.** By the Cube Lemma or otherwise \( T_1T_2T_1 \) is isomorphic to the convolution of the twisted cube

\[ \begin{array}{c}
\cdots \\
M_1^B \otimes M_1 \otimes M_2^B \otimes M_2 \\
| \\
M_1^B \otimes M_1 \otimes M_2^B \otimes M_2 \\
| \\
M_1^B \otimes M_1 \\
| \\
\cdots \\
\end{array} \]

(6.13)

where all the arrows are induced by trace maps, all the dotted arrows are additionally multiplied by \(-1\) and all the maps of degree \(\geq 2\) are zero.

In a similar fashion to the way Lemma 5.10 was proved, the total complex of this twisted cube can be shown to be homotopy equivalent to the twisted complex

\[ \begin{array}{c}
\cdots \\
M_1^B \otimes M_1 \otimes M_2^B \otimes M_2 \oplus M_1^B \otimes M_1 \\
| \\
M_1^B \otimes M_1 \otimes M_2^B \otimes M_2 \oplus M_1^B \otimes M_1 \\
| \\
M_1^B \otimes M_1 \\
| \\
\cdots \\
\end{array} \]

(6.14)

where all the unmarked arrows are induced by trace maps, all the dotted arrows are additionally multiplied by \(-1\) and all the higher differentials are zero. This is in turn is homotopy equivalent to the twisted complex

\[ M_1^B \otimes O_1 \otimes M_1 \xrightarrow{\alpha} M_1^B \otimes M_1 \otimes M_2^B \otimes M_2 \oplus M_1^B \otimes M_2 \oplus M_1^B \otimes M_1 \xrightarrow{\gamma} M_1^B \otimes M_1 \oplus M_2^B \otimes M_2 \xrightarrow{\delta} B \]  

(6.15)

Again, all higher differentials in this twisted complex are zero.

Similarly, \( T_2T_1T_2 \) is the convolution of a twisted complex

\[ M_2^B \otimes O_2 \otimes M_2 \xrightarrow{\beta} M_1^B \otimes M_1 \otimes M_2^B \otimes M_2 \oplus M_2^B \otimes M_2 \oplus M_2^B \otimes M_1 \xrightarrow{\gamma} M_1^B \otimes M_1 \oplus M_2^B \otimes M_2 \xrightarrow{\delta} B \]  

(6.16)

with zero higher differentials.

The complexes (6.15) and (6.16) descend to complexes

\[ S_1O_1R_1 \xrightarrow{(6.9)} S_1R_1S_2R_2 \oplus S_2R_2S_1R_1 \xrightarrow{\left( \frac{S_1R_1 \text{tr}}{\text{tr} S_2R_2} - \frac{\text{tr} S_1R_1}{ S_2R_2 \text{tr}} \right)} S_1R_1 \oplus S_2R_2 \xrightarrow{\text{tr} \oplus \text{tr}} B \]  

(6.17)

\[ S_2O_2R_2 \xrightarrow{(6.10)} S_1R_1S_2R_2 \oplus S_2R_2S_1R_1 \xrightarrow{\left( \frac{S_1R_1 \text{tr}}{\text{tr} S_2R_2} - \frac{\text{tr} S_1R_1}{ S_2R_2 \text{tr}} \right)} S_1R_1 \oplus S_2R_2 \xrightarrow{\text{tr} \oplus \text{tr}} B. \]

(6.18)

in \( D(B-B) \).
By Theorem A.1 to show that 6.15 and 6.16 are homotopy equivalent in Pre-Tr(\(\text{Mod}-B-B\)), and hence that \(T_1T_2T_1\) and \(T_2T_1T_2\) are isomorphic in \(D(B-B)\), it suffices to exhibit

\[
\begin{align*}
 f & \in \text{Hom}_{B-B}^1 (M^B_1 \otimes_{A_1} O_1 \otimes_{A_1} M_1, \ M^B_2 \otimes_{A_2} O_2 \otimes_{A_2} M_2) \\
 s_1 & \in \text{Hom}_{B-B}^1 (M^B_1 \otimes_{A_1} O_1 \otimes_{A_1} M_1, \ (M^B_1 \otimes_{A_1} M_1 \otimes_B M^B_2 \otimes_{A_2} M_2) \otimes (M^B_2 \otimes_{A_2} M_2 \otimes_B M^B_1 \otimes_{A_1} M_1)) \\
 s_2 & \in \text{Hom}_{B-B}^2 (M^B_1 \otimes_{A_1} O_1 \otimes_{A_1} M_1, \ (M^B_1 \otimes_{A_1} M_1) \otimes (M^B_2 \otimes_{A_2} M_2)) \\
 s_3 & \in \text{Hom}_{B-B}^3 (M^B_1 \otimes_{A_1} O_1 \otimes_{A_1} M_1, \ B)
\end{align*}
\]

such that

1. \(f\) is a homotopy equivalence
2. \(ds_1 = \alpha - \beta f\)
3. \(ds_2 = \gamma s_1\)
4. \(ds_3 = -\delta s_2\).

As in the proof of Theorem 6.1 we can lift \(\phi\) to some homotopy equivalence \(f\) and the existence of some \(\tilde{s}_1 \in \text{Hom}_{B-B}^{\infty} (M^B_1 \otimes_{A_1} O_1 \otimes_{A_1} M_1, \ (M^B_1 \otimes_{A_1} M_1 \otimes_B M^B_2 \otimes_{A_2} M_2) \otimes (M^B_2 \otimes_{A_2} M_2 \otimes_B M^B_1 \otimes_{A_1} M_1))\) with \(d\tilde{s}_1 = \alpha - \beta f\) is guaranteed by the commutation of \(\phi\) with (6.9)-(6.10). Since \(\gamma\alpha = \gamma\beta = 0\) we have\(d(\gamma s_1) = 0\). Thus \(\gamma s_1\) defines the class \(\left[\gamma s_1\right]\in \text{Ext}^1_{D(B-B)}(S_1O_1R_1, S_1R_1 \oplus S_2R_2)\) and since \(\delta\gamma = 0\) the composition \(\delta[\gamma s_1]\) vanishes in \(\text{Ext}^1_{D(B-B)}(S_1O_1R_1, B)\). By Cor. 6.2 below there exists

