Zero cycles and complete intersection points on affine varieties[*]

V. Srinivas
School of Mathematics
Tata Institute of Fundamental Research
Mumbai, India
e-mail: srinivas@math.tifr.res.in

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Let me begin with some elementary observations. Let A be a Dedekind domain. Two basic examples are obtained as follows.

(i) Let K be a finitely generated extension field of transcendence degree 1 of an algebraically closed field k,

$$t \in K \setminus k,$$

$$A = \text{integral closure of } k[t] \text{ in } K.$$

These rings arise as the coordinate rings of nonsingular affine algebraic curves over k. In this lecture, we focus on this example and some natural generalizations.

(ii) Let K be an algebraic number field (finite algebraic extension of $\mathbb{Q}$), and let

$$A = \text{integral closure of } \mathbb{Z} \text{ in } K.$$

This is called the ring of algebraic integers in K.

For a Dedekind domain A, let

$$\mathrm{Div}\,(A) = \begin{array}{l}\text{Free abelian group on}\\ \text{maximal ideals of } A\end{array}$$

$$= \text{Group of divisors of } A.$$

If $a \in A$ is a non-zero element, it defines a principal ideal aA, which has a primary decomposition of the form $aA = \mathfrak{M}_1^{n_1} \cdots \mathfrak{M}_r^{n_r}$, where $\mathfrak{M}_i$ are distinct maximal ideals, and n_i are positive integers (if a is a unit, then $aA = A$, and we take $r = 0$). The assignment

$$a \mapsto \sum_{i=1}^{r} n_i[\mathfrak{M}_i] \in \mathrm{Div}\,(A)$$

gives a semigroup homomorphism

$$A \setminus \{0\} \to \mathrm{Div}\,(A).$$

The subgroup $\mathrm{P}\,(A) \subset \mathrm{Div}\,(A)$ generated by the image of $A \setminus \{0\}$ is called the group of principal divisors.

We may now define

$$\begin{aligned}\mathrm{Cl}\,(A) = &\ \text{Divisor class group of } A \\ = &\ \frac{\mathrm{Div}\,(A)}{\mathrm{P}\,(A)}.\end{aligned}$$

Theorem 1 *For a Dedekind domain* A*, the following properties are equivalent.*
(i) A *has the unique factorization property.*
(ii) Every maximal ideal of A *is a principal ideal.*
(iii) $\mathrm{Cl}\,(A) = 0$*.*

Thus the divisor class group measures the failure of the uniqe factorization prperty.

The divisor class group of a Dedekind domain has an interpretation in terms of algebraic K-theory.

Recall that a projective A-module is a direct summand of a free A-module. Let $K_0(A)$ be the Grothendieck group of finitely generated projective A-modules, defined as a quotient

$$K_0(A) = \frac{F(A)}{R(A)},$$

with

$F(A) =$	Free abelian group on isomorphism classes of finitely generated projective A-modules
$R(A) =$	subgroup of $F(A)$ generated by classes $[P_2] - [P_1] - [P_3]$ for all exact sequences $0 \to P_1 \to P_2 \to P_3 \to 0$.

Since a Dedekind domain A has Krull dimenion 1 (i.e., every non-zero prime ideal is a maximal ideal), one can show that there is an isomorphism

$$K_0(A) \cong \mathbb{Z} \oplus \mathrm{Cl}\,(A).$$

The map $\mathbb{Z} \to K_0(A)$ is $n \mapsto [A^{\oplus n}] = n[A]$. It is split by $K_0(A) \to \mathbb{Z}$,

$$[P] \mapsto \text{ rank}\, P = \dim_K P \otimes_A K,$$

where K is the quotient field of A.

Since a maximal ideal $\mathfrak{M}$ is a projective A-module of rank 1, there is a homomorphism

$$\mathrm{Div}\,(A) \to K_0(A)$$

given by

$$\mathfrak{M} \mapsto [A] - [\mathfrak{M}] \in K_0(A),$$

which vanishes on $P(A)$ because a principal ideal aA is a free A-module of rank 1, so that $[A] = [aA]$ in $K_0(A)$. Thus there is an induced map $\mathrm{Cl}\,(A) \to K_0(A)$.

