KUNNETH DECOMPOSITIONS FOR QUOTIENT VARIETIES

REZA AKHTAR AND ROY JOSHUA

Abstract. In this paper we discuss Künneth decompositions for finite quotients of several classes of smooth projective varieties. The main result is the existence of a Chow Künneth decomposition for finite quotients of abelian varieties under some mild hypotheses. This applies in particular to symmetric products of abelian varieties and also to certain smooth quotients in positive characteristics which are known to be not abelian varieties, examples of which were considered by Enriques and Igusa. We also establish a strong Künneth decomposition for finite quotients of projective smooth linear varieties.

1. Introduction

Chow-Künneth decompositions are conjectured (at least by optimists) to exist for all smooth projective varieties $X$; at present, they are known to exist (over $\mathbb{Q}$) for curves [MA], surfaces [MUR1], projective spaces [MA], abelian varieties ([D-M]) and other isolated examples. It was shown in [IG] (and perhaps earlier by Enriques) that one may construct quotients of abelian varieties in positive characteristics which are smooth, but nevertheless not abelian varieties. In this paper we show that one may descend a Chow-Künneth decomposition from abelian varieties to their finite quotients under some mild technical hypotheses and thereby obtain explicit formulae for the projectors in these cases. We show our methods apply not only to smooth quotients in positive characteristics considered by Enriques and Igusa, but also to singular quotients (for example, symmetric products of abelian varieties). We also show that strong Künneth decompositions which are known to exist for linear varieties (cf. [TOT]) may be descended to finite quotients of such. This provides a means of computing the higher (rational) Chow groups of such quotient varieties. Needless to say, we work throughout with rational coefficients.

Here is an outline of the paper. In the rest of this section we set up the basic terminology and conventions for the rest of the paper. In particular, we recall the definitions of Chow-Künneth decomposition and strong Künneth decomposition. In the next section we prove the following theorem:

Theorem 1.1. (See Theorem 2.2.) Let $A$ be an abelian variety of dimension $d$ over a field $k$ and $G$ a finite group acting on $A$. Let $f : A \to A/G$ be the quotient map. Suppose $\Delta_A = \sum_{i=0}^{2d} \pi_i$ is a Chow-Künneth decomposition for $A$ and let $\eta_i = \frac{1}{|G|} (f \times f)^* \pi_i$.

Then

$$\Delta_{A/G} = \sum_{i=0}^{2d} \eta_i$$

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is a Chow-Künneth decomposition for $A/G$.

While the techniques are a modification of those of Denninger-Murre [D-M] and also [Be], there are several non-trivial issues that need to be considered as will become clear from the proof. For example: the quotient of the abelian variety by the action of a finite group need not be an abelian variety nor even a non-singular variety. These show that, apriori, there is no analogue of the Poincaré-bundle which plays a key-role in the Denninger-Murre proof for abelian varieties. We first prove the theorem under the hypothesis that for each $g \in G$, $g(0)$ is a torsion point of the abelian variety, but for abelian varieties defined over arbitrary fields: this is equivalent to the hypothesis that the action of the group preserves the torsion points of the abelian variety. Apriori, it is not clear that the above torsion hypothesis is not needed as may be seen from elementary examples. However, we show that this is indeed the case, so that we are able to obtain an explicit formula for the Chow-Künneth projectors for all actions of finite groups on all abelian varieties. We show that this technique provides Chow-Künneth decompositions for a number of interesting examples of non-abelian quotients of abelian varieties as mentioned earlier. One may observe that the existence of such a Chow-Künneth decomposition is guaranteed by the work of Kimura [KI] and [PED] on finite-dimensionality of motives; however, their results do not yield explicit formulae for the projectors, which is one of our main goals.

In the third section, we extend the strong Künneth decomposition to finite quotients of projective smooth linear varieties. The main result is that if $X$ is a variety possessing a strong Künneth decomposition and $f: X \rightarrow Y$ is a finite surjective map, then $Y$ possesses a strong Künneth decomposition which we may describe explicitly in terms of that for $X$. The methods used are all elementary and require little more than the definitions and basic properties of Chow groups. As an application, we describe a strong Künneth decomposition for symmetric products of projective spaces. We also discuss some formal consequences of such a strong Künneth decomposition: we show that a strong Künneth decomposition implies a Chow Künneth decomposition and that the rational higher Chow groups are determined by the rational higher Chow groups of the base field and the rational (ordinary) Chow groups of the given variety.

We discuss, in an appendix, functoriality properties of cohomology theories for pseudo-smooth schemes as well as consequences of the existence of strong Künneth decompositions for the quotient varieties we consider in this paper. The latter discussion is done in a somewhat more general setting so that it applies not only to determine the higher rational Chow groups of finite quotients of projective smooth linear varieties, but also possibly to other situations not considered in the body of the paper.

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Throughout the paper we will fix a field $k$ of arbitrary characteristic and restrict to the category of quasi-projective schemes over $k$. 
1.1. Group Scheme Actions and Quotients. Following the treatment in [MUM], we review some definitions and results related to group scheme actions.

**Definition 1.2.** Let $G$ be a group scheme over a field $k$ with identity section $e : \text{Spec } k \to G$ and multiplication $m : G \times_k G \to G$.

An *action* of $G$ on a scheme $X$ is a morphism $\mu : G \times X \to X$ such that:

1. The composite
   $$X \cong \text{Spec } k \times_k X \xrightarrow{\text{ex} \times 1_X} G \times_k X \xrightarrow{\mu} X$$
   is the identity map.
2. The diagram below commutes:
   $$\begin{array}{ccc}
   G \times_k G \times_k X & \xrightarrow{m \times 1_X} & G \times_k X \\
   \downarrow{1_G \times \mu} & & \downarrow{\mu} \\
   G \times_k X & \xrightarrow{\mu} & X
   \end{array}$$

In the future, we will identify elements $g \in G$ with the morphism $\mu_g : X \to X$ defined by $\mu_g(x) = \mu(g, x)$ and (by abuse of notation) refer to this morphism simply as $g$.

If $G$ is a finite group (= a constant étale finite group scheme) over $k$ acting on a quasi-projective scheme $X$ (also over $k$), there exists a quasi-projective variety $Y$ together with a finite, surjective $G$-invariant morphism $f : X \to Y$ universal for $G$-invariant morphisms $X \to Z$. The scheme $Y$ is called the *quotient* of $X$ by $G$, and is typically denoted $Y = X/G$.

**Definition 1.3.** We say a scheme $X$ is *pseudo-smooth* if it is the quotient of a smooth scheme by the action of a finite group.

1.1.1. Notation and terminology: review of correspondences. In this section we define the category of *rational correspondences* and *rational Chow motives* for pseudo-smooth projective varieties.

Let $k$ be a field and $\mathcal{V}_k$ the category of schemes pseudo-smooth and projective over $k$. If $X, Y$ are objects of $\mathcal{V}_k$ and $X$ has pure dimension $d$, we define the group of *degree $r$ correspondences* from $X$ to $Y$ by $\text{Corr}^r(X, Y) = CH^{d+r}(X \times_k Y) \otimes \mathbb{Q}$, the group of codimension $d+r$ (rational) cycles on $X \times_k Y$ modulo rational equivalence. In general, let $X_1, \ldots, X_n$ be the irreducible components of $X$; we then define $\text{Corr}^r(X, Y) = \bigoplus_{i=1}^n \text{Corr}^r(X_i, Y)$. When $\alpha \in \text{Corr}^r(X, Y)$ and $\beta \in \text{Corr}^s(Y, Z)$, we define their composition $\beta \circ \alpha \in \text{Corr}^{r+s}(X, Z)$ by the formula

$$\beta \circ \alpha = (p_{13})_*(p_{12}^*\alpha \circ p_{23}^*\beta);$$

here $p_{ij}$ represents projection of $X \times_k Y \times_k Z$ on the $i$th and $j$th factors.

One then constructs a new category $\mathcal{M}_k(\mathbb{Q})$, the category of (rational) *Chow motives of pseudo-smooth projective varieties*. The objects of $\mathcal{M}_k(\mathbb{Q})$ are pairs $(X, \pi)$, where $X$ is an object of $\mathcal{V}_k$ of dimension $d$ and $\pi \in \text{Corr}^0(X, X)$ is a *projector*; that is, an element satisfying $\pi \circ \pi = \pi$. For any two Chow motives $(X, \pi)$ and $(Y, \rho)$, one then defines
\[ \text{Hom}_{M_k}((X, \pi), (Y, \rho)) = \bigoplus_{j} \rho \circ \text{Corr}^0(X, Y) \circ \pi. \]

If \( \Delta_X \) is the diagonal of \( X \times_k X \) and \([\Delta_X]\) its class in \( CH^*(X \times_k X) \otimes \mathbb{Q} \), a straightforward computation shows that \( \Delta_X \) is a projector, and furthermore that \( \Delta_X \circ \alpha = \alpha = \alpha \circ \Delta_X \) for any pseudo-smooth projective scheme \( Y \) and \( \alpha \in \text{Corr}^*(X, Y) \). (See Appendix (H.5) for more details.) Thus, there is a functor \( h : \mathcal{V}^{opp} \rightarrow M_k(\mathbb{Q}) \) defined on objects by \( h(X) = (X, \Delta_X) \) and on morphisms by \( h(X_f) = \Gamma_f \), where \( \Gamma_f \in \text{Hom}_{M_k}(h(Y), h(X)) \) is the class of the graph of \( f \). Furthermore, letting \( \biguplus \) denote disjoint union (of schemes), one may define the sum \( \oplus \) and product \( \otimes \) of motives thus:

\[(X, p) \oplus (Y, q) = (X \biguplus Y, p \biguplus q)\]
\[(X, p) \otimes (Y, q) = (X \times Y, p \times q)\]

We denote by \( \mathbb{I} \) the “trivial” motive \( h(\text{Spec } k) \), a neutral element for \( \otimes \), and by \( \mathbb{L} \) the “Lefschetz motive” \((\mathbb{P}^1_k, \mathbb{P}^1_k \times_k \{x\})\); here \( x \in \mathbb{P}^1_k \) is any rational point. Finally, if \( \alpha \in \text{Corr}^*(X, Y) \) is any correspondence, we define its “transpose” \( ^t\alpha = s^*(\alpha) \in \text{Corr}^*(Y, X) \), where \( s : X \times_k Y \rightarrow Y \times_k X \) is the exchange of factors. For further discussion of motives, we refer the reader to [SCH]. Also see [FUL] Example (8.3.12) and Example (16.1.12) for discussion that shows one can in fact define a category of Chow motives for pseudo-smooth schemes as we have done. In fact it is possible to consider the above theory for all smooth Deligne-Mumford stacks over \( k \); some of our results extend to this situation readily.