\[
t_1 \in \text{Hom}_{B-B}^{\infty} (M^B_1 \otimes_{A_1} O_1 \otimes_{A_1} M_1, \ (M^B_1 \otimes_{A_1} M_1 \otimes_B M^B_2 \otimes_{A_2} M_2) \otimes (M^B_2 \otimes_{A_2} M_2 \otimes_B M^B_1 \otimes_{A_1} M_1))
\]

such that \(dt_1 = 0\) and \(\left[\gamma \tilde{s}_1\right] = [\gamma t_1]\) in \(\text{Ext}^1_{D(B-B)}(S_1O_1R_1, S_1R_1 \oplus S_2R_2)\). Set \(s_1 = \tilde{s}_1 - t_1\). We still have \(ds_1 = \alpha - \beta f\), but the class of \(\gamma s_1\) in \(\text{Ext}^1_{D(B-B)}(S_1O_1R_1, S_1R_1 \oplus S_2R_2)\) is zero, so there exists

\[
\tilde{s}_2 \in \text{Hom}_{B-B}^{\infty} (M^B_1 \otimes_{A_1} O_1 \otimes_{A_1} M_1, \ (M^B_1 \otimes_{A_1} M_1) \otimes (M^B_2 \otimes_{A_2} M_2))
\]

such that \(d\tilde{s}_2 = \gamma s_1\). Since \(\delta\gamma = 0\) we have \(d(d\tilde{s}_2) = 0\). Thus \(\tilde{s}_2\) defines a class in \(\text{Ext}^1_{D(B-B)}(S_1O_1R_1, B)\). By Cor. 6.2 there exists

\[
t_2 \in \text{Hom}_{B-B}^{\infty} (M^B_1 \otimes_{A_1} O_1 \otimes_{A_1} M_1, \ (M^B_1 \otimes_{A_1} M_1) \otimes (M^B_2 \otimes_{A_2} M_2))
\]

with \(dt_2 = 0\) and \([\delta t_2] = [\delta \tilde{s}_2]\). Set \(s_2 = \tilde{s}_2 - t_2\). Once again, we still have \(ds_2 = \gamma s_1\), but the class of \(\delta s_2\) in \(\text{Ext}^2_{D(B-B)}(S_1O_1R_1, B)\) is zero, so there exists

\[
s_3 \in \text{Hom}_{B-B}^{\infty} (M^B_1 \otimes_{A_1} O_1 \otimes_{A_1} M_1, B)
\]

with \(ds_3 = -\delta s_2\).

\[\square\]

**Lemma 6.1.** There is a diagram of Ext groups in \(D(B-B)\)

\[
\begin{array}{ccc}
\text{Ext}^1_{D(B-B)}(\ast, S_1R_1) & \ast & \text{Ext}^1_{D(B-B)}(\ast, S_1R_1) \\
\kappa_1 \downarrow & & \mu_1 \downarrow \\
\text{Ext}^1_{D(B-B)}(\ast, B) & \ast & \text{Ext}^1_{D(B-B)}(\ast, B) \\
\eta_1 \downarrow & & \nu_1 \downarrow \\
\text{Ext}^1_{D(B-B)}(\ast, S_2R_2) & \ast & \text{Ext}^1_{D(B-B)}(\ast, S_2R_2) \\
\kappa_2 \downarrow & & \mu_2 \downarrow \\
\text{Ext}^1_{D(B-B)}(\ast, S_2R_2) & \ast & \text{Ext}^1_{D(B-B)}(\ast, S_2R_2) \\
\eta_2 \downarrow & & \nu_2 \downarrow \\
\text{Ext}^1_{D(B-B)}(\ast, S_2R_2) & \ast & \text{Ext}^1_{D(B-B)}(\ast, S_2R_2)
\end{array}
\]

(6.19)

where \(\ast\) can mean \(S_1O_1R_1\) or \(S_2O_2R_2\) (since they are isomorphic in the derived category).

Moreover, in this diagram

\[\eta_1 \kappa_1 = \text{Id} \quad \text{and} \quad \nu_1 \mu_1 = \text{Id}\]

while

\[\nu_2 \mu_1 = -\kappa_2 \eta_1\]
\[\nu_1 \mu_2 = -\kappa_1 \eta_2\]
\[\eta_1 \nu_1 = -\eta_2 \nu_2.\]
Proof. The maps $\nu_i, \eta_i$ are induced by the following maps:

$$
\begin{align*}
\nu_1 & \quad \text{by} \quad S_1 R_1 S_2 R_2 \oplus S_2 R_2 S_1 R_1 \quad \overset{-S_1 R_1 \text{tr} \oplus \text{tr} S_1 R_1}{\longrightarrow} \quad S_1 R_1 \\
\nu_2 & \quad \text{by} \quad S_1 R_1 S_2 R_2 \oplus S_2 R_2 S_1 R_1 \quad \overset{\text{tr} S_2 R_2 \oplus -S_2 R_2 \text{tr}}{\longrightarrow} \quad S_2 R_2.
\end{align*}
$$

The map $\mu_1$ is given by

$$
\begin{align*}
\text{Ext}^i_{D(B,B)}(S_2 O_2 R_2, S_1 R_1) & \quad \overset{-S_2 R_2}{\longrightarrow} \quad S_2 (-) S_2 R_2 \\
\text{Ext}^i_{D(B,B)}(S_2 R_2 S_2 O_2 R_2 S_2 R_2, S_2 R_2 S_1 R_1 S_2 R_2) & \quad \overset{-\frac{1}{4}(S_2 R_2 S_1 R_1 \text{tr})}{\longrightarrow} \quad \text{Ext}^i_{D(\mathcal{B},\mathcal{B})}(S_2 O_2 R_2, S_1 R_1 S_2 R_2 \oplus S_2 R_2 S_1 R_1) \quad (6.20)
\end{align*}
$$