Let A be a Dedekind domain which is the coordinate ring of an affine algebraic curve C, over an algebraically closed field k. There is a bijection (by the *Nullstellensatz*)

points of $C \cong$ maximal ideals of A.

We write $C = \operatorname{Spec} A$ to denote this relationship. Finitely generated projective A-modules correspond to algebraic vector bundles on the curve C, giving an isomorphism of $K_0(A)$ with the Grothendieck group $K_0(C)$ of vector bundles.

There is an associated projective non-singular curve X over k, such that $C \cong X \setminus S$ for some finite, nonempty set S of points of X. If K is the quotient field of A, then there is a bijection

points of $X \cong$ normalized discrete valuations on K.

This determines X as a set, and the projective algebraic structure of X may also be determined using the intrinsic structure of K, which is then identified with the field of rational functions on the curve X.

Define

$$\begin{aligned}\mathrm{Div}\,(X) &= \text{ Group of Divisors on } X \\ &= \text{ Free abelian group on points of } X.\end{aligned}$$

If f is a rational function on X, its divisor is

$$\mathrm{div}\,(f) = (\text{zeroes of } f) - (\text{poles of } f).$$

Thus there is a subgroup of $\mathrm{Div}\,(X)$ defined by

$$\begin{aligned}\mathrm{P}\,(X) &= \text{ Group of Principal divisors} \\ &= \text{ Divisors of non-zero rational} \\ &\quad\ \text{ functions on } X.\end{aligned}$$

We now define the divisor class group

$$\mathrm{Cl}\,(X) = \mathrm{Div}\,(X)/\mathrm{P}\,(X).$$

There is also a Grothendieck group $K_0(X)$ of algebraic vector bundles (or locally free sheaves) on X, and one can show that there is an isomorphism

$$K_0(X) \cong \mathbb{Z} \oplus \mathrm{Cl}\,(X),$$

given by the rank, and the algebraic first Chern class $c_1 : K_0(X) \to \mathrm{Cl}\,(X)$.

Finally, there is a relationship between the class groups of X and $C = \operatorname{Spec} A = X \setminus S$, given by an isomorphism

$$\begin{aligned} \mathrm{Cl}\,(A) = & \ \mathrm{Cl}\,(C) \\ \cong & \ \frac{\mathrm{Cl}\,(X)}{\text{Subgroup generated by points of } S}. \end{aligned}$$

The geometry comes in now, in terms of the structure of $\mathrm{Cl}\,(X)$. There is a degree homomorphism

$$\deg\ : \mathrm{Cl}\,(X) \to \mathbb{Z}.$$

$$\deg\ : \sum_{x_i \in X} n_i[x_i] \mapsto \sum_i n_i.$$

Now an important structure theorem is that the kernel $\mathrm{Cl}\,(X)_{\mathrm{deg}0}$ has the structure of an abelian variety (a projective algebraic group variety), called the Jacobian variety, denoted by $J(X)$, whose dimension equals the genus of the non-singular projective curve X.

The genus may be defined algebraically as the dimension of the vector space of algebraic regular 1-forms on the curve X, or equivalently (using Serre duality) as the dimension of the sheaf cohomology $H^1(X, \mathcal{O}_X)$ of the sheaf $\mathcal{O}_X$ of algebraic regular functions on X.

If the ground field k is $\mathbb{C}$, the field of complex numbers, then the complex points of X naturally form a compact Riemann surface, and we have

"algebraic genus" of $X =$
"topological genus" of the underlying 2-manifold.

The Jacobian $J(X)$ is identified, as a real Lie group, with the torus $H^1(X, \mathbb{R}/\mathbb{Z})$, which has a natural complex structure coming from the theory of harmonic forms.

We now have the following remarkable result:

Theorem 2 *Let $C = \operatorname{Spec} A$ be an affine algebraic curve over an algebraically closed field k, where A is a Dedekind domain (i.e., C is a nonsingular affine curve over k). Let X be the corresponding nonsingular projective algebraic curve over k. Then:*

every maximal ideal of A is principal
$\Leftrightarrow \mathrm{Cl}\,(A) = 0$
$\Leftrightarrow$ *the projective curve X has genus 0*,
i.e., $H^1(X, \mathcal{O}_X) = 0$.

This is because of a property of abelian varieties: if the Jacobian $J(X)$ is nonzero (equivalently the genus of X is nonzero), then $J(X)$ is not a finitely generated group.

