

Tame Class Field Theory for Singular Varieties over Finite Fields

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1 Introduction

In the 1980’s, Kato and Saito (based on ideas of Bloch) generalized the class field theory for smooth, projective curves over finite fields to smooth, projective varieties of arbitrary dimension [KaS]: The map from the free abelian group generated by the closed points which sends a generator $x \in X$ to the image of the Frobenius of $k(x)$ under $\pi_1^{ab}(k(x)) \rightarrow \pi_1^{ab}(X)$ factors through the Chow group of zero cycles, and induces an isomorphism

$$r_X : \text{CH}_0(X) \xrightarrow{\sim} \pi_1^{ab}(X)_W.$$ 

Here $\pi_1^{ab}(X)_W$ is the subgroup of elements in $\pi_1^{ab}(X)$ whose images in the absolute Galois group of the finite base field are integral Frobenius powers.

If $X$ is not necessarily projective but still smooth, then Schmidt and Spieß [SS, Sc] showed that the same result still holds if one replaces the Chow group by Suslin homology and the fundamental group by its tame version: The reciprocity map induces an isomorphism of finitely generated abelian groups

$$r_X : H^S_0(X, \mathbb{Z}) \xrightarrow{\sim} \pi_1^{t, ab}(X)_W.$$ 

This result does not extend to non-smooth schemes: the example of the node shows that $r_X$ is neither injective nor surjective in general. If $X$ is normal, then $r_X$ is surjective but an example of Matsumi-Sato-Asakura [MAS] shows that $r_X$ may have a nontrivial kernel.

In this paper, we show that the result of Schmidt and Spieß can be generalized to singular varieties if one uses a refined version of Suslin homology on the one hand, and replaces the fundamental group by the enlarged fundamental group of [SGA3, X, §6] on the other hand. We denote the abelian enlarged tame fundamental group by $\Pi_1^{t, ab}$ in order to distinguish it from the usual abelian tame fundamental group $\pi_1^{t, ab}$, which is its profinite completion. The groups coincide if $X$ geometrically unibranch (e.g., normal). Our first result is:

**Theorem 1.1.** For any connected scheme $X$, separated and of finite type over a finite field, the pro-group $\Pi_1^{t, ab}(X)_W$ is isomorphic to a (constant) finitely generated abelian group.

On the other hand, recall from [Ge2] the definition of Weil-Suslin homology: Let $\mathbb{F}$ be the finite base field, $F \in \text{Gal}_\mathbb{F}$ be the Frobenius automorphism and $G \cong \mathbb{Z}$ the
subgroup of Gal$_F$ generated by $F$. For an abelian group $A$, the groups $H^i_{WS}(X, A)$ are defined as the homology of the cone of $1 - F^*$ on the Suslin complex tensored by $A$ of the base change $\bar{X}$ of $X$ to the algebraic closure $\bar{F}$ of $F$. By definition, there are short exact sequences

$$0 \to H^i_S(\bar{X}, A)_G \to H^i_{WS}(X, A) \to H^i_{S-1}(\bar{X}, A)_G \to 0.$$ 

Furthermore, there are natural maps $H^i_S(X, A) \to H^{i+1}_{WS}(X, A)$ for all $i$. If $X$ is smooth and $A$ is finite, then it follows from the proof of Kato’s conjecture by Jannsen, Kerz and Saito [KeS] (and under resolution of singularities) that these maps are isomorphisms (for $i = 0$ this follows from the theorem of Schmidt-Spieß).

We define a refined reciprocity homomorphism $\text{rec}_X : H^1_{WS}(X, \mathbb{Z}) \to \Pi^1_{\text{ab}}(X)_W$ such that the composite with the natural map $H^0_S(X, \mathbb{Z}) \to H^1_{WS}(X, \mathbb{Z})$ is the reciprocity map $r_X$ described above. Our main result, conjectured in [Ge2], is the following

**Theorem 1.2.** For any connected scheme $X$, separated and of finite type over a finite field $F$, the homomorphism $\text{rec}_X : H^1_{WS}(X, \mathbb{Z}) \to \Pi^1_{\text{ab}}(X)_W$ is surjective. The kernel of $\text{rec}_X$ contains, and if resolution of singularities for schemes of dimension $\leq \dim X + 1$ holds over $F$ is equal to, the maximal divisible subgroup of $H^1_{WS}(X, \mathbb{Z})$.

As a corollary, we obtain (under resolution of singularities) an isomorphism of profinite completions

$$\text{rec}^\wedge_X : H^1_{WS}(X, \mathbb{Z})^\wedge \xrightarrow{\sim} \pi^1_{\text{ab}}(X).$$

Under Parshin’s conjecture (cf. [Ge2]), $H^1_{WS}(X, \mathbb{Z})$ is finitely generated, hence rec$_X$ would be an isomorphism.

2 The fundamental group and tame coverings

2.1 Etale and Weil-etale cohomology

Let $X$ be a scheme, separated and of finite type over a finite field $F$. The absolute Galois group Gal$_F$ acts on $X = X \times_F \overline{\mathbb{F}}$ via its action on $\overline{\mathbb{F}}$. Pulling an etale sheaf $\mathcal{F}$ on $X$ back to $\mathcal{F}$ on $\overline{\mathbb{F}}$, we obtain a sheaf with a Gal$_F$-action, cf. [SGA7] XIII §1.1. Using this action, the etale cohomology $H^i_{\text{et}}(X, \mathcal{F})$ can be calculated as the cohomology of $R\Gamma_{\text{et}}(\overline{\mathbb{F}}, \mathcal{F})$. The Weil-etale cohomology of $\mathcal{F}$ is by definition the cohomology of $R\Gamma_G R\Gamma_{\text{et}}(\overline{\mathbb{F}}, \mathcal{F})$, where $G \cong \mathbb{Z}$ is the subgroup of Gal$_F$ generated by the Frobenius. Since $R\Gamma_{\text{Gal}}$ and $R\Gamma_G$ coincide on discrete torsion modules, etale and Weil-etale cohomology coincide on torsion sheaves (cf. [Ge1] §2 for a more detailed account).

We can calculate the Weil-etale cohomology of a sheaf $\mathcal{F}$ as follows: Choose an injective resolution $\mathcal{F} \to I^\bullet$ of sheaves on the big etale site on $\mathbb{F}$. Then

$$H^i_{\text{et}}(X, \mathcal{F}) = H^i(I^\bullet(\bar{X})^G),$$

and

$$H^i_W(X, A) = H^i(I^\bullet(\bar{X}) \xrightarrow{1-F^*} 1^\bullet(\bar{X})).$$
where \( F^* \) is the pull-back along the Frobenius. We form the double complex by using the negative of the differential in the second complex, i.e., the differential of the total complex has the form
\[
\Gamma(\tilde{X}) \oplus \Gamma^{-1}(\tilde{X}) \to \Gamma^{i+1}(\tilde{X}) \oplus \Gamma^i(\tilde{X}), \quad (\alpha, \beta) \mapsto (d\alpha, \alpha - F^*\alpha - d\beta). \tag{1}
\]
From the definition, we obtain short exact sequences
\[
0 \to H_{et}^{i-1}(\tilde{X}, \mathcal{F})_G \to H_{W,t}(X, \mathcal{F}) \to H_{et}^i(\tilde{X}, \mathcal{F})_G \to 0, \tag{2}
\]
as well as a homomorphism
\[
H_{et}^i(X, \mathcal{F}) \to H_{W,t}^i(X, \mathcal{F}) \tag{3}
\]
for each \( i \geq 0 \), which is an isomorphism for \( i = 0 \) and injective for \( i = 1 \).