The map $\kappa_1$ is given by

$$
\begin{align*}
\text{Ext}^i_{D(B,B)}(S_1 O_1 R_1, B) & \quad \overset{S_1 R_1 (-) S_1 R_1}{\longrightarrow} \quad S_1 R_1 S_1 O_1 R_1 S_1 R_1, S_1 R_1 S_1 R_1 \\
\text{Ext}^i_{D(B,B)}(S_1 R_1 S_1 O_1 R_1 S_1 R_1, S_1 R_1 S_1 R_1) & \quad \overset{S_1 \text{act} O_1 \text{act} R_1}{\longrightarrow} \quad \text{Ext}^i_{D(B,B)}(S_1 O_1 R_1, S_1 R_1 S_1 R_1) \quad (6.21) \\
\text{Ext}^i_{D(B,B)}(S_1 O_1 R_1, S_1 R_1 S_1 R_1) & \quad \overset{S_1 R_1 \text{tr}}{\longrightarrow} \quad \text{Ext}^i_{D(B,B)}(S_1 O_1 R_1, S_1 R_1).
\end{align*}
$$

The maps $\mu_2$ and $\kappa_2$ are constructed the same way.

The relation $\eta_1 \nu_1 = -\eta_2 \nu_2$ is clear by functoriality of the tensor product. The relations $\eta_i \kappa_i = \text{Id}$ and $\nu_i \mu_i = \text{Id}$ are verified directly using Prop. 2.1. Let us prove that $\nu_2 \mu_1 = -\kappa_2 \eta_1$. Consider now the composition

$$
\begin{align*}
\text{Ext}^i_{D(B,B)}(S_2 O_2 R_2, B) & \quad \overset{-S_2 R_2}{\longrightarrow} \quad S_2 (-) S_2 R_2 \\
\text{Ext}^i_{D(B,B)}(S_2 R_2 S_2 O_2 R_2 S_2 R_2, S_2 R_2 S_2 R_2) & \quad \overset{-\frac{1}{4}(S_2 R_2 \text{tr})}{\longrightarrow} \quad \text{Ext}^i_{D(B,B)}(S_2 O_2 R_2, S_2 R_2 S_2 R_2) \quad (6.22) \\
\text{Ext}^i_{D(B,B)}(S_2 O_2 R_2, S_2 R_2 S_2 R_2) & \quad \overset{-\frac{1}{4}(S_2 R_2 \text{tr})}{\longrightarrow} \quad \text{Ext}^i_{D(B,B)}(S_2 O_2 R_2, S_2 R_2 \oplus S_2 R_2).
\end{align*}
$$

and the map

$$
\begin{align*}
\text{Ext}^i_{D(B,B)}(S_2 O_2 R_2, S_1 R_1 S_2 R_2 \oplus S_2 R_2 S_1 R_1) & \quad \overset{\text{tr} S_2 R_2 \oplus S_2 R_2 \text{tr}}{\longrightarrow} \quad \text{Ext}^i_{D(B,B)}(S_2 O_2 R_2, S_2 R_2 \oplus S_2 R_2) \quad (6.23)
\end{align*}
$$
Applying the map $S_1R_1 \xrightarrow{\mu_1} B$ to every composant of (6.20) and using functoriality we see that the square

\[ \begin{array}{c}
\Ext^i_{D(B,B)}(S_2O_2R_2, S_1R_1) \\
\downarrow q_i \\
\Ext^i_{D(B,B)}(S_2O_2R_2, B)
\end{array} \quad \mu_1 \quad \begin{array}{c}
\Ext^i_{D(B,B)}(S_2O_2R_2, S_2R_2 \oplus S_2R_2S_1R_1) \\
\downarrow (6.23)
\end{array} \begin{array}{c}
\Ext^i_{D(B,B)}(S_2O_2R_2, S_2R_2 \oplus S_2R_2).
\end{array} \]

commutes. By inspection, the composition of (6.22) with the map

\[ \Ext^i_{D(B,B)}(S_2O_2R_2, S_2R_2 \oplus S_2R_2) \xrightarrow{\Id \oplus \Id} \Ext^i_{D(B,B)}(S_2O_2R_2, S_2R_2) \]  

(6.24)

is $-\kappa_2$, while the composition of (6.23) with (6.24) is $\nu_2$. It follows that $\nu_2\mu_1 = -\kappa_2\eta_1$, as desired. \qed

**Corollary 6.2.** The sequence

\[ \Ext^i_{D(B,B)}(S_1O_1R_1, S_1R_1S_2R_2 \oplus S_2R_2S_1R_1) \xrightarrow{\delta} \Ext^i_{D(B,B)}(S_1O_1R_1, S_1R_1 \oplus S_2R_2) \xrightarrow{\delta} \Ext^i_{D(B,B)}(S_1O_1R_1, B) \]

is exact in its middle term and surjective onto its last term.

**Appendix A. On homotopy equivalences of twisted complexes**

Let $C$ be a strongly pretriangulated DG-category. The example one wants to keep in mind is $P(A)$ for some DG-category $A$, so that $H^0(C) = D(A)$. Let $(E, q_{ij})$ be a twisted complex over $C$. The objects $E_i$ and the degree 0 morphisms $q_{i(i+1)}$ form an ordinary differential complex over $H^0(C)$:

\[ \ldots \xrightarrow{q_{(i-1)0}} E_{i-1} \xrightarrow{q_{i(i-1)}} E_i \xrightarrow{q_{i(i+1)}} E_{i+1} \xrightarrow{q_{(i+1)(i+2)}} \ldots \]

Let $(E_i, q_{ij})$ and $(F_i, r_{ij})$ be two twisted complexes over $C$. We would like to know when their convolutions $(E, q_{ij})$ and $(F, r_{ij})$ are isomorphic in $H^0(C)$. Since $C$ was assumed to be strongly pretriangulated constructing isomorphism of $(E_i, q_{ij})$ and $(F_i, r_{ij})$ in $H^0(C)$ is the same thing as constructing a homotopy equivalence of $(E_i, q_{ij})$ and $(F_i, r_{ij})$ in $\text{Pre-Tr}(C)$.