In fact, a refinement of the above result applies to an arbitrary reduced, finitely generated k-algebra A of Krull dimension 1, where k is an algebraically closed field.

Once again, one can uniquely associate to $C = \operatorname{Spec} A$ a projective algebraic curve X, such that $C = X \backslash S$ for a finite set S of nonsingular points of X. Then one has equalities

$\dim H^1(X, \mathcal{O}_X) =$ arithmetic genus of $X = \dim J(X)$,

where $J(X)$ is a certain algebraic group variety, called the generalized Jacobian of the singular curve X.

A point $x \in C$ is a nonsingular point if for the corresponding maximal ideal $\mathfrak{M}_x$ of A, the localization $A_{\mathfrak{M}_x}$ is a discrete valuation ring; C has only a finite number of singular points.

The maximal ideal corresponding to a nonsingular (or smooth) point will be called a smooth maximal ideal.

Theorem 3 *Let $C = \operatorname{Spec} A$ and X be as above. Then:*

every smooth maximal ideal of A is principal $\Leftrightarrow$

the projective curve X has arithmetic genus 0.

We now turn to the higher dimensional case.

If A is a finitely generated k-algebra which is a normal domain of dimension d, there is a divisor class group, defined using Weil divisors (free abelian group on irreducible $d-1$-dimensional subvarieties), with a relation to the theory of the Picard variety. One result obtained from this theory is the following (it can be refined in several ways, which we do not go into here).

Theorem 4 *Let A be a finitely generated k-algebra, which is an integral domain. Then the following properties hold.*
(i) The group of units of A is of the form $A^* = k^* \times$ (free abelian group of finite rank).
(ii) Assume that A is normal. Let X be a normal projective algebraic k-variety containing $V = \operatorname{Spec} A$ as a dense Zariski open set. Then the divisor class group of A is finitely generated $\Leftrightarrow$ the Picard variety of X (in the sense of Weil) is trivial.

Another generalization, which is our main interest here, is to consider the complete intersection property for maximal ideals. Let A be a reduced, finitely generated algebra of Krull dimension d, over an algebraically closed field k. Let $V = \operatorname{Spec} A$ be the affine variety associated to A, so that maximal ideals of A correspond to points of V (*Nullstellensatz*).

A point $x \in V$ is called a complete intersection point if the corresponding maximal ideal $\mathfrak{M}_x$ is of height d, and is generated by d elements $f_1, \ldots, f_d$. Geometrically, this means that if $H_i \subset V$ is the hypersurface defined by

$$H_i = \{y \in V | f_i(y) = 0\} = \operatorname{Spec} A/f_iA,$$

then $H_1 \cap \cdots \cap H_d = \{x\}$, and $x \in V$ is a nonsingular point, such that the hypersurfaces H_i are also nonsingular at x, and intersect transversally. Note that when $d = \dim A = 1$,

$x \in V = \operatorname{Spec} A$ is a complete intersection point

$\Leftrightarrow \mathfrak{M}_x \subset A$ is a principal ideal.

Recall that a point $x \in V$ is a smooth (or nonsingular) point if the local ring $\mathcal{O}_{V,x} = A_{\mathfrak{M}_x}$ is a regular local ring of dimension d, in the sense of commutative algebra; this means that $\mathfrak{M}_x$ has height d, and the localized maximal ideal $\mathfrak{M}_x A_{\mathfrak{M}_x}$ is generated by d elements.

Equivalently, there is an affine Zariski open subset $W \subset V$ containing x such that $x \in W$ is a complete intersection point. Thus, we may view a smooth point $x \in V$ as a "local complete intersection point".

A maximal ideal $\mathfrak{M}$ of A is called a smooth maximal ideal if it corresponds to a smooth point of $V = \operatorname{Spec} A$. Similarly we may speak of complete intersection maximal ideals.

The main question we want to discuss is the following.

Question Which k-algebras A of dimension $d > 1$ have the property that all smooth maximal ideals are complete intersections? In other words, when are all local complete intersection points on $V = \operatorname{Spec} A$ the same as the complete intersection points?

There are several conjectures and results related to this Question. We first state a general "positive" result.

