

ROBERT M. FOSSUM

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# A CHARACTERISTIC CLASS IN ALGEBRAIC K-THEORY

Robert M. FOSSUM

## 0. INTRODUCTION

This lecture reports on work done jointly with H.-B. FOXBY and B. IVERSEN. Details are found in [FFI]. The interest in this work began when we tried to formalize the following problem : let  $A$  be a noetherian local ring. Consider bounded complexes of projective  $A$ -modules of finite type which have homology of finite length and maps from this category to abelian groups that are additive over exact sequences of complexes and one equal on complexes that are homotopically equivalent. Find a universal group for these maps and generators (and relations) for this group. While studying this problem we rediscovered some relative  $K$ -groups of Bass [B], found a generalization of Mennicke symbols and used some of our techniques to calculate anew some groups of divisors. Since the details are available in preprint form and may be available soon in published form, this report will attempt only to give the highlight of our work. This report is divided into three parts that are described below.

§1.  $\textcircled{\text{Æ}}$ -Theory. This section contains definitions and alludes to some basic properties of family of abelian groups that FOXBY and I denote by  $\textcircled{\text{Æ}}$  (a Danish vowel that is close, in most languages, to "a" or "e" or somewhere in between, that has the sound of e in the english "bed", and that is phonetically written "æ"). One of the groups in the family is the group mentioned in the paragraph above.

§2. Characteristic classes and Mennicke symbols. This section contains some mention of the relations between groups in the family above and relative  $K$ -groups. There is also an indication of the construction of relative Mennicke symbols.

§3. Examples. In this section examples are mentioned of calculations of some of the groups involved.

Again I want to emphasize that this is work done together with FOXBY and IVERSEN. I thank my wife Barbara for her inspiration. This research was partially supported by the United States National Science Foundation.

### § 1. $\mathcal{C}(A)$ -THEORY

Let  $A$  be a commutative ring. Let  $\mathcal{C}(A)$  denote the category of complexes of projective  $A$ -modules of finite type.

Recall that a morphism  $f. : P. \rightarrow Q.$  in  $\mathcal{C}(A)$  is a family of homomorphisms  $f_i : P_i \rightarrow Q_i$  such that

$$\begin{array}{ccc} P_i & \xrightarrow{d_i^P} & P_{i-1} \\ f_i \downarrow & & \downarrow f_{i-1} \\ Q_i & \xrightarrow{d_i^Q} & Q_{i-1} \end{array}$$

commutes for each  $i$ . Such a map induces a homomorphism  $H.(f.) : H.(P.) \rightarrow H.(Q.)$  on homology. A morphism  $f.$  is a quasi-isomorphism if  $H.(f.)$  is an isomorphism.

A sequence

$$0 \longrightarrow P. \longrightarrow Q. \xrightarrow{g.} R. \longrightarrow 0$$

of complexes is exact if the sequences

$$0 \longrightarrow P_i \xrightarrow{f_i} Q_i \xrightarrow{g_i} R_i \longrightarrow 0$$

are split exact for each  $i$ .

Let  $\mathcal{C}^b(A)$  denote the category of bounded complexes in  $\mathcal{C}(A)$ .

Of  $P. \in \mathcal{C}^b(A)$ , the length of  $P.$  is defined by

$$\text{length}(P.) = \sup \{i : P_i \neq 0\} - \inf \{i \mid P_i \neq 0\}.$$

Let  $\mathcal{S}$  be a Serre subcategory of the category of  $A$ -modules. We denote by

$\underline{\mathcal{E}}.(A, \underline{\mathcal{S}})$  and by  $\underline{\mathcal{E}}^b.(A, \underline{\mathcal{S}})$  the subcategories of  $\underline{\mathcal{E}}.(A)$  and  $\underline{\mathcal{E}}^b.(A)$  consisting of those complexes whose homology modules are objects in  $\underline{\mathcal{S}}$ . (For example if  $\underline{\mathcal{S}}$  is the category of  $A$ -modules, then  $\underline{\mathcal{E}}.(A, \underline{\mathcal{S}}) = \underline{\mathcal{E}}.(A)$ . If  $\underline{\mathcal{S}} = \{0\}$ , then  $\underline{\mathcal{E}}.(A, \underline{\mathcal{S}})$  is the category of exact complexes, that is  $H.(P.) \equiv 0$ ).

Note that  $\underline{\mathcal{E}}.(A, \underline{\mathcal{S}})$  and  $\underline{\mathcal{E}}^b.(A, \underline{\mathcal{S}})$  are Serre subcategories in that if

$$0 \longrightarrow P. \longrightarrow Q. \longrightarrow R. \longrightarrow 0$$

is an exact sequence of complexes and any two of the complexes are in  $\underline{\mathcal{E}}.(A, \underline{\mathcal{S}})$ , then the third is also. Note also that by using quasi-isomorphisms or the homology category, we can get triangulated categories in the sense of Verdier [V].

Either using triangulated categories or ab initio we define an abelian group  $\mathbb{A}\mathbb{E}(A, \underline{\mathcal{S}})$  to be a certain Grothendieck group.

**THEOREM 1.1.** *There is an abelian group  $\mathbb{A}\mathbb{E}(A, \underline{\mathcal{S}})$  and an assignment*

$$\mathbb{a}\mathbb{E}: \underline{\mathcal{E}}^b.(A, \underline{\mathcal{S}}) \longrightarrow \mathbb{A}\mathbb{E}(A, \underline{\mathcal{S}}) \text{ such that :}$$

1.2. *if  $0 \longrightarrow P. \longrightarrow Q. \longrightarrow R. \longrightarrow 0$  is exact in  $\underline{\mathcal{E}}^b.(A, \underline{\mathcal{S}})$*

$$\mathbb{a}\mathbb{E}(Q.) = \mathbb{a}\mathbb{E}(P.) + \mathbb{a}\mathbb{E}(R.).$$

1.3. *If  $P.$  is in  $\underline{\mathcal{E}}^b.(A, \underline{\mathcal{S}})$  and  $H.(P.) \equiv 0$ , then  $\mathbb{a}\mathbb{E}(P.) = 0$ .*

1.4. *The pair  $(\mathbb{A}\mathbb{E}(A, \underline{\mathcal{S}}), \mathbb{a}\mathbb{E})$  is universal for such assignments.*

(This means, of course, that if  $\langle \rangle : \underline{\mathcal{E}}^b.(A, \underline{\mathcal{S}}) \longrightarrow L$  is such an assignment to an abelian group  $L$ , then there is a unique  $\mathbb{a}\mathbb{E}' : \mathbb{A}\mathbb{E}(A, \underline{\mathcal{S}}) \longrightarrow L$  such that

$$\begin{array}{ccc} & \mathbb{A}\mathbb{E}(A, \underline{\mathcal{S}}) & \\ \mathbb{a}\mathbb{E} \nearrow & & \downarrow \mathbb{a}\mathbb{E}' \\ \underline{\mathcal{E}}^b.(A, \underline{\mathcal{S}}) & & L \\ & \searrow \langle \rangle & \end{array}$$

commutes).