Suppose that the underlying differential complexes of $(E_i, q_{ij})$ and $(F_i, r_{ij})$ are isomorphic, more specifically - that we have a set of isomorphisms $E_i \xrightarrow{\delta} F_i$ in $H^0(C)$ which gives an isomorphism of these differential complexes. This alone doesn’t ensure that $(E_i, q_{ij})$ and $(F_i, r_{ij})$ are isomorphic in $H^0(C)$, since the same differential complex over $H^0(C)$ can, in general, be lifted to several non-homotopically equivalent twisted complexes over $C$. Thus the question: what are the sufficient conditions on $f$ for us to be able to cook up a homotopy equivalence of $(E_i, q_{ij})$ and $(F_i, r_{ij})$ from them?

When trying to construct this homotopy equivalence even in simplest cases, one encounters a number of conditions which, at first glance, seem unavoidable, but in fact are redundant:

**Example A.1.** Let $E \xrightarrow{q} G$ and $F \xrightarrow{r} G$ be two twisted complexes over $C$. Let $E \xrightarrow{f} F$ be a homotopy equivalence in $C$, such that the square

\[ \begin{array}{cc}
E & \xrightarrow{q} & G \\
\downarrow f & & \downarrow \Id \\
F & \xrightarrow{r} & G
\end{array} \]

(A.1)

commutes in $H^0(C)$. Since $H^0(C)$ is triangulated, there exists an isomorphism $\text{Cone}(q) \rightarrow \text{Cone}(r)$ which extends this square in $H^0(C)$ to an isomorphism of exact triangles. It follows that we can extend $E \xrightarrow{f} F$ and $G \xrightarrow{\Id} G$ to a homotopy equivalence in $\text{Pre-Tr}(C)$ of the twisted complexes $E \xrightarrow{q} G$ and $F \xrightarrow{r} G$.

If we actually try to construct this homotopy equivalence, we run into the following type of problems:

**Claim:** Let $g \in \text{Hom}_C^0(F, E)$ be a homotopy inverse of $f$. In other words, there exist $h \in \text{Hom}_C^{-1}(E, E)$ and $h' \in \text{Hom}_C^{-1}(F, F)$ such that $gf - \Id = dh$ and $fg - \Id = dh'$. 

\[ \begin{array}{cc}
E & \xrightarrow{q} & G \\
\downarrow f & & \downarrow \Id \\
F & \xrightarrow{r} & G
\end{array} \]
Then there exist mutually inverse homotopy equivalences

\[
\begin{array}{ccc}
E & \xrightarrow{q} & G \\
\downarrow f & & \downarrow g \\
F & \xrightarrow{r} & G
\end{array}
\quad \begin{array}{ccc}
F & \xrightarrow{r} & G \\
\downarrow g & & \downarrow h \\
E & \xrightarrow{q} & G
\end{array}
\quad \begin{array}{c}
t \in \text{Hom}_C^{-1}(X,G), \\
t' \in \text{Hom}_C^{-1}(Y,G)
\end{array}
\]

of \(E \xrightarrow{q} G\) and \(F \xrightarrow{r} G\) if and only if \(h\) and \(h'\) can be chosen so that the following equivalent conditions hold:

1. \(r(fh - h'f) = ds\) for some \(s \in \text{Hom}_C^{-2}(E,G)\).
2. \(q(gh' - hg) = ds'\) for some \(s' \in \text{Hom}_C^{-2}(F,G)\).

**Proof:** Straightforward verification.

Apriori, there is no reason to expect a class like \(r(fh - h'f)\) in \(\text{Hom}_C^{-1}(E,G)\) to be null-homotopic. In fact, for general \(h\) and \(h'\) it wouldn’t be. So this may seem like a genuinely necessary condition.

However, it turns out that we can always choose \(h\) and \(h'\) so that even \(fh - h'f\) and \(gh' - hg\) are null-homotopic. Since \(dq = dr = 0\), it would also imply the conditions above.

The explanation is: \(fh - h'f\) and \(gh' - hg\) are both killed by the differential, and thus define classes \(\xi \in \text{Hom}_{H^0(C)}^{-1}(E,F)\) and \(\xi' \in \text{Hom}_{H^0(C)}^{-1}(F,E)\), respectively. Since \(f\) and \(g\) are isomorphisms in \(H^0(C)\), they identify both \(\text{Hom}_{H^0(C)}^{-1}(E,F)\) and \(\text{Hom}_{H^0(C)}^{-1}(F,E)\) with \(\text{Hom}_{H^0(C)}^{-1}(E,E)\). Apriori, neither \(\xi\) nor \(\xi'\) are zero, however one can check that \(\xi\) and \(-\xi'\) give the same class in \(\text{Hom}_{H^0(C)}^{-1}(E,E)\). We can therefore correct \(h \in \text{Hom}_C^{-1}(E,E)\) by this class and kill off both \(\xi\) and \(\xi'\), as required.

It is not a calculation one would want to try and write down in a larger, more complicated scenario. Fortunately, there turns out to be a more conceptual argument. It requires us to consider \(A_\infty\)-categories and \(A_\infty\)-functors, see [Kel01] and [LH03, §8] for the basics. In particular, we use the convention in [LH03, §8] for denoting \(A_\infty\)-functors as \((\hat{i}, \hat{f}_i)\) where \(\hat{i}\) is the object map, \(\hat{f}_i\) is the morphism map and \(\hat{f}_{i \geq 2}\) are the higher morphism maps.