By [SV] Theorem 10.2, etale and qfh-cohomology of a constant sheaf \( A \) coincide. Hence, in order to calculate Weil-etale cohomology of \( A \), we can also work with an injective resolution \( A \to I^* \) in the big qfh-site over \( \mathcal{F} \). If moreover \( A \) is a \( \mathbb{Z}/m \)-module for some \( m \geq 1 \), then we can also work with a resolution of \( A \) by injective \( h \)-sheaves of \( \mathbb{Z}/m \)-modules, see [SV] Theorem 10.7.

For a regular connected curve \( C \) over a field \( k \), we consider the subgroup \( H^1_1(C, A) \subseteq H^{et}_1(C, A) \) of tame cohomology classes (corresponding to those continuous homomorphisms \( \pi^a_1(C) \to A \) which factor through the tame fundamental group \( \pi^t_1(C', C' - C) \), where \( C' \) is the regular compactification of \( C \).

For a general \( k \)-scheme \( X \), we call a cohomology class in \( a \in H^{et}_1(X, A) \) tame if for any morphism \( f : C \to X \) with \( C \) a regular curve, we have \( f^*(a) \in H^1_1(C, A) \).

The tame cohomology classes form a subgroup
\[
H^1_1(X, A) \subseteq H^{et}_1(X, A).
\]
The groups coincide if \( X \) is proper, if \( p = 0 \), or if \( p > 0 \) and \( A \) is \( p \)-torsion free, where \( p \) is the characteristic of the base field \( k \). If \( X \) is smooth with smooth compactification \( X' \), then \( H^1_1(X, \mathbb{Z}/p^r) \cong H^{et}_1(X', \mathbb{Z}/p^r) \) for any \( r \geq 1 \) by [GS] Prop. 2.10.

For \( X \) separated and of finite type over the finite field \( F \), we define the tame Weil-etale cohomology to be the subgroup
\[
H^1_{W,t}(X, A) \subseteq H^{et}_1(X, A)
\]
of those elements, whose image in \( H^{et}_1(\tilde{X}, A) \) in (2) is tame.

Recall that an abstract blow-up square is a cartesian diagram
\[
\begin{array}{ccc}
Z' & \xrightarrow{i'} & X' \\
\downarrow\pi' & & \downarrow\pi \\
Z & \xrightarrow{i} & X
\end{array}
\tag{4}
\]
such that \( i \) is a closed embedding, \( \pi \) is proper, and \( \pi \) induces an isomorphism \((X' - Z')_{\text{red}} \cong (X - Z)_{\text{red}}\).

**Proposition 2.1.** If in the abstract blow-up square (1) \( \pi \) is finite, or if the abelian group \( A \) is torsion, then there is an exact sequence
\[
0 \to H^0_W(X, A) \to H^0_W(X', A) \oplus H^0_W(Z, A) \to H^0_W(Z', A) \to H^1_{W,t}(X, A) \to H^1_{W,t}(X', A) \oplus H^1_{W,t}(Z, A) \to H^1_{W,t}(Z', A).
\]
Proof. If \( A \) is torsion, the proper base change theorem implies an exact triangle

\[
A \to R\pi_* A \oplus i_* A \to i_* R\pi'_* A \to A. \tag{5}
\]

If \( \pi \) finite, the same is true for arbitrary \( A \) since \( \pi_* \) and \( \pi'_* \) are exact. Applying \( R\Gamma(X, -) \) to (5) yields the exact triangle

\[
R\Gamma(\bar{X}, A) \to R\Gamma(\bar{X}', A) \oplus R\Gamma(\bar{Z}, A) \to R\Gamma(\bar{Z}', A) \to \cdots \tag{6}
\]

and the long exact sequence

\[
H^i_{\text{et}}(\bar{X}, A) \to H^i_{\text{et}}(\bar{X}', A) \oplus H^i_{\text{et}}(\bar{Z}, A) \to H^i_{\text{et}}(\bar{Z}', A) \to \cdots. \tag{7}
\]

Applying \( R\Gamma_G \) to (7) and taking cohomology, we obtain the long exact sequence

\[
H^i_W(X, A) \to H^i_W(X', A) \oplus H^i_W(Z, A) \to H^i_W(Z', A) \to \cdots. \tag{8}
\]

By [GS, Prop. 5.1], (7) induces an exact sequence

\[
0 \to H^0_{\text{et}}(\bar{X}, A) \to H^0_{\text{et}}(\bar{X}', A) \oplus \bar{H}^0(\bar{Z}, A) \to H^0_{\text{et}}(\bar{Z}', A) \to \delta \to H^1_{\text{et}}(\bar{X}, A) \to \bar{H}^1(\bar{X}', A) \oplus H^1_{\text{et}}(\bar{Z}, A) \to H^1_{\text{et}}(\bar{Z}', A). \tag{9}
\]

Comparing (6) with the sequences (7) and (8), we obtain the statement of the proposition by a diagram chase. \( \square \)

2.2 The enlarged fundamental group

Let us recall the definition of the enlarged fundamental group of [SGA3, X §6]: Let \( X \) be a connected, locally noetherian scheme. For a group \( G \) (considered as a constant group scheme over \( X \)), a \( G \)-torsor \( P \) over \( X \) is an etale \( X \)-scheme \( P \) (i.e., \( \pi : P \to X \) is unramified, flat and locally of finite type) with a \( G \)-action \( P \times G \to P \) such that \( P \times_X G \to P \times_X P \), \( (x, g) \mapsto (x, xg) \), is an isomorphism.

By [Mi, Prop. 2.7] (see also Ex. 2.6, loc. cit.), for any etale sheaf \( F \) on \( X \) we have a Hochschild-Serre spectral sequence

\[
E^2_{rs} = H^r(G, H^s_{\text{et}}(P, \pi^* F)) \Rightarrow H^{r+s}_{\text{et}}(X, F).
\]

For a geometric point \( \xi \) of \( X \), one defines \( \Pi^1(X, \xi, G) \) to be the set of isomorphism classes of \( G \)-torsors over \( X \) pointed over \( \xi \). The trivial \( G \)-torsor gives a distinguished element in \( \Pi^1(X, \xi, G) \). For a \( G \)-torsor \( P \) on \( X \) and a group homomorphism \( f : G \to H \), consider

\[
f_*(P) := (P \times H)/G,
\]

where \( G \) acts by \((t, h) \cdot g = (tg, f(g^{-1})h)\). Then \( f_*(P) \) is an \( H \)-torsor over \( X \) and we obtain a functor

\[
G \mapsto \Pi^1(X, \xi, G)
\]

from groups to pointed sets. By [SGA3, X §6], this functor is pro-represented by the enlarged fundamental pro-group \( \Pi_1(X, \xi) \), i.e.,

\[
\Pi^1(X, \xi, G) \cong \text{Hom}_{\text{pro-grps}}(\Pi_1(X, \xi), G).
\]

Explicitly, there is a pro-system of groups \( \Pi_1(X, \xi) = (G_i)_{i \in I} \) with \( I \) filtering, and a \( G_i \)-torsor \( P_i \) corresponding to the projection map \( \Pi_1(X, \xi) \to G_i \) for all \( i \) such that for any transition map \( \alpha_{ij} : G_i \to G_j \) in the system we have \( P_j = (\alpha_{ij})_*(P_i) \), and such that for any morphism \( \Pi_1(X, \xi) \to H \) represented by \( f : G_j \to H \) in the filtered colimit, the corresponding \( H \)-torsor is \( f_*(P_j) \).
A $G$-torsor $P$ over a regular connected curve $C$ over a field $k$ is called tame, if the projection $P \to X$ extends to an at most tamely ramified covering of the regular compactification $C'$ of $C$. If $X$ is any scheme, separated and of finite type over $k$, and $P$ is a $G$-torsor on $X$, then we call $P$ tame if its pull back to the normalization of any curve on $X$ is a tame torsor. If $G = A$ is abelian, then an $A$-torsor is tame if and only if its associated class in $H^1_{\text{et}}(X, A)$ lies in $H^1_{\text{t}}(X, A)$.

