BLOCH’S CYCLE COMPLEX OF ZERO CYCLES WITH $\mathbb{Z}/p^n$ COEFFICIENTS FROM GROTHENDIECK’S COHERENT DUALITY POINT OF VIEW

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Abstract. Let $X$ be a separated scheme of finite type over $k$ with $k$ being a perfect field of positive characteristic $p$. In this work we define a complex $K_{n,X,\log}$ via Grothendieck’s duality theory of coherent sheaves following [Kat87] and build up a quasi-isomorphism from the Kato-Moser complex of logarithmic de Rham-Witt sheaves $\tilde{\nu}_{n,X}$ to $K_{n,X,\log}$ for the étale topology, and also for the Zariski topology under the extra assumption $k = \mathbb{F}$. Combined with Zhong’s quasi-isomorphism from Bloch’s cycle complex $Z^c_X$ to $\tilde{\nu}_{n,X}$ [Zho14, 2.16], we deduce certain vanishing, étale descent properties as well as invariance under rational resolutions for higher Chow groups of 0-cycles with $\mathbb{Z}/p^n$-coefficients.

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INTRODUCTION

Let X be a separated scheme of finite type over k of dimension d with k being a perfect field of positive characteristic p. In this work, we show that Bloch’s cycle complex \( \mathbb{Z}^n_X \) of zero cycles mod \( p^n \) is quasi-isomorphic to the Cartier operator fixed part of a certain dualizing complex from coherent duality theory. From this we obtain new vanishing results for the higher Chow groups of zero cycles with mod \( p^n \) coefficients for singular varieties.

As the first candidate for a motivic complex, Bloch introduced his cycle complex \( \mathbb{Z}^n_X \) in [Blo86] under the framework of Beilinson-Lichtenbaum. Let \( i \) be an integer, and \( \Delta^i = \text{Spec } k[T_0, \ldots, T_i]/(\sum T_j - 1) \). Here \( Z_X := z_0(-, -) \) is a complex of sheaves in the Zariski or the ‘étale topology. The global sections of its degree \( (-i) \)-term \( z_0(X, i) \) is the free abelian group generated by dimension \( i \)-cycles in \( X \times \Delta^i \) intersecting all faces properly and the differentials are the alternating sums of the cycle-theoretic intersection of the cycle with each face (cf. Section 2). In this article we define a complex \( K_{n,X,\log} \) via Grothendieck’s duality theory of coherent sheaves following the idea in [Kat87] and build up a quasi-isomorphism from the Kato-Moser complex of logarithmic de Rham-Witt sheaves \( \tilde{\nu}_{n,X} \) (namely the Gersten complex of logarithmic de Rham-Witt sheaves, which is introduced and studied in [Kat86a, §1][Mos99, (1.3)-(1.5)]) to \( K_{n,X,\log} \) for the ‘étale topology and also for the Zariski topology under the extra assumption \( k = \mathbb{k} \). Combined with Zhong’s quasi-isomorphism from Bloch’s cycle complex \( \mathbb{Z}^n_X \) to \( \tilde{\nu}_{n,X} \) [Zho14, 2.16], we deduce certain vanishing and finiteness properties as well as invariance under rational resolutions for higher Chow groups of \( 0 \)-cycles with \( \mathbb{Z}/p^n \)-coefficients. The proofs in this article are self-contained in respect to Kato’s work [Kat87].

Let us briefly recall Kato’s work in [Kat87] and introduce our main object of studies: \( K_{n,X,\log} \). Let \( \pi : X \to \text{Spec } k \) be the structure morphism of \( X \). Let \( W_n X := \langle |X|, W_n O_X \rangle \), where \( |X| \) is the underlying topological space of \( X \), and \( W_n O_X \) is the sheaf of length \( n \) truncated Witt vectors. Let \( W_n \pi : W_n X \to \text{Spec } W_n k \) be the morphism induced from \( \pi \) via functoriality. According to Grothendieck’s duality theory, there exists an explicit Zariski complex \( K_{n,X} \) of quasi-coherent sheaves representing \( (W_n \pi)^! W_n k \) (such a complex \( K_{n,X} \) is called a residual complex, cf. [Har66, VI.3.1]). There is a natural Cartier operator \( C' : K_{n,X} \to K_{n,X} \), which is compatible with the classical Cartier operator \( C : W_n \Omega^d_X \to W_n \Omega^d_X \) in the smooth case via Ekedahl’s quasi-isomorphism (see Theorem 1.7). Here \( W_n \Omega^d_X \) denotes the degree \( d := \text{dim } X \) part of the de Rham-Witt complex. We define the complex \( K_{n,X,\log} \) to be the mapping cone of \( C' - 1 \). What Kato did in [Kat87] is the FRP counterpart, where FRP is the “flat and relatively perfect” topology (this is a topology with ‘étale coverings and with the underlying category lying in between the small and the ‘étale site). Kato then showed that \( K_{n,X,\log} \) in the topology FRP acts as a dualizing complex in a rather big triangulated subcategory of the derived category of \( \mathbb{Z}/p^n \)-sheaves, containing all coherent sheaves and sheaves like logarithmic de Rham-Witt sheaves [Kat87, 0.1]. Kato also showed that in the smooth setting, \( K_{n,X,\log} \) is concentrated in one degree and this only nonzero cohomology sheaf is the top degree logarithmic de Rham-Witt sheaf [Kat87, 3.4]. For the latter, an analogy on the small ‘étale site naturally holds. Rülling later observed that with a trick from \( p^{-1} \)-linear algebra, [Kat87, 3.4] can be done on the Zariski site as well, as long as one assumes \( k = \mathbb{k} \) (cf. Proposition 1.15). Comparing this with the Kato-Moser complex \( \tilde{\nu}_{n,X} \), which is precisely the Gersten resolution of the logarithmic de Rham-Witt sheaf in the smooth setting, one gets an identification in the smooth setting \( \tilde{\nu}_{n,X} \cong K_{n,X,\log} \) on the Zariski topology. Similar as in [Kat87, 4.2] (cf. Proposition 1.21), Rülling also built up the localization sequence for \( K_{n,X,\log} \) on the Zariski site in his unpublished notes (cf. Proposition 1.22). Compared with the localization sequence for \( Z^d_X \) [Blo94, 1.1] and for \( \tilde{\nu}_{n,X} \) (which trivially holds in the Zariski topology), it is reasonable to expect a chain map relating these objects in general.

The aim of this article is to build a quasi-isomorphism \( \tilde{\zeta}_{\log} : \tilde{\nu}_{n,X} \xrightarrow{\sim} K_{n,X,\log} \) in the singular setting, such that when pre-composed with Zhong’s quasi-isomorphism \( \psi : Z^d_X \to \tilde{\nu}_{n,X} \) [Zho14, 2.16], it gives
another perspective of Bloch’s cycle complex with $\mathbb{Z}/p^n$-coefficients in terms of Grothendieck’s coherent duality theory. More precisely, we prove the following result.

**Theorem 0.1** (Theorem 5.10, Theorem 6.1). Let $X$ be a separated scheme of finite type over $k$ with $k$ being a perfect field of positive characteristic $p$. Then there exists a chain map

$$\zeta_{\log, \text{ét}} : \tilde{\nu}_{n, X, \text{ét}} \overset{\sim}{\rightarrow} K_{n, X, \log, \text{ét}},$$

which is a quasi-isomorphism. If moreover $k = \overline{k}$, the chain map

$$\zeta_{\log, \text{Zar}} : \tilde{\nu}_{n, X, \text{Zar}} \overset{\sim}{\rightarrow} K_{n, X, \log, \text{Zar}}$$

is also a quasi-isomorphism.

Composed with Zhong’s quasi-isomorphism $\psi$, we have the following composition of chain maps

$$\zeta_{\log, \text{ét}} \circ \psi \circ \zeta_{\log, \text{ét}} : \tilde{\nu}_{n, X, \text{ét}} \rightarrow \tilde{\nu}_{n, X, \text{Zar}} \overset{\sim}{\rightarrow} K_{n, X, \log, \text{ét}} \overset{\sim}{\rightarrow} K_{n, X, \log, \text{Zar}},$$

which is a quasi-isomorphism. If moreover $k = \overline{k}$, the composition

$$\zeta_{\log, \text{Zar}} \circ \psi \circ \zeta_{\log, \text{Zar}} : \tilde{\nu}_{n, X, \text{Zar}} \rightarrow \tilde{\nu}_{n, X, \text{Zar}} \overset{\sim}{\rightarrow} K_{n, X, \log, \text{Zar}}$$

is also a quasi-isomorphism.

We explain more on the motivation behind the definition of $K_{n, X, \log}$. In the smooth setting, the logarithmic de Rham-Witt sheaves can be defined in two ways: either as the subsheaves of $W^n\Omega^d_X$ generated by log forms, or as the invariant part under the Cartier operator $C$. In the singular case, these two perspectives give two different (complexes of) sheaves. The first definition can also be done in the singular case, and this was studied by Morrow [Mor15]. For the second definition one has to replace $W^n\Omega^d_X$ by a dualizing complex on $W^nX$ for this Grothendieck’s duality theory yields a canonical and explicit choice, and this is what we have denoted by $K_{n, X}$. And then this method leads naturally to Kato’s and also our construction of $K_{n, X, \log}$. Now with our main theorem one knows that $\tilde{Z}_X^n/p^n$ sits in a distinguished triangle

$$\tilde{Z}_X^n/p^n \rightarrow K_{n, X} \xrightarrow{C^t} K_{n, X} \overset{+1}{\rightarrow} \tilde{Z}_X^n/p^n \rightarrow,$$

in the derived category $D^b(X, \mathbb{Z}/p^n)$, in either the étale topology, or the Zariski topology with an extra $k = \overline{k}$ assumption. In particular, when $X$ is Cohen-Macaulay of pure dimension $d$, then the triangle above becomes

$$\tilde{Z}_X^n/p^n \rightarrow W_n\omega_X[d] \xrightarrow{C^t} W_n\omega_X[d] \overset{+1}{\rightarrow} \tilde{Z}_X^n/p^n \rightarrow,$$

where $W_n\omega_X$ is the only non-vanishing cohomology sheaf of $K_{n, X}$ (when $n = 1$, $W_1\omega_X = \omega_X$ is the usual dualizing sheaf on $X$), and $\tilde{Z}_X^n/p^n$ is concentrated at degree $-d$ (cf. Proposition 8.1). This is a generalization of the top degree case of [GL00, 8.3], which in particular implies the above triangle in the smooth case.

As corollaries, we arrive at some properties of the higher Chow groups of 0-cycles with $p$-primary torsion coefficients. (We have specialized several statements here in the introduction part. Please see the main text for more general statements.)

**Corollary 0.2** (Proposition 8.2, Corollary 8.6, Proposition 8.3, Corollary 8.4, Corollary 8.9, Corollary 8.12, Corollary 8.14). Let $X$ be a separated scheme of finite type over a perfect field $k$ of characteristic $p > 0$.

1. (Cartier invariance) Assume $k = \overline{k}$. Then

$$\text{CH}_0(X, q; \mathbb{Z}/p^n) = H^{-q}(W_nX, K_{n, X, \text{Zar}})^{\text{C}^t}.\text{Zar}^{-1}.$$

2. (Semisimplicity) Assume $k = \overline{k}$. Let $X$ be proper over $k$. Then for any $q$,

$$H^{-q}(W_nX, K_{n, X})_{\text{ss}} = \text{CH}_0(X, q; \mathbb{Z}/p^n) \otimes_{\mathbb{Z}/p^n} W_nk.$$

(We refer to Definition A.4 and Remark A.5(2) for the definition of the semisimplicity and the notation (−)$_{\text{ss}}$ in this context.)

3. (Relation with $p$-torsion Poincaré duality) There is an isomorphism in $D^b((W_nX)_\text{ét}, \mathbb{Z}/p^n)$

$$K_{n, X, \log, \text{ét}} \cong R(W_n\pi)^! (\mathbb{Z}/p^n),$$

where $R(W_n\pi)^!$ is the extraordinary inverse image functor defined in [SGA4-3, Exposé XVIII, Thm 3.1.4].
(4) (Affine vanishing) Assume \( k = \overline{k} \). Suppose \( X \) is affine and Cohen-Macaulay of pure dimension \( d \). Then
\[
\text{CH}_0(X, q; \mathbb{Z}/p^n) = 0
\]
for \( q \neq d \).

(5) (Étale descent) Assume \( k = \overline{k} \). Suppose \( X \) is Cohen-Macaulay of pure relative dimension \( d \). Then
\[
R^i\epsilon_*(Z_{X,\text{ét}}^c/p^n) = R^i\epsilon_*\hat{\mu}_{n,X,\text{ét}} = 0, \quad i \neq -d.
\]

(6) (Invariance under rational resolution) Assume \( k = \overline{k} \). For a rational resolution of singularities \( f : \tilde{X} \to X \) (cf. Definition 8.10) of an integral \( k \)-scheme \( X \) of pure dimension, the trace map induces an isomorphism
\[
\text{CH}_0(\tilde{X}, q; \mathbb{Z}/p^n) \cong \text{CH}_0(X, q; \mathbb{Z}/p^n)
\]
for each \( q \).

(7) (Galois descent) Assume \( k = \overline{k} \). Let \( f : X \to Y \) be a finite étale Galois map with Galois group \( G \). Then
\[
\text{CH}_0(Y, d; \mathbb{Z}/p^n) = \text{CH}_0(X, d; \mathbb{Z}/p^n)^G.
\]

Now we give a more detailed description of the structure of this article.

The general setting is that \( X \) is a separated scheme of finite type over a perfect field \( k \) of positive characteristic \( p \) (we sometimes just say \( X \) is a \( k \)-scheme for short). In Part 1, we review the basic properties of the chain complexes to appear. Section 1 is devoted to the properties of the complex \( K_{n,X,\text{log}} \), the most important object of our studies. We study the Zariski version in Section 1.1—Section 1.4. Following the idea in [Kat87], we define the Cartier operator \( C' \) for the residual complex \( K_{n,X} \), and then define the complex \( K_{n,X,\text{log}} \) to be the mapping cone of \( C' - 1 \) in Section 1.1. We compare our \( C' \) with the classical definition of the Cartier operator \( C \) for top degree de Rham-Witt sheaves in Section 1.2.

To avoid interruption of a smooth reading we collect the calculation in the next two subsections (Section 1.2.2—Section 1.2.3). The localization sequence appears in Section 1.3. In these subsections, the most important ingredients are a surjectivity result of \( C' - 1 \) (cf. Proposition 1.15). See also Section A for a short discussion on semilinear algebra), the trace map of a nilpotent thickening (cf. Proposition 1.21), and the localization sequence (cf. Proposition 1.22). They are observed already by Rülling and are only re-presented here by the author. After a short discussion on functoriality in Section 1.4, we move to the étale case in Section 1.5. Most of the properties hold true in a similar manner, except that the surjectivity of \( C_\text{ét} - 1 : W_n\Omega^1_{\text{ét}} \to W_n\Omega^1_{\text{ét}} \) over a smooth \( k \)-scheme \( X \) holds true without any extra assumption of the base field (except perfection, which is already needed in defining the Cartier operator). This enables us to build the quasi-isomorphism \( \zeta_{\text{log},\text{ét}} \) without assuming \( k \) being algebraically closed in the next part. The rest of the sections in Part 1 are introductory treatments of Bloch’s cycle complex \( \mathcal{Z}_X \), Kato’s complex of Milnor \( K \)-theory \( C^M_X \), and the Kato-Moser complex of logarithmic de Rham Witt sheaves \( \tilde{\nu}_{n,X,t} \), respectively. There are no new results in these three sections.

In Part 2 we construct the quasi-isomorphism \( \zeta_{\text{log}} : \tilde{\nu}_{n,X} \cong K_{n,X,\text{log}} \) and study its properties in Section 5. We first build a chain map \( \zeta : C^n_X \to K_{n,X} \) and then we show that it induces a chain map \( \zeta_{\text{log}} : C^M_X \to K_{n,X,\text{log}} \). This map actually factors through a chain map \( \zeta_{\text{log}} : \tilde{\nu}_{n,X} \to K_{n,X,\text{log}} \) via the Bloch-Gabber-Kato isomorphism [BK86, 2.8]. We prove that \( \zeta_{\text{log}} \) is a quasi-isomorphism for \( t = \text{ét} \), and also for \( t = \text{Zar} \) with an extra \( k = \overline{k} \) assumption. In Section 6, we review the main results of [Zho14, §2] and compose Zhong’s quasi-isomorphism \( \psi : \mathcal{Z}_X/p^n \to \tilde{\nu}_{n,X} \) with our \( \zeta_{\text{log}} \). This composite map enables us to use tools from the coherent duality theory in calculation of certain Chow groups of \( 0 \)-cycles.

In Part 3 we discuss the applications. Section 7 mainly serves as a preparation section for Section 8. In Section 8 we arrive at several results for higher Chow groups of \( 0 \)-cycles with \( p \)-primary torsion coefficients: affine vanishing, finiteness (reproof of a theorem of Geisser), étale descent, and invariance under rational resolutions.

Prerequisites. The reader will be assumed to be familiar with Grothendieck duality theory in the sense of [Har66] and [Con00]. One can find a short survey of the properties of the residual complexes and the trace map in [CR12, §1.7].

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preliminary version of this paper with great care and provided detailed comments on the mathematical contents, grammatical errors and typos. Thomas Geisser has also read the preliminary version of this work and pointed out that Proposition 8.8 is in fact a corollary of [GL00, 8.4]. Yun Hao kindly provided me his notes on an elementary proof of Proposition A.3. I am indebted to them all. I thank also the Berlin mathematical school for providing financial support during my studies in Berlin.

Part 1. The complexes

1. Kato’s complex $K_{n,X,log,t}$

1.1. Definition of $K_{n,X,log}$. Let $k$ be a perfect field of characteristic $p$. Let $W_nk$ be the ring of Witt vectors of length $n$ of $k$. Notice that $W_nk$ is an injective $W_nk$-module by Baer’s criterion. So Spec $W_nk$ is a Gorenstein scheme by [Har66, V. 9.1(ii)], and its structure sheaf placed at degree 0 is a residual complex (with codimension function being the zero function and the associated filtration being $Z^*(W_nk) = \{Z^n(W_nk)\}$, where $Z^n(W_nk)$ is the set of the unique point in Spec $W_nk$) by [Har66, p299 1.] and the categorical equivalence [Con00, 3.2.1] (note that in this case the Cousin functor $E_Z(W_nk)$ applied to $W_nk$ is still $W_nk$). This justifies the symbol $(W_nF_k)^{\wedge}$ to appear. To avoid possible confusion we will distinguish the source and target of the absolute Frobenius by using the symbols $k_1 = k_2 = k$. Absolute Frobenius is then written as $F_k : (\text{Spec } k_1, k_1) \rightarrow (\text{Spec } k_2, k_2)$, and the $n$-th Witt lift is written as $W_nF_k : (\text{Spec } W_nk_1, W_nk_1) \rightarrow (\text{Spec } W_nk_2, W_nk_2)$. There is a natural isomorphism of $W_nk_1$-modules (the last isomorphism is given by [Har66, VI.3.1])

\[(1.1.1) \quad W_nk_1 \xhookrightarrow{\simeq} W_nF_k \text{Hom}_{W_nk_2}((W_nF_k)_*(W_nk_1), W_nk_2) \simeq (W_nF_k)^{\wedge}(W_nk_2),\]

where $W_nF_k : (\text{Spec } W_nk_1, W_nk_1) \rightarrow (\text{Spec } W_nk_2, (W_nF_k)_*(W_nk_1))$ is the natural map of ringed spaces, and the Hom set is given the $(W_nF_k)_*(W_nk_1)$-module structure via the first place. In fact, it is clearly a bijection: identify the target with $W_nk_2$ via the evaluate-at-1 map, then one can see that the map \((1.1.1)\) is identified with $a \mapsto (W_nF_k)^{-1}(a)$.

Let $X$ be a separated scheme of finite type over $k$ with structure map $\pi : X \rightarrow k$. Since $W_nk$ is a Gorenstein scheme as we recalled in the last paragraph,

\[K_{n,X} := (W_n\pi)^{\wedge}W_nk\]

is a residual complex on $W_nX$, associated to the codimension function $d_{K_{n,X}}$ with

\[d_{K_{n,X}}(x) = - \text{dim} \{x\},\]

and the filtration $Z^*(K_{n,X}) = \{Z^p(K_{n,X})\}$ with

\[Z^p(K_{n,X}) = \{x \in X \mid \text{dim} \{x\} \leq -p\}.\]

In particular, $K_{n,X}$ is a bounded complex of injective quasi-coherent $W_nO_X$-modules with coherent cohomologies sitting in degrees $[-d, 0]$.

When $n = 1$, we write $K_X := K_{1,X}$. Now we turn to the definition of $C'$. Denote the level $n$ Witt lift of the absolute Frobenius $F_X$ by $W_nF_X : (W_nX_1, W_nO_{X_1}) \rightarrow (W_nX_2, W_nO_{X_2})$. The structure maps of $W_nX_1, W_nX_2$ are $W_n\pi_1, W_n\pi_2$ respectively. These schemes fit into a commutative diagram

\[
\begin{array}{ccc}
W_nX_1 & \xrightarrow{W_nF_X} & W_nX_2 \\
\downarrow W_n\pi_1 & & \downarrow W_n\pi_2 \\
\text{Spec } W_nk_1 & \xrightarrow{W_nF_k} & \text{Spec } W_nk_2.
\end{array}
\]

Denote

\[K_{n,X_i} := (W_n\pi_i)^{\wedge}W_nk_i, \quad i = 1, 2.\]

Via functoriality, one has a $W_nO_{X_i}$-linear map

\[(1.1.2) \quad K_{n,X_1} = (W_n\pi_1)^{\wedge}(W_nk_1) \xrightarrow{(W_n\pi_1)^{\wedge}(1.1.1)} (W_n\pi_1)^{\wedge}(W_nF_k)^{\wedge}(W_nk_2) \simeq (W_nF_X)^{\wedge}(W_n\pi_2)^{\wedge}(W_nk_2) \simeq (W_nF_X)^{\wedge}K_{n,X_2}.
\]
Here the isomorphism at the beginning of the second line is given by [Con00, (3.2.3)]. Then via the adjunction with respect to the morphism $W_nF_X$, one has a $W_n\mathcal{O}_X$-linear map

$$C' := C'_n : (W_nF_X)_{*,\mathcal{O}_X} \xrightarrow{(W_0F_X)_* (1.1.2)} (W_nF_X)_* (W_nF_X) \triangleleft K_{n,X_1} \to^{T_{W_nF_X}} K_{n,X_2},$$

where the last map is the trace map of $W_nF_X$ for residual complexes, cf. [Con00, §3.4]. We call it the (level $n$) Cartier operator for residual complexes. We sometimes omit the $(W_nF_X)_*$-module structure of the source and write simply as $C' : K_{n,X} \to K_{n,X}$.

Now we come to the construction of $K_{n,X,\log}$ (cf. [Kat87, §3]). Define

$$K_{n,X,\log} := \text{Cone}(K_{n,X} \xrightarrow{C'-1} K_{n,X})[-1].$$

This is a complex of abelian sheaves sitting in degrees $[-d, 1].$

When $n = 1$, we set $K_{X,\log} := K_{1,X,\log}$. Writing more explicitly, $K_{n,X,\log}$ is the following complex

$$(K_{n,X}^{-d} \oplus 0) \to (K_{n,X}^{-d+1} \oplus K_{n,X}^{-d}) \to \ldots \to (K_{n,X}^0 \oplus K_{n,X}^{-1}) \to (0 \oplus K_{n,X}^0).$$

The differential of $K_{n,X,\log}$ at degree $i$ is given by

$$d_{\log} = d_n : K_{n,X,\log}^i \to K_{n,X,\log}^{i+1}$$

$$(K_{n,X}^i \oplus K_{n,X}^{i-1}) \to (K_{n,X}^{i+1} \oplus K_{n,X}^i)$$

$$(a, b) \mapsto (d(a), -(C'-1)(a) - (d(b)),$$

where $d$ is the differential in $K_{n,X}$. The sign conventions we adopt here for shifted complexes and the cone construction are the same as in [Con00, p6, p8]. And naturally, one has a distinguished triangle

$$K_{n,X,\log} \to K_{n,X} \xrightarrow{C'-1} K_{n,X} \xrightarrow{+1} K_{n,X,\log}[-1].$$

Explicitly, the first map is in degree $i$ given by

$$K_{n,X,\log}^i = K_{n,X}^i \oplus K_{n,X}^{i-1} \to K_{n,X}^i,$$

$$(a, b) \mapsto a.$$

The "+1" map is given by

$$K_{n,X}^i \to (K_{n,X,\log}^i)[-1]^i = K_{n,X,\log}^{i+1} = (K_{n,X}^{i+1} \oplus K_{n,X}^i),$$

$$b \mapsto (0, b).$$

Both maps are indeed maps of chain complexes.

### 1.2. Comparison of $W_n\Omega_X^d$ with $K_{n,X,\log}$

Recall the following result from classical Grothendieck duality theory [Har66, IV, 3.4] [Con00, 3.1.3] and Ekedahl [Eke84, §1] (see also [CR12, proof of 1.10.3 and Rmk. 1.10.4]).

**Proposition 1.1** (Ekedahl). When $X$ is smooth and of pure dimension $d$ over $k$, then there is a canonical quasi-isomorphism

$$W_n\Omega_X^d[d] \xrightarrow{\sim} K_{n,X}.$$  

**Remark 1.2.** Suppose $X$ is a separated scheme of finite type over $k$ of dimension $d$. Denote by $U$ the smooth locus of $X$, and suppose that the complement $Z$ of $U$ is of dimension $e$. Suppose moreover that $U$ is non-empty and equidimensional (it is satisfied for example, when $X$ is integral). Then Ekedahl's quasi-isomorphism Proposition 1.1 gives a quasi-isomorphism of dualizing complexes

$$W_n\Omega_U^d[d] \xrightarrow{\sim} K_{n,U}.$$  

Note that by the very definition, the associated filtrations of quasi-isomorphic dualizing complexes are the same (cf. [Har66, 3.4]). As explained above, the associated filtration of $K_{n,U}$ is its dimension filtration. Let $Z^\bullet$ be the codimension filtration of $U$ (cf. [Con00, p.105]). Since $U$ is of pure dimension $d$, we know that its dimension filtration is just a shift of the codimension filtration, i.e., $Z^\bullet[d]$. Apply the Cousin functor associated to the shifted codimension filtration $Z^\bullet[d]$ (cf. [Har66, IV, §1, Motif G]) to the quasi-isomorphism (1.2.1) between dualizing complexes, we have an isomorphism of residual complexes

$$E_{Z^\bullet[d]}(W_n\Omega_U^d[d]) \xrightarrow{\sim} K_{n,U}$$

with the same filtration $Z^\bullet[d]$ (cf. [Con00, 3.2.1]). Since $W_n\jmath$ is an open immersion, we can canonically identify the residual complexes $(W_n\jmath)^* K_{n,X} \simeq K_{n,U}$ by [Har66, VI, 3.1 and 5.3]. Since $K_{n,X}$ is a
residual complex and in particular is a Cousin complex (cf. [Con00, p. 105]), the adjunction map $K_{n,X} \rightarrow (W_n)_*\gamma (W_n)_* K_{n,X} \simeq (W_n)_* K_{n,U}$ is an isomorphism at degrees $[-d,-e-1]$. Thus the induced chain map

$$K_{n,X} \rightarrow (W_n)_* E_{Z,d}(W_n \Omega^i_U[d])$$

is an isomorphism at degrees $[-d,-e-1]$.  

1.2.1. Compatibility of $C' \times$ with the classical Cartier operator $C$. We review the absolute Cartier operator in classical literature (see e.g. [BK05, Chapter 1 §3], [Ill79, §2], [Kat70, 7.2], [IR83, III §1]). Let $X$ be a $k$-scheme. The (absolute) Cartier operator $\gamma_X$ of degree $i$ on a scheme $X$ is affine locally, say, on Spec $A \subset X$, given additively by the following expression ($H^i(-)$ denotes the cohomology sheaf of the complex)

$$(1.2.2) \quad \gamma_A : \Omega^i_{A/k} \rightarrow H^i(F_A,\Omega^{i+1}_{A/k})$$

where $a,a_1,\ldots,a_i \in A$. Here $H^i(F_A,\Omega^{i+1}_{A/k})$ denotes the $A$-module structure on $H^i(\Omega^{i+1}_{A/k})$ via the absolute Frobenius $F_A : A \rightarrow A, a \mapsto a^p$ (note that $F_A,\Omega^{i+1}_{A/k}$ is a complex of $A$-modules in positive characteristic). For each degree $i$, $\gamma_A$ thus defined is an $A$-linear map. These local maps patch together and give rise to a map of sheaves

$$(1.2.3) \quad \gamma_X : \Omega^i_X \rightarrow H^i(F_X,\Omega^{i+1}_X)$$

which is $O_X$-linear. When $X$ is smooth of dimension $d$, $\gamma_X$ is a isomorphism of $O_X$-modules, which is called the (absolute) Cartier isomorphism. See [BK05, 1.3.4] for a proof (note that although the authors there assumed the base field to be algebraically closed, the proof of this theorem works for any perfect field $k$ of positive characteristic).

This can be generalized to the de Rham-Witt case.

**Lemma 1.3** (cf. [Kat86a, 4.1.3]). Denote by $W_n \Omega^i_X$ the abelian sheaf $F(W_{n+1} \Omega^i_X)$ regarded as a $W_n O_X$-submodule of $(W_n F_X)_* W_n \Omega^i_X$. When $X$ is smooth of dimension $d$, the map

$$ F : W_{n} \Omega^{d}_{X} \rightarrow W_n \Omega^{d}_{X}/dV^{n-1} \Omega^{d-1}_{X}$$

induced by Frobenius $F : W_{n+1} \Omega^i_X \rightarrow R_*(W_n F_X)_* W_n \Omega^i_X$ is an isomorphism of $W_n O_X$-modules.

In particular, when $i = d$,

$$ F : W_{n} \Omega^{d}_{X} \rightarrow (W_n F_X)_* W_n \Omega^d_X/dV^{n-1} \Omega^{d-1}_X$$

is an isomorphism of $W_n O_X$-modules.

