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Lie algebras and coverings

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Meinem Lehrer Peter Gabriel gewidmet

1. Introduction

1.1. Let A be an associative unitary finite dimensional \mathbb{C} -algebra which is representation finite. This means that the number of isomorphism classes of indecomposable finite dimensional A -left modules is finite. Let us fix a set \mathcal{J} of representatives for these isomorphism classes.

We showed in [Rie] that the free \mathbb{Z} -module

$$L(A) = \bigoplus_{A \in \mathcal{J}} \mathbb{Z}v_A$$

generated by the symbols

$$\{v_A : A \in \mathcal{J}\}$$

can be made into a \mathbb{Z} -Lie algebra in the following way: set

$$[v_A, v_B] = \sum_{X \in \mathcal{J}} (\gamma_{A,B}^X - \gamma_{B,A}^X)v_X,$$

where

$$\gamma_{A,B}^X = \chi(V_A(A, B; X))$$

is the Euler-Poincaré characteristic of the algebraic variety

$$V_A(A, B; X) = \{0 \subseteq Y \subseteq X : Y \text{ is a } A\text{-submodule of } X \text{ isomorphic to } A \text{ with quotient module } X/Y \text{ isomorphic to } B\}.$$

This is the complex version of Ringel's construction of Lie algebras via Hall algebras over finite fields [Rin].

The construction of $L(A)$ carries over easily to the case where A is a locally representation finite \mathbb{C} -category. We will list the most important definitions and

facts about locally representation finite categories and their coverings in chapter 3; the references for these results are [BG] and [Ga].

1.2. If the representation finite algebra – or more generally the locally representation finite \mathbb{C} -category – is simply connected [BG], the Lie algebra $L(\mathcal{A})$ has a particularly simple structure. Indeed, we proved in [Rie] that in this case one of the numbers

$$\gamma_{A,B}^X \quad \text{and} \quad \gamma_{B,A}^X$$

is zero for any choice of A, B, X in \mathcal{J} and that for fixed A and B there is at most one X for which

$$\gamma_{A,B}^X \neq 0.$$

To any locally representation finite \mathbb{C} -category \mathcal{A} one can associate a locally representation finite one which is simply connected: its universal cover $\tilde{\mathcal{A}}$ ([BG], [Ga]). The reason why we consider \mathbb{C} -categories instead of \mathbb{C} -algebras in this paper is that $\tilde{\mathcal{A}}$ is rarely a \mathbb{C} -algebra.

It is tempting to try and use the simple structure of $L(\tilde{\mathcal{A}})$ in order to compute $L(\mathcal{A})$. The aim of this paper is to show that this is actually possible: if we choose a set $\tilde{\mathcal{J}}$ of representatives for the indecomposable $\tilde{\mathcal{A}}$ -modules which is stable under the fundamental group G (see chapter 3), the set of G -orbits $\{\bar{A} = GA : A \in \tilde{\mathcal{J}}\}$ is a set \mathcal{J} of representatives for the indecomposable \mathcal{A} -modules. Our goal is to prove:

$$\chi(V_{\mathcal{A}}(\bar{A}, \bar{B}; \bar{X})) = \sum_{g,h \in G} \chi(V_{\tilde{\mathcal{A}}}(A, g(B); h(X)))$$

for any $A, B, X \in \tilde{\mathcal{J}}$. Thus the structure constants for $L(\mathcal{A})$ are sums of – more easily accessible – structure constants of $L(\tilde{\mathcal{A}})$.

In fact, we will define an “orbit” Lie algebra L/G in chapter 2 for an appropriate action of a group G on a Lie algebra L and show in chapter 4 that the action of the fundamental group G of \mathcal{A} on $L(\tilde{\mathcal{A}})$ is appropriate. Our aim is then:

THEOREM. *Let \mathcal{A} be a locally representation finite \mathbb{C} -category with universal cover $\tilde{\mathcal{A}}$ and fundamental group G . Then $L(\mathcal{A})$ is isomorphic to $L(\tilde{\mathcal{A}})/G$.*

1.3. As a first application, let us prove again that for $\mathcal{A} = \mathbb{C}[T]/(T^n)$ the bracket on $L(\mathcal{A})$ is trivial [Rie]. The universal cover $\tilde{\mathcal{A}}$ of \mathcal{A} is given by the quiver

$$\cdots - 1 \xrightarrow{\alpha_{-1}} 0 \xrightarrow{\alpha_0} 1 \xrightarrow{\alpha_1} 2 \cdots,$$

having \mathbb{Z} as its vertex set and containing an arrow $\alpha_i : i \rightarrow i+1$ for $i \in \mathbb{Z}$, and the ideal of relations generated by all paths of length n . The fundamental group $G = \mathbb{Z}$ is generated by the shift $i \mapsto i+1$. For $\tilde{\mathcal{J}}$ we choose the set

$$\{(i, r) : i \in \mathbb{Z}, 1 \leq r \leq n\},$$

where (i, r) is “the indecomposable with top i of length r ” defined by

$$(i, r)(j) = \begin{cases} \mathbb{C} & \text{for } i \leq j < i+r, \\ 0 & \text{otherwise,} \end{cases}$$

and

$$(i, r)(\alpha_j) = \begin{cases} \text{id}_{\mathbb{C}} & \text{for } i \leq j < i+r-1, \\ 0 & \text{otherwise.} \end{cases}$$

It is easy to see that

$$V_{\tilde{\mathcal{A}}}((i, r), (j, s); (k, t)) = \begin{cases} 1 \text{ point} & \text{for } i = j+s, k = j, t = r+s, \\ \emptyset & \text{otherwise,} \end{cases}$$

for any triple of indecomposables. Therefore

$$\chi(V_{\tilde{\mathcal{A}}}((j+s, r), (j, s); (j, r+s))) = 1 = \chi(V_{\tilde{\mathcal{A}}}((i+r, s), (i, r); (i, r+s)))$$

give the only non-trivial contributions to the bracket $[v_A, v_B]$ with $A = (i, r)$, $B = (j, s)$.