Recall that a complex can be shifted. if  $P. \in \underline{\mathcal{E}}.(A)$ , then for  $n \in \mathbb{Z}$  we define a new complex  $P.[n]$  by

$$(P.[n])_i := P_{n+i}$$

with differential  $d_i^P [n] = (-1)^n d_{n+i}^P$ .

Using mapping cones and an inductive definition of the total complex of a double complex, a very useful result concerning the classes of a total complex is obtained. While no direct use is made in this report, the result is, in some sense, critical in making calculations.

**THEOREM 1.5.** *Let  $P..$  be a bounded double complex such that  $P_i. \in \underline{\mathcal{C}}^b(A, \mathcal{A})$  for each  $i$ . Then the total complex*

$$\text{Tot.}(P..) \in \underline{\mathcal{C}}^b(A, \mathcal{A})$$

and

$$\mathfrak{A}(\text{Tot.}(P..)) = \sum_i (-1)^i \mathfrak{A}(P_i.)$$

in

$$\mathfrak{A}(A, \mathcal{A}) .$$

**COROLLARY 1.6.** *Of  $P. \in \underline{\mathcal{C}}^b(A, \mathcal{A})$ , then*

$$\mathfrak{A}(P.[n]) = (-1)^n \mathfrak{A}(P.) .$$

**COROLLARY 1.7.** *Of  $P..$  is a bounded complex and  $P_i. \in \underline{\mathcal{C}}^b(A, \mathcal{A})$  and  $P_.j \in \underline{\mathcal{C}}^b(A, \mathcal{A})$  for all  $i$  and  $j$ , then*

$$\sum_i (-1)^i \mathfrak{A}(P_i.) = \sum_j (-1)^j \mathfrak{A}(P_.j) \text{ in } \mathfrak{A}(A, \mathcal{A})$$

This last result is particularly useful when considering a square of  $A$ -modules,

$$\begin{array}{ccc} P_1 & \xrightarrow{d_1} & P_0 \\ f_1 \downarrow & & \downarrow f_0 \\ Q_1 & \xrightarrow{e_1} & Q_0 \end{array} .$$

Suppose the four complexes are in  $\underline{\mathcal{C}}(A, \mathcal{A})$ . Then, denoting the class of the complex by  $\mathfrak{A}(f)$ , where  $f$  is the map, we obtain

$$\text{or } -\mathfrak{A}(f_1) + \mathfrak{A}(f_0) = -\mathfrak{A}(d_1) + \mathfrak{A}(e_1) ,$$

$$\text{or } \mathfrak{A}(f_0) + \mathfrak{A}(d_1) = \mathfrak{A}(e_1) + \mathfrak{A}(f_1) ,$$

$$\text{or } \mathfrak{A}(f_0 \circ d_1) = \mathfrak{A}(e_1 \circ f_1)$$

where  $e_1 \circ f_1, f_0 \circ d_1 : P_1 \longrightarrow Q_0$ .

We have in mind two categories  $\underline{\mathcal{A}}$ . Let  $\underline{fl}$  denote the category of  $A$ -modules of finite length. Then  $P. \in \underline{\mathcal{C}}^b(A, \underline{fl})$  if and only if  $H_i(P.)$  has finite length for each  $i$ . There is an obvious map  $\underline{\chi} : \underline{\mathcal{C}}^b(A, \underline{fl}) \longrightarrow \mathbb{Z}$  given by

$$\underline{\chi}(P.) := \sum (-1)^i \text{length}(H_i(P.))$$

and this clearly factors through  $\underline{\mathcal{A}}E(A, \underline{fl})$ . In some special cases we can determine the kernel of this homomorphism (cf. § 3).

Let  $S$  be a multiplicative subset of  $A$ . We can consider those modules  $M$  for which  $S^{-1}M = (0)$ . Then  $\underline{\mathcal{C}}^b(A, \underline{\mathcal{A}})$  consists of those complexes  $P.$  such that  $S^{-1}P.$  is exact. The associated group is denoted by  $\underline{\mathcal{A}}E(A, S^{-1}A)$ . In § 3 we will indicate how useful this group is for classifying singularities.

We introduce another family of abelian groups. Let  $F : \underline{\mathcal{A}} \longrightarrow \underline{\mathcal{B}}$  be an additive functor from the additive category  $\underline{\mathcal{A}}$  to the additive category  $\underline{\mathcal{B}}$ . Define two categories  $\text{Co}(F)$  and  $\text{Hot}(\underline{\mathcal{A}}, F)$  as follows :

The category  $\text{Co}(F)$  consists of triples

$$\pi = (P_1, p, P_0)$$

as objects, where  $P_i \in \underline{\mathcal{A}}$  and  $p : F(P_1) \longrightarrow F(P_0)$  is an isomorphism in  $\underline{\mathcal{B}}$ .

Morphisms in  $\text{Co}(F)$  are pairs

$$f. = (f_1, f_0) : \underline{\pi} \longrightarrow \underline{\rho} := (R_1, r, P_0)$$

where  $f_i : P_i \longrightarrow R_i$  and the diagram

$$\begin{array}{ccc} FP_1 & \xrightarrow{p} & FP_0 \\ Ff_1 \downarrow & & \downarrow Ff_0 \\ FR_1 & \xrightarrow{r} & FR_0 \end{array}$$

is commutative.