**Proof.** Since

$$ Ker(R : W_{n+1} \Omega^i \rightarrow W_n \Omega^i) = V^n \Omega^i + dV^n \Omega^{i-1}, $$

$$ F V^n \Omega^i = 0 \text{ and } F dV^n \Omega^{i-1} = dV^{n-1} \Omega^{i-1}, \quad F : W_{n+1} \Omega^i \rightarrow W_n \Omega^i \text{ reduces to}$$

$$ F : W_{n} \Omega^{i} \rightarrow W_n \Omega^i/dV^{n-1}. $$

Surjectivity is clear. We show injectivity. Suppose $x \in W_{n+1} \Omega^i, y \in \Omega^{i-1}$, such that $F(x) = dV^n y$. Then $F(x - dV^ny) = 0$, which implies by [[Ill79, I (3.21.1.2)]] that $x - dV^n y \in V^n \Omega^i$.

The second claim follows from the fact that $F : W_{n+1} \Omega^d \rightarrow R_*(W_n F_X)_* W_n \Omega^d$ is surjective on top degree $d$ [[Ill79, I (3.21.1.1)]] and therefore $W_n \Omega^d = (W_n F_X)_* W_n \Omega^d$ as $W_n O_X$-modules. \qed

**Definition 1.4** (absolute Cartier operator). Let $X$ be a smooth scheme of dimension $d$ over $k$.

1. The composition

$$(1.2.4) \quad C := C_X : Z^i(F_X,\Omega^i_X) \rightarrow H^i(F_X,\Omega^{i+1}_X) \xrightarrow{(\gamma_X)} \Omega^i_X$$

(with $Z^i(F_X,\Omega^i_X) := Ker(F_X,\Omega^i_X \delta \rightarrow F_X,\Omega^{i+1}_X)$)

is called the (absolute) Cartier operator of degree $i$, denoted by $C$ or $C_X$.

2. (cf. [Kat86a, 4.1.2, 4.1.4]) More generally, for $n \geq 1$, define the (absolute) Cartier operator

$$ C_n := C_{n,X} \text{ of level } n \text{ to be the composite}$$

$$(1.2.5) \quad C_n : W_n \Omega^i_X \rightarrow W_n \Omega^i_X/dV^{n-1} \Omega^{i-1}_X \xrightarrow{\scriptscriptstyle F^{-1}} W_n \Omega^i_X,$$
Remark 1.5.  
(1) According to the explicit formula for $F$, we have $C = C_1$ [Il79, I 3.3]. For this reason we will simply write $C$ for $C_n$ sometimes.
(2) $C_n$ (for all $n$) are compatible with étale pullbacks. Actually any de Rham-Witt system (e.g. $(W_n^\bullet \Omega^n_X, F, V, R, p, d)$) is compatible with étale base change [CR12, 1.3.2].
(3) The $n$-th power of Frobenius $F$ induces a map
\[ F^n : W_n \Omega^n_X \xrightarrow{\sim} H^n((W_n F_X)^n W_n \Omega^n_X), \]
which is the same as [IR83, III (1.4.1)].
(4) Notice that on Spec $W_n k$, $C_n : W_n k \to W_n k$ is simply the map $(W_n F_k)^{-1}$, because $F : W_{n+1} k \to W_n k$ equals $R \circ W_{n+1} F_k$ in characteristic $p$.
(5) We sometimes omit "$(W_n F_X)^n"$ in the source. But one should always keep that in mind and be careful with the module structure.

Remark 1.6. Before we move on, we state a remark on étale schemes over $W_n X$.

(1) Notice that every étale $W_n X$-scheme is of the form $W_n g : W_n U \to W_n X$, where $g : U \to X$ is an étale $X$-scheme. In fact, there are two functors
\[ F : \{\text{étale } W_n X\text{-schemes}\} \rightleftarrows \{\text{étale } X\text{-schemes}\} : G \]
\[ V \mapsto V \times_{W_n X} X \]
\[ W_n U \leftrightarrow U \]
The functor $F$ is a categorical equivalence according to [EGAIV-4, Ch. IV, 18.1.2]. The functor $G$ is well-defined (i.e. produces étale $W_n X$-schemes) and is a right inverse of $F$ by [Hes15, Thm. 1.25]. We want to show that there is a natural isomorphism $GF \simeq id$, and this is the consequence of the following purely categorical statement: If $F : A \to B$ and $G : B \to A$ are two functors satisfying both $F$ being a categorical equivalence and $FG \simeq id$, then $G$ is a quasi-inverse of $F$, i.e., there exists a canonical natural isomorphism $GF \simeq id$. We leave this as an easy exercise for the reader.

(2) The square
\[
\begin{array}{ccc}
W_n U & \xrightarrow{W_n F_U} & W_n U \\
\downarrow W_n g & & \downarrow W_n g \\
W_n X & \xrightarrow{W_n F_X} & W_n X.
\end{array}
\]
is a cartesian square. This is because for any étale map $g : U \to X$, the relative Frobenius $F_{U/X}$ is an isomorphism by [Fu15, 10.3.1]. Thus $W_n F_{U/X}$ is an also isomorphism and the claim follows.

We shall now state the main result in this subsection, which seems to be an old folklore (cf. proof of [Kat87, 3.4]). To eliminate possible sign inconsistency of the Cartier operator with the Grothendieck trace map calculated via residue symbols [Con00, Appendix A], we reproduce the proof by explicit calculations (see Section 1.2.2-Section 1.2.3). And at the same time, this result justifies our notation for $C'$: The classical Cartier operator $C$ is simply the $(-d)$-th cohomology of our $C'$ in the smooth case.

Theorem 1.7 (Compatibility of $C'$ with $C$). Suppose that $X$ is a smooth scheme of dimension $d$ over a perfect field $k$ of characteristic $p > 0$. Then the top degree classical Cartier operator
\[ C : (W_n F_X)^d \Omega^d_X/k \to W_n \Omega^d_X/k \]
as defined in Definition 1.4, agrees with the $(-d)$-th cohomology of the Cartier operator for residual complexes
\[ C' : (W_n F_X)^d \Omega^d_X/k \to W_n \Omega^d_X/k \]
as defined in (1.1.3) via Ekedahl’s quasi-isomorphism Proposition 1.1.

Proof. The Cartier operator is stable under étale base change, i.e., for any étale morphism $W_n g : W_n X \to W_n Y$ (which must be of this form according to Remark 1.6(1)), we have
\[ C_X \simeq (W_n g)^* C_Y : (W_n F_X)^d \Omega^d_X \to W_n \Omega^d_X. \]
We claim that the map $C'$ defined in (1.1.3) is also compatible with étale base change. That is, whenever we have an étale morphism $W_n g : W_n X \to W_n Y$, there is a canonical isomorphism

$$C' \simeq (W_n g)^* C' : (W_n F_X)_* K_{n,X} \to K_{n,Y}.$$ 

First of all, the Grothendieck trace map $\text{Tr}_{W_n F_X}$ for residual complexes is compatible with étale base change by [Har66, VI.5.6], i.e.,

$$\text{Tr}_{W_n F_X} \simeq g^* \text{Tr}_{W_n F_Y} : (W_n F_X)_* (W_n F_Y) \otimes K_{n,X} \to K_{n,Y}.$$ 

Secondly, because of the cartesian square in Remark 1.6(2) and the flat base change theorem

$$(W_n g)^* (W_n F_X)_* \simeq (W_n F_X)^* (W_n g)_*,$$

we are reduced to show that (1.1.2) is compatible with étale base change. And this is true, because we have

$$(W_n g)^* \simeq (W_n g)^\wedge$$

by [Har66, VI, 3.1 and 5.3], and the compatibility of $(-)\wedge$ with composition by [Con00, (3.2.3)]. This finishes the claim.

Note that the question is local on $W_n X$. Thus to prove the statement for smooth $k$-schemes $X$, using the compatibility of $C$ and $C'$ with respect to étale base change, it suffices to prove for $X = \mathbb{A}_k^d$. That is, we need to check that the expression given in Lemma 1.14 for $C'$ agrees with the expression for $C$ given in Lemma 1.10. This is apparent. 

1.2.2. Proof of Theorem 1.7: $C$ for the top Witt differentials on the affine space. Let $k$ be a perfect field of positive characteristic $p$. The aim of this subsection is to provide the formula for the Cartier operator on the top degree de Rham-Witt sheaf over the affine space (Lemma 1.10). But before this, we first show a lemma which will be used in the calculation of Lemma 1.10.

**Lemma 1.8** (cf. [Kat86b, 4.1.2]). Let $X$ be a smooth $k$-scheme. Then

$$V = p \circ C_n : R_n W_n \Omega^i_X \to W_n^{i+1} \Omega^i_X,$$

where $W_n \Omega^i_X$ denotes the abelian sheaf $F(W_n^{i+1} \Omega^i_X)$ regarded as a $W_n \mathcal{O}_X$-submodule of $(W_n F_X)_* W_n^{i+1} \Omega^i_X$. 

**Proof.** Consider the following diagram

\[\begin{array}{ccc}
W_n^{i+1} \Omega^i_X & \xrightarrow{F} & W_n \Omega^i_X \\
\downarrow{R} & & \downarrow{p} \\
W_n \Omega^i_X & \xrightarrow{C_n} & W_n^{i+1} \Omega^i_X.
\end{array}\]

Notice that $\overline{F} : W_n \Omega^i \to W_n \Omega^i / dV^{n-1} \Omega^{-1}$ is an isomorphism by Lemma 1.3, and therefore we can take the inverse. All the small parts commute by definition (among these one notices that the top part commutes because $X$ is of characteristic $p$), except the triangle on the right. Moreover one has the outer diagram commutes, due to the definition of $p$ [Ill79, I 3.4]. Since $F : W_n^{i+1} \Omega^i_X \to W_n \Omega^i_X$ is surjective, commutativity of the right triangle follows from the known commutativities. 

**Notation 1.9.** When we write an element in $W_n \Omega^i_X$ in terms of a product with respect to an totally ordered index set, we make the following assumptions: when an index set is empty, the respective factor of the product does not occur; when an index set is non-empty, the factors of the product are ordered such that the indices are increasing. With these assumptions we avoid any confusion concerning signs.

**Lemma 1.10** ($C_n$ on $\mathbb{A}_k^d$). Let $X = \mathbb{A}_k^d$. Then the Cartier operator (cf. Definition 1.4)

$$C := C_n : W_n \Omega^i_X \to W_n \Omega^i_X$$

is given by the following formula:

$$C = \left( \prod_{\alpha \in I, \alpha \in I} [X^{j_{i-1}}_i n d[X_i] n] \cdot \left( \prod_{\beta \in I, \beta \neq n-1} dV^{n-1} ([X^{j_{i-1}}_i n]_{n-1}) \right) \right) \cdot \left( \prod_{\gamma \in I, \gamma \neq n-1} dV^{n-1} ([X^{j_{i-1}}_i n]_{n-1}) \right)$$
\[ (W_n F_k)^{-1}(\alpha) \left( \prod_{i \in I, \alpha_i(j_i) \geq 1} [X_n^{i_j/p-1}]_n d[X_i]_n \right) \cdot \left( \prod_{i \in I, \alpha_i(j_i) = 0} \frac{1}{j_i} dV([X_i^{i_j}]_{n-1}) \right) \cdot \left( \prod_{i \in I, \alpha_i(j_i) \neq n-1} dV^{s+1}([X_i^{i_j}]_{n-1-s}) \right) \cdot \left( \prod_{i \in I, \alpha_i(j_i) = n-1} 0 \right), \]

where \( \alpha \in W_n k \). As for the sign of the product we follow Notation 1.9.

Proof. Write \( X = \{X_1, \ldots, X_{d-1}\} \) (empty when \( d = 1 \)) and \( S = X_d \). According to [HM04, (4.2.1)], any element in \( W_n \Omega^d_{k[X]} \) is uniquely written as

\[(1.2.7) \sum_{j \geq 1} b_{0,j}^{(n)} [S^{j-1}]_n d[S]_n + \sum_{s=1}^{n-1} \sum_{p \in \ell} dV^{s}(b_{s,j}^{(n-s)}[S]_{n-s}), \]

where \( b_{0,j}^{(n)} \in W_n \Omega^{d-1}_{k[X]} \), and for \( s \in [1, n-1] \), \( b_{s,j}^{(n-s)} \in W_{n-s} \Omega^{d-1}_{k[X]} \). (Here we have used \( W_n \Omega^d_{k[X]} = 0 \) and \( W_{n-s} \Omega^{d}_{k[X]} = 0 \).)

Now compute

\[(1.2.8) F : W_{n+1} \Omega^d_{k[X], S} \to W_n \Omega^d_{k[X], S}, \]

\[b_{0,j}^{(n+1)}[S^{j-1}]_{n+1} d[S]_{n+1} \mapsto F(b_{0,j}^{(n+1)}[S^{j-1}]_{n} d[S]_{n}); \]

\[(1.2.9) V : W_n \Omega^d_{k[X], S} \to W_{n-s} \Omega^d_{k[X], S}, \]

\[b_{0,j}^{(n)} [S^{j-1}]_{n} d[S]_{n} \mapsto (-1)^{d-1} \frac{1}{j} dV(b_{0,j}^{(n)} [S^i]_{n}) \text{ when } v_p(j) = 0. \]

In the last equation we used \( dV_{b_{0,j}^{(n)}} \in W_n \Omega^d_{k[X]} = 0 \).

Therefore, according to

1. \( p = p \circ R \) where \( p \) is injective, by [HIl79, I 3.4],
2. \( V = \overline{p} \circ C_n \), by Lemma 1.8, and
3. \( C_n \circ \overline{F} = R \) (because of (1)(2)),
4. \( F : W_{n+1} \Omega^d_{k[X], S} \to W_n \Omega^d_{k[X], S} \) is surjective,

one gets

\[(1.2.11) C_n : W_n \Omega^d_{k[X], S} \to W_n \Omega^d_{k[X], S}, \]

\[b_{0,j}^{(n)} [S^{j-1}]_{n} d[S]_{n} \mapsto \begin{cases} C_n(b_{0,j}^{(n)}[S^{j/p-1}]_{n} d[S]_{n}, & v_p(j) \neq 0; \quad \text{by (1.2.8)} \\ (\frac{(-1)^{d-1}}{j}) dV(R(b_{0,j}^{(n)}))[S^i]_{n-1}, & v_p(j) = 0. \quad \text{by (1.2.10)} \end{cases} \]

\[dV^{s}(b_{s,j}^{(n-s)}[S]_{n-s}) \mapsto \begin{cases} dV^{s+1}(R(b_{s,j}^{(n-s)}))[S^{i}]_{n-s-1}, & 1 \leq s \leq n-2; \quad \text{by (1.2.9)} \\ 0, & s = n-1. \quad \text{by } C_n = \overline{F}^{-1} \circ pr \end{cases} \]

Note that \( C_n(b_{0,j}^{(n)}) \) is computed via the induction on \( d \): when \( d = 1 \),

\[C_n(b_{0,j}^{(n)}) = (W_n F_k)^{-1}(b_{0,j}^{(n)}) \in W_n k \]

because \( F = R \circ W_n F_k : W_n k \to W_{n-1} k \) (note that \( char k = p \)).

Since \( b_{0,j}^{(n)} \in W_n \Omega^{d-1}_{k[X]} \) could also be written in expression (1.2.7), we could further write (1.2.11) out. That is to say, every element in \( W_n \Omega^d_{k[X]} \) is uniquely written as a sum of expressions of the form

\[(1.2.12) \alpha \left( \prod_{i \in I} [X_i^{i_j}]_n d[X_i]_n \right) \left( \prod_{i \in [1, d] \setminus I} dV^{s_i}([X_i^{i_j}]_{n-s_i}) \right), \]

where \( \alpha \in W_n k, I \subset [1, d] \) an index subset (\( I \) is the set of indices taken the form \( [X_i^{i_j}]_n d[X_i]_n \) and the rest indices takes the form \( dV^{s_i}([X_i^{i_j}]_{n-s_i}) \)), and

\[\{j_i\}_{i \in [1, d]}, \quad \{s_i\}_{i \in [1, d] \setminus I}\]

some integers, satisfying

- \( j_i \geq 1 \), when \( i \in I \), and
1.2.1.2

\[ \text{Lemma 1.11.} \]

The aim of Section 1.2.3 is to calculate \( C' \) for top de Rham-Witt sheaves on the affine space (Lemma 1.14). To do this, one needs to first calculate the trace map of the canonical lift of the absolute Frobenius.

1.2.3.1. Trace map of the canonical lift \( \tilde{F}_X \) of absolute Frobenius \( F_X \). Let \( k \) be a perfect field of positive characteristic \( p \). Let \( X = A_d^d \), and let \( \tilde{X} := \text{Spec } W_n(k)[X_1, \ldots, X_d] \) be the canonical smooth lift of \( X \) over \( W_n(k) \). To make explicit the module structures, we distinguish the source and the target of the absolute Frobenius of Spec \( k \) and write it as

\[ F_k : \text{Spec } k_1 \rightarrow \text{Spec } k_2 \]

Similarly, write the absolute Frobenius on \( X \) as

\[ F_X : X = \text{Spec } k_1[X_1, \ldots, X_d] \rightarrow Y = \text{Spec } k_2[X_1, \ldots, X_d]. \]

There is a canonical lift \( \tilde{F}_X \) of \( F_X \) over \( \tilde{X} \), and we write it as

\[ \tilde{F}_X : \tilde{X} = \text{Spec } W_n(k_1)[X_1, \ldots, X_d] \rightarrow \tilde{Y} := \text{Spec } W_n(k_2)[Y_1, \ldots, Y_d]. \]

\( \tilde{F}_X \) is given by

\[ \tilde{F}_X^a : \Gamma(\tilde{Y}, \mathcal{O}_Y) = W_n(k_2)[Y_1, \ldots, Y_d] \rightarrow W_n(k_1)[X_1, \ldots, X_d] = \Gamma(\tilde{X}, \mathcal{O}_{\tilde{X}}), \]

\[ W_n k_2 \supseteq \alpha \mapsto W_n(F_k)(\alpha), \]

\[ Y_i \mapsto X_i^p. \]

on the level of global sections. Clearly \( \tilde{F}_X \) restricts to \( F_X \) on \( X \). Let

\[ \pi_X : X \rightarrow \text{Spec } k_1, \quad \pi_Y : Y \rightarrow \text{Spec } k_2, \quad \pi_{\tilde{X}} : \tilde{X} \rightarrow \text{Spec } k_1, \quad \pi_{\tilde{Y}} : \tilde{Y} \rightarrow \text{Spec } k_2 \]

be the structure maps. The composition \( \tilde{F}_X \circ \pi_{\tilde{Y}} : \tilde{X} \rightarrow \text{Spec } W_n k_2 \) gives \( \tilde{X} \) a \( W_n k_2 \)-scheme structure, and the map \( \tilde{F}_X \) is then a map of \( W_n k_2 \)-schemes. Therefore the trace map

\[ \text{Tr}_{\tilde{F}_X} : \tilde{F}_X^a \circ \tilde{F}_X \circ \pi_{\tilde{X}} : \tilde{X} \rightarrow \text{Spec } K_{\tilde{Y}} \]

makes sense. Consider the following map of complexes

\[ \tilde{F}_X^a \circ \tilde{F}_X \circ \pi_{\tilde{X}} \Rightarrow \tilde{F}_X^a \circ \pi_{\tilde{Y}} : \tilde{X} \rightarrow \text{Spec } W_n k_1 \rightarrow \text{Spec } W_n k_2 \]

Taking the \((-d)\)-th cohomology, it induces a map

\[ \tilde{F}_X^a \circ \pi_{\tilde{X}} : \Omega^d_{\tilde{X}/W_n k_1} \rightarrow \Omega^d_{\tilde{Y}/W_n k_2} \]

In the following lemma we will compute this map.

**Lemma 1.11.** The notations are the same as above. The map (1.2.13) has the following expression:

\[ (1.2.14) \quad \Omega^d_{\tilde{X}/W_n k_1}, (1.2.13) \rightarrow \Omega^d_{\tilde{Y}/W_n k_2} \]

\[ \alpha(X^{\lambda+pp}dX) \Rightarrow \begin{cases} (W_n F_k)^{-1}(\alpha)Y^\mu dY, & \text{when } \lambda_i = p - 1 \text{ for all } i; \\ 0, & \text{when } \lambda_i \neq p - 1 \text{ for some } i. \end{cases} \]
Proof. Construct a regular immersion of $\tilde{X}$ into $\tilde{P} = \mathbb{A}^d_Y$ associated to the following homomorphism of rings:

$$\Gamma(\tilde{P}, \mathcal{O}_{\tilde{P}}) = W_n(k_2)[Y_1, \ldots, Y_d, T_1, \ldots, T_d] \to W_n(k_1)[X_1, \ldots, X_d] = \Gamma(\tilde{X}, \mathcal{O}_{\tilde{X}}),$$

with $\alpha \mapsto (W_nF_k)(\alpha), \quad \alpha \in W_n(k_2),$ 

$Y_i \mapsto X_i^p, \quad i = 1, \ldots, d,$ 

$T_i \mapsto X_i, \quad i = 1, \ldots, d.$

Its kernel is

$$I = (T_1^p - Y_1, \ldots, T_d^p - Y_d).$$

Denote

$$t_i = T_i^p - Y_i, i = 1, \ldots, d.$$ 

Obviously the $t_i$’s form a regular sequence in $\Gamma(\tilde{P}, \mathcal{O}_{\tilde{P}}).$ Denote by $i$ the associated closed immersion. Then one has a factorization of $\tilde{F}_{\tilde{X}}$:

$$(1.2.15) \quad \tilde{X} = \text{Spec } W_n(k_1)[X_1, \ldots, X_d] \overset{1}{\longrightarrow} \tilde{P} = \text{Spec } W_n(k_2)[Y_1, \ldots, Y_d, T_1, \ldots, T_d] \overset{i}{\longrightarrow} \tilde{Y} = \text{Spec } W_n(k_2)[Y_1, \ldots, Y_d].$$

Regarding $\tilde{X}$ as a $W_nk_2$-scheme via the composite map $\tilde{F}_{\tilde{X}} \circ \pi_{\tilde{Y}},$ the diagram (1.2.15) is then a diagram in the category of $W_nk_2$-schemes.

A general element in $\Gamma(\tilde{X}, \Omega^d_{\tilde{X}/W_nk_1})$ is a sum of expressions of the form

$$(1.2.16) \quad \alpha X^{\lambda + p\mu} dX, \quad \alpha \in W_nk_1, \lambda \in [0, p - 1]^d, \mu \in \mathbb{N}^d.$$

Here $\lambda = \{\lambda_1, \ldots, \lambda_d\},$ $\mu = \{\mu_1, \ldots, \mu_d\}$ are multi-indices, and $X^{\lambda} := x_1^{\lambda_1} \cdots x_d^{\lambda_d}$ (similar for $Y^\mu,$ $X^{\lambda + p\mu},$ etc.). $dX := dx_1 \cdots dx_d$ (similar for $dT,$ etc.). The element (1.2.16) in $\Gamma(\tilde{X}, \Omega^d_{\tilde{X}/W_nk_1})$ corresponds to

$$(1.2.17) \quad (W_nF_k)^{-1}(\alpha)X^{\lambda + p\mu} dX, \quad \alpha \in W_nk_2, \lambda \in [0, p - 1]^d, \mu \in \mathbb{N}^d,$$

in $\Gamma(\tilde{X}, \Omega^d_{\tilde{X}/W_nk_2})$ under $(-d)$-th cohomology of the map $\tilde{F}_{\tilde{X}} \circ \pi_{\tilde{Y}}$ (1.1.1), and

$$(W_nF_k)^{-1}(\alpha)T^\lambda Y^\mu dT, \quad \alpha \in W_nk_2, \lambda \in [0, p - 1]^d, \mu \in \mathbb{N}^d$$

is a lift of (1.2.17) to $\Gamma(\tilde{P}, \Omega^d_{\tilde{P}/W_nk_2}).$ Write

$$\beta := dt_1 \wedge \cdots \wedge dt_d \wedge (W_nF_k)^{-1}(\alpha)T^\lambda Y^\mu dT$$

$$= (-1)^d Y_1 \wedge \cdots \wedge Y_d \wedge (W_nF_k)^{-1}(\alpha)T^\lambda Y^\mu dT$$

in $\Gamma(\tilde{P}, \omega_{\tilde{P}/W_nk_2})$ ($\omega_{\tilde{P}/W_nk_2}$ denotes the dualizing sheaf with respect to the smooth morphism $\tilde{P} \to W_nk_2$). One can write out the image of $\beta$ under map [Con00, p.30 (a)], i.e.,

$$\omega_{\tilde{P}/W_nk_2} \cong \omega_{\tilde{P}/\tilde{Y}} \otimes_{\mathcal{O}_{\tilde{P}}} \pi_{\tilde{Y}}^* \omega_{\tilde{Y}/W_nk_2},$$

$$\beta \mapsto (-1)^{d(3d+1)/2}(W_nF_k)^{-1}(\alpha)T^\lambda dT \otimes \pi_{\tilde{Y}}^* Y^\mu dY.$$ 

where $\omega_{\tilde{P}/\tilde{Y}}$ and $\omega_{\tilde{Y}/W_nk_2}$ denote the dualizing sheaf with respect to the smooth morphisms $\pi : \tilde{P} \to \tilde{Y}$ and $\tilde{Y} \to W_nk_2$. It’s easily seen that $\tilde{F}_{\tilde{X}}$ is a finite flat morphism between smooth $W_nk_2$-schemes. Applying [CR11, Lemma A.3.3], one has

$$\text{Tr}_{\tilde{F}_{\tilde{X}}}((W_nF_k)^{-1}(\alpha)X^{\lambda + p\mu} dX) = (W_nF_k)^{-1}(\alpha) \text{Res}_{\tilde{P}/\tilde{Y}} \left[ T^\lambda dT \right] Y^\mu dY,$$

$$\text{where } \text{Res}_{\tilde{P}/\tilde{Y}} \left[ T^\lambda dT \right] \in \Gamma(\tilde{Y}, \mathcal{O}_{\tilde{Y}}) \text{ is the residue symbol defined in } [\text{Con00}, (A.1.4)], \text{ and } \text{Tr}_{\tilde{F}_{\tilde{X}}} \text{ is the trace map on top differentials of the } W_nk_2\text{-morphism } \tilde{F}_{\tilde{X}} [\text{Con00}, (2.7.36)].$$

We consider the following cases (in the following (RN) with $N \in [1, 10]$ being a positive integer means the corresponding property from [Con00, §A]):
When \((\lambda_1, \ldots, \lambda_n) \neq (p-1, \ldots, p-1)\), \(T^{\lambda_d} dT = d\eta\) for some \(\eta \in \Omega^{\lambda_d}_{\tilde{F}/Y}\). Suppose without loss of generality that \(\lambda_1 \neq p-1\). Then we can take
\[
\eta = \frac{1}{\lambda_1 + 1} T^{\lambda_1+1} T^{\lambda_2} \cdots T^{\lambda_d} dT_1 \cdots dT_d.
\]
Noticing that
\[
dt_i = d(T_i^p - Y_i) = pT_i^{p-1} dT_i
\]
in \(\Omega_{\tilde{F}/Y}\), and that \(\lambda_1 + mp + 1 (m \in \mathbb{Z}_{\geq 0})\) is not divisible by \(p\) when \(\lambda_1 + 1 = \text{so}\). Now we calculate
\[
\begin{align*}
\text{Res}_{\tilde{F}/Y} \left[ \frac{T^{\lambda_1} dT}{t_1, \ldots, t_n} \right] &= \frac{p}{\lambda_1 + 1} \text{Res}_{\tilde{F}/Y} \left[ \frac{d(T_1^{\lambda_1+1} T^{\lambda_2} \cdots T^{\lambda_d} dT_1 \cdots dT_d)}{t_1^2, t_2^2, \ldots, t_n^2} \right] \\
&= \frac{p}{\lambda_1 + 1} \text{Res}_{\tilde{F}/Y} \left[ \frac{d(T_1^{\lambda_1+1} T^{\lambda_2} \cdots T^{\lambda_d} dT_1 \cdots dT_d)}{t_1^2, t_2^2, \ldots, t_n^2} \right] \\
&= \frac{2p^2}{\lambda_1 + 1} \text{Res}_{\tilde{F}/Y} \left[ \frac{d(T_1^{\lambda_1+2p+1} T^{\lambda_2} \cdots T^{\lambda_d} dT_1 \cdots dT_d)}{t_1^2, t_2^2, \ldots, t_n^2} \right] \\
&= \frac{2p^2}{\lambda_1 + 1} \text{Res}_{\tilde{F}/Y} \left[ \frac{d(T_1^{\lambda_1+2p+1} T^{\lambda_2} \cdots T^{\lambda_d} dT_1 \cdots dT_d)}{t_1^2, t_2^2, \ldots, t_n^2} \right] \\
&= \frac{2p^2}{\lambda_1 + 1} \text{Res}_{\tilde{F}/Y} \left[ \frac{d(T_1^{\lambda_1+3p} T^{\lambda_2} \cdots T^{\lambda_d} dT_1 \cdots dT_d)}{t_1^2, t_2^2, \ldots, t_n^2} \right] \\
&= \cdots \\
&= \frac{\prod_{p=1}^{n} (\lambda_1 + 1)p \cdot p^n}{\prod_{p=1}^{n-1} (\lambda_1 + 1)p} \text{Res}_{\tilde{F}/Y} \left[ \frac{T_1^{\lambda_1+np} T^{\lambda_2} \cdots T^{\lambda_d} dT_1 \cdots dT_d}{t_1^2, t_2^2, \ldots, t_n^2} \right] \\
&= 0.
\end{align*}
\]
The last step is because \(p^n = 0 \in \Gamma(Y, \mathcal{O}_Y)\).