As a second example, consider the quotient \mathcal{A} of the algebra of the quiver $\bullet \xrightarrow{\alpha} \bullet \circlearrowleft \beta$ by the ideal generated by β^3 . In this case the quiver of $\tilde{\mathcal{A}}$ is:

$$\begin{array}{ccccccc} \cdots & -1 & \xrightarrow{\beta_{-1}} & 0 & \xrightarrow{\beta_0} & 1 & \xrightarrow{\beta_1} & 2 & \cdots \\ & \uparrow \alpha_{-1} & & \uparrow \alpha_0 & & \uparrow \alpha_1 & & \uparrow \alpha_2 & \\ \cdots & -1' & & 0' & & 1' & & 2' & \cdots \end{array}$$

and the ideal of relations is generated by $\{\beta_{i+2}\beta_{i+1}\beta_i : i \in \mathbb{Z}\}$. The fundamental group is generated by the shift again. Let us consider the indecomposables A, B, X

given by

$$\dim A(x) = \begin{cases} 1 & \text{for } x = 1, 2, 3, \\ 0 & \text{otherwise,} \end{cases}$$

$$\dim B(x) = \begin{cases} 1 & \text{for } x = 0, 1, 2, 1', 2', \\ 0 & \text{otherwise,} \end{cases}$$

$$\dim X(x) = \begin{cases} 2 & \text{for } x = 1, 2, \\ 1 & \text{for } x = 0, 3, 1', 2', \\ 0 & \text{otherwise,} \end{cases}$$

and

$$X(\beta_0) = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad X(\beta_1) = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \quad X(\beta_2) = (0 \ 1),$$

$$X(\alpha_1) = \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \quad X(\alpha_2) = \begin{pmatrix} 1 \\ 1 \end{pmatrix}.$$

The variety of embeddings of \bar{A} into \bar{X} is 6-dimensional, and possible quotients are quite hard to determine. Over \tilde{A} , however, it is easy to see that the only way to embed A into a translate of X with quotient a translate of B is to choose a map $f: A \rightarrow X$ of the form

$$f(1) = \begin{pmatrix} \lambda \\ \mu \end{pmatrix}, \quad f(2) = \begin{pmatrix} \lambda \\ \mu \end{pmatrix}, \quad f(3) = \mu$$

with $\mu \neq 0$. The quotient is isomorphic to B if and only if $\lambda \neq 0, \mu$. Hence

$$\chi(V_A(\bar{A}, \bar{B}; \bar{X})) = -1.$$

2. The “orbit” Lie algebra

2.1. Let L be a \mathbb{Z} -Lie algebra which is generated (as a \mathbb{Z} -module) by some basis \mathcal{B} :

$$L = \bigoplus_{b \in \mathcal{B}} \mathbb{Z}b.$$

Suppose the group G acts on L by Lie algebra automorphisms in such a way that it permutes the elements of \mathcal{B} and that the following condition is satisfied:

$$\forall b, c \in \mathcal{B} : \#\{g \in G : [b, g(c)] \neq 0\} < \infty. \quad (*)$$

This condition is obviously empty in case G is finite. The main example to have in mind here, however, is the fundamental group G of a locally representation finite \mathbb{C} -category \mathcal{A} acting on $\text{ind } \tilde{\mathcal{A}}$ for a G -stable set of representatives, and this is a free group [BG].

Set

$$\bar{\mathcal{B}} = \{\bar{b} = G \cdot b : b \in \mathcal{B}\}$$

and

$$L/G = \bigoplus_{\bar{b} \in \bar{\mathcal{B}}} \mathbb{Z}\bar{b}.$$

Let

$$\bar{\cdot} : L \rightarrow L/G$$

be the \mathbb{Z} -linear map which takes b to \bar{b} for $b \in \mathcal{B}$.

The following result is easy to prove:

PROPOSITION. *The bracket*

$$[\bar{b}, \bar{c}] = \overline{\sum_{g \in G} [b, g(c)]}, \quad \bar{b}, \bar{c} \in \bar{\mathcal{B}},$$

defines a Lie algebra structure on L/G .

Note that the map $\bar{\cdot}$ is *not* a Lie algebra homomorphism in general.

2.2. Comparing the structure constants of L/G with those of L , we find: if

$$[b, c] = \sum_{d \in \mathcal{B}} \gamma_{b,c}^d d$$

and

$$[\bar{b}, \bar{c}] = \sum_{\bar{d} \in \bar{\mathcal{B}}} \bar{\gamma}_{\bar{b}, \bar{c}}^{\bar{d}} \bar{d},$$

then

$$\gamma_{\bar{b}, \bar{c}}^{\bar{d}} = \sum_{d' \in \bar{d}} \sum_{g \in G} \gamma_{b, g(c)}^{d'}.$$

In case the action of G on \mathcal{B} is free as it is in the case we are interested in this formula becomes

$$\gamma_{\bar{b}, \bar{c}}^{\bar{d}} = \sum_{g, h \in G} \gamma_{b, g(c)}^{h(d)}.$$