The category  $\text{Hot}(\underline{\mathcal{A}}, F)$  consists of bounded complexes  $P.$  of objects in  $\underline{\mathcal{A}}$  such that the transforms under  $F$  are contractible in  $\underline{\mathcal{B}}$ ; morphisms are maps of complexes. (Recall that a bounded complex  $Q.$  in  $\underline{\mathcal{B}}$  is contractible if there

are morphisms  $S_i : Q_i \rightarrow Q_{i+1}$  such that

$$S_{i-1} \circ d_i^Q + d_{i+1}^Q \circ S_i = \text{Id}_{Q_i}$$

for each  $i$ . Call  $S$ . the contraction).

Suppose  $P. \in \text{Hot}(\underline{Q}, F)$  with contraction  $S$ . We construct an object

$$(1.6) \quad \underline{\pi}(P., S.) \text{ in } \text{Co}(F)$$

$$\text{by } \underline{\pi}(P., S.) = (P_{\text{odd}}, P, P_{\text{even}})$$

where

$$P_{\text{odd}} := \coprod_i P_{2i+1} = \begin{array}{c} \vdots \\ \oplus \\ P_{2i-1} \\ \oplus \\ P_{2i+1} \\ \oplus \\ \vdots \end{array} \quad \text{and} \quad P_{\text{even}} := \coprod_i P_{2i} = \begin{array}{c} \vdots \\ \oplus \\ P_{2i} \\ \oplus \\ P_{2i+2} \\ \oplus \\ \vdots \end{array}$$

and  $p : F(P_{\text{odd}}) \rightarrow F(P_{\text{even}})$  is given by

$$\left( \begin{array}{ccc} \vdots & & \\ F(d_{2i-1}) & 0 & 0 \\ S_{2i-1} & F(d_{2i+1}) & 0 \\ 0 & S_{2i+1} & F(d_{2i+3}) \\ & \vdots & \vdots \\ \dots & & \end{array} \right)$$

$$\text{Since } \left( \begin{array}{ccc} \dots & S_{2n-2} & F(d_{2n}) & 0 \\ & 0 & S_{2n} & F(d_{2n+2}) \\ & \dots & & \end{array} \right) \circ p = \left( \begin{array}{cc} \text{Id} & 0 \\ & \text{Id} \\ * & \end{array} \right),$$

it follows that  $p$  is an isomorphism and that we have determined an element in  $\text{Co}(F)$ .

Now define two groups denoted respectively by  $K_0(\underline{Q}, F)$  and  $K_0(\text{Hot}(\underline{Q}, F))$  whose existences are guaranteed by the following theorems.

THEOREM 1.7. Let  $F : \underline{Q} \rightarrow \underline{B}$  as above. There is an abelian group  $K_0(\underline{Q}, F)$  and an assignment  $[ ] : \text{Co}(F) \rightarrow K_0(\underline{Q}, F)$  satisfying.

1.8. If  $\underline{\pi}$  and  $\underline{\rho}$  are composable in the sense that  $P_0 = R_1$ , and denoting by  $\underline{\rho\pi}$  the composition then

$$[\underline{\rho\pi}] = [\underline{\rho}] + [\underline{\pi}] .$$

1.9. If  $0 \rightarrow \underline{\pi} \xrightarrow{f_i} \underline{\rho} \xrightarrow{g_i} \underline{\sigma} \rightarrow 0$  is exact (which means that

$$P_i \xrightarrow{f_i} R_i \xrightarrow{g_i} S_i$$

are split exact in  $\underline{Q}$ ), then

$$[\underline{\rho}] = [\underline{\pi}] + [\underline{\sigma}] .$$

1.10. The pair  $(K_0(\underline{Q}, F), [ ])$  is universal for assignments satisfying 1.8 and 1.9.

THEOREM 1.11. There is an abelian group  $K_0(\text{Hot}(\underline{Q}, F))$  and an assignment  $\langle \rangle : \text{Hot}(\underline{Q}, F) \rightarrow K_0(\text{Hot}(\underline{Q}, F))$  satisfying.

1.12. If  $P$  is contractible in  $\underline{Q}$ , then  $\langle P \rangle = 0$ .

1.13. If  $0 \rightarrow P \rightarrow Q \rightarrow R \rightarrow 0$  is exact in  $\text{Hot}(\underline{Q}, F)$ , then

$$\langle Q \rangle = \langle P \rangle + \langle R \rangle .$$

1.14. The pair  $(K_0(\text{Hot}(\underline{Q}, F)), \langle \rangle)$  is universal for maps from  $\text{Hot}(\underline{Q}, F)$  to abelian groups satisfying 1.12 and 1.13.

We note that the triple  $\underline{\pi}(P., S.)$  for  $P.$  in  $\text{Hot}(\underline{Q}, F)$  gives an element in  $\text{Co}(F)$  and hence in  $K_0(\underline{Q}, F)$ . The main theorem in this part of theory is that this element is independent of the contraction  $S$ .

THEOREM 1.15. Suppose  $P.$  is in  $\text{Hot}(\underline{Q}, F)$ . The element  $\underline{\pi}(P., S.)$  is independent of the contraction  $S$ . That is to say, if  $t.$  is another contraction, then

$$[\underline{\pi}(P., S.)] = [\underline{\pi}(P., t.)] .$$



DEFINITION 1.16. The map induced from  $\text{Hot}(\underline{Q}, F)$  to  $K_0(\underline{Q}, F)$  is denoted by  $wh$  and is called the whitehead maps, in order to indicate the influence of whitehead on this subject. The whitehead map satisfies 1.12 and 1.13 and therefore there is a unique map

$$wh : K_0(\text{Hot}(\underline{Q}, F)) \longrightarrow K_0(\underline{Q}, F)$$

satisfying  $wh\langle P. \rangle = [\pi(P., S.)]$ .

In case  $F$  is localizing in the sense of Gabriel, then it can be shown that  $wh$  is an isomorphism. In particular, when this is the case, then  $K_0(\text{Hot}(\underline{Q}, F))$  is generated by complexes of length 1. We return later to this remark.