Theorem 5 *Let $k = \overline{\mathbb{F}}_p$ be the algebraic closure of the finite field $\mathbb{F}_p$. Then for any reduced finitely generated k-algebra A of dimension $d > 1$, every smooth maximal ideal is a complete intersection.*

In the case when $\dim A \geq 3$, or A is smooth of dimension 2, this is a result essentially due to M. P. Murthy. The higher dimensional case is reduced to the 2-dimensional case by showing that any smooth point of $V = \operatorname{Spec} A$ lies on a smooth affine surface $W \subset V$ such that the ideal of W in A is generated by $d - 2$ elements (i.e., W is a complete intersection surface in V). This argument depends on the fact that we are dealing here with affine algebraic varieties. (Ref: M. P. Murthy, N. Mohan Kumar, A. Roy, in *Algebraic geometry and commutative algebra, Vol. I (in honour of Masayoshi Nagata)*, Kinokuniya, Tokyo (1988), 281-287.)

The case of an arbitrary 2-dimensional algebra is a corollary of results of Amalendu Krishna and mine (Annals of Math., 156 (2002)).

Next, we state two conjectures, which are affine versions of famous conjectures on 0-cycles.

Conjecture 6 *(Bloch Conjecture). Let $k = \mathbb{C}$, the complex numbers. Let $V = \operatorname{Spec} A$ be a non-singular affine $\mathbb{C}$-variety of dimension $d > 1$, and let $X \supset V$ be a smooth proper (or projective) $\mathbb{C}$-variety containing V as a dense open subset. Then:*
all maximal ideals of A are complete intersections
$\Leftrightarrow$ X does not support any global regular (or holomorphic) differential d-forms
$\Leftrightarrow$ $H^d(X, \mathcal{O}_X) = 0$.

Here, $\mathcal{O}_X$ is the sheaf of algebraic regular functions on X. The non-existence of d-forms is equivalent to the cohomology vanishing condition, by Serre duality; the open question is the equivalence of either of these properties with the complete intersection property for maximal ideals.

This conjecture has been verified in several "non-trivial" examples (for example, if $V = \operatorname{Spec} A$ is a "small enough" Zariski open subset of the Kummer variety of an odd (> 1) dimensional abelian variety over $\mathbb{C}$, all smooth maximal ideals of A are complete intersections).

One consequence of the conjecture is that, for smooth affine $\mathbb{C}$-varieties, the property that all maximal ideals are complete intersections is a birational invariant (that is, it depends only on the quotient field of A, as a $\mathbb{C}$-algebra). This birational invariance can be proved to hold in dimension 2, using a result of Roitman; in dimensions ≥ 3, it is unknown in general.

Conjecture 7 *(Bloch-Beilinson Conjecture) Let $k = \overline{\mathbb{Q}}$ be the field of algebraic numbers (algebraic closure of the field of rational numbers). Then for any finitely generated smooth k-algebra of dimension $d > 1$, every maximal ideal is a complete intersection.*

This very deep conjecture has not yet been verified in any “nontrivial” example (i.e., one where there do exist smooth maximal ideals of $A \otimes_{\overline{\mathbb{Q}}} \mathbb{C}$ which are not complete intersections).

However, it is part of a more extensive set of interrelated conjectures relating K-groups of motives over algebraic number fields and special values of L-functions, and there are nontrivial examples where some other parts of this system of conjectures can be verified. This is viewed as indirect evidence for the above conjecture.

I will now relate these conjectures to algebraic cycles and K-theory.

The first step is a result of Murthy, giving a K-theoretic interpretation of the complete intersection property.

Recall that $K_0(A)$ denotes the Grothendieck group of finitely generated projective A-modules. If M is an arbitrary finitely generated A-module, recall that M has finite projective dimension if there exists a finite projective resolution of M, i.e., an exact sequence

$$0 \to P_r \to P_{r-1} \to \cdots \to P_0 \to M \to 0$$

where the P_i are finitely generated projective A-modules. Then M has a well-defined class $[M] \in K_0(A)$, obtained by choosing any such resolution, and defining

$$[M] = \sum_{i=0}^{r} (-1)^i [P_i] \in K_0(A).$$

Recall also that a maximal ideal $\mathfrak{M}$ has finite projective dimension precisely when the local ring $A_{\mathfrak{M}}$ is a regular local ring.

