

# Motivic Cohomology Notes

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These notes were taken from a [course](#) on Motivic Cohomology taught by Professor N. Yang in Spring 2024 at BIMSA. Any mistakes and inaccuracies would be my own. References for this course include [\[MVW06\]](#) and [\[Ros96\]](#), and others mentioned in the Reference.

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## 0 INTRODUCTION

Let  $X \in \mathbf{Sm}/k$  be a smooth separated scheme over a field  $k$ . The study of motivic cohomology started with the hope that

**Conjecture 0.1** (Beilinson and Lichtenbaum, 1982-1987). There exists some complexes  $\mathbb{Z}(n)$  for  $n \in \mathbb{N}$  of sheaves in Zariski topology on  $\mathbf{Sm}/k$  such that

1.  $\mathbb{Z}(0)$  is (quasi-isomorphic to) the constant sheaf  $\mathbb{Z}$ , i.e., the complex

$$\cdots \longrightarrow 0 \longrightarrow \mathbb{Z} \longrightarrow 0 \longrightarrow \cdots$$

concentrated at degree 0;

2.  $\mathbb{Z}(1)$  is the complex  $\mathcal{O}^*[-1]$ , i.e., the complex

$$\cdots \longrightarrow 0 \longrightarrow \mathcal{O}^* \longrightarrow 0 \longrightarrow \cdots$$

concentrated at degree 1;

3. for every field  $F/k$ , the hypercohomology over Zariski topology satisfies<sup>1</sup>

$$\mathbb{H}_{\mathrm{Zar}}^n(F, \mathbb{Z}(n)) = H^n(\mathbb{Z}(n)(\mathrm{Spec}(F))) = K_n^M(F),$$

where  $K_n^M(F)$  is the  $n$ th Milnor K-theory of a field  $F$ , given by the quotient of the tensor algebra  $T(F^*)/\{x \otimes (1-x) : x \in F^*\}$  over  $\mathbb{Z}$ ; (lecture 5 of [MVW06], page 29)

**Example 0.2.**

- a.  $K_0^M(F) = K_0(F) = \mathbb{Z}$ ;
  - b.  $K_1^M(F) = K_1(F) = F^\times$ ;
  - c.  $K_2^M(F) = K_2(F)$ .
4.  $\mathbb{H}_{\mathrm{Zar}}^{2n}(X, \mathbb{Z}(n)) = \mathrm{CH}^n(X)$  (lecture 17 of [MVW06], page 135), where the  $n$ th classical Chow group  $\mathrm{CH}^n(X)$  is the free group given by

$$\mathrm{CH}^n(X) = \mathbb{Z}\{\text{cycles of codimension } n\}/\text{rational equivalences};$$

5. there is a natural Atiyah–Hirzebruch spectral sequence

$$E_2^{p,q} = \mathbb{H}_{\mathrm{Zar}}^p(X, \mathbb{Z}(q)) \Rightarrow K_{2q-p}(X).$$

Moreover, tensoring with  $\mathbb{Q}$ , the spectral sequence degenerates and one has

$$\mathbb{H}_{\mathrm{Zar}}^i(X, \mathbb{Z}(n))_{\mathbb{Q}} = \mathrm{gr}_{\gamma}^n(K_{2n-i}(X)_{\mathbb{Q}})$$

where  $\mathrm{gr}_{\gamma}^n$ 's are the quotients (graded pieces) of  $\gamma$ -filtration. ([Lev94]; [Lev99], Theorem 11.7)

**Remark 0.3.** Such choice of complexes  $\mathbb{Z}(q)$  exists, and is called the motivic complex. For a clear definition of these complexes, see Lecture 3 of [MVW06]. Moreover, by convention  $\mathbb{Z}(q) = 0$  for  $q < 0$ .

**Definition 0.4.** The motivic cohomology of  $X$  is defined by  $H^{p,q}(X, \mathbb{Z}) = \mathbb{H}_{\mathrm{Zar}}^p(X, \mathbb{Z}(q))$ , the hypercohomology of the motivic complexes with respect to the Zariski topology.

<sup>1</sup>Here we use the convention that the (hyper)cohomology of  $F$  should be interpreted as of  $\mathrm{Spec}(F)$ , the corresponding space.

**Remark 0.5.** In general, a motivic cohomology with coefficient in an abelian group  $A$  is a family of contravariant functors  $H^{p,q}(-, A) : \mathbf{Sm}/k \rightarrow \mathbf{Ab}$ .

**Remark 0.6.** The motivic cohomology of  $X$  satisfies the cancellation property: set  $\mathbb{G}_m = \mathbb{A}^1 \setminus \{0\}$ , then

$$H^{p,q}(X \times \mathbb{G}_m, \mathbb{Z}) = H^{p,q}(X, \mathbb{Z}) \oplus H^{p-1, q-1}(X, \mathbb{Z}).$$

**Remark 0.7.** It turns out that the group remains unchanged if we replace the Zariski topology by Nisnevich topology.<sup>2</sup> If one uses étale topology instead, we retrieve Lichtenbaum motivic cohomology  $H_L^{p,q}(X, \mathbb{Z})$ . If  $\text{char}(k) \nmid n$ , it admits the comparison

$$H_L^{p,q}(X, \mathbb{Z}/n\mathbb{Z}) = H_{\text{étale}}(X, \mathbb{Z}/n\mathbb{Z}(q)),$$

where  $\mathbb{Z}/n\mathbb{Z}(q)$  is the  $q$ -twist  $\mu_n^{\otimes q}$ .

We may compare Lichtenbaum motivic cohomology with motivic cohomology by the following theorem, formerly known as Beilinson-Lichtenbaum Conjecture<sup>3</sup>:

**Theorem 0.8** ([Voe11]). The natural map

$$H^{p,q}(X, \mathbb{Z}/n\mathbb{Z}) \rightarrow H_L^{p,q}(X, \mathbb{Z}/n\mathbb{Z})$$

is an isomorphism if  $p \leq q$ , is a monomorphism if  $p = q + 1$ , and gives a spectral sequence for any pair of  $p, q$ .

**Corollary 0.9.** For  $p \leq q$ , we have

$$H^{p,q}(X, \mathbb{Z}/n\mathbb{Z}) = H_{\text{étale}}^p(X, \mathbb{Z}/n\mathbb{Z}(q)).$$

In particular, for  $X = \text{Spec}(k)$  as a point, this is the theorem formerly known as Milnor conjecture:

**Corollary 0.10** ([Voe97], [Voe03a], [Voe03b]).

- $H^{p,p}(k, \mathbb{Z}/n\mathbb{Z}) = K_p^M(k)/n = H_{\text{étale}}^p(X, \mathbb{Z}/n\mathbb{Z}(p))$  as the Galois cohomology;
- in general,

$$H^{p,q}(k, \mathbb{Z}/n\mathbb{Z}) = \begin{cases} 0, & p > q \\ H^{p,p}(k, \mathbb{Z}/n\mathbb{Z}) \cdot \tau^{q-p}, & p \leq q \end{cases}$$

where  $\tau \in \mu_n(k) = H^{0,1}(k, \mathbb{Z})$  is a primitive  $n$ th root of unity.

**Remark 0.11.** Unlike the case with finite coefficients,  $H^{p,q}(k, \mathbb{Z})$  is quite hard to compute for small  $p < q$ ; for  $p \geq q$ , this is 0.

A current long-standing conjecture is

**Conjecture 0.12** (Beilinson-Soulé Vanishing Conjecture, [Lev93]).  $H^{p,q}(k, \mathbb{Z}) = 0$  if  $p < 0$ .

**Remark 0.13.** Here are a few known cases:

- for  $\text{char}(k) = 0$ , this is known for number fields ([Bor74]), function fields of genus 0 ([Dég08]), curves over number fields, and their inductive limits ([more precise references required](#)); ([DG05])

<sup>2</sup>Recall that the Nisnevich topology is a Grothendieck topology on the category of schemes that is finer than the Zariski topology but coarser than the étale topology.

<sup>3</sup>This is also known as the norm residue isomorphism theorem, or (formerly) Bloch-Kato conjecture.

- for  $\text{char}(k) > 0$ , this is known for finite fields ([Qui72]) and global fields ([Har77]).

**Remark 0.14.** The motivic cohomology could be realized in a tensor triangulated category, namely the category of effective motives  $\text{DM}(k)$ . For any pair of  $p, q$ , we can find an Eilenberg-MacLane space and a corresponding representable functor so that

$$H^{p,q}(X, \mathbb{Z}) = \text{Hom}_{DM}(\mathbb{Z}(X), \mathbb{Z}(q)[p])$$

where  $\mathbb{Z}(X)$  is the motive of  $X$  and  $\mathbb{Z}(q)[p] = \mathbb{G}_m^{\wedge q}[p - q]$ .<sup>4</sup>

**Remark 0.15.** Dually, we can define the motivic homology by

$$H_{p,q}(X, \mathbb{Z}) = \text{Hom}_{DM}(\mathbb{Z}(q)[p], \mathbb{Z}(X)).$$

**Remark 0.16** ([MVW06] Properties 14.5, page 110). By taking the hom functor from the aspect of motives, we can derive theorems for all (co)homologies which can be represented in  $DM$ . The main derives are the following:

1. If  $E \rightarrow X$  is an  $\mathbb{A}^n$ -bundle, then motives  $\mathbb{Z}(E) = \mathbb{Z}(X)$  in  $DM$ .
2. If  $\{U, V\}$  is a Zariski open covering of  $X$ , we have a Mayer-Vietoris sequence

$$\mathbb{Z}(U \cap V) \longrightarrow \mathbb{Z}(U) \oplus \mathbb{Z}(V) \longrightarrow \mathbb{Z}(X) \longrightarrow \mathbb{Z}(U \cap V)[1]$$

in the form of a distinguished triangle in  $DM$ .

3. If  $Y \subseteq X$  is a closed embedding of codimension  $c$  in  $\text{Sm}/k$ , then we have a Gysin triangle

$$\mathbb{Z}(X \setminus Y) \longrightarrow \mathbb{Z}(X) \longrightarrow \mathbb{Z}(Y)(c)[2c] \longrightarrow \mathbb{Z}(X \setminus Y)[1]$$

which is a distinguished triangle where  $\mathbb{Z}(Y)(c)[2c] := \mathbb{Z}(Y) \otimes \mathbb{Z}(c)[2c]$ .

4. For any vector bundle of rank  $n$  on  $X$ , we have the projective bundle formula

$$\mathbb{Z}(\mathbb{P}(E)) = \bigoplus_{i=0}^n \mathbb{Z}(X)(i)[2i]$$

which defines the Chern class of  $E$ .

5. Let  $X$  be a proper smooth scheme and let  $d_X$  be its dimension, then  $\mathbb{Z}(X)$  has a strong dual  $\mathbb{Z}(X)(-d_X)[-2d_X]$  in  $DM$  by stabilization. This gives a Poincaré duality<sup>5</sup>

$$H^{p,q}(X, \mathbb{Z}) \cong H_{2d_X - p, d_X - q}(X, \mathbb{Z}).$$

<sup>4</sup>Again, this notation goes back to the concise definition of the motivic complexes: see Lecture 3 from [MVW06] as well as the concept of presheaves with transfers.

<sup>5</sup>We can use cohomology with compact support for this.

# 1 INTERSECTION THEORY

## 1.1 CYCLES OF SCHEME

**Definition 1.1.** Let  $X$  be a scheme of finite type over  $k$ . We define the  $i$ th cycle on the scheme  $X$  to be a free abelian group

$$Z_i(X) = \bigoplus_{\substack{\text{irreducible closed } c \subseteq X \\ \text{with } \dim(c)=i}} \mathbb{Z} \cdot c$$

and set  $Z(X) = \bigoplus_i Z_i(X)$ . Define a set  $K_i(X)$  to be the set of coherent sheaves  $\mathcal{F}$  on  $X$  with  $\dim(\text{supp}(\mathcal{F})) \leq i$ .<sup>6</sup>

**Remark 1.2.** Let  $(A, \mathfrak{m})$  be a Noetherian local ring and  $M$  be an  $A$ -module, then by the dimension theorem, we know  $\dim(M) = d(M) = \dim(\text{supp}(M))$ , where  $d(M)$  is the degree of the Hilbert-Samuel polynomial  $P_{\mathfrak{m}}(M, n)$ .

**Definition 1.3.** Let  $X \in \text{Sm}/k$  and let  $U, V \subseteq X$  be irreducible and closed. Suppose  $W \subseteq U \cap V$  is a irreducible and closed component. If  $\dim(W) = \dim(U) + \dim(V) - \dim(X)$ , i.e.,  $\text{codim}(W) = \text{codim}(U) + \text{codim}(V)$ , we say that  $U$  and  $V$  intersect properly at  $W$ .

**Remark 1.4.** This condition is weaker than saying they intersect transversely: we do not require information about tangent spaces.

**Theorem 1.5.** Let  $A \supseteq k$  be a Noetherian regular ring,  $M, N$  be finitely-generated  $A$ -modules, and suppose  $\ell(M \otimes_A N) < \infty$ , then

1.  $\ell(\text{Tor}_i^A(M, N)) < \infty$  for all  $i \geq 0$ ;
2. the Euler-Poincaré characteristic  $\chi(M, N) := \sum_{i=0}^{\dim(A)} (-1)^i \ell(\text{Tor}_i^A(M, N)) \geq 0$ ;
3. by Remark 1.2, we have  $\dim(M) + \dim(N) \leq \dim(A)$ ;
4. in particular, we have  $\dim(M) + \dim(N) < \dim(A)$  if and only if  $\chi(M, N) = 0$ .

*Proof.* See [Ser12], page 106. □

**Remark 1.6.** Part 3. from Theorem 1.5 implies that  $\dim(W) \geq \dim(U) + \dim(V) - \dim(X)$ , i.e.,  $\text{codim}(W) \leq \text{codim}(U) + \text{codim}(V)$  in the notation of Definition 1.3.

**Definition 1.7.** Let  $X, U, V, W$  be as in Definition 1.3, then we define the intersection multiplicity  $m_W(U, V)$  of  $U$  and  $V$  at  $W$  by

$$m_W(U, V) = \chi^{\mathcal{O}_{X,W}}(\mathcal{O}_{X,W}/P_U, \mathcal{O}_{X,W}/P_V)$$

where  $P_U$  and  $P_V$  are prime ideals defining  $U$  and  $V$ , respectively.

**Remark 1.8.** By Theorem 1.5, we know  $m_W(U, V) \geq 0$ , and  $m_W(U, V) = 0$  if and only if  $U$  and  $V$  do not intersect properly at  $W$ .

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<sup>6</sup>Despite the notation, this has nothing to do with a K-theory.

## 1.2 INTERSECTION PRODUCT AND CROSS PRODUCT

**Definition 1.9.** Let  $X \in \mathbf{Sm}/k$ , and let  $U \in Z_a(X)$  and  $V \in Z_b(X)$ . If  $U$  and  $V$  intersect properly at every component, then we define the intersection product to be the cycle

$$U \cdot V = \sum_{\substack{W \subseteq U \cap V \\ \dim(W) = a+b-d_X}} m_W(U, V) \cdot W \in Z_{a+b-d_X}(X).$$

**Example 1.10.** Let  $X$  be a smooth projective surface, and let  $C$  and  $D$  be divisors on  $X$ . For any point  $x \in C \cap D$ , locally we think of  $C = \{f = 0\}$  and  $D = \{g = 0\}$  around  $x$ , then  $m_x(C, D) = \ell_{\mathcal{O}_{X,x}}(\mathcal{O}_{X,x}/(f, g))$ .

**Definition 1.11.** Suppose  $X$  is a scheme of finite type over  $k$ , and  $\mathcal{F} \in K_n(X)$  is a coherent sheaf, then we define  $Z_a(\mathcal{F}) = \sum_{\dim(\bar{\eta})=a} (\mathcal{O}_{X,\eta}(\mathcal{F}_\eta) \cdot \bar{\eta}) \in Z_a(X)$ .

Therefore, we define the cycle of  $\mathcal{F}$  as an element of the cycle of  $X$ .

**Definition 1.12** ([Har13], Exercise III.6.9). Every coherent sheaf  $\mathcal{F}$  on  $X \in \mathbf{Sm}/k$  has a resolution

$$0 \longrightarrow E_k \longrightarrow E_{k-1} \longrightarrow \cdots \longrightarrow E_0 \longrightarrow \mathcal{F} \longrightarrow 0$$

where  $E_i$ 's are locally free of finite rank. Therefore, for any coherent sheaf  $\mathcal{G}$ , we can define the Tor functor<sup>7</sup> of coherent sheaves by

$$\mathrm{Tor}_i^{\mathcal{O}_X}(\mathcal{F}, \mathcal{G}) = H_i(E_* \otimes_{\mathcal{O}_X} \mathcal{G}).$$

**Proposition 1.13.** Let  $X \in \mathbf{Sm}/k$ . Suppose  $\mathcal{F} \in K_a(X)$  and  $\mathcal{G} \in K_b(X)$  intersect properly, then

$$Z_a(\mathcal{F}) \cdot Z_b(\mathcal{G}) = \sum_{i=0}^{d_X} (-1)^i \cdot Z_{a+b-d_X}(\mathrm{Tor}_i^{\mathcal{O}_X}(\mathcal{F}, \mathcal{G})).$$

*Proof.* We only have to do it locally, so we can assume  $X$  to be affine, and count the coefficients of  $\bar{\xi}$  where  $\dim(\xi) = a + b - d_X$ . It suffices to show that the stalks at  $\xi$  satisfies

$$\chi(F_\xi, G_\xi) = \sum_{\substack{\dim(\bar{\lambda})=a \\ \dim(\bar{\eta})=b \\ \xi \in \bar{\lambda} \cap \bar{\eta}}} \ell(\mathcal{F}_\lambda) \cdot \ell(\mathcal{G}_\eta) \cdot m_{\bar{\xi}}(\bar{\lambda}, \bar{\eta}).$$

Because our ring is Noetherian, then  $\mathcal{F}$  admits a filtration

$$0 = M_0 \subseteq \cdots \subseteq M_d = \mathcal{F}$$

such that  $M_i/M_{i-1} \cong \mathcal{O}_X/\mathcal{I}$  is coherent for prime ideal  $\mathcal{I}$ . By the additivity of both sides of the isomorphism, we may assume  $\mathcal{F} = \mathcal{O}_X/\mathfrak{p}$  with dimension at most  $a$ , where  $\mathfrak{p} \sim \lambda \in X$ . Similarly, we may assume  $\mathcal{G} = \mathcal{O}_X/\mathfrak{q}$  with dimension at most  $b$ , where  $\mathfrak{q} \sim \eta \in X$ . Moreover, set  $\xi \in \bar{\lambda} \cap \bar{\eta}$ . By definition, we now have  $\chi(\mathcal{F}_\xi, \mathcal{G}_\xi) = m_{\bar{\xi}}(\bar{\lambda}, \bar{\eta})$ .

- If  $\dim(\bar{\lambda}) = a$  and  $\dim(\bar{\eta}) = b$ , then the equality follows from the fact that  $\ell(\mathcal{F}_\lambda) = \ell(\mathcal{G}_\eta) = 1$ .
- If not, then either  $\dim(\bar{\lambda}) < a$  or  $\dim(\bar{\eta}) < b$ , then  $\bar{\lambda}$  and  $\bar{\eta}$  do not intersect properly at  $\bar{\xi}$ , so both the left-hand side and the right-hand side become 0.

□

<sup>7</sup>Since we are working over sheaves of  $\mathcal{O}_X$ -modules, using the same argument on the level of modules shows that the Tor functor is independent from the choice of resolution.

**Proposition 1.14.** The intersection product is commutative.

*Proof.* This is obvious since the Tor functor is commutative.  $\square$

**Proposition 1.15.** The intersection product is associative.

*Proof.* Suppose we pick  $\mathcal{F} \in K_a(X)$ ,  $\mathcal{G} \in K_b(X)$ , and  $\mathcal{H} \in K_c(X)$  with support dimension at most  $a, b, c$ , respectively, and they intersect properly. Let  $L_*$  and  $M_*$  be free resolutions of  $\mathcal{F}$  and  $\mathcal{H}$ , respectively. Define a double complex  $N_{ij} = L_i \otimes \mathcal{G} \otimes M_j$ , then the associativity of tensor product allows us to calculate triple Tor

$$H_i(L_i \otimes H_j(\mathcal{G}) \otimes M_j) \cong \text{Tor}_i(\mathcal{F}, \mathcal{G}, \mathcal{H}) \cong H_i(H_j(L_i \otimes \mathcal{G}) \otimes M_j)$$

as the homology of two (tensor) double complexes. We obtain two spectral sequences

$$\begin{aligned} {}^I E_{p,q}^2 &= \text{Tor}_p(\mathcal{F}, \text{Tor}_q(\mathcal{G}, \mathcal{H})) \Rightarrow \text{Tor}_{p+q}(\mathcal{F}, \mathcal{G}, \mathcal{H}) \\ {}^{II} E_{p,q}^2 &= \text{Tor}_p(\text{Tor}_q(\mathcal{F}, \mathcal{G}), \mathcal{H}) \Rightarrow \text{Tor}_{p+q}(\mathcal{F}, \mathcal{G}, \mathcal{H}). \end{aligned}$$

Recall Euler-Poincaré characteristic is invariant with respect to taking spectral sequence  $(*)$ , then

$$\begin{aligned} Z_a(\mathcal{F}) \cdot ((Z_b \mathcal{G}) \cdot Z_c(\mathcal{H})) &= Z_a(\mathcal{F}) \cdot \sum_q (-1)^q Z_{b+c-d_X}(\text{Tor}_q(\mathcal{G}, \mathcal{H})) \text{ by Proposition 1.13} \\ &= \sum_{p,q} (-1)^{p+q} Z_{a+b+c-2d_X}({}^I E_{p,q}^2) \text{ by Proposition 1.13} \\ &= \sum_i (-1)^i Z_{a+b+c-2d_X}(\text{Tor}_i(\mathcal{F}, \mathcal{G}, \mathcal{H})) \text{ by } (*) \\ &= \sum_{p,q} (-1)^{p+q} Z_{a+b+c-2d_X}({}^{II} E_{p,q}^2) \text{ by } (*) \\ &= \sum_p Z_{a+b-d_X}(\text{Tor}_p(\mathcal{F}, \mathcal{G})) \cdot Z_c(\mathcal{H}) \text{ by Proposition 1.13} \\ &= (Z_a(\mathcal{F}) \cdot Z_b(\mathcal{G})) \cdot Z_c(\mathcal{H}) \text{ by Proposition 1.13.} \end{aligned}$$

$\square$

**Definition 1.16.** Suppose  $X_1, X_2 \in \text{Sm}/k$ , with  $\mathcal{F}_1 \in K_{a_1}(X_1)$  and  $\mathcal{F}_2 \in K_{a_2}(X_2)$ . We define the cross product of cycles to be

$$Z_{a_1}(\mathcal{F}_1) \times Z_{a_2}(\mathcal{F}_2) = Z_{a_1+d_{X_2}}(p_1^* \mathcal{F}_1) \cdot Z_{a_2+d_{X_1}}(p_2^* \mathcal{F}_2),$$

where  $p_i : X_1 \times X_2 \rightarrow X_i$  is the projection for  $i = 1, 2$ .

**Exercise 1.17.** One should check that this is well-defined.

**Remark 1.18.** Suppose  $X_1, X_2 \in \text{Sm}/k$ , with  $\mathcal{F}_1 \in K_{a_1}(X_1)$ ,  $\mathcal{F}_2 \in K_{b_1}(X_1)$ ,  $\mathcal{G}_1 \in K_{a_2}(X_2)$  and  $\mathcal{G}_2 \in K_{a_2}(X_2)$ . Suppose  $Z_{a_1}(\mathcal{F}_1) \cdot Z_{a_2}(\mathcal{G}_1)$  and  $Z_{b_1}(\mathcal{F}_2) \cdot Z_{b_2}(\mathcal{G}_2)$  are defined, then

- $Z_{a_1}(\mathcal{F}_1) \times Z_{a_2}(\mathcal{G}_1)$  and  $Z_{b_1}(\mathcal{F}_2) \times Z_{b_2}(\mathcal{G}_2)$  intersect properly on  $X_1 \times X_2$ , and
- $(Z_{a_1}(\mathcal{F}_1) \times Z_{a_2}(\mathcal{G}_1)) \cdot (Z_{b_1}(\mathcal{F}_2) \times Z_{b_2}(\mathcal{G}_2)) = (Z_{a_1}(\mathcal{F}_1) \cdot Z_{b_1}(\mathcal{F}_2)) \times (Z_{a_2}(\mathcal{G}_1) \cdot Z_{b_2}(\mathcal{G}_2)).$

## 1.3 PUSHOUT AND PULLBACK

**Definition 1.19.** Suppose  $X, Y$  are schemes of finite type over  $k$ , and let  $f : X \rightarrow Y$  be a proper map. For every irreducible closed subset  $c \subseteq X$  of dimension  $a$ , we define the direct image to be

$$f_*c = \begin{cases} [k(c) : k(f(c))] \cdot f(c) \in Z_a(Y), & \dim(f(c)) = a \\ 0, & \dim(f(c)) < a \end{cases}$$

to be the direct image of  $c$  under  $f$ .