2.3. Let G be a group acting on the Lie algebra

$$L = \bigoplus_{b \in \mathcal{B}} \mathbb{Z}b$$

in such a way that the hypotheses of 2.1 are satisfied. If $H \triangleleft G$ is a normal subgroup, they are satisfied for the action of H on L as well, so that we can consider the Lie algebra

$$L/H = \bigoplus_{\bar{b} \in \bar{\mathcal{B}}} \mathbb{Z}\bar{b}$$

with

$$\bar{\mathcal{B}} = \{\bar{b} = Hb : b \in \mathcal{B}\}.$$

Extending the action given by

$$\bar{g}(\bar{b}) = \overline{g(b)}$$

of $\bar{G} = G/H$ on $\bar{\mathcal{B}}$ by \mathbb{Z} -linearity, we obtain an action of \bar{G} on L/H . It is easy to see that it satisfies again the hypotheses of 2.1 and that the following proposition holds:

PROPOSITION. *The \mathbb{Z} -linear map $L/G \rightarrow (L/H)/(G/H)$ sending the basis element Gb to $(G/H)\bar{b}$ is an isomorphism of Lie algebras.*

3. Locally representation finite categories and coverings

The references for this chapter are [BG], [Ga].

3.1. We begin by recalling some definitions:

A \mathbb{C} -category Λ is locally bounded if the following conditions are satisfied:

- (i) $\Lambda(x, x)$ is a local \mathbb{C} -algebra for all objects x of Λ .
- (ii) Distinct objects of Λ are not isomorphic.
- (iii) For all objects x we have

$$\sum_y \dim_{\mathbb{C}} \Lambda(x, y) < \infty,$$

$$\sum_y \dim_{\mathbb{C}} \Lambda(y, x) < \infty,$$

where y ranges over the objects of Λ .

A finite dimensional Λ -left module is a covariant functor $B : \Lambda \rightarrow \text{mod } \mathbb{C}$ with

$$\sum_x \dim_{\mathbb{C}} B(x) < \infty,$$

where x ranges over the objects of Λ .

We denote by $\text{mod } \Lambda$ the category of finite dimensional Λ -modules and by $\text{ind } \Lambda$ the full subcategory whose objects are a fixed set \mathcal{J} of representatives for the isomorphism classes of indecomposables in $\text{mod } \Lambda$.

A locally bounded \mathbb{C} -category Λ is locally representation finite if, for every object x of Λ , the number of indecomposables B in \mathcal{J} with $B(x) \neq 0$ is finite.

\mathbb{C} -algebras Λ which are sober, i.e. with $\Lambda/\text{rad } \Lambda \xrightarrow{\sim} \mathbb{C} \times \cdots \times \mathbb{C}$, correspond to locally bounded \mathbb{C} -categories with finitely many objects and representation finite \mathbb{C} -algebras to locally representation finite \mathbb{C} -categories with finitely many objects.

3.2. Let $\tilde{\Lambda}$ be the universal cover of Λ , and choose a set $\tilde{\mathcal{J}}$ of representatives for the indecomposable $\tilde{\Lambda}$ -modules which is stable under the action of the fundamental group G of Λ on $\text{mod } \tilde{\Lambda}$. Then G acts on the full subcategory $\text{ind } \tilde{\Lambda}$ of $\text{mod } \tilde{\Lambda}$ whose objects are the elements of $\tilde{\mathcal{J}}$ by \mathbb{C} -linear automorphisms. Moreover, we have

$$g(B) \neq B \quad \text{for every } B \text{ in } \tilde{\mathcal{J}} \text{ and every } g \neq 1 \text{ in } G$$

and

$$\#\{g \in G : \text{Hom}_{\tilde{\Lambda}}(A, g(B)) \neq 0\} < \infty \quad \text{for every pair } A, B \text{ in } \tilde{\mathcal{J}}.$$

Under these circumstances $\text{ind } \tilde{\Lambda}$ has a quotient modulo G : its objects are the G -orbits of objects in $\tilde{\mathcal{J}}$, and the morphisms from the orbit of A to the orbit of B are families $(f_{g,h})_{g,h \in G}$,

$$f_{g,h} : g(A) \rightarrow h(B)$$

with

$$l(f_{g,h}) = f_{lg, lh}$$

for all g, h, l in G .

Similarly, there exists a quotient $\tilde{\Lambda}/G$, which is locally representation finite. The category $(\text{ind } \tilde{\Lambda})/G$ is isomorphic to $\text{ind } (\tilde{\Lambda}/G)$, which is in turn isomorphic to the so called mesh category $\mathbb{C}(\Gamma_{\Lambda})$ associated with the Auslander-Reiten quiver of Λ . So $\tilde{\Lambda}/G$ is the “standard form” of Λ . But by [BGRS] non-standard algebras can exist only over ground fields of characteristic 2. Thus $\tilde{\Lambda}/G$ is isomorphic to Λ and $(\text{ind } \tilde{\Lambda})/G$ to $\text{ind } \Lambda$. We fix the set \mathcal{J} of G -orbits in $\tilde{\mathcal{J}}$ as a set of representatives of the isomorphism classes of indecomposable Λ -modules and identify $\text{ind } \Lambda$ with $(\text{ind } \tilde{\Lambda})/G$.