Theorem 8 *Let A be a reduced finitely generated algebra over an algebraically closed field. A smooth maximal ideal $\mathfrak{M}$ of A is a complete intersection $\Leftrightarrow$ $[\mathfrak{M}] = [A]$ in $K_0(A)$.*

(Ref: M. P. Murthy, Annals of Math. (1994) 405-434.)

Let A be a reduced, finitely generated algebra, of Krull dimension d, over an algebraically closed field k. We can associate to it the group

$F^d K_0(A) =$ subgroup of $K_0(A)$ generated by
$[A] - [\mathfrak{M}]$ for all smooth maximal ideals $\mathfrak{M}$.

If $V = \operatorname{Spec} A$, then $F^d K_0(A)$ is a quotient of the free abelian group on smooth points of V, modulo a suitable equivalence relation.

One can identify this equivalence relation with rational equivalence (defined appropriately if V is singular).

Recall that the Chow group of 0-cycles modulo rational equivalence on a smooth d-dimensional variety X is

$$CH^d(X) = \frac{Z^d(X)}{R^d(X)},$$

where

$$Z^d(X) = \text{Free abelian group on points of } X,$$

and $R^d(X) \subset Z^d(X)$ is the subgroup generated by

$$\operatorname{div}(f)_C = (\text{zeroes of } f) - (\text{poles of } f),$$

for all curves $C \subset X$, and nonzero rational functions f on C.

The Grothendieck group $K_0(X)$ of algebraic vector bundles on X equals the Grothendieck group of coherent sheaves on X, since X is smooth. Let $F^dK_0(X)$ be the subgroup of $K_0(X)$ generated by the classes of points on X. The induced surjective map $Z^d(X) \to F^dK_0(X)$ is easily seen to yield a surjection

$$\psi_d : CH^d(X) \to F^dK_0(X).$$

Grothendieck's algebraic theory of Chern classes, and the Riemann-Roch Theorem ("without denominators"), implies that the d^{th} Chern class gives a homomorphism

$$c_d : F^dK_0(X) \to CH^d(X),$$

so that the compositions $\psi_d \circ c_d$ and $c_d \circ \psi_d$ both equal multplication by $(-1)^{d-1}(d-1)!$.

In particular, ψ_d and c_d are both isomorphisms modulo torsion.

Now assume $V = \operatorname{Spec} A$ is an affine open subset of a nonsingular projective k-variety X of dimension d. Clearly

$$CH^d(V) = \frac{CH^d(X)}{\text{subgroup generated by points of } X \setminus V}.$$

Roitman's Theorem on torsion 0-cycles, extended by Milne to arbitrary characteristic, gives a description of the torsion in $CH^d(X)$, using which it can be shown that $CH^d(V)$ is a torsion free, divisible abelian group (i.e., a vector space over $\mathbb{Q}$). In particular, we see that the map $\psi_d : CH^d(V) \to F^d K_0(V)$ is an isomorphism.

Thus, by Murthy's theorem, all maximal ideals of A are complete intersections $\Leftrightarrow$ $CH^d(X)$ is generated by points of $X \setminus V$.

We now restate the Bloch and Bloch-Beilinson Conjectures in their “original” forms.

Conjecture 9 *(Bloch Conjecture) Let X be a projective smooth variety over $\mathbb{C}$. Suppose that, for some integer $r > 0$, X has no nonzero regular (or holomorphic) s-forms for any $s > r$. Then for any “sufficiently large” subvariety $Z \subset X$ of dimension r, we have $CH^d(X \setminus Z) = 0$.*

For a smooth projective complex surface X, this conjecture states that if X has no holomorphic 2-forms, then $CH^2(X \setminus C) = 0$ for some curve C in X. This has been verified in a few situations, for example, for surfaces of Kodaira dimension ≤ 1 (Bloch, Kas, Lieberman), for general Godeaux surfaces (Voisin), and in some other cases.

In higher dimensions, Roitman proved it for complete intersections in projective space, and there are a few other isolated examples, like the Kummer variety associated to an odd dimensional abelian variety (Bloch and myself).

Conjecture 10 *(Bloch-Beilinson Conjecture) Let X be a smooth projective variety of dimension d over $\overline{\mathbb{Q}}$. Then $CH^d(X)$ is "finite dimensional"; in particular, there is a curve $C \subset X$ so that $CH^d(X \setminus C) = 0$.*

As remarked earlier, there is only indirect evidence for this conjecture: it has not been verified for any smooth projective surface over $\overline{\mathbb{Q}}$ which supports a non-zero 2-form (e.g., any hypersurface in projective 3-space of degree ≥ 4).