1.2. Abelian Varieties. In this section we establish notation and cite a rigidity property for abelian varieties necessary in the sequel. A comprehensive treatment of abelian varieties may be found in [MUM] or [MI].

Let \( k \) be a field and \( A \) an abelian variety over \( k \). Following [MI], we denote by \( m : A \times_k A \rightarrow A \) the morphism representing composition on (the group scheme) \( A \) and use additive notation for this (commutative) operation. For any \( a \in A(k) \), we denote by \( \tau_a : A \rightarrow A \) (translation by \( a \)) the map defined by \( \tau_a(x) = x + a \).

A morphism \( f : A \rightarrow B \) between abelian varieties is called a homomorphism if for every \( a, a' \in A \), \( f(a + a') = f(a) + f(a') \). When \( n \in \mathbb{Z} \) we define \( n : A \rightarrow A \) by \( n(a) = na \) and set \( A[n] = \text{Ker}(A \rightarrow A) \), the (group scheme of) \( n \)-torsion points on \( A \). For clarity of notation, we write \( \sigma \) instead of \(-1\).

The following important result is a consequence of a general rigidity principle; see [MI], Corollary 2.2 for details:

**Proposition 1.4.** Let \( h : A \rightarrow B \) be a morphism of abelian varieties. Then there exists a homomorphism \( h_0 : A \rightarrow B \) and an element \( a \in A(k) \) such that \( h = \tau_a \circ h_0 \).
We remark that $h_0$ and $a$ are in fact unique. Indeed, one must have $a = h(0)$; uniqueness of $h_0$ then follows immediately.

Let $\hat{A}$ be the dual abelian variety; we will denote by $L$ the Poincaré bundle and $\ell$ its class in $CH^1_k(A \times_k \hat{A})$.

We conclude this section by recalling the definition of strong Künneth and Chow Künneth decompositions.

**Definition 1.5.** Suppose $X$ is pseudo-smooth (over $k$). We say that $X$ has a *Chow-Künneth decomposition* if there exist elements $\pi_0, \ldots, \pi_{2d} \in CH^d_k(X \times_k X)$ such that:

- $[\Delta_X] = \sum_{i=0}^{2d} \pi_i$
- For every $i$, $\pi_i \circ \pi_i = \pi_i$ and for all $j \neq i$, $\pi_i \circ \pi_j = 0$. (Thus, $\pi_0, \ldots, \pi_{2d}$ form a system of mutually orthogonal projectors).
- Let $H$ be a Weil cohomology theory $H^*$. (cf. [KL]) and, for any $k$-scheme $Y$, let $cl_Y : CH^*_Q(Y) \to H^*(Y)$ denote the cycle map. We require that $cl_{X \times_k X}(\pi) = \Delta^i(i)$, where $\Delta^i$ is the co-dimension $i$ Künneth component of the class of $\Delta_X$ in $H^*(X \times_k X)$. (We will show later that any Weil cohomology theory admits an extension to the category of pseudo-smooth schemes.)

Next let $X$ be any scheme of pure dimension $d$ over a field $k$.

We say that $X$ possesses a *strong Künneth decomposition* if there exist elements $a_{i,j}, b_{i,j} \in CH^i_k(X)$ such that

\[(1.2.1) \quad [\Delta_X] = \sum_i \sum_j a_{i,j} \times b_{d-i,j}\]

Observe that if $X$ is projective, $X$ having a Chow-Künneth decomposition is equivalent to asserting that $h(X) \cong \oplus_{i=0}^{2d} h^i(X)$ where $h^i(X)$ is the motive $(X, \pi_i)$.

2. **Chow-Künneth decomposition for quotients of abelian varieties**

Our goal in this section is to exhibit an explicit Chow-Künneth decomposition for the quotient of an abelian variety $A$ by the action of a finite group $G$, assuming only that $g(0)$ is a torsion point for each $g \in G$. As before, the quotient $A/G$ may be singular. We rely on the following result, originally due to Shermenev [SH], but later proved in a somewhat more functorial setting by Denninger and Murre ([D-M], Theorem 3.1); in this latter source the result is proved more generally for abelian schemes over a smooth quasi-projective base:

**Theorem 2.1.** Let $A$ be an abelian variety of dimension $d$ over a field $k$. Then there exists a Chow-Künneth decomposition for $A$:

\[
\Delta_A = \sum_{i=0}^{2d} \pi_i
\]
Since we need to make explicit use of the projectors $\pi_i$, we will presently review their construction. First, consider $A \times_k A$ as an abelian $A$-scheme via projection on the first factor; with respect to this structure, the dual abelian scheme is $A \times_k \hat{A}$. Consider then the Fourier transform (cf. [D-M], 2.12, [KU], 1.3):

$$F_{CH} : CH^*_\mathbb{Q}(A \times_k A) \longrightarrow CH^*_\mathbb{Q}(A \times_k \hat{A})$$

defined by $F_{CH}(\alpha) = p_{13*}(p_{12}^* \alpha \cdot F)$, where

$$F = 1 \times \sum_{i=0}^{\infty} \frac{t_i}{i!} \in CH^*_\mathbb{Q}(A \times_k A \times_k \hat{A})$$

and the various $p_{ij}$ represent projections from $A \times_k A \times_k \hat{A}$ on the $i$th and $j$th factor. Note that the sum defining $F$ is actually finite.

Dualizing this construction, we may define

$$\hat{F}_{CH} : CH^*_\mathbb{Q}(A \times_k \hat{A}) \longrightarrow CH^*_\mathbb{Q}(A \times_k A)$$

by $\hat{F}_{CH}(\gamma) = q_{13*}(q_{12}^* \gamma \cdot \hat{F})$, where

$$\hat{F} = 1 \times \sum_{i=0}^{\infty} \frac{t_i}{i!} \in CH^*_\mathbb{Q}(A \times_k \hat{A} \times_k A)$$

and $q_{ij}$ represent the various projections from $A \times_k \hat{A} \times_k A$. By switching the last two factors and changing notation appropriately, we see that in fact

$$\hat{F}_{CH}(\gamma) = p_{12*}(p_{13}^* \gamma \cdot F).$$

An argument involving the theorem of the square (cf. [D-M], Cor. 2.22, also [Be], Prop. 3) then shows that $\hat{F}_{CH}(F_{CH}(\alpha)) = (-1)^d \sigma^* \alpha$ for all $\alpha \in CH^*(A \times_k A)$, and similarly for the other composition.

Observe that $[\Delta_A] \in CH^d(A \times_k A)$, and write $F_{CH}([\Delta_A]) = \sum_{i=0}^{2d} \beta_i$, where $\beta_i \in CH^i\mathbb{Q}(A \times_k \hat{A})$. It is a fact ([D-M], p. 214-216) that $(1 \times n)^* \beta_i = n^* \beta_i$. Now define

$$\pi_i = (-1)^d \sigma^* \hat{F}_{CH}(\beta_i)$$

(2.0.2)

Next we proceed to prove the following weakened form of the main theorem:

**Theorem 2.2.** Let $A$ be an abelian variety of dimension $d$ over a field $k$ and $G$ a finite group acting on $A$ such that $g(0) \in A(k)$ is a torsion point for each $g \in G$. Let $f : A \longrightarrow A/G$ be the quotient map. Suppose $\Delta_A = \sum_{i=0}^{2d} \pi_i$ is a Chow-K"unneth decomposition for $A$ and let

$$\eta_i = \frac{1}{|G|} (f \times f)_* \pi_i.$$ 

Then
\[ \Delta_{A/G} = \sum_{i=0}^{2d} \eta_i \]

is a Chow-Künneth decomposition for \( A/G \).

**Remark.**

The hypothesis that \( g(0) \) be a torsion point of \( A \) is not always satisfied. For example, if \( a \in A(k) \) is any point of infinite order, then the automorphism \( g : x \mapsto -x + a \) defines an action of \( \mathbb{Z}/2\mathbb{Z} \) on \( A \) for which \( g(0) = a \) is not a torsion point. However, if \( k \) is an algebraic extension of a finite field, then it is clear that this hypothesis is always satisfied. Observe also that this hypothesis is equivalent to requiring that \( G \) preserves the torsion points of \( A \). This hypothesis seems quite helpful for being able to descend the Chow-Kunneth projectors of the abelian variety \( A \) to its quotient which apriori has no other structure other than that of an algebraic variety. However, we will show later that this hypothesis is not necessary and could be removed.