When \((\lambda_1, \ldots, \lambda_n) = (p-1, \ldots, p-1)\), consider
\[
X' := \text{Spec } \frac{\mathbb{Z}[Y'_1, \ldots, Y'_d, T'_1, \ldots, T'_d]}{(T'_1 - Y'_1, \ldots, T'_d - Y'_d)} \hookrightarrow \text{Spec } \mathbb{Z}[Y_1, \ldots, Y_d, T_1, \ldots, T_d] =: P'
\]
\[
f \quad | \quad \text{Spec } \mathbb{Z}[Y_1, \ldots, Y_d] =: Y'.
\]
f is given by \(f(Y'_i) = Y'_i = T_i^{p^d} \) in \(\Gamma(X', \mathcal{O}_{X'})\). This is a finite locally free morphism of rank \(p^d\). Consider the map
\[
h : \Gamma(Y', \mathcal{O}_{Y'}) = \mathbb{Z}[Y'_1, \ldots, Y'_d] \to W_n(k_2)[Y_1, \ldots, Y_d] = \Gamma(Y, \mathcal{O}_Y),
\]
\[Y'_i \mapsto Y_i \quad \text{for all } i,
\]
that relates the two diagrams (1.2.18) and (1.2.15). In \(\Gamma(Y', \mathcal{O}_{Y'})\), we have
\[
p^d \cdot \text{Res}_{P'/Y'} \left[ \frac{T_1^{p-1} \cdots T_{d-1}^{p-1} dT_1^{p-1} \cdots dT_d^{p-1}}{T_1^{p-1} - Y_1^{p-1}, \ldots, T_d^{p-1} - Y_d^{p-1}} \right] = \text{Res}_{P'/Y'} \left[ \frac{d(T_1^{p-1} - Y_1^{p-1}) \cdots d(T_d^{p-1} - Y_d^{p-1})}{T_1^{p-1} - Y_1^{p-1}, \ldots, T_d^{p-1} - Y_d^{p-1}} \right] \\
= \text{Tr}_{Y'/Y} (1) \\
= p^d.
\]
The notation \(\text{Tr}_{X'/Y'}\) denotes the classical trace map associated to the finite locally free ring extension \(\Gamma(Y', \mathcal{O}_{Y'}) \to \Gamma(X', \mathcal{O}_{X'})\). As for the last equality, \(\text{Tr}_{X'/Y'} (1) = p^d\) because \(f\) is \(\) a finite locally free map of rank \(p^d\). Since \(p^d\) is a non-zerodivisor in \(\Gamma(Y', \mathcal{O}_{Y'})\), one deduces
\[
\text{Res}_{P'/Y'} \left[ \frac{T_1^{p-1} \cdots T_{d-1}^{p-1} dT_1^{p-1} \cdots dT_d^{p-1}}{T_1^{p-1} - Y_1^{p-1}, \ldots, T_d^{p-1} - Y_d^{p-1}} \right] = 1.
\]
Set
\[
T^{p-1} = T_1^{p-1} \cdots T_d^{p-1},
\]
which is the canonical lift of \( X^\lambda \) via the map \( i : \tilde{X} \hookrightarrow \tilde{Y} \) in our current case. Pulling back to \( \Gamma ( \tilde{Y}, \mathcal{O}_{\tilde{Y}} ) \) via \( h \), one has

\[
\text{Res}_{\tilde{P}/\tilde{Y}} \left[ T^{p-1} dT \right]_{t_1, \ldots , t_d} \quad ( \text{R}) \quad h^* \text{Res}_{P'/Y'} \left[ T_1^{p-1} \ldots T_d^{p-1} dT_1' \ldots dT_d' \right] = 1.
\]

Altogether, we know that the map (1.2.13) takes the following expression

\[
\alpha X^{\lambda + \ell} dX \mapsto \begin{cases} 
(W_n F_k)^{-1}(\alpha) Y^p dY, & \text{when } \lambda_i = p-1 \text{ for all } i; \\
0, & \text{when } \lambda_i \neq p-1 \text{ for some } i.
\end{cases}
\]

\[\square\]

1.2.3.2. \( C' \) for top Witt differentials. Now we turn to the \( W_n \)-version. The aim of this subsection is to calculate \( C' \) for top Witt differentials on \( \mathbb{A}^d_k \) (Lemma 1.14).

Let \( f : X \to Y \) be a finite morphism between smooth, separated and equidimensional \( k \)-schemes of dimension \( d \). Same as before, we denote by \( \pi_X : X \to k \) and \( \pi_Y : Y \to k \) the respective structure maps. \( K_{n,X} := (W_n \pi_X)^{\dagger} W_n k, K_{n,Y} = (W_n \pi_Y)^{\dagger} W_n k \) are residual complexes on \( X \) and \( Y \). Then we define the trace map

\[
\text{Tr}_{W_n,f} : (W_n f)_* (W_n \Omega^d_X) \to W_n \Omega^d_Y
\]

to be the \((-d)\)-th cohomology map of the composition

\[
\text{Tr}_{W_n,f} : (W_n f)_* K_{n,X} \simeq \mathcal{H} \text{om}_{W_n \mathcal{O}_Y} ((W_n f)_* W_n \mathcal{O}_X, K_{n,Y}) \xrightarrow{\text{ev. at } 1} K_{n,Y}
\]

via Ekedahl’s isomorphism \( W_n \Omega^d_X \simeq \mathcal{H}^{-d}(K_{n,X}) \) Proposition 1.1.

Computation of the trace map is a local problem on \( Y \). Thus by possibly shrinking \( Y \) we could assume that \( Y \) and (therefore also \( X \)) is affine. In this case, there exist smooth affine \( W_n k \)-schemes \( \tilde{X} \) and \( \tilde{Y} \) which lift \( X \) and \( Y \). Denote the structure morphisms of \( \tilde{X}, \tilde{Y} \) by \( \pi_{\tilde{X}} \) and \( \pi_{\tilde{Y}} \), respectively. Then there exists a finite \( W_n k \)-morphism \( f : \tilde{X} \to \tilde{Y} \) lifting \( f : X \to Y \) by the formal smoothness property of \( \tilde{Y} \).

Consider the map of abelian sheaves [Eke84, I (2.3)]

\[
\varrho^*_Y : W_n \mathcal{O}_Y \xrightarrow{\varrho_Y} \mathcal{H}^{0}(\Omega^\bullet_{\tilde{Y}/W_n k}) \hookrightarrow \mathcal{O}_{\tilde{Y}},
\]

\[
\sum_{i=0}^{n-1} V_i([a_i]) \mapsto \tilde{a}_0^n + p \tilde{a}_1^{n-1} + \cdots + p^{n-1} \tilde{a}_{n-1},
\]

where \( a_i \in \mathcal{O}_Y \), and \( \tilde{a}_i \in \mathcal{O}_{\tilde{Y}} \) being arbitrary liftings of \( a_i \). The map \( \varrho_Y \) appearing above is the \( i = 0 \) case of the canonical isomorphism defined in [IR83, III. 1.5]

\[
\varrho_Y : W_n \Omega^d_Y \xrightarrow{\varrho_Y} \mathcal{H}^{i}(\Omega^\bullet_{\tilde{Y}/W_n k}).
\]

Note that the map \( \varrho^*_Y : W_n \mathcal{O}_Y \to \mathcal{O}_{\tilde{Y}} \) is a morphism of sheaves of rings, and it induces a finite morphism \( \varrho_Y : W_n Y \to \tilde{Y} \) (cf. [Eke84, I, paragraph after (2.4)]). Altogether we have the following commutative
diagram of schemes (cf. [Eke84, I. (2.4)])

Lemma 1.12. Set $K_X = \pi_X^* W_n k$, and $K_Y = \pi_Y^* W_n k$. The $(-d)$-th cohomology of the map $Tr_f : f_* K_X \to K_Y$ gives a map $f_* \Omega^d_X \to \Omega^d_Y$, which we again denote by $Tr_f$. Then by passing to quotients, this map $Tr_f$ induces a well-defined map

$$
\tau_f : H^d(f_* \Omega^d_X) \to H^d(\Omega^d_Y).
$$

Moreover, the map $\tau_f$ is compatible with $Tr_{W_n f}$ defined in (1.2.21):

$$(W_n f)_* W_n \Omega^d_X \xrightarrow{Tr_{W_n f}} W_n \Omega^d_Y$$

$$\sim \xrightarrow{\vartheta_Y} (\vartheta_Y)_* H^d(\Omega^d_X) \xrightarrow{(\vartheta_Y)_* \tau_f} (\vartheta_Y)_* H^d(\Omega^d_Y)$$

Proof. We do it the other way around, namely we define the map $\tau_f : H^d(f_* \Omega^d_X) \to H^d(\Omega^d_Y)$ via $Tr_{W_n f} : (W_n f)_* W_n \Omega^d_X \to W_n \Omega^d_Y$, and then show that this is the reduction of $Tr_f : f_* \Omega^d_X \to \Omega^d_Y$.

First of all, via isomorphisms $\vartheta_X, \vartheta_Y$, the map $Tr_{W_n f} : (W_n f)_* W_n \Omega^d_X \to W_n \Omega^d_Y$ defined in (1.2.21) induces a well-defined map $\tau_f : H^d(f_* \Omega^d_X) \to H^d(\Omega^d_Y)$. To show compatibility with $Tr_f$, one needs an observation of Ekedahl: Ekedahl observed that the composite

$$
t_Y : (\vartheta_Y)_* H^d(\Omega^d_X/W_n k)[d] \xrightarrow{\simeq} (\vartheta_Y)_* K_Y \simeq (\vartheta_Y)_* \pi_Y^* W_n k \xrightarrow{(\vartheta_Y)_* \pi_Y^{1,1}} H^d(\Omega^{d+1}_Y/W_n k) \xrightarrow{\simeq} (\vartheta_Y)_* \pi_Y^*(W_n F^n) W_n k \cong (\vartheta_Y)_* (\vartheta_Y)_* W_n \Omega^d_Y/W_n k \xrightarrow{Tr_{W_n Y}} K_n Y
$$

factors through $\gamma_Y : (\vartheta_Y)_* H^d(\Omega^d_X/W_n k)[d] \to K_n Y$ (cf. [Eke84, §1 (2.6)]). Then he defined the map $W_n \Omega^d_Y/W_n k[d] \to K_n Y$ to be the composite

$$(1.2.24) \quad s_Y : W_n \Omega^d_Y/W_n k \xrightarrow{\simeq} H^d(\Omega^d_X/W_n k)[d] \xrightarrow{\gamma_Y} K_n Y.$$
Now consider the following diagram of complexes of sheaves

\[
\begin{array}{cccccc}
(W_n f)_* \Omega_{nX}^d & \xrightarrow{\mathbf{Tr}_{W_n f}} & W_n \Omega_{nY}^d & \xrightarrow{s_Y} & W_{n+1} \Omega_{nY}^d \\
(W_n f)_* \Omega_{nX}^d & \xrightarrow{\mathbf{Tr}_{W_n f}} & W_n \Omega_{nY}^d & \xrightarrow{s_Y} & W_{n+1} \Omega_{nY}^d \\
(W_n f)_* \Omega_{nX}^d & \xrightarrow{\mathbf{Tr}_{W_n f}} & W_n \Omega_{nY}^d & \xrightarrow{s_Y} & W_{n+1} \Omega_{nY}^d \\
(W_n f)_* \Omega_{nX}^d & \xrightarrow{\mathbf{Tr}_{W_n f}} & W_n \Omega_{nY}^d & \xrightarrow{s_Y} & W_{n+1} \Omega_{nY}^d \\
(W_n f)_* \Omega_{nX}^d & \xrightarrow{\mathbf{Tr}_{W_n f}} & W_n \Omega_{nY}^d & \xrightarrow{s_Y} & W_{n+1} \Omega_{nY}^d \\
\end{array}
\]

The unlabeled arrows are given by the natural quotient maps. The front commutes by the definition of \( \tau_f \). The top commutes by the definition of \( \mathbf{Tr}_{W_1} \). The triangles in the right (resp. the left) side commute due to the definition of \( \tau_Y \) and \( s_Y \) (resp. \( \tau_X \) and \( s_X \)). The back square commutes, because the trace map \( \mathbf{Tr}_f \) is functorial with respect to maps residual complexes with the same associated filtration by \cite{Con00, 3.4.1.1}. We want to show that the bottom square commutes. To this end, it suffices to show \((\varphi_Y)_* \mathbf{Tr}_f : (W_1 f)_* \Omega_{1X}^d \xrightarrow{\mathbf{Tr}_{W_1 f}} (W_1 f)_* \Omega_{1Y}^d \) is compatible with \((\varphi_Y)_* \mathbf{Tr}_{W_1} : (W_1 f)_* \Omega_{1X}^d \xrightarrow{\mathbf{Tr}_{W_1}} (W_1 f)_* \Omega_{1Y}^d \) via \( \vartheta_X \) and \( \vartheta_Y \). Because the map \( \mathbf{Tr}_{W_1 f} : (W_1 f)_* \Omega_{1X}^d \rightarrow (W_1 f)_* \Omega_{1Y}^d \) is determined by the degree \(-d\) part of the map \( \mathbf{Tr}_{W_1 f} : (W_1 f)_* \Omega_{1X}^d \rightarrow (W_1 f)_* \Omega_{1Y}^d \) with \( \mathbf{Tr}_{W_1 f} : (W_1 f)_* \Omega_{1X}^d \rightarrow K_{nY} \) we are reduced to show compatibility of \((\varphi_Y)_* \mathbf{Tr}_f : (W_1 f)_* \Omega_{1X}^d \rightarrow (W_1 f)_* \Omega_{1Y}^d \) with \( \mathbf{Tr}_{W_1 f} : (W_1 f)_* \Omega_{1X}^d \rightarrow (W_1 f)_* \Omega_{1Y}^d \) via \( \varphi_Y \) and \( \varphi_Y^{-1} \). By commutativity of the two squares, this is reduced to the commutativity of the trace square on the back, which is known. Therefore the bottom square commutes as a result.

\( \tau_f \) is just a temporary notation for the lemma above. Later we will denote \( \tau_f \) by \( \mathbf{Tr}_f \).

Before we proceed to the main result of this subsection, we present the following lemma, which gives the explicit formula for \( \vartheta_Y \). We will use \( W_n \Omega_{nY/W_n k}^* \) to denote the relative de Rham-Witt complex defined by \cite{LZ04}.

**Lemma 1.13** ([BER12, 8.4(ii)]). Notations are the same as above. There is a commutative diagram

\[
\begin{array}{ccc}
W_{n+1} \Omega_{nY/W_n k}^d & \xrightarrow{F^n} & Z^q(\Omega_{nY/W_n k}^*) \\
W_n \Omega_{nY}^d & \xrightarrow{\varrho_Y} & \mathcal{H}^q(\Omega_{nY/W_n k}^*). \\
\end{array}
\]

In particular,

\[
\varrho_Y(\sum_{i=0}^{n-1} dV^i([a_i])) = \sum_{i=0}^{n-1} F^n dV^i([a_i]) = \tilde{a}_0^{n-1} d\tilde{a}_0 + \tilde{a}_1^{n-1} d\tilde{a}_1 + \cdots + \tilde{a}_{n-1}^{n-1} d\tilde{a}_{n-1}.
\]

**Proof.** One just need to check for \( q = 0 \): for higher \( q \), both \( \varrho_Y \) and \( F^n \) are generated by the \( q = 0 \) case as morphisms of differential graded algebras. Take \( \sum_{i=0}^{n-1} V^i([a_i]) ) \in W_n \Omega_Y^d \). Then \( \sum_{i=0}^{n-1} V^i([a_i]) ) \in W_{n+1} \Omega_Y^d \) is a lift. \( F^n(\sum_{i=0}^{n-1} V^i([a_i]) ) = \sum_{i=0}^{n} p^i F^n(\sum_{i=0}^{n-1} V^i([a_i]) ) = \sum_{i=0}^{n} p^i \tilde{a}_{n-1}^{n-1} \). We are done with the relation \( p^i \tilde{a}_{n-1}^{n-1} = 0 \) in \( \Omega_Y^d \). \( \square \)

**Lemma 1.14.** Let \( X = \mathbb{A}^d_k \). Let

\[
C' = C'_n : W_n \Omega_{nX}^d \rightarrow W_n \Omega_{nX}^d.
\]

be the map given by the \(-d\)-th cohomology of the level \( n \) Cartier operator for residual complexes (cf. (1.1.3)). Then \( C' \) is given by the following formula:

\[
C' \left( \prod_{i \in I, \delta(p(i)) \geq 1} [X_i^{h-1}]_n d[X_i]_n \right) = \prod_{i \in I, \delta(p(i)) = 0} [X_i^{h-1}]_n d[X_i]_n
\]
Consider the map \( W_n F_X : W_n X \to W_n X \) with \( X := A^d_{k[1]} \). It is not a map of \( W_n k \)-schemes a priori, but after labeling the source by \( W_n X := W_n A^d_{k[1]} \) and the target by \( W_n Y := W_n A^d_{k[2]} \), one can realize \( W_n F_X \) as a map of \( W_n k_2 \)-schemes (the \( W_n k_2 \)-scheme structure of \( W_n X \) is given by \( W_n \hat{F}_X \circ W_n \pi_Y \), where \( \pi_Y : Y \to k_2 \) denotes the structure morphism of the scheme \( Y \)). Write

\[
\hat{X} = A^d_{W_n k_1} = \text{Spec} W_n k_1[X_1, \ldots, X_d] \quad (\text{resp.} \quad \hat{Y} = A^d_{W_n k_2} = \text{Spec} W_n k_2[X_1, \ldots, X_d]),
\]

and take the canonical lift \( \hat{F}_X \) of \( F_X \) as in Lemma 1.11. Consider (1.2.25)

\[
(W_n F_X)_* W_n \Omega^d_{X/k_1} \cong (W_n F_X)_* W_n \Omega^d_{X/k_2} \xrightarrow{\text{Tr}_{W_n F_X}} W_n \Omega^d_{Y/k_2}
\]

The composite map of the top row is \( C' \) (cf. (1.1.3) and Ekedahl’s quasi-isomorphism Proposition 1.1). The composite of the bottom row is induced from \( \vartheta_Y \circ (1.2.13) \). The right side commutes due to Lemma 1.12. The left side commutes by naturality.

Given an index set \( I \subset [1, d] \) and integers \( \{j_i\}_{i \in [1, d]} \), \( \{s_i\}_{i \in [1, d]} \) satisfying

- \( j_i \geq 1 \) for all \( i \in I \), and
- \( v_p(j_i) = 0 \) and \( s_i [1, n - 1] \) when \( i \in [1, d] \setminus I \),

recall that a general element in \( W_n \Omega^d_{X/k_1} \) is the sum of expressions of the following form (cf. (1.2.12))

\[
\alpha \left( \prod_{i \in I} [X_i^{j_i - 1}] d[X_i] \right) \left( \prod_{i \notin I} [X_i^{j_i - 1}] d[X_i] \right),
\]

(1.2.26) where \( \alpha \in W_n k_1 \). One can also write this expression (1.2.26) in terms of finer index sets:

\[
\alpha \left( \prod_{i \in I, v_p(j_i) \geq 1} [X_i^{j_i - 1}] d[X_i] \right) \left( \prod_{i \notin I, v_p(j_i) = 0} [X_i^{j_i - 1}] d[X_i] \right)
\]

\[
\left( \prod_{i \notin I, s_i \neq 1} dV^{s_i}([X_i^{j_i - 1}] d[X_i]) \right) \left( \prod_{i \notin I, s_i = 1} dV^{s_i}([X_i^{j_i - 1}] d[X_i]) \right)
\]

where \( \alpha \in W_n k_1 \) (which might differ from the \( \alpha \) in (1.2.26) by a sign because we might have changed the order of the factors in the wedge product). As we explained after diagram (1.2.25), we can decompose \( C' \) in the following way:

\[
C' = \vartheta_Y^{-1} \circ (1.2.13) \circ \vartheta_X : W_n \Omega^d_{X/k_1} \to W_n \Omega^d_{Y/k_2}.
\]

According to the explicit formula (1.2.14) of the map (1.1.3), and the explicit formula for the maps \( \vartheta_X, \vartheta_Y \) (Lemma 1.13), one could perform the following calculations:

\[
C' \left( \prod_{i \in I, v_p(j_i) \geq 1} [X_i^{j_i - 1}] d[X_i] \right) \left( \prod_{i \notin I, v_p(j_i) = 0} [X_i^{j_i - 1}] d[X_i] \right)
\]

\[
\left( \prod_{i \notin I, s_i \neq 1} dV^{s_i}([X_i^{j_i - 1}] d[X_i]) \right) \left( \prod_{i \notin I, s_i = 1} dV^{s_i}([X_i^{j_i - 1}] d[X_i]) \right)
\]

\[
= (\vartheta_Y^{-1} \circ (1.2.13)) \left( W_n(F_k)^n (\alpha) \prod_{i \notin I, v_p(j_i) \geq 1} X_i^{p^{n-j_i - 1}} dX_i \right) \left( \prod_{i \in I, v_p(j_i) = 0} X_i^{p^{n-j_i - 1}} dX_i \right)
\]
\[ (\prod_{i \in \mathcal{I}, s_i \neq n-1} j_{i!}X^{p^{-s_i} j_i-1}dX_i) \left( \prod_{i \in \mathcal{I}, s_i = n-1} j_{i!}X^{p^{-s_i} j_i-1}dX_i \right) \]

\[ = \delta_{n-1}^{-1} \left( W_n(F_n)^{n-1}(\alpha) \left( \prod_{i \in \mathcal{I}, s_i \geq 1} \chi^{p^{-s_i} j_i-1}dX_i \right) \left( \prod_{i \in \mathcal{I}, s_i = 0} X_i^{p^{-s_i} j_i-1}dX_i \right) \right) \]

\[ = (W_nF_n)^{-1}(\alpha) \left( \prod_{i \in \mathcal{I}, s_i \geq 1} |X_i^{j_i/p-1}|_n d[X_i]_n \right) \left( \prod_{i \in \mathcal{I}, s_i = 0} 1 \right) \frac{dV([X_i^{j_i}]_{n-1})}{j_i} \]

\[ = \left( \prod_{i \in \mathcal{I}, s_i \neq n-1} dV^{s_i+1}([X_i^{j_i}]_{n-s_i-1}) \right) \left( \prod_{i \in \mathcal{I}, s_i = n-1} 0 \right). \]

1.2.4. **Criterion for surjectivity of \( C' - 1 \).** The following proposition is proven in the smooth case by Illusie-Raynaud-Suwa [Suw95, 2.1]. The proof presented here is due to Rülling.

**Proposition 1.15** (Raynaud-Illusie-Suwa). Let \( k = \overline{k} \) be an algebraically closed field of characteristic \( p > 0 \). \( X \) is a separated scheme of finite type over \( k \). Then for every \( i \), \( C' - 1 \) induces a surjective map on global cohomology groups

\[ H^i(W_nX, K_{n,X}) := R^i\Gamma(W_nX, K_{n,X}) \xrightarrow{C'-1} H^i(W_nX, K_{n,X}). \]

In particular,

\[ R^i\Gamma(W_nX, K_{n,X, \log}) \simeq H^i(W_nX, K_{n,X})^{C'-1}. \]

**Proof.** Take a Nagata compactification of \( X \), i.e., an open immersion

\[ j : X \hookrightarrow \overline{X} \]

such that \( \overline{X} \) is proper over \( k \). The boundary \( \overline{X} \setminus X \) is a closed subscheme in \( \overline{X} \). By blowing up in \( \overline{X} \) one could assume \( \overline{X} \setminus X \) is the closed subscheme associated to an effective Cartier divisor \( D \) on \( \overline{X} \). We could thus assume \( j \) is an affine morphism. Therefore

\[ W_n j : W_nX \hookrightarrow W_n\overline{X} \]

is also an affine morphism.

For any quasi-coherent sheaf \( M \) on \( W_n\overline{X} \), the difference between \( M \) and \((W_nj)_*(W_nj)^*M\) are precisely those sections that have poles (of any order) at \( \text{Supp} D = W_n\overline{X} \setminus W_nX \). Suppose that the effective Cartier divisor \( D \) is represented by \((U_i, f_i)_i\), where \( \{U_i\}_i \) is an affine cover of \( \overline{X} \), and \( f_i \in \Gamma(U_i, \mathcal{O}_X) \). Recall that \( \mathcal{O}_{\overline{X}}(mD) \) denotes the line bundle on \( \overline{X} \) which is the inverse (as line bundles) of the \( m \)-th power of the ideal sheaf of \( \overline{X} \setminus X \). Locally, one has an isomorphism

\[ \mathcal{O}_{\overline{X}}(mD) \mid U_i \simeq \mathcal{O}_{U_i} \cdot \frac{1}{f_i^m} \]

for each \( i \). Denote by \( W_n \mathcal{O}_{\overline{X}}(mD) \) the line bundle on \( W_n\overline{X} \) such that

\[ W_n \mathcal{O}_{\overline{X}}(mD) \mid U_i \simeq W_n \mathcal{O}_{U_i} \cdot \frac{1}{|f_i|^m}, \]

where \( |x| = |x|_n \) denotes the Teichmüller lift. Denote

\[ M(mD) := M \otimes_{W_n \mathcal{O}_{\overline{X}}} W_n \mathcal{O}_{\overline{X}}(mD). \]

The natural map

\[ (1.2.27) \quad M(*D) := \colim_m M(mD) \xrightarrow{\sim} (W_n j)_*(W_n j)^*(M(mD)) = (W_n j)_*(W_n j)^* M \]

is an isomorphism of sheaves. Here the inductive system on the left hand side is given by the natural map

\[ M(mD) := M \otimes_{W_n \mathcal{O}_{\overline{X}}} W_n \mathcal{O}_{\overline{X}}(mD) \to M \otimes_{W_n \mathcal{O}_{\overline{X}}} W_n \mathcal{O}_{\overline{X}}((m + 1)D) \]

induced from the inclusion \( W_n \mathcal{O}_{\overline{X}}(mD) \hookrightarrow W_n \mathcal{O}_{\overline{X}}((m + 1)D) \), i.e., locally on \( U_i \), this inclusion is the map

\[ W_n \mathcal{O}_{\overline{X}}(mD) \mid U_i \hookrightarrow W_n \mathcal{O}_{\overline{X}}((m + 1)D) \mid U_i. \]
where \( a \in W_n \mathcal{O}_{U_i} \). As a result,
\[
(1.2.28) \quad H^i(W_n X, (W_n)^* \mathcal{M}) = H^i(R(\Gamma(W_n X, R(W_n)^* \mathcal{M}))
\]
\[
= H^i(\Gamma(W_n X, (W_n)^* \mathcal{M})) \quad (W_n \text{ is affine})
\]
\[
= H^i(\Gamma(W_n X, \text{colim}_m \mathcal{M}(mD)) \quad (1.2.27)
\]
\[
= \text{colim}_m H^i(W_n X, \mathcal{M}(mD)).
\]

Apply this to the bounded complex \( K_{n,X} \) of injective quasi-coherent \( W_n \mathcal{O}_X \)-modules. Taking into account \( K_{n,X} \simeq (W_n)^* K_{n,X} \) by [Har66, VI.5.3], (1.2.27) gives an isomorphism of complexes
\[
(1.2.29) \quad K_{n,X}(sD) := \text{colim}_m K_{n,X}(mD) \xrightarrow{\simeq} (W_n)^* K_{n,X},
\]
and (1.2.28) gives an isomorphism of \( W_n k \)-modules
\[
\text{colim}_m H^i(W_n X, K_{n,X}(mD)) = H^i(W_n X, K_{n,X}).
\]

Via the projection formula [Har66, II.5.6] and tensoring
\[
C' : (W_n F_X)_*, K_{n,X} \rightarrow K_{n,X}
\]
with \( W_n \mathcal{O}_X(mD) \), one gets a map
\[
(W_n F_X)_*(K_{n,X} \otimes_{W_n \mathcal{O}_X} W_n \mathcal{O}_X(pmD)) \simeq (W_n F_X)_*((K_{n,X} \otimes_{W_n \mathcal{O}_X} (W_n F_X)^* W_n \mathcal{O}_X(mD)))
\]
\[
\simeq ((W_n F_X)_* K_{n,X}) \otimes_{W_n \mathcal{O}_X} W_n \mathcal{O}_X(mD).
\]

Precomposing with the natural map
\[
(W_n F_X)_*(K_{n,X} \otimes_{W_n \mathcal{O}_X} W_n \mathcal{O}_X(mD)) \rightarrow (W_n F_X)_*((K_{n,X} \otimes_{W_n \mathcal{O}_X} W_n \mathcal{O}_X(pmD))),
\]
and taking global section cohomologies, one gets
\[
C' : H^i(W_n X, K_{n,X}(mD)) \rightarrow H^i(W_n X, K_{n,X}(mD)).
\]

To show surjectivity of
\[
C' : H^i(W_n X, K_{n,X}) \rightarrow H^i(W_n X, K_{n,X}),
\]
it suffices to show surjectivity for
\[
C' - 1 : H^i(W_n X, K_{n,X}(mD)) \rightarrow H^i(W_n X, K_{n,X}(mD)).
\]

Because \( H^q(K_{n,X}) \) are coherent sheaves on the proper scheme \( X \) for all \( q \), \( H^q(K_{n,X} \otimes_{W_n \mathcal{O}_X} W_n \mathcal{O}_X(mD)) = H^q(K_{n,X}) \otimes_{W_n \mathcal{O}_X} W_n \mathcal{O}_X(mD) \) are also coherent, therefore the local-to-global spectral sequence implies that
\[
M := H^i(W_n X, K_{n,X}(mD))
\]
is a finite \( W_n k \)-module. Now \( M \) is equipped with an endomorphism \( C' \) which acts \( p^{-1} \)-linearly (cf. Definition A.4). The proposition is then a direct consequence of Proposition A.6. \( \square \)

The following proposition is a corollary of [Suw95, Lemma 2.1]. We restate it here as a convenient reference.

**Proposition 1.16** (Raynaud-Illusie-Suwa). Assume \( k = \overline{k} \). When \( X \) is separated smooth over \( k \) of pure dimension \( d \),
\[
C - 1 : W_n \Omega^d_X \rightarrow W_n \Omega^d_X
\]
is surjective.

**Proof.** Apply affine locally the \( H^{-d} \)-case of Proposition 1.15. Then Ekedahl’s quasi-isomorphism \( W_n \Omega^d_X[d] \simeq K_{n,X} \) from Proposition 1.1 together with compatibility of \( C' \) and \( C \) from Theorem 1.7 gives the claim. \( \square \)

**Remark 1.17.** When \( X \) is Cohen-Macaulay of pure dimension \( d \), \( W_n X \) is also Cohen-Macaulay by Serre’s criterion of the same pure dimension, and thus \( K_{n,X} \) is concentrated at degree \(-d \) for all \( n \) [Con00, 3.5.1]. Denote by \( W_n \omega_X \) the only nonzero cohomology sheaf of \( K_{n,X} \) in this case. Then the same reasoning as in Proposition 1.16 shows that when \( k = \overline{k} \) and \( X \) is Cohen-Macaulay over \( k \) of pure dimension, the map
\[
C' - 1 : W_n \omega_X \rightarrow W_n \omega_X
\]
is surjective.
1.2.5. **Comparison between** $W_n\Omega^d_X,\log$ and $K_{n,X,\log}$. Let $X$ be a $k$-scheme. Denote by $d\log$ the following map of abelian étale sheaves

$$d\log : (\mathcal{O}^\times_X) \to W_n\Omega^d_X,\log,$$

where $a, \ldots, a_q \in \mathcal{O}^\times_X$, $\lbrack - \rbrack : \mathcal{O}_X \to W_n\mathcal{O}_X$ denotes the Teichmüller lift, and $d\log[a_i] = \frac{d[a_i]}{[a_i]}$.

