Research Article

Demazure Descent and Representations of Reductive Groups

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We introduce the notion of Demazure descent data on a triangulated category \( \mathcal{C} \) and define the descent category for such data. We illustrate the definition by our basic example. Let \( G \) be a reductive algebraic group with a Borel subgroup \( B \). Demazure functors form Demazure descent data on \( D^B(\text{Rep}(B)) \) and the descent category is equivalent to \( D^B(\text{Rep}(G)) \).

1. Motivation

The present paper is the first one in a series devoted to various cases of categorical descent. Philosophically, our interest in the subject grew out of attempts to understand the main construction from the recent paper by Ben-Zvi and Nadler [1] in plain terms that would not involve higher category theory.

1.1. Beilinson-Bernstein Localization and Derived Descent. Let \( G \) be a reductive algebraic group with the Lie algebra \( \mathfrak{g} \). Denote the Flag variety of \( G \) by \( \mathcal{G} \). A major part of Geometric Representation Theory originated in the seminal work of Beilinson and Bernstein [2] devoted to investigation of the globalization functor \( \text{D-mod}(\mathcal{G}) \rightarrow \text{U}(\mathfrak{g})\text{-mod} \). This functor turns out to be fully faithful and provides geometric and topological tools to investigate a wide class of \( \text{U}(\mathfrak{g})\text{-modules} \), in particular the ones from the famous category \( \mathcal{O} \). Various generalizations of this result lead to the investigation of the categories of twisted D-modules on the Flag variety and on the base affine space for \( G \) and of their derived categories.

Beilinson and Bernstein defined a certain comonad acting on a higher categorical version for the derived category of D-modules on the base affine space. In fact, the functor is built into the higher categorical treatment of Beilinson-Bernstein localization-globalization construction.

Using the heavy machinery of Barr-Beck-Lurie descent, the authors argue that the derived category of \( \text{U}(\mathfrak{g})\text{-modules} \) is equivalent to the category of D-modules equivariant with respect to this comonad. Thus the global sections functor becomes equivariant with respect to the action. The comonad is called the Hecke comonad. It provides a categorification for the classical action of the Weyl group on various homological and K-theoretic invariants of the Flag variety.

Notice that the descent construction fails to work on the level of the usual triangulated categories. Ideally one would like to replace it by a categorical action of the Weyl group or rather of the Braid group on categories of D-modules related to the Flag variety. One would need to define a notion of “invariants” with respect to such action.

1.2. Descent in Equivariant K-Theory. Another source of inspiration for the present paper is a recent article of Harada et al. [3]. Given a compact space \( X \) with an action of a compact reductive Lie group \( G \), the authors express the \( G \)-equivariant K-theory of \( X \) via the \( T \)-equivariant one. Here \( T \) denotes a fixed maximal torus in \( G \). Harada et al. show that the natural action of the Weyl group \( W \) on \( K_T(X) \) extends to an action of a degenerate Hecke ring generated by divided difference operators which was introduced earlier in the context of Schubert calculus by Demazure. The operators are called Demazure operators.

The main result in the paper [3] states that the ring \( K_T(X) \) is isomorphic to the subring of \( K_T(X) \) annihilated by the augmentation ideal in the degenerate Hecke algebra. In other words, a \( T \)-equivariant class is \( G \)-equivariant if and only if it is killed by the Demazure operators.
In the present paper, we define a notion of Demazure descent on a triangulated category \(\mathcal{C}\). Thus Demazure operators are replaced by Demazure functors. These functors satisfy a categorified version of degenerate Hecke algebra relations and form a Demazure descent data on \(\mathcal{C}\). We define the descent category for such data. Demazure descent is supposed to be a technique replacing the naive notion of Weyl group invariants, on the categorical level.