The functor $G \mapsto \Pi_{1, \text{t}}(X, \xi, G)$ sending $G$ to the set of isomorphism classes of pointed tame $G$-torsors on $X$ is pro-represented by the enlarged tame fundamental group $\Pi_{1, \text{t}}(X, \xi)$, a quotient of $\Pi_1(X, \xi)$ in the category of pro-groups.

The abelianizations $\Pi_1^{\text{ab}}(X)$ and $\Pi_{1, \text{ab}}^{\text{t}}(X)$ of $\Pi_1(X, \xi)$ and $\Pi_{1, \text{t}}(X, \xi)$ represent the restrictions of the respective functors to the category of abelian groups and are independent of the chosen base point $\xi$.

**Lemma 2.2.** For any abelian group $A$ we have

$$\text{Hom}_{\text{pro-grps}}(\Pi_{1, \text{t}}^{\text{ab}}(X), A) \cong H^1_{\text{et}}(X, A)$$

and similarly for the tame version.

**Proof.** Write $\Pi_{1, \text{t}}^{\text{ab}}(X) = (A_i)$ and $P_i$ for the $A_i$-torsor corresponding to the projection $\Pi_{1, \text{t}}^{\text{ab}}(X) \to A_i$. We obtain a filtered direct system of Hochschild-Serre spectral sequences

$$H^r(A_i, H^s_{\text{et}}(P_i, A)) \Rightarrow H^{r+s}_{\text{et}}(X, A)$$

inducing a system of short exact sequences

$$0 \to H^1(A_i, A) \to H^1_{\text{et}}(X, A) \to H^0(A_i, H^1_{\text{et}}(P_i, A)).$$

The right map is the zero map in the colimit over all $i$, because if the $A$-torsor $P$ arises from a map $f : A_i \to A$, i.e., $P = f_*(P_i)$, then $P$ trivializes over $P_i$. Finally,

$$\text{colim} H^1(A_i, A) \cong \text{colim Hom}(A_i, A) = \text{Hom}_{\text{pro-grps}}(\Pi_{1, \text{t}}^{\text{ab}}(X), A).$$

\[ \square \]

From now let $X$ be a connected scheme, separated and of finite type over the finite field $\mathbb{F}$. As above, we denote the subgroup of $\text{Gal}_{\mathbb{F}}$ consisting of integral powers of the Frobenius automorphism by $G$.

**Definition 2.3.** The enlarged Weil-tame fundamental group $\Pi_{1, \text{W}}(X, \xi)$ is defined by the cartesian diagram of pro-groups

$$\begin{array}{ccc}
\Pi_{1, \text{W}}(X, \xi) & \longrightarrow & \Pi_{1}(X, \xi) \\
\downarrow & & \downarrow \\
G & \longrightarrow & \Pi_{1}(\mathbb{F}).
\end{array}$$

The abelianization $\Pi_{1, \text{W}}^{\text{ab}}(X)$ of $\Pi_{1, \text{W}}(X, \xi)$ fits into the analogous cartesian diagram

$$\begin{array}{ccc}
\Pi_{1, \text{W}}^{\text{ab}}(X) & \longrightarrow & \Pi_{1}^{\text{ab}}(X) \\
\downarrow & & \downarrow \\
G & \longrightarrow & \Pi_{1}(\mathbb{F}).
\end{array}$$

The profinite completion of $\Pi_{1, \text{W}}^{\text{ab}}(X)$ is the usual abelian tame fundamental group $\pi_{1, \text{ab}}^{\text{t}}(X)$. 

5
Proposition 2.4. For any abelian group $A$, there is a functorial isomorphism
\[ \text{Hom}_{\text{pro-grps}}(\Pi_1^{ab}(X)_W, A) \cong H_1^W(X, A) \]
compatible with the isomorphism of Lemma 2.2 and there is a similar isomorphism for the tame version.

Proof. Replacing $\mathbb{F}$ by its maximal algebraic extension in $\Gamma(X, \mathcal{O}_X)$ changes $G$ to a subgroup of finite index, but does not change the groups on both sides of the statement. Hence we may assume that $X$ is geometrically connected [DG I, §4, 6.7]. Setting $\bar{X} = X \times_{\mathbb{F}} \bar{\mathbb{F}}$, we have the exact sequence of pro-groups
\[ 1 \rightarrow \Pi_1^t(\bar{X}, \xi) \rightarrow \Pi_1(X, \xi)_W \rightarrow G \rightarrow 1. \]
If we write $\Pi_1(X, \xi)_W = (G_i)$, then $\Pi_1^t(\bar{X}, \xi) = (\bar{G}_i)$ with $\bar{G}_i = \ker(G_i \rightarrow G)$. We denote the $\bar{G}_i$-torsor over $\bar{X}$ associated with the projection map $\Pi_1(\bar{X}, \xi) \rightarrow \bar{G}_i$ by $\bar{P}_i$.

Consider the functor $\mathcal{F} \mapsto \Gamma(\bar{P}_i, \mathcal{F})$ from the category of etale sheaves on $X$ to $G_i$-modules. The inclusion $A \rightarrow \Gamma(\bar{P}_i, A)$ induces a map $\Gamma_{G_i}(A) \rightarrow \Gamma_{\bar{G}_i}(\bar{P}_i, A)$ in the derived category of abelian groups. Since $\Gamma_{G_i} = \Gamma_{\bar{G}_i} \Gamma_{\bar{G}_i}$, we can write this map in the form
\[ R\Gamma_{G_i}(A) \rightarrow R\Gamma_{G_i} R\Gamma_{\bar{G}_i} R\Gamma_{\bar{G}_i}(\bar{P}_i, A). \] (10)

Since taking global sections over $\bar{P}_i$ has an exact left adjoint, it sends injectives sheaves on $X$ to injective $\mathbb{Z}\bar{G}_i$-modules, and we obtain $\Gamma_{G_i} R\Gamma_{\bar{G}_i}(\bar{P}_i, A) = \Gamma(\bar{X}, A)$. We thus can write (10) in the form
\[ R\Gamma_{G_i}(A) \rightarrow R\Gamma_{G_i} R\Gamma(\bar{X}, A). \] (11)

Taking cohomology, and passing to the colimit over $i$, we obtain maps
\[ H^n(\Pi_1^{ab}(X)_W, A) \rightarrow H_0^i(X, A), \quad n \geq 0. \]
For $n = 1$ this is the map of the proposition and we have to show that it is an isomorphism. For this we rewrite (11) in the form
\[ R\Gamma_{G_i} R\Gamma_{G_i}(A) \rightarrow R\Gamma_{G_i} R\Gamma(\bar{X}, A) \] (12)
and consider the map of associated spectral sequences, which degenerate to short exact sequences. In degree 1, we obtain the commutative diagram with exact lines
\[ 0 \rightarrow A_G \rightarrow H^1(\Pi_1(X)_W, A) \rightarrow H^1(\Pi_1(\bar{X}), A)^G \rightarrow 0 \]
\[ 0 \rightarrow H^0(\bar{X}, A)_G \rightarrow H^1_W(\bar{X}, A) \rightarrow H^1_W(\bar{X}, A)^G \rightarrow 0. \]

Since $X$ is geometrically connected, the left hand vertical map is an isomorphism. The right hand vertical map is an isomorphism by Lemma 2.2. Hence the middle map is an isomorphism.