We will denote its sheaf theoretic image by $W_n\Omega^d_X,\log$, and call it the étale sheaf of log forms. We denote by $W_n\Omega^1_{X,\log} := W_n\Omega^1_X,\log,\z_{\text{Zar}}$, and call it the Zariski sheaf of log forms.

**Lemma 1.18** ([CSS83, lemma 2], [GS88a, 1.6(ii)]). Let $X$ be a smooth $k$-scheme. Then we have the following left exact sequences

$$0 \rightarrow W_n\Omega^d_X,\log \rightarrow W_n\Omega^d_X \xrightarrow{1-\mathcal{F}} W_n\Omega^d_X \otimes \mathcal{D}^{n-1},$$

$$0 \rightarrow W_n\Omega^q_{X,\log} \rightarrow W_n\Omega^q_{X} \xrightarrow{C-1} W_n\Omega^q_X,$$

where $W_n\Omega^q_X := F(W_n^{1+}\Omega^q_X)$. The last maps are also surjective when $t = \hat{e}$.

The following proposition collects what we have done so far.

**Proposition 1.19** (cf. [Kat87, Prop. 4.2]). $X$ is smooth of pure dimension $d$ over a perfect field $k$. Then

1. we have $\mathcal{H}^{d}(K_{n,X,\log}) = W_n\Omega^d_X,\log$, and $\mathcal{H}^{i}(K_{n,X,\log}) = 0$ for all $i \neq -d, -d + 1$.
2. When $k = \overline{k}$, the natural map $W_n\Omega^d_{X,\log}[d] \rightarrow K_{n,X,\log}$

is a quasi-isomorphism of complexes of abelian sheaves.

**Proof.** (1) Since $C$ is compatible with $C'$ by Theorem 1.7, the natural map $\text{cone}(W_n\Omega^d[X][d] \xrightarrow{C-1} W_n\Omega^d\lbrack -1\rbrack \rightarrow K_{n,X,\log})$ is a quasi-isomorphism by the five lemma and the Ekedahl quasi-isomorphism Proposition 1.1. The claim thus follows from the exact sequence (1.2.31).

(2) Proposition 1.16+(1) above.

\[
\]

1.3. **Localization triangle associated to** $K_{n,X,\log}$.

1.3.1. **Definition of** $\text{Tr}_{W_n,f,log}$.

**Proposition 1.20** (Proper pushforward, cf. [Kat87, (3.2.3)]). Let $f : X \rightarrow Y$ be a proper map between separated schemes of finite type over $k$. Then so is $W_n f : W_n X \rightarrow W_n Y$, and we have a map

$$\text{Tr}_{W_n,f,log} : (W_n f)_{\ast}K_{n,X,\log} \rightarrow K_{n,Y,\log}$$

of complexes that fits into the following commutative diagram of complexes, where the two rows are distinguished triangles in $D^b(W_n X,Z/p^n)$

$$\begin{array}{ccc}
(W_n f)_{\ast}K_{n,X,\log} & \xrightarrow{(W_n f)_{\ast}C-1} & (W_n f)_{\ast}K_{n,X} \\
\xrightarrow{\text{Tr}_{W_n,f,log}} & & \xrightarrow{\text{Tr}_{W_n,f}} \\
K_{n,Y,\log} & \xrightarrow{C-1} & K_{n,Y}
\end{array}$$

Moreover $\text{Tr}_{W_n,f,log}$ is compatible with composition and open restriction.

This is the covariant functoriality of $K_{n,X,\log}$ with respect to proper morphisms. Thus we also denote $\text{Tr}_{W_n,f,log}$ by $f_{\ast}$.

**Proof.** It suffices to show the following diagrams commute

$$\begin{array}{ccc}
(W_n f_{\ast})_{\ast}(W_n f)_{\ast}K_{n,X} & \cong & (W_n f_{\ast})_{\ast}(W_n f)_{\ast}K_{n,X} \\
\xrightarrow{(W_n f_{\ast})_{\ast}(W_n f)_{\ast}(1.1.2)} & & \xrightarrow{(W_n f_{\ast})_{\ast}(W_n f)_{\ast}(1.1.2)} \\
(W_n f_{\ast})_{\ast}K_{n,Y} & \cong & (W_n f_{\ast})_{\ast}K_{n,Y}
\end{array}$$

\[
\]
which is naturally a short exact sequence. Now we have the whole commutative diagram of complexes,

\[
\begin{array}{c}
(W_n F_X)_*(W_n f)_*(W_n F_X)^{\triangle} K_{n,X} \xrightarrow{\simeq} (W_n f)_*(W_n F_X)_*(W_n F_X)^{\triangle} K_{n,X} \xrightarrow{(W_n f)_*, Tr_{n,f}} (W_n f)_* K_{n,X} \\
(W_n F_Y)_*(W_n F_Y)^{\triangle} K_{n,Y} \xrightarrow{Tr_{n,f}} K_{n,Y},
\end{array}
\]

where \( Tr_{n,f} \) on the right of the first diagram and the left of the second diagram denotes the trace map of residual complex \((W_n F_Y)^{\triangle} K_{n,Y} \):

\[
Tr_{n,f} : (W_n f)_*(W_n F_X)^{\triangle} K_{n,X} \simeq (W_n f)_*(W_n f)^{\triangle} (W_n F_Y)^{\triangle} K_{n,Y} \rightarrow (W_n F_Y)^{\triangle} K_{n,Y}.
\]

Commutativity of the first diagram is due to functoriality of the trace map with respect to residual complexes with the same associated filtration \([\text{Con00}, 3.4.1(1)]\). Commutativity of the second is because of compatibility of the trace map with composition of morphisms \([\text{Con00}, 3.4.1(2)]\). □

1.3.2. \( Tr_{n,f,\log} \) in the case of a nilpotent immersion.

**Proposition 1.21** (Rülling. Cf. \([\text{Kat87}, 4.2\])]. Let \( i : X_0 \hookrightarrow X \) be a nilpotent immersion (thus so is \( W_n i : W_n(X_0) \rightarrow W_n(X) \). Then the natural map

\[
Tr_{n,\log} : (W_n i)_* K_{n,X_0,\log} \rightarrow K_{n,X,\log}
\]

is a quasi-isomorphism.

**Proof.** Put \( I_n := \text{Ker}(W_n O_X \rightarrow (W_n i)_* W_n O_{X_0}) \). Apply \( \text{Hom}_{W_n O_X}(-, K_{n,X}) \) to the sequence of \( W_n O_X \)-modules

\[
0 \rightarrow I_n \rightarrow W_n O_X \rightarrow (W_n i)_* W_n O_{X_0} \rightarrow 0,
\]

we get again a short exact sequence of complexes of \( W_n O_X \)-modules

\[
0 \rightarrow (W_n i)_* K_{n,X_0} \xrightarrow{Tr_{n,f}} K_{n,X} \xrightarrow{Q_n := \text{Hom}_{W_n O_X} (I_n, K_{n,X})} 0.
\]

The first map is clearly \( Tr_{n,f} \) by duality. The restriction of the map \((W_n F_X)_* : W_n O_X \rightarrow (W_n F_X)_* W_n O_X \) to \( I_n \) gives a map

\[
(W_n F_X)_* |_{I_n} : I_n \rightarrow (W_n F_X)_* I_n,
\]

\[
\sum_{i=0}^{n-1} V([a_i]) \rightarrow \sum_{i=0}^{n-1} V([a_i^n]).
\]

Define

\[
(1.3.2) \quad C'_I_n : (W_n F_X)_* Q_n = (W_n F_X)_* \text{Hom}_{W_n O_X} (I_n, K_{n,X})
\]

\[
\xrightarrow{\text{Hom}_{W_n O_X} ((W_n F_X)_* I_n, (W_n F_X)_* K_{n,X})}
\]

\[
\simeq (W_n F_X)_* ((W_n F_X)_* I_n, (W_n F_X)_* K_{n,X})
\]

\[
\xrightarrow{Tr_{n,f}} \text{Hom}_{W_n O_X} ((W_n F_X)_* I_n, K_{n,X})
\]

\[
\xrightarrow{((W_n F_X)_* I_n)^{\vee}} \text{Hom}_{W_n O_X} (I_n, K_{n,X}) = Q_n.
\]

According to the definition of \( C' \) in (1.1.3), \( C' \) is compatible with \( C'_I_n \). Thus one has the following commutative diagram

\[
\begin{array}{ccccccccc}
0 & \rightarrow & (W_n F_X)_* (W_n i)_* K_{n,X_0} & \xrightarrow{C'} & (W_n F_X)_* K_{n,X} & \rightarrow & (W_n F_X)_* Q_n & \rightarrow & 0 \\
0 & \rightarrow & (W_n i)_* K_{n,X_0} & \xrightarrow{\text{Tr}_{n,\log}} & K_{n,X} & \rightarrow & Q_n & \rightarrow & 0.
\end{array}
\]

Replace \( C' \) by \( C' - 1 \), and \( C'_I_n \) by \( C'_I_n - 1 \), we arrive at the two lower rows of the following diagram. Denote

\[
Q_{n,\log} := \text{Cone}(Q_n \xrightarrow{C'_I_n - 1} Q_n)[-1] .
\]

Taking into account the shifted cones of \( C' - 1 \) and \( C'_I_n - 1 \), we get the first row of the following diagram which is naturally a short exact sequence. Now we have the whole commutative diagram of complexes,
where all the three rows are exact, and all the three columns are distinguished triangles in the derived category:

\[
\begin{array}{ccccccc}
0 & \to & (W_n)i_*K_{n,X,\log} & \xrightarrow{\text{Tr}_{W_n i, \log}} & K_{n,X,\log} & \to & Q_{n,\log} & \to & 0 \\
0 & \to & (W_n)i_*K_{n,X_0} & \xrightarrow{\text{Tr}_{W_n i}} & K_n, X & \to & Q_n & \to & 0 \\
0 & \to & (W_n)i_*K_{n,X_0} & \xrightarrow{\text{Tr}_{W_n i}} & K_{n,X} & \to & Q_n & \to & 0.
\end{array}
\]

We want to show that $\text{Tr}_{W_n i, \log}$ is a quasi-isomorphism. By the exactness of the first row, it suffices to show $Q_{n,\log}$ is an acyclic complex. Because the right column is a distinguished triangle, it suffices to show $C_{i_n - 1}^n : Q_n \to Q_n$ is a quasi-isomorphism. Actually it’s even an isomorphism of complexes: since $(W_n F X)^* |_{I_n} : I_n \to (W_n F X)_I$ is nilpotent (because $I_1 = \text{Ker}(O_X \to i_* O_{X_0})$ is a finitely generated nilpotent ideal of $O_X$), $C_{i_n - 1}^n : Q_n \to Q_n$ is therefore nilpotent (because one can alter the order of the three labeled maps in (1.3.2) in the obvious sense), and $C_{i_n - 1}^n$ is therefore an isomorphism of complexes. □

1.3.3. Localization triangles associated to $K_{n,X,\log}$. Let $i : Z \to X$ be a closed immersion with $j : U \hookrightarrow X$ its open complement. Recall

\[(1.3.3) \quad \Gamma_Z(\mathcal{F}) := \text{Ker}(\mathcal{F} \to j_* j^{-1} \mathcal{F})\]

for any abelian sheaf $\mathcal{F}$. Denote its $i$-th derived functor by $H'_Z(\mathcal{F})$. Notice that

- $\Gamma_Z(\mathcal{F}) = \Gamma_Z(F)$ for any nilpotent thickening $Z'$ of $Z$ (e.g. $Z' = W_n Z$),
- $F \to j_* j^{-1} F$ is surjective whenever $F$ is flasque, and
- flasque sheaves are $\Gamma_Z$-acyclic ([Har67, 1.10]) and $f_*$-acyclic for any morphism $f$.

Therefore, for any complex of flasque sheaves $\mathcal{F}^\bullet$ of $\mathbb{Z}/p^n$-modules on $W_n X$, 

\[0 \to \Gamma_Z(\mathcal{F}^\bullet) \to \mathcal{F}^\bullet \to (W_n j)_*(\mathcal{F}^\bullet|_{W_n U}) \to 0\]

is a short exact sequence of complexes. Thus the induced triangle

\[(1.3.4) \quad \Gamma_Z(\mathcal{F}^\bullet) \to \mathcal{F}^\bullet \to (W_n j)_*(\mathcal{F}^\bullet|_{W_n U}) \xrightarrow{+1}\]

is a distinguished triangle in $D^b(W_n X, \mathbb{Z}/p^n)$, whenever $\mathcal{F}^\bullet$ is a flasque complex with bounded cohomologies. In particular, since $K_{n,X,\log}$ is a bounded complex of flasque sheaves, this is true for $\mathcal{F}^\bullet = K_{n,X,\log}$.

The following proposition is proven in the smooth case by Gros-Milne-Suwa [Suw95, 2.6]. The proof presented here comes from unpublished manuscript of Rülling.

**Proposition 1.22** (Rülling). Let $i : Z \hookrightarrow X$ be a closed immersion with $j : U \hookrightarrow X$ its open complement. Then

1. (Purity) The map

\[(W_n i)_* K_{n,Z,\log} = \Gamma_Z((W_n i)_* K_{n,Z,\log}) \xrightarrow{\text{Tr}_{W_n i, \log}} \Gamma_Z(K_{n,X,\log})\]

is a quasi-isomorphism of complexes of sheaves.

2. (Localization triangle) The following

\[(1.3.5) \quad (W_n i)_* K_{n,Z,\log} \xrightarrow{\text{Tr}_{W_n i, \log}} K_{n,X,\log} \to (W_n j)_* K_{n,U,\log} \xrightarrow{+1} \]

is a distinguished triangle in $D^b(W_n X, \mathbb{Z}/p^n)$.

Note that we are working on the Zariski site and abelian sheaves on $W_n X$ can be identified with abelian sheaves on $X$ canonically. Thus we can replace $(W_n i)_* K_{n,Z,\log}$ by $i_* K_{n,Z,\log}$, and $(W_n j)_* K_{n,U,\log}$ by $j_* K_{n,U,\log}$ freely.

**Proof.**

1. Let $I_n$ be the ideal sheaf associated to the closed immersion $W_n i : W_n Z \hookrightarrow W_n X$, and let $Z_{n,m}$ be the closed subscheme of $W_n X$ determined by $m$-th power ideal $I_n^m$. In particular, $Z_{n,1} = W_n Z$. Denote by $i_{n,m} : Z_{n,m} \hookrightarrow W_n X$ and by $j_{n,m} : W_n Z \hookrightarrow Z_{n,m}$ the associated closed

...
immersions. In this way one has a series of decomposition of $W_n i$ as maps of $W_n k$-schemes indexed by $m$:

\[
\begin{array}{cccc}
W_n Z' & \xrightarrow{j_{n,m}} & Z_{n,m} & \xrightarrow{i_{n,m}} & W_n X \\
& \xrightarrow{\pi_{Z_{n,m}}} & & \xrightarrow{\pi_{Z_{n,m}}} & \\
& \xrightarrow{\pi_{W_n k}} & & & \\
W_n \pi_X & & W_n \pi_X & & W_n k.
\end{array}
\]

Denote $K_{Z_{n,m}} := (\pi_{Z_{n,m}})^*(W_n k)$, where $\pi_{Z_{n,m}} : Z_{n,m} \rightarrow W_n k$ is the structure morphism. We have a canonical isomorphism

\[
i_{n,m,*} H^i(K_{Z_{n,m}}) \simeq Ext^i_{W_n O_X}(i_{n,m,*}O_{Z_{n,m}}, K_{n,X})
\]

by [Con00, (3.2.3)] and [Har66, VI.3.1] associated to the closed immersion $i_{n,m}$. The trace maps associated to the closed immersions

\[
Z_{n,m} \hookrightarrow Z_{n,m+1}
\]

for different $m$ make the left hand side of (1.3.6) an inductive system. The right hand side also lies in an inductive system when $m$ varies: the canonical surjections

\[
i_{n,m+1,*} O_{Z_{n,m+1}} \rightarrow i_{n,m,*} O_{Z_{n,m}}
\]

induce the maps

\[
\text{Hom}_{W_n O_X}(i_{n,m,*} O_{Z_{n,m}}, K_{n,X}) \rightarrow \text{Hom}_{W_n O_X}(i_{n,m+1,*} O_{Z_{n,m+1}}, K_{n,X})
\]

whose $i$-th cohomologies are the connecting homomorphisms of the inductive system. By duality, the map (1.3.7) is the trace map associated to the closed immersion $Z_{n,m} \hookrightarrow Z_{n,m+1}$, and thus is compatible with the inductive system on the left hand side of (1.3.6).

Consider the trace map associated to the closed immersion $i_{n,m} : Z_{n,m} \hookrightarrow W_n X$, i.e., the evaluation-at-1 map

\[
\text{Hom}_{W_n O_X}(i_{n,m,*} O_{Z_{n,m}}, K_{n,X}) \rightarrow K_{n,X}.
\]

Its image naturally lies in $\Gamma_{W_n Z}(K_{n,X})$. It induces an isomorphism on cohomology sheaves after taking colimit on $m$

\[
\colim_m Ext^i_{W_n O_X}(i_{n,m,*} O_{Z_{n,m}}, K_{n,X}) \xrightarrow{\text{ev}_1} H^i_2(K_{n,X})
\]

by [Har66, V.4.3].

Now we consider

\[
\colim_m i_{n,m,*} H^i(K_{Z_{n,m}}) \simeq \colim_m Ext^i_{W_n O_X}(i_{n,m,*} O_{Z_{n,m}}, K_{n,X}) \xrightarrow{\text{ev}_1} H^i_2(K_{n,X}).
\]

The composite map of (1.3.8) is $\colim_m Tr_{i_{n,m}}$. On the other hand, consider the log trace associated to the closed immersion $i_{n,m}$ (cf. Proposition 1.20)

\[
Tr_{i_{n,m}, log} : H^i(i_{n,m,*} K_{Z_{n,m}, log}) = H^i(\Gamma_{Z}(i_{n,m,*} K_{Z_{n,m}, log})) \rightarrow H^i(\Gamma_{Z}(K_{n,X, log})) = H^i_2(K_{n,X, log}).
\]

The maps (1.3.8), (1.3.9) give the vertical maps in the following diagram (due to formatting reason we omit $i_{n,m,*}$ from every term of the first row) which are automatically compatible by Proposition 1.20:

\[
\begin{array}{cccc}
\mathcal{H}^i_{Z^{-1}}(K_{Z_{n,m}}) & \xrightarrow{C^{-1}} & \mathcal{H}^i_{Z^{-1}}(K_{Z_{n,m}}) & \xrightarrow{\text{Tr}_{i_{n,m}}} & \mathcal{H}^i(K_{Z_{n,m}, log}) \\
\text{Tr}_{i_{n,m}} & & \text{Tr}_{i_{n,m}, log} & & \text{Tr}_{i_{n,m}} \\
\mathcal{H}^i_{Z^{-1}}(K_{n,X}) & \xrightarrow{C^{-1}} & \mathcal{H}^i_{Z^{-1}}(K_{n,X}) & \xrightarrow{\text{Tr}_{i_{n,m}}} & \mathcal{H}^i_2(K_{n,X, log})
\end{array}
\]

Taking the colimit with respect to $m$, the five lemma immediately gives that $\colim_m Tr_{i_{n,m}, log}$ is an isomorphism. Then $Tr_{W_n i, log}$, which is the composition of

\[
\colim_m Tr_{i_{n,m}, log} \xrightarrow{\text{Proposition 1.21}} \colim_m i_{n,m,*} H^i(K_{Z_{n,m}, log}) \xrightarrow{\text{colim_m}} H^i_2(K_{n,X, log}),
\]

is an isomorphism. This proves the statement.
1.4. Functoriality. The push-forward functoriality of $K_{n,X,log}$ has been done in Proposition 1.20 for proper $f$. Now we define the pullback map for an étale morphism $f$. Since $W_n f$ is then also étale, we have an isomorphism of functors $(W_n f)^* \simeq (W_n f)\triangleleft$ by [Har66, VI, 3.1 and 5.3]. Define a chain map of complexes of $W_n \mathcal{O}_Y$-modules

\[(1.4.1) \quad f^* : K_{n,Y} \xrightarrow{\text{adj}} (W_n f)_* (W_n f)^* K_{n,Y} \simeq (W_n f)_* (W_n f)^\triangleleft K_{n,Y} \simeq (W_n f)_* K_{n,X}.
\]

Here adj stands for the adjunction map of the identity map of $(W_n f)^* K_{n,Y}$.

**Proposition 1.23** (Étale pullback). Suppose $f : X \rightarrow Y$ is an étale morphism. Then

\[f^* : K_{n,Y,log} \rightarrow (W_n f)_* K_{n,X,log},\]

defined by termwise applying (1.4.1), is a chain map between complexes of abelian sheaves.

**Proof.** It suffices to prove that $C_\ast$ is compatible with $f^*$ defined above. Consider the following diagram in the category of complexes of $W_n \mathcal{O}_Y$-modules

\[
\begin{array}{c}
(W_n F_Y)_* K_{n,Y} \xrightarrow{(1.1.2)} (W_n F_Y)_* (W_n F_Y)^\triangleleft K_{n,Y} \xrightarrow{\text{Tr}_{W_n F_Y}} K_{n,Y} \\
\downarrow \text{adj} \quad \downarrow \text{adj} \quad \downarrow \text{adj} \\
(W_n f)_* (W_n f)^* K_{n,Y} \simeq (W_n f)_* (W_n f)^* K_{n,Y} \xrightarrow{\text{Tr}_{W_n f}} (W_n f)_* (W_n f)^* K_{n,X} \\
\alpha \quad \beta \quad \gamma \quad \delta \quad \epsilon \\
(W_n f)_* (W_n F_X)_* K_{n,X} \xrightarrow{(1.1.2)} (W_n f)_* (W_n F_X)_* (W_n F_X)^\triangleleft K_{n,X} \xrightarrow{\text{Tr}_{W_n f}} (W_n f)_* K_{n,X} \\
\end{array}
\]

In this diagram we use shortened notations for the maps due to formatting reasons, e.g., we write $1.1.2$ instead of $(W_n f)_* (W_n F_X)_*$, etc. The maps labelled $\alpha$ and $\beta$ are base change maps, and they are isomorphisms because $W_n f$ is flat (actually $W_n f$ is étale because $f$ is étale) [Har66, II.5.12]. The composite of the maps on the very left and very right are $(W_n F_Y)_* (f^*)$ and $f^*$ (where $f^*$ is as defined in (1.4.1)). The composite of the maps on the very top and very bottom are $C_\ast$ and $(W_n f)_* C_\ast$. Diagrams $a), b), c), d)$ commute due to naturality. Diagram $c)$ commutes, because we have a cartesian square

\[
\begin{array}{ccc}
W_n X & \xrightarrow{W_n F_X} & W_n X \\
\downarrow \text{W}_n f \downarrow W_n f \downarrow \text{W}_n f \\
W_n Y & \xrightarrow{W_n F_Y} & W_n Y
\end{array}
\]

by Remark 1.6(2), and then the base change formula of the Grothendieck trace map as given in [Har66, VI.5.6] gives the result. □

**Lemma 1.24.** Consider the following cartesian diagram

\[
\begin{array}{ccc}
W & \xrightarrow{f'} & Z \\
\downarrow g' & \downarrow g & \downarrow g \\
X & \xrightarrow{f} & Y
\end{array}
\]

with $g$ being proper, and $f$ being étale. Then we have a commutative diagram of residual complexes

\[
\begin{array}{ccc}
(W_n g)_* K_{n,Z} & \xrightarrow{(W_n g)_* (W_n f)^*} & (W_n f)_* K_{n,W} \simeq (W_n f)_* (W_n g)_* K_{n,W} \\
\downarrow \text{Tr}_{W_n g} \downarrow \text{Tr}_{W_n g} \downarrow \text{Tr}_{W_n g} \\
K_{n,Y} & \xrightarrow{f^*} & (W_n f)_* K_{n,X}.
\end{array}
\]
Proof. We decompose the diagram into the following two diagrams and show their commutativity one by one.

\[
\begin{array}{ccc}
(W_n g)_* K_{n,Z} & \xrightarrow{\text{adj}} & (W_n g)_* (W_n f')_* (W_n f')^* K_{n,Z} \\
\downarrow \cong & & \downarrow \cong \\
(W_n f)_* (W_n g')_* (W_n f')^* (W_n g)^\Delta K_{n,Y} & \xrightarrow{\alpha} & (W_n f)_* (W_n g')_* (W_n g)^\Delta K_{n,Y} \\
\text{Tr}_{W_n g} & & \text{Tr}_{W_n g} \\
K_{n,Y} & \xrightarrow{\text{adj}} & (W_n f)_* (W_n f')^* K_{n,Y}.
\end{array}
\]

Here \(\alpha\) denotes the base change map, it is an isomorphism because \(W_n f\) is flat [Har66, II.5.12]. This diagram commutes by naturality. Next consider

\[
\begin{array}{ccc}
(W_n g)_* (W_n f')_* (W_n f')^* K_{n,Z} & \xrightarrow{\cong} & (W_n g)_* (W_n f')_* K_{n,W} \\
\downarrow \cong & & \downarrow \cong \\
(W_n f)_* (W_n g')_* (W_n f')^* (W_n g)^\Delta K_{n,Y} & \xrightarrow{\alpha} & (W_n f)_* (W_n g')_* K_{n,W} \\
\text{Tr}_{W_n g'} & & \text{Tr}_{W_n g'} \\
(W_n f)_* (W_n f')^* K_{n,Y} & \xrightarrow{\cong} & (W_n f)_* K_{n,X}.
\end{array}
\]

The top part commutes by naturality. The bottom part commutes by the base change formula of the Grothendieck trace maps with respect to étale morphisms [Har66, VI.5.6]. \(\square\)

Since both \(f^*\) for log complexes in Proposition 1.23 and \(g_* := \text{Tr}_{W_n g, \log}\) are defined termwise, we arrive immediately the following compatibility as a consequence of Lemma 1.24.

**Proposition 1.25.** Notations are the same as Lemma 1.24. One has a commutative diagram of complexes

\[
\begin{array}{ccc}
(W_n g)_* K_{n,Z,\log} & \xrightarrow{f^*} & (W_n g)_* (W_n f)_* K_{n,W,\log} \\
\downarrow g_* & & \downarrow g_* \\
K_{n,Y,\log} & \xrightarrow{f^*} & (W_n f)_* K_{n,X,\log}.
\end{array}
\]

1.5. **Étale counterpart** \(K_{n, X, \log, \text{ét}}\). Let \(X\) be a separated scheme of finite type over \(k\) of dimension \(d\). In this subsection we will use \(t = \text{Zar}\), \(\text{ét}\) to distinguish objects, morphisms on different sites. When \(t\) is omitted, it means \(t = \text{Zar}\) unless otherwise stated.

Denote the structure sheaf on the small étale site \((W_n X)_\text{ét}\) by \(W_n \mathcal{O}_X, \text{ét}\). Denote

\[
(\epsilon_*, \epsilon^*) : ((W_n X)_\text{ét}, W_n \mathcal{O}_X, \text{ét}) \to ((W_n X)_\text{Zar}, W_n \mathcal{O}_X)
\]

the module-theoretic functors. Recall that every étale \(W_n X\)-scheme is of the form \(W_n g : W_n U \to W_n X\), where \(g : U \to X\) is an étale \(X\)-scheme by Remark 1.6(1). Now let \(\mathcal{F}\) be a \(W_n \mathcal{O}_X, \text{ét}\)-module on \((W_n X)_\text{ét}\).

Consider the following map (cf. [Kat87, p. 264])

\[
\tau : (W_n F_X)_* \mathcal{F} \to \mathcal{F},
\]

which is defined to be

\[
((W_n F_X)_* \mathcal{F})(W_n U) \xrightarrow{W_n g} W_n X = \mathcal{F}(W_n X \times_{W_n F_X, W_n U} W_n U) \xrightarrow{pr_1} W_n X
\]

\[
\cong \mathcal{F}(W_n U) \xrightarrow{W_n g} W_n X
\]
for any étale map $W_n g : W_n U \to W_n X$ (here we use $pr_1$ to denote the first projection map of the fiber product). This is an automorphism of $\mathcal{F}$ as an abelian étale sheaf, but it changes the $W_n \mathcal{O}_{X, \text{ét}}$-module structure of $\mathcal{F}$.