**Lemma 1.20.** Suppose  $X$  and  $Y$  are schemes of finite type over  $k$  of the same dimension  $n$ , and that  $f : X \rightarrow Y$  is proper, then there exists an open subset  $U \subseteq Y$  such that  $\dim(Y \setminus U) < n$  and  $f : f^{-1}(U) \rightarrow U$  is a finite morphism.

*Proof.* Suppose  $\xi \in Y$  has  $\dim(\bar{\xi}) = n$ . We can find  $U \ni \xi$  such that  $f|_U$  has finite fibers by Exercise II.3.7 from [Har13]. By Exercise III.11.2 in [Har13], such  $f$  is finite.  $\square$

**Proposition 1.21.** Let  $f : X \rightarrow Y$  be a proper morphism between schemes over  $k$  of finite type, and let  $\mathcal{F} \in K_a(X)$ , then

1.  $f_*\mathcal{F} \in K_a(Y)$  and the right derived  $R^i f_*\mathcal{F} \in K_{a-1}(Y)$  for  $i > 0$ .
2.  $f_*Z_a(\mathcal{F}) = Z_a(f_*\mathcal{F})$ .

*Proof.* 1. By Theorem III.8.8 from [Har13],  $R^i f_*\mathcal{F}$  is coherent for all  $i \geq 0$ . We have  $\text{supp}(R^i f_*\mathcal{F}) \subseteq \text{supp}(\mathcal{F})$ . If  $f$  is finite, then  $f_*$  is exact, so  $R^i f_*\mathcal{F} = 0$  for  $i > 0$ . For general cases, we may assume  $\dim(f(\text{supp}(\mathcal{F}))) = a$  and set  $W = \text{supp}(\mathcal{F})$ . We have a commutative diagram

$$\begin{array}{ccc} W & \xrightarrow{h} & f(W) \\ i \downarrow & & \downarrow j \\ X & \xrightarrow{f} & Y \end{array}$$

where  $h$  is also proper. By Lemma 1.20, there exists  $V \subseteq f(W)$  such that  $\dim(f(W) \setminus V) < a$  and  $h|_V$  is finite. Let  $\mathcal{J}$  be the ideal sheaf of  $W$ , then  $\mathcal{J}^s \mathcal{F} / \mathcal{J}^{s+1} \mathcal{F} = i_* i^* \mathcal{J}^s \mathcal{F} / \mathcal{J}^{s+1} \mathcal{F}$ . By the long exact sequence, it suffices to prove the case for  $\mathcal{F} = i_* \mathcal{G}$ . Then

$$(R^k f_*) i_* \mathcal{G} = R^k (f i)_* \mathcal{G} = j_* R^k h_* \mathcal{G}.$$

It suffices to consider  $h$ , but

$$(R^k h_* \mathcal{G})V = R^k h(\mathcal{G}|_{f^{-1}(V)}) = 0$$

for  $k > 0$ , so  $\text{supp}(R^k h_* \mathcal{G}) \subseteq f(W) \setminus V$  if  $k > 0$ .

2. If  $f$  is finite, let us write down the coefficients of  $\xi$  of dimension  $a$  on both sides, namely

$$\ell((f_*\mathcal{F})_\xi) = \sum_{\substack{\eta \in f^{-1}(\xi) \\ \dim(\bar{\eta})=a}} \ell(F_\eta) \cdot [k(\bar{\eta}) : k(\overline{f(\eta)})].$$

By additivity, one reduces to the case when  $X$  is affine and  $F = \mathcal{O}_X/\mathfrak{p}$ . For the general case, use Lemma 1.20, and the case where  $f$  is finite.  $\square$



**Definition 1.22.** Suppose  $f : X \rightarrow Y$  where  $Y \in \mathbf{Sm}/k$  and  $X$  is closed in  $Z \in \mathbf{Sm}/k$ . Define  $j : X \rightarrow Z \times Y$  to be the graph map. For any  $C \in Z_a(X)$  and  $D \in Z_b(Y)$  such that  $C$  and  $f^{-1}(D)$  intersect properly, define the intersection cycle to be

$$C \cdot_f D = j_*^{-1}(j(C) \cdot (Z \times D)) \in Z_{a+b-d_Y}(X)$$

In particular,  $f^*(D) = X \cdot_f D$  for  $C = X$ .

**Proposition 1.23.** Using the notation above, for  $\mathcal{F} \in K_a(X)$  and  $\mathcal{G} \in K_b(Y)$ , if  $\mathcal{F}$  and  $f^*\mathcal{G}$  intersect properly, we have

$$Z_a(\mathcal{F}) \cdot_f Z_b(\mathcal{G}) = \sum_{i=0}^{d_Y} (-1)^i Z_{a+b-d_Y}(L_i(\mathcal{F} \otimes f^*\mathcal{G}))$$

*Proof.* Denote  $p_2 : Z \times Y \rightarrow Y$  to be the projection onto the second coordinate. By linearity,  $Z_a(\mathcal{F}) \cdot_f Z_b(\mathcal{G}) = j_*^{-1}(Z_a(j_*\mathcal{F}) \cdot Z_{b+d_Z}(p_2^*\mathcal{G}))$  for  $j : X \rightarrow Z \times Y$ . Suppose  $L_* \rightarrow \mathcal{G}$  is the locally free resolution of  $\mathcal{G}$ . Note that for all  $i \geq 0$ , we have

$$j^*(j_*\mathcal{F} \otimes p_2^*L_i) = F \otimes f^*L_i,$$

which induces an isomorphism

$$j_*\mathcal{F} \otimes p_2^*L_i = j_*(\mathcal{F} \otimes f^*L_i).$$

Hence  $\mathrm{Tor}_i^{\mathcal{O}_{Z \times Y}}(j_*\mathcal{F}, p_2^*\mathcal{G}) = j_*L_i(F \otimes f^*\mathcal{G})$ . So

$$j_*^{-1} Z_{a+b-d_Y}(\mathrm{Tor}_i^{\mathcal{O}_{Z \times Y}}(j_*\mathcal{F}, p_2^*\mathcal{G})) = Z_{a+b-\dim(Y)}(L_i(F \otimes f^*\mathcal{G})).$$

Therefore the statement follows.  $\square$

**Proposition 1.24.** Let  $X \in \mathbf{Sm}/k$ ,  $\mathcal{F} \in K_a(X)$  and  $\mathcal{G} \in K_b(X)$  such that  $\mathcal{F}$  and  $\mathcal{G}$  intersect properly. Let  $\Delta : X \rightarrow X \times X$  be the diagonal map, then

$$\Delta^*(Z_a(\mathcal{F}) \times Z_b(\mathcal{G})) = Z_a(\mathcal{F}) \cdot Z_b(\mathcal{G}).$$

*Proof.* See page 115 of [Ser12].  $\square$

**Proposition 1.25.**  $f^*$  is compatible with intersection product, and  $f^*g^* = (gf)^*$ .

*Proof.* See page 119 of [Ser12].  $\square$

**Lemma 1.26.** Let  $\mathcal{A}$  be an abelian category with enough projectives (respectively, injectives) and  $F$  be a right (respectively, left) exact functor from  $\mathcal{A}$ . Suppose  $C$  is chain complex in  $\mathcal{A}$ , then there exists a double complex  $M_{*,*}$  in  $\mathcal{A}$  such that

$${}^I E_{p,q}^2 = L_p F H_q(C) \quad (\text{respectively, } R^{-p} F(H_q(C))).$$

*Proof.* To do this when  $F$  is right exact, use the Cartan-Eilenberg resolution<sup>8</sup>  $C_* \rightarrow C$  and consider the double complex  $FC_*$ .  $\square$

**Proposition 1.27.** Suppose  $f : X \rightarrow Y$  is in  $\mathbf{Sm}/k$ , suppose  $\mathcal{F} \in K_a(X)$  and  $\mathcal{G} \in K_b(Y)$ , then

$$Z_a(\mathcal{F}) \cdot_f Z_b(\mathcal{G}) = Z_a(\mathcal{F}) \cdot f^* Z_b(\mathcal{G})$$

if both sides are defined.

---

<sup>8</sup>See Proposition 11 on page 210 of [GM13].

*Proof.* We may assume  $X$  is affine. Let  $L_* \rightarrow \mathcal{G}$  be a free resolution and apply [Lemma 1.26](#) to  $f^*L_*$  and  $F \otimes -$ , then we find a double complex such that

$$\begin{aligned} {}^I E_{p,q}^2 &= \mathrm{Tor}_p(\mathcal{F}, L_q f^* \mathcal{G}) \\ {}^{II} E_{p,q}^2 &= L_p(F \otimes f^*) \mathcal{G}. \end{aligned}$$

□

**Proposition 1.28.** Let  $X \subseteq Z$  and  $Y, Z \in \mathrm{Sm}/k$  and  $f : X \rightarrow Y$  be proper. Suppose  $\mathcal{F} \in K_a(X)$  and  $\mathcal{G} \in K_b(Y)$ , and suppose  $\mathcal{F}$  and  $f^* \mathcal{G}$  intersect properly, then

$$f_*(Z_a(\mathcal{F}) \cdot_f Z_b(\mathcal{G})) = (f_* Z_a(\mathcal{F})) \cdot Z_b(\mathcal{G}).$$

*Proof.* Pick  $L_* \rightarrow \mathcal{G}$  to be a resolution and apply [Lemma 1.26](#) to  $F \otimes f^* L_*$  and  $f_*$ , then we have a double complex  $M_{*,*}$  such that

$${}^I E_{p,q}^2 = R^{-p} f_* L_q(F \otimes f^*) \mathcal{G}.$$

On the other hand,  $H_q(M_{*,n}) = R^{-q} f_*(F \otimes f^* L_n) = (R^{-q} f_* \mathcal{F}) \otimes L_n$ , therefore

$${}^{II} E_{p,q}^2 = \mathrm{Tor}_p(R^{-q} f_* \mathcal{F}, \mathcal{G}).$$

□

**Corollary 1.29.** Under the same hypothesis as [Proposition 1.28](#), we have

$$f_*(Z_a(\mathcal{F}) \cdot f^*(Z_b(\mathcal{G}))) = f_*(Z_a(\mathcal{F})) \cdot Z_b(\mathcal{G}).$$

## 2 SHEAVES WITH TRANSFERS

We fix a base scheme  $S \in \mathbf{Sm}/k$ .

### 2.1 ALGEBRA OF CORRESPONDENCES

**Definition 2.1.** Let  $X, Y \in \mathbf{Sm}/S$ , then we define the group of finite correspondences

$$\mathrm{Cor}_S(X, Y) = \mathbb{Z}\{\text{irreducible closed } C \subseteq X \times_S Y \mid C \rightarrow X \text{ finite, } \dim(C) = \dim(X)\}$$

to be the free abelian group generated by elementary correspondences from  $X$  to  $Y$ .

**Example 2.2.** For any  $f : X \rightarrow Y$ , the graph  $\Gamma_f = (x, f(x)) \subseteq X \times_S Y$  is a finite correspondence from  $X \rightarrow Y$ .

**Example 2.3.** If  $f : X \rightarrow Y$  is finite and  $\dim(X) = \dim(Y)$ , then the graph  $\Gamma_f$  is also a finite correspondence from  $Y \rightarrow X$ .

**Definition 2.4.** Define an additive category  $\mathrm{Cor}_S$  whose objects are the same as  $\mathbf{Sm}/S$ , and the hom sets defined as  $\mathrm{Hom}_{\mathrm{Cor}_S}(X, Y) = \mathrm{Cor}_S(X, Y)$  as in [Definition 2.1](#). The contravariant additive functors

$$F : \mathrm{Cor}_S^{\mathrm{op}} \rightarrow \mathbf{Ab}$$

are called presheaves with transfers. The corresponding category is denoted by  $\mathrm{PSh}(S) = \mathrm{PSh}(\mathrm{Cor}_S)$ , which is abelian with enough injectives and projectives. We have a functor  $\gamma : \mathbf{Sm}/S \rightarrow \mathrm{Cor}_S$  by [Example 2.3](#).

**Remark 2.5.** For any additive  $F$  and  $X, Y \in \mathbf{Sm}/S$ , there is a pairing

$$\mathrm{Cor}_S(X, Y) \otimes F(Y) \rightarrow F(X).$$

Restricting to  $\mathbf{Sm}/S$  over  $\mathrm{Cor}_S$ , we note that  $F$  is a presheaf of abelian groups over  $\mathbf{Sm}/S$  with transfer map  $F(Y) \rightarrow F(X)$  indexed by finite correspondences from  $X$  to  $Y$ .

**Example 2.6.** Every  $X \in \mathbf{Sm}/S$  gives an element  $\mathbb{Z}(X) \in \mathrm{PSh}(S)$  defined by  $\mathbb{Z}(X)(Y) = \mathrm{Cor}_S(Y, X)$ . Therefore, we say  $\mathbb{Z}(X)$  is the presheaf with transfers represented by  $X$ . By Yoneda Lemma we know there is a natural isomorphism

$$\mathrm{Hom}_{\mathrm{PSh}(S)}(\mathbb{Z}(X), F) \cong F(X).$$

Moreover, representable functors give embeddings of  $\mathbf{Sm}/S$  and  $\mathrm{Cor}_S$  into  $\mathrm{PSh}(S)$  via

$$\begin{aligned} \mathbf{Sm}/S &\xrightarrow{\gamma} \mathrm{Cor}_S \longrightarrow \mathrm{PSh}(S) \\ X &\longmapsto X \longmapsto \mathbb{Z}(X) \end{aligned}$$

In particular,  $\mathbb{Z}(S) = \mathbb{Z}$ .

**Example 2.7.** The presheaves  $\mathcal{O}$  and  $\mathcal{O}^*$  are in  $\mathrm{PSh}(S)$ . For any  $C \in \mathrm{Cor}_S(X, Y)$  and  $f \in \mathcal{O}(Y)$  (respectively,  $\mathcal{O}^*(Y)$ ), we have a diagram

$$\begin{array}{ccc} C & \xrightarrow{i} & X \times_S Y \xrightarrow{p_2} Y \\ & & \downarrow p_1 \\ & & X \end{array}$$

and can define  $\mathcal{O}(C)(f) = \mathrm{Tr}_{C/X}((p_2 \circ i)^*(f))$  (respectively,  $\mathcal{O}^*(C)(f) = \mathrm{N}_{C/X}((p_2 \circ i)^*(f))$ ).

We study the properties of finite correspondence through Chapter 16.1 in [\[Ful13\]](#).

**Definition 2.8.** Let us describe the composition in  $\text{Cor}_S$ . Suppose  $f \in \text{Cor}_S(X, Y)$  and  $g \in \text{Cor}_S(Y, Z)$ , then from the diagram

$$\begin{array}{ccc} & X \times_S Z & \\ p_{13} \uparrow & & \\ X \times_S Y \times_S Z & \xrightarrow{p_{23}} & Y \times_S Z \\ p_{12} \downarrow & & \\ & X \times_S Y & \end{array}$$

we define the composition  $g \circ f = p_{13*}(p_{23}^*(g)p_{12}^*(f))$ .

**Exercise 2.9.** One should check that all intersections are proper.

**Remark 2.10.** Using this language, given a correspondence  $\alpha \in \text{Cor}_S(X, Y)$ , we can define pullbacks and pushouts on the cycles as homomorphisms

$$\begin{aligned} \alpha_* : Z(X) &\rightarrow Z(Y) \\ x &\mapsto p_{Y*}^{XY}(\alpha \cdot p_X^{XY*}(x)) \end{aligned}$$

and

$$\begin{aligned} \alpha^* : Z(Y) &\rightarrow Z(X) \\ y &\mapsto p_{X*}^{XY}(\alpha \cdot p_Y^{XY*}(y)) \end{aligned}$$

**Remark 2.11** ([Ful13], Proposition 1.7, Base-change Formula). Let

$$\begin{array}{ccc} X' & \xrightarrow{g'} & X \\ f' \downarrow & & \downarrow f \\ Y' & \xrightarrow{g} & Y \end{array}$$

be a fiber square where  $f$  is proper and  $g$  is flat, then  $f'$  is proper and  $g'$  is flat, and that  $f'_*g'^* = g^*f_*$  over  $Y'$ .

**Proposition 2.12** ([Ful13], Proposition 16.1.1). The composition law is associative.

*Proof.* Suppose

$$X \xrightarrow{f} Y \xrightarrow{g} Z \xrightarrow{h} W$$

are morphisms in  $\text{Cor}_S$ , then we have two Cartesian squares

$$\begin{array}{ccc} X \times_S Y \times_S Z \times_S W & \longrightarrow & X \times_S Z \times_S W \\ \downarrow & & \downarrow \\ X \times_S Y \times_S Z & \longrightarrow & X \times_S Z \end{array}$$

and

$$\begin{array}{ccc} X \times_S Y \times_S Z \times_S W & \longrightarrow & X \times_S Y \times_S W \\ \downarrow & & \downarrow \\ Y \times_S Z \times_S W & \longrightarrow & Y \times_S W \end{array}$$

Now using the base-change formula, we know

$$h \circ (g \circ f) = p_{XW*}^{XZW}(p_{ZW*}^{XZW}(h)p_{XZ*}^{XZW}(p_{XZ*}^{XYZ}(p_{YZ*}^{XYZ}(g)p_{XY*}^{XYZ}(f))))$$

$$\begin{aligned}
&= p_{XW}^{XZW} (p_{ZW}^{XZW*}(h) p_{XZW}^{XYZW} p_{XYZ}^{XYZW*}(p_{YZ}^{XYZ*}(g) p_{XY}^{XYZ*}(f))) \\
&= p_{XW}^{XZW} (p_{ZW}^{XZW*}(h) p_{XZW}^{XYZW} (p_{YZ}^{XYZW*}(g) p_{XY}^{XYZW*}(f))) \\
&= p_{XW}^{XZY} p_{XZW}^{XYZW*}(h) p_{YZ}^{XYZW*}(g) p_{XY}^{XYZW}(f) \\
&= p_{XW}^{XYW} p_{XYW}^{XYZW} (p_{ZW}^{XYZW*}(h) p_{YZ}^{XYZW*}(g) p_{XY}^{XYZW}(f)) \\
&= p_{XW}^{XYW} (p_{XYW}^{XYZW} (p_{ZW}^{XYZW*}(h) p_{YZ}^{XYZW*}(g)) p_{XY}^{XYW*}(f)) \\
&= p_{XW}^{XYW} (p_{XYW}^{XYZW} p_{YZ}^{YZW*}(h) p_{YZ}^{YZW}(g) p_{XY}^{XYW*}(f)) \\
&= p_{XW}^{XYW} (p_{YZ}^{YZW*}(h) p_{YZ}^{YZW}(g) p_{XY}^{XYW*}(f)) \\
&= p_{XW}^{XYW} (p_{YZ}^{YZW*}(h) p_{YZ}^{YZW}(g) p_{XY}^{XYW*}(f)) \\
&= h \circ g \circ f.
\end{aligned}$$

□

**Theorem 2.13.** We have  $\mathcal{O}(g \circ f) = \mathcal{O}(f) \circ \mathcal{O}(g)$  and  $\mathcal{O}^*(g \circ f) = \mathcal{O}^*(f) \circ \mathcal{O}^*(g)$ .

*Proof.* We sketch the proof for  $\mathcal{O}$ . Pick  $X \in \text{Sm}/k$ . For every  $a \in \mathbb{N}$ , define  $\mu_a(x) = \bigoplus_{\dim(V)=a} K(V)$ . Therefore, we have a pairing

$$\begin{aligned}
\mathcal{O}(X) \times Z_a(X) &\rightarrow \mu_a(X) \\
(s, V) &\mapsto s|_V
\end{aligned}$$

by restricting the regular function on the closed subset. For any map  $f : X \rightarrow Y$  where  $X$  contains irreducible and closed  $C$ , suppose  $C$  is finite over  $Y$  and  $s \in K(C)$ , then we define  $f_*(s) = \text{Tr}_{K(C)/K(f(C))}(s)$ .<sup>9</sup> Therefore, for any finite correspondence  $C \in \text{Cor}(Y, X)$  and  $s \in \mathcal{O}(X)$ , we have

$$\begin{array}{ccc}
C & \hookrightarrow & X \times Y \xrightarrow{p_2} Y \\
& & \downarrow p_1 \\
& & X
\end{array}$$

and thus  $\mathcal{O}(C)(s) = p_{2*}(p_1^*(s)|_C)$ .

Now suppose we have closed subsets  $C \subseteq X$  and  $D \subseteq Y$ , with

$$\begin{array}{ccc}
X & \xrightarrow{f} & Y \\
\uparrow & \nearrow \text{finite} & \\
C & & 
\end{array}$$

and that  $C$  and  $f^{-1}(D)$  intersect properly, then one can show that

$$f_*(s|_C)|_D = f_*(s|_{C \cdot_f D})$$

by Tor formula. Moreover, for diagrams like

$$\begin{array}{ccc}
X \times_S Y \times_S Z & \xrightarrow{p_{23}} & YZ \\
\downarrow p_{12} & & \downarrow p_1 \\
X \times_S Y & \xrightarrow{p_2} & Y
\end{array}$$

where  $C \subseteq YZ$  and  $C$  is finite over  $Y$ , then one can show that for all  $s \in \mathcal{O}(Y \times_S Z)$  and  $C$  finite over  $Y$ , we have

$$p_2^* p_{1*}(s|_C) = p_{12*}(p_{23}^*(s)|_{p_{23}^*(C)}).$$

We finish the proof by working with formal calculation. □

<sup>9</sup>Here  $f(C)$  is closed since  $f$  is finite.

**Remark 2.14** ([[Ful13](#)], Proposition 16.1.2). For  $\alpha \in \text{Cor}_S(X, Y)$  and  $\beta \in \text{Cor}_S(Y, Z)$ , we have

$$(\beta \circ \alpha)_* = \beta_* \circ \alpha_*$$

and

$$(\beta \circ \alpha)^* = \alpha^* \circ \beta^*.$$

## 2.2 OPERATIONS ON PRESHEAVES WITH TRANSFERS

**Definition 2.15.** Suppose  $\mathcal{F}_1, \mathcal{F}_2, \mathcal{G} \in \text{PSh}(S)$  be presheaves with transfers. A bilinear function  $\varphi : \mathcal{F}_1 \times \mathcal{F}_2 \rightarrow \mathcal{G}$  is a collection of bilinear maps

$$\varphi_{x_1, x_2} : \mathcal{F}_1(x_1) \times \mathcal{F}_2(x_2) \rightarrow \mathcal{G}(x_1 \times_S x_2)$$

for every  $x_1, x_2 \in \text{Sm}/S$  any any morphisms  $f_i \in \text{Cor}_S(x_i, x'_i)$  for  $i = 1, 2$ , such that the following diagram commutes

$$\begin{array}{ccc} \mathcal{F}_1(x'_1) \times \mathcal{F}_2(x_2) & \xrightarrow{\varphi_{x'_1, x_2}} & \mathcal{G}(x'_1 \times_S x_2) \\ \mathcal{F}_1(f_1) \times \text{id} \downarrow & & \downarrow (f_1 \times \text{id}) \\ \mathcal{F}_1(x_1) \times \mathcal{F}_2(x_2) & \xrightarrow{\varphi_{x_1, x_2}} & \mathcal{G}(x_1 \times_S x_2) \end{array}$$

for  $f_1$  and similarly there is a diagram that commutes for  $f_2$ .

**Definition 2.16.** Define the tensor product  $\mathcal{F}_1 \otimes \mathcal{F}_2$  to be the presheaf such that for every  $\mathcal{G}$ , the hom set  $\text{Hom}(\mathcal{F}_1 \otimes \mathcal{F}_2, \mathcal{G})$  is the same as the collection of bilinear functions  $\mathcal{F}_1 \times \mathcal{F}_2 \rightarrow \mathcal{G}$ .