3.3. The \mathbb{C} -linear functor

$$F : \text{ind } \tilde{\Lambda} \rightarrow (\text{ind } \tilde{\Lambda})/G = \text{ind } \Lambda$$

defined by

$$F(B) = G \cdot B$$

for B in $\tilde{\mathcal{J}}$ and by associating to $f : A \rightarrow B$, $A, B \in \tilde{\mathcal{J}}$, the family

$$Ff = (f'_{g,h}), \quad g, h \in G$$

with

$$f'_{g,h} = \begin{cases} g(f) & g = h \\ 0 & g \neq h \end{cases}$$

is a covering functor. This means that, for all A, B in $\tilde{\mathcal{J}}$, F induces \mathbb{C} -linear isomorphisms

$$\bigoplus_{g \in G} \text{Hom}_{\tilde{\Lambda}}(A, g(B)) \xrightarrow{\sim} \text{Hom}_{\Lambda}(FA, FB),$$

$$\bigoplus_{g \in G} \text{Hom}_{\tilde{\Lambda}}(g(A), B) \rightarrow \text{Hom}_{\Lambda}(FA, FB).$$

We will need also that F induces \mathbb{C} -linear isomorphisms:

$$\bigoplus_{g \in G} \text{Ext}_{\tilde{\Lambda}}^1(A, g(B)) \xrightarrow{\sim} \text{Ext}_{\Lambda}^1(FA, FB),$$

$$\bigoplus_{g \in G} \text{Ext}_{\tilde{\Lambda}}^1(g(A), B) \xrightarrow{\sim} \text{Ext}_{\Lambda}^1(FA, FB),$$

for all A, B in $\tilde{\mathcal{J}}$. This is an easy consequence of the isomorphisms for Hom-sets and the fact that F is an exact functor preserving projectivity.

3.4. If $H \triangleleft G$ is a normal subgroup, it is the fundamental group of $\tilde{\Lambda}/H$, and again we identify $(\text{ind } \tilde{\Lambda})/H$ with $\text{ind } (\tilde{\Lambda}/H)$ and note this quotient simply $\text{ind } \tilde{\Lambda}/H$. There is a commutative triangle of covering functors:

$$\begin{array}{ccc} \text{ind } \tilde{\Lambda} & & \\ \downarrow F & \searrow F' & \\ & \text{ind } \tilde{\Lambda}/H & \\ & \swarrow \bar{F} & \\ \text{ind } \tilde{\Lambda}/G = \text{ind } \Lambda & & \end{array}$$

, where F' is a curved arrow from $\text{ind } \tilde{\Lambda}$ to $\text{ind } \tilde{\Lambda}/H$.

where \bar{F} sends HB to GB for B in $\tilde{\mathcal{J}}$ and a morphism

$$(f_{h_1, h_2} : h_1(A) \rightarrow h_1(B))_{h_1, h_2 \in H}$$

to

$$(f'_{g_1, g_2} : g_1(A) \rightarrow g_2(B))_{g_1, g_2 \in G}$$

with

$$f'_{g_1, g_2} = \begin{cases} g_2(f_{g_2^{-1}g_1, 1}) & \text{if } g_2^{-1}g_1 \in H, \\ 0 & \text{if not.} \end{cases}$$

As \bar{F} is a covering functor, \bar{F} induces \mathbb{C} -linear isomorphisms:

$$\bigoplus_{\bar{g} \in G/H} \text{Ext}_{\tilde{A}/H}^1(F'A, \bar{g}(F'B)) \xrightarrow{\sim} \text{Ext}_A^1(FA, FB),$$

$$\bigoplus_{\bar{g} \in G/H} \text{Ext}_{\tilde{A}/H}^1(\bar{g}(F'A), F'B) \xrightarrow{\sim} \text{Ext}_A^1(FA, FB),$$

for any two elements A, B in $\tilde{\mathcal{J}}$.

4. The theorem – and its proof in some cases

4.1. Let A be a locally representation finite \mathbb{C} -category with universal cover \tilde{A} and fundamental group G . Fix a G -stable set $\tilde{\mathcal{J}}$ of representatives for the isomorphism classes of indecomposable \tilde{A} -modules and identify $\text{ind } A$ with $\text{ind } \tilde{A}/G$.

Extend the action of G on $\tilde{\mathcal{J}}$ to a \mathbb{Z} -linear action of G on $L(\tilde{A})$. Note that, for $A, B, X \in \tilde{\mathcal{J}}$ and $g \in G$, the varieties $V_{\tilde{A}}(A, B; X)$ and $V_{\tilde{A}}(g(A), g(B); g(X))$ are isomorphic and hence homeomorphic. Therefore G acts by Lie algebra automorphisms.

Moreover, the sets

$$\{h \in G : \text{Hom}_{\tilde{A}}(A, h(X)) \neq 0\}$$

and, for any $h \in G$

$$\{g \in G : \text{Hom}_{\tilde{A}}(h(X), g(B)) \neq 0\}$$

are finite for any A, B, X by 3.2. This implies that the action of G on $L(\tilde{A})$ satisfies the condition $(*)$ of 2.1 as well.

Now the statement of our theorem makes sense at least. In fact, both Lie algebras $L(A)$ and $L(\tilde{A})/G$ have as a basis the set of G -orbits in $\tilde{\mathcal{J}}$. The isomorphism is the identity on this basis.

4.2. We recall from [Rie] that there is another way to compute the structure constants of $L(A)$, which is more adapted to coverings: let A, B and X be indecomposable A -modules. Then the following Euler-Poincaré characteristics coincide:

$$\chi(V_A(B, A; X)) = \chi(\text{Ext}_A^1(A, B)_X / \mathbb{C}^*).$$

The variety on the left hand side has been introduced in 1.1. As to the right hand side, $\text{Ext}_A^1(A, B)_X$ is the algebraic subset of equivalence classes of short exact

sequences in the \mathbb{C} -vector space $\text{Ext}_\Lambda^1(A, B)$ whose middle term is isomorphic to X . It is stable under the action of \mathbb{C}^* by homotheties on $\text{Ext}_\Lambda^1(A, B)$.

