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# DEGREES OF ITERATES OF RATIONAL MAPS ON NORMAL PROJECTIVE VARIETIES

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# DEGREES OF ITERATES OF RATIONAL MAPS ON NORMAL PROJECTIVE VARIETIES

NGUYEN-BAC DANG

ABSTRACT. Let  $X$  be a normal projective variety defined over an algebraically closed field of arbitrary characteristic. We study the sequence of intermediate degrees of the iterates of a dominant rational selfmap of  $X$ , recovering former results by Dinh, Sibony [DS05b], and by Truong [Tru16]. Precisely, we give a new proof of the submultiplicativity properties of these degrees and of its birational invariance. Our approach exploits intensively positivity properties in the space of numerical cycles of arbitrary codimension. In particular, we prove an algebraic version of an inequality first obtained by Xiao [Xia15] and Popovici [Pop16], which generalizes Siu's inequality to algebraic cycles of arbitrary codimension. This allows us to show that the degree of a map is controlled up to a uniform constant by the norm of its action by pull-back on the space of numerical classes in  $X$ .

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## INTRODUCTION

Let  $f : X \dashrightarrow X$  be any dominant rational self-map of a normal projective variety  $X$  of dimension  $n$  defined over an algebraically closed field  $\kappa$  of arbitrary characteristic. Given any big and nef (e.g ample) Cartier divisor  $\omega_X$  on  $X$ , and any integer  $0 \leq k \leq n$ , one defines the  $k$ -th degree of  $f$  as the intersection product:

$$\deg_{k,\omega_X}(f) = (\pi_1^* \omega_X^{n-k} \cdot \pi_2^* \omega_X^k),$$

where  $\pi_1$  and  $\pi_2$  are the projections from the graph of  $f$  in  $X \times X$  onto the first and the second factor respectively.

The behaviour of the sequence of degrees  $(\deg_{k,\omega_X}(f^p))_p$  and especially its growth when  $p \rightarrow +\infty$  is of crucial importance in the study of the dynamics of  $f$ . It controls the topological entropy of  $f$  ([Yom87], [Gro87], [DS05b]), and the growth of the number of isolated periodic points when the period goes to infinity ([DNT16]). Its understanding is also the key for the construction of ergodic invariant measures ([BS92], [Sib99],[DS05a], [Gue05], [DTV10], [DS10], [DDG11]). The growth of the degrees appears as an essential tool when exploring algebraic properties of groups of birational transformations of projective varieties (see [Giz80], [DF01], [Can11], [BD15], [BC16] for surfaces, [DS04a] for the study of commutative automorphism groups in dimension  $\geq 3$  and [CZ12], [Zha14] for some characterizations of positive entropy automorphisms in higher dimension).

Our main theorem can be stated as follows.

**Theorem 1.** *Let  $X$  be a normal projective variety of dimension  $n$  and let  $\omega_X$  be a big and nef Cartier divisor on  $X$ .*

- (1) *There is a positive constant  $C > 0$  such that for any dominant rational self-maps  $f, g$  on  $X$ , one has:*

$$\deg_{k,\omega_X}(f \circ g) \leq C \deg_{k,\omega_X}(f) \deg_{k,\omega_X}(g).$$

- (2) *For any big nef Cartier divisor  $\omega'_X$  on  $X$ , there exists a constant  $C > 0$  such that for any rational self-map  $f$  on  $X$ , one has:*

$$\frac{1}{C} \leq \frac{\deg_{k,\omega_X}(f)}{\deg_{k,\omega'_X}(f)} \leq C.$$

Observe that Theorem 1.(2) implies that the degree growth of  $f$  is a birational invariant, in the sense that there is a positive constant  $C$  such that for any birational map  $g : X' \dashrightarrow X$  with  $X'$  projective, and any big nef Cartier divisor  $\omega_{X'}$  on  $X'$ , one has

$$\frac{1}{C} \leq \frac{\deg_{k,\omega_X}(f^p)}{\deg_{k,\omega_{X'}}(g^{-1} \circ f^p \circ g)} \leq C,$$

for any  $p \in \mathbb{N}$ . Fekete's lemma and Theorem 1.(1) also imply the existence of the dynamical degree (first introduced in [RS97] for rational maps of the projective space) as the following quantity:

$$\lambda_k(f) := \lim_{p \rightarrow +\infty} \deg_{k,\omega_X}(f^p)^{1/p}.$$

The independence of  $\lambda_k(f)$  under the choice of  $\omega_X$ , and its birational invariance are the consequence of Theorem 1.(2) .