Define

$$K_{n,X, \text{ét}} := \epsilon^* K_{n,X}$$

to be the complex of étale $W_n \mathcal{O}_{X, \text{ét}}$-modules associated to the Zariski complex $K_{n,X}$ of $W_n \mathcal{O}_X$-modules. This is still a complex of quasi-coherent sheaves with coherent cohomologies. For a proper map $f : X \to Y$ of $k$-schemes, define

$$\text{Tr} W_n f, \text{ét} : (W_n f)_* K_{n,X, \text{ét}} = \epsilon^* ((W_n f)_* K_{n,X}) \xrightarrow{\epsilon^* \text{Tr} W_n f} K_{n,Y, \text{ét}}$$
to be the étale map of $W_n \mathcal{O}_{Y, \text{ét}}$-modules associated to the Zariski map $\text{Tr} W_n f : K_{n,X} \to K_{n,Y}$ of $W_n \mathcal{O}_X$-modules. Define the Cartier operator $C'_{\text{ét}}$ for étale complexes to be the composite

$$C'_{\text{ét}} : K_{n,X, \text{ét}} \xrightarrow{\tau^{-1}} (W_n F_X)_* K_{n,X, \text{ét}} = \epsilon^* ((W_n F_X)_* K_{n,X}) \xrightarrow{\epsilon^* (1.13)} K_{n,X, \text{ét}}.$$

Define

$$K_{n,X, \text{log, ét}} := \text{Cone}(K_{n,X, \text{ét}} \xrightarrow{C'_{\text{ét}}^{-1}} K_{n,X, \text{ét}})[-1].$$

We also have the sheaf-level Cartier operator. Let $X$ be a smooth $k$-scheme. Recall that by definition, $C_{\text{ét}}$ is the composition of the inverse of $(1.5.1)$ with the module-theoretic etalization of the $W_n \mathcal{O}_X$-linear map $(1.2.6)$ (it has appeared in Lemma 1.18 before):

$$C_{\text{ét}} : W_n \Omega^d_{X, \text{ét}} \xrightarrow{\tau^{-1}} (W_n F_X)_* W_n \Omega^d_{X, \text{ét}} = \epsilon^* ((W_n F_X)_* W_n \Omega^d_{X}) \xrightarrow{\epsilon^* (1.2.6)} W_n \Omega^d_{X, \text{ét}}.$$

**Proposition 1.26** (cf. Theorem 1.7). $C_{\text{ét}}$ is the natural extension of $C'$ to the small étale site, i.e.,

$$\epsilon_* C_{\text{ét}} = C' : K_{n,X} \to K_{n,X}.$$

When $X$ is smooth, $C_{\text{ét}}$ is the natural extension of $C$ to the small étale site

$$\epsilon_* C_{\text{ét}} = C : W_n \Omega^d_{X} \to W_n \Omega^d_{X}.$$

And one has compatibility

$$C_{\text{ét}} = \mathcal{H}^{-d}(C'_{\text{ét}}).$$

**Proof.** The first two claims are clear. The last claim follows from the compatibility of $C$ and $C'$ in the Zariski case Theorem 1.7. \hfill \Box

**Proposition 1.27** (cf. Proposition 1.15). Let $X$ be a separated scheme of finite type over $k$ with $k = \overline{k}$. Then

$$H^i(W_n X, K_{n,X, \text{ét}}) := R^i \Gamma((W_n X)_t, K_{n,X, \text{ét}}) \xrightarrow{C'_{\text{ét}}^{-1}} H^i(W_n X, K_{n,X, \text{ét}})$$
is surjective for every $i$. In particular,

$$R^i \Gamma(W_n X, K_{n,X, \text{log, ét}}) \simeq H^i(W_n X, K_{n,X, \text{ét}}) C'_{\text{ét}}^{-1}.$$

**Proof.** The quasi-coherent descent from the étale site to the Zariski site gives

$$R^i \Gamma((W_n X)_\text{ét}, K_{n,X, \text{ét}}) = R^i \Gamma((W_n X)_{\text{Zar}}, K_{n,X, \text{Zar}}).$$

Taking the $i$-th cohomology groups, the desired surjectivity then follows from the compatibility of $C'$ and $C_{\text{ét}}$ Proposition 1.26 and the Zariski case Proposition 1.15. \hfill \Box

In the étale topology and for any perfect field $k$, surjectivity of

$$C_{\text{ét}} - 1 : W_n \Omega^d_{X, \text{ét}} \to W_n \Omega^d_{X, \text{ét}}$$
is known without the need of Proposition 1.27 (cf. Lemma 1.18). For the same reasoning as in Proposition 1.19, we have

**Proposition 1.28** (cf. Proposition 1.19). Assume $X$ is smooth of pure dimension $d$ over a perfect field $k$. Then the natural map

$$W_n \Omega^d_{X, \text{log, ét}}[d] \to K_{n,X, \text{log, ét}}$$
is a quasi-isomorphism of complexes of abelian complexes.

We go back to the general non-smooth case. The proper pushforward property in the étale setting is very similar to the Zariski case.
Proposition 1.29 (Proper pushforward, cf. Proposition 1.20). For $f : X \to Y$ proper, we have a well-defined map of complexes of étale sheaves

$$\text{Tr}_{W_n f, \log, \text{ét}} : (W_n f)_* K_{n X, \log, \text{ét}} \to K_{n Y, \log, \text{ét}}$$

given by applying $\text{Tr}_{W_n f, \text{ét}}$ termwise.

Proof. The map $\tau^{-1}$ is clearly functorial with respect to any map of abelian sheaves. The rest of the proof goes exactly as in Proposition 1.20. □

Proposition 1.30 (cf. Proposition 1.21). Let $i : X_0 \to X$ be a nilpotent immersion. Then the natural map

$$\text{Tr}_{W_n i, \log, \text{ét}} : (W_n i)_* K_{n X_0, \log, \text{ét}} \to K_{n X, \log, \text{ét}}$$
is a quasi-isomorphism.

Proof. This is a direct consequence of the functoriality of the map $\tau^{-1}$ and Proposition 1.21. □

Let $i : Z \to X$ be a closed immersion with $j : U \to X$ being the open complement as before. Define

$$\nabla_Z(F) := \text{Ker}(F \to j_* j^{-1} F)$$

for any étale abelian sheaf $F$ on $X$, just as in the Zariski case (cf. (1.3.3)). Replacing $Z$ (resp. $X$) by a nilpotent thickening will define the same functor as $\nabla_Z(-)$, because the étale site of any scheme is the same as the étale site of its reduced scheme [EGAIV-4, Ch. IV, 18.1.2]. Recall that when $F = \mathcal{I}$ is an injective $\mathbb{Z}/p^n$-sheaf,

$$0 \to \nabla_Z(\mathcal{I}) \to \mathcal{I} \to j_* j^{-1} \mathcal{I} \to 0$$
is exact. In fact, because $j_* \mathbb{Z}/p^n$ is a subsheaf of the constant sheaf $\mathbb{Z}/p^n$ on $X$, the map $\text{Hom}_X(\mathbb{Z}/p^n, \mathcal{I}) \to \text{Hom}_X(j_* \mathbb{Z}/p^n, \mathcal{I})$ is surjective. Since $\text{Hom}_X(j_* \mathbb{Z}/p^n, \mathcal{I}) = \text{Hom}_X(\mathbb{Z}/p^n, j_* j^{-1} \mathcal{I}) = \text{Hom}_X(\mathcal{I}/j_* \mathcal{I}, \mathcal{I})$, $\text{Hom}_X(\mathbb{Z}/p^n, \mathcal{I}) \to \text{Hom}_X(\mathbb{Z}/p^n, j_* j^{-1} \mathcal{I})$ is surjective, hence the claim. This implies that for any complex $F^\bullet$ of étale $\mathbb{Z}/p^n$-sheaves with bounded cohomologies,

$$(1.5.3) \quad R\nabla_Z(F^\bullet) \to F^\bullet \to j_* j^{-1} F^\bullet \xrightarrow{+1}$$
is a distinguished triangle in $D^b(X, \mathbb{Z}/p^n)$ (cf. (1.3.4)).

Proposition 1.31 (cf. Proposition 1.22). Let $i : Z \to X$ be a closed immersion with $j : U \to X$ being the open complement as before. Then

1. (Purity) We can identify canonically the functors

$$(W_n i)_* \circ (W_n i)_* : D^b((W_n \mathcal{Z})_{\text{ét}}, \mathbb{Z}/p^n) \to D^b((W_n X)_{\text{ét}}, \mathbb{Z}/p^n).$$

The composition of this canonical identification with the trace map

$$(W_n i)_* K_{n Z, \log, \text{ét}} \xrightarrow{\text{Tr}_{W_n i, \log, \text{ét}}} R\nabla_Z(K_{n X, \log, \text{ét}})$$
is a quasi-isomorphism of complexes of étale $\mathbb{Z}/p^n$-sheaves.

2. (Localization triangle)

$$\begin{array}{c}
(W_n i)_* K_{n Z, \log, \text{ét}} \xrightarrow{\text{Tr}_{W_n i, \log, \text{ét}}} K_{n X, \log, \text{ét}} \to (W_n j)_* K_{n U, \log, \text{ét}} \xrightarrow{+1}
\end{array}$$
is a distinguished triangle in $D^b((W_n X)_{\text{ét}}, \mathbb{Z}/p^n)$.

Proof. (1) One only needs to show that $(W_n i)_* = R\nabla_Z \circ (W_n i)_*$, and then the rest of the proof is the same as in Proposition 1.22(1). Let $\mathcal{I}$ be an injective étale $\mathbb{Z}/p^n$-sheaf on $W_n \mathcal{Z}$. Since $\text{Hom}_{W_n X}(-, (W_n i)_* \mathcal{I}) = \text{Hom}_{W_n Z}((W_n i)^{-1}(-), \mathcal{I})$ and $(W_n i)^{-1}$ is exact, we know $(W_n i)_* \mathcal{I}$ is an injective abelian sheaf on $(W_n X)_{\text{ét}}$. This implies that $R\nabla_Z \circ (W_n i)_* = R\nabla_Z \circ (W_n i)_*$ by the Leray spectral sequence, and thus $(W_n i)_* = R(W_n i)_* = R\nabla_Z \circ (W_n i)_* = R\nabla_Z \circ (W_n i)_*$.

(2) One only need to note that $(W_n j)_* K_{n U, \log, \text{ét}} = R(W_n j)_* K_{n U, \log, \text{ét}}$. In fact, the terms of $K_{n U, \log, \text{ét}}$ are quasi-coherent $W_n \mathfrak{O}_{X, \text{ét}}$-modules which are $(W_n j)_*$-acyclic in the étale topology (because $R^f_* (\mathbb{Z}/p^n) = e^* (R^f_* \mathbb{Z}/p^n)$ for any quasi-coherent Zariski sheaf $F$ and any quasi-compact quasi-separated morphism $f$ [Stacks, Tag 071N]). Now the first part and the distinguished triangle (1.5.3) imply the claim. □
2. Bloch's cycle complex $Z_{X,t}^c$

Let $X$ be a separated scheme of finite type over $k$ of dimension $d$. Let

$$\Delta' = \text{Spec } k[T_0, \ldots, T_i]/(\sum T_j - 1).$$

Define $z_0(X,i)$ to be the free abelian group generated by closed integral subschemes $Z \subset X \times \Delta'$ that intersect all faces properly and $\dim Z = i$. We say two closed subschemes $Z_1, Z_2$ of a scheme $Y$ intersect properly if for every irreducible component $W$ of the schematic intersection $Z_1 \cap Z_2 := Z_1 \times_Y Z_2$, one has

$$\dim W \leq \dim Z_1 + \dim Z_2 - \dim Y$$

(cf. [Gei05, A.1]). A subvariety of $X \times \Delta'$ is called a face if it is determined by some $T_{j_1} = T_{j_2} = \cdots = T_{j_2} = 0$ ($0 \leq j_1 < \cdots < j_2 \leq i$). Note that a face is Zariski locally determined by a regular sequence of $X \times \Delta'$. Therefore the given inequality condition (2.0.1) in the definition of $z_0(X,i)$ is equivalent to the equality condition [Gei05, (53)].

The above definition defines a sheaf $z_0(-,i)$ in both the Zariski and the étale topology on $X$ ([Blo86, p.270]. See also [Gei04, Lemma 3.1]). Define the complex of sheaves

$$\to z_0(-,i) \xrightarrow{d_2} z_0(-,i-1) \to \cdots \to z_0(-,0) \to 0$$

with differential map

$$d(Z) = \sum_j (-1)^j [Z \cap V(T_j)].$$

Here we mean by $V(T_j)$ the closed integral subscheme determined by $T_j$ and by $[Z \cap V(T_j)]$ the linear combination of the reduced irreducible components of the scheme theoretic intersection $Z \cap V(T_j)$ with coefficients being intersection multiplicities. $z_0(X,\bullet)$ is then a homological complex concentrated in degree $[0, \infty)$. Labeling cohomologically, we set

$$(Z_X^c)^i = z_0(-,-i).$$

This complex is nonzero in degrees $(-\infty, 0].$

Define the higher Chow group

$$\text{CH}_0(X,i) := H_i(z_0(X,\bullet)) = H^{-i}(Z_X^c(X))$$

for any $i$. The higher Chow groups with coefficients in an abelian group $A$ will be denoted

$$\text{CH}_0(X,i; A) := H^{-i}(Z_X^c(X) \otimes_Z A).$$

The complex $Z_X^c$, with either $t = \text{Zar}$ or $t = \text{ét}$, is covariant for proper morphisms, and contravariant for quasi-finite flat morphisms [Blo86, Prop. 1.3].

3. Kato's complex of Milnor $K$-theory $C_{X,t}^M$

Recall that given a field $L$, the $q$-th Milnor $K$-group $K^M_q(L)$ of $L$ is defined to be the $q$-th graded piece of the non-commutative graded ring

$$\bigoplus_{q \geq 0} K^M_q(L) = \bigoplus_{q \geq 0} (\{L^*\}^{\otimes q} \cdot \{a \in L^* \mid a, 1-a \in L^*\}),$$

where $\{a \in L^* \mid a, 1-a \in L^*\}$ denotes the two-sided ideal of the non-commutative graded ring $\bigoplus_{q \geq 0} (\{L^*\}^{\otimes q})$ generated by elements of the form $a \otimes (1-a)$ with $a, 1-a \in L^*$. The image of an element $a_1 \otimes \cdots \otimes a_q \in (\{L^*\})^{\otimes q}$ in $K^M_q(L)$ is denoted by $\{a_1, \ldots, a_q\}$.\footnote{Recall the definition of a Milnor $K$-sheaf on a point $X = \text{Spec } L$, where $L$ is any field. $K^M_{\text{Spec } L,q,\text{Zar}}$ is the constant sheaf associated to the abelian group $K^M_q(L)$ (without the assumption that $L$ is an infinite field, cf. [Ker10, Prop. 10(4)]), and $K^M_{\text{Spec } L,q,\text{ét}}$ is the étale sheaf associated to the presheaf

$L' \mapsto K^M_q(L')$; $L'/L$ finite separable.

Choose a separable closure $L^\text{sep}$ of $L$. Then the geometric stalk at the geometric point $\text{Spec } L^\text{sep}$ over $\text{Spec } L$ is $\text{colim}_{L \subset L' \subset L^\text{sep}} K^M_q(L')$, which is equal to $K^M_q(L^\text{sep})$ because the filtered colimit commutes with the tensor product and the quotient. Now by Galois descent of the étale sheaf condition, the sheaf $K^M_{\text{Spec } L,q,\text{ét}}$ is precisely

$L' \mapsto K^M_q(L^\text{sep})^\text{Gal}(L^\text{sep}/L')$; $L'/L$ finite separable.

Choose a separable closure $L^\text{sep}$ of $L$. Then the geometric stalk at the geometric point $\text{Spec } L^\text{sep}$ over $\text{Spec } L$ is $\text{colim}_{L \subset L' \subset L^\text{sep}} K^M_q(L')$, which is equal to $K^M_q(L^\text{sep})$ because the filtered colimit commutes with the tensor product and the quotient. Now by Galois descent of the étale sheaf condition, the sheaf $K^M_{\text{Spec } L,q,\text{ét}}$ is precisely

$L' \mapsto K^M_q(L^\text{sep})^\text{Gal}(L^\text{sep}/L')$; $L'/L$ finite separable.
Here the Galois action is given on each factor, according to the very definition of the étale presheaf $K_{X,q,\mathrm{ét}}^\delta$.

Let $X$ be a separated scheme of finite type over $k$ of dimension $d$. Now with the topology $t = \mathrm{Zar}$ or $t = \mathrm{ét}$, we have the corresponding Gersten complex of Milnor $K$-theory, denote by $C^M_{X,t}$ (the differentials $d^M$ will be introduced below):

\[(3.0.1) \quad \bigoplus_{x \in X(0)} t_xK^M_{x,d,t} \xrightarrow{d^M} \bigoplus_{x \in X(1)} t_xK^M_{x,1,t} \xrightarrow{d^M} \bigoplus_{x \in X(n)} t_xK^M_{x,0,n,t},\]

where $t_x : \mathrm{Spec} k(x) \hookrightarrow X$ the natural inclusion map. As part of the convention,

\[(3.0.2) \quad (C^M_{X,t})^i = \bigoplus_{x \in X_{-i}} t_xK^M_{x,-i,t}.\]

In other words, $(3.0.1)$ sits in degrees $[-d, 0]$.

It remains to introduce the differential maps.

When $t = \mathrm{Zar}$, the differential map $d^M$ in $(3.0.1)$ is defined in the following way. Let $x \in X(q)$ be a dimension $q$ point, and $\rho : X' \to \{x\}$ be the normalization map. Define

\[(d^M)^e_y : K^M_q(x) = K^M_q(k(x)) \xrightarrow{\rho^e_y} \bigoplus y' \in X(n-1) K^M_q(y) \xrightarrow{\left(\sum \mathrm{Nm}_{y'/y}\right)} K^M_q(y).\]

Here we have used the shortened symbol $K^M_q(x) := K^M_q(k(x))$. The notation $y' | y$ means that $y' \in X^{(1)}$ is in the fiber of $y$.

\[(3.0.3) \quad \partial_y^e : K^M_q(x') \to K^M_q(y')\]

is the Milnor tame symbol defined by $y'$. And

\[(3.0.4) \quad \partial_y^e : K^M_q(x') \to K^M_q(y')\]

is the Milnor norm map of the finite field extension $k(y') \subset k(y)$. The differential $d^M$ of this complex is given by

\[(d^M)^e_y : K^M_q(x) \to \bigoplus y \in X(n-1) K^M_q(y).\]

There are different sign conventions concerning the tame symbol in the literature and we clarify the one that we adopt. Following [Ros96, p.328], we define the tame symbol $\partial_{\mathrm{Spec} L} : K^M_n(L) \to K^M_{n-1}(k(v))$ for a field $L$, a normalized discrete valuation $v$ on $L$ and $k(v)$ the residue field with respect to $v$, via

\[(3.0.5) \quad \partial_v((\pi_v, u_1, \ldots, u_{n-1})) = \{\overline{u}_1, \ldots, \overline{u}_{n-1}\}.\]

Here $\pi_v$ is a local parameter with respect to $v$, $u_1, \ldots, u_{n-1}$ are units in the valuation ring of $v$, and $\overline{u}_1, \ldots, \overline{u}_{n-1}$ are the images of $u_1, \ldots, u_{n-1}$ in the residue field $k(v)$.

When $t = \mathrm{ét}$, set $x \in X(q)$, $y \in X_{(q-1)} \cap \{x\}$. Denote by $\rho : X' \to \{x\}$ the normalization map and denote by $x'$ the generic point of $X'$. One can canonically identify the étale abelian sheaves $K^M_1$ and $\rho_*K^M_{1,q,\mathrm{ét}}$ on $\{x\}$, and thus identify $t_x, K^M_{1,q,\mathrm{ét}}$ and $t_{x'}, \rho_*K^M_{1,q,\mathrm{ét}}$ on $X$. Let $y' \in X^{(1)}$ such that $\rho(y') = y$. Then the componentwise differential map

\[(d^M)^e_y : t_{x'}, K^M_{1,q,\mathrm{ét}} \to t_{y'}, K^M_{1,q-1,\mathrm{ét}}\]

is defined to be the composition

\[(d^M)^e_y = t_{y,*}(\mathrm{Nm}) \circ \rho_* (\partial)\]

Here $\partial := \sum_{y' \in X^{(1)} \cap \left(\rho^{-1}(y)\right)} \partial_{y'}^e$, where

\[(3.0.6) \quad \partial_{y'}^e : t_{x'}, K^M_{1,q,\mathrm{ét}} \to t_{y'}, K^M_{1,q-1,\mathrm{ét}}\]

on $X'$ is defined to be the sheafification of the tame symbol on the presheaf level. Indeed, the tame symbol is a map of étale presheaves by [Ros96, R3a]. And $\mathrm{Nm} := \sum_{y' \in X^{(1)} \cap \left(\rho^{-1}(y)\right)} \mathrm{Nm}_{y'/y}$, where

\[(3.0.7) \quad \mathrm{Nm}_{y'/y} : \rho_*K^M_{1,q-1,\mathrm{ét}} \to K^M_{1,q-1,\mathrm{ét}}\]

on $y$ is defined to be the sheafification of the norm map on the presheaf level. The norm map is a map of étale presheaves by [Ros96, R1c].
The complex $C^M_X$, either $t = \text{Zar}$ or $t = \text{ét}$, is covariant for proper morphisms and contravariant for quasi-finite flat morphisms ([Ros96, (4.6)(1)(2)]). The pushforward map associated to a proper morphism is induced by the Milnor norm map, and the pullback map associated to a quasi-finite flat morphism is induced by the pullback map of the structure sheaves.

4. Kato-Moser’s complex of logarithmic de Rham-Witt sheaves $\tilde{\nu}_{n,t}$

Let $X$ be a separated scheme of finite type over $k$ of dimension $d$. Kato first defined the Gersten complex of the logarithmic de Rham-Witt sheaves in [Kat86a, §1]. Moser in [Mos99, (1.3)-(1.5)] sheafified Kato’s construction on the étale site and studied its dualizing properties. We will adopt here the sign conventions in [Ros96].

Let $Y$ be a $k$-scheme. Let $q \in \mathbb{N}$ be an integer. Recall that in Section 1.2.5, we have defined $W_n\Omega^q_{Y,\log,t}$, with either $t = \text{Zar}$ or $t = \text{ét}$, to be the abelian subsheaf of $W_n\Omega^q_{k(x),\log}$ étale locally generated by log forms. We will freely use $W_n\Omega^q_{\text{Spec } L,\log,t}$ for $W_n\Omega^q_{\text{Spec } L,\log}$ below.

Now let $X$ be a separated scheme of finite type over $k$ of dimension $d$. Define the Gersten complex $\tilde{\nu}_{n,t}$, in the topology $t = \text{Zar}$ or $t = \text{ét}$, to be the complex of $t$-sheaves isomorphic to $C^M_X/p^n$ via the Bloch-Gabber-Kato isomorphism [BK86, 2.8]:

\[
\begin{align*}
0 \to & \bigoplus_{x \in X(0)} t_xW_n\Omega^0_{k(x),\log,t} \to \bigoplus_{x \in X(1)} t_xW_n\Omega^1_{k(x),\log} \to \bigoplus_{x \in X(0)} t_xW_n\Omega^0_{k(x),\log,t} \to 0.
\end{align*}
\]

Here $t_x : \text{Spec } k(x) \to X$ is the natural map. We will still denote by $\partial$ the reduction of the tame symbol $\partial$ mod $p^n$ (cf. (3.0.2)(3.0.5)), but denote by $\text{tr}$ the reduction of Milnor’s norm $Nm \mod p^n$ (cf. (3.0.3)(3.0.6)). The reason for the later notation will be clear from Lemma 5.3. As part of the convention, $\tilde{\nu}_{n,X,t}$ is concentrated in degrees $[-d,0]$.

Proposition 4.1. Let $i : Z \hookrightarrow X$ be a closed immersion with $j : U \to X$ its open complement. We have the following short exact sequence for $t = \text{Zar}$:

\[
\begin{array}{c}
0 \longrightarrow i_*\tilde{\nu}_{n,Z,\text{Zar}} \longrightarrow \tilde{\nu}_{n,X,\text{Zar}} \longrightarrow j_*\tilde{\nu}_{n,U,\text{Zar}} \longrightarrow 0.
\end{array}
\]

For $t = \text{ét}$, one has the localization triangle

\[
i_*\tilde{\nu}_{n,Z,\text{ét}} \to \tilde{\nu}_{n,X,\text{ét}} \to Rj_*\tilde{\nu}_{n,U,\text{ét}} \xrightarrow{+1} .
\]

Proof. $\tilde{\nu}_{n,X,\text{Zar}}$ is a complex of flasque sheaves (therefore $Rj_*\tilde{\nu}_{n,X,\text{Zar}} = j_*\tilde{\nu}_{n,X,\text{Zar}}$), and one has the sequence being short exact in this case. When $t = \text{ét}$, the purity theorem holds [Mos99, Corollary on p.130], i.e., $i_*\tilde{\nu}_{n,Z,\text{ét}} = \bigoplus x \in X_{(q)} \tilde{\nu}_{n,x,\text{ét}} \xrightarrow{\gamma} R\Gamma^e_x(\tilde{\nu}_{n,X,\text{ét}})$. We are done with the help of the distinguished triangle (1.5.3) in the étale topology.

Functionality of $\tilde{\nu}_{n,X,t}$ is the same as that of $C^M_X$, via $d\log$. We omit the statement.

Part 2. The maps

5. Construction of the chain map $\zeta_{n,X,\log,t} : C^M_X \to K_{n,X,\log,t}$

5.1. Construction of the chain map $\zeta_{n,X,\log,t} : C^M_X \to K_{n,X,\log,t}$. Let $x \in X_{(q)}$ be a dimension $q$ point. $t_x : \text{Spec } k(x) \to X$ is the canonical map and $i_x : \{x\} \hookrightarrow X$ the closed immersion. At degree $i = -q$, and over a point $x$, we define the degree $i$ map to be $\zeta_{n,x,t} := \sum x \in X_{(q)} \tilde{\nu}_{n,x,t}$, with

\[
\begin{align*}
\zeta_{n,x,t} : & (W_n t_x)_*K^M_{x,q,t} \overset{\text{dlog}}{\longrightarrow} (W_n t_x)_*W_n\Omega^q_{k(x),\log,t} \subset (W_n t_x)_*W_n\Omega^q_{k(x),t} \\
& = (W_n t_x)_*K^M_{x,1} \xrightarrow{(-1)^i \text{Tr} t} K^M_{n,x,t}.
\end{align*}
\]

We will use freely the notation $\zeta_{n,X,t}$ with some of its subscript or superscript dropped.

It’s worth noticing that all the maps of étale sheaves involved here are given by the sheafification of the respective Zariski maps on the étale presheaf level. So to check commutativity of a composition of such maps between étale sheaves, it suffices to check on the $t = \text{Zar}$ level. Keeping the convention as before, we usually omit the subscript Zar when we are working over the Zariski topology.
Proposition 5.1. Let $X$ be a separated scheme of finite type over $k$ with $k$ being a perfect field of characteristic $p > 0$. For $t = \text{Zar}$ and $t = \text{ét}$, the map

$$\zeta_{n,X,t} : C^M_{X,t} \rightarrow K_{n,X,t},$$

as defined termwise in (5.1.1), is a chain map of complexes of sheaves on the site $(W_n X)_t$.

Note that we have a canonical identification $(W_n X)_t = X_t$ for both $t = \text{Zar}$ and $t = \text{ét}$. We use $(W_n X)_t$ just for the convenience of describing the $W_n \mathcal{O}_X$-structure of residual complexes appearing later.

Proof. To check $\zeta_{n,X,t}$ is a map of complexes, it suffices to check that the diagram

$$(C^M_{X,t})^i \xrightarrow{d^M_{n,i}} (C^M_{X,t})^{i+1}$$

commutes for $t = \text{Zar}$. To this end, it suffices to show: for each $x \in X(q)$, and $y \in X(q-1)$ which is a specialization of $x$, the diagram

$$(5.1.2) \quad (W_n\iota_{x})_* K^M_{X,y,q} \xrightarrow{(d^M_{n,y})_{\iota}} (W_n\iota_{y})_* K^M_{y,q-1}$$

commutes (denotes the canonical closed immersion).

Since the definition of the differential maps in $C^M_X$ involves normalization, consider the normalization $\rho : X' \rightarrow \{x\}$ of $\{x\}$, and form the cartesian square

$$\begin{array}{ccc}
\{y\} \times_{\{x\}} X' & \xrightarrow{i_{y,x}} & X' = \{x'\} \\
\{y\} & \xrightarrow{i_{y,x}} & \{x\}.
\end{array}$$

Denote the generic point of $X'$ by $x'$. Suppose $y'$ is one of the generic points of the irreducible components of $\{y\} \times_{\{x\}} X'$, and denote by $Y'$ the irreducible component corresponding to $y'$. In particular, $y'$ is a codimension 1 point in the normal scheme $X'$, thus is regular. Because the base field $k$ is perfect, $y'$ is also a smooth point in $X'$. According to Remark 1.2, the degree $[-q, -q + 1]$ terms of $K_{n,X'}$ are of the form

$$(W_n\iota_{x'})_* H^0_{x'}(W_n\Omega^q_{X'}) \xrightarrow{\delta} \bigoplus_{y' \in X'(q-1)} (W_n\iota_{y'})_* H^1_{y'}(W_n\Omega^q_{X'}) \rightarrow \ldots,$$

where $\delta$ denotes the differential map of the Cousin complex $K_{n,X}$. After localizing at a single $y' \in X'(1)$ in the Zariski sense, one gets

$$(W_n\iota_{x'})_* H^0_{x'}(W_n\Omega^q_{X'}) \xrightarrow{\delta_{y'}} (W_n\iota_{y'})_* H^1_{y'}(W_n\Omega^q_{X'}) \rightarrow \ldots.$$
Consider the following diagrams. Write \( i_{x'} : \text{Spec } k(x') \hookrightarrow X' \), \( i_{y'} : \text{Spec } k(y') \hookrightarrow X' \) the inclusions, \( i_{y',x'} : Y' = \{ y' \} \hookrightarrow X' \) the closed immersion, we have a diagram

\[
(W_n i_{x'})_* K^M_{x',q} \xrightarrow{\partial^i_{x'}} (W_n i_{y'})_* K^M_{y',q-1}
\]
\[
\xrightarrow{d \log} (W_n i_{y'})_* W_n \Omega^q_{y,k(y')} \xrightarrow{d \log} (W_n i_{y'})_* \Omega^q_{k(y')}^{-1}
\]
\[
\delta_{y'} \xrightarrow{- \text{Tr}_{W_n(i_{y'},x')}} (W_n i_{y'})_* H^1_{y'}(W_n \Omega^q_{X'})
\]

For any \( y' \in \rho^{-1}(y) \subset X^{(1)} \), we have a diagram

\[
(W_n \rho)_* K^M_{y',q-1} \xrightarrow{\text{Nm}_{y'/y}} K^M_{y,q-1}
\]
\[
\xrightarrow{d \log} (W_n \rho)_* W_n \Omega^q_{y,k(y')} \xrightarrow{d \log} W_n \Omega^q_{k(y)}^{-1}
\]

Write \( i_{y',x'} : Y' = \{ y' \} \hookrightarrow X' \), \( i_{y,x} : \{ y \} \hookrightarrow \{ x \} \), we have a diagram

\[
(W_n \rho)_* (W_n i_{y'})_* W_n \Omega^q_{y,k(y')} \xrightarrow{\text{Tr}_{W_n(i_{y'},x')}} (W_n i_{y'})_* W_n \Omega^q_{k(y)}^{-1}
\]
\[
\xrightarrow{\text{Tr}_{W_n(i_{y},x')}} (W_n \rho)_* (W_n i_{y'})_* H^1_{y'}(W_n \Omega^q_{X'}) \xrightarrow{\text{Tr}_{W_n(i_{y},x')}} K^{-q}_{n,[x]}
\]

and a diagram

\[
(W_n i_{x'})_* W_n \Omega^q_{k(x')} \xrightarrow{\Delta_{x'} = \sum \delta_{y'}} \bigoplus_{y' \in \rho^{-1}(y)} (W_n i_{y'})_* H^1_{y'}(W_n \Omega^q_{X'})
\]
\[
\xrightarrow{\text{Tr}_{W_n(i_{y},x')}} K^{-q}_{n,[x]}
\]

All the trace maps above are trace maps of residual complexes at a certain degree. (5.1.5) is the degree \( q - 1 \) part of the diagram

\[
(W_n \rho)_* (W_n i_{y',x'})_* K_{n,Y'} \xrightarrow{\text{Tr}_{W_n,i_{y',x'}}} (W_n i_{y,x})_* K_{n,[x]}
\]

(the trace map on top is the trace map of the restriction of \( W_n \rho \) to \( W_n Y' \)), and thus is commutative by the functoriality of the Grothendieck trace map with respect to composition of morphisms [Con00, 3.4.1(2)]. (5.1.6) is simply the degree \(-q\) to \(-q+1\) terms of the trace map \( \text{Tr}_{W_n,i} : (W_n \rho)_* K_{n,X'} \to K_{n,[x]} \), thus is also commutative. It remains to check the commutativity of (5.1.3) and (5.1.4). And these are Lemma 5.2 and Lemma 5.3.
One notices that diagram (5.1.2) decomposes into the four diagrams (5.1.3)-(5.1.6):

\[
\begin{array}{c}
(W_n)_*(W_{t_x}^*), K_{x',q}^M & \xrightarrow{d\log} & (W_n)_*(W_{t_y}^*), K_{y',q-1}^M \\
(5.1.3) & & (5.1.4)
\end{array}
\]

\[
\begin{array}{c}
(W_n)_*(W_{t_x}^*), W_n^\Omega_{y'}^{-1} & \xrightarrow{\delta y'} & (W_n)_*(W_{t_y}^*), W_n^\Omega_{y'}^{-1}
\end{array}
\]

\[
\begin{array}{c}
\text{Tr}_{W_n^\rho} & \xrightarrow{\delta y'} & \text{Tr}_{W_n^\rho}
\end{array}
\]

\[
\begin{array}{c}
K_{q,n,x}^{-\rho} & \xrightarrow{d\log} & K_{q,n,x}^{-\rho}
\end{array}
\]

Here by symbol \(y'|y\) we mean that \(y' \in \rho^{-1}(y)\). Notice that we have added a minus sign to both vertical arrows of (5.1.5) in the corresponding square above, but this does not affect its commutativity. Since one can canonically identify

\[
(W_n)_*(W_{t_x}^*), K_{x',q}^M \quad \text{with} \quad (W_n)_*(W_{t_x}^*), K_{x',q}^M,
\]
to show the commutativity of the diagram (5.1.2), it only remains to show Lemma 5.2 and Lemma 5.3. \(\square\)

**Lemma 5.2.** For an integral normal scheme \(X'\), with \(x' \in X'\) being the generic point and \(y' \in X'^{(1)}\) being a codimension 1 point, the diagram (5.1.3) is commutative.