4.3. PROPOSITION. *Let Λ be a locally representation finite \mathbb{C} -category with universal cover $\tilde{\Lambda}$ and fundamental group G , and suppose that the set*

$$\{g \in G : \text{Ext}_\Lambda^1(A, g(B)) \neq 0\}$$

has at most one element for any pair A, B in $\tilde{\mathcal{J}}$. Then $L(\Lambda)$ is isomorphic to $L(\tilde{\Lambda})/G$.

Proof. Let

$$F : \text{ind } \tilde{\Lambda} \rightarrow \text{ind } \tilde{\Lambda}/G = \text{ind } \Lambda$$

be the orbit covering functor. Choose A and B in $\tilde{\mathcal{J}}$ in such a way that

$$\text{Ext}_\Lambda^1(FA, FB) \neq 0.$$

According to our hypothesis and 3.3 there is a unique element $g \in G$ such that $\text{Ext}_\Lambda^1(A, g(B)) \neq 0$, and F induces a \mathbb{C} -linear isomorphism

$$\text{Ext}_\Lambda^1(A, g(B)) \xrightarrow{\sim} \text{Ext}_\Lambda^1(FA, FB).$$

Clearly the inverse image of $\text{Ext}_\Lambda^1(FA, FB)_{FX}$ under this isomorphism is the disjoint union

$$\bigcup_{h \in G} \text{Ext}_\Lambda^1(A, g(B))_{h(X)}$$

for any X in $\tilde{\mathcal{J}}$.

As the characteristic $\chi(\mathcal{C})$ of a finite disjoint union $\mathcal{C} = \bigcup \mathcal{C}_i$ of constructible subsets of a variety \mathcal{C} is the sum $\sum \chi(\mathcal{C}_i)$, we conclude that

$$\begin{aligned} \chi(\text{Ext}_\Lambda^1(FA, FB)_{FX}/\mathbb{C}^*) &= \sum_{h \in G} \chi(\text{Ext}_\Lambda^1(A, g(B))_{h(X)}/\mathbb{C}^*) \\ &= \sum_{g, h \in G} \chi(\text{Ext}_\Lambda^1(A, g(B))_{h(X)}/\mathbb{C}^*). \end{aligned}$$

Remarks.

(i) As $\tilde{\Lambda}$ is simply connected, there is in fact at most one $h \in G$ with $\text{Ext}_{\tilde{\Lambda}}^1(A, g(B))_{h(X)} \neq 0$, as indecomposables are determined by their composition factors [Ha].

(ii) Note also that in case

$$\{g \in G : \text{Ext}_{\tilde{\Lambda}}^1(A, g(B)) \neq 0\}$$

contains at most one element for just a pair A, B in $\tilde{\mathcal{J}}$, it is still true that

$$\chi(\text{Ext}_{\tilde{\Lambda}}^1(FA, FB)_{FX}/\mathbb{C}^*) = \sum_{g, h \in G} \chi(\text{Ext}_{\tilde{\Lambda}}^1(A, g(B))_{h(X)}/\mathbb{C}^*).$$

5. \mathbb{C}^* -actions

We fix a locally representation finite \mathbb{C} -category Λ with universal cover $\tilde{\Lambda}$ and fundamental group G as well as a G -stable set $\tilde{\mathcal{J}}$ of representatives for the isomorphism classes of indecomposable $\tilde{\Lambda}$ -modules. We denote by F the orbit covering functor

$$F : \text{ind } \tilde{\Lambda} \rightarrow \text{ind } \tilde{\Lambda}/G = \text{ind } \Lambda.$$

5.1. Any map $\lambda : G \rightarrow \mathbb{Z}$ gives rise to a \mathbb{C} -linear \mathbb{C}^* -action on the \mathbb{C} -vector space

$$\bigoplus_{g \in G} \text{Ext}_{\tilde{\Lambda}}^1(A, g(B))$$

by

$$t \cdot (\varepsilon_g)_{g \in G} = (t^{\lambda(g)} \varepsilon_g)_{g \in G}$$

for $t \in \mathbb{C}^*$, $\varepsilon_g \in \text{Ext}_{\tilde{\Lambda}}^1(A, g(B))$ and for any $A, B \in \tilde{\mathcal{J}}$. A line through the origin in this vector space is stable under \mathbb{C}^* if and only if there exists an integer n such that the line lies in

$$\bigoplus_{\substack{g \in G \\ \lambda(g) = n}} \text{Ext}_{\tilde{\Lambda}}^1(A, g(B)).$$

Using the \mathbb{C} -isomorphism

$$\bigoplus_{g \in G} \text{Ext}_{\tilde{\Lambda}}^1(A, g(B)) \rightarrow \text{Ext}_{\tilde{\Lambda}}^1(FA, FB),$$

induced by F (see 3.3) we obtain a \mathbb{C}^* -action on

$$\mathrm{Ext}_A^1(FA, FB)/\mathbb{C}^*,$$

whose fixed points are the disjoint union

$$\dot{\bigcup}_{n \in \mathbb{Z}} \left[F \left[\bigoplus_{\substack{g \in G \\ \lambda(g) = n}} \mathrm{Ext}_A^1(A, g(B))/\mathbb{C}^* \right] \right]$$

Recall that the Euler-Poincaré characteristic of a variety Z admitting an algebraic action of \mathbb{C}^* equals the characteristic of the fixed point set $Z^{\mathbb{C}^*}$.

Therefore our theorem would be proved if we could exhibit a map $\lambda : G \rightarrow \mathbb{Z}$ satisfying:

- (i) the middle term of a short exact sequence in $\mathrm{Ext}_A^1(FA, FB)$ changes only up to isomorphism under the \mathbb{C}^* -action defined by λ .
- (ii) for each integer n there is at most one $g \in G$ with $\lambda(g) = n$.