It is not the intention here to list all the functorial properties of these groups  $\mathbb{E}(A, \mathcal{A})$ ,  $K_0(\text{Hot}(\underline{Q}, F))$  and  $K_0(\underline{Q}, F)$ . Some of them are obvious. One question that comes immediately to mind is the relation that might exist between  $\mathbb{E}(A, \mathcal{A})$  and some  $K_0(\text{Hot}(\underline{Q}, F))$ . For example, let  $\underline{Q}$  be the additive category generated by the projective  $A$ -modules of finite type. Is there a functor  $F : \underline{a} \rightarrow \underline{b}$  such that  $\text{Hot}(\underline{a}, F) = \mathbb{E}^b(A, \mathcal{A})$ ? Is there an  $F$  that is localizing?

## § 2. CHARACTERISTIC CLASSES AND GENERALIZED MENNICKE SYMBOLS.

In this section  $A$  denotes a ring with 1 (not necessarily commutative). We work with right  $A$ -modules.

DEFINITION 2.1. A pair  $(F, \underline{f})$  is a based  $A$ -module if  $F$  is a free module with ordered basis  $\underline{f} = (f_1, \dots, f_n)$ . If  $(F, \underline{f}), (G, \underline{g})$  is a pair of based  $A$ -modules, then the direct sum  $\left( \begin{smallmatrix} F \\ \oplus \\ G \end{smallmatrix}, \begin{smallmatrix} \underline{f} \\ \underline{g} \end{smallmatrix} \right)$  is a based  $A$ -module with basis

$$\left( \begin{smallmatrix} \underline{f} \\ \underline{g} \end{smallmatrix} \right) = \left( \begin{smallmatrix} f_1 \\ 0 \end{smallmatrix} \right), \dots, \left( \begin{smallmatrix} f_n \\ 0 \end{smallmatrix} \right), \left( \begin{smallmatrix} 0 \\ g_1 \end{smallmatrix} \right), \dots, \left( \begin{smallmatrix} 0 \\ g_m \end{smallmatrix} \right) .$$

A homomorphism  $f : (F, \underline{f}) \rightarrow (G, \underline{g})$  of based modules is a homomorphism of the underlying  $A$ -modules.

A bounded complex of based A-modules  $F$ . is exact if the complex of underlying A-modules is exact and

$$\sum_i (-1)^i \text{rk}(F_i) = 0.$$

Suppose  $F$ . is exact. Construct based A-modules

$$F_{\text{odd}} = \begin{array}{c} \vdots \\ F_{2i-1} \\ \oplus \\ F_{2i+1} \\ \vdots \end{array} \quad \text{and} \quad F_{\text{even}} = \begin{array}{c} \vdots \\ \oplus \\ F_{2i-2} \\ \oplus \\ F_{2i} \\ \oplus \\ \vdots \end{array}$$

and a matrix  $W(S.) : F_{\text{odd}} \rightarrow F_{\text{even}}$  defined by this complex as follows :

let  $S$ . be a contraction of  $F$ . (which exists because the complex is exact and consists of free modules). Then each  $S_i$  has a matrix with respect to the bases of  $F_i$  and  $F_{i+1}$ . Then set

$$W(S.) = \begin{pmatrix} \vdots & & & & \\ & d_{2n-1} & & & \\ & S_{2n-1} & d_{2n+1} & 0 & \\ & 0 & S_{2n+1} & & 0 \\ & & 0 & & \end{pmatrix} .$$

As before, it follows that  $W(S.) \in GL_N(A)$ . Using a proof similar to that used to show the independence of the Whitehead map in the previous section, we can show that the class of  $W(S.)$  in  $K_1(A)$  is independent of the contraction.

THEOREM 2.2. *The class of  $W(S.)$  in  $K_1(A)$  is independent of  $S$ .*

DEFINITION 2.3. *Call the element obtained in  $K_1(A)$  the whitehead torsion of the complex  $F$ . and denote it by  $\text{wt}(F.)$ .*

Using techniques developed in examining the properties for wh, it possible to write formulas for  $\text{wt}(F.[n])$  and  $\text{wt}(\text{Tot.}(F.))$  which are similar to those

found in 1.6. and 1.7.

This construction is used to define generalized Mennicke symbols. For the remainder of this section we suppose  $A$  is a commutative ring.

If  $(E, \underline{e})$  is a based module, then the exterior powers  $(\wedge^p E, \wedge^p \underline{e})$  become based modules by ordering the tensors  $e_{i_1} \wedge e_{i_2} \wedge \dots \wedge e_{i_p}$  lexicographically. Suppose  $(a_1, \dots, a_n) \in A^n$  and that this row is unimodular. Then the Koszul complex  $K.(a_1, \dots, a_n)$  becomes a based complex which is exact.

DEFINITION 2.4. If  $(a_1, \dots, a_n)$  is a unimodular row in  $A^n$ , the the generalized  $n^{\text{th}}$  order Mennicke symbol, denoted by  $[a_1, \dots, a_n]$ , is defined by

$$[a_1, \dots, a_n] := \text{wt}(K.(a_1, \dots, a_n)).$$

THEOREM 2.5. The  $n^{\text{th}}$  order Mennicke symbol is

- i) symmetric,
- ii) multilinear, and
- iii) unimodular.

It is clear what it means to be symmetric. To be multilinear means

$$[ab, a_2, \dots, a_n] = [a, a_2, \dots, a_n] [b, a_2, \dots, a_n].$$

While to be unimodular means

$$[a_1 + X_1 a_n, \dots, a_{n-1} + X_{n-1} a_n, a_n] = [a_1, \dots, a_n]$$

for any  $(X_1, \dots, X_{n-1}) \in A^{n-1}$ .

Examples. For  $n = 2$ , we obtain

$$[a_1, a_2] = \begin{bmatrix} a_1 & a_2 \\ X_1 & X_2 \end{bmatrix}$$

where  $a_1 X_2 - a_2 X_1 = 1$ .