We provide the first example of Demazure descent. Consider a reductive algebraic group \(G\) and fix a Borel subgroup \(B \subset G\). Denote the set of roots for \(G\) by \(\Phi = \Phi^+ \cup \Phi^-\). Let \(\{\alpha_1, \ldots, \alpha_n\}\) be the set of simple roots. The Weyl group \(W = \text{Norm}(T)/T\) of the fixed maximal torus acts naturally on the lattices \(X\) and \(Y\) and on the \(R\)-vector spaces spanned by them, by reflections in root hyperplanes. The simple reflection corresponding to \(\alpha_i\) is denoted by \(s_i\). The elements \(s_1, \ldots, s_n\) form a set of generators for \(W\). For \(w \in W\) denote the length of a minimal expression of \(w\) via the generators by \(\ell(w)\). We have a partial ordering on \(W\) called the Bruhat ordering, \(w' \leq w\), if there exists a reduced expression for \(w'\) that can be obtained from a reduced expression for \(w\) by deleting a number of simple reflections.

The monoid \(Br^+\) with generators \(\{T_w, w \in W\}\) and relations
\[
T_{w_1}T_{w_2} = T_{w_1w_2} \quad \text{if} \quad \ell(w_1) + \ell(w_2) = \ell(w_1w_2) \quad \text{in} \quad W
\]
is called the braid monoid of \(G\).

2. Categories of Representations. For an algebraic group \(H\), we denote the Hopf algebra of polynomial functions on \(H\) by \(\mathcal{O}(H)\). Let \(\text{Rep}(H)\) be the category of \(\mathcal{O}(H)\)-comodules. This is an Abelian tensor category.

Let \(P_i\) be the parabolic subgroup of \(G\) containing \(B\) whose Levi subgroup has the root system \(\{\alpha_i, -\alpha_i\}\). Using the natural Hopf algebra maps \(\mathcal{O}(G) \rightarrow \mathcal{O}(B)\) and \(\mathcal{O}(P_i) \rightarrow \mathcal{O}(B)\) we can get restriction functors
\[
\text{Res}_i : \text{Rep}(P_i) \rightarrow \text{Rep}(B),
\]
\[
\text{Res} : \text{Rep}(G) \rightarrow \text{Rep}(B).
\]

The restriction functors are exact and naturally commute with taking tensor product of representations. Let \(H\) be a subgroup of \(G\) and \(M \in \text{Rep}(G)\). Define the \(H\)-invariant part of \(M\) to be \(M^H := \text{Hom}_{\text{Rep}(H)}(k, M)\). Consider the induction functors
\[
\text{Ind}_i : \text{Rep}(B) \rightarrow \text{Rep}(P_i), \quad M \mapsto (\mathcal{O}(P_i) \otimes M)^B,
\]
\[
\text{Ind} : \text{Rep}(B) \rightarrow \text{Rep}(G), \quad M \mapsto (\mathcal{O}(G) \otimes M)^B.
\]

3. The Derived Categories. For an algebraic group \(H\), the regular comodule \(\mathcal{O}(H)\) is injective in \(\text{Rep}(H)\); moreover, for any \(M \in \text{Rep}(H)\) the coaction map \(M \rightarrow \mathcal{O}(H) \otimes M\) provides an embedding of \(M\) into an injective object. In particular, \(\text{Rep}(H)\) has enough injectives. The algebraic De Rham complex \(\Omega^\cdot(H)\) provides an injective resolution for the trivial comodule, of the length equal to the dimension of \(H\). For any \(M \in \text{Rep}(H)\) the complex \(\Omega^\cdot(H) \otimes M\) provides an injective resolution for \(M\) of the same length.

Consider now the bounded derived categories \(D^b(\text{Rep}(B)), D^b(\text{Rep}(P_i)),\) and \(D^b(\text{Rep}(G))\). Let \(L_i\) and \(L\) be the derived functors of \(\text{Res}_i\) and \(\text{Res}\), respectively. Denote the right derived functors of \(\text{Ind}_i\) and \(\text{Ind}\) by \(I_i\) and \(I\), respectively. Let \(D_i = L_i \circ I_i\) and \(D = L \circ I\) be the right derived functors of \(\text{Δ}_i\) and \(\text{Δ}\), respectively.

Proposition 1. (a) The functors \(L_i\) and \(L\) are left adjoint to \(I_i\) and \(I\), respectively.