**Proof.** Given a \(y' \in X'^{(1)}\) lying over \(y\), \(K_q^M(x')\) is generated by

\[
\{\pi', u_1, \ldots, u_{q-1}\} \quad \text{and} \quad \{v_1, \ldots, v_{q-1}, v_q\}
\]
as an abelian group, where \(u_1, \ldots, u_{q-1}, v_1, \ldots, v_{q-1}, v_q \in \mathcal{O}_{X',y'}\), and \(\pi'\) is a chosen uniformizer of the discrete valuation ring \(\mathcal{O}_{X',y'}\). It suffices to check the commutativity for these generators.

In the first case, the left-bottom composition gives

\[
(\delta_{y'} \circ d\log)(\{\pi', u_1, \ldots, u_{q-1}\}) = \delta_{y'}(d\log[\pi']_n d\log[u_1]_n \ldots d\log[u_{q-1}]_n) = \left[ d[\pi']_n d\log[u_1]_n \ldots d\log[u_{q-1}]_n \bigg/ [\pi']_n \right].
\]
The last equality above is given by [CR11, A.1.2]. Here we have used the fact that \([\pi']\) is a regular element in \(W_nX'\), since \(\pi'\) is regular in \(X'\). The top-right composition gives

\[
-\text{Tr}_{W_n(i_y',x')} \circ d\log \circ \delta_{y'}'(\{\pi', u_1, \ldots, u_{q-1}\}) = -\text{Tr}_{W_n(i_y',x')} \circ d\log \{\pi', u_1, \ldots, u_{q-1}\} = -\text{Tr}_{W_n(i_y',x')} \circ d\log(\{\pi']_n \ldots d\log(\{\pi']_n) = \left[ d[\pi']_n d\log[\pi']_n \ldots d\log[\pi']_n \bigg/ [\pi']_n \right].
\]
The last equality is given by [CR11, A.2.12]. So the diagram (5.1.3) is commutative in this case.

In the second case, since \(\delta_{y'}'(\{v_1, v_2, \ldots \}) = 0\), we need to check the left-bottom composite also gives zero. In fact,

\[
(\delta_{y'} \circ d\log)(\{v_1, \ldots, v_q\}) = \delta_{y'}(d\log[v_1]_n \ldots d\log[v_q]_n) = \left[ [\pi']_n \cdot d\log[v_1]_n \ldots d\log[v_q]_n \bigg/ [\pi']_n \right] = 0.
\]
The second equality is due to [CR11, A.1.2]. The last equality is because, in a small neighborhood \(V\) of \(y'\), the element \([\pi']_n \cdot d\log[v_1]_n \ldots d\log[v_q]_n \in W_n\Omega_{y'}^1\) lies in the \(W_n\mathcal{O}_V\)-submodule \([\pi']_n \cdot W_n\Omega_{y'}^1\). \(\square\)
Lemma 5.3 (Compatibility of Milnor norm and Grothendieck trace). Let \( F/E \) be a finite field extension with both fields \( E \) and \( F \) being of transcendence degree \( q-1 \) over \( k \). Suppose there exists a finite morphism \( g \) between integral separated finite type \( k \)-schemes, such that \( F \) is the function field of the source of \( g \) and \( E \) is the function field of the target of \( g \), and the field extension \( F/E \) is induced via the map \( g \). Then the following diagram commutes

\[
\begin{align*}
K_{q-1}^M(F) & \xrightarrow{Nm_{F/E}} K_{q-1}^M(E) \\
W_n\Omega_{E/k}^{q-1} & \xrightarrow{\text{Tr}_{W_n,g}} W_n\Omega_{E}^{q-1}.
\end{align*}
\]

Here the norm map \( Nm_{F/E} \) denotes the norm map from Milnor \( K \)-theory, and \( \text{Tr}_{W_n,g} \) denotes the Grothendieck trace map associated to the finite morphism \( g \).

Remark 5.4. The compatibility of the trace map with the norm and the pushforward of cycles in various settings has been a folklore, and many definitions and properties of the trace map in the literature reflect this viewpoint. But since we have not found a proof of the compatibility of the Milnor norm with the trace map defined via the Grothendieck duality theory, we include a proof here.

Proof. We start the proof by some reductions. Since both \( Nm_{F/E} \) and \( Tr_{F/E} \) are independent of the choice of towers of simple field extensions, without loss of generality, one could suppose \( F \) is a finite simple field extension over \( E \). Now \( F = E(a) = \frac{E[T]}{f(T)} \) for some monic irreducible polynomial \( f(T) \in E[T] \) with \( a \in F \) being one of its roots. This realizes \( \text{Spec } F \) as an \( F \)-valued point \( P \) of \( \mathbb{P}^1_E \), namely,

\[
\text{Spec } F = P \xrightarrow{ip} \mathbb{P}^1_E \xrightarrow{g} \text{Spec } E.
\]

All the three morphisms on above are morphisms of finite type (although not between schemes of finite type over \( k \)), so it makes sense to talk about the associated trace maps for residual complexes. But for the particular residual complexes we are interested in, we need to enlarge the schemes involved to schemes of finite type over \( k \), while preserving the morphism classes (e.g., closed immersion, smooth morphism, etc) of the morphisms between them.

To this end, take \( Y \) to be any separated smooth connected scheme of finite type over \( k \) with \( E \) being the function field. Since \( \mathbb{P}^1_k \) is the generic fiber of \( Y \times_k \mathbb{P}^1_k \), by possibly shrinking \( Y \) to an affine neighborhood \( \text{Spec } B \) of \( pr_1(P) \) (here \( \text{pr}_1 : Y \times_k \mathbb{P}^1_k \to Y \) is the first projection map) one can extend the above diagram to the following:

\[
\begin{align*}
\text{Spec } F & \in W^C \xrightarrow{iw} \mathbb{P}^1_Y \xrightarrow{g} Y = \text{Spec } B \supset \text{Spec } E.
\end{align*}
\]

Here \( W := \overline{\{P\}^P} \) is the closure of the point \( P \) in \( \mathbb{P}^1_Y \). This is a commutative diagram of finite type \( k \)-schemes. In particular, it makes sense to talk about the residual complexes \( K_{n,Y}, K_{n,W} \) and \( K_{n,P^1} \).

Now it remains to show the commutativity of the following diagram

\[
(5.1.7) \quad K_{q-1}^M(E(a)) \xrightarrow{Nm_{E(a)/E}} K_{q-1}^M(E) \xrightarrow{d\log} W_n\Omega_{E/k}^{q-1} \xrightarrow{\text{Tr}_{W_n,g}} W_n\Omega_{E}^{q-1},
\]

where \( \text{Tr}_{W_n,g} \) denotes the trace map for residual complexes \( \text{Tr}_{W_n,g} : (W_n,g)_*K_{n,W} \to K_{n,Y} \) at degree \(-q-1\).

We do induction on \( |E(a) : E| \). When \( |E(a) : E| = 1 \), then both the Grothendieck trace \( \text{Tr}_{W_n,g} : W_n\Omega_{E/k}^{q-1} \to W_n\Omega_{E}^{q-1} \) and the norm map \( Nm_{E(a)/E} : K_{q-1}^M(E(a)) \to K_{q-1}^M(E) \) are the identity, therefore the claim holds. Now the induction step. Suppose the diagram (5.1.7) commutes for \( |E(a) : E| \leq r-1 \). We will need to prove the commutativity for \( |E(a) : E| = r \).
First note that \( \text{Tr}_{W_n,g} : (W_n,g)_*, K_{n,Y} \to K_{n,Y} \) naturally decomposes into

\[
(W_n g)_* K_{n,W} \xrightarrow{(W_n \pi)_* \text{Tr}_{W_n,g}^W} (W_n \pi)_* K_{n,P_Y} \xrightarrow{\text{Tr}_{W_n \pi}} K_{n,Y}.
\]

by [Con00, 3.4.1(2)]. \( H^1_P(W_n, \Omega^q_{P_E}) \) is a direct summand of the degree \(-(q - 1)\) part of \( K_{n,P_Y} \). One can canonically identify

\[
H^1_P(W_n, \Omega^q_{P_E}) = H^1_P(W_n, \Omega^q_{E_P}),
\]

via pulling back along the natural map \( P_Y \to P_E \). Thus on degree \(-(q - 1)\) and at the point \( P \), the map (5.1.8) is canonically identified with

\[
W_n \Omega^q_{E(T)} \xrightarrow{\text{Tr}_{W_n,\pi}^W} H^1_P(W_n, \Omega^q_{P_E}) \xrightarrow{\text{Tr}_{W_n \pi}} W_n \Omega^{q-1}_{E}.
\]

We have used the identification (5.1.9) in this diagram. We have seen that the left square is commutative up to sign \(-1\), as a special case of Lemma 5.2 (i.e. take normal scheme \( X' = P_E \) and \( Y' := P = \text{Spec } F \)). Since \( \partial_P \) is surjective, to show the commutativity of the trapezoid on the right, it suffices to show that the composite square is commutative up to \(-1\). For any element

\[
s := \{ s_1, \ldots, s_{q-1} \} \in K^M_{q-1}(E(a)),
\]

one can always find a lift

\[
\tilde{s} := \{ \tilde{s}_1, \ldots, \tilde{s}_{q-1} \} \in K^M_{q}(E(T)),
\]

such that each of the \( s_i = s_i(T) \) is a polynomial of degree \( \leq r - 1 \) (e.g. decompose \( E(a) \) as a \( r \)-dimensional \( E \)-vector space \( E(a) = \bigoplus_{j=0}^{r-1} Ea^j \) and suppose \( s_i = \sum_{j=0}^{r-1} b_{i,j}a^j \) with \( b_{i,j} \in E \), then \( \tilde{s}_i = \tilde{s}_i(T) = \sum_{j=0}^{r-1} b_{i,j} T^j \) satisfies the condition), and \( \partial_P(s) = s \). Denote by

\[
y_1, \ldots, y_{n,a_i} \quad (1 \leq i \leq q - 1)
\]

the closed points of \( P^1_E \) corresponding to the irreducible factors of the polynomials \( \tilde{s}_1, \ldots, \tilde{s}_{q-1} \). Note that the local section \( \tilde{s}_{i,l} \) cutting out \( y_{i,l} \) is by definition an irreducible factor of \( \tilde{s}_i \), and therefore \( \deg \tilde{s}_{i,l} < r \) for all \( i \) and all \( l \).

We claim that

\[
\sum_{y \in (P^1_E)_{(0)}} (\text{Tr}_{W_n,\pi})_y \circ \delta_y = 0 : W_n \Omega^q_{E(T)/k} \to W_n \Omega^{q-1}_{E/k}.
\]

In fact,

\[
0 \to W_n \Omega^q_{P_E} \to W_n \Omega^q_{E(T)} \xrightarrow{\bigoplus_{y \in (P^1_E)_{(0)}} (W_n \tau_y)_* H^1_W(W_n, \Omega^q_{P_E})} 0
\]

is an exact sequence [CR12, 1.5.9], where \( \tau_y : y \to P^1_E \) is the natural inclusion of the point \( y \). Taking the long exact sequence with respect to the global section functor, one arrives at the following diagram with the row being a complex

\[
W_n \Omega^q_{E(T)} \xrightarrow{\delta} \bigoplus_{y \in (P^1_E)_{(0)}} H^1_P(W_n, \Omega^q_{P_E}) \xrightarrow{\text{Tr}_{W_n \pi}} H^1(P^1_E, W_n \Omega^q_{P_E})
\]

\[
\xrightarrow{\sum_{y \in (P^1_E)_{(0)}} (\text{Tr}_{W_n,\pi})_y} W_n \Omega^{q-1}_{E/k}.
\]

The trace maps on left of the above are induced from the degree 0 part of \( \text{Tr}_{W_n,\pi} : (W_n \pi)_* K_{n,P_Y} \to K_{n,Y} \). The trace map on the right of the above is induced also by \( \text{Tr}_{W_n,\pi} : (W_n \pi)_* K_{n,P_Y} \to K_{n,Y} \), while the global cohomology group is calculated via (5.1.11), i.e., one uses the last two terms of (5.1.11) as an
injective resolution of the sheaf $W_n\Omega^1_{\mathbb{P}^1_E}$, and then $\text{Tr}_{W_n, \pi}: (W_n, \pi)_*K_{n, \mathbb{P}^1_Y} \to K_{n, Y}$ induces the map of complexes on global sections (sitting in degrees $[-1, 0]$), and then the map of cohomologies on degree 0 gives our trace map $H^1(\mathbb{P}^1_E, W_n\Omega^1_{\mathbb{P}^1_E}) \to W_n\Omega^1_{\mathbb{P}^1_E}$ on the right. From the construction of these trace maps, the diagram on above is by definition commutative. Therefore (5.1.10) holds.

One notices that $\delta_y \circ d \log(\tilde{s}) = 0$ unless $y \in \{ p, y_1, \ldots, y_{q-1}, a_{q-1}, \infty \}$. Now calculate

$$
(\text{Tr}_{W_n, g} \circ d \log)(s) = -(\text{Tr}_{W_n, g} \circ d \log \circ \partial_P)(\tilde{s}) \quad \text{(Lemma 5.2)}
$$

$$
= - \sum_{y \in \{ y_1, \ldots, y_{q-1}, a_{q-1}, \infty \}} (\text{Tr}_{W_n, \pi})_y \circ \delta_y \circ d \log(\tilde{s}) \quad \text{(5.1.10)}
$$

$$
= - \sum_{y \in \{ y_1, \ldots, y_{q-1}, a_{q-1}, \infty \}} (d \log \circ \text{Nm}_{E(k(y))/E} \circ \partial_P)(\tilde{s}) \quad \text{(induction hypothesis)}
$$

$$
= (d \log \circ \text{Nm}_{E(q)/E} \circ \partial_P)(s) \quad \text{([Ros96, 2.2 (RC)])}
$$

This finishes the induction. \qed

5.2. **Functoriality of $\zeta_{n, X, t}: C^M_{X, t} \to K_{n, X, t}$**. Let $k$ denote a perfect field of positive characteristic $p$.

**Proposition 5.5** (Proper pushforward). $\zeta$ is compatible with proper pushforward. I.e., for $f: X \to Y$ a proper map, the following diagram is commutative

$$
(W_n, f)_*C^M_{X, t} \xrightarrow{\zeta_{n, X, t}} (W_n, f)_*K_{n, X, t} \xrightarrow{f_*} K_{n, Y, t}.
$$

Here $f_*$ on the left denotes the pushforward map for Kato’s complex of Milnor $K$-theory (cf. Section 3), and $f_*$ on the right denotes the Grothendieck trace map $\text{Tr}_{W_n, f, t}$ for residual complexes.

**Proof.** We only need to prove the proposition for $t = \text{Zar}$ and for degree $i \in [-d, 0]$. Then by the very definition of the $\zeta$ map and the compatibility of the trace map with morphism compositions [Con00, 3.4.1(2)], it suffices to check the commutativity at points $x \in X(q)$, $y \in Y(q)$, where $q = -i$:

$$
\begin{align*}
K^M_q(x) & \xrightarrow{d \log} W_n\Omega^q_{k(x)} \\
& \xrightarrow{f_*} W_n\Omega^q_{k(y)} \\
K^M_q(y) & \xrightarrow{d \log} W_n\Omega^q_{k(y)}.
\end{align*}
$$

(1) When $y \neq f(x)$, both pushforward maps are zero maps, therefore we have the desired commutativity.

(2) When $y = f(x)$, by definition of $\zeta$ and the pushforward maps, we need to show commutativity of the following diagram for finite field extension $k(y) \subset k(x)$

$$
\begin{align*}
K^M_q(x) & \xrightarrow{d \log} W_n\Omega^q_{k(x)} \\
& \xrightarrow{\text{Nm}_{k(x)/k(y)}} W_n\Omega^q_{k(y)} \\
K^M_q(y) & \xrightarrow{d \log} W_n\Omega^q_{k(y)}.
\end{align*}
$$

This is precisely Lemma 5.3. \qed
Proposition 5.6 (Étale pullback). \( \zeta \) is compatible with étale pullbacks. I.e., for \( f : X \rightarrow Y \) an étale morphism, the following diagram is commutative

\[
\begin{array}{ccc}
C^M_{Y,t} & \xrightarrow{\zeta_{n,Y,t}} & K_{n,Y,t} \\
\downarrow f^* & & \downarrow f^* \\
(W_n f)_* C^M_{X,t} & \xrightarrow{\zeta_{n,X,t}} & (W_n f)_* K_{n,X,t}.
\end{array}
\]

Here \( f^* \) on the left denotes the pullback map for Kato’s complex of Milnor \( K \)-theory (cf. Section 3), and \( f^* \) on the right denotes the pullback map for residual complexes (1.4.1).

Proof. It suffices to prove the proposition for \( t = \text{Zar} \). Take \( y \in Y_{(q)} \). Consider the cartesian diagram

\[
X \times_Y \{ y \} =: W \xrightarrow{f|_W} \{ y \} \\
\downarrow i_W & \downarrow i_y \\
X & \xrightarrow{f} Y.
\]

Then the desired diagram at point \( y \) decomposes in the following way at degree \(-q\):

\[
\begin{array}{cccc}
K^M_q(y) & \xrightarrow{d_{\log}} & W_n \Omega^q_{k(y)} & \text{Tr}_{W_n Y} \\
\downarrow f^* & & \downarrow (f|_W)^* \\
\bigoplus_{x \in W(q)} K^M_q(x) & \xrightarrow{d_{\log}} & \bigoplus_{x \in W(q)} W_n \Omega^q_{k(x)} & \text{Tr}_{W_n Y}.
\end{array}
\]

The left square commutes because both \( f^* \) and \((f|_W)^*\) are induced by the natural map \( f^* : O_Y \rightarrow f_* O_X \).

The right square commutes due to Lemma 1.24. \( \square \)

5.3. Extend to \( K_{n,X,\text{log},t} \). Recall the complex \( K_{n,X,\text{log},t} := \text{Cone}(K_{n,X,t} \xrightarrow{C^M_{i-1}t} K_{n,X,t})[-1] \), i.e.,

\[
K_i^{n,X,\text{log},t} = K_i^{n,X,t} \oplus K^{i-1}_{n,X,t}.
\]

Notice that

\[
(5.3.1) \quad K_{n,X,t} \rightarrow K_{n,X,\text{log},t}, \quad a \mapsto (a,0)
\]

is not a chain map. Nevertheless,

Proposition 5.7. We keep the same assumptions as in Proposition 5.1. The chain map \( \zeta_{n,X,t} : C^M_{X,t} \rightarrow K_{n,X,t} \) composed with (5.3.1) gives a chain map

\[
\zeta_{n,X,\text{log},t} := (5.3.1) \circ \zeta_{n,X,t} : C^M_{X,t} \rightarrow K_{n,X,\text{log},t}
\]

of complexes of abelian sheaves on \( (W_n X)_t \).

We will also use the shortened notation \( \zeta_{\text{log},t} \) for \( \zeta_{n,X,\text{log},t} \). When \( t = \text{Zar} \), the subscript Zar will also be omitted.

Proof. Given \( x \in X_{(q)} \), we prove commutativity of the following diagram

\[
\begin{array}{ccc}
t_x K^M_{n,X,q,t} & \xrightarrow{d_{\log}} & t_x W_n \Omega^q_{k(x),\text{log},t} \\
\downarrow \text{Tr}_{W_n t_x} & & \downarrow \text{Tr}_{W_n t_x} \\
K^M_{n,X,q,t} & \xrightarrow{C_t^{n,X,t}} & K^{n,X,t}.
\end{array}
\]

The left square naturally commutes. The right square also commutes, because \( C^t \) is compatible with the Grothendieck trace map \( \text{Tr}_{W_n t_x} \) (the proofs of Proposition 1.20 and Proposition 1.29 give the case for \( t = \text{Zar} \) and \( t = \acute{\text{et}} \), respectively). Now because \( C^{n,X,t}_{(x)} - 1 : W_n \Omega^q_{k(x),t} \rightarrow W_n \Omega^q_{k(x),t} \), which is identified with \( C^{n,X,t}_{(x)} - 1 \) as a result of Theorem 1.7 and Proposition 1.26, annihilates \( W_n \Omega^q_{k(x),\text{log},t} \), the composite of the second row is zero. Thus the composite of the first row is zero. This yields a unique chain map

\[
\zeta_{n,X,\text{log},t} : C^M_{X,t} \rightarrow K_{n,X,\text{log},t}.
\]
i.e., on degree $i = -q$, we have $\zeta_{n,X,\log,t} = \sum_{x \in X^{(q)}} \zeta_{n,x,\log,t}$ with

$$
\zeta_{n,x,\log,t} : K_{x,q,t}^i \to K_{n,X,\log,t}^i = K_{n,X,t}^i \oplus K_{n,x,t}^{i-1}, \quad s = \{s_1, \ldots, s_q\} \mapsto (\zeta_{n,x,t}(s), 0).
$$

As a direct corollary of Proposition 5.5 and Proposition 5.6, one has the following proposition.

**Proposition 5.8 (Functoriality).** (1) $\zeta_{\log,t}$ is compatible with proper pushforward. I.e., for $f : X \to Y$ a proper map, the following diagram of complexes is commutative

\[
\begin{array}{ccc}
(W_n f)_* C_{X,t}^M & \xrightarrow{f_*} & (W_n f)_* K_{n,X,\log,t} \\
\downarrow \zeta_{n,X,\log,t} & & \downarrow f_* \\
C_{Y,t}^M & \xrightarrow{\zeta_{n,Y,\log,t}} & K_{n,Y,\log,t}
\end{array}
\]

Here $f_*$ on the left denotes the pushforward map for Kato’s complex of Milnor $K$-theory (cf. Section 3), and $f_*$ on the right denotes $\text{Tr}_{W_n f, \log,t}$ as defined in Proposition 1.20 and Proposition 1.29.

(2) $\zeta_{\log,t}$ is compatible with étale pullbacks. I.e., for $f : X \to Y$ an étale morphism, the following diagram of complexes is commutative

\[
\begin{array}{ccc}
C_{Y,t}^M & \xrightarrow{f^*} & K_{n,Y,\log,t} \\
\downarrow \zeta_{n,Y,\log,t} & & \downarrow f^* \\
(W_n f)_* C_{X,t}^M & \xrightarrow{\zeta_{n,X,\log,t}} & (W_n f)_* K_{n,X,\log,t}
\end{array}
\]

Here $f^*$ on the left denotes the pullback map for Kato’s complex of Milnor $K$-theory (cf. Section 3), and $f^*$ on the right denotes the pullback map defined in Proposition 1.23.

5.4. $\zeta_{n,X,\log,t} : C_{X,t}^M/p^n \simeq \tilde{\nu}_{n,X,t} \Rightarrow K_{n,X,\log,t}$ is a quasi-isomorphism. Since $\zeta_{n,X,t}$ is termwise defined via the $d\log$ map, it annihilates $p^n C_{X,t}^M$. Therefore $\zeta_{n,X,\log,t}$ annihilates $p^n C_{X,t}^M$ as well, and induces a chain map

$$\zeta_{n,X,\log,t} : C_{X,t}^M/p^n \to K_{n,X,\log,t}.$$

Since the $d\log$ map induces an isomorphism of complexes $C_{X,t}^M/p^n \simeq \tilde{\nu}_{n,X,t}$, to show $\zeta_{n,X,\log,t}$ is a quasi-isomorphism, it is equivalent to show

$$\tilde{\zeta}_{n,X,\log,t} : \tilde{\nu}_{n,X,t} \to K_{n,X,\log,t}$$

is a quasi-isomorphism.

**Lemma 5.9.** Suppose $X$ is separated smooth over the perfect field $k$ of characteristic $p > 0$. Then for any level $n$,

$$\zeta_{n,X,\log,\text{ét}} : \tilde{\nu}_{n,X,\text{ét}} \Rightarrow K_{n,X,\log,\text{ét}}$$

is a quasi-isomorphism. If we moreover have $k = \overline{k}$, then

$$\zeta_{n,X,\log,\text{Zar}} : \tilde{\nu}_{n,X,\text{Zar}} \Rightarrow K_{n,X,\log,\text{Zar}}$$

is also a quasi-isomorphism.

**Proof.** This is a local problem, thus it suffices to prove the statement for each connected component of $X$. Therefore we assume $X$ is of pure dimension $d$ over $k$. Then for any level $n$, we have a quasi-isomorphism ([GS88b, Cor 1.6])

$$W_n \Omega_{X,\log,\text{ét}}^d[d] \xrightarrow{\simeq} \tilde{\nu}_{n,X,t}.$$

We also have

$$W_n \Omega_{X,\log,\text{ét}}^d[d] \xrightarrow{\simeq} K_{n,X,\log,\text{ét}} \quad \text{(by Proposition 1.28)},$$

and

$$W_n \Omega_{X,\log,\text{Zar}}^d[d] \xrightarrow{\simeq} K_{n,X,\log,\text{Zar}} \quad \text{when } k = \overline{k} \text{ (by Proposition 1.19).}$$
On degree $-d$, we have a diagram

$$
\widetilde{\nu}^{-d}_{n,X,t} = \bigoplus_{x \in X^{(0)}} (W_n t_x)_* W_{n,X} \Omega^d_{k(z), \log_t} \rightarrow K^{-d}_{n,X,\log_t} = \bigoplus_{x \in X^{(0)}} (W_n t_x)_* H^0_n (W_n \Omega^d_{X,t})
$$

which is naturally commutative, due to the definition of $\widetilde{\zeta}_{n,X,\log_t}$. It induces quasi-isomorphisms as stated in the lemma.

**Theorem 5.10.** Let $X$ be a separated scheme of finite type over $k$ with $k$ being a perfect field of characteristic $p > 0$. Then the chain map

$$
\widetilde{\zeta}_{n,X,\log_\et}: \widetilde{\nu}_{n,X,\et} \rightarrow K_{n,X,\log_\et}
$$

is a quasi-isomorphism. Moreover if $k = \overline{k}$,

$$
\widetilde{\zeta}_{n,X,\log_\Zar}: \widetilde{\nu}_{n,X,\Zar} \rightarrow K_{n,X,\log_\Zar}
$$

is also a quasi-isomorphism.

**Proof.** One can assume that $X$ is reduced. In fact, the complex $\widetilde{\nu}_{n,X,t}$ is defined to be the same complex as $\widetilde{\nu}_{n,X,\text{red},t}$ (see (4.0.1)), and we have a quasi-isomorphism $K_{n,X,\log_\text{red},t} \xrightarrow{\sim} K_{n,X,\log_t}$ given by the trace map, according to Proposition 1.21 and Proposition 1.30. One notices that $\widetilde{\zeta}_{n,X,\log_\text{red},t}$ is compatible with $\widetilde{\zeta}_{n,X,\log_t}$ because of the functoriality of the map $\zeta_{\log_t}$ with respect to proper maps Proposition 5.8(1).

As long as we have a quasi-isomorphism

$$
\widetilde{\zeta}_{n,X,\log_\text{red},t}: \widetilde{\nu}_{n,X,\text{red},t} \rightarrow K_{n,X,\log_\text{red}},
$$

we get automatically that

$$
\widetilde{\zeta}_{n,X,\log_t}: \widetilde{\nu}_{n,X,t} = \widetilde{\nu}_{n,X,\text{red},t} \rightarrow K_{n,X,\log_t}
$$

is a quasi-isomorphism.