A choice of \(h\) and \(h'\) as above and also of \(j \in \text{Hom}_C^{-2}(X,Y)\) and \(j' \in \text{Hom}_C^{-2}(Y,X)\) such that \(fh - h'f = dj\) and \(fh - h'f = dj'\) can readily be checked to be a part of precisely the data necessary to define a strictly unital \(A_\infty\)-functor

\[
\begin{array}{c}
\psi \phi = \text{Id}_x, \\
\phi \psi = \text{Id}_y, \\
\phi \beta = \alpha, \\
\psi \alpha = \beta,
\end{array}
\]

which sends \(x, y, a\) to \(E, F, G\) and \(\phi, \psi, \alpha, \beta\) to \(f, g, q, r\). Here, the quiver on the left defines an additive \(k\)-category whose objects are the vertices of the quiver and whose Hom-spaces are generated by the paths in the quiver, modulo the indicated relations. The trivial path from a vertex to itself correspond to its identity morphism. Denote this category by \(B_1\), we think of it as of a DG-category concentrated in degree zero.

Conversely, any \(A_\infty\)-functor \(B_1 \xrightarrow{(\hat{i}, \hat{f}_i)} C\) as above contains the data of homotopy equivalences (A.2). This is because \((\hat{i}, \hat{f}_i)\) extends naturally to an \(A_\infty\)-functor \(\text{Pre-Tr}(B_1) \xrightarrow{(\hat{i}, \hat{f}_i)} \text{Pre-Tr}(C)\). In \(\text{Pre-Tr}(B_1)\) the twisted complexes \(x \xrightarrow{\alpha} a\) and \(y \xrightarrow{\beta} a\) are isomorphic. Specifically,

\[
\begin{array}{c}
\begin{array}{ccc}
x & \xrightarrow{\alpha} & a \\
\downarrow \phi & & \downarrow \text{Id} \\
y & \xrightarrow{\beta} & a
\end{array}
\quad \begin{array}{ccc}
x & \xrightarrow{\alpha} & a \\
\downarrow \phi & & \downarrow \text{Id} \\
y & \xrightarrow{\beta} & a
\end{array}
\end{array}
\]
are mutually inverse isomorphisms. Their images under \( f_1 \) are the morphisms

\[
\begin{array}{ccc}
E & \xrightarrow{q} & G \\
\downarrow f & & \downarrow \text{Id} \\
F & \xrightarrow{r} & G
\end{array}
\quad \text{and} \quad
\begin{array}{ccc}
F & \xrightarrow{r} & G \\
\downarrow g & & \downarrow \text{Id} \\
E & \xrightarrow{q} & G
\end{array}
\]

in \( \text{Pre-Tr}(C) \). Since \( \left( \hat{i}, H^0(f_1) \right) \) is an exact functor, these become mutually inverse isomorphisms in \( H^0(\text{Pre-Tr}(C)) \). Thus, they are the mutually inverse homotopy equivalences (A.2) we want.

To construct a strictly unital \( A_\infty \)-functor \( \bar{B}_1 \xrightarrow{(\hat{i}, \hat{f})} C \) it suffices to construct a strictly unital \( A_\infty \)-functor \( B_1 \xrightarrow{\Phi} C \) where \( B_1 \) is the category

\[
\begin{array}{ccc}
z & \xrightarrow{\alpha} & x \\
\downarrow \phi & & \downarrow \phi \\
y & \xrightarrow{\beta} & y
\end{array}
\quad \text{with} \quad \phi \beta = \alpha.
\]

Roughly, this is because \( \bar{B}_1 \) is the minimal \( A_\infty \)-structure of a certain DG-quotient of \( B_1 \) whose universal properties ensure that \( B_1 \xrightarrow{\Phi} C \) filters through some \( \bar{B}_1 \xrightarrow{(\hat{i}, \hat{f})} C \). We’ll give the full argument in a greater generality later on in this section.

Thus we are reduced to constructing a strictly unital \( A_\infty \)-functor \( B_1 \xrightarrow{\Phi} C \) which sends \( x,y,a \) to \( E,F,G \) and \( \phi, \alpha, \beta \) to \( f,q,r \). The data of such functor is simply the choice of \( \hat{f}_2(\beta, \phi) \in \text{Hom}_{C}^{-1}(E,G) \) such that

\[
q - rf = \hat{f}_2(\beta, \phi).
\]

The existence of such class in \( \text{Hom}_{C}^{-1}(E,G) \) is precisely the condition that (A.1) commutes in \( H^0(C) \).

To sum up, a sufficient condition for the homotopy equivalence \( E \xrightarrow{f} F \) to induce a homotopy equivalence \( \{ E \xrightarrow{q} G \} \rightarrow \{ F \xrightarrow{r} G \} \) (A.3) is that \( f \) must commute with \( q \) and \( r \) in \( H^0(C) \). This is also precisely the condition that a strictly unital \( A_\infty \)-functor \( B_1 \rightarrow C \) exists which sends \( x,y,a \) to \( E,F,G \) and \( \phi, \alpha, \beta \) to \( f,q,r \). All the other conditions which seemingly arise when one naively tries to construct the homotopy equivalence (A.3) are part of the data necessary to lift this functor to a functor \( B_1 \rightarrow C \). Which gets done for us automatically by the universal properties of DG-quotients.

The method outlined in Example A.1 can be applied in full generality to any pair of twisted complexes \( (E_i, q_{ij}), (F_i, r_{ij}) \) and any set of homotopy equivalences \( E_i \xrightarrow{\hat{i}} F_i \) to answer the question posed in the beginning of this subsection. In such a generality, however, the answer would not only look fearsome, but also quite obfuscating.

Below, we only argue it in the generality we need for the proofs in Section 6.

**Definition A.2.** Denote by \( \bar{B}_n \) the category defined by

\[
\begin{array}{ccc}
z & \xrightarrow{\alpha} & a_n \\
\downarrow \phi & & \downarrow \gamma_n \\
y & \xrightarrow{\beta} & a_{n-1}
\end{array}
\quad \text{with} \quad \psi \phi = \text{Id}_z, \quad \phi \psi = \text{Id}_y, \quad \phi \beta = \alpha, \quad \psi \alpha = \beta, \quad \gamma_1 \alpha = \gamma_1 \beta = 0, \quad \gamma_{i+1} \gamma_i = 0.
\]
We consider it as a DG-category concentrated in degree 0. Denote by $\mathcal{B}_n$ its subcategory defined by the same quiver but with the arrow $\psi$ removed.