To show the statement for the tame variant, we note that there is a similar diagram as above for the tame groups. Indeed, a torsor on $X$ is tame if and only if its base change to $\bar{X}$ is tame, so we obtain the exact sequence
\[ 1 \rightarrow \Pi_1^t(\bar{X}, \xi) \rightarrow \Pi_1^t(X, \xi)_W \rightarrow G \rightarrow 1. \]
On the other hand, the lower sequence of the above diagram induces a similar sequence for the tame Weil-etale cohomology by definition. This time, the right hand vertical map is an isomorphism by the tame version of Lemma 2.2. $\square$
For a finite disjoint union of connected schemes \( X = \amalg X_i \) we write by abuse of notation

\[
\Pi^1_{ab}(X)_W = \prod_i \Pi^1_{ab}(X_i)_W.
\]

**Theorem 2.5.** For any \( X \), separated and of finite type over a finite field \( \mathbb{F} \), \( \Pi^1_{ab}(X)_W \) is isomorphic to a finitely generated abelian group.

**Proof.** Let us first assume that \( X \) is normal and connected. We claim that the kernel

\[
\Pi^1_{ab}(X)_{\text{geo}} := \ker \left( \Pi^1_{ab}(X)_W \longrightarrow \Pi_1(\mathbb{F})_W \cong \mathbb{Z} \right)
\]

is a finite abelian group. If \( X \) is smooth, this follows from the main theorem of Schmidt-Spieß \([SS, Sc]\). For a general normal \( X \), choose a dense open smooth subscheme \( U \subset X \). Then \( \Pi^1_{ab}(U)_{\text{geo}} \) surjects onto \( \Pi^1_{ab}(X)_{\text{geo}} \), hence the latter group is finite.

Now let \( X \) be arbitrary. We can assume that \( X \) is connected and reduced. Let \( X' \to X \) be the normalization. The cokernel \( \Pi^1_{ab}(X'/X) \) of \( \Pi^1_{ab}(X') \to \Pi^1_{ab}(X) \) represents the functor \( \Pi^1_{ab}(X'/X) \) which sends an abelian group \( A \) to the set of isomorphism classes of \( A \)-torsors on \( X \) which trivialize over \( X' \). We denote the tame version of this group by \( \Pi^1_{ab}(X'/X) \) and the cokernel of \( \Pi^1_{ab}(X'/X)_W \to \Pi^1_{ab}(X)_W \) by \( C \). Consider the diagram

\[
\begin{array}{ccc}
\Pi^1_{ab}(X') & \longrightarrow & \Pi^1_{ab}(X) \longrightarrow \Pi^1_{ab}(X'/X) \longrightarrow 0 \\
\downarrow & & \downarrow \alpha \quad \uparrow \beta & \\
\Pi^1_{ab}(X') & \longrightarrow & \Pi^1_{ab}(X) \longrightarrow \Pi^1_{ab}(X'/X) \longrightarrow 0 \\
\downarrow & & \downarrow \gamma & \\
\Pi^1_{ab}(X')_W & \longrightarrow & \Pi^1_{ab}(X)_W \longrightarrow C \longrightarrow 0.
\end{array}
\]

Since \( X' \to X \) is proper, a torsor on \( X \) which trivializes over \( X' \) is tame. Hence \( \alpha \) is an isomorphism, and it is not difficult to see that \( \beta \) is an isomorphism. By \([SGA3, X \ S6, p.109]\), \( \Pi^1_{ab}(X'/X) \) is a finitely generated abelian group, hence so is \( C \). We proved above that the geometric part of \( \Pi^1_{ab}(X')_W \) (defined componentwise if \( X' \) is not connected) is finite. This implies that \( \Pi^1_{ab}(X)_W \) is constant and finitely generated.

\[\square\]

### 3 Weil-Suslin homology

Let \( k \) be a perfect field and \( X \) a scheme, separated and of finite type over \( k \). We recall that, for a smooth \( k \)-scheme \( T \), the group of finite correspondences \( \text{Cor}(T, X) \) is the free abelian group generated by closed integral \( Z \subseteq T \times X \) which are finite and surjective over a component of \( T \). The Suslin complex of \( X \) is the complex \( C_*^{\text{Sus}}(X) = \text{Cor}^{\text{Sus}}(X) \), where \( \Delta^i = \text{Spec}(k[T_0, \ldots, T_i]/\Sigma T_i - 1) \). Putting \( \partial := \sum_{j=0}^{i-1}(-1)^j\delta^j_i \in \text{Cor}^{\text{Sus}}(\Delta^{i-1}, \Delta^i) \), where \( \delta^j_i : \Delta^{i-1} \to \Delta^i, j = 0, \ldots, i \), are the face maps, the differential \( \text{Cor}^{\text{Sus}}(\Delta^i, X) \to \text{Cor}^{\text{Sus}}(\Delta^{i-1}, X) \) is given as the composition of correspondences \( x \mapsto x \circ \partial \). The following lemma is easy to check from the definitions:

**Lemma 3.1.** Let \( f : X \to Y \) be a morphism of schemes.

a) If \( X \) and \( T \) are smooth and \( c \in \text{Cor}(T, X) \), then \((\text{id}_T \times f)_*c = f \circ c\). Here the left hand side is push-forward of cycles, and the right hand side is composition of correspondences.
b) If $X$ and $Y$ are smooth and $d \in \text{Cor}(Y, Z)$, then $(f \times \text{id}_Z)^* d = d \circ f$. Here the left hand side is pull-back of cycles, and the right hand side is composition of correspondences.

c) If $f$ is an automorphism of the smooth scheme $X$, then $f^* \epsilon = f_{-1}^* \epsilon$ for any cycle $\epsilon$.

Let $T$ and $X$ be separated schemes of finite type over $k$ and $\sigma \in \text{Gal}(\overline{k}/k)$. Then $\sigma$ acts on $\overline{X} = X \times_k \overline{k}$ via its action on $\overline{k}$, and on algebraic cycles by pull-back.

**Lemma 3.2.** The action of $\sigma$ on $\text{Cor}_{\overline{k}}(\overline{T}, \overline{X})$ induced by pull-back of algebraic cycles sends a correspondence $\alpha$ to the composition $\sigma_X^{-1} \alpha \circ \sigma_T$, where $\sigma_X$ and $\sigma_T$ are the automorphisms of $\overline{X}$ and $\overline{T}$ induced by $\sigma$. In other words, the following diagram of correspondences commutes:

$$
\begin{array}{ccc}
\overline{T} & \xrightarrow{\sigma_T} & \overline{T} \\
\sigma^* & \downarrow & \alpha \\
\overline{X} & \xrightarrow{\sigma_X} & \overline{X}
\end{array}
$$

**Proof.** From Lemma 3.1 we have

$$
\sigma_X \circ \sigma^* \alpha = (\text{id}_T \times \sigma_X)_* (\sigma_T \times \sigma_X)^* \alpha = (\text{id}_T \times \sigma_X)^{-1}_* (\text{id}_T \times \sigma_X)^* \alpha = \alpha \circ \sigma_T.
$$

Now we assume that $k = \mathbb{F}$ is a finite field. Let $\overline{X}$ be the extension to the algebraic closure $\overline{\mathbb{F}}$, and let $F$ be the Frobenius automorphism of $\overline{\mathbb{F}}/\mathbb{F}$. Let $G \cong \mathbb{Z}$ be the Weil group of $\mathbb{F}$, generated by the Frobenius.