For  $n = 3$ , suppose  $a_1 X_3 - a_2 X_2 + a_3 X_1 = 1$ . Then

$$[a_1, a_2, a_3] = \left[ \begin{array}{cccc} a_1 & a_2 & a_3 & 0 \\ X_2 & X_3 & 0 & a_3 \\ -X_1 & 0 & X_3 & -a_2 \\ 0 & -X_1 & -X_2 & a_1 \end{array} \right]$$

When  $n=4$ , then for  $a_1 X_4 - a_2 X_3 + a_3 X_2 - a_4 X_1 = 1$  we obtain

$$[a_1, a_2, a_3, a_4] = \left[ \begin{array}{cccc|cccc} (a_1 & a_2 & a_3 & a_4) & 0 & 0 & 0 & 0 \\ X_3 & X_4 & 0 & 0 & a_3 & a_4 & 0 & 0 \\ -X_2 & 0 & -X_4 & 0 & -a_2 & 0 & -a_4 & 0 \\ X_1 & 0 & 0 & X_4 & 0 & -a_2 & -a_3 & 0 \\ 0 & -X_2 & -X_3 & 0 & a_1 & 0 & 0 & a_4 \\ 0 & X_1 & 0 & -X_3 & 0 & a_1 & 0 & -a_3 \\ 0 & 0 & X_1 & X_2 & 0 & 0 & a_1 & a_2 \\ \hline 0 & 0 & 0 & 0 & (X_1 & X_2 & X_3 & X_4) \end{array} \right]$$

Example. Let  $S^k$  denote the  $k$ -sphere  $\mathbb{R}^{k+1}$  given as the locus of  $X_1^2 + X_2^2 + \dots + X_{k-1}^2 = 1$ . Let  $A_k$  denote the ring of complex valued continuous functions on  $S^k$ . From [M] and the periodicity theorem it follows that

$$SK_1(A_k) = \begin{cases} \mathbb{Z} & k = 3, 5, 7, \dots \\ 0 & \text{otherwise.} \end{cases}$$

Suppose  $k$  is odd, say  $k = 2n-1$ . Then  $\mathbb{R}^{k+1} = \mathbb{C}^n$  with coordinate functions  $Z_1, \dots, Z_n$ . Furthermore  $S^{2n-1}$  is the locus of  $Z_1 \bar{Z}_1 + \dots + Z_n \bar{Z}_n = 1$ . Hence  $(Z_1, \dots, Z_n)$  is a unimodular row in  $A_{2n-1}$  (where we restrict the  $Z_i$ ).

THEOREM 2.6. For  $n \geq 2$ , the Mennicke symbol  $[Z_1, \dots, Z_n]$  generates  $SK_1(A_{2n-1})$ .

Let  $B_k = \mathbb{C}[X_1, X_2, \dots, X_{k+1}] / (X_1^2 + X_2^2 + \dots + X_{k+1}^2 = 1)$ . When  $k+1 = 2n$ , set  $Z_m = X_{2m-1} + iX_{2m}$  and  $\bar{Z}_m = X_{2m-1} - iX_{2m}$  for  $m = 1, 2, \dots, n$ .

Then  $B_{2n-1} = \mathbb{C}[Z_1, \bar{Z}_1, \dots, Z_n, \bar{Z}_n] / (Z_1 \bar{Z}_1 + \dots + Z_n \bar{Z}_n - 1)$ .

There is an injection  $B_{2n-1} \hookrightarrow A_{2n-1}$  and hence a homomorphism

$$SK_1(B_{2n-1}) \longrightarrow SK_1(A_{2n-1}).$$

The generalized Mennicke symbol  $[Z_1, \dots, Z_n]$  lives in  $SK_1(B_{2n-1})$  and hence we conclude that

$$SK_1(B_{2n-1}) \neq 0$$

for  $n \geq 2$ .

The interested reader is referred to [FFI] for further computations and the demonstrations of these results.

### § 3. EXAMPLES.

In this last section we indicate how sensitive the group  $\mathbb{E}(A, \underline{f1})$  is to the properties of  $A$ . We assume that  $A$  is noetherian. Suppose  $\underline{\mathcal{A}}$  is a Serre subcategory of the category of  $A$ -modules of finite type. Let  $G_0(\underline{\mathcal{A}})$  denote the Grothendieck group on  $\underline{\mathcal{A}}$ .

DEFINITION 3.1. The Euler characteristic of a complex  $P$  in  $\mathcal{E}^b(A, \underline{\mathcal{A}})$  is defined to be

$$\underline{\chi}(P) := \sum_i (-1)^i [H_i(P)],$$

where  $[H_i(P)]$  denotes the class of  $H_i(P)$  in  $G_0(\underline{\mathcal{A}})$ .

There is induced a unique homomorphism

$$\underline{\chi} : \mathbb{E}(A, \underline{\mathcal{A}}) \longrightarrow G_0(\underline{\mathcal{A}})$$

such that

$$\underline{\chi}(\mathbb{E}(P)) = \underline{\chi}(P).$$

THEOREM 3.2. Let  $A$  be a regular local ring. Then

$$\underline{\chi} : \mathbb{E}(A, \underline{f1}) \longrightarrow \mathbb{Z} = G_0(\underline{f1})$$

is an isomorphism.

### Problem 3.3.

- a) Compute  $\mathbb{E}(A, \underline{f1})$  for  $A$  a regular, but not necessarily local, ring.

b) Compute  $\mathbb{E}(A, \underline{fl})$  for all local rings.

We mention at this point a problem suggested by L. SZPIRO. If  $P.$  is a bounded complex with finite length homology, where we assume  $A$  is a local ring, then the same is true of its dual  $\text{Hom}_A^{\bullet}(P., A) = : P^{\vee}.$

If  $P.$  is exact then so is  $P^{\vee}.$  Also if

$$0 \longrightarrow P. \longrightarrow Q. \longrightarrow R. \longrightarrow 0$$

is exact, then

$$0 \longrightarrow R^{\vee} \longrightarrow Q^{\vee} \longrightarrow P^{\vee} \longrightarrow 0$$

is exact. We get induced an involution  $\vee : \mathbb{E}(A, \underline{fl}) \longrightarrow \mathbb{E}(A, \underline{fl}).$  satisfying  $\mathbb{E}(P^{\vee}) = \mathbb{E}(P.)^{\vee}.$

**Problem 3.4.** (Szpiro). Let  $\chi$  be as in definition 3.1. What is the relation between  $\chi(P.)$  and  $\chi(P^{\vee})$ ? More generally what properties does  $\vee$  have as a homomorphism of  $\mathbb{E}(A, \underline{fl})$ ? (Cf [PS]) where a formula is discussed in the graded case).