Our method of proof is based on that of [D-M], Theorem 3.1; however, there are further technicalities which complicate it somewhat. The content of the proof is, of course, to show that the elements \( \frac{1}{|G|} (f \times f)_+ \pi_i, 0 \leq i \leq 2d \), are mutually orthogonal projectors. Unfortunately, \( A/G \) is in general not an abelian variety, so we cannot exploit any special properties of this variety. However, the map \( f^* \) establishes an isomorphism ([FUL], Example 1.7.6):

\[ CH^\ast_Q(A/G) \longrightarrow CH^\ast_Q(A)^G \]

with inverse \( \frac{1}{|G|} f_+ \). (See also (H.0) in the appendix for an explanation of this from the point of view of equivariant Chow groups.) Thus, we will work in the group \( CH^\ast_Q(A)^G \), constructing mutually orthogonal \( G \times G \)-invariant elements which may be descended to elements of \( CH^\ast_Q(A/G) \) by the following device:

**Lemma 2.3.** Suppose \( X \) is a pseudo-smooth projective variety of dimension \( d \) and \( G \) a finite group of automorphisms of \( X \). Let \( f : X \longrightarrow Y = X/G \) be the quotient map and suppose

\[ \sum_{g,h \in G} (g \times h)_+ \Delta_X = \sum_{i=0}^{2d} \rho_i \]

where \( \rho_i \circ \rho_j = 0 \) if \( i \neq j \), \( \rho_i \circ \rho_i = |G|^2 \rho_i \) and the \( \rho_i \) are \( G \times G \)-invariant, i.e. for any \( g, h \in G \), \( (g \times h)_+ \rho_i = \rho_i \).

Then

\[ \Delta_Y = \sum_{i=0}^{2d} \frac{1}{|G|^3} (f \times f)_+ \rho_i \]
is a Chow-Künneth decomposition for $Y$.

Proof.

We have

$$(f \times f)_*(f \times f)^* = |G|^2, \text{ and } \sum_{g,h \in G}(g \times h)^* = (f \times f)^*(f \times f)_*$$

and therefore:

$$|G|^2(f \times f)_*\Delta_X = (f \times f)_* \sum_i \rho_i$$

Hence

$$\Delta_Y = \frac{1}{|G|^3} \sum_i (f \times f)_*\rho_i$$

It remains to show that $\frac{1}{|G|^3}(f \times f)_*\rho_i$ are mutually orthogonal idempotents. As in Proposition 3.4, we add subscripts and superscripts to $p$ (respectively, $q$) to denote the various projections between products of $X$ (respectively, $Y$), and for convenience of notation set $r = (f \times f) : X \times_k X \times_k X \longrightarrow Y \times_k Y \times_k Y$. Now,

$$\text{(2.0.3)} \quad (f \times f)_*\rho_i \circ (f \times f)_*\rho_j = q_{12}^{123}_* (q_{12}^{123}_*(f \times f)_*\rho_i \cdot q_{23}^{123}_*(f \times f)_*\rho_j)$$

Since the degree of $r$ is $|G|^3$, $r_*r^*$ corresponds to multiplication by $|G|^3$, and therefore, the last expression equals:

$$\text{(2.0.4)} \quad \frac{1}{|G|^3} q_{12}^{123}_* (r_*r^* q_{12}^{123}_*(f \times f)_*\rho_i \cdot q_{23}^{123}_*(f \times f)_*\rho_j)$$

Finally, because $q_{12}^{123} \circ r = (f \times f) \circ p_{12}^{123}$, the above simplifies to

$$\frac{1}{|G|^3} q_{12}^{123}_* (r_*p_{12}^{123}_*(f \times f)^*(f \times f)_*\rho_i \cdot q_{23}^{123}_*(f \times f)_*\rho_j)$$

Because the $\rho_i$ are $G \times G$-invariant, we have $(f \times f)^*(f \times f)_*$ is multiplication by $|G|^2$, so the expression equals:

$$\frac{1}{|G|^3} q_{12}^{123}_* (r_*p_{12}^{123}_* |G|^2 \rho_i \cdot q_{23}^{123}_*(f \times f)_*\rho_j)$$

Finally, applying the projection formula, the formula $q_{12}^{123} \circ r = (f \times f) \circ p_{12}^{123}$ and $(G \times G)$-invariance of the $\rho_i$, one may identify the last expression with:

$$\frac{1}{|G|} q_{12}^{123}_* r_* (p_{12}^{123}_* \rho_i \cdot r^* q_{23}^{123}_*(f \times f)_*\rho_j) = \frac{1}{|G|} (f \times f)_* p_{12}^{123}_* (p_{12}^{123}_* \rho_i \cdot p_{23}^{123}_*(f \times f)^*(f \times f)_*\rho_j)$$

$$= |G|(f \times f)_* p_{12}^{123}_* (p_{12}^{123}_* \rho_i \cdot p_{23}^{123}_* \rho_j)$$

$$= |G|(f \times f)_*(\rho_i \circ \rho_j) = 0, \quad i \neq j$$
The last equality is by our assumption on the $\rho_i$s. If $i = j$, then this equals $|G|^3(f \times f)_*(\rho_i)$ again by our assumption. In [D-M], the crucial step in the proof of the Chow-Künneth decomposition for abelian varieties is the following computation, which may be proved using the seesaw theorem ([MI], Corollary 5.2):

**Proposition 2.4.** ([D-M], 2.15)

For any integer $n$,

$$(1 \times n)^* \ell = n \ell$$

The analogous strategy in our context would seem to be to study the action of $(1 \times n)^*$ on $(g \times h)^* \ell$; however, the induced action by $G$ on $\hat{A}$ is by pulling back line bundles by elements of $G$. Therefore, the induced action by elements of $G$ on $\hat{A}$ is by homomorphisms and hence on double-dualizing this provides an action on $A$ which differs from the original action unless $G$ acts by homomorphisms on $A$ to begin with. (i.e. If $G$ acts on $A$ “by isogenies”; that is, if all of the maps $g : \hat{A} \rightarrow A$ are in fact homomorphisms of $A$, then duality gives a natural action of $G$ on $\hat{A}$, but we are not assuming this). Instead, we rely on the fact ([MI], p.119) that the Poincaré bundle on $\hat{A} \times_k A$ is the transpose of the Poincaré bundle on $A \times_k \hat{A}$. Hence:

$$\text{(2.0.5)} \quad (n \times 1)^* \ell = t((1 \times n)^* t \ell) = t(n t \ell) = n \ell$$

and we prove the following:

**Proposition 2.5.** There is an infinite subset $E \subset \mathbb{N}$ such that for all $n \in E$ and all $g \in G$:

$$\text{(g \times 1).}(n \times 1) = (n \times 1).\text{(g \times 1)}, \quad \text{and}$$

$$\text{(2.0.6)} \quad (n \times 1)^*(g \times 1)^* \ell = n(g \times 1)^* \ell$$

Moreover, one has:

$$\text{(2.0.7)} \quad (n \times 1)^*(g \times 1)^* (\tau_{-2g(0)} \times 1)^* \ell = n(g \times 1)^* (\tau_{-2g(0)} \times 1)^* \ell$$

**Proof.** For each $g \in G$, write $g = a_g \circ g_0$ as in Proposition 1.4. Let $m_g$ be the order of $a_g = g(0)$; this is guaranteed to be finite by our hypothesis. Next, let $m = \prod_{g \in G} m_g$, and $E = \{n \in \mathbb{N} : n \equiv 1(\text{mod } m)\}$.

Note that if $n \in E$, $m_g$ divides $n - 1$ (for any $g$), so $na_g = a_g$.

Now, if $n \in E$, we have

$$\text{(2.0.8)} \quad (g \times 1).\text{(n \times 1)} = (\tau_{a_g} \times 1).\text{(g_0 \times 1).}(n \times 1)$$

Since $g_0$ is a homomorphism, $n \circ g_0 = g_0 \circ n$; therefore the last expression equals $(\tau_{a_g} \times 1).\text{(n \times 1)}.(g_0 \times 1)$. Since $a_g = na_g$, this equals $(n \times 1).\text{(n \times 1)}.(g_0 \times 1) = (n \times 1).(g \times 1)$. This proves the first equality in the proposition.
Therefore,
\[(n \times 1)^*(g \times 1)^*\ell = (g_0 \times 1)^* (\tau_{a_g} \times 1)^*(n \times 1)^*\ell\]

By (2.0.5) the last term equals,
\[n(g_0 \times 1)^* (\tau_{a_g} \times 1)^*\ell = n(g \times 1)^*\ell\]

This completes the proof of the first statement. The second follows similarly.

The next step in the proof of Theorem 2.2 is to construct the elements \(\rho_i\) appearing in Lemma 2.3; for each \(i\), we simply set
\[\rho_i = \sum_{g,h \in G} (g \times h)^* \pi_i\]
where \(\pi_i\) are the Chow-Künneth components of \(\Delta_A\) from Theorem 2.1. It is clear from the formula that the \(\rho_i\) are \(G \times G\)-invariant and that \(\sum_{i=0}^{2d} \rho_i = \sum_{g,h \in G} (g,h)^* \Delta_A\); so it remains to prove that they are mutually orthogonal. In preparation for this, we study the action of \((1 \times n)^*\) on \(\rho_i\):

**Proposition 2.6.** For \(n \in E\), \((1 \times n)^*(g \times h)^* \pi_i = n^{2d-i}(g \times h)^* \pi_i\). Hence, \((1 \times n)^* \rho_i = n^{2d-i} \rho_i\).