**Definition 3.3.** Weil-Suslin homology $H_{\text{WS}}^i(X, A)$ with coefficients in the abelian group $A$ is defined as the homology of the cone of

$$
C^\bullet(\overline{X}) \otimes A \xrightarrow{1-F^*} C^\bullet(\overline{X}) \otimes A,
$$

i.e., the total complex of the double complex

$$
\cdots \rightarrow C_2(\overline{X}) \otimes A \xrightarrow{-\partial} C_1(\overline{X}) \otimes A \xrightarrow{-\partial} C_0(\overline{X}) \otimes A \\
\downarrow 1-F^* \downarrow 1-F^* \downarrow 1-F^* \\
\cdots \rightarrow C_2(\overline{X}) \otimes A \xrightarrow{-\partial} C_1(\overline{X}) \otimes A \xrightarrow{-\partial} C_0(\overline{X}) \otimes A.
$$

In degree $i$, the total complex consists of elements

$$(x_i, x_{i-1}) \in \text{Cor}(\overline{\Delta^i}, \overline{X}) \otimes A \oplus \text{Cor}(\overline{\Delta^{i-1}}, \overline{X}) \otimes A$$

with differential

$$(x, y) \mapsto (x \partial + y - F^{-1} y F, -y \partial).$$

(14)

The spectral sequence for double complexes gives short exact sequences

$$
0 \rightarrow H^S_{i}(\overline{X}, A)_G \rightarrow H^*_{i}(X, A) \rightarrow H^*_{i+1}(\overline{X}, A)_G \rightarrow 0
$$

(15)

where the left hand side and right hand side are the coinvariants and invariants with respect to $G$, respectively. The map $C_*(X) \rightarrow C_*(\overline{X})$, sending a generator $Z \subseteq X \times \Delta^i$ to its pull-back to the algebraic closure, has image in the kernel of $1 - F^*$. Therefore, we obtain natural maps $H^S_i(X, A) \rightarrow H^*_{i+1}(X, A)$, $i \geq 0$. 8
Remark 3.4. The definition of Weil-Suslin homology depends on the finite base field \( F \) (via \( F \in \text{Gal}(\bar{\mathbb{F}}) \)). However, if \( X \to \mathbb{F} \) factors through \( \mathbb{F}'/\mathbb{F} \), then the Weil-Suslin homology of \( X \) does not depend on whether we consider \( X \) as a scheme over \( \mathbb{F}' \) or over \( \mathbb{F} \).

Proposition 3.5. An abstract blow-up diagram [1] induces a long exact sequence of Weil-Suslin homology groups

\[
\begin{align*}
H^{WS}_1(Z', A) &\longrightarrow H^{WS}_1(X', A) \oplus H^{WS}_1(Z, A) \longrightarrow H^{WS}_1(X, A) \longrightarrow \\
H^{WS}_0(Z', A) &\longrightarrow H^{WS}_0(X', A) \oplus H^{WS}_0(Z, A) \longrightarrow H^{WS}_0(X, A) \longrightarrow 0
\end{align*}
\]

Proof. By definition of Weil-Suslin homology, only the terms \( C_i(\bar{?}) \) for \( i \leq 2 \) are involved in the definition of the terms in the sequence, hence a diagram chase shows that it suffices to show that in the short exact sequence of complexes

\[
0 \to C_\ast(Z') \to C_\ast(X') \oplus C_\ast(Z) \to C_\ast(X) \to K_\ast \to 0
\]

one has \( H_i(K_\ast) = 0 \) for \( i \leq 2 \). This was shown in the proof of [GS, Prop. 5.2].

The following improves [Ge2, Prop. 7.8]:

Proposition 3.6. Let \( X \) be connected. Then the structure map induces an isomorphism

\[
\text{deg}: H^{WS}_0(X, \mathbb{Z}) \cong H^S_0(\bar{X}, \mathbb{Z}) \cong \mathbb{Z}.
\]

In particular, the canonical injection \( H^{WS}_1(X, \mathbb{Z})/m \to H^{WS}_1(X, \mathbb{Z}/m) \) is an isomorphism for any \( m \geq 1 \).

Proof. We have \( H^{WS}_0(X, \mathbb{Z}) \cong H^S_0(\bar{X}, \mathbb{Z})_G \), hence \( \text{deg} \) is surjective and it remains to show that its kernel is trivial. Since elements in \( H^S_0(\bar{X}, \mathbb{Z}) \) are represented by zero-cycles, any element of \( H^{WS}_0(X, \mathbb{Z}) \) comes by push-forward from \( H^{WS}_0(C, \mathbb{Z}) \) for some connected curve \( C \subset X \) (use, e.g., [Mu], II §6 Lemma). We therefore can assume that \( X = C \) is a connected curve.

If \( C' \to C \) is finite and surjective, then \( H^{WS}_0(C', \mathbb{Z}) \to H^{WS}_0(C, \mathbb{Z}) \) is surjective. Moreover, any element of degree zero in \( H^{WS}_0(C', \mathbb{Z}) \) can be lifted to an element in the kernel of the multi-degree map

\[
H^{WS}_0(C', \mathbb{Z}) \to \mathbb{Z}^{\pi_0(C')}.
\]

We therefore can assume that \( C \) is a normal, connected curve. Moreover, we can assume that \( C \) has an \( \mathbb{F} \)-rational point (use Remark 3.4). Let \( \mathcal{A} \) be the semi-abelian Albanese variety of \( C \). Then, by [SV, Thm. 3.1], the degree zero part of \( H^S_0(C, \mathbb{Z}) \) is isomorphic to \( \mathcal{A}(\bar{\mathbb{F}}) \). The \( G \)-coinvariants of this group are both finite and divisible, hence trivial.

4 Duality

We say that “resolution of singularities holds for schemes of dimension \( \leq d \) over a perfect field \( k \)” if the following two conditions are satisfied.

(1) For any integral separated scheme of finite type \( X \) of dimension \( \leq d \) over \( k \), there exists a projective birational morphism \( Y \to X \) with \( Y \) smooth over \( k \) which is an isomorphism over the regular locus of \( X \).
(2) For any integral smooth scheme $X$ of dimension $\leq d$ over $k$ and any birational proper morphism $Y \to X$ there exists a tower of morphisms $X_n \to X_{n-1} \to \cdots \to X_0 = X$, such that $X_n \to X_{n-1}$ is a blow-up with a smooth center for $i = 1, \ldots, n$, and such that the composite morphism $X_n \to X$ factors through $Y \to X$.

In this paper, we do not use the full duality statement below, but only the equality of the orders of the respective groups.