(b) For \(M \in D^b(\text{Rep}(B))\) and \(N \in D^b(\text{Rep}(P_i))\) (resp., for \(M \in D^b(\text{Rep}(B))\) and \(N \in D^b(\text{Rep}(G))\)) we have the tensor identities:
\[
I_i(M \otimes L_i(N)) \cong I_i(M) \otimes N, \quad (\text{resp.}, I(M \otimes L(N)) \cong I(M) \otimes N).
\]

(c) The functors \(I_i\) and \(I\) take the trivial \(\mathcal{O}(B)\)-comodule to the trivial \(\mathcal{O}(P_i)\)-comodule (resp., to the trivial \(\mathcal{O}(G)\)-comodule).

(d) \(D_i\) and \(D\) are comonads for which the comonad maps \(D_i \rightarrow D_i^2\) and \(D \rightarrow D^2\) are isomorphisms.

Proof. The statements corresponding to (a) and (b) for \(\text{Res}\) and \(\text{Ind}\) (resp., \(\text{Res}_i\) and \(\text{Ind}_i\)) are Propositions 3.4 and 3.6 in [4]. The derived functors of a pair of adjoint functors are adjoint. (b) also follows from these statements for the non-derived functors since tensoring over a field is exact.

\[
I_i(\text{Id} \otimes L_i) = R(\text{Ind}_i(\text{Id} \otimes \text{Res}_i)) = R(\text{Ind}_i \otimes \text{Id}) = I_i \otimes \text{Id}.
\]

By (a) \(D_i = L_i \circ I_i\) and \(D = L \circ I\) are comonads (see [5, Section VI.3.1]). (b) and (c) imply that \(I_i \circ L_i(N) = N\) for \(N \in D^b(\text{Rep}(P_i))\) and \(I \circ L(N) = N\) for \(N \in D^b(\text{Rep}(G))\). Thus, \(I_i \cong I_i \circ L_i\) (resp., \(I \cong I \circ L\)) and from this we get the desired isomorphism
\[
D_i = L_i \circ I_i = L_i \circ \text{Id} \cong L_i \circ I_i \circ L_i \circ I_i = D_i^2.
\]

and likewise for \(D\).\]
Remark 2. It follows that the restriction functors $L_i$ and $L$ are fully faithful.

3. Demazure Descent

Fix a root data $(I, X, Y)$ of the finite type, with the Weyl group $W$ and the braid monoid $B_r$. Consider a triangulated category $\mathcal{C}$.

Definition 3. A weak braid monoid action on the category $\mathcal{C}$ is a collection of triangulated functors

$$D_w : \mathcal{C} \longrightarrow \mathcal{C}, \quad w \in W$$

satisfying braid monoid relations; that is, for all $w_1, w_2 \in W$ there exist isomorphisms of functors

$$D_{w_1} \circ D_w = D_{w_1 w_2}, \quad \text{if } \ell(w_1 w_2) = \ell(w_1) + \ell(w_2).$$

Notice that we neither fix the braid relations isomorphisms nor impose any additional relations on them.

Definition 4. Demazure descent data on the category $\mathcal{C}$ is a weak braid monoid action $\{D_w\}$ such that for each simple root $s_i$ the corresponding functor $D_s$ is a comonad for which the comonad map $D_s \rightarrow D_s^2$ is an isomorphism.

Here is the central construction of the paper. Consider a triangulated category $\mathcal{C}$ with a fixed Demazure descent data $\{D_w\}$ of the type $(I, X, Y)$.

Definition 5. The descent category $\mathcal{D} \mathcal{E} \mathcal{S}(\mathcal{C}, D_w, w \in W)$ is the full subcategory in $\mathcal{C}$ consisting of objects $M$ such that for all $i$ the cones of the counit maps $D_s(M) \xrightarrow{\varepsilon} M$ are isomorphic to $0$.

Remark 6. Suppose that $\mathcal{C}$ has functorial cones. Then $\mathcal{D} \mathcal{E} \mathcal{S}(\mathcal{C}, D_w, w \in W)$ is naturally equipped with structures of a comodule over each $D_i$ and any morphism in $\mathcal{D} \mathcal{E} \mathcal{S}(\mathcal{C}, D_w, w \in W)$ is a morphism of $D_i$-comodules.