Indeed, such a λ would give rise to a \mathbb{C}^* -action stabilizing $\mathrm{Ext}_A^1(FA, FB)_{FX}$ for any $X \in \tilde{\mathcal{J}}$ by (i), and we could write

$$\begin{aligned} \chi(\mathrm{Ext}_A^1(FA, FB)_{FX}/\mathbb{C}^*) &= \chi((\mathrm{Ext}_A^1(FA, FB)_{FX}/\mathbb{C}^*)^{\mathbb{C}^*}) \\ &= \chi \left[\dot{\bigcup}_{\substack{n \in \mathbb{Z} \\ \exists g_n : \lambda(g_n) = n}} \dot{\bigcup}_{h \in G} \mathrm{Ext}_A^1(A, g_n(B))_{h(X)}/\mathbb{C}^* \right] \\ &= \sum_{g, h \in G} \chi(\mathrm{Ext}_A^1(A, g(B))_{h(X)}/\mathbb{C}^*). \end{aligned}$$

Here we used again that the inverse image of $\mathrm{Ext}_A^1(FA, FB)_{FX}$ in $\mathrm{Ext}_A^1(A, g_n(B))$ is the disjoint union

$$\dot{\bigcup}_{h \in G} \mathrm{Ext}_A^1(A, g_n(B))_{h(X)}.$$

Unfortunately, such λ 's need not exist. We will concentrate first on the condition (i), which is indispensable.

5.2. For $A, B, U \in \tilde{\mathcal{J}}$ we consider the pull-back map

$$\pi : \mathrm{Ext}_A^1(FA, FB) \times \mathrm{Hom}_A(FU, FA) \rightarrow \mathrm{Ext}_A^1(FU, FB)$$

which associates to an exact sequence

$$\varepsilon : 0 \rightarrow FB \rightarrow Z \rightarrow FA \rightarrow 0$$

with Z in $\text{mod } \Lambda$ and a homomorphism $f : FB \rightarrow FU$ the pull-back sequence $\pi(\varepsilon, f)$ in $\text{Ext}_\Lambda^1(FU, FB)$:

$$\begin{array}{ccccccccc} \varepsilon & : & 0 & \rightarrow & FB & \rightarrow & Z & \rightarrow & FA & \rightarrow & 0 \\ & & & & \parallel & & \uparrow & & \uparrow f & & \\ \pi(\varepsilon, f) & : & 0 & \rightarrow & FB & \rightarrow & Z' & \rightarrow & FU & \rightarrow & 0. \end{array}$$

By Auslander's criterion [AR] two Λ -modules Z_1 and Z_2 are isomorphic if and only if

$$\dim_{\mathbb{C}} \text{Hom}_\Lambda(FU, Z_1) = \dim_{\mathbb{C}} \text{Hom}_\Lambda(FU, Z_2)$$

for all indecomposables FU over Λ . Thus two exact sequences

$$\begin{array}{l} \varepsilon_1 : 0 \rightarrow FB \rightarrow Z_1 \rightarrow FA \rightarrow 0 \\ \varepsilon_2 : 0 \rightarrow FB \rightarrow Z_2 \rightarrow FA \rightarrow 0 \end{array}$$

have isomorphic middle terms if and only if

$$\dim_{\mathbb{C}} \ker \pi(\varepsilon_1, ?) = \dim_{\mathbb{C}} \ker \pi(\varepsilon_2, ?)$$

for the two maps $\pi(\varepsilon_1, ?)$ and $\pi(\varepsilon_2, ?)$ from $\text{Hom}_\Lambda(FU, FA)$ to $\text{Ext}_\Lambda^1(FU, FB)$ and all indecomposables FU .

Let $\lambda : G \rightarrow \mathbb{Z}$ be a map and consider the \mathbb{C}^* -action on

$$\bigoplus_{l \in G} \text{Hom}_\Lambda(l(U), A)$$

given by

$$t \cdot (f_l)_{l \in G} = (t^{-\lambda(l)} f_l)_{l \in G},$$

for B, U in $\tilde{\mathcal{J}}$. The \mathbb{C} -isomorphism

$$\bigoplus_{l \in G} \text{Hom}_\Lambda(l(U), A) \xrightarrow{\sim} \text{Hom}_\Lambda(FU, FA)$$

allows us to transfer this action of \mathbb{C}^* to $\text{Hom}_\Lambda(FU, FA)$.

LEMMA. Let $\lambda : G \rightarrow \mathbb{Z}$ be a group homomorphism. Then the map

$$\pi : \text{Ext}_A^1 (FA, FB) \times \text{Hom}_A (FU, FA) \rightarrow \text{Ext}_A^1 (FU, FB)$$

is \mathbb{C}^* -equivariant, where on the left \mathbb{C}^* acts diagonally.

Proof. It suffices to check that, for g, l in G , the pull-back map

$$\pi : \text{Ext}_{\tilde{A}}^1 (A, g(B)) \times \text{Hom}_{\tilde{A}} (l(U), A) \rightarrow \text{Ext}_{\tilde{A}}^1 (l(U), g(B))$$

has the property

$$\pi(t^{\lambda(g)} \varepsilon_g, t^{-\lambda(l)} f_l) = t^{\lambda(l^{-1}g)} \pi(\varepsilon_g, f_l),$$

for $t \in \mathbb{C}^*$. This is clear, as $\lambda(l^{-1}g) = \lambda(g) - \lambda(l)$.

COROLLARY. If $\lambda : G \rightarrow \mathbb{Z}$ is a group homomorphism, the \mathbb{C}^* -action on $\text{Ext}_A^1 (FA, FB)$ associated with λ stabilizes $\text{Ext}_A^1 (FA, FB)_{FX}$, for all A, B, X in $\tilde{\mathcal{F}}$.