Consider now the case where  $S$  is a multiplicatively closed subset of  $A$ . We want to consider  $\mathbb{E}(A, S^{-1}A)$ . The theory developed in § 1 can be used. Let  $\mathcal{P}(A) =$  be the category of projective  $A$ -modules of finite type and let  $\underline{\mathcal{B}}$  be  $S^{-1}A$ -modules, the functor  $S : \mathcal{P}(A) \longrightarrow \underline{\mathcal{B}}$  is just  $P \longrightarrow S^{-1}P$ . It is clearly localizing. Hence  $\mathbb{E}(A, S^{-1}A) = K_0(\text{Hot}(\mathcal{P}(A), S)) = K_0(A, S^{-1}A)$ . There is a resulting exact sequence [B] of  $K$ -groups

$$\begin{array}{ccccccccc} K_1(A) & \longrightarrow & K_1(S^{-1}A) & \longrightarrow & \mathbb{E}(A, S^{-1}A) & \longrightarrow & K_0(A) & \longrightarrow & K_0(S^{-1}A) \\ \downarrow \det & & \downarrow \det & & \downarrow \det & & \downarrow \det & & \downarrow \det \\ \underline{\mu}(A) & \longrightarrow & \underline{\mu}(S^{-1}A) & \longrightarrow & \text{Pic}(A, S^{-1}A) & \longrightarrow & \text{Pic}(A) & \longrightarrow & \text{Pic}(S^{-1}A) \end{array}$$

which fits into the diagram above. (Let  $\underline{\mu}(A)$  be the group of units of  $A$ , let  $\underline{\alpha}(A)$  be the additive group of  $A$ ).

Apply this to the case

- $A$  is a reduced local ring of dimension 1
- $S$  is the set of non-zero divisors in  $A$

- B is the normal closure of A in  $S^{-1}A$ , which we assume to be of finite type as an A-module. Then the exact sequences of K-theory become, respectively,

$$\begin{array}{ccccccc}
 1 & \longrightarrow & \underline{\mu}(A) & \longrightarrow & \underline{\mu}(S^{-1}A) & \longrightarrow & \mathbb{E}(A, S^{-1}A) \longrightarrow 0 \\
 & & \downarrow & & \cong \downarrow & & \downarrow \\
 1 & \longrightarrow & \underline{\mu}(B) & \longrightarrow & \underline{\mu}(S^{-1}A) & \longrightarrow & \mathbb{E}(B, S^{-1}A) \longrightarrow 0
 \end{array}$$

which yields an exact sequence

$$0 \longrightarrow \underline{\mu}(B)/\underline{\mu}(A) \longrightarrow \mathbb{E}(A, S^{-1}A) \longrightarrow \mathbb{E}(B, S^{-1}B) \longrightarrow 0 .$$

Since B is a semi local regular ring, the local Euler maps induce an isomorphism

$$\mathbb{E}(B, S^{-1}B) \cong \mathbb{Z}^b$$

where b is the number of branches of A, or the number of maximal ideals of B.

**THEOREM 3.5.** *Of the residue class field k of A is algebraically closed, then*

$$K_0(A, S^{-1}A) = \mathbb{E}(A, S^{-1}A) = Q(k) \times \mathbb{Z}^b$$

where  $Q(k)$  is an abelian group that is g divisible for all g with  $(g, \text{char } k) = 1$  and b is the number of branches of A.

Let  $\underline{f}$  be the conductor from B to A. Then the diagram

$$\begin{array}{ccc}
 A & \longrightarrow & A/\underline{f} \\
 \downarrow & & \downarrow \\
 B & \longrightarrow & B/\underline{f}
 \end{array}$$

is cartesian and so there results an isomorphism

$$\underline{\mu}(B)/\underline{\mu}(A) \cong \underline{\mu}(B/\underline{f})/\underline{\mu}(A/\underline{f}) .$$

Suppose  $\underline{\Delta}$  is a subsemi group of  $\mathbb{N}_0 = \mathbb{N} \cup \{0\}$ . Let  $\underline{\Delta} = \mathbb{N}_0 - \underline{\Delta}$ . Suppose further that  $\underline{\Delta}\mathbb{Z} = \mathbb{Z}$  (i.e. the greatest common divisor of elements in  $\underline{\Delta}$  is 1). This is the same as to say  $\underline{\Delta}$  is finite. Let  $f+1 = \min n : n \notin \underline{\Delta}$ . Suppose k is a field. Let  $A_{\underline{\Delta}}$  be the subring of  $k[[t]]$  consisting of those power series  $a_0 + a_1t + a_2t^2 + \dots =: p(t)$  such that  $a_i = 0$  if  $i \notin \underline{\Delta}$ . Set  $B = k[[t]]$ . Then B is the normal closure of A and the conductor  $\underline{f}$  of  $A_{\underline{\Delta}}$  in B is the principal ideal  $t^{f+1}B = \{p(t) : a_0 = a_1 = \dots = a_f = 0\}$ . Then  $B/\underline{f} = k[t]/t^{f+1}[t]$  and

$A_{\Delta}/\underline{F}$  is the subring consisting of those truncated polynomials whose coefficients of  $t^i$  are zero unless  $i \in \Lambda$ .

Let  $R$  be a commutative ring. For an integer  $n \in \mathbb{N}$ , let  $W_n(R)$  denote the set of  $n \times n$  unipotent upper triangular matrices of the form

$$\begin{pmatrix} 1 & a_1 & a_2 & a_3 & a_n \\ 0 & 1 & a_1 & a_2 & a_{n-1} \\ \vdots & & & & \\ 0 & 0 & 0 \dots 1 & a_1 & \\ 0 & 0 & 0 \dots 0 & 1 & \end{pmatrix} = : (1, a_1, a_2, \dots, a_n) .$$

If  $(1, a_1, \dots, a_n)$  and  $(1, b_1, \dots, b_n)$  are two such matrices, then the product is  $(1, c_1, \dots, c_n)$  where

$$\begin{aligned} c_1 &= a_1 + b_1 \\ c_2 &= a_2 + a_1 b_1 + b_2 \\ &\vdots \\ c_n &= a_n + a_{n-1} b_1 + a_{n-2} b_2 + \dots + a_1 b_{n-1} + b_n . \end{aligned}$$