DG quotients were introduced by Drinfeld in [Dri04] where we refer the reader to for all the details.

**Lemma A.3.** Let $\mathcal{B}_n^f$ be the full subcategory of the DG-quotient $\text{Pre-Tr}(\mathcal{B}_n)/\text{Cone}(\phi)$ supported at the objects of $\mathcal{B}_n$. Then $\mathcal{B}_n^f$ is isomorphic to the DG category defined by

\[
\phi\beta = \alpha, \\
\psi\alpha = \beta, \\
\gamma_1\alpha = \gamma_1\beta = 0, \\
\gamma_{i+1}\gamma_i = 0 \\
d\theta_x = -\text{Id}_x + \psi\phi, \\
d\theta_y = \text{Id}_y - \phi\psi, \\
d\psi = 0, \\
d\xi = -\phi\theta_x - \theta_y\phi.
\]

where dotted arrows denote the morphisms of degree $-1$ and dashed arrows the morphisms of degree $-2$.

**Proof.** In $\text{Pre-Tr}(\mathcal{B}_n)$ the cone of $\phi$ is the twisted complex $x \xrightarrow{\phi} y$. As explained in [Dri04, §3.1] the DG quotient of $\text{Pre-Tr}(\mathcal{B}_n)$ by $x \xrightarrow{\phi} y$ is constructed by adding a single endomorphism $\epsilon$ of $x \xrightarrow{\phi} y$ of degree $-1$ with $d\epsilon = \text{Id}$ and no other relations.

As $\mathcal{B}_n$ is a subcategory of (A.5), every twisted complex over $\mathcal{B}_n$ is a twisted complex over (A.5). Let $\mathcal{A}$ be the full subcategory of $\text{Pre-Tr}((A.5))$ consisting of all the objects in $\text{Pre-Tr}(\mathcal{B}_n)$. Define a functor from $\text{Pre-Tr}(\mathcal{B}_n)/\langle x \xrightarrow{\phi} y \rangle$ to $\mathcal{A}$ by sending $\epsilon$ to $\phi$.

Define a functor in the opposite direction by sending $\theta_x, \theta_y, \psi$ and $\xi$ to the compositions

\[
\begin{array}{ccc}
x & \xrightarrow{\phi} & y \\
\xrightarrow{\theta_x} & \xrightarrow{\psi} & \xrightarrow{\theta_y} \\
x & \xrightarrow{\xi} & y
\end{array}
\]

in $\text{Pre-Tr}(\mathcal{B}_n)/\langle x \xrightarrow{\phi} y \rangle$, respectively. One can readily check that these functors are mutually inverse. Hence $\text{Pre-Tr}(\mathcal{B}_n)/\langle x \xrightarrow{\phi} y \rangle$ is isomorphic to $\mathcal{A}$, and the result follows. $\square$

Recall that an $A_\infty$-category is called *minimal* if it has $m_1 = 0$. Let $\mathcal{A}$ be an $A_\infty$-category. The *minimal model* of $\mathcal{A}$ is a minimal $A_\infty$-category $\mathcal{A}'$ together with an $A_\infty$-quasi-isomorphism $\mathcal{A}' \to \mathcal{A}$. Such model always exists and is unique up to an $A_\infty$-isomorphism, see [LH03, §1.4.1] and [KS01, S6.4].

**Lemma A.4.** There exists a strictly unital $A_\infty$-quasi-isomorphism

\[
\mathcal{B}_n \xrightarrow{(\phi, \theta_x)} \mathcal{B}_n^f
\]

which gives $\mathcal{B}_n$ the structure of the minimal model of $\mathcal{B}_n^f$. 
Proof. Recall that $\mathcal{B}_n$ is an ordinary category considered as an $A_\infty$-category concentrated in degree 0. In particular, $\mathcal{B}_n$ can be identified with its own graded homotopy category $H^*(\mathcal{B}_n)$.

The category $\mathcal{B}_n$ is defined by the quiver (A.4), while Lemma A.3 identifies $\mathcal{B}_n^1$ with the category defined by the DG-quiver (A.5). Forgetting the relations, identifying vertices and arrows which have the same labels gives the quiver (A.4) the structure of a subquiver of (A.5). This structure defines a map $\hat{g}$ from object set of $\mathcal{B}_n$ to the object set of $\mathcal{B}_n^1$ and a map $g_1$ of morphism spaces of $\mathcal{B}_n$ into the morphisms spaces of $\mathcal{B}_n^1$. These are compatible with differentials, but are not compatible with compositions.

By inspection, $(\hat{g}, g_1)$ does define an isomorphism

$$\mathcal{B}_n \xrightarrow{\sim} H^*(\mathcal{B}_n^1)$$

of graded homotopy categories. We can therefore apply the procedure described in [KS01, §6.4]. It can be readily checked that it constructs $g_{\geq 2}$ which extend $\hat{g}$ and $g_1$ to a strictly unital $A_\infty$-quasi-isomorphism $\mathcal{B}_n \xrightarrow{(\hat{g}, g_1)} \mathcal{B}_n^1$, as required. \hfill $\square$

Before we proceed, we need to state the following well-known fact:

Lemma A.5. Let $A$ be a DG-category, let $m \leq n$ be two integers and let $A_m, \ldots, A_n$ be the objects of $A$. The one-sided twisted complexes

$$(E_i, q_{ij}) \in \text{Pre-Tr}(A) \quad \text{with} \quad \begin{cases} E_i = A_i & \text{for } m \leq i \leq n \\ E_i = 0 & \text{otherwise} \end{cases}$$

are in 1-to-1 correspondence with the strictly unital $A_\infty$-functors

$$\gamma_i \gamma_{i+1} = 0 \quad \begin{array}{ccccccc} a_m & a_{m+1} & \cdots & a_{n-1} & a_n \\ \gamma_m & \gamma_{m+1} & \cdots & \gamma_{n-1} & \gamma_n \end{array} \xrightarrow{(f, \eta)} \mathcal{C}$$

with $\hat{f}(a_i) = A_i$.