**Proposition 2.17.** The tensor product  $\mathcal{F}_1 \otimes \mathcal{F}_2$  exists.

*Proof.* For every  $Z \in \text{Sm}/S$ , define

$$(\mathcal{F}_1 \otimes \mathcal{F}_2)(Z) = \bigoplus_{X, Y \in \text{Sm}/S} \mathcal{F}_1(X) \otimes_Z \mathcal{F}_2(Y) \otimes_Z \text{Cor}_S(Z, X \times_S Y) / \sim$$

where  $\sim$  is the subgroup generated by the relations  $\varphi \otimes \psi(f \times \text{id}_Y) \circ h = f^*(\varphi) \otimes \psi \otimes h$  where  $f \in \text{Cor}_S(X', X)$ ,  $\varphi \in \mathcal{F}_1(X)$ ,  $\psi \in \mathcal{F}_2(Y)$ ,  $h \in \text{Cor}_S(Z, X' \times Y)$ , and the relations  $\varphi \otimes \psi(\text{id}_X \times g) \circ h = \varphi \otimes g^*(\psi) \otimes h$  where  $g \in \text{Cor}_S(Y', Y)$ ,  $\varphi \in \mathcal{F}_1(X)$ ,  $\psi \in \mathcal{F}_2(Y)$ ,  $h \in \text{Cor}_S(Z, X \times Y')$ .  $\square$

**Definition 2.18.** A pointed presheaf  $(\mathcal{F}, x)$  is a split injective map given by the constant presheaf  $x : \mathbb{Z} \rightarrow \mathcal{F}$  for some  $\mathcal{F} \in \text{PSh}(S)$ . We set  $\mathcal{F}^{\wedge 1} = \mathcal{F}/x$ . For any two pointed presheaves  $(\mathcal{F}_1, x_1)$  and  $(\mathcal{F}_2, x_2)$ , define  $\mathcal{F}_1 \wedge \mathcal{F}_2 = (\mathcal{F}_1 \otimes \mathcal{F}_2) / ((\mathcal{F}_1 \otimes x_2) \oplus (x_1 \otimes \mathcal{F}_2))$ . This allows us to define  $\mathcal{F}^{\wedge n}$  inductively as a cokernel, c.f., Definition 2.12 from [[MVW06](#)].

**Proposition 2.19.**

- $\mathbb{Z}(X) \otimes \mathbb{Z}(Y) = \mathbb{Z}(X \times Y)$ ;
- $\mathcal{F}^{\wedge 1} \otimes \mathcal{G}^{\wedge 1} = \mathcal{F} \wedge \mathcal{G}$ .

**Definition 2.20.** For any  $\mathcal{F} \in \text{PSh}(S)$  and  $X \in \text{Sm}/S$ , define  $\mathcal{F}^X \in \text{PSh}(S)$  by  $\mathcal{F}^X(Y) = \mathcal{F}(X \times_S Y)$ . For any  $\mathcal{F}, \mathcal{G} \in \text{PSh}(S)$ , define the internal hom  $\underline{\text{Hom}}(\mathcal{F}, \mathcal{G}) \in \text{PSh}(S)$  by  $\underline{\text{Hom}}(\mathcal{F}, \mathcal{G})(X) = \text{Hom}(\mathcal{F}, \mathcal{G}^X)$ .

**Proposition 2.21.** We have a tensor-hom adjunction

$$\text{Hom}(\mathcal{F} \otimes \mathcal{G}, \mathcal{H}) \cong \text{Hom}(\mathcal{F}, \underline{\text{Hom}}(\mathcal{G}, \mathcal{H})).$$

## 2.3 NISNEVICH TOPOLOGY

Let us give a brief introduction to Nisnevich topology, c.f., section 3 and 4 from Chapter I of [Mil80].

**Definition 2.22.** Suppose  $f : Y \rightarrow X$  is a morphism between schemes that are locally of finite type.

1. It is called unramified if for all  $y \in Y$ , the maximal ideals satisfy  $\mathfrak{m}_{f(y)}\mathcal{O}_{Y,y} = \mathfrak{m}_y$ , and  $k(y)/k(f(y))$  is a finite separable field extension of function fields.
2. It is called étale if it is both flat and unramified.
3. It is called Nisnevich if for all  $x \in X$ , there is some  $y \in Y$  such that  $f(y) = x$ ,  $k(y) = k(x)$ , and  $f$  is étale.

**Definition 2.23.** A morphism  $f : Y \rightarrow X$  is called a Nisnevich covering if  $f$  is Nisnevich and surjective.

**Definition 2.24.** Suppose  $\mathcal{F} \in \text{PSh}(S)$ . We say that it is a Nisnevich sheaf with transfers if for any  $X \in \text{Sm}/S$  and Nisnevich covering  $\pi : Y \rightarrow X$ , the sequences

$$\begin{aligned} 0 \longrightarrow \mathcal{F}(X) &\xrightarrow{\pi^*} \mathcal{F}(Y) \xrightarrow{p_1^* - p_2^*} \mathcal{F}(Y \times_X Y) \xrightarrow{p_1} Y \\ 0 \longrightarrow \mathcal{F}(X) &\xrightarrow{\pi^*} \mathcal{F}(Y) \xrightarrow{p_1^* - p_2^*} \mathcal{F}(Y \times_X Y) \xrightarrow{p_2} Y \end{aligned}$$

are exact. The category of Nisnevich sheaves with transfers is denoted by  $\text{Sh}(S)$ .

**Definition 2.25.** A local ring is called Henselian if for any monic polynomial  $f \in A[t]$  such that its image  $\bar{f}$  in the residue field satisfies  $\bar{f} = g_0 h_0$  in  $k(A)[T]$  where  $g_0, h_0$  are monic and relatively prime, there are monic  $g, h \in A[T]$  such that  $\bar{g} = g_0, \bar{h} = h_0$  in the residue fields, and  $f = gh$ .

**Example 2.26.** Complete local rings are Henselian.

**Theorem 2.27** ([Mil80], Theorem I.4.2). Let  $A$  be a local ring,  $X = \text{Spec}(A)$ , and  $x \in X$  be the closed point, then the following are equivalent:

1.  $A$  is Henselian;
2. any finite  $A$ -algebra  $B$  is a direct product of local rings  $B \cong \prod_{i \in I} B_i$ , where each  $B_i$  is of the form  $B_{\mathfrak{m}_i}$  for some maximal ideal  $\mathfrak{m}_i$  of  $B$ ;
3. if  $f : Y \rightarrow X$  has finite fibers and is separated, then  $Y = \coprod_{i=0}^n Y_i$  where  $X \notin f(Y_0)$ , and for  $i \geq 1$ ,  $Y_i$  is finite over  $X$  and is the spectrum of a local ring;
4. if  $f : Y \rightarrow X$  is étale and there exists  $y \in Y$  such that  $f(y) = x$  and  $k(y) = k(x)$ , then  $f$  has a section  $s : X \rightarrow Y$  such that  $f \circ s = \text{id}_X$ .

Now let  $A$  be a Noetherian ring and  $\mathfrak{p} \in \text{Spec}(A)$ . Consider the set  $I$  whose elements are pairs  $(B, \mathfrak{q})$ , where  $B$  is a connected étale  $A$ -algebra,  $\mathfrak{q} \in \text{Spec}(B)$ ,  $\mathfrak{q} \cap A = \mathfrak{p}$ , i.e.,  $\mathfrak{q}$  lies over  $\mathfrak{p}$ , and  $k(\mathfrak{p}) = k(\mathfrak{q})$ . We say that  $(B_1, \mathfrak{q}_1) \leq (B_2, \mathfrak{q}_2)$  if there is an  $A$ -morphism  $f : B_1 \rightarrow B_2$  such that  $f^{-1}(\mathfrak{q}_2) = \mathfrak{q}_1$ . This gives a poset structure.

**Proposition 2.28.** The set  $I$  is a directed set and the ring  $\varinjlim_{(B, \mathfrak{q})} B = A_{\mathfrak{p}}^h$ , i.e., the Henselization of  $A_{\mathfrak{p}}$ , is Henselian and admits the following universal property: for any Henselian  $A$ -algebra  $C$  such that  $\mathfrak{m}_C \cap A = \mathfrak{p}$ , there is a unique morphism  $\varphi : A_{\mathfrak{p}}^h \rightarrow C$  (as a local homomorphism) such that the diagram

$$\begin{array}{ccc} A & \longrightarrow & C \\ \downarrow & \nearrow \exists! \varphi & \\ A_{\mathfrak{p}}^h & & \end{array}$$

*Proof.* This makes use of Lemma I.4.8 from [Mil80].  $\square$

Let  $\varphi_X$  be the smallest Nisnevich site on  $X$ . Suppose  $X$  is Noetherian, pick  $x \in X$ , and  $\mathcal{F} \in \text{PSh}(\varphi_X)$ . We write  $\mathcal{F}_x = \mathcal{F}(\mathcal{O}_{X,x}^h) = \varinjlim_{(V,u)} \mathcal{F}(V)$  as the stalk of  $\mathcal{F}$  at  $x$ , taking all the pairs  $(V, u)$  with étale morphism

$$\begin{aligned} V &\rightarrow X \\ u &\mapsto x \end{aligned}$$

with  $k(u) = k(x)$ .

**Proposition 2.29.** Let

$$0 \longrightarrow \mathcal{F} \longrightarrow \mathcal{G} \longrightarrow \mathcal{H} \longrightarrow 0$$

be a complex in  $\text{Sh}(\varphi_X)$ . The following are equivalent:

1. the complex is exact;
2. for every  $x \in X$ , the complex

$$0 \longrightarrow \mathcal{F}_x \longrightarrow \mathcal{G}_x \longrightarrow \mathcal{H}_x \longrightarrow 0$$

is exact.

*Proof.* This mimics the idea in the usual sheaf theory with Zariski topology. To do so, we need to construct a sheafification in the sense of Nisnevich, explained as follows: suppose  $\mathcal{F} \in \text{PSh}(\varphi_X)$ , define  $\mathcal{F}^+$  as the following: for every Nisnevich covering  $\{V_i\}$  of  $U$ , define

$$\mathcal{F}(U) = \{(s_i) \in \prod_i \mathcal{F}(V_i) : s_i|_{V_i \times_X V_j} = s_j|_{V_i \times_X V_j}\}.$$

Now let  $\mathcal{F}^+(U) = \varinjlim_{V \supseteq U} \mathcal{F}(V)$ , then  $\mathcal{F}^{++}$  is a Nisnevich sheaf with the same stalks as  $\mathcal{F}$ , with a map  $\mathcal{F} \rightarrow \mathcal{F}^{++}$ .

If the complex is exact, then the sequence of stalks is also exact because the direct limit functor is exact. Conversely, if we have an exact sequence of stalks, then we prove that the given sequence is exact using the usual proof in the Zariski case.  $\square$

For any Noetherian scheme  $X$  with  $\dim(X) < \infty$ , we define the cochain to be

$$C^p(X) = \{Y \subseteq X \mid \text{codim}(Y) \geq p\} = \bigoplus_{\substack{y \in X \\ \text{codim}(\bar{y}) \geq p}} \mathbb{Z} \cdot \bar{y}.$$

For  $\mathcal{F} \in \text{Sh}(\varphi_X)$ . For closed subschemes  $Z \subseteq W$  of  $X$  where  $Z \in C^{p+1}(X)$  and  $W \in C^p(X)$ , we have a long exact sequence

$$\cdots \longrightarrow H_Z^i(X, \mathcal{F}) \longrightarrow H_W^i(X, \mathcal{F}) \longrightarrow H_{W \setminus Z}^i(X, \mathcal{F}) \longrightarrow H_Z^{i+1}(X, \mathcal{F}) \longrightarrow \cdots$$

with supports specified as subscripts, using the exactness of

$$0 \longrightarrow \mathcal{F}_Z(X) \longrightarrow \mathcal{F}(X) \longrightarrow \mathcal{F}(X \setminus Z)$$

and defining  $H_Z^i = R^i \Gamma_Z(X, -) : D(X_{\text{étale}}) \rightarrow D(\text{Ab})$  as the right exact functor, where

$$\Gamma_Z(X, \mathcal{F}) = \{s \in \mathcal{F}(X) \mid \text{supp}(s) \subseteq Z\}$$



for closed subscheme  $Z \subseteq X$ . Now define  $H^i(C^p(X), \mathcal{F}) = \varinjlim_{Z \in C^p(X)} H_Z^i(X, \mathcal{F})$ , then

$$H^i(C^p(X)/C^{p+1}(X), \mathcal{F}) = \varinjlim_{\substack{Z \subseteq W \\ W \in C^p, Z \in C^{p+1}}} H_{W \setminus Z}^i(X \setminus Z, \mathcal{F}).$$

Taking limit with respect to pairs  $Z \subseteq W$  where  $W \in C^p(X)$  and  $Z \in C^{p+1}(X)$ , we get a long exact sequence

$$\cdots \rightarrow H^i(C^{p+1}(X), \mathcal{F}) \rightarrow H^i(C^p(X), \mathcal{F}) \rightarrow H^i(C^p(X)/C^{p+1}(X), \mathcal{F}) \rightarrow H^{i+1}(C^{p+1}(X), \mathcal{F}) \rightarrow \cdots$$

Set the  $p$ th filtration to be  $F^p H^i(X, \mathcal{F}) = \text{im}(H^i(C^p(X), \mathcal{F}) \rightarrow H^i(X, \mathcal{F}))$ , then we obtain the Coniveau spectral sequence

$$E_1^{p,q} = H^{p+q}(C^p(X)/C^{p+1}(X), \mathcal{F}) \Rightarrow H^{p+q}(X, \mathcal{F}).$$

**Remark 2.30.**  $E_1^{p,q} = 0$  if  $p > \dim(X)$  and  $q > 0$ .

**Definition 2.31.** Suppose  $x \in X$ . Define the local cohomology

$$H_x^i(X, \mathcal{F}) = \varinjlim_{\text{open } x \in V \subseteq X} H_{\bar{x} \cap V}^i(V, \mathcal{F}).$$

This allows us to calculate  $E_1^{p,q}$  as

$$E_1^{p,q} = \bigoplus_{\text{codim}(\bar{x})=p} H_x^{p+q}(X, \mathcal{F}).$$

**Proposition 2.32** (Étale Excision). Suppose  $\varphi : Y \rightarrow X$  is a étale morphism of sheaves, and suppose  $Z \subseteq X$  is a closed subset such that  $\varphi^{-1}(Z) = Z$ . For any  $\mathcal{F} \in \text{Sh}(\varphi_X)$ , we have

$$H_Z^i(Y, \varphi^* \mathcal{F}) = H_Z^i(X, \mathcal{F}).$$

*Proof.* The morphism

$$Y \coprod (X \setminus Z) \rightarrow X$$

is a Nisnevich covering, but by the (Nisnevich) sheaf condition on  $\mathcal{F}$ , we have a Cartesian square

$$\begin{array}{ccc} \mathcal{F}(X) & \longrightarrow & \mathcal{F}(Y) \\ \downarrow & & \downarrow \\ \mathcal{F}(X \setminus Z) & \longrightarrow & \mathcal{F}(Y \setminus Z) \end{array}$$

which shows the result for  $i = 0$ . The map  $\varphi^*$  is exact and has a left adjoint  $\varphi_!$ , namely the extension by zero, which is the sheafification of the presheaf defined by

$$(\varphi_! \mathcal{F})(U) = \begin{cases} \mathcal{F}(U), & U \subseteq Y \\ 0, & U \not\subseteq Y \end{cases}$$

In particular,  $\varphi^*$  preserves injective objects. Using the case where  $i = 0$  and the  $\delta$ -functor, we prove that the case for  $i > 0$  follows.  $\square$

**Corollary 2.33.** The local cohomology (think of  $x \in X$  as a point) agrees with the supported cohomology (think of  $x \in X$  as a maximal ideal in  $\text{Spec}(\mathcal{O}_{X,x}^h)$ ), i.e.,

$$H_x^i(X, \mathcal{F}) \cong H_x^i(\text{Spec}(\mathcal{O}_{X,x}^h), \mathcal{F}_x).$$

**Theorem 2.34.** For all  $n > \dim(X)$ ,  $H^n(X, \mathcal{F}) = 0$ .

*Proof.* We proceed by induction on  $\dim(X)$ . If  $\dim(X) = 0$ , then  $X$  is a disjoint union of spectra of Henselian rings<sup>10</sup>, but over each Henselian, the higher cohomology vanishes since henselization is an exact functor. so the statement holds. Now suppose the statement is true for any scheme  $Y$  such that  $\dim(Y) < \dim(X)$ , then we have a long exact sequence

$$\cdots \rightarrow H^i(\mathrm{Spec}(\mathcal{O}_{X,x}^h), \mathcal{F}_x) \rightarrow H^i(\mathrm{Spec}(\mathcal{O}_{X,x}^h \setminus \{x\}), \mathcal{F}_x) \rightarrow H^{i+1}(\mathrm{Spec}(\mathcal{O}_{X,x}^h), \mathcal{F}_x) \rightarrow H^{i+1}(\mathrm{Spec}(\mathcal{O}_{X,x}^h), \mathcal{F}_x) \rightarrow \cdots$$

For  $i > 0$ , we know that  $H^i(\mathrm{Spec}(\mathcal{O}_{X,x}^h), \mathcal{F}_x) = H^{i+1}(\mathrm{Spec}(\mathcal{O}_{X,x}^h), \mathcal{F}_x) = 0$ , therefore

$$H^i(\mathrm{Spec}(\mathcal{O}_{X,x}^h \setminus \{x\}), \mathcal{F}_x) \cong H^{i+1}(\mathrm{Spec}(\mathcal{O}_{X,x}^h), \mathcal{F}_x)$$

for  $i > 0$ . By induction,  $H^{n-1}(\mathrm{Spec}(\mathcal{O}_{X,x}^h \setminus \{x\}), \mathcal{F}_x) = 0$  if  $n > \dim(\bar{x})$ ,<sup>11</sup> therefore  $H_x^n(\mathrm{Spec}(\mathcal{O}_{X,x}^h), \mathcal{F}_x) = 0$  if  $n > \dim(\bar{x})$ . This tells us that the Coniveau spectral sequence satisfies

$$E_1^{p,q} \cong \bigoplus_{\mathrm{codim}(\bar{x})=p} H_x^{p+q}(\mathrm{Spec}(\mathcal{O}_{X,x}^h), \mathcal{F}_x) = 0$$

when  $p + q > \dim(X)$  (since  $n > \dim(\bar{x})$ ). Therefore the spectral sequence collapses, i.e.,  $H^n(X, \mathcal{F}) = 0$  for  $n > \dim(X)$ .  $\square$

**Theorem 2.35.** Let  $X, U \in \mathrm{Sm}/S$  and  $p : U \rightarrow X$  be a Nisnevich covering. Denote the  $n$ -fold product  $A \times_B A \times_B \cdots \times_B A$  by  $A_B^n$ , then the Čech complex of sheaves (associated to the complex over  $\mathrm{Sm}/S$ )

$$\check{C}(U/X) = (\cdots \longrightarrow \mathbb{Z}(U_X^n) \xrightarrow{d_n} \cdots \longrightarrow \mathbb{Z}(U \times_X U) \xrightarrow{d_2} \mathbb{Z}(U) \longrightarrow \mathbb{Z}(X) \longrightarrow 0)$$

is exact<sup>12</sup>, where  $d_n = \sum_i (-1)^{i-1} \mathbb{Z}(p_i)$  for  $i$ th omission map  $p_i : U_X^n \rightarrow U_X^{n-1}$ .

*Proof.* It suffices to show exactness stalkwise, so to do things locally, we suppose  $Y = \mathrm{Spec}(A)$  where  $A$  is Henselian, regular and local, and  $a \in \mathrm{Cor}_S(Y, U_X^n) = \mathbb{Z}(U_X^n)(Y)$  such that  $d_n(a) = 0$ . Define  $T = \mathrm{supp}(a)$  and  $R = T \times_{X \times Y} (U \times Y)$ . Since  $U$  is Nisnevich over  $X$ , then  $R$  is Nisnevich over  $T$ . Since  $a$  is a finite correspondence, and  $T \subseteq Y \times_S U_X^n$  is a closed subset, then  $T$  is finite over  $Y$ . But  $Y$  is Henselian, then  $T$  is the spectrum of a disjoint union of Henselian rings by Theorem 2.27. Since  $R$  is a Nisnevich covering of  $T$ , so the map  $R \rightarrow T$  admits a section  $s : T \rightarrow R$ ,<sup>13</sup> where  $s$  is both an open immersion and a closed immersion, i.e.,  $T$  is clopen in  $R$ . This gives a diagram of Cartesian squares

$$\begin{array}{ccc} R_T^n & \longrightarrow & (U \times Y)_{X \times Y}^n \times_{X \times Y} ((U \times Y) \setminus (R \setminus T)) \\ \mathrm{id}^n \times s \downarrow & & \downarrow j_{n+1} \\ R_T^{n+1} & \longrightarrow & (U \times Y)_{X \times Y}^{n+1} \\ p_{n+1} \downarrow & & \downarrow p_{n+1} \\ R_T^n & \longrightarrow & (U \times Y)_{X \times Y}^n \end{array}$$

where  $j_{n+1}$  is a closed immersion. But note that the composition of the left column is just identity, so we define

$$b = (j_{n+1} \circ (p_{n+1} \circ j_{n+1})^*)(a) \in \mathrm{Cor}_S(Y, U_X^{n+1}).$$

By intersection theory, one can check that  $d_{n+1}(b) = a$ .  $\square$

<sup>10</sup>Being Artinian local rings, they should be complete and therefore Henselian.

<sup>11</sup>Note that removing the closure of the point (as a maximal ideal) reduces the length by 1, therefore drops the dimension by 1, so the inductive hypothesis still works.

<sup>12</sup>To be precise, we consider this sequence to be the sheafification of Nisnevich presheaves restricted on Nisnevich sites.

<sup>13</sup>We have an étale morphism  $R \rightarrow T$  that is Nisnevich at the maximal ideal of  $T$ , so we admit a section by Theorem 2.27.

**Theorem 2.36.** There is a unique sheafification function  $a : \text{PSh}(S) \rightarrow \text{Sh}(S)$  such that the following diagram commutes:

$$\begin{array}{ccc} \text{PSh}(S) & \xrightarrow{a} & \text{Sh}(S) \\ \downarrow & & \downarrow \\ \text{PSh}(\text{Sm}/S) & \xrightarrow{+} & \text{Sh}(\text{Sm}(S)) \end{array}$$

*Proof.* Take  $\mathcal{F}_1, \mathcal{F}_2 \in \text{Sh}(S)$ . We first prove uniqueness. Suppose  $\mathcal{F}_1|_{\text{Sm}/S} = \mathcal{F}_2|_{\text{Sm}/S} = (\mathcal{F}|_{\text{Sm}/S})^+$ , set  $s \in \mathcal{F}_1(Y) = \mathcal{F}_2(Y)$  and  $T \in \text{Cor}_S(X, Y)$  where  $X$  is Henselian, then there is a Nisnevich covering  $p : U \rightarrow Y$  such that  $s|_U = t^+$  where  $t \in \mathcal{F}(U)$ . Consider the Cartesian square

$$\begin{array}{ccc} T_U & \longrightarrow & X \times U \\ \downarrow & & \downarrow \\ T & \longrightarrow & X \times Y \end{array}$$

then since  $T$  is irreducible so  $T$  is the spectrum of some Henselian ring, which gives a section  $s$  of the map  $T_U \rightarrow T$ . Denote  $D = \text{im}(s)$ , then  $D \in \text{Cor}_S(X, U)$ . Therefore  $p \circ D = T$ , so we have a commutative diagram

$$\begin{array}{ccc} \mathcal{F}_1(X) & \xlongequal{\quad} & \mathcal{F}_2(X) \\ \mathcal{F}_1(D) \uparrow & & \uparrow \mathcal{F}_2(D) \\ \mathcal{F}_1(U) & \xlongequal{\quad} & \mathcal{F}_2(U) \\ \mathcal{F}_1(p) \uparrow & & \uparrow \mathcal{F}_2(p) \\ \mathcal{F}_1(Y) & \xlongequal{\quad} & \mathcal{F}_2(Y) \end{array} \quad \begin{array}{c} \mathcal{F}_1(T) \curvearrowright \\ \mathcal{F}_2(T) \curvearrowleft \end{array}$$

In particular,  $\mathcal{F}_1 = \mathcal{F}_2$ , so we have uniqueness. To prove existence, we make  $(\mathcal{F}|_{\text{Sm}/S})^+$  a sheaf with transfers. Suppose  $y \in (\mathcal{F}|_{\text{Sm}/S})^+(Y)$ , and  $y|_U = Z^+$ , where  $p : U \rightarrow Y$  is a Nisnevich covering and  $Z \in \mathcal{F}(U)$  (and so  $Z^+$  is the image of  $Z$  over sheafification). By shrinking  $U$ , we allow  $Z$  to agree on the intersection, i.e., we may assume that  $Z$  is mapped to 0 in  $\mathcal{F}(U \times_Y U)$ . This gives a sequence

$$0 \longrightarrow \text{Hom}(\mathbb{Z}(Y), (\mathcal{F}|_{\text{Sm}/S})^+) \longrightarrow \text{Hom}(\mathbb{Z}(0), (\mathcal{F}|_{\text{Sm}/S})^+) \longrightarrow \text{Hom}(\mathbb{Z}(U \times_X U), (\mathcal{F}|_{\text{Sm}/S})^+)$$

which is exact by [Theorem 2.35](#). We know that  $p^*(Z) = 0$ , so there exists  $[y] : \mathbb{Z}(Y) \rightarrow (\mathcal{F}|_{\text{Sm}/S})^+$  such that  $[y]|_U = y|_U$ . Take  $f \in \text{Cor}_S(X, Y)$ , then by Yoneda lemma we know the composition

$$\mathbb{Z}(X) \xrightarrow{f} \mathbb{Z}(Y) \xrightarrow{[y]} (\mathcal{F}|_{\text{Sm}/S})^+$$

of Nisnevich sheaves produces the transfer of  $y$  with respect to  $f$ . □

**Remark 2.37.** The category  $\text{Sh}(S)$  is an abelian category, then the statement in [Proposition 2.29](#) holds for  $\text{Sh}(S)$ .