**Proof.** Observe that \((1 \times n)^*(g \times h)^* \pi_i = (1 \times n)^*(g \times 1)^*(1 \times h)^* \pi_i = (g \times 1)^*(1 \times n)^*(1 \times h)^* \pi_i\), so it suffices to consider the case \(g = 1\).

We recall the construction of \(\pi_i\) from (2.0.2):
\[(1 \times n)^*(1 \times h)^* \pi_i = (-1)^d (1 \times n)^*(1 \times h)^* \sigma^* \hat{F}_{CH}(\beta_i)\]

One may verify, by writing \(h = \tau_{h_0} \circ h_0\) as in the proof of the last proposition, that \(\sigma \circ (1 \times h) = (1 \times \tau_{-2h_0}) \circ (1 \times h) \circ \sigma\). Therefore, using the definition of \(\hat{F}_{CH}\) the last expression identifies with:
\[= (-1)^d \sigma^* (1 \times n)^*(1 \times h)^*(1 \times \tau_{-2h_0})^* p_{12,4} (p_{13}^* \beta_i \cdot (1 \times \sum_{i=0}^{\infty} \frac{(\ell \mu)}{\mu!}))\]

Since \(\hat{F}_{CH}(\beta_i)\) has degree \(d\), one may readily see that all terms in \(\hat{F}_{CH}(\beta_i)\) (and hence in the expression above) except for \(\mu = 2d - i\) are trivial (see, for example, [D-M] Lemma 2.8 and Theorem 2.19). Next, in view of the Cartesian square
\[
\begin{array}{ccc}
A \times_k A \times_k A & \xrightarrow{p_{12}} & A \times_k A \\
(1 \times \tau_{-2h_0} \times 1) \circ (1 \times h \times 1) & \downarrow & (1 \times \tau_{-2h_0}) \circ (1 \times h) \\
A \times_k A \times_k A & \xrightarrow{p_{12}} & A \times_k A
\end{array}
\]
the above expression becomes:
\[
(-1)^d \sigma^*(1 \times n)^* p_{12*}(1 \times h \times 1)^*(1 \times \tau_{-2h(0)} \times 1)^* (p_{13}^* \beta_i \cdot (1 \times \frac{(2d-i)}{(2d-i)!}))
\]

Now using another Cartesian square
\[
\begin{array}{c}
A \times_k A \times_k \hat{A}^p \rightarrow A \times_k A \\
\downarrow 1 \times n \times 1 \downarrow 1 \times n \\
A \times_k A \times_k \hat{A}^p \rightarrow A \times_k A
\end{array}
\]
this equals
\[
(-1)^d \sigma^* p_{12*}(1 \times n \times 1)^*(1 \times h \times 1)^*(1 \times \tau_{-2h(0)} \times 1)^* (p_{13}^* \beta_i \cdot (1 \times \frac{(2d-i)}{(2d-i)!}))
\]

Since \( p_{13}^* \) leaves the second factor unchanged, this expression identifies with:
\[
(-1)^d \sigma^* p_{12*}(p_{13}^* \beta_i \cdot (1 \times n \times 1)^*(1 \times h \times 1)^*(1 \times \tau_{-2h(0)} \times 1)^* (1 \times \frac{(2d-i)}{(2d-i)!}))(n \times 1)^*(h \times 1)^*(\tau_{-2h(0)} \times 1)^*(\ell^{2d-i}))
\]

By the second statement in Proposition 2.5 the last term is given by
\[
(2.0.11) \quad n^{2d-i} (-1)^d \sigma^* p_{12*}(p_{13}^* \beta_i \cdot (1 \times \frac{1}{(2d-i)!}))(h \times 1)^*(\tau_{-2h(0)} \times 1)^*(\ell^{2d-i}))
\]

By applying the same steps above in essentially the opposite order one obtains the identification of the last expression with (observe again that all terms except the one with \( \mu = 2d - i \) are trivial):
\[
\begin{align*}
& n^{2d-i} (-1)^d \sigma^* p_{12*}(p_{13}^* \beta_i \cdot (1 \times h \times 1)^*(1 \times \tau_{-2h(0)} \times 1)^* (1 \times (\sum_{\mu=0}^{\infty} \frac{(\ell^\mu)}{\mu!}))) \\
& = n^{2d-i} (-1)^d \sigma^* p_{12*}(1 \times h \times 1)^*(1 \times \tau_{-2h(0)} \times 1)^* (p_{13}^* \beta_i \cdot (1 \times (\sum_{\mu=0}^{\infty} \frac{(\ell^\mu)}{\mu!}))) \\
& = n^{2d-i} (-1)^d \sigma^* (1 \times h)^*(1 \times \tau_{-2h(0)})^* p_{12*}(p_{13}^* \beta_i \cdot (1 \times (\sum_{\mu=0}^{\infty} \frac{(\ell^\mu)}{\mu!}))) \\
& = n^{2d-i} (1 \times h)^* (1 \times h)^* \pi_i
\end{align*}
\]

To prove orthogonality of the \( \rho_i \), we need a version of Liebermann’s trick (cf. [D-M], Proof of Theorem 3.1); first we prove the following simple lemma:

**Lemma 2.7.** For every \( g, h \in G \), \( \rho_j \circ (g \times h)^* \Delta_A = \rho_j \).
Proof.
Certainly the lemma is true if $g = h = 1$. In the general case,

\[(2.0.12)\]

\[\rho_j \circ (g \times h)^* \Delta_A = p_{13*}(p_{12}^*(g \times h)^* \Delta_A \cdot p_{23}^* \rho_j) = p_{13*}((g \times h \times 1)^* p_{12}^* \Delta_A \cdot p_{23}^* \rho_j) = (g \times 1)^* p_{13*}(p_{12}^* \Delta_A \cdot p_{23}^*(h^{-1} \times 1)^* \rho_j)\]

Since $\rho_j$ is $G \times G$-invariant the last term equals

\[(g \times 1)^* p_{13*}(p_{12}^* \Delta_A \cdot p_{23}^* (h^{-1} \times 1)^* \rho_j) = (g \times 1)^* (\rho_j \circ \Delta_A) = (g \times 1)^* (\rho_j) = \rho_j\]

Proposition 2.8. (Liebermann’s trick) For every $i, j, i \neq j$, $\rho_i \circ \rho_j = 0$.
Proof. Suppose $n \in E$. By Proposition 2.6,

\[n^{2d-j} \rho_j = (1 \times n)^* \rho_j = (1 \times n)^* (\rho_j \circ \Delta_A)\]

By Lemma 2.7, the last term equals

\[\frac{1}{|G|^2} (1 \times n)^*(\rho_j \circ \sum_{g,h} (g \times h)^* \Delta_A) = \frac{1}{|G|^2} (1 \times n)^*(\rho_j \circ \sum_{i=0}^{2g} \rho_i) = \frac{1}{|G|^2} \sum_{i=0}^{2d} (1 \times n)^* p_{13*}(p_{12}^* \rho_j \cdot p_{23}^* \rho_i) = \frac{1}{|G|^2} \sum_{i=0}^{2d} p_{13*}(1 \times 1 \times n)^* (p_{12}^* \rho_j \cdot p_{23}^* \rho_i) = \frac{1}{|G|^2} \sum_{i=0}^{2d} p_{13*}(p_{12}^* \rho_j \cdot p_{23}^*(1 \times n)^* \rho_i) = \frac{1}{|G|^2} \sum_{i=0}^{2d} n^{2d-i} (\rho_j \circ \rho_i)\]

Hence

\[n^{2d-j} ((\rho_j \circ \rho_j) - |G|^2 \rho_j) + \sum_{i \neq j} n^{2d-i} (\rho_i \circ \rho_j) = 0\]

for all $n \in E$. Since $E$ is infinite, this forces $\rho_i \circ \rho_j = 0$ for all $i \neq j$, and also $\rho_j \circ \rho_j = |G|^2 \rho_j$.

This final step in the proof of Theorem 2.2 is to show that the images of the $\eta_i$ under the cycle map $cl_{A/G \times k A/G} : C^*(A/G \times k A/G) \longrightarrow H^*(X/G \times k X/G)$ to any Weil cohomology
theory are in fact the Künneth components of the class of the diagonal. This follows easily from the analogous fact for the variety $A$ and commutativity of the following diagram:

\[
\begin{array}{ccc}
CH^*_Q(A \times_k A) & \xrightarrow{\text{cl}_{A \times_k A}} & H^*(A \times_k A) \\
\downarrow{(f \times_k f)_*} & & \downarrow{(f \times_k f)_*} \\
CH^*_Q(A/G \times_k A/G) & \xrightarrow{\text{cl}_{A/G \times_k A/G}} & H^*(A/G \times_k A/G)
\end{array}
\]

Here we will show that any Weil cohomology theory, $H^*$, extends to pseudo-smooth schemes and show that the above square commutes. First observe that if $G$ is a finite group acting on a smooth scheme $X$, each $g \in G$ acts on $X$ as an automorphism: therefore, the action of $G$ on $X$ induces an action on the given Weil cohomology theory applied to $X$, i.e. on $H^*(X)$. Since $H^n(X)$ are all vector spaces over a field of characteristic 0, one obtains a decomposition of $H^*(X)$ into irreducible representations of $G$. One defines $H^*(X/G)$ to be $H^*(X)^G$. Corresponding assertions also hold for the rational Chow groups.