Thus our first condition is satisfied. But it is clear that a group homomorphism will rarely satisfy the second one.

5.3. PROPOSITION. Let $\lambda : G \rightarrow \mathbb{Z}$ be a group homomorphism. Then $L(\Lambda)$ is isomorphic to $L(\tilde{\Lambda}/\ker \lambda)/(G/\ker \lambda)$.

COROLLARY. If the fundamental group G is \mathbb{Z} , $L(\Lambda)$ is isomorphic to $L(\tilde{\Lambda})/G$.

Proof of the proposition. We have to show that, for any A, B, X in $\tilde{\mathcal{F}}$,

$$\chi(\text{Ext}_A^1 (FA, FB)_{FX}/\mathbb{C}^*) = \sum_{\tilde{g}, \tilde{h} \in G/\ker \lambda} \chi(\text{Ext}_{\tilde{A}/\ker \lambda}^1 (F'A, \tilde{g}(F'B))_{\tilde{h}(F'X)}/\mathbb{C}^*)$$

where $F' : \text{ind } \tilde{\Lambda} \rightarrow \text{ind } \tilde{\Lambda}/\ker \lambda$ is the orbit functor. This follows easily from the formula for fixed points in 5.1, as the inverse image of $\text{Ext}_A^1 (FA, FB)_{FX}$ in $\text{Ext}_{\tilde{A}/\ker \lambda}^1 (F'A, \tilde{g}(F'B))$ is the disjoint union

$$\bigcup_{\tilde{h} \in G/\ker \lambda} \text{Ext}_{\tilde{A}/\ker \lambda}^1 (F'A, \tilde{g}(F'B))_{\tilde{h}(F'B)}.$$

6. The proof

6.1. The last ingredient for our proof is the following:

PROPOSITION. $L(\Lambda)$ is isomorphic to $L(\tilde{\Lambda}/G')/(G/G')$, where G' is the commutator subgroup of G .

Proof. As G is free [BG], the quotient G/G' is free abelian. Let $\rho : G \rightarrow G/G'$ be the projection.

Fix A and B in \mathcal{J} , and let S be the finite subset

$$S = \{g \in G : \text{Ext}_{\tilde{\Lambda}}^1(A, g(B)) \neq 0\}$$

of G . As G/G' is free abelian, there exists a group homomorphism $\bar{\lambda} : G/G' \rightarrow \mathbb{Z}$ whose restriction to $\rho(S)$ is injective. Choose for $\lambda : G \rightarrow \mathbb{Z}$ the composition $\bar{\lambda} \circ \rho$.

The following picture explains the notations we choose for orbit functors related to the groups $G' \subseteq \ker \lambda \subseteq G$:

$$\begin{array}{ccc}
 \text{ind } \tilde{\Lambda} & & \\
 \downarrow F & \searrow F' & \\
 & \text{ind } \tilde{\Lambda}/G' & \\
 & \downarrow \overline{F''} & \\
 & \text{ind } \tilde{\Lambda}/\ker \lambda & \\
 & \swarrow \tilde{F} & \\
 \text{ind } \Lambda & &
 \end{array}$$

We denote the residue class of an element g in G modulo G' by \bar{g} and modulo $\ker \lambda$ by \tilde{g} .

We know from 5.3 that, for any X in \mathcal{J} ,

$$\chi(\text{Ext}_{\Lambda}^1(FA, FB)_{FX}/\mathbb{C}^*) = \sum_{\tilde{g}, \tilde{h} \in G/\ker \lambda} \chi(\text{Ext}_{\tilde{\Lambda}/\ker \lambda}^1(F''A, \tilde{g}(F''B))_{\tilde{h}(F''X)}/\mathbb{C}^*).$$

Applying 3.4 to $\tilde{\Lambda}/\ker \lambda$, $G' \subseteq \ker \lambda$ and the elements $A, g(B) \in \tilde{\mathcal{J}}$, we find that $\overline{F''}$ induces an isomorphism

$$\bigoplus_{\bar{l} \in \ker \lambda/G'} \text{Ext}_{\tilde{\Lambda}/G'}^1(F'A, \bar{l}(F'(gB))) \rightarrow \text{Ext}_{\tilde{\Lambda}/\ker \lambda}^1(F''A, F''(gB)).$$

We claim that, by our choice of λ , there is a unique $\bar{l} \in \ker \lambda/G'$ for which

$$\text{Ext}_{\tilde{\Lambda}/G'}^1(F'A, \bar{l}(F'(gB))) \neq 0$$

provided that

$$\text{Ext}_{\tilde{\Lambda}/\ker \lambda}^1(F''A, F''(gB)) \neq 0.$$

Indeed, for $l \in \ker \lambda$, the space

$$\text{Ext}_{\tilde{\Lambda}/G'}^1(F'A, F'(lgB))$$

is isomorphic to

$$\bigoplus_{g' \in G'} \text{Ext}_{\tilde{\Lambda}}^1(A, g'lgB).$$

If now for $l_1, l_2 \in \ker \lambda$ there exists $g'_1, g'_2 \in G'$ such that

$$\text{Ext}_{\tilde{\Lambda}}^1(A, g'_i l_i gB) \neq 0, \quad i = 1, 2,$$

the elements $g'_i l_i g$ both belong to S , and their residue class modulo $\ker \lambda$ is \bar{g} . Thus their classes modulo G' coincide, and therefore $\bar{l}_1 = \bar{l}_2$.