**Theorem 4.1.** Let $X$ be separated and of finite type over the finite field $\mathbb{F}$ of characteristic $p$. If $m$ is prime to $p$, then there is a perfect pairing of finite groups

$$H^1_{\text{WS}}(X, \mathbb{Z}/m) \times H^1_{\text{et}}(X, \mathbb{Z}/m) \to \mathbb{Z}/m.$$  

If $X$ is smooth and resolution of singularities for schemes of dimension $\leq \dim X + 1$ holds over $\mathbb{F}$, then there is a perfect pairing of finite groups for any $r \geq 1$,

$$H^1_{\text{WS}}(X, \mathbb{Z}/p^r) \times H^1_{\text{et}}(X, \mathbb{Z}/p^r) \to \mathbb{Z}/p^r.$$  

**Proof.** By [Ge2, Thm. 5.4, Thm. 5.5], we have a perfect pairing of finite groups

$$H^1_{\text{et}}(X, \mathbb{Z}/m) \times H^1_{\text{et}}(X, \mathbb{Z}/m) \to \mathbb{Z}/m,$$

where $H^1_{\text{et}}$ is Galois-Suslin homology. By [Ge2, §7.1], we have $H^1_{\text{et}}(X, \mathbb{Z}/m) \cong H^1_{\text{WS}}(X, \mathbb{Z}/m)$, showing the first statement. For the second statement, let $X'$ be a smooth, proper variety containing $X$ as a dense open subscheme. Then, by [GS, Prop. 6.2], we have $H^1_{\text{et}}(X, \mathbb{Z}/p^r) \cong H^1_{\text{et}}(X', \mathbb{Z}/p^r)$ for $i = 0, 1$, and the exact sequence (15) above implies that $H^1_{\text{WS}}(X, \mathbb{Z}/p^r) \cong H^1_{\text{WS}}(X', \mathbb{Z}/p^r)$. Furthermore, $H^1_{\text{et}}(X, \mathbb{Z}/p^r) \cong H^1_{\text{et}}(X', \mathbb{Z}/p^r)$ by [GS, Prop. 2.10]. Hence we may assume $X = X'$, and in this case the duality follows from the main theorem of [Ge3]. \hfill \Box

## 5 The reciprocity map

For any $X$ and any abelian group $A$, we construct a functorial pairing

$$H^1_{\text{WS}}(X, \mathbb{Z}) \times H^1_{\text{et}}(X, A) \to A,$$  

(16)

which induces natural maps

$$\text{Hom}(\Pi^1_{\text{et}}(X)_W, A) \cong H^1_{\text{et}}(X, A) \to \text{Hom}(H^1_{\text{WS}}(X, \mathbb{Z}), A)$$

for any abelian (pro-)group $A$, hence the Yoneda lemma induces

$$\text{rec}_X : H^1_{\text{WS}}(X, \mathbb{Z}) \to \Pi^1_{\text{et}}(X)_W.$$  

(17)

In order to construct the pairing (16), let $A$ be an abelian group and $A \to \mathbb{1}^*$ an injective resolution of the constant sheaf $A$ in the category of qfh-sheaves. An element of $H^1_{\text{et}}(X, A)$ is represented by a pair

$$(\alpha, \beta) \in \mathbb{1}^0(\bar{X}) \oplus \mathbb{1}^0(\bar{X}),$$

with $d\alpha = 0$, $[\alpha] \in H^1_1(\bar{X}, A)$ and $d\beta = \alpha - F^*\alpha$. An element in $H^1_{\text{WS}}(X, \mathbb{Z})$ is represented by a pair

$$(x, y) \in \text{Cor}(\Delta^1, \bar{X}) \oplus \text{Cor}(\Delta^0, \bar{X}),$$

with $x\partial = F^{-1}yF - y$. 

10
Since \( H^1_W(\Delta^1, A) = 0 = H^1_S(\Delta^0, A) \), we can find \( s \in I^0(\Delta^1) \) with \( ds = x^* F^* \alpha \in I^1(\Delta^1) \) and \( t \in I^0(\Delta^0) \) with \( dt = y^* \alpha \in I^1(\Delta^0) \). Then
\[
\langle (x, y), (\alpha, \beta) \rangle := F^* t - t - \partial^* s + y^* \beta
\]
lies in
\[
A = H^0_{et}(\Delta^0, A) = \ker(I^0(\Delta^0) \xrightarrow{d} I^1(\Delta^0)).
\]
Indeed, we have
\[
d(F^* t - t - \partial^* s + y^* \beta) = F^* y^* \alpha - y^* \alpha - \partial^* x^* F^* \alpha + y^* (\alpha - F^* \alpha) \\
= F^* y^* \alpha - (F^* y^* F^* - 1 - y^*) (\alpha - F^* \alpha) - y^* F^* \alpha = 0.
\]
One checks without difficulty that \( \langle (x, y), (\alpha, \beta) \rangle \) does not depend on the choice of \( s \) and \( t \).

**Lemma 5.1.** \( \langle (x, y), (\alpha, \beta) \rangle \in A \) only depends on the class of \( (x, y) \) in \( H^1_{WS}(X, \mathbb{Z}) \) and on the class of \( (\alpha, \beta) \) in \( H^1_{W,t}(X, A) \).

**Proof.** For \( \gamma \in I^0(\bar{X}), s = x^* F^* \gamma \) and \( t = y^* \gamma \) satisfy the condition and we have
\[
\langle (x, y), (d_\gamma, \gamma - F^* \gamma) \rangle = F^* t - t - \partial^* s + y^* (\gamma - F^* \gamma) \\
= F^* y^* \gamma - y^* \gamma - (x\partial)^* F^* \gamma = F^* y^* \gamma - y^* \gamma - F^* y^* \gamma + y^* F^* \gamma = 0.
\]
Let \( (u, v) \in \text{Cor}(\Delta^2, \bar{X}) \oplus \text{Cor}(\Delta^1, \bar{X}) \). Since \( H^1_W(\Delta^2, A) = 0 = H^1_S(\Delta^1, A) \), we can find \( \sigma \in I^0(\Delta^2) \) with \( d\sigma = u^* F^* \alpha \) and \( \tau \in I^0(\Delta^1) \) with \( d\tau = -v^* \alpha \). Then
\[
s = \partial^* \sigma + F^* \tau - \tau - v^* \beta \quad \text{and} \quad t = \partial^* \tau \quad \text{satisfy}
\]
and
\[
\langle (u\partial + v - F^{-1} v F, -v\partial), (\alpha, \beta) \rangle = F^* t - t - \partial^* s - (v\partial)^* \beta = \\
F^* \partial^* \tau - \partial^* \tau - \partial^* (\partial + \sigma^* F^* \tau - \tau - v^* \beta) - \partial^* v^* \beta = 0.
\]

By Lemma 5.1, we obtain the pairing \( \langle 10 \rangle \) and the reciprocity map \( \langle 17 \rangle \). If \( f : X \to Y \) is an \( \mathbb{F} \)-morphism, then the diagram
\[
\begin{array}{ccc}
H^1_{WS}(X, \mathbb{Z}) & \times & H^1_{W,t}(X, A) \\
\downarrow f_* & & \downarrow f_* \\
H^1_{WS}(Y, \mathbb{Z}) & \times & H^1_{W,t}(Y, A)
\end{array}
\]
commutes, hence \( \text{rec}_X : H^1_{WS}(X, \mathbb{Z}) \to \Pi^1_{X,W}(X) \) is functorial in \( X \).