Proof. Mutually inverse maps between the two sets can be defined by setting

$$f_k(\gamma_i, \gamma_{i+1}, \gamma_{i+k}, \ldots, \gamma_{i+k}) = (-1)^{i-1} q_{ij+k} \quad \forall \ i \in \{m, \ldots, n\} \ \text{and} \ k \in \{1, \ldots, n-i\}$$

and vice versa. \hfill $\square$

Let $\mathcal{C}$ be a strongly pretriangulated category and let $(A_i, q_{ij})$ be a one-sided twisted complex over $\mathcal{C}$ concentrated in degrees $1, \ldots, n$. Let $(E_i, q_{ij})$ and $(F_i, r_{ij})$ be one-sided twisted complexes over $\mathcal{C}$ concentrated in degrees $0, \ldots, n$ whose twisted subcomplexes supported in degrees $1, \ldots, n$ are both equal to $(A_i, q_{ij})$.

Let $A$ denote the convolution of $(A_i, q_{ij})$. Consider the closed degree 1 morphisms $(q_{0i})$ and $(r_{0j})$ from $E_0$ and $F_0$ to $(A_i, q_{ij})$ in Pre-Tr($\mathcal{C}$). Denote by $E_0 \xrightarrow{q_0} A$ and $F_0 \xrightarrow{r_0} A$ the corresponding morphisms in $\mathcal{C}$.

Recall that $\mathcal{B}_n$ is the category defined by

$$\phi \beta = \alpha, \quad \gamma_1 \alpha = \gamma_1 \beta = 0, \quad \gamma_{i+1} \gamma_i = 0.$$  

Proposition A.6. There exists a strictly unital $A_\infty$-functor

$$\mathcal{B}_n \xrightarrow{(f, \eta)} \mathcal{C}$$

whose restrictions to the full subcategories of $\mathcal{B}_n$ supported at $x, a_1, \ldots, a_n$ and $y, a_1, \ldots, a_n$ correspond to the twisted complexes $(E_i, q_{ij})$ and $(F_i, r_{ij})$ if and only if the following two equivalent conditions hold:

1. There exist $f \in \text{Hom}^0_{\mathcal{C}}(E_0, F_0)$ and $s_i \in \text{Hom}_{\mathcal{C}}^{-k}(E_0, A_k)$ for $k \in \{1, \ldots, n\}$ such that

$$q_{0k} - r_{0k} f = \sum_{1 \leq j < k-1} q_{jk} s_j + (-1)^k ds_k. \quad (A.8)$$
(2) There exists \( f \in \text{Hom}_{H^0(C)}(E_0, F_0) \) such that

\[
E_0 \xrightarrow{q_0} A[1] \xleftarrow{f} F_0
\]

commutes in \( H^0(C) \).

Proof. The existence of \( \left( \tilde{f}, f_1 \right) \leftrightarrow (1) \):

The condition that \( \left( \tilde{f}, f_1 \right) \) restricts on \( x, a_1, \ldots, a_n \) and \( y, a_1, \ldots, a_n \) to the functors corresponding to \((E_i, q_{ij})\) and \((F_i, r_{ij})\) determines \( \tilde{f} \) and all the values of \( f_1 \) other than

\[
\begin{align*}
\tilde{f}_1(\phi), \tilde{f}_2(\beta, \phi), \tilde{f}_3(\gamma_1, \beta, \phi), & \ldots, \tilde{f}_{n+1}(\gamma_n-1, \ldots, \gamma_1, \beta, \phi). 
\end{align*}
\]

(A.9)

One can readily verify that if we set these to \( f, s_1, \ldots, s_n \), then the standard relations which (A.9) must satisfy according to the definition of a \( A_\infty \)-functor [Kel01, §3.4] become precisely the equations (A.8). And vice versa.

(1) \( \leftrightarrow (2) \):

Let \( s_k \in \text{Hom}_{C}^{-k}(E_0, A_k) \) for \( k \in \{1, \ldots, n\} \). Consider the defines the degree 0 morphism \( E_0 \xrightarrow{(s_k)} (A_i, g_{ij}) \) in \( \text{Pre-Tr}(C) \). It is a straightforward verification that \( d(s_k) \) is the morphism \( E_0 \rightarrow (A_i, g_{ij}) \) whose component in \( \text{Hom}_{C}^{-k+1}(E_0, A_k) \) is precisely the RHS of (A.9).

On the other hand, for any \( f \in \text{Hom}_{C}(E_0, F_0) \) the LHS of (A.9) is the component in \( \text{Hom}_{C}^{-k+1}(E_0, A_k) \) of the morphism \( E_0 \xrightarrow{(g_{ij})-(r_{ij})f} (A_i, g_{ij}) \) in \( \text{Pre-Tr}(C) \).

We conclude that (1) is equivalent to there existing \( f \in \text{Hom}_{C}(E_0, F_0) \) and \( s \in \text{Hom}_{C}(E_0, A) \) such that \( q_0 - r_0 f = ds \). This is precisely the claim of (2). \( \square \)

The following is the main result of this section:

**Theorem A.1.** Let \( E_0 \xrightarrow{f} F_0 \) be a homotopy equivalence satisfying the equivalent conditions of Prop. A.6. Then there exists a homotopy equivalence

\[
(E_i, q_{ij}) \xrightarrow{(f_{ij})} (F_i, r_{ij})
\]

in \( \text{Pre-Tr}(C) \).