**Proposition 2.38.** Suppose  $X \in \text{Sm}/S$  and  $\{U_1, U_2\}$  is a Zariski covering of  $X$ , then we have an exact sequence

$$\begin{aligned} 0 &\longrightarrow \mathbb{Z}(U_1 \cap U_2) \longrightarrow \mathbb{Z}(U_1) \oplus \mathbb{Z}(U_2) \longrightarrow \mathbb{Z}(X) \longrightarrow 0 \\ s &\longmapsto (s|_{U_1}, -s|_{U_2}) \\ (s_1, s_2) &\longmapsto s_1 + s_2 \end{aligned}$$

*Proof.* Note that  $U_1 \coprod U_2$  is a Nisnevich covering of  $X$ . Applying the Čech complex of  $X$  in [Theorem 2.35](#), we obtain an exact sequence

$$\mathbb{Z}(U_1) \oplus \mathbb{Z}(U_1 \cap U_2)^{\oplus 2} \oplus \mathbb{Z}(U_2) \xrightarrow{d} \mathbb{Z}(U_1) \oplus \mathbb{Z}(U_2) \xrightarrow{+} \mathbb{Z}(X) \longrightarrow 0$$

where  $d(x, y, a, b) = (a - y, y - a)$ . □

**Definition 2.39.** Define  $\mathbf{Sim}$  to be the category of simplicial sets  $[n] = \{0, \dots, n\}$  for  $n \in \mathbb{N}$ , where  $\mathrm{Hom}_{\mathbf{Sim}}([n], [m])$  is the set of non-decreasing simplicial maps  $[n] \rightarrow [m]$ .

For any category  $\mathcal{C}$ , we define a simplicial (respectively, cosimplicial) object in  $\mathcal{C}$  to be a functor  $\mathbf{Sim}^{\mathrm{op}} \rightarrow \mathcal{C}$  (respectively,  $\mathbf{Sim} \rightarrow \mathcal{C}$ ).

For any  $n \in \mathbb{N}$ , we define a scheme  $\Delta^n = \mathrm{Spec}(k[x_0, \dots, x_n]) / \{(x_0, \dots, x_n) : \sum_{i=0}^n x_i = 1\}$  that is isomorphic to  $\mathbb{A}^n$ . This is a cosimplicial object in  $\mathbf{Sm}/k$ . For any  $f : [n] \rightarrow [m]$ , we have

$$\Delta(f)(x_i) = (y_j)$$

where  $y_j = \sum_{i \in f^{-1}(j)} x_i$ .

**Definition 2.40.** For any  $F \in \mathbf{PSh}(S)$ , we define a simplicial object

$$(C_*F)_n = F^{\Delta^n}$$

which associates to the Suslin complex of  $F$

$$C_*F : \dots \longrightarrow F^{\Delta^n} \xrightarrow{d_n} F^{\Delta^{n-1}} \longrightarrow \dots \longrightarrow F^{\Delta^1} \xrightarrow{d_1} F \longrightarrow 0$$

with  $d_n = \sum_i (-1)^{i-1} \partial_i$ , where  $\partial_i : \Delta^{n-1} \rightarrow \Delta^n$  is the  $i$ th face map.

**Remark 2.41.** In [Theorem 2.34](#), we showed that the cohomological dimension of Nisnevich topology on  $X$  is just  $\dim(X)$ , so for every bounded-above (cochain) complex  $C \in C^-(\mathrm{Sh}(S))$ , we could find a quasi-isomorphism  $i : C \rightarrow I^*$  where  $H^n(X, I^m) = 0$  for any  $m$  and any  $n > 0$ . Therefore, we can define the  $n$ th hypercohomology of  $C$  with respect to  $X$  as

$$\mathbb{H}^n(X, C) = H^n(I^*(X)).$$

It is a standard argument to show that  $\mathbb{H}^n(X, C)$  is independent of  $I^*$ .

**Definition 2.42.** For every  $q \in \mathbb{N}$ , we define the motivic complex to be

$$\mathbb{Z}(q) = C_*(\mathbb{Z}(\mathbb{G}_m^{\wedge q})[-q]),$$

given by the augmentation of the smashing with a shifting by  $-q$ , where  $\mathbb{Z}(\mathbb{G}_m^{\wedge q}) = (\mathbb{Z}(\mathbb{G}_m), 1)^{\wedge q}$ , and  $\mathbb{Z}(q)^i = C_{q-i}\mathbb{Z}(\mathbb{G}_m^{\wedge q})$  in the Suslin complex for  $q \geq 0$ . For  $q < 0$ , we define  $\mathbb{Z}(q) = 0$ .

For any group  $A$ , we write  $\mathbb{Z}(q) \otimes_{\mathbb{Z}}^L A$  as  $A(q)$ .

**Example 2.43.**  $\mathbb{Z}(0)$  is the constant sheaf  $\mathbb{Z}$ .

**Definition 2.44.** For every  $X \in \mathbf{Sm}/k$ , we define the motivic cohomology to be the hypercohomology with respect to Nisnevich topology

$$H^{p,q}(X, A) = \mathbb{H}_{\mathrm{Nis}}^p(X, A(q))$$

with coefficients in  $A$ .

**Remark 2.45.** It turns out that this is equivalent to giving the hypercohomology the Zariski topology instead.

**Proposition 2.46.** For any  $X \in \mathbf{Sm}/k$ , we have

$$H^{p,q}(X, A) = 0$$

if  $p > \dim(X) + q$ . In particular, if  $A$  is a field, then  $H^{p,q}(X, A) = 0$  if  $p > q$ .

*Proof.* Using [Lemma 1.26](#), we obtain a spectral sequence

$$H^s(X, H^t(A(q))) \Rightarrow \mathbb{H}^{s+t}(X, A(q)) = H^{s+t,q}(X, A)$$

Let  $p = s + t$ . If  $p > \dim(X) + q$ , then either  $t > q$  or  $s > \dim(X)$ . This gives  $H^s(X, H^t(A(q))) = 0$ .  $\square$

### 3 MILNOR K-THEORY

#### 3.1 K-THEORY OF RESIDUE FIELD

**Definition 3.1.** For any field  $F$ , define the Milnor K-theory to be the graded algebra

$$K_*^M(F) = T(F^\times) / \{x \otimes (1-x) : x \in F \setminus \{0, 1\}\},$$

defined as the tensor algebra of  $F^\times$  quotient by the Steinberg relation.

**Example 3.2.**

- $K_0^M(F) = \mathbb{Z}$ ;
- $K_1^M(F) = F^\times$ .

**Proposition 3.3.** For any  $x \in F^\times$ , let  $[x] \in K_1^M(F)$  be its representative, then obviously  $[xy] = [x] + [y]$ . Moreover,

1.  $[x][y] + [y][x] = 0$  for all  $x, y \in F^\times$ ;
2.  $[x][x] = [x][-1]$  for all  $x \in F^\times$ .

*Proof.*

1. We have

$$\begin{aligned} [x][-x] &= [x] \left[ \frac{1-x}{1-x^{-1}} \right] \\ &= [x][1-x] + [x^{-1}][1-x^{-1}] \\ &= 0 + 0 \\ &= 0, \end{aligned}$$

therefore

$$\begin{aligned} [x][y] + [y][x] &= [x][-x] + [x][y] + [y][x] + [y][-y] \\ &= [x][-xy] + [y][-xy] \\ &= [xy][-xy] \\ &= 0. \end{aligned}$$

2. Using the previous part, we know

$$\begin{aligned} [x][x] &= [x][-1] + [x][-x] \\ &= [x][-1]. \end{aligned}$$

□

**Proposition 3.4** ([Hes05], Proposition 1). Let  $k$  be a field and  $\nu$  be a normalized discrete valuation on  $k$ . We define the residue field of  $k$  with respect to  $\nu$  as  $k(\nu) = \mathcal{O}_\nu / \mathfrak{m}_\nu$ , then there exists a unique homomorphism (known as the Milnor residue map)

$$\partial_\nu : K_n^M(k) \rightarrow K_{n-1}^M(k(\nu))$$

such that for all  $u_1, \dots, u_{n-1} \in \mathcal{O}_\nu^\times$  and  $x \in k^\times$ ,

$$\partial_\nu([x][u_1] \cdots [u_{n-1}]) = \nu(x) \cdot [\bar{u}_1] \cdots [\bar{u}_{n-1}]$$

where  $\bar{u}_i \in k(\nu)^\times$  is the image of  $u_i$  in the residue field.

*Proof.* The uniqueness is obvious by the universal property, so we shall prove existence. We choose a uniformizer  $\pi$ , and define a graded ring morphism

$$\begin{aligned}\theta_\pi : K_*^M(k) &\rightarrow K_*^M(k(\nu))[\varepsilon]/(\varepsilon^2 - \varepsilon[-1]) \\ [\pi^i u] &\mapsto [\bar{u}] + i\varepsilon\end{aligned}$$

for  $u \in \mathcal{O}_\nu^\times$  and some variable  $\varepsilon$  of degree 1, then this morphism satisfies the Steinberg relation. Now if we decompose it into

$$\theta_\pi(z) = s_\pi(z) + \partial_\nu(z)\varepsilon,$$

then

$$\begin{aligned}\theta_\pi([\pi^i u][u_1] \cdots [u_{n-1}]) &= ([u] + i\varepsilon)[\bar{u}_1] \cdots [\bar{u}_{n-1}] \\ &= [\bar{u}][\bar{u}_1] \cdots [\bar{u}_{n-1}] + i[\bar{u}_1] \cdots [\bar{u}_{n-1}]\varepsilon.\end{aligned}$$

In particular, the  $\partial_\nu$  map does what we want. □

**Theorem 3.5** ([Hes05], Theorem 5). There is a split exact sequence

$$0 \longrightarrow K_*^M(k) \xrightarrow{i} K_*^M(k(T)) \xrightarrow{(\partial_p)} \bigoplus_{\text{irreducible monic } p} K_{*-1}^M(k[T]/p) \longrightarrow 0$$

where each  $\partial_p$  is given by evaluation of  $p$  using the partial map defined in Proposition 3.4.

*Proof.* It is easy to see that this is an exact sequence, and that we have  $s_\pi \circ i = \text{id}$ . Now we want to construct an isomorphism

$$\tau_{n,p} : \bigoplus_{\text{irreducible monic } p} K_n^M(k[T]/p) \rightarrow K_{n+1}^M(k(T))/K_{n+1}^M(k)$$

with inverse  $(\partial_p)_p$ . We define  $\tau_{n,p}$  inductively on  $\deg(p)$ . Suppose  $p = T - \lambda$ , then we define  $\tau_{n,p}$  as the composite

$$K_n^M(k[T]/p) \xrightarrow{\text{ev}} K_n^M(k) \xrightarrow{[p]} K_{n+1}^M(k(T))/K_{n+1}^M(k).$$

Let  $f_i \in k[T]$  for each  $i$ , then this composite maps  $[\bar{f}_1] \cdots [\bar{f}_n]$  to  $[p][f_1(\lambda)] \cdots [f_n(\lambda)]$ . Moreover,

$$\partial_q \circ \tau_{n,p} = \begin{cases} \text{id}, & q = p \\ 0, & q \neq p. \end{cases}$$

For general polynomial  $p$  and general  $f_1, \dots, f_n \in k[T]$  such that  $\deg(f_i) < \deg(p)$  for all  $i$ <sup>14</sup>, then we define

$$\tau_{n,p}([\bar{f}_1] \cdots [\bar{f}_n]) = [\bar{p}] \cdot [f_1] \cdots [f_n] - \sum_{\substack{\text{irreducible monic } q \\ \text{such that } \deg(q) < \deg(p)}} \tau_{n,q}(\partial_q([p][f_1] \cdots [f_n])),$$

then by inductive hypothesis we are done. It remains to check that this is well-defined, and that

•

$$\partial_q \circ \tau_{n,p} = \begin{cases} \text{id}, & q = p \\ 0, & q \neq p. \end{cases}$$

<sup>14</sup>This makes sense since we can pick it in the residue field.

$$\bullet \sum_{\deg(q) < \deg(p)} \tau_{n,q}(\partial_q(x)) = x \text{ if } x = \sum_{\deg(f_{ij}) < \deg(p)} [f_{i1}] \cdots [f_{in}].$$

□

**Remark 3.6.** The map  $-d_\infty$  from

$$\begin{array}{ccc} K_*^M(k(T)) & \xrightarrow{-d_\infty} & K_{*-1}^M(k) \\ \uparrow i & \nearrow 0 & \\ K_*^M(k) & & \end{array}$$

and the exact sequence from [Theorem 3.5](#) together induce a norm map

$$(N_p) : \bigoplus_p K_*^M(k[T]/p) \rightarrow K_*^M(k)$$

with  $N_\infty = \text{id}$ .

**Definition 3.7.** Suppose  $k(a)/k$  is a finite simple extension and the minimal polynomial of  $a$  is  $p$ . Define the norm

$$N_{a/k} : K_*^M(k(a)) \rightarrow K_*^M(k)$$

to be  $N_p$ . In general, suppose  $K/k$  is a finite extension where  $K = k(a_1, \dots, a_n)$ , then define the norm map to be

$$N_{a_1, \dots, a_r/k} = N_{a_1/k} \circ N_{a_1/k(a_1)} \circ \cdots \circ N_{a_r/k(a_1, \dots, a_{r-1})}.$$

**Theorem 3.8** ([\[Hes05\]](#), Theorem 3). The norm map  $N_{a_1, \dots, a_r/k}$  is independent from the choices of  $a_1, \dots, a_r$ . In particular, this gives rise a well-defined norm map

$$N_{K/k} : K_*^M(K) \rightarrow K_*^M(k)$$

on all finite extensions  $K/k$ .

### 3.2 PROOF OF THEOREM 3.8

**Proposition 3.9** ([\[Hes05\]](#), Lemma 10). Let  $k$  be a field and  $p$  be a prime, then there exists an algebraic extension  $L/k$  such that every finite extension of  $L$  has order a power of  $p$ , and localization at  $p$  gives a map

$$K_*^M(k)_{(p)} \rightarrow K_*^M(L)_{(p)}$$

is injective.

*Proof.* Recall an ordinal  $W$  is a limit ordinal if and only if  $W = \bigcup_{\alpha < W} \alpha$ . Define a poset

$$S = \{(\alpha, \{L_\beta \mid \beta \leq \alpha\}) : \alpha \text{ ordinal number, } p \nmid [L_\beta : k] < \infty, [L_{\beta+1} : L_\beta] > 1, L_W = \bigcup_{\alpha < W} L_\alpha \text{ for limit ordinal } W\}$$

for some field extensions  $k \subseteq L_\beta \subseteq \bar{k}$  in the algebraic closure  $\bar{k}$ . The partial order on  $S$  is given by  $(\alpha, \{L_\beta \mid \beta \leq \alpha\}) \leq (\alpha', \{L_{\beta'} \mid \beta' \leq \alpha'\})$  if and only if  $\alpha \leq \alpha'$ ,  $L_\beta = L_{\beta'}$ ,  $\beta \leq \alpha$ . We note that  $\text{card}(\alpha) \leq \text{card}(\bar{k})$ , so  $S$  must be a set. Every totally ordered subset of  $S$  has a maximal element by taking the union, therefore there is a maximal element  $(\alpha, \{L_\beta \mid \beta \leq \alpha\})$  in  $S$ . Now  $L = L_\alpha$  does not have an extension with order prime to  $p$ , hence every finite extension of  $L$  has order a power of  $p$ . For any simple extension  $k(a)/k$ , the composite

$$K_*^M(k) \longrightarrow K_*^M(k(a)) \xrightarrow{N_{a/k}} K_*^M(k)$$

is the multiplication by  $[k(a) : k]$  by direct computation. Therefore, for any  $\beta \leq \alpha$ , the composite

$$K_*^M(L_\beta)_{(p)} \longrightarrow K_*^M(L_{\beta+1})_{(p)} \xrightarrow{N} K_*^M(L_\beta)_{(p)}$$

is an injection, hence  $K_*^M(k)_{(p)} \rightarrow K_*^M(L)_{(p)}$  is also injective by transfinite induction. □

**Proposition 3.10** ([Hes05], Lemma 2). Suppose  $k'/k$  is a field extension and  $\nu$  (respectively,  $\nu'$ ) is a discrete valuation on  $k$  (respectively,  $k'$ ) such that  $\nu'|_k = \nu$ . Then there is a commutative diagram

$$\begin{array}{ccc} K_*^M(k) & \xrightarrow{\partial_\nu} & K_{*-1}^M(k(\nu)) \\ \downarrow & & \downarrow \\ K_*^M(k') & \xrightarrow{e\partial_{\nu'}} & K_{*-1}^M(k(\nu')) \end{array}$$

where  $e$  is the ramification index, i.e.,  $\pi_\nu = u \cdot \pi_{\nu'}^e$  for some uniformizer  $u \in \mathcal{O}_{\nu'}^*$ .

**Proposition 3.11** ([Hes05], Lemma 11). Let  $k' = k(a)$  be a finite extension of  $k$ , and let  $p$  be the minimal polynomial of  $a$  over  $k$ . Let  $L/k$  be a field extension and suppose  $p = \prod_i p_i^{e_i}$  is the prime decomposition for some polynomials  $p_i$  in  $L$ , then for each  $i$  we define  $L'_i \supseteq k'$  to be  $L[t]/p_i$ , and set  $a_i = \bar{t} \in L'_i$ , then we have a commutative diagram

$$\begin{array}{ccc} K_*^M(k') & \xrightarrow{(e_i)} & \bigoplus_i K_*^M(L'_i) \\ N_{a/k} \downarrow & & \downarrow \sum_i N_{a_i/L} \\ K_*^M(k) & \xrightarrow{\text{base-change}} & K_*^M(L) \end{array}$$

where  $e_i$  is the (multiplication of) ramification index of  $L'_i$  over  $k'$ .

*Proof.* Let  $f_1, \dots, f_n \in k[i]$  be prime to  $p$ , then  $\partial_{p_i}([p][f_1] \cdots [f_n]) = e_i[\bar{f}_1] \cdots [\bar{f}_n]$ . Therefore, there is a commutative diagram

$$\begin{array}{ccc} K_*^M(k(t)) & \longrightarrow & K_*^M(L(t)) \\ \downarrow & & \downarrow \\ \bigoplus_R K_{*-1}^M(k[T]/R) & \xrightarrow{\varphi_{R,Q}} & \bigoplus_Q K_{*-1}^M(L[T]/Q) \end{array}$$

where

$$\varphi_{R,Q} = \begin{cases} \text{ord}_Q(p), & R = p \\ 0, & R \neq p \end{cases}$$

The statement follows from the definition of the map  $(N_p) : \bigoplus_p K_*^M(k[T]/p) \rightarrow K_*^M(k)$ .  $\square$

**Corollary 3.12** ([Hes05], Corollary 12). Let  $k \subseteq k' \subseteq K$  be extensions of fields, then

1. for any  $x \in K_*^M(k')$  and  $y \in K_*^M(k)$ , we have a projection formula

$$N_{k'/k}(x \cdot y) = N_{k'/k}(x) \cdot y;$$

2. if  $k'/k$  is normal and  $x \in K_*^M(k')$ , then the base-change of norm over  $K$  is  $N_{k'/k}(x)_K = [k' : k]_{\text{insep}} \sum_{j: k' \rightarrow K} j_*(x)$ , where  $[k' : k]_{\text{insep}}$  is the inseparable degree of  $k'/k$ ;
3.  $N_{k'/k} \circ N_{K/k'} = N_{K/k}$ .

*Proof.*

1. It suffices to assume  $k' = k(a)$  by choosing generators of  $k'/k$  and [Theorem 3.8](#), then the statement follows from the construction in [Theorem 3.5](#).



2. If  $k'/k$  is separable where  $k' = k(a)$ , then [Proposition 3.11](#) gives a diagram

$$\begin{array}{ccc} K_*^M(k') & \longrightarrow & \bigoplus_{j:k' \rightarrow k} K_*^M(k') \\ N_{k'/k} \downarrow & & \downarrow (j_*) \\ K_*^M(k) & \longrightarrow & K_*^M(K) \end{array}$$

which gives the statement.

If  $k'/k$  is purely inseparable, it suffices to assume  $k' = k(a)$  and proceed inductively. We have  $k(a) \otimes_k K = k[t]/(t - a^{\frac{1}{d}})^d$  where  $d = [k(a) : k]$ . The statement now follows from [Proposition 3.11](#).

For general  $k'/k$ , denote by  $k^s$  the separable closure of  $k'/k$ . The map  $\text{Hom}(k', k) \rightarrow \text{Hom}(k^s, k)$  is an isomorphism. Therefore, the base-change over  $K$  gives

$$\begin{aligned} N_{k'/k}(x)_K &= N_{k^s/k}(N_{k'/k^s}(x))_K \\ &= \sum_{j:k^s \rightarrow K} j_* N_{k'/k^s}(x) \\ &= \sum_{j:k' \rightarrow K} j_*(N_{k'/k^s}(x)_{k'}) \\ &= [k' : k]_{\text{insep}} \sum_{k' \rightarrow K} j_*(x). \end{aligned}$$

3. This will be obvious once we prove [Theorem 3.8](#). □

**Proposition 3.13** ([Hes05], Proposition 13). Let  $k$  be a field and set  $k' = k(a)$  to be such that the extension  $k(a)/k$  has prime degree, then the map

$$N_{a/k} : K_n^M(k') \rightarrow K_n^M(k)$$

is independent of the choice of the generator  $a$ .

*Proof.* Suppose all finite extensions of  $k$  have order a power of  $k$ , then we write  $k' = k[T]/p$  where the image  $\bar{T} = a$  and  $\deg(p) = p$ . For any monic  $f, g \in k[T]$  of the same degree, we get to write  $f = g + h$  for  $\deg(h) < \deg(f)$ . If  $h = 0$ , then  $[f][g] = [f][-1]$ , otherwise we have  $([h] - [f])([g] - [f]) = \left[\frac{h}{f}\right] \left[\frac{g}{f}\right] = \left[\frac{h}{f}\right] \left[1 - \frac{h}{f}\right] = 0$  by the Steinberg relation. Therefore,  $[f][g] = [h][g] - [h][f] + [f][-1]$ , hence every element in  $K_n^M(k')$  is a sum of the form  $[f_1] \cdots [f_n]$  where  $f_i$ 's are irreducible or constant and that  $p > \deg(f_1) > \cdots > \deg(f_n)$ . But we know  $f_2, \dots, f_n$  are constant by the condition on  $k$ , so for any choice of  $a$ , we must have

$$N_{a/k}([f_1] \cdots [f_n]) = N_{k'/k}(f_1)[\bar{f}_2] \cdots [\bar{f}_n]$$

according to the projection formula and the Weil reciprocity formula, therefore it is independent of  $a$ .