4. Main Theorem

We now go back to considering $D_1 = L_1 \circ I_1$ and $D = L \circ I$.

Proposition 9. Let $w \in W$ and let $w = s_{i_1} \cdots s_{i_n}$ be a reduced expression. Then $D_w := D_{i_n} \circ \cdots \circ D_{i_1}$ is independent of the choice of reduced expression and the $D_w$'s form Demazure descent data on $\mathcal{C} = D^1(\operatorname{Rep}(B))$.

Lemma 10. Let $w = s_{i_1} \cdots s_{i_n}$ be a reduced expression. Then

$$P_{s_{i_1}} \cdots P_{s_{i_n}} = \bigcup_{w' \leq w} Bu'B,$$

where the union is over all $w' \in W$ which is $\leq w$ in the Bruhat order.

Proof. The proof goes by induction on $n = \ell(w)$. It is true for $n = 1$ by definition of $P_i$. Set $v = s_{i_1} \cdots s_{i_{n-1}}$. Using the hypotheses we get

$$P_{s_{i_1}} \cdots P_{s_{i_{n-1}}} P_{s_{i_n}} = \bigcup_{w' \leq sv} Bu'B \cup (Bu'B) = \bigcup_{w' \leq v} (Bu'B) \cup (Bs_{i_n}B).$$

(13)

Let $w'$ be any element in $W$ and $s$ a simple reflection. Then by [6, Corollary 28.3] we have $(Bu'B)(Bs_{i_n}B) \subseteq Bu'sB \cup BuB$. Thus, if $w'< w \leq v$, then $(Bu'B)(Bs_{i_n}B)$ is contained in the first union. If $w' \leq w's_{i_n}$, then we have
\[ (B w')(B s, B) = B w's_1 B \] by [6, Lemma 29.3A and section 29.1]. Thus, the product can be written as
\[
P_1 \cdots P_n = \bigcup \limits_{w' \leq v} Bu' \bigcup \bigcup \limits_{w' \leq v} Bu' s_i B
\]
\[ = \bigcup \limits_{w' \leq v} Bu' \bigcup \bigcup \limits_{w' \leq v} Bu' s_i B
\]
(14)

Claim. The conditions \( w'' s_i \leq v \) and \( w'' s_i \leq w'' \) are equivalent to the conditions \( w'' \leq w \) and \( w'' s_i \leq w'' \).

Proof of the Claim. Assume that \( w'' s_i \leq v \). By [7, Proposition 5.9] this implies that \( w'' \leq v \) or \( w'' \leq vs_i = w \). In both cases we get \( w'' \leq w \) since \( v \leq w \). Assume now that \( w'' \leq w \) and \( w'' s_i \leq w'' \). \( w'' \) has a reduced expression of the form
\[
w'' = s_{i_1} \cdots \hat{s}_{i_j} \cdots \hat{s}_{i_k} \cdots s_{i_n},
\]
(15)
where the \( \hat{\ } \) indicates that the term has been removed from the product. If \( j_k \neq n \), then
\[
w'' s_i = s_{i_1} \cdots \hat{s}_{i_j} \cdots \hat{s}_{i_k} \cdots s_{i_{k+1}} \cdots \hat{s}_{i_{k-1}} \cdots s_{i_{j-1}} \cdots s_{i_n} \leq v.
\]
(16)
If \( j_k = n \), then \( w'' \leq v \). Since \( w'' s_i \leq w'' \) by assumption we get \( w'' s_i \leq v \).

This completes the proof of the claim.