When  $\kappa = \mathbb{C}$ , Theorem 1 was proved by Dinh and Sibony in [DS05b], and further generalized to compact Kähler manifolds in [DS04b]. The core of their argument relied on a procedure of regularization for closed positive currents of any bidegree ([DS04b, Theorem 1.1]) and was therefore transcendental in nature. By Lefschetz principle Dinh and Sibony's argument also proves that the  $k$ -th dynamical degree of any rational dominant map is well-defined when  $\kappa$  is a field of characteristic zero. Recently, Truong [Tru15] managed to get around this problem and proved Theorem 1 for arbitrary smooth varieties using an appropriate Chow's moving lemma. He went further in [Tru16] and obtained Theorem 1 for any normal variety in all characteristic by applying de Jong's alteration theorem ([Jon96]). Note however that he had to deal with correspondences since a rational self-map can only be lifted as a correspondence through a general alteration map. Our approach avoids this technical difficulty.

To illustrate our method, let us explain the proof of Theorem 1, when  $X$  is smooth,  $k = 1$  and  $f, g$  are regular following the method initiated in [BFJ08, Proposition 3.1]. Recall that a divisor  $\alpha$  on  $X$  is *pseudo-effective* and one writes  $\alpha \geq 0$  if for any ample Cartier divisor  $\omega$  on  $X$ , and any rational  $\epsilon > 0$ , a suitable multiple of the  $\mathbb{Q}$ -divisor  $\alpha + \epsilon\omega$  is linearly equivalent to an effective one.

Recall also the fundamental Siu's inequality<sup>1</sup> ([Laz04, Theorem 2.2.13], [Cut15]) which states:

$$\alpha \leq n \frac{(\alpha \cdot \beta^{n-1})}{(\beta^n)} \beta, \quad (1)$$

for any nef divisor  $\alpha$ , and any big and nef divisor  $\beta$ .

Since the pullback by a dominant morphism of a big nef divisor remains big and nef, we may apply (1) to  $\alpha = g^*f^*\omega_X$  and  $\beta = f^*\omega_X$ , and we get

$$g^*f^*\omega_X \leq n \frac{\deg_{k,\omega_X}(f)}{(\omega_X^n)} \times g^*\omega_X .$$

Intersecting with the cycle  $\omega_X^{n-1}$  yields the submultiplicativity of the degrees with the constant  $C = n/(\omega_X^n)$ .

We observe that the previous inequality (1) can be easily extended to complete intersections by cutting out by suitable ample sections. In particular, we get a positive constant  $C$  such that for any big nef divisors  $\alpha$  and  $\beta$ , one has:

$$\alpha^k \leq C \frac{(\alpha^k \cdot \beta^{n-k})}{(\beta^n)} \beta^k. \quad (2)$$

Such inequalities have been obtained by Xiao ([Xia15]) and Popovici ([Pop16]) in the case  $\kappa = \mathbb{C}$ . Their proof uses the resolution of complex Monge-Ampère operators and yields a constant  $C = \binom{k}{n}$ . On the other hand, our proof applies in arbitrary characteristic and in fact to more general classes than complete intersection ones. We refer to Theorem 3 below and the discussion preceding it for more details. Note however that we only obtain  $C = (n - k + 1)^k$ , far from the expected optimal constant of Popovici and Xiao. Once (2) is proved, Theorem 1 follows by a similar argument as in the case  $k = 1$ .

Going back to the case where  $X$  is a complex smooth projective variety, recall that the degree of  $f$  is controlled up to a uniform constant by the norm of the linear operator  $f^{\bullet,k}$ , induced by pullback on the de Rham cohomology space  $H_{dR}^{2k}(X)_{\mathbb{R}}$  ([DS05b, Lemma 4]). One way to construct  $f^{\bullet,k}$  is to use the Poincaré duality isomorphisms  $\psi_X : H_{dR}^{2k}(X, \mathbb{R}) \rightarrow H_{2n-2k}(X, \mathbb{R})$ ,

<sup>1</sup>this inequality is also referred to as the weak transcendental holomorphic Morse inequality in [LX15]

$\psi_{\Gamma_f} : H_{dR}^{2k}(\Gamma_f, \mathbb{R}) \rightarrow H_{2n-2k}(\Gamma_f, \mathbb{R})$  where  $H_k(X, \mathbb{R})$  denotes the  $k$ -th simplicial homology group of  $X$ . The operator  $f^{\bullet, k}$  is then defined following the commutative diagram below:

$$\begin{array}{ccccc} H_{dR}^{2k}(\Gamma_f, \mathbb{R}) & \xrightarrow{\psi_{\Gamma_f}} & H_{2n-2k}(\Gamma_f, \mathbb{R}) & \xrightarrow{\pi_{1*}} & H_{2n-2k}(X, \mathbb{R}) \\ \pi_2^* \uparrow & & & & \downarrow \psi_X^{-1} \\ H_{dR}^{2k}(X, \mathbb{R}) & \xrightarrow{f^{\bullet, k}} & & & H_{dR}^{2k}(X, \mathbb{R}), \end{array}$$

where  $\Gamma_f$  is the desingularization of the graph of  $f$  in  $X \times X$ , and  $\pi_1, \pi_2$  are the projections from  $\Gamma_f$  onto the first and second factor respectively.