For a general field  $k$ , it suffices to show that

$$N_{a/k} : K_*^M(k')_{(l)} \rightarrow K_*^M(k)_{(l)}$$

does not depend on  $a$  for every prime  $l$ . By [Proposition 3.9](#), there exists some extension  $L/k$  such that every finite extension of  $L$  has degree a power of  $l$  and  $K_*^M(k)_{(l)} \rightarrow K_*^M(L)_{(l)}$  is injective. Since  $[k' : k]$  is prime, then the extension  $k'/k$  is either separable or purely inseparable.

- Suppose  $k'/k$  is separable, then  $L' = L \otimes_k k'$  is étale over  $L$  by base-change, therefore it is a reduced Artinian ring, hence it is a field of  $p$  products of  $L$ .

- If  $L'$  is a field,  $[k' : k] = p$ , otherwise  $L'/L$  would be a finite extension of degree prime to  $p$ . In particular  $l = p$ , so by [Proposition 3.11](#) we know there is a commutative diagram

$$\begin{array}{ccc} K_*^M(k') & \xrightarrow{\partial_\nu} & K_*^M(L') \\ N_{a/k} \downarrow & & \downarrow N_{L'/L} \\ K_*^M(k) & \xrightarrow{e\partial_{\nu'}} & K_*^M(L) \end{array}$$

- If  $L'$  is a product of  $p$  fields, then by [Proposition 3.11](#) we know there is a commutative diagram

$$\begin{array}{ccc} K_*^M(k') & \xrightarrow{(\partial_\nu)} & \bigoplus K_*^M(L) \\ N_{a/k} \downarrow & & \downarrow \sum \text{id} = \sum N_{L/L} \\ K_*^M(k) & \xrightarrow{e\partial_{\nu'}} & K_*^M(L) \end{array}$$

over all possible embeddings of  $k'$  in  $L$ .

Regardless,  $N_{a/k}$  is independent of  $a$ .

- Suppose  $k'/k$  is purely separable, so we can write  $k' = k[t]/(t^p - a)$ . If  $a^{\frac{1}{p}} \notin L$ , then  $L'$  is a field; if not, then  $L' = L^{\times p}$ . By applying [Proposition 3.11](#) to both cases, we are done.

□

**Definition 3.14.** Suppose  $K$  is a field with discrete valuation  $\nu$ . Fix  $a \in (0, 1)$ , then we can define an absolute value  $\|x\| = a^{\nu(x)}$  for every  $x \in K$ . Taking the completion  $\hat{K}$  of  $K$ , we obtain a metric space, at the same time getting a field with discrete valuation. In particular, if  $\hat{K} = K$ , then we say the valuation is complete.

**Remark 3.15.** Recall from section II.2 of [\[Ser13\]](#) that if  $K$  is a complete discrete valuation field and if  $L/K$  is a finite extension, then the discrete valuation on  $K$  extends uniquely to a discrete valuation on  $L$ , and  $L$  is complete with respect to the valuation. Moreover, we have  $[L : K] = e_{L/K} \cdot [k(\mathcal{O}_L) : k(\mathcal{O}_K)]$  where  $e_{L/K}$  is the ramification index.

**Proposition 3.16** ([\[Hes05\]](#), Lemma 14). Let  $K$  be a complete discrete valuation field, and let  $K'/K$  be a normal extension of prime degree  $p$ . Let  $k$  and  $k'$  be the residue field of  $K$  and  $K'$ , respectively. Since the extension has prime degree, then the norm  $N_{K'/K}$  is well-defined, and the following diagram commutes.

$$\begin{array}{ccc} K_n^M(K') & \xrightarrow{\partial_{K'}} & K_{n-1}^M(k') \\ N_{K'/K} \downarrow & & \downarrow N_{k'/k} \\ K_n^M(K) & \xrightarrow{\partial_K} & K_{n-1}^M(k) \end{array}$$

*Proof.* We show that  $\delta_{K'/K} := \partial_K \circ N_{K'/K} - N_{k'/k} \circ \partial_{K'}$  is 0. We first show that  $p\delta_{K'/K} = 0$ .

- Suppose that  $K'/K$  is unramified, i.e.,  $e_{K'/K} = 1$ .
  - If  $K'/K$  is separable, then  $k'/k$  is normal by Proposition 20 in section 1.7 of [\[Ser13\]](#).
    - \* If, in addition, that  $k'/k$  is separable, then  $\text{Gal}(K'/K) \cong \text{Gal}(k'/k)$ . By the fact that  $e_{K'/K} = 1$  and by [Corollary 3.12](#), we know

$$\begin{aligned} K_*^M(k'/k) \circ \delta_{K'/K} &= K_*^M(k'/k) \circ (\partial_K \circ N_{K'/K} - N_{k'/k} \circ \partial_{K'}) \\ &= \partial_{K'} \circ K_*^M(K'/K) \circ N_{K'/K} - K_*^M(k'/k) \circ N_{k'/k} \circ \partial_{K'} \\ &= \sum_{\sigma \in \text{Gal}(K'/K)} \partial_{K'} \circ \sigma - \sum_{\bar{\sigma} \in \text{Gal}(k'/k)} \bar{\sigma} \circ \partial_{K'} \\ &= 0. \end{aligned}$$

\* If  $k'/k$  is purely inseparable instead, then by [Corollary 3.12](#) we know that

$$K_*^M(k'/k) \circ \delta_{K'/K} = \sum_{\sigma \in \text{Gal}(K'/K)} \partial_{K'} \circ \sigma - p\partial_{K'}. \quad (3.17)$$

However, since  $k'/k$  is purely inseparable, then  $\sigma \in \text{Gal}(K'/K)$  induces identity map on  $k'$ , hence [Equation \(3.17\)](#) must be zero.

- If  $K'/K$  is purely inseparable instead, then  $k'/k$  is also purely inseparable by Proposition 16 in section 1.6 of [\[Ser13\]](#), therefore the same argument shows that

$$K_*^M(k'/k) \circ \delta_{K'/K} = p\partial_{K'} - p\partial_{K'} = 0$$

since  $K'/K$  is unramified. Finally, by [Corollary 3.12](#) we know  $N_{k'/k} \circ K_*^M(k'/k) = p$ , so we have proven the claim for the case where  $K'/K$  is unramified.

- Now suppose  $K'/K$  is totally ramified, i.e.,  $e_{K'/K} = p$ .

- If  $K'/K$  is Galois, then

$$\begin{aligned} p\delta_{K'/K} &= p\partial_K \circ N_{K'/K} - p\partial_{K'} \\ &= \partial_{K'} \circ K_*^M(k'/k) \circ N_{K'/K} - p\partial_{K'} \\ &= \sum_{\sigma \in \text{Gal}(K'/K)} \partial_{K'} \circ \sigma - p\partial_{K'} \\ &= 0. \end{aligned}$$

- If  $K'/K$  is purely inseparable, then by [Corollary 3.12](#) we have

$$\begin{aligned} p\delta_{K'/K} &= \partial_{K'} \circ K_*^M(K'/K) \circ N_{K'/K} - p\partial_{K'} \\ &= p\partial_{K'} - p\partial_{K'} \\ &= 0. \end{aligned}$$

This shows that  $p\delta_{K'/K} = 0$ . It now suffices to show that, for every  $Z \in K_n^M(K')$ , there exists some integer  $m$  coprime to  $p$  such that  $m\delta_{K'/K}(Z) = 0$ .

Suppose that  $L$  is an extension of  $K$  of degree prime to  $p$ , and let  $L' = [L, K'] = L \otimes_K K'$  (since they are linearly disjoint) be a field generated by  $L$  and  $K'$  in  $\bar{K}$ , therefore  $[L' : L] = p$ . By [Proposition 3.11](#), the diagram

$$\begin{array}{ccc} K_n^M(K') & \longrightarrow & K_n^M(L') \\ N_{K'/K} \downarrow & & \downarrow N_{L'/L} \\ K_n^M(K) & \longrightarrow & K_n^M(L) \end{array}$$

commutes. Here we have  $e_{L'/L}[k(\mathcal{O}_{L'}) : k(\mathcal{O}_L)] = p$  and  $e_{K'/K}[k(\mathcal{O}_{K'}) : k(\mathcal{O}_K)] = p$ , therefore  $e_{L'/L}e_{L/K} = e_{L'/K} = e_{K'/K}e_{L'/K'}$ . Therefore,  $e_{L'/L} = e_{K'/K}$  and  $k(\mathcal{O}_L) \otimes_k k' = k(\mathcal{O}_{L'})$  since  $[L : K]$  and  $[K' : K]$  are coprime. Therefore, we have a commutative diagram

$$\begin{array}{ccc} K_n^M(k') & \longrightarrow & K_n^M(k(\mathcal{O}_{L'})) \\ N_{k'/k} \downarrow & & \downarrow N_{k(\mathcal{O}_{L'})/k(\mathcal{O}_L)} \\ K_n^M(k) & \longrightarrow & K_n^M(k(\mathcal{O}_L)) \end{array}$$

by [Proposition 3.11](#). Now fix  $Z \in K_n^M(K')$ , then

$$\begin{aligned}
 e_{L/K} \cdot K_*^M(k(\mathcal{O}_L)/k) \circ \delta_{K'/K} &= e_{L/K} \cdot K_*^M(k(\mathcal{O}_L)/k) \circ (\partial_K - N_{K'/K} - N_{k'/k} \circ \partial_{K'}) \\
 &= \partial_L \circ K_*^M(L/K) \circ N_{K'/K} - e_{L/K} \circ K_*^M(k(\mathcal{O}_L)/k) \circ N_{k'/k} \circ \partial_{K'} \\
 &= \partial_L \circ K_*^M(L/K) \circ N_{K'/K} - e_{L/K} \cdot N_{k(\mathcal{O}_{L'})/k(\mathcal{O}_L)} \circ K_*^M(k(\mathcal{O}_{L'})/k') \circ \partial_{K'} \\
 &= \partial_L \circ K_*^M(L/K) \circ N_{K'/K} - N_{k(\mathcal{O}_{L'})/k(\mathcal{O}_L)} \circ \partial_{L'} \circ K_*^M(L'/K') \\
 &= \partial_L \circ N_{L'/L} \circ K_*^M(L'/K') - N_{k(\mathcal{O}_{L'})-k(\mathcal{O}_L)} \circ \partial_{L'} \circ K_*^M(L'/K') \\
 &= \delta_{L'/L} \circ K_*^M(L'/K').
 \end{aligned} \tag{3.18}$$

We claim that for our fixed  $Z$ , there exists some extension  $L/K$  such that [Equation \(3.18\)](#) is 0. If this is true, then by applying  $N_{k(\mathcal{O}_L)/k}$ , we obtain that  $[L : K]\delta_{K'/K}(Z) = 0$  since  $[L : K]$  is coprime to  $p$ , and we are done.

To find such extension, suppose  $\bar{L}$  is the algebraic extension of  $K$  obtained in [Proposition 3.9](#) with respect to  $p$ , then since  $[K' : K] = p$ , hence we know  $K' \otimes_K \bar{L}$  is also a field. Now  $K_*^M(K' \otimes_K \bar{L})(Z)$  can be written in the form of  $\sum[x][y_2] \cdots [y_n]$  where  $x \in K' \otimes_K \bar{L}$  and  $y_i \in \bar{L}$ , using statements similar to [Proposition 3.13](#).

Therefore, there exists some subextension  $K \subseteq L \subseteq \bar{L}$  where  $p \nmid [L : K]$  such that  $K_*^M(L'/K')(Z)$  has similar properties where  $L' = K' \otimes_K L$ . Therefore we may assume that we are working over  $K'$  already, so  $Z = \sum[x][y_2] \cdots [y_n]$  where  $x \in K'$  and  $y_i \in K$  for all  $i$ . By considering the cases where  $K'/K$  is either totally ramified or unramified, the projective formula gives  $\delta_{K'/K}(Z) = 0$ .  $\square$

**Proposition 3.19** ([Hes05], Proposition 15). Let  $k$  be a field and let  $k'$  be a finite normal extension of  $k$  of prime degree  $p$ . Let  $F = k(a)$  be a finite extension, and suppose that  $F = k'(a)$  is a field, then the following diagram commutes.

$$\begin{array}{ccc}
 K_n^M(F') & \xrightarrow{N_{a/k'}} & K_n^M(k') \\
 N_{F'/F} \downarrow & & \downarrow N_{k'/k} \\
 K_n^M(F) & \xrightarrow{N_{a/k}} & K_n^M(k)
 \end{array}$$

*Proof.* We first talk about homotopy invariance. Let  $\nu$  be a discrete valuation on  $k(t)/k$ , and let  $k(t)_\nu$  be the completion of  $k(t)$  at  $\nu$ . Since  $k(t)_\nu/k(t)$  (respectively,  $k'(t)_\nu/k'(t)$ ) is separable, then the minimal polynomial  $\pi \in k(t)[x]$  where  $k' = k(\alpha)$  with respect to a generator  $\alpha$  of  $k'(t)/k(t)$  (which gives a correspondence  $w/\nu$ ). Since  $k(t)_\nu/k(t)$  is separable, then we have a decomposition of  $\alpha$  as a product

$$\pi = \prod_{w/\nu} \pi_{w/\nu}$$

where  $\pi_{w/\nu} \in k(t)_\nu[x]$  are distinct monic irreducible polynomials, and where  $w$  ranges over the possible extensions of  $\nu$  to a discrete valuation on  $k'(t)/k'$ . We then consider the following diagram:

$$\begin{array}{ccccc}
 K_{n+1}^M(k'(t)) & \xrightarrow{j_{k'(t)/k'(t)}^*} & \bigoplus_{w/\nu} K_{n+1}^M(k'(t)_w) & \xrightarrow{\bigoplus \partial_w} & \bigoplus_{w/v} K_n^M(k(\mathcal{O}_w)) \\
 N_{k'(t)/k(t)} \downarrow & & \downarrow \sum N_{k'(t)_w/k(t)_\nu} & & \downarrow \sum N_{k(\mathcal{O}_w)/k(\mathcal{O}_\nu)} \\
 K_{n+1}^M(k(t)) & \xrightarrow{j_{k(t)_\nu/k(t)}^*} & K_{n+1}^M(k(t)_\nu) & \xrightarrow{\partial_\nu} & K_n^M(k(\mathcal{O}_\nu))
 \end{array} \tag{3.20}$$

The commutativity of the left-hand square follows from [Proposition 3.10](#), and the commutativity of the right-hand square follows from [Proposition 3.16](#). Let  $\theta \in k[t]$  and  $\theta' \in k'[t]$  be the minimal polynomial of  $a$  over  $k$  and  $k'$ , respectively. Given  $x' \in K_n^M(F')$ , [Theorem 3.5](#) shows that there exists  $y' \in K_{n+1}^M(k'(t))$  such that  $\partial_{w_{\theta'}}(y') = x'$  and  $\partial_w(y') = 0$  if  $w \neq w_{\theta'}, w_\infty$ , then by definition we know

$$N_{a/k}(x') = -\partial_\infty(y').$$

We now define  $x = N_{F'/F}(x')$  and  $y = N_{k'(t)/k(t)}(y')$ . Therefore, Equation (3.20) shows that  $\partial_{\nu_\theta}(y) = x$  and  $\partial_\nu(y) = 0$  if  $\nu \neq \nu_\theta, \nu_\infty$ , and this gives

$$N_{a/k'}(x) = -\partial_{\nu_\infty}(y).$$

Again, applying Equation (3.20) to  $\nu = \nu_\infty$  shows that

$$\begin{aligned} N_{a/k}(N_{F'/F}(x')) &= N_{a/k}(x) \\ &= -\partial_{\nu_\infty}(y) \\ &= -\partial_{\nu_\infty}(N_{k'(t)/k(t)}(y')) \\ &= -N_{k'/k}(\partial_{w_\infty}(y')) \\ &= N_{k'/k}(N_{a/k'}(x')) \end{aligned}$$

as desired.  $\square$

*Proof of Theorem 3.8.* Let  $K = k(a_1, \dots, a_r)$ , then we claim that  $N_{K/k}$  is independent of  $a_1, \dots, a_r$ . We proceed by induction on  $[K : k]$  and prove the statement after localizing at a prime  $p$ . Choose  $L/k$  as in Proposition 3.9, and define  $L' = L \otimes_k K$  which is finite over  $L$  and therefore Artinian. Therefore,  $L'$  has finitely many prime ideals  $\mathfrak{p}_1, \dots, \mathfrak{p}_m$ . Suppose  $e_i = \ell_{L'_{\mathfrak{p}_i}}(L'_{\mathfrak{p}_i})$ .

1. By Proposition 3.11, we can show that the diagram

$$\begin{array}{ccc} K_*^M(K)_{(p)} & \xrightarrow{(e_i)} & \bigoplus_{i=1}^m K_*^M(L'_i)_{(p)} \\ N_{a_1, \dots, a_r/k} \downarrow & & \downarrow \Sigma N_{L'_i/L} \\ K_*^M(k)_{(p)} & \longrightarrow & K_*^M(L)_{(p)} \end{array}$$

commutes. Therefore, if  $m > 1$ , we conclude by induction that the composition does not depend on the choice of elements. Taking the localization gives what we want.

2. Hence we suppose  $L'$  is a field, and choose  $M/L'$  to be a Galois extension, now  $\text{Gal}(M/L)$  is a  $p$ -group, hence we have a composition series

$$\text{Gal}(M/L) = G_1 \supseteq \dots \supseteq G_n = \text{Gal}(M/L'),$$

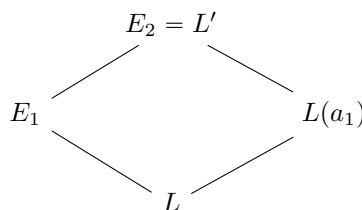
i.e.,  $G_{i+1} \triangleleft G_i$  and  $G_i/G_{i+1} \cong \mathbb{Z}/p\mathbb{Z}$  for all  $i$ . Therefore, set  $E_i = M^{G_{n-i+1}}$ , so we obtain a sequence

$$L' = E_1 \supseteq \dots \supseteq E_n = L$$

such that  $[E_i : E_{i+1}] = p$  and  $E_i/E_{i+1}$  is normal.

3. We need to show that the norm over  $L'/L$  satisfies  $N_{a_1, \dots, a_r/k} = N_{E_1/E_0} \circ \dots \circ N_{E_n/E_{n-1}}$ , where the right-hand side is independent of the choice of  $a_1, \dots, a_r \in k'$ . Therefore we are done by Proposition 3.13.  $\square$

**Example 3.21.** Suppose  $r = n = 2$ , and take



If  $a_1 \in E_1$ , then  $N_{a_2/L(a_1)} = N_{E_2/E_1}$  and  $N_{a_1/L} = N_{E_1/L}$ ; if  $a_1 \notin E_1$ , then  $N_{a_2/L(a_1)} = N_{E_2/L(a_1)}$  and  $N_{a_1/L} \circ N_{E_2/L(a_1)} = N_{E_1/L} \circ N_{a_1/E_1} = N_{E_1/L} \circ N_{E_2/E_1}$  by [Proposition 3.19](#).

**Remark 3.22** ([Hes05], Remark 4). By homotopy invariance, [Theorem 3.5](#) says that  $\sum_{\nu \in \mathbb{P}_k^1} N_{k(\nu)/k} \circ \partial_\nu = 0$  on  $K_*^M(k(t))$ , c.f., residue theorem. Moreover, this holds for any algebraic function field  $L/k$ .

**Theorem 3.23** ([BT06], Theorem 5.6; [MVW06], Theorem 5.4; Weil Reciprocity). For any algebraic function field  $L/k$ , we have  $\sum_{\nu \in \text{DV}(L/k)} N_{k(\nu)/k} \circ \partial_\nu = 0$  on  $K_*^M(L)$ .

*Proof.* The key idea is that there is a finite map from every curve to  $\mathbb{P}_k^1$ , c.f., [Sus83], where we want to show the statement on the fibers. That is, we want to show that for every finite extension  $E/F$  between algebraic function fields and  $w \in \text{DV}(F/k)$  as a discrete valuation, then we have

$$\sum_{\substack{\nu \in \text{DV}(E/k) \\ \nu \text{ lying over } w}} N_{k(\nu)/k(w)} \circ \partial_\nu = \partial_w \circ N_{E/F} \quad (3.24)$$

on  $K_*^M(E)$  using [Proposition 3.16](#). Since  $L$  is a finite extension of  $k(t)$ , we have

$$\begin{aligned} \sum_{\nu \in \text{DV}(L/k)} N_{k(\nu)/k} \circ \partial_\nu &= \sum_{w \in \mathbb{P}_k^1} \sum_{\nu/w} N_{k(\nu)/k(w)} \circ \partial_\nu \\ &= \left( \sum_{w \in \mathbb{P}_k^1} N_{k(w)/k} \circ \partial_w \right) \circ N_{L/k(t)} \\ &= 0 \end{aligned}$$

by homotopy invariance, c.f., [Remark 3.22](#). □

### 3.3 ROST COMPLEX

**Definition 3.25.** Suppose  $X$  is an integral scheme. We define the Milnor K-theory  $K_*^M(X)$  of a scheme to be the kernel of  $\partial_y^x$ <sup>15</sup> on the exact sequence

$$0 \longrightarrow K_*^M(X) \longrightarrow K_*^M(K(X)) \xrightarrow{\partial_y^{\xi_x}} \bigoplus_{y \in X^{(1)}} K_{*-1}^M(k(y))$$

Here for any point  $x \in X^{(n)}$  with codimension  $n$ , we have a divisor  $y \in X^{(n+1)} \cap \bar{X}$ , we define  $\partial_y^x : K_*^M(k(x)) \rightarrow K_*^M(k(y))$  as the following: let  $Z = \overline{\{x\}}$  and  $p : \tilde{Z} \rightarrow Z \ni y$  be the normalization, then define

$$\partial_y^x = \sum_{\substack{u \in \tilde{Z} \\ p(u)=y}} N_{k(u)/k(y)} \circ \partial_u$$

with  $u$  running through finitely many points of  $\tilde{Z}$  lying over  $y$ .<sup>16</sup>

**Definition 3.26.** For any scheme  $X$ , define the Rost complex by

$$C^p(X, K_n^M) = \bigoplus_{x \in X^{(p)}} K_{n-p}^M(k(x)).$$

<sup>15</sup>Here we denote  $\partial_y^x = \partial_y^{\xi_x}$  to be the map from the K-theory of the function field  $K(X) = \mathcal{O}_{X, \xi_x}$  where  $\xi_x$  corresponds to the generic point, therefore this map is the corresponding residue homomorphism.

<sup>16</sup>Without making precise formalization, the K-groups above are just cycle premodules over  $X$ , c.f., [Ros96], page 337. Moreover, the whole “ $(-)_y^x$ ” notation means a specific component for  $x \in X$  and  $y \in Y$  of the  $(-)$ -map about direct sums.

Define

$$\begin{aligned} d_X : C^p(X, K_n^M) &\rightarrow C^{p+1}(X, K_n^M) \\ x \in X^{(p)} &\mapsto y \in X^{(p+1)} \\ d_X &= \begin{cases} \partial_y^x, & y \in \bar{x} \\ 0, & y \notin \bar{x} \end{cases} \end{aligned}$$

**Remark 3.27.** Note that the last two terms of the complex is given by the principal divisor map

$$\text{div} : C^{n-1}(X, K_n^M) = \bigoplus_{x \in X^{(n-1)}} k(x)^\times \rightarrow C^n(X, K_n^M) = \bigoplus_{x \in X^{(n)}} \mathbb{Z},$$

and its cokernel is the classical Chow groups  $\text{CH}^n(X)$  of  $n$ -dimensional cocycles on  $X$ . In particular, the  $n$ th cohomology of the complex agrees with the  $n$ th Chow group, i.e.,

$$H^n(C^*(X, K_n^M)) = \text{CH}^n(X).$$

Therefore, the Rost complex gives rise to a notion of higher Chow group, which is a bit different from the usual notion.

Our main goal is to show that  $C^*(X; K_n^M)$  is indeed a complex, which shows how Rost complex connects Milnor K-theory with the Chow group, c.f., [Ros96].