If \( w' \leq v \) in the first union satisfies that \( w' s_i \leq w' \), then it is also contained in the second union. Using the claim we get
\[
P_1 \cdots P_n = \bigcup \limits_{w' \leq v} Bu' \bigcup \bigcup \limits_{w' \leq v} Bu' s_i B.
\]
(17)

Assume that \( w' \leq w \) and \( w' \leq w' s_i \). Then \( w' \) has a reduced expression of the form
\[
w' = s_{i_1} \cdots \hat{s}_{i_j} \cdots \hat{s}_{i_k} \cdots s_{i_n}.
\]
(18)
If \( j_k = n \), then \( w' \leq v \). If \( j_k \neq n \), then \( w' s_i \leq v \), but since \( w' \leq w' s_i \), we get \( w' \leq v \). Hence, the conditions \( w' \leq v \) and \( w' \leq w' s_i \) can be replaced by \( w' \leq w \) and \( w' \leq w' s_i \). Thus,
\[
P_1 \cdots P_n = \bigcup \limits_{w' \leq w} Bu' \bigcup \bigcup \limits_{w' \leq w} Bu' s_i B
\]
(19)
This finishes the induction step.

Proof of the Proposition. Let \( w \in W \) and let \( s_i \cdots s_{i_n} = \sigma_j \cdots \sigma_{j_k} \) be two reduced expressions for \( w \). By Lemma 10 this implies that \( P_1 \cdots P_n = P_{j_1} \cdots P_{j_k} \). By [8, Theorem 3.1] the \( B \)-module structure of \( \Delta_{j_1} \cdots \Delta_{j_k} \) is determined up to a natural isomorphism by the set \( P_{j_1} \cdots P_{j_k} \). Hence
\[
\Delta_{j_1} \cdots \Delta_{j_k} = \Delta_{j_1} \circ \cdots \circ \Delta_{j_k}.
\]
(20)

Hence, for any choice of reduced expression we can define
\[
\Delta_w := \Delta_{j_1} \circ \cdots \circ \Delta_{j_k}.
\]
(21)

Let \( w_1 \) and \( w_2 \) be elements in \( W \) such that \( \ell(w_1 w_2) = \ell(w_1) + \ell(w_2) \). Pick reduced expressions \( s_{i_1} \cdots s_{i_k} \) and \( s_{j_1} \cdots s_{j_L} \) for \( w_1 \) and \( w_2 \), respectively. Then \( s_{i_1} \cdots s_{i_k} s_{j_1} \cdots s_{j_L} \) is a reduced expression for \( w_1 w_2 \) and we get braid relations for the \( \Delta_w \)
\[
\Delta_{w_1} \circ \Delta_{w_2} = \Delta_{w_1} \circ \Delta_{w_2} \circ \Delta_{w_2} = \Delta_{w_1} \circ \Delta_{w_2}.
\]
(22)

Define
\[
D_w := R(\Delta_w) = R(\Delta_{w_1}) \circ \cdots \circ R(\Delta_{w_k})
\]
(23)

The braid relations for \( D_w \) now follows from the braid relations for \( \Delta_w \):
\[
D_{w_1} \circ D_{w_2} = R(\Delta_{w_1}) \circ R(\Delta_{w_2}) = \Delta_{w_1} \circ \Delta_{w_2}.
\]
(24)

Theorem 11. \( \mathcal{D}_{\mathfrak{B}}(6, D_{w_1}, w \in W) \) is equivalent to \( \mathcal{D}(\text{Rep } G) \).

Proof. Let \( M \in \mathcal{D}(\text{Rep } G) \). Being able to extend \( M \) to an element in \( \mathcal{D}(\text{Rep } G) \) is equivalent to \( M \) being in the image of \( L \). Assume \( M = L(N) \) for some \( N \in \mathcal{D}(\text{Rep } G) \). Then \( D(M) = L \circ I \circ L(N) = L(N) \). If \( D(M) \neq M \), then \( M = L(I(M)) \), so \( M \) is in the image of \( L \). Thus, being in the image of \( L \) is equivalent to \( D(M) \neq M \) being an isomorphism which is again equivalent to \( M \in \ker(C) \), where \( C := \text{Cone}(D \to \text{Id}) \). Set \( C_0 := \text{Cone}(D_1 \to \text{Id}) \).

Claim. \( \ker(C) = \bigcap_i \ker(C_i) \).