Observe that if $f : X \to X/G$ is the quotient map, one may identify $f_* : CH^*_Q(X) \to CH^*_Q(X/G)$ ($f_* : H^*(X) \to H^*(X/G)$) with the projection $CH^*_Q(X) \to CH^*_Q(X)^G$ (the projection $H^*(X) \to H^*(X)^G$, respectively). Since the cycle map commutes with group action, one can now see that it commutes with $f_*$: we obtain the commutativity of the square above.

This concludes the proof of Theorem 2.2.

Among the formulae proved by Künnemann is the so-called Poincaré duality for abelian varieties ([KU], Theorem 3.1.1 (iii)); in our notation, this reads $\pi_{2d-i} = ^t\pi_i$ for each $i$. This fact immediately implies the analogue for quotients:

**Corollary 2.9. (Poincaré duality for quotients)** The Chow-Künneth decomposition for $A/G$ of Theorem 2.2 satisfies Poincaré duality; that is, for any $i$, $\eta_{2d-i} = ^t\eta_i$.

Next we proceed to show that the torsion hypothesis in Theorem 2.2 may be removed. This will follow from the sequence of results considered below.

Let $G$ denote a finite group and let $M$ denote an abelian group that is a $G$-module. Now recall that a derivation $d : G \to M$ is a function $d$ so that $d(g_1.g_2) = dg_1 + g_1 \circ dg_2$ where $\circ$ denotes the $G$-action on $M$. Given a fixed element $m \in M$, an inner derivation associated to $m$ is the map $d : G \to M$ defined by $d(g) = g \circ m - m, \ g \in G$. Clearly every inner derivation is a derivation. We will denote the set of all derivations of $G$ in $M$ (the set of all inner derivations of $G$ in $M$) by $\text{Der}(G, M)$ ($\text{IDer}(G, M)$, respectively). It is well-known that one has the isomorphism (see, for example:[HS]):

\[(2.0.13) \quad H^1(G, M) = \text{Der}(G, M)/\text{IDer}(G, M)\]

It follows readily from this isomorphism that if $M$ is torsion, then so is $H^1(G, M)$. Next recall that if $A$ is an Abelian variety defined over the field $k$ and $G$ acts on $A$, one has an induced
action on \( A(k) \). We will denote the given action of \( G \) on \( A \) by \( \mu \). For each \( g \in G \), the action of \( g \) on \( A(k) \) is given by translation by \( g(0) \) composed with a homomorphism of Abelian varieties which we will denote by \( g_h \).

2.0.14. Moreover, the assignment \( g \mapsto g_h \) followed by the action of \( g_h \) on \( A \) defines a new action of \( G \) on \( A \), which we will denote by \( \mu_h \).

**Lemma 2.10.** Assume the above situation. Then \( \mu \) defines a derivation of \( G \) in the \( G \)-module \( A(k) \) where this \( G \)-module structure is provided by the action \( \mu_h \).

**Proof.** One simply observes that \( \mu \) satisfies the defining property of a derivation when \( G \)-acts on \( A(k) \) through \( \mu_h \).

**Proposition 2.11.** Assume the above situation. Then \( H^1(G, A(k)) \) is torsion where \( G \) acts on \( A(k) \) through \( \mu_h \).

**Proof.** Let \( A(k)_{\text{tors}} \) denote the torsion sub-module of \( A(k) \). When \( G \) acts on \( A \) through \( \mu_h \), it is clear that the \( G \)-action preserves the torsion points so that \( A(k)_{\text{tors}} \) is a \( G \)-module. By our observation above, \( H^1(G, A(k)_{\text{tors}}) \) is torsion.

The short-exact sequence \( 0 \rightarrow A(k)_{\text{tors}} \rightarrow A(k) \rightarrow A/A(k)_{\text{tors}} \rightarrow 0 \) provides a long-exact sequence

\[
\cdots \rightarrow H^1(G, A(k)_{\text{tors}})^{\alpha} \rightarrow H^1(G, A(k))^{\beta} \rightarrow H^1(G, A/A(k)_{\text{tors}}) \rightarrow \cdots
\]

This provides the short-exact sequence: \( 0 \rightarrow \text{Image}(\alpha) = \ker(\beta) \rightarrow H^1(G, A(k)) \rightarrow \text{Image}(\beta) \rightarrow 0 \). \( \text{Image}(\alpha) \) is torsion since \( A(k)_{\text{tors}} \) is torsion. Therefore, the conclusion of the proposition will follow once we show that \( H^1(G, A(k)/A(k)_{\text{tors}}) \) is torsion.

If the field \( k \) is algebraically closed, \( A(k) \) is divisible; the divisibility of \( A(k) \) shows that \( A(k)/A(k)_{\text{tors}} \) is a \( \mathbb{Q} \)-vector space and hence \( H^1(G, A(k)/A(k)_{\text{tors}}) = 0 \) in this case. In general, any given class \( \alpha \in H^1(G, A(k)/A(k)_{\text{tors}}) \) maps to zero in \( H^1(G, A(L)/A(L)_{\text{tors}}) \) where \( L \) is a finite extension of \( k \) (depending on \( \alpha \)). It suffices to show that then some integral multiple of \( \alpha \) itself is zero in \( H^1(G, A(k)/A(k)_{\text{tors}}) \). The conclusion that \( H^1(G, A(k)/A(k)_{\text{tors}}) \) is torsion follows from this and hence the proposition.

2.0.16. Let \( \alpha \in H^1(G, A(k)/A(k)_{\text{tors}}) \) map to zero in \( H^1(G, A(L)/A(L)_{\text{tors}}) \) where \( L \) is a finite extension of \( k \) (depending on \( \alpha \)). We proceed to show that then some integral multiple of \( \alpha \) itself is zero in \( H^1(G, A(k)/A(k)_{\text{tors}}) \).

First of all since finite radical extensions of the base field do not change the rational Chow groups we may assume without loss of generality that the base field \( k \) is its own radical closure (in an algebraic closure \( \bar{k} \) of \( k \)). Therefore it suffices to consider the case where \( L \) is a finite separable extension which is in fact a Galois extension of \( k \). Let \( H = Gal(L/k) \) be the Galois group of \( L \) over \( k \). The group \( H \) acts on \( A(L) \) on the right as follows. Suppose \( x \in A(L) \); that is, \( x \) is a \( k \)-morphism \( x : \text{Spec} \ L \rightarrow A \). If \( \sigma \) is an element of \( H \), we also denote by \( \sigma \) the naturally
induced morphism of Spec $k$-schemes $\text{Spec} \ L \to \text{Spec} \ L$. We let $x \cdot \sigma = x \circ \sigma$ where $\circ$ denotes the composition of maps.

Recall the group structure on $A(L)$: if $x : \text{Spec} \ L \to A$ and $y : \text{Spec} \ L \to A$ are two elements of $A(L)$, there is a naturally induced map $x \times y : \text{Spec} \ L \to A \times A$, which may then be composed with group law $\mu$ on $A$ to give the sum $x + y : \text{Spec} \ L \to A$. It is equally clear from this definition that for any $\sigma \in H$, $(x + y) \cdot \sigma = x \cdot \sigma + y \cdot \sigma$. In particular $(nx) \cdot \sigma = n(x \cdot \sigma)$ so that the above action of $H$ preserves the torsion points in $A(L)$.

Now we proceed to define a Norm map $N_{L/k} : A(L) \to A(k)$. For $x \in A(L)$, define $N_{L/k}(x) = \sum_{\tau \in H} \tau \cdot x$, where the sum is the group sum in $A(L)$.

**Lemma 2.12.** Then the following hold:

(i) $N_{L/k}(x) : \text{Spec} \ L \to A$ factors through a map $\tilde{N}_{L/k} : \text{Spec} \ k \to A$, i.e. if $i : k \hookrightarrow L$ is the inclusion, then there is a commutative diagram:

$$
\begin{array}{ccc}
\text{Spec} \ L & \xrightarrow{N_{L/k}(x)} & A \\
& i^* & \downarrow \\
\text{Spec} \ k & \xrightarrow{N_{L/k}(x)} & A
\end{array}
$$

(ii) if $x \in A(L)$ is a torsion point, then so is $N_{L/k}(x)$

(iii) if $i : \text{Spec} \ L \to \text{Spec} \ k$ denotes the obvious map corresponding to the inclusion $k \subseteq L$ and the corresponding induced map $A(k) \to A(L)$ is denoted $i^*$, the composition $N_{L/k} \circ i^* = \text{multiplication by the order of } H$.

**Proof.** To prove (i), it suffices to show that the map $N_{L/k}(x)^* : \kappa(P_x) \to L$ on residue fields induced by $N_{L/k}(x)$ has image contained in $k$. Since $k = L^H$ (the subfield of $L$ fixed by $H$), this reduces to showing that $\sigma \circ N_{L/k}(x)^* = N_{L/k}(x)^*$ for all $\sigma \in H$. However, this is tantamount to showing that $\sigma \cdot N_{L/k}(x) = N_{L/k}(x)$ for all $\sigma \in H$. This is clearly true, because $\sigma \cdot N_{L/k}(x) = \sum_{\tau \in H} \tau \cdot x = \sum_{\tau \in H} \sigma \cdot (\tau \cdot x) = N_{L/k}(x)$. This proves (i). The second statement follows from the observation that $N_{L/k}(x + y) = N_{L/k}(x) + N_{L/k}(y)$, so that $N_{L/k}$ is also additive. The last statement is clear. This concludes the proof of the lemma.