**Definition 3.28.** Suppose  $f : X \rightarrow Y$  is a proper morphism between schemes of finite type over a field  $k$ . We define the pushforward of the Rost complex to be

$$f_* : C^p(X, K_n^M) = \bigoplus_{x \in X^{(p)}} K_{n-p}^M(k(x)) \rightarrow C^{p+\dim(Y)-\dim(X)}(Y, K_{n+\dim(Y)-\dim(X)}^M)$$

such that for  $x \in X$  and  $y \in Y$ , if  $y = f(x)$  and  $[k(x) : k(y)] < \infty$ , then  $(f_*)_y^x = N_{k(x)/k(y)}$ , otherwise  $(f_*)_y^x = 0$ .

**Definition 3.29.** Suppose  $f : Y \rightarrow X$  is a flat morphism between schemes of finite type over  $k$ , and define  $Y_x = Y \times_X \text{Spec}(k(x)) = f^{-1}(x)$  to be the fiber of  $x$ . We define the pullback of the Rost complex to be

$$f^* : C^p(X, K_n^M) \rightarrow C^p(Y, K_n^M)$$

using the following procedure. Suppose we have  $x \in X$  and a generic point  $y \in Y_x^{(0)}$  on the fiber, then the localization  $Y_{x,(y)}$  of  $Y_x$  in  $y$  is the spectrum of an Artinian ring  $R = \mathcal{O}_{Y_x,y}$ , the stalk of the local ring  $\mathcal{O}_{Y_x}$  at  $y \in Y$ , with unique residue class field  $k(y)$ . As a module over itself, we obtain a notion of length  $\ell_{\mathcal{O}_{Y_x,y}}(\mathcal{O}_{Y_x,y})$ . With the embedding  $K_*^M(k(x))$  into  $K_*^M(k(y))$ , we define  $(f^*)_y^x = \ell_{\mathcal{O}_{Y_x,y}}(\mathcal{O}_{Y_x,y}) \cdot (K_*^M(k(x)) \rightarrow K_*^M(k(y)))$ . For other choices of  $x \in X$  and  $y \in Y$ , we have  $(f^*)_y^x = 0$ .

**Proposition 3.30** ([Ros96], Proposition 4.4 & 4.6). Let  $d_X, d_Y$  be the differential of the Rost complex of  $X$  and of  $Y$  respectively.

1. If  $f : X \rightarrow Y$  is proper, then  $d_Y \circ f_* = f_* \circ d_X$ .
2. If  $f : Y \rightarrow X$  is flat, then  $d_Y \circ f^* = f^* \circ d_X$ .

*Proof.*

1. We show that  $\delta(f_*) := d_Y \circ f_* - f_* \circ d_X = 0$ . Let  $x \in X^{(p)}$  and  $y \in Y^{(p+\dim(Y)-\dim(X))}$ . We should discuss the possible relations between  $f(x)$  and  $y$ .

- if  $y \notin \overline{f(x)}$ , since the differential maps a closed subset to some subset of the closed subset, we know the image  $\delta(f_*)_y^x = 0$  by definition;
- if  $f(x) = y$ , we can perform base-change, given by the pullback square

$$\begin{array}{ccc} X_y & \longrightarrow & X \\ \downarrow & & \downarrow f \\ \mathrm{Spec}(k(y)) & \longrightarrow & Y \end{array}$$

so that we get a proper curve  $\bar{x} \subseteq X_y \rightarrow \mathrm{Spec}(X_y)$  according to the dimension condition, now apply [Theorem 3.23](#);

- if  $y \in \overline{f(x)}^{(1)}$ , then  $[k(x) : k(f(x))] < \infty$ , so we can use the compatibility between  $\partial$ 's and norms from [Equation \(3.24\)](#).
2. Define  $\delta(f^*) := d_Y \circ f^* - f^* \circ d_X$ , and suppose  $y \in Y^{(p+1)}$  and  $x \in X^{(p)}$ , The only non-trivial case is when  $f(y) \in \bar{X}^{(1)}$ . By normalization and localization at  $y$  and  $f(y)$ , we reduce to the case when  $X = \mathrm{Spec}(R)$  for some discrete valuation ring  $R$  and  $Y = \mathrm{Spec}(S)$  for some local ring  $S$  of dimension at most 1. By definition,

$$\delta(f^*)_y^x = \sum_{u \in Y^{(0)}} \ell_{\mathcal{O}_{Y,u}}(\mathcal{O}_{Y,u}) \cdot \partial_y^u \circ K_*^M(k(u)/k(x)) - \ell_{\mathcal{O}_Y}(\mathcal{O}_Y/\mathfrak{m}_x \mathcal{O}_Y) K_*^M(k(u)/k(f(y))) \circ \partial_{f(y)}^x$$

Suppose  $\hat{S}$  is the normalization of  $S$ . We have

$$\begin{aligned} \partial_y^u \circ K_*^M(k(u)/k(x)) &= \sum_{w \in \hat{S}^{(1)}} N_{k(w)/k(u)} \circ \partial_w^u \circ K_*^M(k(u)/k(x)) \\ &= \sum_{w \in \hat{S}^{(1)}} \ell_{\hat{S}_{(u)}}(\hat{S}_{(u)}/\mathfrak{m}_x \hat{S}_{(u)}) N_{k(w)/k(y)} \circ K_*^M(k(w)/k(f(y))) \circ \partial_{f(y)}^x \\ &= \sum_{w \in \hat{S}^{(1)}} \ell_{\hat{S}_{(u)}}(\hat{S}_{(u)}/\mathfrak{m}_x \hat{S}_{(u)}) [k(u) : k(y)] K_*^M(k(y)/k(f(y))) \circ \partial_{f(y)}^x \end{aligned}$$

by [Proposition 3.11](#). Then the question is reduced to computations of lengths. □

**Theorem 3.31** ([Ros96], Lemma 3.3 & page 355<sup>17</sup>). For any scheme  $X$  of finite type over  $k$ , we have  $d_X \circ d_X = 0$ .

*Proof.* For any choice of  $x \in X^{(p)}$  and  $y \in X^{(p+1)}$ , we know it suffices to prove the statement for any integral affine scheme  $X = \mathrm{Spec}(R)$  over  $k$ , where  $R$  is a local ring of dimension 2. Let  $x_0$  be the<sup>18</sup> closed point on  $X$ , i.e., maximal ideal  $\mathfrak{m}_x$ , and  $\xi_x$  be the generic point of  $X$ , then on the divisor,

$$\sum_{x \in X^{(1)}} \partial_{x_0}^x \circ \partial_x^{\xi_x} = 0.$$

We choose a lift of a transcendental basis of  $k(x_0)/k$  to  $R$  using the extension  $k(x_0)/R/k$ , so we can find a field  $k \subseteq K \subseteq R$  such that  $k(x_0)/K$  is finite, by defining  $K$  to be the extension on  $k$  attaching the said transcendental basis. Choose  $u \in X \times_K k(x_0) =: X'$  which lies over  $x_0$  with respect to the projection  $p : X' \rightarrow X$ , then  $k(u) = k(x_0)$ . Moreover, we know that  $d_X \circ d_X = 0$  if and only if at  $u$ , we have  $(p^* \circ d_X \circ d_X)_u = 0$ , if and only if at  $u$ ,  $(d_{X'} \circ d_{X'} \circ p^*)_u = 0$ , so it suffices to prove the case when  $k(x_0) = k$ .

<sup>17</sup>The proof has been reorganized: also see page 342-343 of [Ros96].

<sup>18</sup>There is a unique point of codimension 2.



Suppose  $X$  is a localization of  $Y \subseteq \mathbb{P}_k^n$  at a rational point  $y$ , where  $Y$  is closed and  $\dim(Y) = 2$ . We define the flag variety  $H = \text{Gr}(1, n-2, n+1) \subseteq \mathbb{P}^n \times \text{Gr}(n-2, n+1)$  as a Grassmannian in  $V$  of dimension  $n+1$  by the set  $\{(x, V) \mid X \subseteq V\}$ , i.e.,  $x$  is a line and  $V \in \text{Gr}(n-2, n+1)$ , then we have a map

$$\begin{aligned} \mathbb{P}^n \times \text{Gr}(n-2, n+1) \setminus H &\rightarrow \mathbb{P}^2 \times \text{Gr}(n-2, n+1) \\ (x, V) &\mapsto (P_V(x), V) \end{aligned}$$

where  $x \not\subseteq V$  and  $P_V(x)$  is the projection of  $x$  centered at  $V$ . Let  $F$  be the function field  $K(\text{Gr}(n-2, n+1))$ , then a dimension argument shows that  $H_F \cap Y_F = \emptyset$ .<sup>19</sup> To see this, note that  $\dim(Y) = 2$ , and note that for any  $v \in \text{Gr}(n-2, n+1)$ ,  $\text{codim}(v) = 3$ , and we want to find  $V \in \text{Gr}(n-2, n+1)$  such that  $Y \cap V = \emptyset$ . We now have a projection  $\varphi : H = \text{Gr}(1, n-2, n+1) \rightarrow \mathbb{P}^n$  by forgetting the line. We know the flag variety  $H$  has dimension  $4n-9$ , moreover, it not only has a projection  $\varphi$  but also a projection to  $\text{Gr}(n-2, n+1)$  by definition.

$$\begin{array}{ccc} H = \text{Gr}(1, n-2, n+1) & \xrightarrow{\psi} & \text{Gr}(n-2, n+1) \\ \varphi \downarrow & & \\ \mathbb{P}^n & & \end{array}$$

We know  $\varphi$  has relative dimension  $3n-9$  as a flat morphism, therefore the subspace  $Y \subseteq \mathbb{P}^n$  satisfies

$$\dim(\varphi^{-1}(Y)) = 2 + 3n - 9 = 3n - 7 < 3n - 6 = (n-2) \cdot 3 = \dim(\text{Gr}(n-2, n+1)).$$

Therefore, the composite

$$Y \xrightarrow{\varphi^{-1}} \varphi^{-1}(Y) \xrightarrow{\psi} \text{Gr}(n-2, n+1)$$

is a proper subset of  $\text{Gr}(n-2, n+1)$ , i.e., the composition

$$\varphi^{-1}(Y) \hookrightarrow H \longrightarrow \text{Gr}(n-2, n+1)$$

is not surjective. Pick any  $V \notin \text{im}(\varphi^{-1}(Y))$ , then it satisfies  $V \cap Y = \emptyset$ . Therefore, we have maps  $\pi : \mathbb{P}_F^2 \setminus H_F \rightarrow \mathbb{P}_F^2$  and a diagram

$$\begin{array}{ccccc} & & p & & \\ & \swarrow & & \searrow & \\ Y_F & \xhookrightarrow{\subseteq} & \mathbb{P}_F^2 \setminus H_F & \xrightarrow{\pi} & \mathbb{P}_F^2 \\ q \downarrow & & & & \\ & & Y & & \end{array}$$

where  $p$  is proper. Since  $y \in Y$  is a rational point, then it has a unique fiber, therefore we identify  $q(y) = y \in Y$ . Hence,  $p^{-1}(p(y)) \cap Y_{\{0\}} = \{y\}$ , so for any  $s \in K_*^M(K(y))$ , we have

$$\begin{aligned} \sum_{\substack{p \in (\mathbb{P}_F^2)^{(1)} \\ p(y) \in \bar{u}}} \partial_{p(y)}^u \partial_u^{\xi_{\mathbb{P}_F^2}} (p_* q^*(s)) &= (d_{\mathbb{P}_F^2} \circ d_{\mathbb{P}_F^2} (p_* q^*(s)))_{p(y)} \\ &= (p_* q^*(d_Y \circ d_Y(s)))_{p(y)} \\ &= K_*^M(F/k) \circ (d_Y \circ d_Y(s))_y. \end{aligned}$$

However, because the Grassmannian is a rational variety, then  $F/k$  is purely transcendental, therefore  $K_*^M(F/k)$  is injective, hence the embedding  $K_*^M(k) \hookrightarrow K_*^M(k(t))$  is an injection by homotopy invariance. Therefore, we may assume

<sup>19</sup>Here  $H_F = H \times_{\text{Gr}(n-2, n+1)} F$  is the base-change.

$X = \operatorname{Spec}(\mathcal{O}_{\mathbb{A}^2, (0,0)}) = \mathbb{A}_{(0,0)}^2$ . Suppose  $\mathbb{A}^2$  has coordinates of the form  $(s, t)$ . By [Theorem 3.5](#), we have a split exact sequence

$$0 \longrightarrow K_*^M(k(s)) \xrightarrow{i} K_*^M(k(s, t)) \xrightarrow{(\tau_x)} \bigoplus_{x \in \mathbb{A}_{k(s)}^1} K_{*-1}^M(k(x)) \longrightarrow 0$$

Since the transfer is defined, we have an explicit description of the splitting  $(\tau_x)_{x \in X}$ , which is defined componentwise to be

$$\tau_x(a) = N_{k(x)(t)/k(s, t)}([t - t(x)]K_*^M(k(x)(t)/k(x))(a))$$

where  $t(x)$  is the canonical generator of  $k(x)/k(s)$ . Fix  $y \in \mathbb{A}_{k(s)}^1$ , then we can check that

$$\partial_y \circ \tau_x = \begin{cases} \operatorname{id}, & y = x \\ 0, & y \neq x \end{cases}$$

since  $[t - t(x)]K_*^M(k(x)(t)/k(x))(a)$  has non-zero valuation only at  $t - t(x)$ , which lies over the valuation at  $x \in k(s)$ .

Suppose  $b \in K_*^M(k(s, t))$ ,  $y = \{s = 0\} \in X = \mathbb{A}^2$ ,  $\nu$  runs through valuations  $k(x)(t)/k(t)$  and  $\bar{\nu} = \nu/k(x)$ . If  $b \in \operatorname{im}(i)$ , then  $d_X \circ d_X(b) = 0$  by naturality of the pullback along

$$\begin{aligned} p : \mathbb{A}^2 &\rightarrow \mathbb{A}^2 \\ (s, t) &\mapsto s \end{aligned}$$

which is given by

$$p^* : k(s) \rightarrow k(s, t),$$

and now  $i = K_*^M(p^*)$ . Therefore, it suffices to prove the statement  $d_X \circ d_X = 0$  for  $X = \mathbb{P}^1$ . Since  $\dim(\mathbb{A}^1) = 1$ , then assume  $b = \tau_x(a)$  for  $x \in (\mathbb{A}^2)^{(1)}$ , i.e.,  $x \in \mathbb{A}_{k(s)}^1$  corresponds to a divisor  $\bar{x}$  in  $\mathbb{A}^2$  different from  $\{s = 0\}$ , then it suffices to prove that

$$\partial_0^y \circ \partial_y^{\xi_{\mathbb{A}^2}} \circ \tau_x = -\partial_{(0,0)}^x \quad (3.32)$$

where  $p(x) = \xi_{\mathbb{A}^1}$  and  $\bar{x} \ni (0, 0)$ .

We know that

$$\sum_{0 \in y} \partial_0^y \circ \partial_y^{\xi_{\mathbb{A}^2}} = 0. \quad (3.33)$$

However, one can show that [Equation \(3.32\)](#) and [Equation \(3.33\)](#) are equivalent: a divisor in  $\mathbb{A}^2$  is either  $\{s = 0\}$  or a point  $x \in \mathbb{A}_{k(s)}^1$  corresponding to an irreducible polynomial, then note that the first case corresponds to  $-\partial_{(0,0)}^x$ , and the second case corresponds to  $\partial_0^y \circ \partial_y^{\xi_{\mathbb{A}^2}} \circ \tau_x$ .  $\square$

## 4 COMPARISON THEOREM OF MILNOR K-THEORY AND MOTIVIC COHOMOLOGY

In this section, we will compute  $H^{n,n}(\text{Spec}(F), \mathbb{Z})$ , the  $n$ th motivic cohomology of  $F$ , where  $F/k$  is a field. This requires studying the connections between motivic cohomology and Milnor K-theory, c.f., lecture 5 of [MVW06].

**Proposition 4.1** ([MVW06], Lemma 5.2).

$$H^{p,q}(\text{Spec}(F), \mathbb{Z}) = H_{q-p}(C_*\mathbb{Z}(\mathbb{G}_m^{\wedge q})(\text{Spec}(F)))$$

for all  $p, q$ , where  $C_*$  is the Suslin complex, c.f., Definition 2.40. In particular, if  $p = q = n$ , then

$$\begin{aligned} H^{n,n}(\text{Spec}(F), \mathbb{Z}) &= \text{coker}(\mathbb{Z}(\mathbb{G}_m^{\wedge n})(\mathbb{A}^1) \xrightarrow{\partial_0 - \partial_1} \mathbb{Z}(\mathbb{G}_m^{\wedge n})(\text{Spec}(F))) \\ &= \text{coker}(\text{Cor}_k(\mathbb{A}^1, \mathbb{G}_m^{\wedge n}) \xrightarrow{\partial_0 - \partial_1} \text{Cor}_k(\text{Spec}(F), \mathbb{G}_m^{\wedge n})) \end{aligned}$$

*Proof.* By definition, we have  $H^{p,q}(\text{Spec}(F), \mathbb{Z}) = \mathbb{H}^p(\text{Spec}(F), C_*(\mathbb{Z}(\mathbb{G}_m^{\wedge q})[-q]))$ . Since the functor defined by  $\mathcal{G} \mapsto \mathcal{G}(\text{Spec}(F))$  is exact, then we retrieve

$$\mathbb{H}^p(\text{Spec}(F), C_*\mathbb{Z}(\mathbb{G}_m^{\wedge q})[-q]) = H^p(C_*\mathbb{Z}(\mathbb{G}_m^{\wedge q})[-q](\text{Spec}(F))) = H_{q-p}(C_*\mathbb{Z}(\mathbb{G}_m^{\wedge q})(\text{Spec}(F)))$$

using the duality  $H^n = H_{-n}$ .  $\square$

Now suppose  $E/F$  is a finite field extension over  $k$ , then by Proposition 4.1, the pushforward of cycles gives a map

$$N_{E/F} : H^{n,n}(\text{Spec}(E), \mathbb{Z}) \rightarrow H^{n,n}(\text{Spec}(F), \mathbb{Z}).$$

**Proposition 4.2** ([MVW06], Lemma 5.3). Suppose  $x \in H^{n,n}(\text{Spec}(E), \mathbb{Z})$  and  $y \in H^{m,m}(\text{Spec}(F), \mathbb{Z})$ , then

1.  $N_{E/F}(y_E \cdot x) = y \cdot N_{E/F}(x)$  and  $N_{E/F}(x \cdot y_E) = N_{E/F}(x) \cdot y$ ;
2. suppose  $F \subseteq E \subseteq K$  are finite extensions, where  $K/F$  is normal, then similar to Corollary 3.12, we have

$$N_{E/F}(x)_K = [E : F]_{\text{insep}} \sum_{j \in \text{Hom}(E, K)} j(x);$$

3. if  $F \subseteq E' \subseteq E$ , then  $N_{E/F} = N_{E'/F} \circ N_{E/E'}$ .

*Proof.* The finite correspondence  $\mathbb{Z}(\mathbb{G}_m^{\wedge n})(\text{Spec}(F))$  is the quotient of free abelian group given by closed points of  $\mathbb{G}_m^{\times n}$  over those of the form  $(x_1, \dots, 1, \dots, x_n)$ . The exterior product

$$\text{Cor}(\text{Spec}(F), \mathbb{G}_m^{\times n}) \times \text{Cor}(\text{Spec}(F), \mathbb{G}_m^{\times m}) \rightarrow \text{Cor}(\text{Spec}(F), \mathbb{G}_m^{\times(n+m)})$$

gives a ring structure on  $\bigoplus_n H^{n,n}(\text{Spec}(F), \mathbb{Z})$ .

1. This comes from the projection formula of cycles, c.f., Proposition 1.28.
2. We have a Cartesian square

$$\begin{array}{ccc} (\mathbb{G}_m^{\times n})_E & \longleftarrow & (\mathbb{G}_m^{\times n}) \otimes_F (E \otimes_F K) \\ \downarrow & & \downarrow \\ (\mathbb{G}_m^{\times n})_F & \longleftarrow & (\mathbb{G}_m^{\times n})_K \end{array}$$

We have a similar property as Proposition 3.11, as in

$$\begin{array}{ccc} K_*^M(E) & \longrightarrow & \bigoplus_{p \in \text{Spec}(E) \otimes_F K} K_*^M(k(p)) \\ N \downarrow & & \downarrow \sum N_{k(p)/K} \\ K_*^M(F) & \longrightarrow & K_*^M(K). \end{array}$$

then the proof is the same as Corollary 3.12.

3. This follows from the same transitivity statement for the pushforward of cycles.  $\square$

**Proposition 4.3** ([MVW06], Corollary 5.5). Let  $p : Z \rightarrow \mathbb{A}_F^1$  be a finite surjective morphism of schemes and suppose that  $Z$  is integral. Let  $f_1, \dots, f_n \in \mathcal{O}^*(Z)$  be invertible functions on  $Z$ , and define the pullbacks  $p^*(0) = \sum_i n_i^0 z_i^0$  and  $p^*(1) = \sum_i n_i^1 z_i^1$  in  $Z_0(Z)$ , i.e.,  $n_i^t \in \mathbb{N}$  is the multiplicity at  $z_i^t$  and  $z_i^t \in Z$  for  $t = 0, 1$ . For  $t = 0, 1$ , we define

$$\varphi_t = \sum_i n_i^t N_{k(z_i^t)/F}([f_1] \cdots [f_n]_{z_i^t}),$$

then  $\varphi_0 = \varphi_1 \in K_n^M(F)$ .

*Proof.* The extension  $k(Z)/F$  is an algebraic function field. Denote  $\mathbb{A}_F^1 = \text{Spec}(F(t))$ , then  $x = \left[\frac{t}{t-1}\right] [f_1] \cdots [f_n]$ , i.e.,  $t$  is a parameter in  $\mathbb{A}_F^1$ , and  $\nu \in \text{DV}(k(Z)/F)$ . We consider the valuation of  $\nu$  at  $K(\mathbb{A}_F^1)$ .

- If  $\nu|_{k(\mathbb{A}_F^1)} = \nu_\infty$  is the valuation at  $\infty$ , then  $\left[\frac{t}{t-1}\right] = 1$  at  $t = \infty$  since other functions  $[f_i]$  has no evaluation as invertible functions, so  $\partial_\nu(x) = 0$ .
- If  $\nu|_{k(\mathbb{A}_F^1)} \neq \nu_\infty$ , then  $\frac{t}{t-1}, f_1, \dots, f_n \in \mathcal{O}_\nu^\times$ , i.e., valued to be 0 via  $\nu$ . Therefore,  $\partial_\nu(x) = 0$  at all finite places except those at 0 or 1.
- For  $t = 0, 1$ , if  $\nu|_{k(\mathbb{A}_F^1)} = \nu_t$ , then  $\nu$  centers at some fibers  $z_i^t$  of  $t$ . Let  $p_Z : \tilde{Z} \rightarrow Z$  be the normalization, then for any  $i$ , we have

$$\sum_{p_Z(\nu)=z_i^t} N_{k(\nu)/k(z_i^t)}(\partial_\nu(x)) = (-1)^t n_i^t [f_1] \cdots [f_n]_{z_i^t}$$

for  $t = 0, 1$ . For the case when  $t = 0$ , we have  $\left[\frac{t}{t-1}\right] = -1$ , then the valuation here is 1 since  $t$  has a zero of order 1. Taking  $\partial_\nu(x)$  gives  $[f_1] \cdots [f_n]$ , and by definition the degree of extension  $k(\nu)/k(z_i^0)$  is just  $n_i^0$ , and now the formula follows from the projection formula. When  $t = 1$ , the valuation of  $\left[\frac{t}{t-1}\right]$  at  $t = 1$  is  $-1$ , which contributes to the difference.

We find that  $\sum_{p_Z(\nu)} N_{k(\nu)/F}(\partial_\nu(x)) = \varphi_0 - \varphi_1$  since the only non-zero valuations are at 0 and at 1, then by Weil reciprocity

[Theorem 3.23](#) we know the difference is 0, as desired.  $\square$

Now we define a map

$$\theta : H^{n,n}(\text{Spec}(F), \mathbb{Z}) \rightarrow K_n^M(F)$$

as follows: every closed point  $x$  of  $(\mathbb{G}_m^{\times n})_F$  corresponds to an  $n$ -tuple  $(x_1, \dots, x_n)$  where each  $x_i \in k(x)^\times$ , then define

$$\begin{aligned} f : \mathbb{Z}(\mathbb{G}_m^{\wedge n})(\text{Spec}(F)) &\rightarrow K_n^M(F) \\ x &\mapsto N_{k(x)/F}([x_1] \cdots [x_n]) \end{aligned}$$

If one of  $x_i$ 's is 1, then  $f(x) = 0$ ,<sup>20</sup> so it is well-defined.