Now note that  $f(t) \in R[t]/(t^{n+1})$  is a unit if and only if  $f(0)$  in  $R$  is a unit. Write such an element as

$$a_0 g(t) = a_0 (1 + c_1 t + \dots + c_n t^n) .$$

Define a map

$$\begin{aligned} \underline{\mu}(R[t]/(t^{n+1})) &\longrightarrow \underline{\mu}(R) \times W_n(R) \\ \text{by} \quad a_0 g(t) &\longrightarrow (a_0, (1, c_1, \dots, c_n)) . \end{aligned}$$

(This looks like the matrix

$$\begin{pmatrix} a_0 & a_1 & \dots & a_n \\ 0 & a_0 & a_1 & a_{n-1} \\ \vdots & & & \\ 0 & 0 & a_0 & a_1 \\ 0 & 0 & 0 & a_0 \end{pmatrix}$$

where  $a_i = a_0 c_i$ ). This map is clearly an isomorphism. If  $\Delta$  is as above and  $(R[t]/(t^{f+1}))_{\Delta}$  denotes those polynomials whose coefficients of  $t^d$  are zero



for  $d$  in  $\underline{\Delta}$ , then  $W_{f,\underline{\Delta}}(R)$ , the subgroup of  $W_f(R)$  for which  $a_i = 0$  if  $i \in \underline{\Delta}$ , is in the image of  $\mu(R[t]/(t^{f+1}))_{\underline{\Delta}}$ . Hence

$$\mu(R[t]/(t^{f+1}))_{\underline{\Delta}} / \mu((R[t]/(t^{f+1}))_{\underline{\Delta}}) \cong W_f(R) / W_{f,\underline{\Delta}}(R).$$

Note that multiplication by an element of the form

$(1, 0, 0, \dots, 0, a_r, a_{r+1}, \dots, a_f)$  leaves the first  $r$  coordinates of  $(1, b_1, \dots, b_f)$  unchanged. So given  $(1, b_1, b_2, \dots, b_f)$  in  $W_f(R)$ , there is an element  $u$  in  $W_{f,\underline{\Delta}}(R)$  such that  $u(1, b_1, \dots, b_f) = (1, c_1, c_2, \dots, c_f)$  where  $c_i = 0$  if  $i \notin \underline{\Delta}$ . Let  $\alpha_{\underline{\Delta}}(R) := W_f(R) / W_{f,\underline{\Delta}}(R)$ . Then  $\alpha_{\underline{\Delta}}$  is an algebraic group of dimension  $\text{Card}(\underline{\Delta})$  and  $\alpha_{\underline{\Delta}} = \text{Spec}(Z[X_1, \dots, X_d])$  where  $\text{Card } \underline{\Delta} = d$ .

Example 1. Take  $\underline{\Delta} = \{1, 2, 3, \dots, f\}$ . So the semi-group is  $S = \{0, f+1, f+2, \dots\}$ .

Then

$$\alpha_{\underline{\Delta}} = W_f.$$

Thus for  $A_{\underline{\Delta}} = \{a_0 + a_{f+1}t^{f+1} + a_{f+2}t^{f+2} + \dots\}$  we get

$$\mathbb{E}(A_{\underline{\Delta}}, L) = W_f(k) \times \mathbb{Z}.$$

Example 2. The cusp. Take  $\underline{\Delta} = \{1\}$ . Then

$$A_{\underline{\Delta}} = k[[t^2, t^3]] = k[[X, Y]] / (Y^2 - X^3).$$

Then

$$\mathbb{E}(A_{\underline{\Delta}}, L) = \alpha(k) \times \mathbb{Z}.$$

Example 3. Take  $\underline{\Delta} = \{1, 3\}$ . Then

$$A_{\underline{\Delta}} = k[[t^2, t^5]] = k[[X, Y]] / (Y^2 - X^5).$$

Then

$$\mathbb{E}(A_{\underline{\Delta}}, L) = \alpha_{\{1,3\}}(k) \times \mathbb{Z}.$$

Now  $\alpha_{\{1,3\}}(k) = k \times k$ . We consider an element  $(a_1, a_3) = (1, a_1, 0, a_3)$

mod  $W_{4,\underline{\Delta}}(k)$ . So  $(a_1, a_3) \otimes (b_1, b_3) \equiv (1, a_1, 0, a_3)(1, b_1, 0, b_3) \pmod{W_{4,\underline{\Delta}}(k)}$ . Then

$$(1, a_1, 0, a_3)(1, b_1, 0, b_3) = (1, a_1 + b_1, a_1 b_1, a_3 + b_3).$$

Multiply this by  $(1, 0, -a_1 b_1, 0)$  to get

$$\equiv (1, a_1+b_1, 0, a_3+b_3-(a_1b_1)(a_1+b_1)) = (a_1+b_1, a_3+b_3-a_1b_1(a_1+b_1)).$$

So in  $\alpha_{\{1,3\}}(h)$  we have

$$(a_1, a_3) \oplus (b_1, b_3) = (a_1+b_1, a_3+b_3-a_1b_1(a_1+b_1))$$

(which is addition of 3-Witt vectors of length 2).

**Example 4.** Take  $\underline{\Delta} = \{1, 3, 5\}$ . Then

$$A_{\underline{\Delta}} = k[[t^2, t^7]] = k[[X, Y]]/(Y^2 - X^7)$$

and

$$\mathbb{E}(A_{\underline{\Delta}}, L) = \alpha_{\{1,3,5\}}(k) \times \mathbb{Z}.$$

The multiplication in  $\alpha_{\{1,3,5\}}(k)$  is

$$(a_1, a_3, a_5) \cdot (b_1, b_3, b_5) = (a_1+b_1, a_3+b_3-a_1b_1(a_1+b_1), a_5+b_5-a_1b_1(a_3+b_3) \\ + [(a_1b_1)^2 - (a_1b_3+a_3b_1)](a_1+b_1)).$$

The computations for the rational cases are the same. Then  $B' = k[t]_{(t)}$  with field of fractions  $k(t)$ . Then  $B' = k[[t]] \cap k(t)$ . Let  $A'_{\underline{\Delta}} = A_{\underline{\Delta}} \cap B'$ . Then

$$\mathbb{E}(A'_{\underline{\Delta}}, k(t)) = \alpha_{\underline{\Delta}}(k) \times \mathbb{Z}.$$

**Example 5.** The node. This plane curve is the locus of  $y^2 = X^2(X-1)$ . We suppose

$(-1)^{1/2} \in k$  and that  $\frac{1}{2} \in k$ . In  $k[[X]]$  let  $t = (X-1)^{1/2} = (-1)^{1/2}(1-x)^{1/2}$ .