Now we do induction on the dimension of the reduced scheme $X$. Suppose $X$ is of dimension $d$, and suppose $\widetilde{\zeta}_{n,Y,\log_t}$ is a quasi-isomorphism for schemes of dimension $\leq d - 1$. Now decompose $X$ into the singular part $Z$ and the smooth part $U$

$$
U \xrightarrow{\iota} X \xleftarrow{\iota} Z.
$$

Then $Z$ has dimension $\leq d - 1$. Consider the following diagram in the derived category of complexes of $\mathbb{Z}/p^n$-modules

\begin{equation}
(5.4.1)
\begin{array}{ccc}
i_* \tilde{\nu}_{n,Z,t} & \rightarrow & \tilde{\nu}_{n,X,t} \\
\iota_* \tilde{\nu}_{n,Z,\log_t} & \rightarrow & \tilde{\nu}_{n,X,\log_t} \\
\end{array}
\begin{array}{ccc}
\rightarrow & R j_* \tilde{\nu}_{n,U,t} & +1 \\
\rightarrow & R j_* \tilde{\nu}_{n,U,\log_t} & +1 \\
\end{array}
\begin{array}{ccc}
i_* \tilde{\nu}_{n,Z,t}[1] & \rightarrow & i_* \tilde{\nu}_{n,Z,t}[1] \\
i_* K_{n,Z,\log_t} & \rightarrow & i_* K_{n,Z,\log_t}[1], \\
\end{array}
\end{equation}

where the two rows are distinguished triangles coming from Proposition 1.22, Proposition 1.31 and Proposition 4.1. We show that the three squares in (5.4.1) are commutative in the derived category. The left square is commutative because of Proposition 5.8(1). The middle square of (5.4.1) is induced from the diagram

\begin{equation}
(5.4.2)
\begin{array}{ccc}
\tilde{\nu}_{n,X,t} & \rightarrow & j_* \tilde{\nu}_{n,U,t} \\
j_* \tilde{\nu}_{n,X,\log_t} & \rightarrow & j_* \tilde{\nu}_{n,U,\log_t} \\
K_{n,X,\log_t} & \rightarrow & j_* K_{n,U,\log_t} \\
\end{array}
\end{equation}

of chain complexes. Let $x \in X_{(q)}$. When $x \in X_{(q)} \cap U$, both $\tilde{\nu}_{n,X,t} \rightarrow j_* \tilde{\nu}_{n,U,t}$ and $K_{n,X,\log_t} \rightarrow j_* K_{n,U,\log_t}$ give identity maps at $x$, therefore the square (5.4.2) commutes in this case. When $x \in X_{(q)} \cap Z$,
both of these give the zero map at \( x \), therefore the square (5.4.2) is also commutative. The right square of (5.4.1) can be decomposed in the following way (cf. (1.3.4) and (1.5.3)):

\[
\begin{array}{c}
Rj_*\tilde{\nu}_{n,U,t} \overset{+1}{\longrightarrow} R\Gamma_{\mathcal{Z}}(\tilde{\nu}_{n,X,t})[1] \overset{i_*}{\longrightarrow} i_*\tilde{\nu}_{n,Z,t}[1] \\
| Rj_*\overline{\nu}_{n,U,log,t} \quad R\Gamma_{\mathcal{Z}}(\overline{\nu}_{n,X,log,t})[1] \quad i_*\overline{\nu}_{n,Z,log,t}[1]
\end{array}
\]

The map \( i_* \) on the first row is induced by the norm map of Milnor K-theory Section 3. It is clearly an isomorphism of complexes when \( t = \text{Zar} \). It is a quasi-isomorphism when \( t = \text{ét} \) due to the purity theorem [Mos99, p.130 Cor.]. The map \( i_* \) on the second row is induced from \( \text{Tr}_{n,i,\log,t} \) as defined in Proposition 1.20 and Proposition 1.29, and it is an isomorphism due to Proposition 1.22(1) when \( t = \text{Zar} \), and Proposition 1.31 when \( t = \text{ét} \). The first square commutes by naturality of the +1 map. The second commutes because of the compatibility of \( \zeta_{log,t} \) with the proper pushforward Proposition 5.8(1). We thus deduce that the right square of (5.4.1) commutes.

Now consider over any perfect field \( k \) for either of the two cases:

1. \( t = \text{ét} \) and \( k \) is a perfect field, or
2. \( t = \text{Zar} \) and \( k = \mathbb{F} \).

The left vertical arrow of (5.4.1) is a quasi-isomorphism because of the induction hypothesis. The third one counting from the left is also a quasi-isomorphism because of Lemma 5.9. Thus so is the second one. \( \square \)

6. COMBINE \( \psi_{X,t} : \mathbb{Z}_{\mathbb{C}}^c_{X,t} \to C_M^{M}_{X,t} \) WITH \( \zeta_{n,X,log,t} : C_M^{M}_{X,t} \to K_{n,X,log,t} \)

6.1. The map \( \psi_{X,t} : \mathbb{Z}_{\mathbb{C}}^c_{X,t} \to C_M^{M}_{X,t} \). In [Zho14, 2.14], Zhong constructed a map of abelian groups \( \psi_{X,t}(X) : \mathbb{Z}_{\mathbb{C}}^c(X) \to C_M^{M}_{X,\text{Zar}}(X) \) based on the Nesterenko-Suslin-Totaro isomorphism [NS89, Thm. 4.9][Tot92]. It is straightforward to check that Zhong’s construction induces a well-defined map of complexes \( \psi := \psi_{X,t} : \mathbb{Z}_{\mathbb{C}}^c_{X,t} \to C_M^{M}_{X,t} \) of sheaves for both \( t = \text{Zar} \) and \( t = \text{ét} \). Zhong in [Zho14, 2.15] proved that \( \psi \) is covariant with respect to proper morphisms, and contravariant with respect to quasi-finite flat morphisms.

6.2. \( \overline{\zeta}_{n,X,log,t} \circ \overline{\psi}_{X,t} : \mathbb{Z}_{\mathbb{C}}^c_{X,t}/p^n \overset{\simeq}{\longrightarrow} K_{n,X,log,t} \) is a quasi-isomorphism. In [Zho14, 2.16] Zhong proved that \( \psi_{X,\text{ét}} \) combined with the Bloch-Gabber-Kato isomorphism [BK86, 2.8], gives a quasi-isomorphism

\[
\overline{\psi}_{X,\text{ét}} : \mathbb{Z}_{\mathbb{C}}^c_{X,\text{ét}}/p^n \overset{\simeq}{\longrightarrow} \tilde{\nu}_{n,X,\text{ét}}.
\]

In the proof, Zhong actually showed that these two complexes of sheaves on each section of the big Zariski site over \( X \) are quasi-isomorphic. Therefore by restriction to the small Zariski site, we have

\[
\overline{\psi}_{X,\text{Zar}} : \mathbb{Z}_{\mathbb{C}}^c_{X,\text{Zar}}/p^n \overset{\simeq}{\longrightarrow} \tilde{\nu}_{n,X,\text{Zar}}.
\]

Combining Zhong’s quasi-isomorphism with Theorem 5.10:

**Theorem 6.1.** Let \( X \) be a separated scheme of finite type over \( k \) with \( k \) being a perfect field of positive characteristic \( p \). Then the following composition

\[
\overline{\zeta}_{n,X,log,\text{ét}} \circ \overline{\psi}_{X,\text{ét}} : \mathbb{Z}_{\mathbb{C}}^c_{X,\text{ét}}/p^n \overset{\simeq}{\longrightarrow} K_{n,X,log,\text{ét}},
\]

is a quasi-isomorphism. If moreover \( k = \mathbb{F} \), then the following composition

\[
\overline{\zeta}_{n,X,log,\text{Zar}} \circ \overline{\psi}_{X,\text{Zar}} : \mathbb{Z}_{\mathbb{C}}^c_{X,\text{Zar}}/p^n \overset{\simeq}{\longrightarrow} K_{n,X,log,\text{Zar}},
\]

is also a quasi-isomorphism.

**Remark 6.2.** From the construction of the maps \( \overline{\zeta}_{n,X,log,t} \) and \( \overline{\psi}_{X,t} \), we can describe explicitly their composite map. We write here only the Zariski case, and the étale case is just given by the Zariski version on the small étale site and then doing the étale sheafification.

Let \( U \) be a Zariski open subset of \( X \). Let \( Z \in (\mathbb{Z}_{\mathbb{C}}^{\mathbb{C}}_{X,\text{Zar}})'(U) = \mathcal{Z}_{0}(U, -i) \) be a prime cycle.

- When \( i \in [-d, 0] \) and \( \dim p_U(Z) = -i \), set \( q = -i \). Then \( Z \) as a cycle of dimension \( q \) in \( U \times \Delta^q \), is dominant over some \( u = u(Z) \in U^{(q)} \) under projection \( p_U : U \times \Delta^q \to U \). By slight abuse of notation, we denote by \( T_0, \ldots, T_q \in k(Z) \) the pullbacks of the corresponding coordinates via \( Z \hookrightarrow U \times \Delta^q \). Since \( Z \) intersects all faces properly, \( T_0, \ldots, T_q \in k(Z) \). Thus \( \{\frac{T_0}{q}, \ldots, \frac{T_q}{q}\} \in K^B_q(k(Z)) \) is well-defined. Take the Zariski closure of \( \text{Spec} k(Z) \) in \( U \times \Delta^q \),
and denote it by $Z'$. Then $p_U$ maps $Z'$ to $\overline{\{u\}} = \overline{\{u\}}^X \cap U$. Denote by $i_U : \overline{\{u\}}^X \hookrightarrow X$ the closed immersion, and denote the composition

$$Z' \xrightarrow{p_U} \overline{\{u\}} \xrightarrow{i_U} X$$

by $h$. $h$ is clearly generically finite, then there exists an open neighborhood $V$ of $u$ in $X$ such that the restriction $h : h^{-1}(V) \to V$ is finite. Then $W_n h : W_n(h^{-1}(V)) \to W_nV$ is also finite. Therefore it makes sense to consider the trace map $\text{Tr}_{W_n h}$ near the generic point of $Z'$. Similarly, it makes sense to consider the trace map $\text{Tr}_{W_n p_U}$ near the generic point of $Z'$. Then we calculate

$$\zeta_{\log}(\psi(Z)) = (-1)^i \text{Tr}_{W_n i_U} d \log(\text{Nm}_{k(Z)/k(u(Z))}(\frac{-T_0}{T_q}, \ldots, \frac{-T_q}{T_q}))$$

$$= (-1)^i \text{Tr}_{W_n i_U} (\text{Tr}_{W_n p_U} d \log(\frac{-T_0}{T_q}, \ldots, \frac{-T_q}{T_q})) \quad (\text{Lemma 5.3})$$

$$= (-1)^i \text{Tr}_{W_n h} \left( \frac{T_q dt_0 - T_0 dt_q}{T_0 T_q}, \ldots, \frac{T_q dt_{q-1} - T_{q-1} dt_q}{T_{q-1} T_q} \right)$$

Here in the last step we have used the functoriality of the trace map with respect to composition of morphisms [Con00, 3.4.1(2)].

- When $i \notin [-d, 0]$ or $\dim p_U(Z) \neq -i$, we have $\zeta_{\log}(\psi(Z)) = 0$.

Combining the functoriality of Zhong’s map $\psi$ with Proposition 5.8, one arrives at the following proposition.

**Proposition 6.3** (Functoriality). The composition $\overline{\tau}_{n,X,\log t} \circ \overline{\psi}_{X,t} : \mathbb{Z}_{X,t}/p^n \xrightarrow{\sim} K_{n,X,\log t}$ is covariant with respect to proper morphisms, and contravariant with respect to étale morphisms for both $t = \text{Zar}$ and $t = \text{ét}$.

**Part 3. Applications**

7. **De Rham-Witt Analysis of $\overline{\nu}_{n,X,t}$ and $K_{n,X,\log t}$**

Let $X$ be a separated scheme of finite type over $k$ of dimension $d$. In this section we will use terminologies as defined in [CR12, §1], such as Witt residual complexes, etc.

Recall that Ekedahl defined a map of complexes of $W_n O_X$-modules (cf. [CR12, Def. 1.8.3])

$$\overline{p} := \overline{p}_{(K_n,X)_n} : R_* K_{n-1,X,t} \to K_{n,X,t}.$$  

By abuse of notations, we denote by $R : W_n^{-1} X \hookrightarrow W_n X$ the closed immersion induced by the restriction map on the structure sheaves $R : W_n O_X \to W_n^{-1} O_X$.

**Lemma 7.1.** The map $\overline{p} : R_* K_{n-1,X,t} \to K_{n,X,t}$ induces a map of complexes of abelian sheaves

$$\overline{p} : K_{n-1,X,\log t} \to K_{n,X,\log t}$$

by applying $p$ on each summand.

**Proof.** It suffices to show that $C^t_{p} : K_{n,X,t} \to K_{n,X,t}$ commutes with $p$ for both $t = \text{ét}$ and $t = \text{Zar}$. For $t = \text{ét}$, $C^t_{p}$ is the composition of $\tau^{-1} : K_{n,X,\text{ét}} \to (W_n F_X)_* K_{n,X,\text{ét}}$ and $p^{\ast} (C^t_{\text{Zar}}) : (W_n F_X)_* K_{n,X,\text{ét}} \to K_{n,X,\text{ét}}$. Since $\tau^{-1}$ is functorial with respect to any map of abelian sheaves, we know that

$$\begin{array}{ccc}
R_* K_{n-1,X,\text{ét}} & \xrightarrow{\tau^{-1}} & (W_n F_X)_* R_* K_{n-1,X,\text{ét}} \\
\downarrow \overline{p} & & \downarrow \overline{p} \\
K_{n,X,\text{ét}} & \xrightarrow{\tau^{-1}} & (W_n F_X)_* K_{n,X,\text{ét}}
\end{array}$$

is commutative, thus it suffices to prove the proposition for $t = \text{Zar}$. That is, it suffices to show the diagrams (7.0.2) and (7.0.3) commute:

$$\begin{array}{ccc}
R_* K_{n-1,X} & \xrightarrow{R_* (1.1.2)} & R_*(W_n^{-1} F_X) \triangleleft K_{n-1,X} \\
\downarrow \overline{p} & & \downarrow \overline{p}_{(W_n p_X) \triangleleft K_{n,X}_n} \\
K_{n,X} & \xrightarrow{(1.1.2)} & (W_n F_X)_* K_{n,X}
\end{array}$$
(7.0.3)\[ (W_n F X)_* R_*(W_n-1 F X) \triangle K_{n-1,X} \xrightarrow{\simeq} R_*(W_n-1 F X)_* (W_n-1 F X) \triangle K_{n-1,X} \xrightarrow{R_\ast Tr W_{n-1} F X} R_\ast K_{n-1,X}, \]
\[ (W_n F X)_* (W_n F X) \triangle K_{n,X} \xrightarrow{Tr W_n F X} K_{n,X}. \]

Here \( p := p_{(W_n F X)K_{n,X}} \) is the lift-and-multiplication-by-\( p \) map associated to the Witt residual complex \( \{K_{n,X}\}_n \), while \( p_{(W_n F X)K_{n,X}} \) denotes the one associated to Witt residual system \( \{(W_n F X)\triangle K_{n,X}\}_n \) (cf. [CR12, 1.8.7]). By definition,
\[ p_{(W_n F X)K_{n,X}} : R_*(W_n-1 F X) \triangle K_{n-1,X} \to (W_n F X) \triangle K_{n,X} \]
is given by the adjunction map of
\[ (W_n-1 F X) \triangle K_{n-1,X} \xrightarrow{(W_n-1 F X)^\triangle (\ast p)} (W_n-1 F X) \triangle R \triangle K_{n,X} \simeq R \triangle (W_n F X) \triangle K_{n,X}, \]
where \( \ast p \) is the adjunction of \( p \) for residual complexes (cf. [CR12, Def. 1.8.3]). The second diagram (7.0.3) commutes because the trace map \( Tr W_{n,X} \) induces a well-defined map between Witt residual complexes [CR12, Lemma 1.8.9].

It remains to show the commutativity of (7.0.2). According to the definition of \( p_{(W_n F X)K_{n,X}} \) in [CR12, 1.8.7], we are reduced to show the adjunction square commutes:
\[ R \triangle K_{n,X} \xrightarrow{\simeq (1.1.2)} R \triangle (W_n F X) \triangle K_{n,X} \xrightarrow{\simeq (\ast p)} (W_n-1 F X) \triangle R \triangle K_{n,X} \]
\[ K_{n-1,X} \xrightarrow{(1.1.2)} (W_n-1 F X) \triangle K_{n-1,X}. \]

And this is \((W_n-1 \pi)^\triangle \) applied to the following diagram
\[ R \triangle W_n k \xrightarrow{R \triangle (1.1.1)} R \triangle (W_n F_k) \triangle W_n k \xrightarrow{\simeq (\ast p)} (W_n-1 F_k) \triangle R \triangle W_n k \]
\[ W_n-1 k \xrightarrow{(1.1.1)} (W_n-1 F_k) \triangle W_n-1 k. \]

We are reduced to show its commutativity. Notice that this diagram is over \( Spec W_n-1 k \), where the only possible filtration is the one-element set consisting of the unique point of \( Spec W_n-1 k \). This means that the Cousin functor associated to this filtration sends any dualizing complex to itself, and the map \( \ast p \) in the sense of a map either between residual complexes [CR12, Def. 1.8.3] or between dualizing complexes [CR12, Def. 1.6.3] actually agree.

Now we start the computation. Formulas for (1.1.1) and for \( \ast p \) (in the sense of a map between dualizing complexes) are explicitly given in Section 1.1 and [CR12, 1.6.4(1)], respectively. Label the source and the target of \( W_n F_k \) by \( Spec W_n k_1 \) and \( Spec k_2 \) respectively. Take \( a \in W_n-1 k_1 \). Denote \( W_n F_k : (Spec W_n k_1, W_n k_1) \to (Spec W_n k_2, (W_n F_k)_+(W_n k_1)) \), and \( Tr : (Spec W_n-1 k_1, W_n-1 k_1) \to (Spec W_n k_1, R_\ast W_n-1 k_1) \) \( i = 1, 2 \) the natural maps of ringed spaces. Now the down-right composition \(((W_n-1 F_k)^\triangle (\ast p)) \circ (1.1.1)\) equals to the Cousin functor \( E_{(W_n-1 F_k)R \triangle Z^\bullet} \) applied to the following composition
\[ W_n-1 k_1 \xrightarrow{(1.1.1)} W_n-1 F_k \xrightarrow{\ast p} Hom_{W_n-1 k_2}(W_n-1 F_k)_+(W_n-1 k_1), W_n-1 k_2) \]
\[ \simeq W_n-1 F_k \xrightarrow{\ast p} Hom_{W_n-1 k_2}(W_n-1 F_k)_+(W_n-1 k_1), R_\ast W_n-1 k_2, W_n k_2), \]
\[ a \mapsto [(W_n-1 F_k)_1, a] \mapsto (W_n-1 F_k)_1, a \mapsto [R_\ast k_1, a] \mapsto (W_n-1 F_k)_1, a]. \]

And \(R \triangle (1.1.1) \circ (\ast p)\) equals to the Cousin functor \( E_{(W_n-1 F_k)R \triangle Z^\bullet} \) applied the following composition
\[ W_n-1 k_1 \xrightarrow{\ast p} Tr \xrightarrow{Hom_{W_n k_2}(R_\ast W_n-1 k_1, W_n k_1)} \]

and

\[ (\ref{1.1.1}) \quad \overline{R} \otimes_{\mathcal{O}_X,k_1} (R \mathcal{W}_{n-1}k_1, \mathcal{W}_n F_k) \otimes_{\mathcal{O}_X,k_2} (\mathcal{W}_n F_k, (W_n k_1), W_n k_2)), \]

\[ a \mapsto [R, 1 \mapsto p(a)] \]

\[ \mapsto [R, 1 \mapsto ([W_n F_k], 1 \mapsto (W_n F_k) \otimes (a)]]. \]

It remains to identify \( p(W_n F_k)^{-1} a \) and \((W_n F_k)^{-1} p(a)\). And this is straightforward: write \( a = \sum_{i=0}^{n-2} V^i [a_i] \in W_{n-1} k_1, \)

\begin{equation}
(7.0.4) \quad (W_n F_k)^{-1} p(a) = \sum_{i=0}^{n-2} (W_n F_k)^{-1} p(V^i [a_i]) = \sum_{i=0}^{n-2} (W_n F_k)^{-1} (V^i [a_i])
\end{equation}

\[ = \sum_{i=0}^{n-2} (V^i [a_i]) = p(W_n F_k)^{-1} a. \]

Hence we finish the proof. \( \square \)

However we don’t naturally have a restriction map \( R \) between residual complexes. Nevertheless, we could use the quasi-isomorphism \( \tilde{\nu}_{n,X,t} : \tilde{\nu}_{n+1,X,t} \xrightarrow{\sim} K_{n,X,\log,t} \) to build up a map

\begin{equation}
(7.0.5) \quad R : K_{n,X,\log,t} \rightarrow K_{n-1,X,\log,t}
\end{equation}

in the derived category \( \text{D}^b(X, \mathbb{Z}/p^n) \). For this we will need to show that \( p \) and \( R \) induce chain maps for \( \tilde{\nu}_{n,X.t} \). This should be well-known to experts, we add here again due to a lack of reference.

**Lemma 7.2.**

\[ p : \tilde{\nu}_{n,X,t} \rightarrow \tilde{\nu}_{n+1,X,t}, \quad R : \tilde{\nu}_{n+1,X,t} \rightarrow \tilde{\nu}_{n,X,t} \]

given by \( p \) and \( R \) termwise, are well defined maps of complexes for both \( t = \text{Zar} \) and \( t = \text{ét} \).

**Proof.** It suffices to prove for \( t = \text{Zar} \). Let \( x \in X(q) \) be a point of dimension \( q \). Let \( \rho : X' \rightarrow [\overline{x}] \) be the normalization of \( [\overline{x}] \). Let \( x' \) be the generic point of \( X' \) and \( y' \in X'^{(1)} \) be a codimension 1 point. Denote \( y := \rho(y') \). It suffices to check the commutativity of the following diagrams in (1) and (2).

1. Firstly,

\[
\begin{array}{ccc}
W_n \Omega_{X',\log}^{n} & \xrightarrow{\partial} & W_n \Omega_{X',\log}^{n+1} \\
W_{n+1} \Omega_{X',\log}^{n} & \xrightarrow{\partial} & W_{n+1} \Omega_{X',\log}^{n+1}
\end{array}
\]

\[ p \]

\[ R \]

Notice that \( p = p \circ R \). Suppose \( \pi' \) is a uniformizer of discrete valuation ring \( \mathcal{O}_{X',y'} \) and \( u_1, \ldots, u_q \) are invertible elements in \( \mathcal{O}_{X',y'} \). Calculate

\[
p(\partial(d \log[\pi']_n d \log[u_2]_n \ldots d \log[u_q]_n))
\]

\[ = p(d \log[u_2]_n \ldots d \log[u_q]_n) \]

\[ = p(d \log[u_2]_n \ldots d \log[u_q]_n) \]

\[ = p(\partial(d \log[\pi']_n+1 d \log[u_2]_n+1 \ldots d \log[u_q]_n+1)) \]

\[ = \partial(p(d \log[\pi']_n+1 d \log[u_2]_n+1 \ldots d \log[u_q]_n+1)) \]

\[ = \partial(p(d \log[\pi']_n d \log[u_2]_n \ldots d \log[u_q]_n)), \]

and

\[
p(\partial(d \log[u_1]_n d \log[u_2]_n \ldots d \log[u_q]_n))
\]

\[ = 0 \]

\[ = p(\partial(d \log[u_1]_n+1 d \log[u_2]_n+1 \ldots d \log[u_q]_n+1)) \]

\[ = \partial(p(d \log[u_1]_n+1 d \log[u_2]_n+1 \ldots d \log[u_q]_n+1)) \]

\[ = \partial(p(d \log[u_1]_n d \log[u_2]_n \ldots d \log[u_q]_n)). \]

This proves the first diagram. Now the second.

\[
R(\partial(d \log[\pi']_n+1 d \log[u_2]_n+1 \ldots d \log[u_q]_n+1))
\]

\[ = R(d \log[u_2]_n+1 \ldots d \log[u_q]_n+1) \]

\[ = d \log[u_2]_n \ldots d \log[u_q]_n \]
and

\[ R(\partial(d \log[u_1]_{n+1}d \log[u_2]_{n+1} \cdots d \log[u_q]_{n+1})) = 0 \]

\[ = \partial(R(d \log[u_1]_{n+1}d \log[u_2]_{n+1} \cdots d \log[u_q]_{n+1})). \]

(2) Secondly, \[ W_n^q \Omega^{-1}_{y,log} \xrightarrow{\text{tr}} W_{n+1}^q \Omega^{-1}_{y,log} \]

\[ W_{n+1}^q \Omega^{-1}_{y,log} \xrightarrow{\text{tr}} W_{n+1}^q \Omega^{-1}_{y,log}. \]

Notice that \( \rho : X' \rightarrow \{x\}^X \) can be restricted to a map from \( \{y'\}^{X'} \) to \( \{y\}^X \) (\( \{x\}^X \) denotes the closure of \( x \) in \( X \), and similarly for \( \{y'\}^{X'} \), \( \{y\}^X \)). Furthermore, \( y' \) (resp. \( y \)) belongs to the smooth locus of \( \{y'\}^{X'} \) (resp. \( \{y\}^X \)), and there \( p \) and \( R \) come from the restriction of the \( p \) and \( R \) on the respective smooth locus. The map \( \text{tr} \), induced by Milnor’s norm map, agrees with the Grothendieck trace map \( \text{Tr}_{W_n, \rho} \) due to Lemma 5.3. And according to compatibility of the Grothendieck trace map with the Witt system structure (i.e. de Rham-Witt system with zero differential) on canonical sheaves [CR12, 4.1.4(6)], we arrive at the desired commutativity.

\[ \square \]

**Lemma 7.3.** Assume either

- \( t = \text{Zar} \) and \( k = \overline{k} \), or
- \( t = \text{ét} \) and \( k \) being a perfect field of characteristic \( p > 0 \).

Then we have the following short exact sequence

\[ 0 \rightarrow W_i \Omega^q_{x,log,t} \xrightarrow{\rho^i} W_{i+j} \Omega^q_{x,log,t} \xrightarrow{\text{tr}} W_j \Omega^q_{x,log,t} \rightarrow 0, \]

in the category of complexes of sheaves over \( X_t \), and a distinguished triangle

\[ K_i \Omega^q_{x,log,t} \xrightarrow{\rho^i} K_{i+j} \Omega^q_{x,log,t} \xrightarrow{\text{tr}} K_j \Omega^q_{x,log,t} \xrightarrow{+1} \]

in the derived category \( D^b(X_t, \mathbb{Z}/p^n) \).

**Proof.** (1) Because of Lemma 7.2, it suffices to show

\[ 0 \rightarrow W_i \Omega^q_{x,log,t} \xrightarrow{\rho^i} W_{i+j} \Omega^q_{x,log,t} \xrightarrow{\text{tr}} W_j \Omega^q_{x,log,t} \rightarrow 0 \]

is short exact for any given point \( x \in X(q) \). And this is true for \( t = \text{ét} \) because of [CSS83, Lemme 1]. And for \( t = \text{Zar} \), one further needs \( R^1 \epsilon_* W_n \Omega^q_{x,log,\text{ét}} = 0 \) for any \( x \in X(q) \) when \( k = \overline{k} \), which is proved in [Suw95, Cor. 2.3].

(2) Now it suffices to show that \( p \) and \( R \) for the system \( \{K_n \Omega^q_{x,log,t}\}_n \) are compatible with \( p \) and \( R \) of the system \( \{\nu_{*} (\text{p})\}_n \). Via the quasi-isomorphism \( \phi_{n, X, log, t} \). The compatibility for \( R \) is clear by definition. It remains to check the compatibility for \( p \) because \( \phi_{n, X, log, t} = \phi_{n, X, log, t} \) it suffices to check compatibility of \( p : \nu_{n-1, X, t} \rightarrow \nu_{n, X, t} \) with \( p : K_n-1, X, t \rightarrow K_n, X, t \) via \( \phi_{n, X, log, t} \). At a given degree \(-q\) and given point \( x \in X(q) \), the map \( \tilde{\nu}_{n, X, t} : \nu_{n, X, t} \rightarrow K_n, X, t \) factors as

\[ (W_n, \nu_{x,log,t}) \rightarrow (W_n \nu_{x,log,t}) \rightarrow (W_n \nu_{x,log,t}) \rightarrow (W_n \nu_{x,log,t}) \rightarrow \text{ker}(W_n \text{Tr}_{\nu_{n, X, t}^{-1}}) \rightarrow K_n \nu_{x,log,t}. \]

The first arrow is the inclusion map and is naturally compatible with \( p \). The compatibility of \( p \) via the trace map is given in [CR12, Lemma 1.8.9].

\[ \square \]
8. Higher Chow groups of zero cycles

Let $k$ be a perfect field of characteristic $p > 0$ and $X$ be a separated scheme of finite type over $k$ of dimension $d$.

8.1. Vanishing and finiteness results.

**Proposition 8.1.** There is a distinguished triangle

$$
\mathbb{Z}_X^{\bullet}/p^n \to K_{n,X,\text{ét}} \xrightarrow{C_{\text{ét}}^{-1}} K_{n,X,\text{ét}} \xrightarrow{+1}
$$

in the derived category $D^b(X_{\text{ét}}, \mathbb{Z}/p^n)$. When $k = \overline{k}$, one also has the Zariski counterpart. Namely, we have a distinguished triangle

$$(8.1.1) \quad \mathbb{Z}_X^{\bullet}/p^n \to K_{n,X} \xrightarrow{C_{\text{Zar}}^{-1}} K_{n,X} \xrightarrow{+1},$$

in the derived category $D^b(X, \mathbb{Z}/p^n)$.

In particular, when $k = \overline{k}$ and $X$ is Cohen-Macaulay of pure dimension $d$, then $\mathbb{Z}_X^{\bullet}/p^n$ is concentrated at degree $-d$, and the triangle $(8.1.1)$ becomes

$$
\mathbb{Z}_X^{\bullet}/p^n \to W_n\omega_X[d] \xrightarrow{C_{\text{Zar}}^{-1}} W_n\omega_X[d] \xrightarrow{+1}
$$

in this case. Here $W_n\omega_X$ is the only non-vanishing cohomology sheaf of $K_{n,X}$ (when $n = 1$, $W_1\omega_X = \omega_X$ is the usual dualizing sheaf on $X$).