Recall that  $H^{n,n}(\text{Spec}(F), \mathbb{Z}) = \text{coker}(\mathbb{Z}(\mathbb{G}_m^{\wedge n})(\mathbb{A}^1) \xrightarrow{\partial_1 - \partial_0} \mathbb{Z}(\mathbb{G}_m^{\wedge n})(\text{Spec}(F)))$ , so to construct  $\theta$ , we need to show that  $f$  vanishes on  $\text{im}(\partial_1 - \partial_0)$ . In particular, this induces a unique  $\theta$  via

$$\begin{array}{ccc} \mathbb{Z}(\mathbb{G}_m^{\wedge n})(\mathbb{A}^1) & \xrightarrow{\partial_1 - \partial_0} & \mathbb{Z}(\mathbb{G}_m^{\wedge n})(\text{Spec}(F)) & \twoheadrightarrow & H^{n,n}(\text{Spec}(F), \mathbb{Z}) \\ & & \searrow f & & \downarrow \theta \\ & & & & K_n^M(F) \end{array}$$

<sup>20</sup>To see this, again recall that  $\mathbb{Z}(\mathbb{G}_m^{\wedge n})$  is the free abelian group generated by adjoining  $\mathbb{Z}$  with the closed points in  $\mathbb{G}_m^{\times n}$ , and then quotienting the equivalence relation on the  $n$ -tuple  $(x_1, \dots, x_n)$  where  $x_i = 1$  for some  $i$ .

Now  $\mathbb{Z}(\mathbb{G}_m^{\wedge n})(\mathbb{A}^1)$  is generated by irreducible subset  $C \subseteq \mathbb{A}^1 \times \mathbb{G}_m^{\times n}$ , such that  $C$  is finite and surjective over  $\mathbb{A}^1$ :

$$\begin{array}{ccc} C & \xhookrightarrow{\quad} & \mathbb{A}^1 \times \mathbb{G}_m^{\times n} \\ & \searrow \text{finite surjective} & \downarrow \\ & & \mathbb{A}^1 \end{array}$$

Since  $C$  has a projection to  $\mathbb{G}_m^{\wedge n}$ , then it gives invertible functions  $f_1, \dots, f_n \in \mathcal{O}^*(C)$  via pullback of the parameter of each copy of  $\mathbb{G}_m$ . Since  $C$  is surjective and finite over  $\mathbb{A}^1$ , then by [Proposition 4.3](#), we have  $f \circ (\partial_0 - \partial_1) = 0$ , hence  $\theta$  is defined.

Conversely, we define a map  $\lambda_F : K_n^M(F) \rightarrow H^{n,n}(\text{Spec}(F), \mathbb{Z})$  as follows: every  $x \in F^\times$  corresponds to a map  $x : \text{Spec}(F) \rightarrow \mathbb{G}_m$ , which gives  $\lambda_F([x]) \in H^{1,1}(\text{Spec}(F), \mathbb{Z})$ , since  $\partial$  is an isomorphism on  $H^{1,1}(\text{Spec}(F), \mathbb{Z})$  already. Recall that the Milnor K-group is given by a tensor algebra, therefore we need to show that  $\lambda_F$  is well-defined. To show this, we define  $[x : 1 - x] = \lambda_F([x]) \cdot \lambda_F([1 - x]) \in H^{2,2}(\text{Spec}(F), \mathbb{Z})$ , then we need to show that  $[x : 1 - x] = 0$  if  $x \neq 0, 1$ .

**Remark 4.4.**

- Note that  $[ab : c] = [a : c] + [b : c]$ , which follows from the linearity of  $\lambda_F$ . Similar fact holds on the second coordinate as well.
- In particular,  $[1 : x] = 0$ . Indeed, we know  $[1 : x] + [1 : x] = [1 : x]$ .

**Proposition 4.5** ([MVW06], Lemma 5.8). Suppose there exists  $n > 0$ , such that  $n[x : 1 - x] = 0$  for all finite extensions of  $F$  and all  $x \neq 0, 1$ , then  $[x : 1 - x] = 0 \in H^{2,2}(\text{Spec}(F), \mathbb{Z})$  for all  $x \neq 0, 1$ .

*Proof.* We proceed by induction on the number of factors of  $n$ . Essentially, we just need to suppose  $n = mp$  where  $p$  is prime, and then show that  $m[x : 1 - x] = 0$ . In the cases below, let  $y = \sqrt[p]{x}$ , i.e.,  $y^p = x$ .

- First suppose  $y \notin F$ , then we define  $E = F(y)$ , then  $0 = mp[y : 1 - y] = m[x : 1 - y]$ , and  $1 - x = N_{E/F}(1 - y)$ . By the projection formula, we have

$$0 = N_{E/F}(m[x : 1 - y]) = m[x : N_{E/F}(1 - y)] = m[x : 1 - x].$$

In the following cases, suppose  $y \in F$ .

- Suppose  $F$  is a splitting field of the polynomial  $T^p - x \in F[T]$ , i.e., there is a primitive  $p$ th root of unity  $\omega$  in  $F$ , so we know all the  $p$ th root of unity of  $x$ , given by the collection  $\{y\omega^i\}$ , is contained in  $F$ . By linearity and distributivity we know

$$\begin{aligned} m[x : 1 - x] &= \sum_i m[x : 1 - y\omega^i] \\ &= \sum_i mp[y\omega^i : 1 - y\omega^i] \\ &= \sum_i n[y\omega^i : 1 - y\omega^i] \\ &= 0. \end{aligned}$$

Alternatively, we have

$$m[x : 1 - x] = mp[y : 1 - y^p]$$

$$\begin{aligned}
 &= \sum_i mp[y : \omega^i - y] \\
 &= \sum_i mp\left([y : \omega^i] + \left[\frac{y}{\omega^i} : 1 - \frac{y}{\omega^i}\right] + \left[\omega^i : 1 - \frac{y}{\omega^i}\right]\right) \\
 &= \sum_i mp\left([y : \omega^i] + \left[\omega^i : 1 - \frac{y}{\omega^i}\right]\right) \\
 &= \sum_i m\left([y : \omega^{ip}] + \left[\omega^{ip} : 1 - \frac{y}{\omega^i}\right]\right) \\
 &= \sum_i m\left([y : 1] + \left[1 : 1 - \frac{y}{\omega^i}\right]\right) \\
 &= 0
 \end{aligned}$$

by [Remark 4.4](#).

- Now suppose  $F$  is not a splitting field of  $T^p - x \in F[T]$ , then the primitive  $p$ th root of unity  $\omega \notin F$ .<sup>21</sup> In this case, let  $E = F(\omega)$ . It is easy to show that  $N_{E/F}(\omega - y) = (-1)^p(y^p - 1)$ , which is just  $1 - x$  since  $p \neq 2$ , then by projection formula

$$\begin{aligned}
 m[x : 1 - x] &= m[x : N_{E/F}(\omega - y)] \\
 &= N_{E/F}(m[x : \omega - y]) \\
 &= N_{E/F}(n[y : \omega - y]) \\
 &= 0.
 \end{aligned}$$

□

**Proposition 4.6** ([MVW06], Proposition 5.9). For  $x \neq 0, 1$  in  $F$ ,  $[x : 1 - x] = 0$ .

*Proof.* Recall that we can represent a finite correspondence  $Z \in \text{Cor}(\mathbb{A}^1, \mathbb{G}_m)$  as a cycle in  $\mathbb{A}^1 \times \mathbb{G}_m$ . Using the parametrization  $(t, a) \in \mathbb{A}^1 \times \mathbb{G}_m$ , we define  $Z$  to be

$$a^3 - t(x^3 + 1)a^2 + t(x^3 + 1)a - x^3 = 0.$$

Let  $\omega$  be a root of  $a^2 + a + 1$ , so  $\omega^3 = 1$ . Suppose  $E = F(\omega)$ , then the fibers over  $t = 0$  are  $\{a = x\}$ ,  $\{a = \omega x\}$ , and  $\{a = \omega^2 x\}$ , and the fibers over  $t = 1$  are  $\{a = x^3\}$ ,  $\{a = -\omega\}$ , and  $\{a = -\omega^2\}$ . Since  $x \neq 0$ , then  $x^3 \neq 0$ , therefore  $a \neq 0$ .

Suppose  $x^3 \neq 1$ , we know  $a \neq 1$ , then  $Z$  is a pushforward coming from  $\text{Cor}(\mathbb{A}^1, \mathbb{G}_m \setminus \{1\})$ . Solving  $t$  with respect to  $a$ , we know  $Z \cong \mathbb{G}_m \setminus \{1\}$ . In particular,  $Z$  is integral. In the category of finite correspondence,  $Z$  is just a morphism  $\mathbb{A}^1 \rightarrow \mathbb{G}_m \setminus \{1\}$ , so composing  $Z$  with the map

$$\begin{aligned}
 \mathbb{G}_m \setminus \{1\} &\rightarrow \mathbb{G}_m^{\times 2} \\
 a &\mapsto (a, 1 - a),
 \end{aligned}$$

we obtain  $Z' \in \text{Cor}(\mathbb{A}^1, \mathbb{G}_m^{\times 2})$ . Recall that the motivic cohomology in  $H^{2,2}(\text{Spec}(E), \mathbb{Z})$  is defined as the cokernel of the map  $\partial_1 - \partial_0$ , so  $(\partial_1 - \partial_0)(Z') = 0$  in the cohomology. Therefore,  $\partial_0(Z')$  and  $\partial_1(Z')$  should give the same motivic cohomology class in  $H^{2,2}(\text{Spec}(E), \mathbb{Z})$ , namely

$$\partial_0(Z') = [x : 1 - x] + [\omega x : 1 - \omega x] + [\omega^2 x : 1 - \omega^2 x]$$

<sup>21</sup>In particular, this implies  $p \neq 2$ . If  $p = 2$ , then we have  $y^2 = (-y)^2 = x$ , therefore  $y$  and  $-y$  are the only roots of unity of  $x$ . Since  $y \in F$ , then  $-y \in F$ , contradiction.

$$\begin{aligned}
&= [x : 1 - x] + ([x : 1 - \omega x] + [\omega : 1 - \omega x]) + ([\omega^2 : 1 - \omega^2 x] + [x : 1 - \omega^2 x]) \\
&= [x : 1 - x] + ([x : 1 - \omega x] + [\omega : 1 - \omega x]) + ([\omega : (1 - \omega^2 x)^2] + [x : 1 - \omega^2 x]) \\
&= [x : 1 - x^3] + [\omega : (1 - \omega x)(1 - \omega^2 x)^2]
\end{aligned}$$

is the same as

$$\partial_1(Z') = [x^3 : 1 - x^3] + [-\omega : 1 + \omega] + [-\omega^2 : 1 + \omega^2]$$

over  $F(\omega)$ . By [Remark 4.4](#), we have

$$\begin{aligned}
[x^3 : 1 - x^3] &= 3\partial_0(Z') \\
&= 3\partial_1(Z') \\
&= 3[x^3 : 1 - x^3],
\end{aligned}$$

thus  $2[x^3 : 1 - x^3] = 0$  over  $E$ , so

$$\begin{aligned}
0 &= N_{E/F}(2[x^3 : 1 - x^3]) \\
&= 2[N_{E/F}(x^3) : 1 - x^3] \\
&= 2[x^6 : 1 - x^3] \\
&= 4[x^3 : 1 - x^3]
\end{aligned} \tag{4.7}$$

over  $F$ .

**Claim 4.8.** For arbitrary element  $x \neq 0, 1$  in  $F$  such that  $x^3 \neq 1$ , we have  $12[x : 1 - x] = 0$  over  $F$ .

*Subproof.*

- If  $x = y^3$  for some  $y \in F$ , then [Equation \(4.7\)](#) shows that  $4[x : 1 - x] = 0$  over  $F$ .
- If all  $y \in \bar{F}$  such that  $y^3 = x$  are not in  $F$ , then we set  $K = F(y)$ , so  $N_{K/F}(1 - y) = 1 - x$ , thus  $4[x : 1 - x] = 0$  over  $K$  by [Equation \(4.7\)](#), hence  $0 = N_{K/F}(4[x : 1 - x]) = 4[N_{K/F}(x) : 1 - x] = 12[x : 1 - x]$  over  $F$ . ■

By [Claim 4.8](#) and [Proposition 4.5](#) we know  $[x : 1 - x] = 0$  for arbitrary element  $x \neq 0, 1$  in  $F$  such that  $x^3 \neq 1$ .

Finally, suppose  $x^3 = 1$ . By [Remark 4.4](#),  $3[x : 1 - x] = [x^3 : 1 - x] = [1 : 1 - x] = 0$  in  $F$ , and again  $[x : 1 - x] = 0$  by [Proposition 4.5](#). □

To show that  $\lambda_F$  is an isomorphism, since  $\theta \circ \lambda_F = \text{id}$ , it suffices to show that  $\lambda_F$  is surjective.

**Proposition 4.9** ([[MVW06](#)], Lemma 5.11). For any finite extension  $E/F$ , the diagram

$$\begin{array}{ccc}
K_n^M(E) & \xrightarrow{\lambda_E} & H^{n,n}(\text{Spec}(E), \mathbb{Z}) \\
N_{E/F} \downarrow & & \downarrow N_{E/F} \\
K_n^M(F) & \xrightarrow{\lambda_F} & H^{n,n}(\text{Spec}(F), \mathbb{Z})
\end{array}$$

commutes.

*Proof.* Assume that all finite extensions of  $F$  has order  $l^n$  for  $l$  prime. Suppose we have an extension  $[E : F] = l$ . By the statement in [Proposition 3.13](#), we know that  $K_n^M(E)$  is generated by  $[f_1] \cdots [f_n]$  where  $f_1 \in E, f_2, \dots, f_n \in F$ , then the statement follows from projection formulas in [Corollary 3.12](#) and [Proposition 4.2](#).

If  $[E : F] = l^m$ , then we take an extension  $M/E$  such that  $M/F$  is Galois, then  $\text{Gal}(M/F)$  is an  $l$ -group. Using the decomposition series

$$E = E_n \supseteq \cdots \supseteq E_0 = F$$

where  $E_{i-1} \triangleleft E_i$  and  $[E_i : E_{i-1}] = l$ , we know the transitivity of norms reduces the question to the former case.

For general fields  $F$ , using [Proposition 3.9](#), we know the maps  $K_n^M(F)_{(l)} \rightarrow K_n^M(L)_{(l)}$  and  $H^{n,n}(\text{Spec}(F), \mathbb{Z})_{(l)} \rightarrow H^{n,n}(\text{Spec}(L), \mathbb{Z})_{(l)}$  are injective for some algebraic extension  $L/F$  such that every finite extension of  $L$  has degree a power of  $l$ . Moreover, we may assume  $E/F$  is a simple extension which is either separable or purely inseparable. In both cases, we could apply [Proposition 3.11](#), which reduces the proof to the previous case.  $\square$

**Theorem 4.10** ([MVW06], Lemma 5.10). The map  $\lambda_F : K_n^M(F) \rightarrow H^{n,n}(\text{Spec}(F), \mathbb{Z})$  is an isomorphism of rings.

*Proof.* If  $x \in (\mathbb{G}_m^{\times n})_F$  is a rational point, it is in  $\text{im}(\lambda_F)$  by construction. In general, a closed point  $x \in (\mathbb{G}_m^{\times n})^{(1)}$  is the pushforward of a rational point of  $(\mathbb{G}_m^{\times n})_{k(x)}$ , so the statement follows from [Proposition 4.9](#).  $\square$



## 5 EFFECTIVE MOTIVIC CATEGORIES OVER SMOOTH BASES

We discuss a few categorical results formulated via Grothendieck's six operations on the level of sheaves, as discussed in [CD19], section A.5.

### 5.1 GROTHENDIECK'S SIX-FUNCTOR FORMALISM

**Lemma 5.1.** Let  $\varphi : \mathcal{C} \rightarrow \mathcal{D}$  be a functor of small categories and  $\mathcal{M}$  be a category with arbitrary colimits, then the functor

$$\begin{aligned} \varphi_* : \text{PreShv}(\mathcal{D}, \mathcal{M}) &\rightarrow \text{PreShv}(\mathcal{C}, \mathcal{M}) \\ F &\mapsto F \circ \varphi \end{aligned}$$

has a left adjoint  $\varphi^*$ .

*Proof.* Suppose that  $\mathcal{G} \in \text{PreShv}(\mathcal{C}, \mathcal{M})$ . For every  $Y \in \mathcal{D}$ , define  $C_Y$  to be the category whose objects are  $\{Y \rightarrow \varphi(X) \mid X \in \mathcal{C}\}$  and morphisms from  $a_1 : Y \rightarrow \varphi(X_1)$  to  $a_2 : Y \rightarrow \varphi(X_2)$  are those  $b : X_1 \rightarrow X_2$  such that  $a_2 = \varphi(b) \circ a_1$ . We have a contravariant functor

$$\begin{aligned} \theta_Y : C_Y &\rightarrow \mathcal{M} \\ (Y \mapsto \varphi(X)) &\mapsto \mathcal{G}X \end{aligned}$$

then define  $(\varphi^*\mathcal{G})(Y) = \varinjlim \theta_Y$ . For any morphism  $c : Y_1 \rightarrow Y_2$  in  $\mathcal{D}$ , we define  $(\varphi^*\mathcal{G})(c)$  by the commutative diagram

$$\begin{array}{ccc} \theta_{Y_2}(Y_2 \rightarrow \varphi(X)) & \xrightarrow{c^*} & \theta_{Y_2}(Y_1 \rightarrow \varphi(X)) \\ \downarrow & & \downarrow \\ \varinjlim \theta_{Y_2} & \xrightarrow{(\varphi^*\mathcal{G})(c)} & \varinjlim \theta_{Y_1} \end{array}$$

□

**Definition 5.2.** Suppose that  $f : S \rightarrow T$  is a morphism in  $\text{Sm}/k$ . We have a functor

$$\begin{aligned} \varphi^f : \text{Cor}_T &\rightarrow \text{Cor}_S \\ X &\mapsto X \times_T S \\ f &\mapsto f \times_T S \end{aligned}$$

then Lemma 5.1 provides adjunction pairs

$$\begin{array}{c} \text{PSh}(T) \\ f^* \updownarrow f_* \\ \text{PSh}(S) \end{array}$$

where  $f_* = (\varphi^f)_*$ , and

$$\begin{array}{c} \text{Sh}(T) \\ f^* \updownarrow f_* \\ \text{Sh}(S) \end{array}$$

**Proposition 5.3.** Suppose that  $f : S \rightarrow T$  is a morphism in  $\text{Sm}/k$ .

1.  $f^*\mathbb{Z}_T(Y) = \mathbb{Z}_S(Y \times_T S)$  for any  $Y \in \text{Sm}/T$ , where  $\mathbb{Z}_T(Y)(X) = \text{Cor}_T(X, Y)$ .

2.  $(f_*\mathcal{F})^Y = f_*(\mathcal{F}^{Y \times_T S})$  for any  $\mathcal{F} \in \text{Sm}(S)$  and  $Y \in \text{Sm}/T$ , where  $\mathcal{F}^X(Y) = \mathcal{F}(X \times_S Y)$  for  $X, Y \in \text{Sm}/S$  is defined in [Definition 2.20](#).
3.  $\underline{\text{Hom}}_T(\mathcal{F}, f_*\mathcal{G}) = f_*\underline{\text{Hom}}_S(f^*\mathcal{F}, \mathcal{G})$  for any  $\mathcal{F} \in \text{Sh}(T)$  and  $\mathcal{G} \in \text{Sh}(S)$ , and for internal hom  $\underline{\text{Hom}}$  defined as in [Definition 2.20](#).
4.  $f^*\mathcal{F} \otimes_S f^*\mathcal{G} = f^*(\mathcal{F} \otimes_S \mathcal{G})$  for  $\mathcal{F}, \mathcal{G} \in \text{Sh}(T)$ .

*Proof.*

1. We have

$$\begin{aligned} \text{Hom}_S(f^*\mathbb{Z}_T(Y), -) &= \text{Hom}_T(\mathbb{Z}_T(Y), f_*(-)) \\ &= \text{Hom}_S(\mathbb{Z}_S(Y \times_T S), -). \end{aligned}$$

2. Note that

$$\begin{aligned} (f_*\mathcal{F})^Y(Z) &= \mathcal{F}((Y \times_T Z) \times_T S) \\ &= \mathcal{F}((Z \times_T S) \times_S (Y \times_T S)) \\ &= (f_*(\mathcal{F}^{Y \times_T S})) \\ &= (f_*(\mathcal{F}^{Y \times_T S})(Z)) \end{aligned}$$

for  $Z \in \text{Sm}/T$ .

3. For any  $Y \in \text{Sm}/T$ , we have

$$\begin{aligned} \underline{\text{Hom}}_T(\mathcal{F}, f_*\mathcal{G})(Y) &= \text{Hom}_T(\mathcal{F}, (f_*\mathcal{G})^Y) \\ &= \text{Hom}_T(\mathcal{F}, f_*(\mathcal{G}^{Y \times_T S})) \\ &= \text{Hom}_S(f^*\mathcal{F}, \mathcal{G}^{Y \times_T S}) \\ &= (f_*\underline{\text{Hom}}_S(f^*\mathcal{F}, \mathcal{G}^{Y \times_T S})) \\ &= (f_*\underline{\text{Hom}}_S(f^*\mathcal{F}, \mathcal{G}))(Y). \end{aligned}$$

4. For any  $\mathcal{H} \in \text{Sh}(S)$ , we have

$$\begin{aligned} \text{Hom}_S(f^*\mathcal{F} \otimes_S f^*\mathcal{G}, \mathcal{H}) &= \underline{\text{Hom}}_S(f^*\mathcal{G}, \underline{\text{Hom}}_S(f^*\mathcal{F}, \mathcal{H})) \\ &= \text{Hom}_T(\mathcal{G}, f_*\underline{\text{Hom}}_S(f^*\mathcal{F}, \mathcal{H})) \\ &= \text{Hom}_T(\mathcal{G}, \underline{\text{Hom}}_T(\mathcal{F}, f_*\mathcal{H})) \\ &= \text{Hom}_T(\mathcal{F} \otimes_T \mathcal{G}, f_*\mathcal{H}) \\ &= \text{Hom}_S(f^*(\mathcal{F} \otimes_T \mathcal{G}), \mathcal{H}). \end{aligned}$$

□

**Definition 5.4.** Suppose that  $f : S \rightarrow T$  is a smooth morphism in  $\text{Sm}/k$ , then every  $X \in \text{Sm}/S$  is naturally an object in  $\text{Sm}/T$ . Moreover, for  $X_1, X_2 \in \text{Sm}/S$ , then the Cartesian diagram

$$\begin{array}{ccc} X_1 \times_S X_2 & \xrightarrow{q_f} & X_1 \times_T X_2 \\ \downarrow & & \downarrow \\ S & \xrightarrow{\Delta} & S \times_T S \end{array}$$

commutes, so  $q_f$  is a closed immersion. Thus we define

$$\begin{aligned}\varphi_f : \text{Cor}_S &\rightarrow \text{Cor}_T \\ X &\mapsto X \\ g &\mapsto (q_f)_*(g).\end{aligned}$$

So by [Lemma 5.1](#), we obtain adjunction pairs

$$\begin{array}{c} \text{PSh}(T) \\ (q_f)_* \updownarrow f_{\#} \\ \text{PSh}(S) \end{array}$$

and

$$\begin{array}{c} \text{Sh}(T) \\ (q_f)_* \updownarrow f_{\#} \\ \text{Sh}(S) \end{array}$$

**Proposition 5.5.** We have  $(q_f)_* = f^*$  for smooth  $f : S \rightarrow T$ .

*Proof.* For any  $Y \in \text{Sm}/S$ ,  $\text{id}_Y \in \text{Cor}_T(Y, Y) = \text{Cor}_S(Y, Y \times_T S)$  is the initial element of  $C_Y$  in [Lemma 5.1](#). Because  $f^*(Y) = \varinjlim C_Y$ , then the direct limit is itself. Therefore, for any  $\mathcal{F} \in \text{PSh}(T)$ , we have  $(f^*\mathcal{F})(Y) = \mathcal{F}Y = (q_{f*}\mathcal{F})(Y)$ .  $\square$

**Proposition 5.6.** Let  $f : S \rightarrow T$  be smooth.

1.  $f_{\#}\mathbb{Z}_S(X) = \mathbb{Z}_T(X)$  for any  $X \in \text{Sm}/S$ .
2.  $f^*(\mathcal{F}^Y) = (f^*\mathcal{F})^{Y \times_T S}$  for any  $\mathcal{F} \in \text{Sm}(T)$  and  $Y \in \text{Sm}/T$ .
3.  $\underline{\text{Hom}}_T(f_{\#}\mathcal{F}, \mathcal{G}) = f_*\underline{\text{Hom}}_S(\mathcal{F}, f^*\mathcal{G})$  for any  $\mathcal{F} \in \text{Sm}(S)$  and  $\mathcal{G} \in \text{Sm}(T)$ .
4.  $f_{\#}(\mathcal{F} \otimes_S f^*\mathcal{G}) = (f_{\#}\mathcal{F}) \otimes_T \mathcal{G}$ , where  $\mathcal{F} \in \text{Sm}(S)$  and  $\mathcal{G} \in \text{Sm}(T)$ .