Next observe that the $G$-action on $A$ considered in (2.0.14) induces an action of $G$ on $A(L)$: if $x : \text{Spec} \ L \to A$ is an element of $A(L)$ and $g \in G$, $g(x)$ will denote the composition $\text{Spec} \ L \xrightarrow{\sigma} A \xrightarrow{g} A$. i.e. $g(x)$ is obtained by composing with $g$ on the right. Since the action of $h \in H$ on $A(L)$ is by precomposing with $x$ (i.e. composing with $x$ on the left), it is clear that the $G$ and $H$ actions on $A(L)$ commute. i.e. The norm map $N_{L/k} : A(L)/A(L)_{\text{tors}} \to A(k)/A(k)_{\text{tors}}$ is a map of $G$-modules. Therefore, the norm map $N_{L/k}$ induces a map $N_{L/k*} : H^1(G, A(L)/A(L)_{\text{tors}}) \to H^1(G, A(k)/A(k)_{\text{tors}})$.
Let $i_* : H^1(G, A(k)/A(k)_{\text{tors}}) \to H^1(G, A(L)/A(L)_{\text{tors}})$ denote the map induced by the inclusion $k \subseteq L$. The above arguments show that the composition $\mathcal{N}_{L/k} \circ i_*$ is multiplication by the order of $H$. This proves the assertion in 2.0.17 and completes the proof of the proposition.

**Proposition 2.13.** Let $\bullet : G \times A \to A$ denote the action of a finite group on an abelian variety $A$ defined over an algebraically closed field $k$. Then there exists a point $a \in A$ so that the new action of $G$ on $A$ defined by $(g, b) \mapsto g \cdot a = g \circ T_a(b)$ satisfies the torsion hypothesis in Theorem 2.2. Here $A = A(R)$, where $R$ is any $k$-algebra, $T_a$ denotes the translation by $a \in A(k)$ and $\cdot$ denotes composition. Moreover the geometric quotients of $A$ by $G$ for the actions $\bullet$ and $\bullet_a$ are isomorphic.

**Proof.** In view of the last proposition, observe that there exists a point $a \in A(k)$ so that

$$(2.0.17) \quad g(0) - g_h(a_0) + a \text{ is torsion for all } g \in G$$

Moreover $g \mapsto g(0) - g_h(a_0) + a = g_a(0)$ is a 1-cocycle so that one may define a new action of $G$ on $A(R)$ by $(g, b) \mapsto g_a(0) + g_h(b), b \in A(R)$, for any $k$-algebra $R$. Observe that $T_a \circ g \circ T_{-a}(b) = a + g_h(b - a) + g(0) = g(0) - g_h(a) + a + g_h(b) = g_a(0) + g_h(b)$ for any $b \in A(R)$. Therefore the new $G$-action defined above satisfies the torsion hypothesis of Theorem 2.2.

The last statement of the Proposition follows from the commutative square:

$$
\begin{array}{ccc}
G \times A & \xrightarrow{\bullet} & A \\
\downarrow{\text{id} \times T_a} & & \downarrow{T_a} \\
G \times A & \xrightarrow{\bullet_a} & A \\
\end{array}
$$

### 2.1. Proof of the main theorem.

In view of the last proposition, if the torsion hypothesis in Theorem 2.2 is not satisfied by the given $G$-action, one may replace that action by the above modified action. Then the quotient schemes are isomorphic and the new action satisfies the torsion hypothesis of Theorem 2.2. This completes the proof of the theorem 1.1.

### 2.2. Examples.

1. **Symmetric products of abelian varieties** Let $X$ denote an abelian variety and $X^n/\Sigma_n$ the $n$-fold symmetric power of $X$. Observe that for every $\sigma \in \Sigma_n$, $\sigma(0, \cdots, 0) = (0, \cdots, 0)$. Therefore the hypotheses of Theorem 2.2 are satisfied irrespective of the base field $k$. Therefore, we obtain a Chow Kunneth decomposition for $X^n/\Sigma_n$. (Observe that the action of $\Sigma_n$ is not in general free so that the quotient $X^n/\Sigma_n$ is only pseudo-smooth and not smooth.)

2. **Example of Igusa** (See [IG]) Let $X$ be an elliptic curve (or more generally any abelian variety) over $k$, with $\text{char}(k) \neq 2$. Let $t$ denote a point of order 2 on $X$. Define an action of $\mathbb{Z}/2\mathbb{Z}$ on $X \times X$ by $(x, y) \mapsto (x + t, -y)$, and let $Y$ denote the quotient variety for this action. Now one may see easily that the action is free so that $Y$ is smooth. Nevertheless, in positive characteristic, $Y$ need not be an abelian variety as is shown in [IG]. Theorem 2.2 provides a Chow Kunneth decomposition for $Y$. 
3. The strong K"unneth decomposition for finite quotients

Now suppose $X$ is a pseudo-smooth, projective, equidimensional scheme over a field $k$ and $G$ a finite group of automorphisms of $X$. As in [MUM], we may form the quotient variety $Y = X/G$ and ask whether an explicit strong K"unneth decomposition for $X$ may be used to construct a strong K"unneth decomposition for $Y$. We answer this question in the affirmative below.

First we consider an elementary calculation showing that strong K"unneth decompositions are preserved under finite maps.

**Proposition 3.1.** Let $X$ and $Y$ be pseudo-smooth proper varieties and $f : X \longrightarrow Y$ a finite surjective map. If $X$ has a strong K"unneth decomposition, then $Y$ also has a strong K"unneth decomposition.

**Proof.**
Let $d = \dim X$, $m = \deg f$. The hypothesis that $X$ has a strong K"unneth decomposition allows us to write

$$\Delta_X = \sum_i \sum_j a_{i,j} \times b_{d-i,j}$$

where as before $a_{i,j}, b_{d-i,j} \in \text{CH}^i \mathbb{Q}(X)$. Furthermore, $(f \times f)^* \Delta_X = m \Delta_Y$, so it suffices to prove that $(f \times f)^* (a_{i,j} \times b_{d-i,j}) = f^* (a_{i,j}) \times f^* (b_{d-i,j})$. This is accomplished by the next lemma, whose proof is immediate.

**Lemma 3.2.** Let $f : X \longrightarrow Y$ be a morphism of pseudo-smooth varieties

1. If $f$ is proper, then for all $\alpha, \beta \in \text{CH}^* \mathbb{Q}(X)$, $f^*(\alpha \times \beta) = f^*(\alpha) \times f^*(\beta)$.
2. For all $\gamma, \delta \in \text{CH}^* \mathbb{Q}(Y)$, $f^*(\gamma \times \delta) = f^*(\gamma) \times f^*(\delta)$.

We note the following as a special case:

**Corollary 3.3.** Let $X$ be a pseudo-smooth quasi-projective variety, $G$ a finite group of automorphisms of $X$. If $X$ possesses a strong K"unneth decomposition, so does $Y = X/G$.

The utility of the previous statements becomes evident from the following easy result:

**Proposition 3.4.** Let $X$ be a pseudo-smooth projective variety possessing a strong K"unneth decomposition. Then $X$ has a Chow-K"unneth decomposition.

**Proof.**
Suppose $\Delta_X = \sum_{i=0}^{d} \sum_j a_{i,j} \times b_{d-i,j}$, where $a_{i,j}, b_{d-i,j} \in \text{CH}^i \mathbb{Q}(X)$. For $0 \leq r \leq d$, set $\pi_r = \sum_j a_{r,j} \times b_{d-r,j}$ and for $d+1 \leq r \leq 2d$, set $\pi_r = 0$. Then $\Delta_X = \sum_{r=0}^{2d} \pi_r$. We decorate $p$ with subscripts and superscripts to denote the various projectors from and to subfactors of $X \times_k X \times_k X$; for example, $p_{13}^{23} : X \times_k X \times_k X \longrightarrow X \times_k X$ sends $(x, y, z)$ to $(x, z)$, etc. Finally, we let $\sigma : X \longrightarrow \text{Spec} \ k$ and $\tau : X \times_k X \longrightarrow \text{Spec} \ k$ denote the respective structure maps. We claim that $\pi_r \circ \pi_s = 0$ when $r \neq s$ and $\pi_r \circ \pi_r = \pi_r$ for all $r$, $0 \leq r \leq 2d$. The first equality is a consequence of the following more general fact proved in Lemma 3.5 (below). To conclude the proof of Proposition 3.4, we calculate:
\[ \pi_r \circ \pi_r = (\Delta_X - \sum_{s \neq r} \pi_s) \circ \pi_r = \Delta_X \circ \pi_r = \pi_r \]

**Lemma 3.5.** With notation as above, suppose \( a_r \in CH^r(X), b_{d-r} \in CH^{d-r}(X), a_s \in CH^s(X), b_s \in CH^{d-s}(X) \), and set \( \gamma_r = a_r \times b_{d-r}, \gamma_s = a_s \times b_{d-s} \). If \( r \neq s \), then \( \gamma_s \circ \gamma_r = 0 \).