**Proposition 5.2.** The composite of \( \text{rec}_X \) with the natural map \( H^0_S(X, \mathbb{Z}) \to H^1_{WS}(X, \mathbb{Z}) \) is the map
\[
r_X : H^0_S(X, \mathbb{Z}) \to \Pi^1_{X,W}(X),
\]
which sends the class \( [x] \) of a closed point \( x \in X \) to its Frobenius in \( \Pi^1_{X,W}(X) \).
Proof. By functoriality, it suffices to consider the case \( X = \Delta^0 \). In this case, we have natural identifications \( Z = H^0_0(\Delta^0, Z) = H^1_0(\Delta^0, Z) \) (sending \( 1 \in Z \) to \( \text{id}_{\Delta^0} \in \text{Cor}(\Delta^0, \Delta^0) \)), and for any abelian group \( A \), we have \( A = H^0_0(\Delta^0, A) = H^1_0(\Delta^0, A) \). With respect to these identifications, the pairing (16) is just multiplication \( \mathbb{Z} \times A \to A, (n, a) \mapsto na \). Furthermore, the isomorphism of Proposition 2.4

\[
A = H^1_0(\Delta^0, A) \cong \text{Hom}(\Pi_{W,t}^1(\Delta^0, A), A) = \text{Hom}(G, A)
\]

maps \( a \in A \) to the homomorphism \( G \to A \), which sends the Frobenius \( F \in G \cong \mathbb{Z} \) to \( a \). Using all this, the statement of the proposition follows from the definition of the reciprocity map.

\[\square\]

6 Comparison of blow-up sequences

If \( A = \mathbb{Z}/m \), then Weil-etale and etale cohomology agree, and by Proposition 3.6, the pairing (16) induces a pairing

\[
H^1_0(\Delta^0, \mathbb{Z}/m) \times H^1_0(\Delta^0, \mathbb{Z}/m) \to \mathbb{Z}/m, \tag{19}
\]

and hence a map

\[
\Phi^1_X : H^1_0(\Delta^0, \mathbb{Z}/m) \to H^1_0(\Delta^0, \mathbb{Z}/m)^*, \tag{20}
\]

which is the mod \( m \)-version of \( \text{rec}_X \).

In addition, we consider the pairing

\[
H^0_0(\Delta^0, \mathbb{Z}/m) \times H^0_0(\Delta^0, \mathbb{Z}/m) \to \mathbb{Z}/m \tag{21}
\]

defined as follows: Choose \( x \in \text{Cor}(\Delta^0, \Delta^0) \) representing a class in \( H^0_0(\Delta^0, \mathbb{Z}/m) = H^0_0(\Delta^0, \mathbb{Z}/m) \) and \( \alpha \in I^0(\Delta^0) \) with \( d\alpha = 0 \) and \( \alpha - F^*\alpha = 0 \). Then put \( \langle x, \alpha \rangle = x^*\alpha \in H^0_0(\Delta^0, \mathbb{Z}/m) = \mathbb{Z}/m \). We obtain a map

\[
\Phi^0_X : H^0_0(\Delta^0, \mathbb{Z}/m) \to H^0_0(\Delta^0, \mathbb{Z}/m)^*. \tag{22}
\]

The maps \( \Phi^0 \) and \( \Phi^1 \) extend in a natural way to non-connected schemes. They induce a map from the exact sequence of Proposition 3.5 to the dual of the exact sequence of Proposition 2.1. The compatibility with the boundary map is given by

Proposition 6.1. For any abstract blow-up square

\[
\begin{array}{ccc}
Z' & \rightarrow & X' \\
\downarrow \pi' & & \downarrow \pi \\
Z & \rightarrow & X
\end{array}
\]

the following diagram is commutative

\[
\begin{array}{ccc}
H^1_0(\Delta^0, \mathbb{Z}/m) & \to & \delta H^0_0(\Delta^0, \mathbb{Z}/m) \\
\downarrow \Phi^1_X & & \downarrow \Phi^0_Z \\
H^1_0(\Delta^0, \mathbb{Z}/m)^* & \to & \delta^* H^0_0(\Delta^0, \mathbb{Z}/m)^*.
\end{array}
\]

Here \( \delta \) is the boundary map of the exact sequence of Proposition 3.5 and \( \delta^* \) is the dual of the boundary map of the exact sequence of Proposition 2.1.
Proof. We have to show that the diagram

\[
\begin{array}{ccc}
H_1^{WS}(X, \mathbb{Z}/m) & \times & H_1^t(X, \mathbb{Z}/m) \\
\downarrow \delta & & \downarrow \varphi' \\
H_0^{WS}(Z', \mathbb{Z}/m) & \times & H_0^t(Z', \mathbb{Z}/m)
\end{array}
\]

commutes. Let \(a \in H_1^{WS}(X, \mathbb{Z}/m)\) and \(b \in H_0^t(Z', \mathbb{Z}/m)\). We put

\[
C_i^W(X) = C_i(\hat{X}) \otimes \mathbb{Z}/m \oplus C_{i-1}(\hat{X}) \otimes \mathbb{Z}/m,
\]
i.e., \(C_*^W(X)\) is the complex calculating \(H_*^{WS}(X, \mathbb{Z}/m)\). Consider the diagram

\[
\begin{array}{ccc}
0 & \rightarrow & C_i^W(Z') \xrightarrow{(\gamma'_*, -\gamma'_*')} C_i^W(X') \oplus C_i^W(Z) \xrightarrow{(\tau_*', i_*')} C_i^W(X) \\
& & \downarrow (\partial^*, 1 - F^*) \\
0 & \rightarrow & C_i^W(Z') \xrightarrow{(\gamma'_*, -\gamma'_*')} C_i^W(X') \oplus C_i^W(Z) \xrightarrow{(\tau_*', i_*')} C_i^W(X).
\end{array}
\]

By Proposition 3.5 and its proof, \(a \in H_1^{WS}(X, \mathbb{Z}/m)\) can be represented by a cocycle \(\alpha \in C_1^W(X)\) which can be lifted to \(C_1^W(X') \oplus C_1^W(Z)\). We choose \(\hat{\alpha} \in C_1^W(X') \oplus C_1^W(Z)\) with \((\pi'_*, i'_*)(\hat{\alpha}) = \alpha\), hence \((\pi'_*, i'_*)(\partial^*, 1 - F^*)(\hat{\alpha}) = 0\). We conclude that \(\delta(a) \in H_0^{WS}(Z', \mathbb{Z}/m)\) is represented by an element \(\gamma \in C_0^W(Z')\) with

\[
(\gamma'_*, -\gamma'_*)(\gamma) = (\partial^*, 1 - F^*)(\hat{\alpha}). \tag{23}
\]

Let \(I^*\) be an injective resolution of \(\mathbb{Z}/m\) in the category of sheaves of \(\mathbb{Z}/m\)-modules on the \(h\)-site on Sch/\(S\), and let \(\beta \in I^0(Z')\), \(d\beta = 0\), be a representative of \(b \in H_0^t(Z', \mathbb{Z}/m)\). Consider the diagram

\[
\begin{array}{ccc}
I^0(X') \oplus I^0(Z) & \xrightarrow{(t^*_*, -t^*_*)} & I^0(Z') \\
\downarrow d & & \downarrow d \\
I^1(X) & \xrightarrow{(t^*_*, i^*_*)} & I^1(X') \oplus I^1(Z) \xrightarrow{(t^*_*, -t^*_*)} I^1(Z') \\
\downarrow \alpha^* & & \downarrow \alpha^* \\
I^0(\Delta^1) \oplus I^0(\Delta^0) & \xrightarrow{(\partial^*, 1 - F^*)} & I^1(\Delta^1) \oplus I^2(\Delta^0) \xrightarrow{(\partial^*, 1 - F^*)} I^2(\Delta^0) \\
\downarrow d & & \downarrow d \\
I^0(\Delta^0) & \xrightarrow{d} & I^1(\Delta^0) \xrightarrow{d} I^1(\Delta^0) \xrightarrow{d} I^2(\Delta^0)
\end{array}
\]