Proof. By Prop. A.6 there exists a strictly unital \( A_\infty \)-functor

\[
\mathcal{B}_\infty \xrightarrow{\left( \tilde{f}, f_1 \right)} \mathcal{C}
\]

with \( \tilde{f}_1(\phi) = f \). It extends naturally to a strictly unital \( A_\infty \)-functor

\[
\text{Pre-Tr}(\mathcal{B}_n) \xrightarrow{\left( \tilde{f}, f_1 \right)} \text{Pre-Tr}(\mathcal{C}).
\]

By [Kel06, §4.3] there exists a corresponding quasi-functor

\[
\text{Pre-Tr}(\mathcal{B}_n) \xrightarrow{\Phi} \text{Pre-Tr}(\mathcal{C})
\]

in \( \text{Ho}(DG-Cat) \) with \( H\Phi \simeq H\tilde{f} \) as functors \( H^0(\text{Pre-Tr}(\mathcal{B}_n)) \rightarrow H^0(\text{Pre-Tr}(\mathcal{C})) \). Since \( H\tilde{f}(\phi) = f \) and since \( f \) is an isomorphism in \( H^0(\mathcal{C}) \), it follows that \( H\Phi(\text{Cone}(\phi)) = 0 \). By the universal property of DG-quotients [Dri04, Theorem 1.6.2] quasi-functor \( \Phi \) lifts to a quasi-functor

\[
\text{Pre-Tr}(\mathcal{B}_n)/\text{Cone}(\phi) \xrightarrow{\Phi'} \text{Pre-Tr}(\mathcal{C})
\]

such that \( \Phi = \Phi'Q \) where \( Q \) is the quotient quasi-functor \( \text{Pre-Tr}(\mathcal{B}_n) \rightarrow \text{Pre-Tr}(\mathcal{B}_n)/\text{Cone}(\phi) \). Denote by

\[
\text{Pre-Tr}(\mathcal{B}_n)/\text{Cone}(\phi) \xrightarrow{\left( \tilde{f}', f_1' \right)} \text{Pre-Tr}(\mathcal{C})
\]

the corresponding strictly unital \( A_\infty \)-functor. We have \( \left( \tilde{f}, f_1 \right) = \left( \tilde{f}', f_1' \right)Q \) and hence restricting to the full subcategory \( \mathcal{B}_\infty^f \) of \( \text{Pre-Tr}(\mathcal{B}_n)/\text{Cone}(\phi) \) consisting of objects of \( \mathcal{B}_n \) we obtain a strictly unital \( A_\infty \)-functor

\[
\mathcal{B}_\infty^f \xrightarrow{\left( \tilde{f}', f_1' \right)} \mathcal{C}.
\]
Recall that in Lemma A.4 we have constructed a strictly unital $A_\infty$-quasi-isomorphism $\bar{B}_n \xrightarrow{(\hat{\phi}, h)} B'_n$ which gives $\bar{B}_n$ the structure of the minimal model of $B'_n$. Taking the composition of $\bar{B}_n \xrightarrow{(\hat{\phi}, h)} B'_n \xrightarrow{(\hat{f}, f)} C$ we obtain the strictly unital $A_\infty$-functor denoted

$$\bar{B}_n \xrightarrow{(\hat{h}, h)} C.$$  

We claim that $\bar{B}_n \xrightarrow{(\hat{h}, h)} C$ restricts on the full subcategory $B_n \hookrightarrow \bar{B}_n$ to $B_n \xrightarrow{(\hat{f}, f)} C$. As $(\hat{f}, f) = (\hat{f}, f) Q$ this reduces to the following diagram being commutative

$$\begin{array}{c} 
\bar{B}_n \\
\downarrow \ Q \\
B_n \\
\end{array}$$

(A.10)

This is a straightforward check. On one hand, in Lemma A.3 we have constructed an explicit isomorphism between $B'_n$ and the category defined by (A.5). One can check that it identifies the DG-quotient functor $B_n \xrightarrow{Q} B'_n$ with the functor induced by the inclusion of (A.7) into (A.5) as quivers with relations. On the other hand, in Lemma A.4 we have used the above isomorphism between $B'_n$ and (A.5) to define $\hat{g}$ and $g_1$ by the quiver inclusion of (A.4) into (A.5) which ignores relations. However, restricted from (A.4) to (A.7) this inclusion does respect the relations. Therefore $(\hat{g}, g_1)$ restricted to $B_n$ is a genuine functor. One can check that this forces $g_{2,3}$ constructed by the procedure in [KS01, §6.4] to be zero when restricted to $B_n$. Thus $(\hat{g}, g_1)$ restricted to $B_n$ is just the functor $(\hat{g}, g_1)$, i.e. the functor defined by the inclusion of (A.7) into (A.5). The claim follows.

In $\text{Pre-Tr}(B_n)$ the twisted complexes $x \xrightarrow{\alpha} a_2 \xrightarrow{\gamma_1} a_3 \xrightarrow{\gamma_2} \cdots \xrightarrow{\gamma_{n-1}} a_n$ and $y \xrightarrow{\beta} a_1 \xrightarrow{\gamma_1} a_2 \xrightarrow{\gamma_2} \cdots \xrightarrow{\gamma_{n-1}} a_n$ are isomorphic, for instance the following

is an isomorphism of twisted complexes. Hence they are also isomorphic in $H_0(\text{Pre-Tr}(B_n))$, and hence their images under $(\hat{h}, H^0(\hat{h}))$ are isomorphic in $H_0(\text{Pre-Tr}(C))$. But by the claim above $(\hat{h}, h)$ and $(\hat{f}, f)$ agree on the subcategory $\text{Pre-Tr}(B_n)$ of $\text{Pre-Tr}(\bar{B}_n)$. Hence $(\hat{h}, h)$ takes $x \xrightarrow{\alpha} a_2 \xrightarrow{\gamma_1} a_3 \xrightarrow{\gamma_2} \cdots \xrightarrow{\gamma_{n-1}} a_n$ and $y \xrightarrow{\beta} a_1 \xrightarrow{\gamma_1} a_2 \xrightarrow{\gamma_2} \cdots \xrightarrow{\gamma_{n-1}} a_n$ to $(E_i, q_{ij})$ and $(F_i, r_{ij})$. The claim of the theorem follows. 

$$\square$$

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