Then  $y^2 - X^2(X-1) = y^2 - X^2t^2 = (y-Xt)(y+Xt)$ . Note that  $t$  is a unit. Let  $u = y-Xt$ ,

$v = y+Xt$ . Then  $k[[X, y]] = k[[u, v]]$ . The local ring at the origin of  $y^2 = X^2(X-1)$

completed is then  $A = k[[u, v]]/(uv)$ . The normal closure in the total ring of quotients is  $B = k[[r]] \times k[[s]]$  with

$$f(u, v) \longmapsto (f(r, 0), f(0, s))$$

for  $f(u, v) \in A$ . The conductor  $\underline{\mathcal{F}} = (r, s)B = (u, v)A$ . Hence  $B/\underline{\mathcal{F}} = k \times k$  and

$A/\underline{\mathcal{F}} = k$ , the map  $A/\underline{\mathcal{F}} \rightarrow B/\underline{\mathcal{F}}$  being the diagonal. Hence

$$\mu(B/\underline{\mathcal{F}})/\mu(A/\underline{\mathcal{F}}) \simeq \mu(k),$$

the map being

$$(a, b) \longmapsto ab^{-1}$$

for  $(a,b) \in \underline{\mu}(k) \times \underline{\mu}(k) = \underline{\mu}(B/\underline{\mathcal{F}})$ . There fore

$$\textcircled{\mathbb{A}}(A,L) = \underline{\mu}(k) \times \mathbb{Z}^2 .$$

Example 6. Consider the homomorphism

$$k[[X,y]] \longrightarrow k[[S_1]] \times k[[S_2]] \times k[[S_3]] = B$$

given by  $X \longmapsto (S_1, 0, S_2)$

$$y \longmapsto (0, S_2, S_3).$$

It is clear that  $Xy(X-y)$  is in the kernel. Since  $k[[X,y]]$  is factorial and the image ring is reduced of dimension 1, the kernel is the intersection of prime principal ideals. Hence the ideal generated by  $Xy(X-y)$  is the kernel.

Also let  $A = k[[X,y]]/(Xy(X-y))$ . Then  $B$  is the normal closure of  $A$  in its total quotient ring. The conductor is  $(S_1^2, S_2^2, S_3^2)B = (x,y)^2 A$ . In this case

$$\underline{\mu}(B/\underline{\mathcal{F}}) = (\underline{\mu}(k) \times \underline{\alpha}(k)) \times (\underline{\mu}(k) \times \underline{\alpha}(k)) \times (\underline{\mu}(k) \times \underline{\alpha}(k))$$

and

$$\underline{\mu}(A/\underline{\mathcal{F}}) = \underline{\mu}(k) \times \underline{\alpha}(k) \times \underline{\alpha}(k).$$

The map is given by

$$(u, a, b) \longmapsto ((u, a), (u, d), (u, a+b))$$

for  $u \in \underline{\mu}(k)$ ,  $(a,b) \in \underline{\alpha}(k) \times \underline{\alpha}(k)$ . (The élément  $(u, a, b)$  corresponds to the unit

$$u(1+ax+by) \text{ in } A/\underline{\mathcal{F}}.$$

The element

$$((u_1, a_1), (u_2, a_2), u_3, a_3))$$

corresponds to the unit

$$(u_1(1+a_1s_1), u_2(1+a_2s_2), u_3(1+a_3s_3))$$

in  $B/\underline{\mathcal{F}}$ ). Hence

$$\underline{\mu}(B/\underline{\mathcal{F}})/\underline{\mu}(A/\underline{\mathcal{F}}) \simeq \underline{\mu}(k) \times \underline{\mu}(k) \times \underline{\alpha}(k)$$

the map being given by

$$((u_1, a_1), (u_2, a_2), (u_3, a_3)) \longmapsto (u, u_3^{-1}, u_2 u_3^{-1}, a_1 + a_2 - a_3) .$$

Hence

$$\textcircled{\mathbb{A}}(A,L) \simeq \underline{\mu}(k) \times \underline{\mu}(k) \times \underline{\alpha}(k) \times \mathbb{Z}^3 .$$

(This example was told to we by F. Orecchia).

We contrast these local examples with the case of global example, again the cusp.

Example 7. Consider the cusp  $k[X,y]/(y^2-X^3) = A$  with normal closure  $B = k[t]$ .

We get exact sequences

$$\begin{array}{ccccccccc} K_1(A) & \longrightarrow & K_1(k(t)) & \longrightarrow & \mathbb{A}(A, k(t)) & \longrightarrow & K_0 A & \longrightarrow & K_0(k(t)) & \longrightarrow & 0 \\ \downarrow & & \downarrow = & & \downarrow & & \downarrow & & \downarrow = & & \\ K_1(B) & \longrightarrow & K_1(k(t)) & \longrightarrow & \mathbb{A}(B, k(t)) & \longrightarrow & K_0(B) & \longrightarrow & K_0(k(t)) & \longrightarrow & 0 \end{array}$$

as before. We obtain the isomorphism

$$\mathbb{A}(A, L) \cong \text{Div } B \times \widetilde{K_0(A)},$$

where  $\widetilde{K_0(A)} = \text{Ker}(K_0(A) \xrightarrow{\text{rk}} \mathbb{Z})$ . It follows that  $\widetilde{K_0(A)} = \text{Pic } A = \underline{\alpha}(k)$ . Thus

$$\mathbb{A}(A, L) \cong \text{Div } B \times \underline{\alpha}(k),$$

the  $\underline{\alpha}(k)$  corresponding to the one singular point.

Concluding remarks : These calculations shoned give some indication of the role played by the groups  $\mathbb{A}(A, \underline{f1})$ , and the importance of considering complexes rather than modules.

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