Suppose now that

$$\text{Ext}_{\tilde{\Lambda}/\ker \lambda}^1(F''A, F''(gB)) \neq 0,$$

and fix l in $\ker \lambda$ with

$$\text{Ext}_{\tilde{\Lambda}/G'}^1(F'A, F'(lgB)) \neq 0.$$

Then $\overline{F''}$ induces an isomorphism

$$\text{Ext}_{\tilde{\Lambda}/G'}^1(F'A, F'(lgB)) \rightarrow \text{Ext}_{\tilde{\Lambda}/\ker \lambda}^1(F''A, F''(gB)).$$

The inverse image of

$$\text{Ext}_{\tilde{\Lambda}/\ker \lambda}^1(F''A, F''(gB))_{F''(hX)}$$

under this isomorphism is the disjoint union

$$\bigcup_{\bar{k} \in \ker \lambda/G'} \text{Ext}_{\tilde{\Lambda}/G'}^1(F'A, F'(lgB))_{\bar{k}F'(hX)}.$$

Summing up we find

$$\chi(\text{Ext}_{\tilde{\Lambda}}^1(FA, FB)_{FX}/\mathbb{C}^*) = \sum_{\bar{g}, \bar{h} \in G/G'} \chi(\text{Ext}_{\tilde{\Lambda}/G'}^1(F'A, \bar{g}(F'B))_{\bar{h}(F'X)}/\mathbb{C}^*).$$

6.2. The higher commutator subgroups $G^{(i)}$ of G , $i \in \mathbb{N}$, are defined inductively by

$$G^{(i+1)} = [G^{(i)}, G^{(i)}].$$

They are normal subgroups of G . As a consequence of Magnus' theorem on the lower central series, they intersect in the neutral element of G , since G is free.

COROLLARY. *For any $i \in \mathbb{N}$, $L(\Lambda)$ is isomorphic to $L(\tilde{\Lambda}/G^{(i)})/(G/G^{(i)})$.*

Proof. Indeed, proposition 6.1 applied to $\tilde{\Lambda}/G^{(i)}$ tells us that

$$L(\tilde{\Lambda}/G^{(i)}) \xrightarrow{\sim} L(\tilde{\Lambda}/G^{(i+1)})/(G^{(i)}/G^{(i+1)})$$

for all i . We conclude by induction applying 2.3.

6.3. **PROPOSITION.** *If Λ has finitely many objects there exists a natural number such that $L(\tilde{\Lambda}/G^{(n)})$ is isomorphic to $L(\tilde{\Lambda})/G^{(n)}$.*

Proof. In view of proposition 4.3 (applied to $\tilde{\Lambda}/G^{(n)}$) we only need to find $t \in \mathbb{N}$ such that

$$\{g \in G^{(t)} : \text{Ext}_{\tilde{\Lambda}}^1(A, g(B)) \neq 0\}$$

has at most one element for all $A, B \in \tilde{\mathcal{J}}$. For $A, B \in \tilde{\mathcal{J}}$ we set

$$S(A, B) = \{g \in G : \text{Ext}_{\tilde{\Lambda}}^1(A, g(B)) \neq 0\}$$

and

$$T(A, B) = \{g_1 g_2^{-1} : g_1, g_2 \in S(A, B)\}.$$

Clearly we have

$$S(h(A), l(B)) = hS(A, B)l^{-1}$$

and

$$T(h(A), l(B)) = hT(A, B)h^{-1}.$$

Since \mathcal{A} has finitely many objects, \mathcal{J} contains only finitely many G -orbits, and therefore the set

$$T = \bigcup_{A, B \in \mathcal{J}} T(A, B)$$

is a finite union of conjugacy classes in G .

Use now that the intersection $\bigcap_{i \in \mathbb{N}} G^{(i)}$ is reduced to $\{1\}$. Fix an integer t with

$$T \cap G^{(t)} = \{1\}.$$

Then the set

$$S(A, B) \cap G^{(t)} = \{g \in G^{(t)} : \text{Ext}_{\tilde{\mathcal{A}}}^1(A, g(B)) \neq 0\}$$

contains at most one element for all $A, B \in \mathcal{J}$, and our proof is complete.

6.4. In case \mathcal{A} is finite the preceding proposition proves our theorem. Indeed, we have a chain of isomorphisms

$$L(\mathcal{A}) \xrightarrow{\sim} L(\tilde{\mathcal{A}}/G^{(t)})/(G/G^{(t)}) \xrightarrow{\sim} (L(\tilde{\mathcal{A}})/G^{(t)})/(G/G^{(t)}) \xrightarrow{\sim} L(\tilde{\mathcal{A}})/G.$$

In general, there is no reason why proposition 6.3 should hold. But “ t exists locally”, and this suffices to prove our theorem: for $A, B \in \mathcal{J}$ there exists $t = t(A, B)$ such that

$$T(A, B) \cap G^{(t)} = \{1\},$$

as $T(A, B)$ is finite.

Again this implies that

$$\{g \in G^{(t)} : \text{Ext}_{\tilde{\mathcal{A}}}^1(A, g(B)) \neq 0\}$$

contains at most one element. By the second remark in 4.2 the Lie bracket of $v_{G^{(t)} \cdot A}$ with $v_{G^{(t)} \cdot B}$ is “the same” in $L(\tilde{A}/G^{(t)})$ as in $L(\tilde{A})/G^{(t)}$. We finish the proof as in case A is finite, comparing the brackets of $v_{G \cdot A}$ and $v_{G \cdot B}$ in $L(A)$, $L(\tilde{A}/G^{(t)})/(G/G^{(t)})$, $(L(\tilde{A})/G^{(t)})/(G/G^{(t)})$ and $L(\tilde{A})/G$.

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