**Proof.**

\[ \gamma_s \circ \gamma_r = p_{13}^{123} \cdot (p_{12}^{123} \cdot \gamma_r \cdot p_{23}^{123} \cdot \gamma_s) \]

\[ = \sum_j p_{13}^{123} \cdot (p_{12}^{123} \cdot (p_1^{123} a_r \cdot p_2^{123} b_{d-r}) \cdot p_{23}^{123} \cdot (p_2^{23} a_s \cdot p_3^{23} b_{d-s})) \]

\[ = p_{13}^{123} \cdot (p_{12}^{123} \cdot (p_1^{13} a_r \cdot p_3^{13} b_{d-s}) \cdot p_2^{123} \cdot (p_2^{23} a_s \cdot b_{d-r})) \]

\[ = p_{13}^{123} \cdot (p_1^{13} a_r \cdot p_3^{13} b_{d-s} \cdot p_{13}^{123} \cdot p_2^{123} \cdot (a_s \cdot b_{d-r})) \]

\[ = p_{13}^{123} \cdot (p_1^{13} a_r \cdot p_3^{13} b_{d-s} \cdot \tau^* \sigma_s (a_s \cdot b_{d-r})) \]

Note that \( \sigma_s (a_s \cdot b_{d-r}) \in CH^{s-r}(X) \), so if \( r \neq s \), then \( \sigma_s (a_s \cdot b_{d-r}) = 0 \), and hence \( \gamma_s \circ \gamma_r = 0 \). This concludes the proof of Lemma 3.5.

As an application, we compute the strong Künneth decomposition for the \( n \)th symmetric product of projective space \( \mathbb{P}^m_k \). Let \( \ell \in CH^1_\mathbb{Q}(\mathbb{P}^m_k) \) be the class of a generic hyperplane in \( \mathbb{P}^m_k \). It is well-known (cf. [MA], p. 455) that \( \mathbb{P}^m_k \) has a strong Künneth decomposition:

\[ \Delta_{\mathbb{P}^m_k} = \sum_{i=0}^{m} \ell^i \times \ell^{m-i} \]

Let \( X = (\mathbb{P}^m_k)^n \). By the Künneth formula for motives, we have

\[ \Delta_X = \sum_{0 \leq i_1, \ldots, i_n \leq m} f_{i_1, \ldots, i_n} \]

where \( f_{i_1, \ldots, i_n} = \ell^{i_1} \times \ldots \times \ell^{i_n} \times \ell^{m-i_1} \times \ldots \times \ell^{m-i_n} \in CH^m_\mathbb{Q}(X \times_k X) \).

Now consider the action of the symmetric group on \( n \) letters (denoted \( S_n \)) on \( X = (\mathbb{P}^m_k)^n \) by interchanging of factors. Let \( Y = X/S_n \) and \( q : X \longrightarrow Y \) the quotient map. Note also that for any \( \sigma \in S_n, (q \times q)_* f_{i_1, \ldots, i_n} = (q \times q)_* f_{\sigma(i_1), \ldots, \sigma(i_n)}. \)

Applying \((q \times q)_*\) to the strong Künneth decomposition for \( \Delta_X \) given above, and noting that \( \deg q = n! \), we obtain

\[ (n!) \Delta_Y = \sum_{0 \leq i_1, \ldots, i_n \leq m} (q \times q)_* f_{i_1, \ldots, i_n} \]

\[ = \sum_{0 \leq i_1 \leq i_2 \leq \ldots \leq i_n \leq m} (q \times q)_* f_{\sigma(i_1), \ldots, \sigma(i_n)} \]

\[ = \sum_{0 \leq i_1 \leq i_2 \leq \ldots \leq i_n \leq m} n! (q \times q)_* f_{i_1, \ldots, i_n} \]
Now let $\bar{\ell} = q_s(\ell^i)$. Then

$$\Delta_Y = \sum_{0 \leq i_1 \leq i_2 \leq \ldots \leq i_n \leq m} (q \times q)_{s_{i_1, \ldots, i_n}}$$

$$= \sum_{0 \leq i_1 \leq i_2 \leq \ldots \leq i_n \leq m} \bar{\ell}_{i_1} \times \ldots \times \bar{\ell}_{i_n} \times \bar{\ell}_{m-i_1} \times \ldots \times \bar{\ell}_{m-i_n}$$

giving a strong Künneth decomposition for $Y$.

**Corollary 3.6.** Let $Y$ denote the $n$-th symmetric product of $\mathbb{P}_k^m$. Then

$$CH^*(Y, Q, r) \cong CH^*(Y, Q, 0) \otimes CH^*(\text{Spec } k, Q, r)$$

where $CH^*(Z, Q, r) = \pi_r(z^*(Z, \ldots) \otimes Q)$ and $z^*(Z, \ldots)$ denotes the higher cycle complex of the scheme $Z$.

**Proof.** This follows readily from the above strong Künneth decomposition for the class $\Delta_Y$ and Theorem 4.1.
4. Appendix: Functoriality for the cohomology of pseudo-smooth schemes and the strong relative Künneth decomposition of cohomology

In this appendix, we first discuss various functoriality properties of cohomology theories for pseudo-smooth schemes with rational coefficients. We conclude, with a view to applications in the Corollary 3.6, a relative form of the strong Künneth decomposition in arbitrary cohomology theories satisfying certain mild conditions. It should be remarked that in this section, it suffices to assume the cohomology theory is, at least in principle, part of a twisted duality theory in the sense of Bloch-Ogus, but extended to the category of pseudo-smooth schemes. (See [Bl-O].)

Recall that a pseudo-smooth scheme $X$ is the quotient of a smooth scheme by a finite group $G$; the associated Deligne-Mumford stack $[X/G]$ is smooth although the quotient $X/G$ is not in general. Nevertheless, one may readily identify any cohomology of the quotient stack $[X/G]$ with that of the geometric quotient $X/G$ provided one works with rational coefficients. This provides a convenient mechanism for extending the formalism of Bloch-Ogus style cohomology theories to pseudo-smooth schemes as is done below. One may first make the following definitions (mainly for conveniently stating the results below). Let $\tilde{X}$ ($\tilde{Y}$) be a smooth scheme provided with the action of a finite group $G$ ($H$, respectively). Let $\tilde{f}: \tilde{X} \to \tilde{Y}$ denote a map compatible with the group actions, i.e. we are given a homomorphism $G \to H$ such that $\tilde{f}$ is equivariant for the given action of $G$ on $\tilde{X}$ and the induced action of $G$ on $\tilde{Y}$. Let $f: X = \tilde{X}/G \to Y = \tilde{Y}/H$ be the induced map. We say $f$ is pseudo-flat (pseudo-smooth, respectively) if the map $\tilde{f}$ is flat (smooth, respectively). Since the groups $G$ and $H$ are finite, one may verify that $f$ is proper if and only if $\tilde{f}$ is proper.

4.0.2. In this situation, we may replace $\tilde{f}$ with the map $\hat{f} : H\times X \to Y$ which is now $H$-equivariant.

(H.0) The cohomology theory will be denoted by $H^*(X, r)$, where $r$ is the twist or weight and will be defined on the category of all pseudo-smooth schemes of finite type over a given field $k$: this will always be a vector space over $\mathbb{Q}$. One may assume that $H^*(X, r) = H^*(EG \times X, r)^G \cong H^*(\tilde{X}, r)^G$ where $EG \to BG$ is a principal $G$-bundle with $BG$ denoting a suitable model for the classifying space of the group $G$: one may assume this is the simplicial scheme defined by the usual bar construction and that the given cohomology theories extend to all simplicial schemes with smooth face maps. (Using the observation that $EG \times X \to EG \times \tilde{X}$ is a principal $G$-bundle and since we are working with rational coefficients, one may establish the isomorphisms $H^*(X, r) \cong H^*(EG \times X, r)^G \cong H^*(\tilde{X}, r)^G$ readily.) Throughout this section we will make the following additional hypotheses on our cohomology theories: these should be easy to establish by viewing them as equivariant cohomology theories in the above sense and by making use of the observation in 4.0.2. Observe that, in this situation, $H^*(EH \times (H\times X); .) \cong H^*(EG \times X; .)$.

(H.1) for every pseudo-flat map $f : X \to Y$, there is an induced map $f^* : H^*(Y, r) \to H^*(X, r)$ and this is natural in $f$. 


(H.2) for every proper and pseudo-smooth map \( f : X \to Y \) of relative dimension \( d \), there is a push-forward \( f_* : H^r(X; j) \to H^{r-2d}(Y; j - d) \) so that if \( g : Y \to Z \) is another proper map of relative dimension \( d' \), one obtains \( g_* \circ f_* = (g \circ f)_* \). In case \( f \) is proper and pseudo-flat, the obvious projection formula \( f_*(x \circ f^*(y)) = f_*(x) \circ y, x \in H^r(X, r), y \in H^s(Y, r) \) holds.

(H.3) for each pseudo-smooth scheme \( X = \tilde{X}/G \) and closed pseudo-smooth sub-scheme \( Y = \tilde{Y}/H \) (with \( \tilde{Y} \) a smooth closed sub-scheme of pure codimension \( c \) in \( \tilde{X} \) and \( H \) a subgroup of \( G \)), there exists a canonical class \([Y] \in H^{2c}(X; c)\). Moreover the last class lifts to a canonical class \([Y] \in H^c_{\text{rel}}(X; c)\). (The latter has the obvious meaning in the setting Bloch-Ogus twisted duality theories. In case the cohomology theory is defined as hyper-cohomology with respect to a complex, we let \( H_Y(X; c) = \text{the canonical homotopy fiber of the obvious map } H(X; c) \to H(X - Y; c)\); now \( H^c_{\text{rel}}(X; c) = H^c_{\text{rel}}(H^c_{\text{rel}}(X, H))\). The cycle classes are required to pull-back under flat pull-back and push-forward under proper push-forwards.