**Proof.** This is direct from the main result Theorem 6.1 and Remark 1.17. 

**Proposition 8.2.** Assume $k = \overline{k}$. Then higher Chow groups of zero cycles equals the $C'$-invariant part of the cohomology groups of Grothendieck’s coherent dualizing complex, i.e.,

$$
\text{CH}_0(X, q; \mathbb{Z}/p^n) = H^{-q}(W_n, K_{n,X})^{C'_{-1}}.
$$

**Proof.** This follows directly from the Proposition 1.15 and the main result Theorem 6.1. 

**Proposition 8.3.** There is an isomorphism in $D^b(W_nX_{\text{ét}}, \mathbb{Z}/p^n)$

$$
K_{n,X,\text{log, ét}} \simeq R(W_n\pi)'(\mathbb{Z}/p^n),
$$

where $R(W_n\pi)'$ is the extraordinary inverse image functor defined in [SGA4-3, Exposé XVIII, Thm 3.1.4].

**Proof.** This follows directly from the main theorem Theorem 5.10 and [JSS14, Thm. 4.6.2].

**Corollary 8.4 (Affine vanishing).** Suppose $X$ is affine and Cohen-Macaulay of pure dimension $d$. Then

1. When $t = \text{Zar}$ and $k = \overline{k}$,

$$
\text{CH}_0(X, q; \mathbb{Z}/p^n) = 0
$$

for $q \neq d$.

2. When $t = \text{ét}$,

$$
R^{-q}(X_{\text{ét}}, \mathbb{Z}_X^{\bullet}/p^n) = 0
$$

for $q \neq d, d - 1$. If one further assumes $k = \overline{k}$ or smoothness, the possible non-vanishing occurs only in degree $q = d$.

**Proof.** When $X$ is Cohen-Macaulay of pure dimension $d$, $W_nX$ is also Cohen-Macaulay of pure dimension $d$ by Serre’s criterion, and $K_{n,X,\text{ét}}$ is concentrated at degree $-d$ for all $n$ [Con00, 3.5.1]. Now Serre’s affine vanishing theorem implies $H^{-q}(W_nX, K_{n,X,\text{ét}}) = 0$ for $q \neq d$. This implies that $R^{-q}(W_nX, K_{n,X,\text{log, ét}}) = 0$ unless $q = d, d - 1$. With the given assumptions, Theorem 6.1 implies that $\text{CH}_0(X, q; \mathbb{Z}/p^n) = R^{-q}(X_{\text{ét}}, \mathbb{Z}_X^{\bullet}/p^n) = 0$ unless $q = d, d - 1$. If one also assumes $k = \overline{k}$, Proposition 8.2 gives the vanishing result for $q = d - 1$.

When $X$ is smooth, $C_{\text{ét}} = 1 : W_n\Omega^d_{X,\text{ét}} \to W_n\Omega^d_{X,\text{ét}}$ is surjective by [GS88a, 1.6(ii)] (see (1.2.31)). By compatibility of $C_{\text{ét}}$ and $C_{\text{Zar}}$ Proposition 1.26, one deduces that $C' = 1 : H^{-d}(K_{n,X,\text{ét}}) \to H^{-d}(K_{n,X,\text{ét}})$ is surjective. 

Generalizing Bass’s finiteness conjecture for $K$-groups (cf. [Wei13, IV.6.8]), the finiteness of higher Chow groups in various arithmetic settings has been a “folklore conjecture” in literature (expression taken from [KS12, §9]). The following result was first proved by Geisser [Gei10, §5, eq. (12)] using the finiteness result from étale cohomology theory, and here we deduce it as a corollary of our main theorem, which essentially relies on the finiteness of coherent cohomologies on a proper scheme. We remark that Geisser’s result is more general than ours in that he allows arbitrary torsion coefficients.
**Corollary 8.5** (Finiteness, Geisser). Assume \( k = \overline{k} \). Let \( X \) be proper over \( k \). Then for any \( q \),

\[
\mathrm{CH}_0(X, q; \mathbb{Z}/p^n)
\]

is a finite \( \mathbb{Z}/p^n \)-module.

**Proof.** According to Theorem 6.1, \( R^{-q}\Gamma(X, \mathbb{Z}_p/p^n) = R^{-q}\Gamma(X, K_{n,X,\log}) \). Thus it suffices to show that for every \( q \), \( R^{-q}\Gamma(X, K_{n,X,\log}) \) is a finite \( \mathbb{Z}/p^n \)-module. First of all, since \( R^{-q}\Gamma(X, K_{n,X,\log}) \) is the \( C' \)-invariant part of \( R^{-q}\Gamma(X, K_{n,X}) \) by Proposition 1.15 and Proposition 1.27, \( R^{-q}\Gamma(X, K_{n,X,\log}) \) is a module over the invariant ring \((W_n)^{1-W_n}F_p^{-1} = \mathbb{Z}/p^n\). Because \( X \) is proper, \( R^{-q}\Gamma(X, K_{n,X}) \) is a finite \( W_n \)-module by the local-to-global spectral sequence. Then Proposition A.7 gives us the result.

Alternatively, we can also do induction on \( n \). In the \( n = 1 \) case, because \( R^{-q}\Gamma(X, K_{1,X,\log}) \) is the \( C' \)-invariant part of the finite dimensional \( k \)-vector space \( H^{-q}(X, K_X) \) again by Proposition 1.15 and Proposition 1.27, it is a finite \( \mathbb{F}_p \)-module by \( p^{-1} \)-linear algebra Proposition A.3. The desired result then follows from the long exact sequence associated to \((7.0.7)\) by induction on \( n \).

We refer to Definition A.4 and Remark A.5.2 for the definition of the semisimplicity and the notation \((\,-)_{\text{ss}}\) in this context.

**Corollary 8.6** (Semisimplicity). Assume \( k = \overline{k} \). Let \( X \) be proper over \( k \). Then for any \( q \),

\[
H^{-q}(W_nX, K_{n,X})_{\text{ss}} = \mathrm{CH}_0(X, q; \mathbb{Z}/p^n) \otimes_{\mathbb{Z}/p^n} W_nk.
\]

**Proof.** Since \( X \) is proper, \( H^{-q}(W_nX, K_{n,X}) \) is a finite \( W_nk \)-module for any \( q \). Then according to Proposition A.8,

\[
H^{-q}(W_nX, K_{n,X})_{\text{ss}} = H^{-q}(W_nX, K_{n,X})^{C'-1} \otimes_{\mathbb{Z}/p^n} W_nk.
\]

The claim now follows from Proposition 8.2.

**8.2. Étale descent.** The results Proposition 8.7, Proposition 8.8 in this subsection are well-known to experts.

**Proposition 8.7** (Gros-Suwa). Assume \( k = \overline{k} \). Then one has a canonical isomorphism

\[
\tilde{\nu}_{n, X, \text{Zar}} = \epsilon_* \tilde{\nu}_{n, X, \text{ét}} \xrightarrow{\sim} R\epsilon_* \tilde{\nu}_{n, X, \text{ét}}
\]

in the derived category \( D^b(X, \mathbb{Z}/p^n) \).

**Proof.** When \( k = \overline{k} \), terms of the étale complex \( \tilde{\nu}_{n, X, \text{ét}} \) are \( \epsilon_* \)-acyclic according to [GS88a, 3.16].

The étale descent of Bloch’s cycle complex with \( \mathbb{Z} \)-coefficients is shown in [Gei10, Thm 3.1], assuming the Beilinson-Lichtenbaum conjecture. Looking into the proof one sees that the mod \( p^n \) version holds conjecture-free, and is a corollary of [GL00, 8.4] (we thank Geisser for pointing this out). But one could also deduce this as a corollary of Proposition 8.7 via Zhong’s quasi-isomorphism in Section 6.2 (which is again dependent on the main result of Geisser-Levine [GL00, 1.1]).

**Proposition 8.8** (Geisser-Levine). Assume \( k = \overline{k} \). Then one has a canonical isomorphism

\[
\mathbb{Z}^c_{X, \text{Zar}}/p^n = \epsilon_* \mathbb{Z}^c_{X, \text{ét}}/p^n \xrightarrow{\sim} R\epsilon_* \mathbb{Z}^c_{X, \text{ét}}/p^n.
\]

in the derived category \( D^b(X, \mathbb{Z}/p^n) \). As a result,

\[
\mathrm{CH}_0(X, q; \mathbb{Z}/p^n) \simeq R^{-q}\Gamma(X, \mathbb{Z}^c_{X, \text{ét}}/p^n).
\]

**Proof.** Clearly, we have the compatibility

\[
\mathbb{Z}^c_{X, \text{Zar}}/p^n \xrightarrow{\sim} R\epsilon_* \mathbb{Z}^c_{X, \text{ét}}/p^n \xrightarrow{\psi_{X, \text{Zar}}} \tilde{\nu}_{n, X, \text{Zar}} \xrightarrow{\sim} R\epsilon_* \tilde{\nu}_{n, X, \text{ét}} \xrightarrow{\sim} R\epsilon_* \mathbb{Z}^c_{X, \text{ét}}/p^n.
\]

Thus \( \mathbb{Z}^c_{X, \text{Zar}}/p^n \xrightarrow{\sim} \tilde{\nu}_{n, X, \text{Zar}} = \epsilon_* \tilde{\nu}_{n, X, \text{ét}} \xrightarrow{\text{Proposition 8.7}} R\epsilon_* \tilde{\nu}_{n, X, \text{ét}} \xrightarrow{\text{Proposition 8.7}} R\epsilon_* \mathbb{Z}^c_{X, \text{ét}}/p^n \).

**Corollary 8.9.** Assume \( k = \overline{k} \). Suppose \( X \) is affine and Cohen-Macaulay of pure dimension \( d \). Then

\[
R^i \epsilon_*(\mathbb{Z}^c_{X, \text{ét}}/p^n) = R^i \epsilon_*(\tilde{\nu}_{n, X, \text{ét}}) = 0, \quad i \neq -d.
\]

**Proof.** This is a direct consequence of Proposition 8.8, Proposition 8.7 and Corollary 8.4.
8.3. Birational geometry and rational singularities. Recall the following definition of resolution-rational singularities, which are more often called rational singularities before in the literature, but here we follow the terminology from [Kov17] (see also Remark 8.11(1)).

Definition 8.10 (cf. [Kov17, 9.1]). An integral $k$-scheme $X$ is said to have resolution-rational singularities, if

1. there exists a birational proper morphism $f : \tilde{X} \to X$ with $\tilde{X}$ smooth (such a $f$ is called a resolution of singularities or simply a resolution of $X$), and
2. $R^if_*\mathcal{O}_{\tilde{X}} = R^if_*\omega_{\tilde{X}} = 0$ for $i \geq 1$. And $f_*\omega_{\tilde{X}} = \mathcal{O}_X$.

Such a map $f : \tilde{X} \to X$ is called a rational resolution of $X$.

Note that the cohomological condition (2) is equivalent to the following condition

(2') $\mathcal{O}_X \simeq Rf_*\mathcal{O}_{\tilde{X}}, f_*\omega_{\tilde{X}} \simeq Rf_*\omega_{\tilde{X}}$ in the derived category of abelian Zariski sheaves.

Remark 8.11. (1) According to [Kov17, 8.2], on integral $k$-schemes of pure dimension, our definitions for resolution-rational singularities and for rational resolutions are the same as the ones in [Kov17, 9.1].

(2) A necessary condition for an integral scheme to have such singularities is being Cohen-Macaulay. This is a standard result, cf. [Kov17, 8.3].

(3) According to [Kov17, 9.6], resolution-rational singularities are pseudo-rational. By definition [Kov17, 1.2], a $k$-scheme $X$ is said to have pseudo-rational singularities, if it is normal Cohen-Macaulay, and for every normal scheme $X'$, every projective birational morphism $f : X' \to X$, the composition $f_*\omega_{X'} \to Rf_*\omega_{X'} \xrightarrow{\sim} \omega_X$ is an isomorphism.

Corollary 8.12. Let $X$ and $Y$ be integral $k$-schemes of pure dimensions which have pseudo-rational singularities and are properly birational, i.e., there are proper birational $k$-morphisms $f : X \to X$ and $g : Z \to Y$ with $Z$ being some integral scheme. Then we have

$$R^{-q}\Gamma(X_{\text{et}}, \mathcal{O}_{X_{\text{et}}}/p^n) = R^{-q}\Gamma(Y_{\text{et}}, \mathcal{O}_{Y_{\text{et}}}/p^n)$$

for all $q$ and all $n \geq 1$. If we assume furthermore $k = \overline{k}$, we also have

$$\text{CH}_0(X, q, \mathbb{Z}/p^n) = \text{CH}_0(Y, q, \mathbb{Z}/p^n)$$

for all $q$ and all $n \geq 1$.

Remark 8.13. (1) In particular, since for any rational resolution of singularities $f : \tilde{X} \to X$, $\tilde{X}$ and $X$ are properly birational as $k$-schemes (i.e., take $Z$ to be $\tilde{X}$), one can compute the higher Chow groups of zero cycles of $X$ via those of $\tilde{X}$.

(2) Deleting the pseudo-rational singularities assumption (in particular, we relax the Cohen-Macaulay assumptions on $X$ and $Y$), the proof still passes through with the following assumption: $X$ and $Y$ are linked by a chain of proper birational maps and each of these maps has its trace map being a quasi-isomorphism between the residual complexes. Such a proper birational map is called a cohomological equivalence in [Kov17, 8.4].

Proof. Using Chow’s Lemma [Kov17, 4.1], we know that there exist projective birational morphisms $f' : Z_1 \to Z$ and $g' : Z_2 \to Z$ such that the compositions $Z_1 \xrightarrow{f'} Z \xrightarrow{g'} Z_2$ and $Z_2 \xrightarrow{g'} Z \xrightarrow{f'} Y$ are also birational and projective. Let $U \subset Z$ be an open dense subset such that $f'$ and $g'$ restricted to the preimage of $U$ are isomorphisms. Take $Z'$ be the Zariski closure of the image of the diagonal of $U$ in $Z_1 \times_Z Z_2$ with the reduced scheme structure. Then the two projections $Z' \to Z_1$ and $Z' \to Z_2$ are also projective and birational. This means that by replacing $Z'$ with $Z$, $f$ with $Z' \to X$ and $g$ with $Z' \to Y$, we can assume our $f : Z \to X, g : Z \to Y$ to be projective birational and our $Z$ to be integral. Using Macaulayfication [Kov17, 4.3, 4.4] we can additionally assume that $Z$ is Cohen-Macaulay. This implies that $f$ and $g$ are pseudo-rational modifications by [Kov17, 9.7].

Suppose that $X$ is of pure dimension $d$. Then so is $Z$. Now [Kov17, 8.6] implies that the trace map of $f$ induces an isomorphism

$$\text{Tr}_f : Rf_*K_{Z,t} \xrightarrow{\sim} K_{X,t}$$

in $D^b(X_t, \mathbb{Z}/p)$. Thus

$$\text{Tr}_{f,\text{log}} : Rf_*K_{Z,\text{log},t} \xrightarrow{\sim} K_{X,\text{log},t}$$
Thus implies

\[ (8.3.1) \]

\[
\begin{array}{c}
\xymatrix{ f_* K_{Z,\log, t} \ar[r]^{\beta^{n-1}} & f_* K_{n,Z,\log, t} \ar[r]^R & f_* K_{n-1,Z,\log, t} \ar[r]^{+1} & f_* K_{Z,\log, t}[1] \\
\Tr_{f,\log} \ar[u] & \Tr_{W_n f,\log} \ar[u] & \Tr_{W_{n-1} f,\log} \ar[u] & \Tr_{f,\log}[1] \ar[u]
\end{array}
\]

in \( D^b(X_t, \mathbb{Z}/p) \). The first row is \( Rf_* \) applied to the triangle (7.0.7) on \( Z \). The second row is the triangle (7.0.7) on \( X \). The left square commutes on the level of complexes by compatibility of the trace map with \( \beta \) [CR12, 1.8.9]. To prove commutativity of the middle square in the derived category, it suffices to show the square

\[
\begin{array}{c}
\xymatrix{ f_* \nu_{n,Z,t} \ar[r]^R & f_* \nu_{n-1,Z,t} \\
\bar{\nu}_{n,X,t} \ar[u]_{f_*} & \bar{\nu}_{n-1,X,t} \ar[u]_{f_*}
\end{array}
\]

commutes on the level of complexes. Since the vertical maps \( f_* \) for Kato-Moser complexes are tr (cf. §4), which are by definition the reduction of the norm maps for Milnor \( K \)-theory, they agree with the Grothendieck trace maps \( \Tr_{W_n f}, \Tr_{W_{n-1} f} \) by Lemma 5.3. And according to the compatibility of \( R \) with the Grothendieck trace maps [CR12, 4.1.4(6)], we arrive at the desired commutativity. The right square in (8.3.1) commutes by naturality of the \( \cdot +1 \) map. With all these commutativitiies we conclude that the vertical maps in (8.3.1) define a map of triangles. By induction on \( n \) we deduce that

\[
\Tr_{W_n f,\log} : Rf_* K_{n,Z,\log, t} \xrightarrow{\cong} K_{n,X,\log, t}
\]

is an isomorphism in \( D^b(X_t, \mathbb{Z}/p^n) \) for every \( n \). The main result Theorem 6.1 thus implies

\[
R^{-d} \Gamma(Z_{\et}, \mathbb{Z}_c^{\mathcal{X}, \et}/p^n) = R^{-d} \Gamma(X_{\et}, \mathbb{Z}_c^{\mathcal{X}, \et}/p^n)
\]

for all \( q \) and \( n \). When \( k = \overline{k} \), the same theorem also implies that

\[
\CH_0(Z, q, \mathbb{Z}/p^n) = \CH_0(X, q, \mathbb{Z}/p^n)
\]

for all \( q \) and \( n \).

Now replacing \( f \) with \( g \) everywhere in the above argument and we get the result. \( \square \)

8.4. Galois descent.

**Corollary 8.14.** Let \( f : X \to Y \) be a finite étale Galois map with Galois group \( G \). Then

\[
R^{-d} \Gamma(Y_{\et}, \mathbb{Z}_c^{\mathcal{Y}, \et}/p^n) = R^{-d} \Gamma(X_{\et}, \mathbb{Z}_c^{\mathcal{X}, \et}/p^n)^G
\]

When \( k = \overline{k} \), we also have

\[
\CH_0(Y, d; \mathbb{Z}/p^n) = \CH_0(X, d; \mathbb{Z}/p^n)^G.
\]

**Proof.** The pullback \( f^* \) induces two canonical maps

\[
f^* : \mathbb{Z}_c^{\mathcal{Y}, \et} \to (f_* \mathbb{Z}_c^{\mathcal{X}, \et})^G, \quad f^* : K_{n,Y,\log, \et} \to (f_* K_{n,X,\log, \et})^G.
\]

Both of them are isomorphisms of complexes, because each term of these complexes are étale sheaves. Because of the contravariant functoriality with respect to étale morphisms (Proposition 6.3 and [Zho14, 2.15]), \( \zeta_{\log} \circ \psi \) is \( G \)-equivariant. In particular, the diagram

\[
\begin{array}{c}
\xymatrix{ \mathbb{Z}_c^{\mathcal{Y}, \et}/p^n \ar[r]_{\zeta_{\log} \circ \psi} & K_{n,Y,\log, \et} \\
(f_* \mathbb{Z}_c^{\mathcal{X}, \et}/p^n)^G \ar[u]_{f^*} & (f_* K_{n,X,\log, \et})^G \ar[u]_{f^*}
\end{array}
\]

commutes.

Apply \( R^{-d} \Gamma(Y_{\et}, -) \) to the isomorphism \( f^* : K_{n,Y,\log, \et} \to (f_* K_{n,X,\log, \et})^G \), one gets

\[
R^{-d} \Gamma(Y_{\et}, K_{n,Y,\log, \et}) = R^{-d} \Gamma(Y_{\et}, (f_* K_{n,X,\log, \et})^G).
\]
Consider the local-to-global spectral sequence associated to the right hand side of this equality, there’s only one non-zero term in the $E_\infty$-page with total degree $-d$ (which is a term in the $E_2$-page), thus we have

$$R^{-d}\Gamma(Y_{\text{ét}}, (f_* K_{n,X,log,\text{ét}})^G) = H^0(Y_{\text{ét}}, H^{-d}(f_* K_{n,X,log,\text{ét}})^G).$$

Because $(-)^G$ commutes with taking kernels and with $H^0$, we have

$$H^0(Y_{\text{ét}}, H^{-d}(K_{n,Y,log,\text{ét}})) = H^0(Y_{\text{ét}}, H^{-d}(f_* K_{n,X,log,\text{ét}}))^G.$$

Because $f_*$ preserves kernels, we have

$$H^0(Y_{\text{ét}}, H^{-d}(f_* K_{n,X,log,\text{ét}}))^G = H^0(X_{\text{ét}}, H^{-d}(K_{n,X,log,\text{ét}}))^G.$$

Again by the observation from the spectral sequence, this means

$$H^0(X_{\text{ét}}, H^{-d}(K_{n,X,log,\text{ét}}))^G = R^{-d}\Gamma(X_{\text{ét}}, K_{n,X,log,\text{ét}})^G.$$

Since $\zeta_{\log} \circ \psi$ is $G$-equivariant, the main theorem Theorem 6.1 implies

$$R^{-d}\Gamma(Y_{\text{ét}}, \mathbb{Z}_k/p^n) = R^{-d}\Gamma(X_{\text{ét}}, \mathbb{Z}_k/p^n)^G.$$

When $k = \overline{k}$, Proposition 8.8 implies

$$\text{CH}_0(Y, d; \mathbb{Z}/p^n) = \text{CH}_0(X, d; \mathbb{Z}/p^n)^G.$$

\qed

Appendix

A. Semilinear algebra

**Definition A.1.** Let $k$ be a perfect field of positive characteristic $p$, and $V$ be a finite dimensional $k$-vector space. A $p$-linear map (resp. $p^{-1}$-linear map) on $V$ is a map $T : V \to V$, such that

\[ T(v + w) = T(v) + T(w), \quad T(cv) = c^p T(v), \quad v, w \in V, c \in k. \]

(resp. $T(v + w) = T(v) + T(w)$, $T(cv) = c^{-p} T(v)$, $v, w \in V, c \in k$.)

We say a map $T : V \to V$ is semilinear if it is either $p$-linear or $p^{-1}$-linear. A semilinear map $T : V \to V$ is called semisimple, if $\text{Im} T = V$.

**Remark A.2.** Let $T$ be a semilinear map.

1. Note that

\[ \{ c \in k \mid c^p = c \} = \mathbb{F}_p = \{ c \in k \mid c^{-p} = c \}. \]

The fixed points of $T$

\[ V^{1-T} := \{ v \in V \mid T(v) = v \} \]

is a $\mathbb{F}_p$-vector space.

2. There is a descending chain of $k$-vector subspaces of $V$

\[ \text{Im} T \supset \text{Im} T^2 \supset \cdots \supset \text{Im} T^n \supset \cdots. \]

Since $V$ is finite dimensional, it becomes stationary for some large $N \in \mathbb{N}$. Define

\[ V_{ss} := \bigcap_{n \geq 1} \text{Im}(T^n) = \text{Im}(T^N) = \text{Im}(T^{N+1}) = \cdots. \]

Obviously,

(a) $V_{ss}$ is a $k$-vector subspace of $V$ that is stable under $T$. $T$ is semistable on $V_{ss}$.

(b) $V^{1-T} \subset V_{ss}$.

The proof of the following result is given in [SGA7-II] for $p$-linear maps, but an analogous proof also works for $p^{-1}$-linear maps.

**Proposition A.3** ([SGA7-II, Exposé XXII, Cor. 1.1.10, Prop. 1.2]). Suppose $k$ is a separably closed field of positive characteristic $p$. Then

\[ 1 - T : V \to V \]

is surjective. And

\[ V_{ss} \simeq V^{1-T} \otimes_{\mathbb{F}_p} k, \]

which in particular means $V^{1-T}$ is a finite dimensional $\mathbb{F}_p$-vector space with $\dim_{\mathbb{F}_p} V^{1-T} = \dim_k V_{ss}$.

We generalize the definition of a semilinear map.
Definition A.4. Let $k$ be a perfect field of positive characteristic $p$, and let $W_n k$ be the ring of the $n$-th truncated Witt vectors of $k$. Let $M$ be a finitely generated $W_n k$-module. A $p$-linear map (resp. $p^{-1}$-linear map) on $M$ is a map $T: M \to M$, such that
\[
T(m + m') = T(m) + T(m'), \quad T(cm) = W_n F_k(c)T(m), \quad m, m' \in M, c \in W_n k.
\]
(resp. $T(m + m') = T(m) + T(m')$, $T(cm) = W_n F_k^{-1}(c)T(m)$, $m, m' \in M, c \in W_n k$.)

Proposition A.5. Let $M$ be a finitely generated $W_n k$-module, then $M$ is a $k$-vector space. Then Proposition A.6.

Proof.

Let $M$ be a finitely generated $W_n k$-module, then $M$ is a $k$-vector space. Then Proposition A.6.

Remark A.5. Let $T$ be a semilinear map in the sense of Definition A.4.

(1) Write $\sigma = W_n F_k$ (resp. $\sigma = W_n F_k^{-1}$). Then
\[
(W_n k)^{1 - \sigma} := \{ c \in W_n k \mid \sigma(c) = c \} = \mathbb{Z}/p^n
\]
for both cases. The fixed points of $T$
\[
M^{1 - T} := \{ m \in M \mid T(m) = m \}
\]
is a $\mathbb{Z}/p^n$-module.

(2) As in the case of vector spaces,
\[
\text{Im} T \supset \text{Im} T^2 \supset \cdots \supset \text{Im} T^n \supset \cdots
\]
is a descending chain of $W_n k$-submodules of $M$. It becomes stationary for some large $N \in \mathbb{N}$, because $M$ as a finitely generated $W_n k$-module is artinian. Define the $W_n k$-submodule of $M$
\[
M_{ss} := \bigcap_{n \geq 1} \text{Im}(T^n) = \text{Im}(T^N) = \text{Im}(T^{N+1}) = \ldots.
\]
Then
(a) $M_{ss}$ is a $W_n k$-submodule of $M$ that is stable under $T$. $T$ is semistable on $M_{ss}$.
(b) $M^{1 - T} \subseteq M_{ss}$.
(c) $(M/p)_{ss} = M_{ss}/p \subset M/p$.

Proposition A.6. Let $k$ be a separably closed field of positive characteristic $p$. Then
\[
1 - T : M \to M
\]
is surjective.

Proof.

Take $m \in M$. Because $M$ is finitely generated as a $W_n k$-module, $M/pM$ is a finite dimensional $k$-vector space. Then Proposition A.3 implies that there exists a $m' \in M$, such that $(1 - T)(m') - m \in pM$. That is, there exists a $m_1 \in M$ such that
\[
(1 - T)(m') = m + pm_1.
\]
Do the same process with $m_1$ instead of $m$, one gets a $m'_1 \in M$ and a $m_2 \in M$ such that
\[
(1 - T)(m'_1) = m_1 + pm_2.
\]
Thus
\[
(1 - T)(m' - pm'_1) = m - pm_2.
\]
Repeat this process. After finitely many times, because $p^n = 0$ in $W_n k$,
\[
(1 - T)(m' - pm'_1 + \cdots + (-1)^{n-1} p^{n-1} m'_{n-1}) = m.
\]
\qed

Proposition A.7. Let $k$ be a separably closed field of positive characteristic $p$. Then
\[
(1) \quad M^{1 - T}/(pM)^{1 - T} = (M/p)^{1 - T}.
\]
(2) $M^{1 - T}$ is a finite $\mathbb{Z}/p^n$-module.

Proof.

Since $W_n k$ is of $p^n$-torsion, we know that $p^n M = 0$ for some $m \leq n$. Do induction on the smallest number $m$ such that $p^n M = 0$. When $m = 1$, the first claim is trivial, and $M = M/p$ is actually a finite dimensional $k$-vector space, thus the second claim follows from Proposition A.3.
Now we assume \( m > 1 \). Note that \( T \) induces a semilinear map on \( pM \) and \( pM \) is a finite \( W_n k \)-module, so by Proposition A.6 the map \( 1 - T : pM \rightarrow pM \) is surjective. Now we have the two rows on the bottom of the following diagram being exact:

\[
\begin{array}{cccc}
0 & \rightarrow & M^{1-T}/(pM)^{1-T} & \rightarrow & M/p^{1-T} & \rightarrow & M/p & \rightarrow & 0 \\
0 & \rightarrow & M^{1-T} & \rightarrow & M & \rightarrow & M & \rightarrow & 0 \\
0 & \rightarrow & (pM)^{1-T} & \rightarrow & pM & \rightarrow & pM & \rightarrow & 0.
\end{array}
\]

The vertical maps between the last two rows are natural inclusions, and the first row is the cokernels of these inclusion maps. The snake lemma implies that the first row is exact, which means that

\[
M^{1-T}/(pM)^{1-T} = (M/p)^{1-T}.
\]

This is a finite \( \mathbb{Z}/p^n \)-module by the case \( m = 1 \). On the other hand, since \( p^{m-1} \cdot pM = 0 \), the induction hypothesis applied to the \( W_n k \)-module \( pM \) gives \((M/p)^{1-T}\) is a finite \( \mathbb{Z}/p^n \)-module. Now the vertical exact sequence on the left gives that \( M^{1-T} \) is a finite \( \mathbb{Z}/p^n \)-module. □

**Proposition A.8.** Let \( k \) be a separably closed field of positive characteristic \( p \). Then we have an identification of \( W_n k \)-modules

\[
M_{ss} \approx M^{1-T} \otimes_{\mathbb{Z}/p^n} W_n k.
\]

**Proof.** For the finite dimensional \( k \)-vector space \( M/p \), Proposition A.3 tells us that

\[
(M/p)_{ss} \approx (M/p)^{1-T} \otimes_{\mathbb{F}_p} k
\]

In other words, there exists \( m_1, \ldots, m_d \in M \) (\( d = \dim_{\mathbb{F}_p} M/p \)), such that \( m_1 + pM, \ldots, m_d + pM \in (M/p)^{1-T} \) generate \((M/p)_{ss} \) as a \( k \)-vector space. Because of Proposition A.7(1), one can choose \( m_1, \ldots, m_d \in M^{1-T} \). Since \( M \) is a finite generated \( W_n k \)-module, \( M_{ss} \) as a submodule is also finitely generated over \( W_n k \). Note moreover that \((M/p)_{ss} = M_{ss}/p \). Apply Nakayama’s lemma, \( m_1, \ldots, m_d \in M^{1-T} \) generate \( M_{ss} \) as an \( W_n k \)-module. □

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