To exhibit one such nontrivial example is already an interesting open question.

From the algebraic viewpoint, it seems restrictive to work only with smooth varieties. In any case, it is unknown in characteristic $p > 0$ that a smooth affine variety V can be realized as an open subset of a smooth proper variety X (in characteristic 0, this follows from Hironaka's theorem on resolution of singularities).

Inspite of this, it is possible to make a systematic study of the singular case, and to try to extend the above conjectures.

For the purposes of this lecture, let me focus on one very special situation. Let

$$Z \subset \mathbb{P}^N_k$$

be a non-singular projective algebraic k-variety, and

$$\begin{aligned} A = &\ \oplus_{n\geq 0} A_n \\ = &\ \text{homogeneous coordinate ring of } Z. \end{aligned}$$

The affine variety $V = \operatorname{Spec} A$ is the "affine cone" over Z with "vertex" corresponding to the unique graded maximal ideal $\mathfrak{M} = \oplus_{n>0} A_n$, and the vertex is the unique singular point of V.

The projective cone $C(Z)$ over Z with the same vertex naturally contains V as an open subset, whose complement is a divisor isomorphic to Z, and the vertex is again the only singular point of $C(Z)$.

The following theorem is obtained using results from my paper with Amalendu Krishna (Annals of Math., (2002)), in the 2-dimensional case, and a preprint of Krishna's in the higher dimensional case.

Theorem 11 *(i) Let* $k = \mathbb{C}$*. Assume that* V *is Cohen-Macaulay (for example,* $d = 2$ *and* A *is normal). Then every smooth maximal ideal of* A *is a complete intersection* $\Leftrightarrow H^{d-1}(Z, \mathcal{O}_Z(1)) = 0 \Leftrightarrow H^d(C(Z), \mathcal{O}_{C(Z)}) = 0$

(ii) Let $k = \overline{\mathbb{Q}}$*. Then every smooth maximal ideal of* A *is a complete intersection.*

Here, (i) is analogous to the Bloch Conjecture, while (ii) is analogous to the Bloch-Beilinson Conjecture.

Let me close with two examples.

Example 1 (Amalendu Krishna + V. S.)

$$A = \frac{\overline{\mathbb{Q}}[x, y, z]}{(x^4 + y^4 + z^4)}.$$

Here, all smooth maximal ideals of A are complete intersections, while "most" smooth maximal ideals of $A \otimes_{\overline{\mathbb{Q}}} \mathbb{C}$ are not complete intersections. The complete intersection smooth maximal ideas are those determined by points on the rulings of the affine cone over points of the Fermat Quartic curve with $\overline{\mathbb{Q}}$ coordinates. This is a consequence of Theorem 11.

Example 2

$$A = \frac{\overline{\mathbb{Q}}[x, y, z]}{(xyz(1 - x - y - z))}.$$

Again, all smooth maximal ideals of A are complete intersections, while "most" smooth maximal ideals of $A \otimes_{\overline{\mathbb{Q}}} \mathbb{C}$ are not complete intersections. In fact, there is an identification

$$F^2 K_0(A \otimes_{\overline{\mathbb{Q}}} k) = K_2(k),$$

where K_2 denotes the Milnor K_2. Now one has the result of Garland (vastly generalized by Borel) that $K_2(\overline{\mathbb{Q}}) = 0$, while $K_2(\mathbb{C})$ is "very large".

Here are some references for further reading on the topic.

1. V. Srinivas, *Zero cycles on singular varieties*, in *The Arithmetic and Geometry of Algebraic Cycles*, ed. B. B. Gordon *et al.*, NATO Science Series Vol. C 548, Kluwer (2000), pp. 347-382.

2. V. Srinivas, *Some Geometric Methods in Commutative Algebra*, in *Computational Commutative Algebra and Combinatorics (Osaka, 1999)*, Advanced Studies in Pure Math. 33 (2002) 231-276.

3. Amalendu Krishna, V. Srinivas, *Zero cycles and K-theory on normal surfaces*, Annals of Math. 156 (2002) 155-195.