(H.4) if \( X \) is a pseudo-smooth scheme, there exists the structure of a graded commutative ring on \( H^*(X; :) = \bigoplus_{r,s} H^r(X; s) \), i.e. \( \circ : H^r(X; s) \otimes H^r(X; s') \to H^{r+r'}(X; s + s') \). In addition to this, there exists an external product \( H^r(X; s) \otimes H^r(X; s') \to H^{r+r'}(X \times X; s + s') \) so that the internal product is obtained from the latter by pull-back with the diagonal.

(H.5) if \( X \) is a pseudo-smooth projective scheme \( H^*(X \times X; :) \) has the structure of a ring under the composition of correspondences defined as in section 1. The class of the diagonal acts as the unit for this operation. The ring structure by composition of correspondences is easy to establish. In order to show that the class of the diagonal \( \Delta_X \) is the unit for this operation, one may proceed as follows. Assume \( X = \tilde{X}/G \) for some smooth scheme \( \tilde{X} \) and finite group \( G \). The proof as in lemma 2.7 shows that for any class \( \hat{\alpha} \in H^*(\tilde{X} \times \tilde{X}; :) \otimes G \), \( \hat{\alpha} \circ (g \times h)^* \Delta_X = \hat{\alpha} \). Therefore, \( \hat{\alpha} \circ \Sigma_{(g,h)G}(g \times h)^* \Delta_X = |G|^2 \hat{\alpha} \). If \( \alpha \in H^*(X \times X; :) \), \( \hat{\alpha} = (f \times f)^*(\alpha) \in H^*(\tilde{X} \times \tilde{X}; :) \) and so \( (f \times f)_*(\hat{\alpha}) = |G|^2 \alpha \); moreover \( (f \times f)_*(\Sigma_{(g,h)G}(g \times h)^* \Delta_X) = |G|^3 \Delta_X \). Now the arguments in lemma 2.3 show that if \( f : \tilde{X} \to \tilde{X}/G = X \) is the quotient map, \( (f \times f)_*(\hat{\alpha}) = (f \times f)_*(\Sigma_{(g,h)G}(g \times h)^* \Delta_X) = |G|\Gamma^2(f \times f)_*(\hat{\alpha}) = |G|^3 \alpha \). i.e. \( |G|^2 \alpha \) or \( |G|^3 \Delta_X \) is \( |G|^3 \alpha \), so that \( \alpha \circ \Delta_X = \alpha \).

We will next consider an application of the strong relative Kunneth decomposition of cohomology for pseudo-smooth schemes. For the purposes of this discussion it is also convenient to consider only cohomology theories that are singly graded or non-weighted. Given a bi-graded cohomology theory \( H^*(X, r) \), we will re-index it as follows: we let

\[
(4.0.1) \quad h^r(X; 2r - s) = H^s(X; r) \quad \text{and} \quad h^*(X; n) = \bigoplus_r h^r(X; n)
\]

We view \( \{h^*(X; n)|n\} \) as a singly graded cohomology theory. Observe that if \( f : X \to Y \) is a proper smooth map of relative dimension \( d \), the induced map \( f_* \) sends \( h^*(X; n) \) to \( h^*(Y; n) \). Similarly if \( f : X \to Y \) is a flat map, the induced map \( f* \) sends \( h^*(Y; n) \) to \( h^*(X; n) \).

**Theorem 4.1.** Let \( \tilde{f} : \tilde{X} \to \tilde{Y} = Y \) denote a proper smooth map of smooth schemes of relative dimension \( d \). We will assume that the scheme \( \tilde{X} \) is provided with the action of a finite group \( G \) so that with the trivial action of \( G \) on \( Y \), the map \( \tilde{f} \) is \( G \)-equivariant. Let \( X = X/G, \)
[Δ] ∈ H^{2d}(X × X; d) denote the class of the diagonal. Assume that [Δ] = Σ_{i,j} a_{i,j} × b_{d-i,j}, with each a_{i,j} ∈ H^{2i}(X; i), b_{d-i,j} ∈ H^{2d-2i}(X; d - i). Then for every fixed integer n one obtains the isomorphism:

\[(4.0.2) \quad h^*(X; n) \cong h^*(X; 0) \otimes_{h^*(Y; n)} h^*(Y; n)\]

**Proof.** We will first prove that the classes \(\{a_{i,j}i\}\) generate \(h^*(X; n)\) as a module over \(h^*(Y; .)\) i.e. the obvious map from the right hand side to the left hand side of 4.0.2 (which we will denote by \(\rho\)) is surjective.

Let \(p_i : X × X \to X\) denote the projection to the \(i\)-th factor. For each \(x \in h^*(X; n)\) we will first observe the equality:

\[(4.0.3) \quad x = p_{1*}(\Delta \bullet p_{2*}(x))\]

where \(\bullet\) denotes the intersection pairing. To see this observe that \([\Delta] = \Delta_*(1), 1 \in H^*(X; \Gamma(\cdot))\). Therefore, \(\Delta \bullet p_{2*}(x) = \Delta_*(\Delta^* p_2^*(x))\) and hence

\[p_{1*}(\Delta \bullet p_{2*}(x)) = p_{1*}(\Delta_*(\Delta^* p_2^*(x))) = (p_1 \bullet \Delta)_*(p_2 \bullet \Delta^*)(x) = x.\]

The corresponding formulae hold in the cohomology of \(\tilde{X}\) and \(\tilde{X} × \tilde{X}\); by taking the \(G\) and \(G × G\)-invariants one may establish these formulae in the cohomology of \(X\) and \(X × X\).

Now we substitute \([\Delta] = \Sigma_{i,j} a_{i,j}^* \bullet p_2^*(b_{d-i,j})\) into the above formula to obtain:

\[(4.0.3) \quad x = p_{1*}(\Sigma_{i,j} a_{i,j}^* \bullet p_2^*(b_{d-i,j} \bullet x))\]

\[= p_{1*}(\Sigma_{i,j} a_{i,j}^* \bullet p_2^*(b_{d-i,j} \bullet x))\]

\[= \Sigma_{i,j} a_{i,j} \cdot p_{1*} p_2^*(b_{d-i,j} \bullet x)\]

\[= \Sigma_{i,j} a_{i,j} \cdot f^*(f_*(b_{d-i,j} \bullet x))\]

(The base-change formula is justified by observing that in the cartesian square

\[
\begin{array}{ccc}
\tilde{X} × \tilde{X} & \xrightarrow{p_2} & \tilde{X} \\
\downarrow{p_1} & & \downarrow{f} \\
\tilde{X} & \xrightarrow{f} & Y
\end{array}
\]

all maps may be made \(G × G\)-equivariant by letting \(G × G\) act by the appropriate factor on the two copies of \(\tilde{X}\). Clearly the base-change formula holds in \(G × G\)-equivariant cohomology applied to the vertices of the above diagram. By our hypothesis, the \(G × G\)-equivariant cohomology identifies with the cohomology of the appropriate quotient variety.)

This proves the assertion that the classes \(\{a_{i,j}i\}\) generate \(h^*(X; .)\) i.e. the map \(\rho\) is surjective.

The rest of the proof is to show that the map \(\rho\) is injective. The key is the following diagram:
where the map $\alpha (\mu (x), x \in h^*(X, 0))$ is defined by $\alpha (x \otimes y) = \text{the map } x' \mapsto f_*(x' \bullet x) \otimes y$ (the map $x' \mapsto f_*(x' \bullet x)$, respectively). The commutativity of the above diagram is an immediate consequence of the projection formula: observe $\rho (x \otimes y) = x \bullet f^*(y)$. Therefore, to show the map $\rho$ is injective, it suffices to show the map $\alpha$ is injective. For this we define a map $\beta$ to be a splitting for $\alpha$ as follows: if $\phi \in \text{Hom}_{h^*(Y, 0)}(h^*(X, 0), h^*(Y; n))$, we let $\beta (\phi) = \Sigma_{i,j} a_{i,j} \otimes (\phi (b_{d-i,j})).$

Observe that $\beta (\alpha (x \otimes y)) = \beta (\text{the map } x' \mapsto f_*(x' \bullet x) \otimes y) = (\Sigma_{i,j} a_{i,j} \otimes f_*(b_{d-i,j} \bullet x)) \otimes y$. Now observe that $f_*(b_{d-i,j} \bullet x) \in h^*(Y; 0)$ so that we may write the last term as $= (\Sigma_{i,j} a_{i,j} \bullet f^*f_*(b_{d-i,j} \bullet x)) \otimes y$. By (4.0.3), the last term $= x \otimes y$. This proves that $\alpha$ is injective and hence that so is $\rho$.

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[PED]


Department of Mathematics, Miami University, Oxford, Ohio, 45056, USA.
E-mail address: reza@calico.mth.muohio.edu

Department of Mathematics, Ohio State University, Columbus, Ohio, 43210, USA
Current address: School of Mathematics, Institute for Advanced Study, Princeton, New Jersey, 08540, USA
E-mail address: joshua@ias.edu, joshua@math.ohio-state.edu