*Proof.*

1. For any  $\mathcal{F} \in \text{Sh}(T)$ , we have

$$\begin{aligned}\text{Hom}_T(f_{\#}\mathbb{Z}_S(X), \mathcal{F}) &= \text{Hom}_S(\mathbb{Z}_S(X), f^*\mathcal{F}) \\ &= (f^*\mathcal{F})(X) \\ &= \mathcal{F}X.\end{aligned}$$

2. For any  $X \in \text{Sm}/S$ , we have

$$\begin{aligned}(f^*(\mathcal{F}^Y))(X) &= \mathcal{F}(Y \times_T X) \\ &= \mathcal{F}((Y \times_T S) \times_S X) \\ &= (f^*\mathcal{F})^{Y \times_T S}(X).\end{aligned}$$

3. For  $Y \in \text{Sm}/T$ , we have

$$\begin{aligned}\underline{\text{Hom}}_T(f_{\#}\mathcal{F}, \mathcal{G})(Y) &= \text{Hom}_T(f_{\#}\mathcal{F}, \mathcal{G}^Y) \\ &= \text{Hom}_S(\mathcal{F}, f^*(\mathcal{G}^Y))\end{aligned}$$

$$\begin{aligned}
 &= \mathrm{Hom}_S(\mathcal{F}, (f^*\mathcal{G})^{Y \times_T S}) \\
 &= \underline{\mathrm{Hom}}_S(\mathcal{F}, f^*\mathcal{G})(Y \times_T S) \\
 &= (f_*\underline{\mathrm{Hom}}_S(\mathcal{F}, f^*\mathcal{G}))(Y).
 \end{aligned}$$

4. For  $\mathcal{H} \in \mathrm{Sh}(T)$ , we know

$$\begin{aligned}
 \mathrm{Hom}_T(f_{\#}(\mathcal{F} \otimes_S f^*\mathcal{G}), \mathcal{H}) &= \mathrm{Hom}_S(\mathcal{F} \otimes_S f^*\mathcal{G}, f^*\mathcal{H}) \\
 &= \mathrm{Hom}_S(f^*\mathcal{G}, \underline{\mathrm{Hom}}_S(\mathcal{F}, f^*\mathcal{H})) \\
 &= \mathrm{Hom}_S(\mathcal{G}, f_*\underline{\mathrm{Hom}}_S(\mathcal{F}, f^*\mathcal{H})) \\
 &= \mathrm{Hom}_T(\mathcal{G}, \underline{\mathrm{Hom}}_T(f_{\#}\mathcal{F}, \mathcal{H})) \\
 &= \mathrm{Hom}_T((f_{\#}\mathcal{F}) \otimes_T \mathcal{G}, \mathcal{H})
 \end{aligned}$$

□

Given these operations on the level of sheaves, namely  $\otimes_S$ ,  $f_{\#}$ , and  $f^*$ , we want to define them again on the level of derived categories.

**Definition 5.7.** Let  $C^-(S)$  be the category of bounded-above complexes, then we define  $K^-(S) = C^-(S)/\sim$ , quotient by the chain homotopy equivalences, to be the homotopy category of bounded-above complexes of  $\mathrm{Sh}(S)$ .

We also define  $D^-(S) = K^-(S)[\text{inversion of quasi-isomorphisms}]$  to be the derived category of bounded-above complexes of  $\mathrm{Sh}(S)$ .

**Definition 5.8.** A presheaf  $F \in \mathrm{PSh}(S)$  is free if it is a direct sum of Yoneda presheaves  $\mathbb{Z}_S(X)$ , and is projective if it is a direct summand of a free presheaf.

A sheaf  $F \in \mathrm{Sh}(S)$  is free (respectively, projective) if it is a sheafification of a free (respectively, projective) presheaf.

A bounded-above complex of  $\mathrm{Sh}(S)$  is free (respectively, projective) if all its terms are free (respectively, projective).

**Definition 5.9.** A projective resolution of  $K \in C^-(S)$  is a quasi-isomorphism  $P \rightarrow K$  with  $P$  being projective.

Now suppose  $S, T \in \mathrm{Sm}/k$ , and let  $Y$  be a scheme with morphisms  $S \xleftarrow{f} Y \xrightarrow{g} T$  where  $g$  is smooth (but  $f$  may not be smooth in general). We consider functors

$$\begin{array}{ccccc}
 & & \varphi & & \\
 & \nearrow & & \searrow & \\
 \mathrm{Cor}_S & \xrightarrow{\varphi_f} & \mathrm{Cor}_Y & \xrightarrow{\varphi_g} & \mathrm{Cor}_T \\
 X & \longmapsto & & \longmapsto & X \times_S Y
 \end{array}$$

and

$$\begin{array}{ccc}
 \mathrm{Sm}/S & \xrightarrow{\psi} & \mathrm{Sm}/T \\
 X & \longmapsto & X \times_S Y
 \end{array}$$

determined by the triple  $(Y, S, T)$ .

Recall that  $\mathrm{PSh}(S)$  has enough projectives, then it is possible to derive any left exact functor, e.g., to  $\mathrm{Ab}$ . Moreover we obtain  $\varphi_*$  defined by the composition, and its left adjoint  $\varphi^*$  by [Lemma 5.1](#).

**Proposition 5.10.** For any  $\mathcal{F} \in \mathrm{PSh}(S)$ , the sheafification  $(L_i\varphi^*(\mathcal{F}^+))^+ = (L_i\varphi^*(\mathcal{F}))^+$  for  $i \geq 0$ , where  $L_i\varphi^*$  is the  $i$ th left derived functor of  $\varphi^*$ .

*Proof.* It suffices to show that for any  $\mathcal{F} \in \text{PSh}(S)$  with  $\mathcal{F}^+ = 0$ , we have  $((L_i\varphi^*)\mathcal{F})^+ = 0$  for all  $i \geq 0$ . Suppose this is true, then for any presheaf  $\mathcal{F}$ , we consider the natural morphism  $\theta : \mathcal{F} \rightarrow \mathcal{F}^+$  satisfying  $(\text{coker}(\theta))^+ = (\ker(\theta))^+ = 0$  by the properties of sheafification. Hence for all  $i \geq 0$ , we know by the long exact sequence that

$$((L_i\varphi^*)\mathcal{F}^+)^+ = ((L_i\varphi^*)\text{im}(\theta))^+ = ((L_i\varphi^*)\mathcal{F})^+,$$

so the proposition follows.

To prove the statement, we proceed by induction on  $i$ . The case when  $i = 0$  is trivial, as  $\varphi^*$  commutes with the sheafification functor. Now we may suppose that it is true for  $i < n$ , and we want to show it for  $i = n$ . For any  $\mathcal{F} \in \text{PSh}(S)$ , we cover it by presheaves

$$(i_\alpha) : \bigoplus_{\alpha \in \mathcal{F}(X)} \mathbb{Z}_S(X) \rightarrow \mathcal{F}$$

for sections  $\alpha \in \mathcal{F}(X)$  over  $X$ . By the Yoneda lemma, this construction is a surjection. Since  $\mathcal{F}^+ = 0$ , then for any  $\alpha \in \mathcal{F}(X)$  where  $X \in \text{Sm}/S$ , there is a Nisnevich covering  $U_\alpha \rightarrow X$  of  $X$  such that  $\alpha|_{U_\alpha} = 0$ , therefore the composite

$$\bigoplus_{\alpha \in \mathcal{F}(X)} \mathbb{Z}_S(U_\alpha) \longrightarrow \bigoplus_{\alpha \in \mathcal{F}(X)} \mathbb{Z}_S(X) \xrightarrow{(i_\alpha)} \mathcal{F}$$

is zero. Since the composite is zero, then each  $i_\alpha$  factors through the cokernel of  $\bigoplus_{\alpha \in \mathcal{F}(X)} \mathbb{Z}_S(U_\alpha) \rightarrow \bigoplus_{\alpha \in \mathcal{F}(X)} \mathbb{Z}_S(X)$ , which is the direct sum of Čech complexes of form

$$\check{C}(U_\alpha/X) : (\cdots \longrightarrow \mathbb{Z}_S(U_\alpha \times_X U_\alpha) \longrightarrow \mathbb{Z}_S(U_\alpha) \longrightarrow \mathbb{Z}(X) \longrightarrow \cdots)$$

Taking the cokernel gives the cokernel of the Čech complex, and using the fact that the sheafification of this Čech complex gives an exact sequence, we first obtain a surjective map  $\bigoplus_{\alpha \in \mathcal{F}(X)} H_0(\check{C}(U_\alpha/X)) \rightarrow \mathcal{F}$  since  $(i_\alpha)$  factors through it, then taking the kernel  $K$  gives an exact sequence of presheaves

$$0 \longrightarrow K \longrightarrow \bigoplus_{\alpha \in \mathcal{F}(X)} H_0(\check{C}(U_\alpha/X)) \longrightarrow \mathcal{F} \longrightarrow 0$$

By [Theorem 2.35](#), we know that  $H_p(\check{C}(U_\alpha/X))^+ = 0$  for every  $\alpha \in \mathcal{F}(X)$  and  $p \in \mathbb{Z}$ . Since the two other terms in the short exact sequence are zero after sheafification, then  $K^+ = 0$  as well. By [Lemma 1.26](#), we have a hypercohomology spectral sequence

$$(L_p\varphi^*)H_q(\check{C}(U_\alpha/X)) \Rightarrow (L_{p+q}\varphi^*)\check{C}(U_\alpha/X).$$

Since  $H_q(\check{C}(U_\alpha/X))^+ = 0$ , then by the inductive hypothesis, if  $q < n$ , then  $(L_p\varphi^*H_q(\check{C}(U_\alpha/X)))^+ = 0$ . Therefore, taking sheafification on both sides gives  $(L_n\varphi^*H_0(\check{C}(U_\alpha/X)))^+ = (L_n\varphi^*\check{C}(U_\alpha/X))^+$ . Since  $\check{C}(U_\alpha/X)$  is a projective complex, we also have

$$\begin{aligned} (L_n\varphi^*\check{C}(U_\alpha/X))^+ &= H_n(\varphi^+\check{C}(U_\alpha/X))^+ \\ &= H_n(\check{C}(\psi U_\alpha/\psi X))^+ \\ &= 0. \end{aligned}$$

Therefore, we have  $(L_n\varphi^*)H_0(\check{C}(U_\alpha/X)) = 0$ , so  $(L_n\varphi^*\mathcal{F})^+ = (L_{n-1}\varphi^*K)^+ = 0$  by the long exact sequence and the inductive hypothesis with  $K^+ = 0$ .  $\square$

**Proposition 5.11.** The functor  $\varphi^*$  takes acyclic projective complexes of sheaves to acyclic projective complexes of sheaves.

*Proof.* For any projective sheaf  $\mathcal{F} \in \text{Sh}(S)$ , we know  $\mathcal{F} = \mathcal{G}^+$  for some projective  $\mathcal{G} \in \text{PSh}(S)$ , therefore

$$(L_i \varphi^* \mathcal{F})^+ = (L_i \varphi^* \mathcal{G})^+ = 0$$

for any  $i > 0$  by [Proposition 5.10](#). Given a short exact sequence

$$0 \longrightarrow K \longrightarrow \mathcal{F} \longrightarrow P \longrightarrow 0$$

be a short exact sequence in  $\text{Sh}(S)$  with  $(L_i \varphi^* P)^+ = 0$  for  $i > 0$ , then the sequence is still exact after applying  $\varphi^*$ . Moreover, if  $\mathcal{F}$  is projective, we have  $(L_i \varphi^* K)^+ = 0$  for  $i > 0$ . This concludes the proof.  $\square$

**Proposition 5.12.** We have an exact functor

$$\begin{aligned} L\varphi^* : D^-(S) &\rightarrow D^-(T) \\ K &\mapsto \varphi^* P \end{aligned}$$

where  $P \rightarrow K$  is a projective resolution.

*Proof.* By [Proposition 5.11](#), the class of projective complexes is adapted, c.f., III.6.3 of [\[GM13\]](#), to the functor  $\varphi^*$ . We conclude the proof by using applying III.6.6 from [\[GM13\]](#).  $\square$

In the following, we write  $\varphi^*$  in place of  $L\varphi^*$  for convenience.

**Proposition 5.13.**

1. The category  $D^-(S)$  is endowed with a tensor product defined by

$$\begin{aligned} \otimes_S : D^-(S) \times D^-(S) &\rightarrow D^-(S) \\ (K, L) &\mapsto P \otimes_S Q \end{aligned}$$

where  $P, Q$  are projective resolutions of  $K$  and  $L$ , respectively, and  $P \otimes_S Q = \text{Tot}(\{P_i \otimes_S Q_j\})$ . Moreover, for any  $K \in D^-(S)$ , the functor  $K \otimes_S -$  is exact.

2. Suppose that  $f : S \rightarrow T$  is smooth, then there is an exact functor

$$\begin{aligned} f_{\#} : D^-(S) &\rightarrow D^-(T) \\ K &\mapsto f_{\#} P \end{aligned}$$

where  $P \rightarrow K$  is a projective resolution.

3. Suppose that  $f : S \rightarrow T$  is in  $\text{Sm}/k$ , there is an exact functor

$$\begin{aligned} f^* : D^-(S) &\rightarrow D^-(T) \\ K &\mapsto f^* P \end{aligned}$$

where  $P \rightarrow K$  is a projective resolution.

*Proof.*

1. Let  $Y \in \text{Sm}/S$ . From the definition of  $\varphi$ , we take  $(Y, S, T) = (Y, S, S)$ , then  $\varphi^* \mathcal{F} = \mathcal{F} \otimes_S \mathbb{Z}_S(Y)$  for any  $\mathcal{F} \in \text{Sh}(S)$  by the projection formula in [Proposition 5.6](#). Given an acyclic projective complex  $P$  and a projective sheaf  $\mathcal{F}$ , then the complex  $\mathcal{F} \otimes_S P$  is also acyclic by [Proposition 5.11](#). Therefore, for any projective complex  $K$ , the complex  $P \otimes_S K$  is also acyclic by the spectral sequence of the double complex  $\{P_i \otimes_S K_j\}$ . Then for any projective complexes  $P, Q, R$  with a quasi-isomorphism  $a : P \rightarrow Q$ , we have a projective complex  $C(a \otimes_S R)$  where  $C$  is a mapping cone given by  $C(a)^i = P^{i+1} \oplus Q^i$ , then  $C(a \otimes_S R) = C(a) \otimes_S R$ . Since  $a$  is a quasi-isomorphism, then  $C(a)$  is acyclic, so  $C(a \otimes_S R) = C(a) \otimes_S R$  is acyclic as well. Therefore,  $a \otimes_S R$  is also a quasi-isomorphism.

2. Take  $(Y, S, T) = (S, S, T)$  and apply [Proposition 5.12](#).
3. Take  $(Y, S, T) = (T, S, T)$  and apply [Proposition 5.12](#).

□

**Remark 5.14.** There is no  $f_*$  in the current system of bounded above complexes. However, we can consider the category of unbounded complexes instead and construct it using model categories instead, c.f., [\[CD09\]](#).

**Definition 5.15** ([\[GM13\]](#), III.2.9). Let  $\mathcal{A}$  be a category and  $\mathcal{S}$  be a localizing class of morphisms in  $\mathcal{A}$ .

- A left roof between  $M$  and  $N$  is a diagram

$$\begin{array}{ccc} & L & \\ s \swarrow & & \searrow f \\ M & & N \end{array}$$

where  $s \in \mathcal{S}$ .

- A right roof between  $M$  and  $N$  is a diagram

$$\begin{array}{ccc} & L & \\ g \nearrow & & \nwarrow t \\ M & & N \end{array}$$

where  $t \in \mathcal{S}$ .

**Proposition 5.16.** Let  $f : S \rightarrow T$  be a smooth morphism in  $\mathbf{Sm}/k$ , then we have an adjunction

$$\begin{array}{c} D^-(T) \\ f_{\#} \uparrow \downarrow f^* \\ D^-(S) \end{array}$$

*Proof.* We have an adjunction

$$\begin{array}{c} K^-(T) \\ f_{\#} \uparrow \downarrow f^* \\ K^-(S) \end{array}$$

by the adjunction between sheaves. Since  $f^*$  has both left and right adjoints, it is exact, hence  $Lf^* = f^*$ . Suppose that  $K \in D^-(S)$  and  $L \in D^-(T)$ , and that  $p : P \rightarrow K$  is a projective resolution. We construct a morphism

$$\alpha : \mathrm{Hom}_{D^-(S)}(f_{\#}K, L) \rightarrow \mathrm{Hom}_{D^-(T)}(K, f^*L)$$

as follows: suppose that  $s \in \mathrm{Hom}_{D^-(S)}(f_{\#}K, L)$  is written as a right roof

$$\begin{array}{ccc} & R & \\ a \nearrow & & \nwarrow b \\ f_{\#}P & \xrightarrow{\quad s \quad} & L \end{array}$$

where  $b$  is a quasi-isomorphism, denoted by  $\Rightarrow$ . We now define  $\theta(s)$  to be the map

$$\begin{array}{ccc} & f^*R & \\ a' \nearrow & & \nwarrow f^*b \\ K \longleftarrow P & & f^*L \end{array}$$

where  $f^*b$  is also a quasi-isomorphism since  $f^*$  is exact.

Next, we construct a morphism

$$\xi : \mathrm{Hom}_{D^-(T)}(K, f^*L) \rightarrow \mathrm{Hom}_{D^-(S)}(f_{\#}K, L)$$

Suppose that  $t \in \mathrm{Hom}_{D^-(T)}(K, f^*L)$  and  $t \circ p$  is written as a left roof

$$\begin{array}{ccc} & R & \\ a \swarrow & & \searrow b \\ P & & f^*L \end{array}$$

Without loss of generality, here we can take  $R$  to be projective, or to take a projective resolution. Define  $\xi(t)$  as

$$\begin{array}{ccc} & f_{\#}R & \\ f_{\#}a \swarrow & & \searrow b' \\ f_{\#}P & & L \end{array}$$

with  $f_{\#}a$  being a quasi-isomorphism by [Proposition 5.13](#). One checks that  $\theta$  and  $\xi$  are inverses to each other.  $\square$

## 5.2 HOMOTOPY INVARIANT PRESHEAVES

Now let us get the homotopy relation  $X \times \mathbb{A}^1 \sim X$  involved. Being a derived category is not enough for motives, as we also have to fully invert those relations.

**Definition 5.17.** An  $\mathcal{F} \in \mathrm{PSh}(S)$  is called homotopy invariant if for every  $X \in \mathrm{Sm}/S$ , the map  $p^* : \mathcal{F}(X) \rightarrow \mathcal{F}(X \times \mathbb{A}^1)$ , induced from the projection  $p : X \times \mathbb{A}^1 \rightarrow X$ , is an isomorphism.

**Remark 5.18.** Since  $p : X \times \mathbb{A}^1 \rightarrow X$  has a section, then  $p^*$  above is split injective. Hence,  $\mathcal{F}$  is homotopy invariant if and only if  $p^*$  is surjective.

**Remark 5.19.** The homotopy invariant presheaves of abelian groups form a Serre subcategory of presheaves. In particular, if  $\mathcal{F}$  and  $\mathcal{G}$  are homotopy invariant presheaves with transfers, then the kernel and cokernel of every map  $f : \mathcal{F} \rightarrow \mathcal{G}$  are homotopy invariant presheaves with transfers.

**Lemma 5.20** ([MVW06], Lemma 2.16). For any  $\mathcal{F} \in \mathrm{PSh}(S)$ , we have

$$\begin{aligned} i_{\alpha} : X &\hookrightarrow X \times \mathbb{A}^1 \\ x &\mapsto (x, \alpha) \end{aligned}$$

for  $\alpha = 0, 1$ , then the maps

$$i_0^*, i_1^* : (C_*(\mathcal{F}))(X \times \mathbb{A}^1) \rightarrow (C_*\mathcal{F})(X),$$

are defined as  $\mathcal{F}(i_0)$  and  $\mathcal{F}(i_1)$ .  $\mathcal{F}$  is homotopy invariant if and only if  $i_0^* = i_1^* : \mathcal{F}(X \times \mathbb{A}^1) \rightarrow \mathcal{F}(X)$  for all  $X$ .

*Proof.* One direction is obvious. Now suppose  $i_0^* = i_1^*$ , we want to show that  $\mathcal{F}$  is homotopy invariant. Denote by

$$\begin{aligned} m : \mathbb{A}^1 \times \mathbb{A}^1 &\rightarrow \mathbb{A}^1 \\ (x, y) &\mapsto Ky \end{aligned}$$

the multiplication map, we have a commutative diagram

$$\begin{array}{ccccc} & \mathcal{F}(X \times \mathbb{A}^1) & \xrightarrow{i_0^*} & \mathcal{F}(X) & \\ \swarrow \mathrm{id}_{X \times \mathbb{A}^1} \cong & \downarrow (\mathrm{id}_X \times m)^* & & \downarrow p^* & \\ \mathcal{F}(X \times \mathbb{A}^1) & \xleftarrow{(i_1 \times \mathrm{id}_{\mathbb{A}^1})^*} \mathcal{F}(X \times \mathbb{A}^1 \times \mathbb{A}^1) & \xrightarrow{(i_0 \times \mathrm{id}_{\mathbb{A}^1})^*} & \mathcal{F}(X \times \mathbb{A}^1) & \end{array}$$



By the condition, we have  $p^*i_0^* = (\text{id}_{\mathbb{A}^1} \times i_0)^*m^* = (\text{id}_{\mathbb{A}^1} \times i_1)^*m^* = \text{id}_{X \times \mathbb{A}^1}$ . Since  $i_0^*p^* = \text{id}$ , then  $p^*$  is an isomorphism.  $\square$

**Lemma 5.21** ([MVW06], Lemma 2.18). For any  $\mathcal{F} \in \text{PSh}(S)$ , the maps

$$i_0^*, i_1^* : (C_*(\mathcal{F}))(X \times \mathbb{A}^1) \rightarrow (C_*\mathcal{F})(X)$$

are chain homotopic, where  $(C_*\mathcal{F})_n = \mathcal{F}^{\Delta^n}$ .

*Proof.* For any  $i = 0, \dots, n$ , we define

$$\begin{aligned} \theta_i : \Delta^{n+1} &\rightarrow \Delta^n \times \mathbb{A}^1 \\ v_j &\mapsto \begin{cases} (v_i, 0), & 0 \leq j \leq i \\ (v_{j-1}, 1), & i < j \leq n+1 \end{cases} \end{aligned}$$

where  $v_j$  is  $(0, \dots, 0, 1, 0, \dots, 0)$  at the  $j$ th coordinate.<sup>22</sup> Each  $\theta_i$  induces a map

$$h_i = \mathcal{F}(\text{id}_X \times \theta_i) : \mathcal{F}^{\Delta^n}(X \times \mathbb{A}^1) = \mathcal{F}(X \times \mathbb{A}^1 \times \Delta^n) \rightarrow \mathcal{F}^{\Delta^{n+1}}(X) = \mathcal{F}(X \times \Delta^{n+1})$$

Then by using a technique similar to the proof of prism decomposition in topology, we can show that  $s_n = \sum_i (-1)^i h_i$  is a chain homotopy from  $i_1^*$  to  $i_0^*$ , c.f., [Wei94], Lemma 8.3.13.  $\square$

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<sup>22</sup>These are the algebraic analogues of the top-dimensional simplices in the standard simplicial decomposition of the polyhedron  $\Delta^n \times \Delta^1$ , c.f., [MVW06], Definition 2.17.

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