Proof of Claim. Assume that \( M \in \ker(C) \). Then \( M = L(N) \) for some \( N \in \mathcal{D}(\text{Rep } G) \). But then \( M = L(N) \) for all \( i \), so \( D_i(M) \neq M \) is an isomorphism for all \( i \). Hence, \( M \in \bigcap_i \ker(C(i)) \). Assume that \( M \in \bigcap_i \ker(C(i)) \). Then all \( D_i(M) \neq M \) are isomorphisms. Choose a reduced expression \( s_{i_1} \cdots s_{i_n} \).
for the longest element in the Weyl group. Then \( P_{i_1} \cdots P_{i_N} = G \). By [8] we have \( D = D_{i_1} \circ \cdots \circ D_{i_N} \).

\[
D(M) = D_{i_1} \circ \cdots \circ D_{i_N}(M) = \cdots = D_{i_1}(M) = M.
\]

Hence,

\[
\text{Cone}(D(M) \to M) = \text{Cone}(D(D(M)) \to D(M)) = 0.
\]

By definition of a comonad we have the following commutative diagram:

\[
\begin{array}{ccc}
\text{Id} \circ D & \xymatrix{ D \ar[d]_{\eta} & D^2 \ar[l]_{eD} } \\
& D \ar[u]_{\eta} \\
\end{array}
\]

Since \( \eta \) is an isomorphism so is \( eD \) and thus

\[
\text{Cone}(D(D(M)) \to D(M)) = 0.
\]

This shows that \( M \in \ker(C) \).

This completes the proof of the claim.

From the claim we get that

\[
D^b(\text{Rep}(G)) = \bigcap_i \ker(C_i),
\]

which is exactly the descent category.

5. Further Directions

5.2. Equivariant Sheaves. Let \( X \) be an affine scheme equipped with an action of a reductive algebraic group \( G \). Fix a Borel subgroup \( B \subset G \). In the main body of the present paper, consider the minimal parabolic subgroups in \( G \) denoted by \( P_1, \ldots, P_n \). Denote the derived categories of quasicoherent sheaves on \( X \) equivariant with respect to \( G \) (resp., \( B \), resp., \( P_i \)) by \( D^B(\text{QCoh}^G(X)) \) (resp., by \( D^B(\text{QCoh}^B(X)) \), resp., by \( D^B(\text{QCoh}^P(X)) \)). We have the natural functors provided by restriction of equivariance \( L : D^B(\text{QCoh}^G(X)) \to D^B(\text{QCoh}^B(X)) \) and \( L_i : D^B(\text{QCoh}^P(X)) \to D^B(\text{QCoh}^P(X)) \). These functors have the right adjoint ones \( I \), resp. \( I_1, \ldots, I_n \). The comonads \( D_1, \ldots, D_n \) given by the compositions of extension and restriction of equivariance define a Demazure descent data on the category \( D^B(\text{QCoh}^B(X)) \). The corresponding descent category is equivalent to \( D^B(\text{QCoh}^G(X)) \).

5.3. Algebraic Loop Group. For a simple algebraic group \( G \) consider the algebraic loop group \( LG = \text{Map}(\hat{D}, G) \) (resp., the formal arcs group \( L' G = \text{Map}(D, G) \)). Here \( D \) (resp., \( \hat{D} \)) denotes the formal disc (resp., the formal punctured disc). Consider the affine Kac-Moody central extension

\[
1 \longrightarrow G_m \longrightarrow \hat{L}G \longrightarrow LG \longrightarrow 1.
\]

The affine analog of the Borel subgroup \( B \subset G \) is the Iwahori subgroup \( \text{Iw} \subset \hat{L}G \). Let \( P_0, \ldots, P_n \) be the standard parahoric subgroups in \( L'G \). One considers the adjoint pairs of coinduction-restriction functors \( I_0, L_0, \ldots, I_n, L_n \) between \( D^B(\text{Rep}(\text{Iw})) \) and \( D^B(\text{Rep}(P)) \). Denote the comonads \( L_i \circ I_i \) by \( D_i \) for \( i = 0, \ldots, n \). We claim that \( D_0, \ldots, D_n \) form affine Demazure descent data on \( D^B(\text{Rep}(\text{Iw})) \). We conjecture that the descent category is equivalent to \( D^B(\text{Rep}(\text{Iw})) \) (direct sum of the categories over all positive integral levels).

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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