Since the complex coker \(I^*(X') \oplus I^*(Z) \rightarrow I^*(Z')\) is exact (cf. the exact triangle \([6]\) in the proof of Proposition 2.1), we find \(\hat{\beta} \in I^0(X') \oplus I^0(Z)\) with \((t^*_*, -t^*_*)(\hat{\beta}) = \beta\). By the argument of [MVW] Lemma 12.7, the sequence

\[
0 \rightarrow \mathcal{F}(X) \rightarrow \mathcal{F}(X') \oplus \mathcal{F}(Z) \rightarrow \mathcal{F}(Z')
\]

is exact for every \(h\)-sheaf \(\mathcal{F}\). Therefore the second line in the diagram is exact and there is a unique \(\varepsilon \in I^1(X)\) with \((t^*_*, i^*_*)(\varepsilon) = \hat{\beta}\), representing \(\delta(b) \in H_1^t(X, \mathbb{Z}/m)\). We see that \(\hat{\alpha}^*(d\hat{\beta}) = \alpha^*(d\beta)\). It follows that

\[
d(\hat{\alpha}^*(\hat{\beta})) = \alpha^*(\varepsilon) \in \ker(\partial^*, 1 - F^*).
\]
By definition, we have
\[ \langle a, bd \rangle = - \langle \partial^*, 1 - F^* \rangle \hat{\alpha}^*(\hat{\beta}) \in \ker(I^0(\Delta^0) \to I^1(\Delta^0)) = H^0_{\operatorname{et}}(\Delta^0, \mathbb{Z}/m). \]
On the other hand, \[ \langle a_\sigma, b \rangle = \gamma^*(b) \in H^0_{\operatorname{et}}(\Delta^0, \mathbb{Z}/m) \] is represented by \( \gamma^* \beta \in I^0(\Delta^0) \)
and
\[ \gamma^* \beta = \gamma^*(\iota^* - \pi^*) \hat{\beta} = \{ (\iota^* \gamma, - \pi^* \gamma)(\hat{\beta}) \} = \{ (\partial^*, 1 - F^*) \hat{\alpha} \} \hat{\beta}. \]
Now we write \( \hat{\alpha} = (\hat{\alpha}_1, \hat{\alpha}_2) \) with \( \hat{\alpha}_1 \in C_1(X') \oplus C_1(Z) \) and \( \hat{\alpha}_2 \in C_0(X') \oplus C_0(Z). \)
Then \( (\partial^*, 1 - F^*) \hat{\alpha} = \alpha_1 \partial + \alpha_2 - F^{-1} \alpha_2 F. \)
Since \( F^* \hat{\beta} = \hat{\beta} \), we conclude
\[ (\partial^*, 1 - F^*) \hat{\alpha} \hat{\beta} = (\delta^*, 1 - F^*) \hat{\alpha} \hat{\beta}. \]
This completes the proof.

\[ \square \]

\section{7 Proof of the main theorem}

To prove our main theorem, we first consider finite coefficients.

\begin{proposition}
The map \( \Phi_X^1 \) is an isomorphism for any \( X \) and \( m \).
\end{proposition}

\begin{proof}
We can assume that \( X \) is connected. Then, by Proposition \ref{prop:finite},
the degree map induces an isomorphism \( H^0_{\operatorname{et}}(X, \mathbb{Z}/m) \xrightarrow{\sim} H^0_{\operatorname{et}}(\mathbb{F}, \mathbb{Z}/m) \cong \mathbb{Z}/m. \)
Furthermore, \( H^0_{\operatorname{et}}(\mathbb{F}, \mathbb{Z}/m) \xrightarrow{\sim} H^0_{\operatorname{et}}(X, \mathbb{Z}/m). \)
Hence, by functoriality, we can reduce the statement to the case \( X = \text{Spec}(\mathbb{F}) \), where it is easy.
\end{proof}

\begin{theorem}
For any separated scheme of finite type over a finite field \( \mathbb{F} \),
the map
\[ \Phi_X^1 : H^1_{\operatorname{et}}(X, \mathbb{Z}/m) \to H^1(X, \mathbb{Z}/m)^* \]
is surjective. It is an isomorphism if \( m \) is prime to the characteristic or if
resolutions of singularities holds for schemes of dimension \( \leq \dim X + 1 \) over \( \mathbb{F} \).
\end{theorem}

\begin{proof}
By Propositions \ref{prop:finite} \ref{prop:ses} \ref{prop:ab} and \ref{prop:iso}
and induction on the dimension, we can assume that \( X \) is normal and connected.
Then, by Proposition \ref{prop:iso} \ref{prop:iso} \ref{prop:iso} and Chebotarev-Lang density,
the composite
\[ H^0_{\operatorname{et}}(X, \mathbb{Z}/m/m \to H^1_{\operatorname{et}}(X, \mathbb{Z}/m) \xrightarrow{\Phi_X^1} H^1(X, \mathbb{Z}/m)^* \]
is surjective, hence so is \( \Phi_X^1 \).
To get the isomorphism, we note that by Theorem \ref{thm:iso}
the source and the target of \( \Phi_X^1 \) have the same order under the given hypothesis.
\end{proof}

\begin{proof} \[ \text{of Theorem} \ref{thm:iso} \]
Consider the diagram (for any \( m \))
\[ \begin{array}{ccc}
H^1_{\operatorname{et}}(X, \mathbb{Z}) & \xrightarrow{\text{rec}_X} & \Pi^1_{\text{ab}}(X)_W \\
\varphi \downarrow & \quad & \downarrow \psi \\
H^1_{\operatorname{et}}(X, \mathbb{Z}/m) & \xrightarrow{\Phi_X^1} & \Pi^1_{\text{ab}}(X)_{W/m}.
\end{array} \]
The composite \( \Phi_X^1 \circ \varphi \) is surjective by Proposition \ref{prop:finite} and Theorem \ref{thm:iso}.
Hence the cokernel of \( \text{rec}_X \) is divisible. Since \( \Pi^1_{\text{ab}}(X)_W \) is finitely generated,
all divisible elements of \( H^1_{\operatorname{et}}(X, \mathbb{Z}) \) are in the kernel of \( \text{rec}_X \),
and the cokernel of \( \text{rec}_X \) is finitely generated and divisible, hence trivial.
Now assume that resolution of singularities holds for schemes of dimension \( \leq \dim X + 1 \) over \( \mathbb{F} \).
Then \( \Phi_X^1 \) is an isomorphism for all \( m \).
Hence the kernel of \( \text{rec}_X \) is the set \( \text{div} \) \( H^1_{\operatorname{et}}(X, \mathbb{Z}) \) of divisible elements.
This agrees with the maximal divisible subgroup by the following Lemma \ref{lem:div}.
\end{proof}
Lemma 7.3. Let $A$ be an abelian group. If $A/\text{div} A$ is finitely generated, then $\text{div} A$ is divisible.

Proof. Let $B = A/\text{div} A$, choose an integer $n$ such that $nB$ is free, and let $C \subseteq A$ be the inverse image of $nB$ in $A$. Then $\text{div} C = \text{div} A$ because $nA \subseteq C \subseteq A$. By freeness of $nB$, we obtain that $C = nB \oplus \text{div} A$, hence $\text{div} A = \text{div} C = \text{div} A$. 

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