To generalize this control to our setting we need to find a replacement for the de Rham cohomology group  $H_{dR}^{2k}(X)_{\mathbb{R}}$  and define suitable pullback operators. When  $X$  is smooth, one natural way to proceed is to consider the spaces  $N^k(X)_{\mathbb{R}}$  of algebraic  $\mathbb{R}$ -cycles of codimension  $k$  modulo numerical equivalence. The operator  $f^{\bullet, k}$  is then simply given by the composition  $\pi_{1*} \circ \pi_2^* : N^k(X)_{\mathbb{R}} \rightarrow N^k(X)_{\mathbb{R}}$ .

When  $X$  is singular, then the situation is more subtle because one cannot intersect arbitrary cycles in general <sup>2</sup>. One can consider two natural spaces of numerical cycles  $N^k(X)_{\mathbb{R}}$  and  $N_k(X)_{\mathbb{R}}$  on which pullback operations and pushforward operations by proper morphisms are defined respectively. More specifically, the *space of numerical  $k$ -cycles*  $N_k(X)_{\mathbb{R}}$  is defined as the group of  $\mathbb{R}$ -cycles of dimension  $k$  modulo the relation  $z \equiv 0$  if and only if  $(p^*z \cdot D_1 \cdot \dots \cdot D_{e+k}) = 0$  for any proper flat surjective map  $p : X' \rightarrow X$  of relative dimension  $e$  and any Cartier divisors  $D_i$  on  $X'$ . One can prove that  $N_k(X)_{\mathbb{R}}$  is a finite dimensional vector space and one defines  $N^k(X)_{\mathbb{R}}$  as its dual  $\text{Hom}(N_k(X)_{\mathbb{R}}, \mathbb{R})$ .

Note that our presentation differs slightly from Fulton's definition (see Appendix A for a comparison), but we also recover the main properties of the numerical groups.

As in the complex case, we are able to construct Poincaré linear maps  $\psi_X : N^k(X)_{\mathbb{R}} \rightarrow N_{n-k}(X)_{\mathbb{R}}$  and  $\psi_{\Gamma_f} : N^k(\Gamma_f)_{\mathbb{R}} \rightarrow N_{n-k}(\Gamma_f)_{\mathbb{R}}$ , but they are not necessarily isomorphisms due to the presence of singularities. As a consequence, we are only able to define a linear map  $f^{\bullet, k}$  as  $f^{\bullet, k} := \pi_{1*} \circ \psi_{\Gamma_f} \circ \pi_2^* : N^k(X)_{\mathbb{R}} \rightarrow N_{n-k}(X)_{\mathbb{R}}$  between two distinct vector spaces. Despite this limitation, we prove a result analogous to the one of Dinh and Sibony. The next theorem was obtained by Truong for smooth varieties ([Tru16, Theorem 1.1.(5)]).

**Theorem 2.** *Let  $X$  be a normal projective variety of dimension  $n$ . Fix any norms on  $N^k(X)_{\mathbb{R}}$  and  $N_{n-k}(X)_{\mathbb{R}}$ , and denote by  $\|\cdot\|$  the induced operator norm on linear maps from  $N^k(X)_{\mathbb{R}}$  to  $N_{n-k}(X)_{\mathbb{R}}$ . Then there is a constant  $C > 0$  such that for any rational selfmap  $f : X \dashrightarrow X$ , one has:*

$$\frac{1}{C} \leq \frac{\|(f)^{\bullet, k}\|}{\text{deg}_{k, \omega_X}(f)} \leq C. \quad (3)$$

Our proof of Theorem 2 exploits a natural notion of positive classes in  $N^k(X)_{\mathbb{R}}$  combined with a strengthening of (2) to these classes that we state below (see Theorem 3).

To simplify our exposition, let us suppose again that  $X$  is smooth. As in codimension 1, one can define the *pseudo-effective cone*  $\text{Psef}^k(X)$  as the closure in  $N^k(X)_{\mathbb{R}}$  of the cone generated by effective cycles of codimension  $k$ . Its dual with respect to the intersection product is the *nef cone*  $\text{Nef}^{n-k}(X)$ , which however does not behave well when  $k \geq 2$  (see [DELV11]). Some alternative notions of positive cycles have been introduced by Fulger and Lehmann in [FL14b], among which

<sup>2</sup>an arbitrary curve can only be intersected with a Cartier divisor, not with a general Weil divisor.

the notion of pliant classes emerges. Pliant classes have many good properties such as being both pseudo-effective and nef, being invariant by pull-backs by morphisms and by intersection products, and forming a salient convex cone with non-empty interior. We shall consider a subcone of the pliant cone that formally satisfies the same properties as the pliant cone (see Theorem 3.2.4) but is better suited to our purposes. We call it the *strongly pliant cone* of  $X$  and denote it by  $\mathcal{C}^k(X)$ . It is defined as the closure in  $N^k(X)_{\mathbb{R}}$  of the cone generated by  $\mathbb{R}$ -cycles of the form  $p_*(D_1 \cdots D_{e+k})$  where  $D_i$  are ample Cartier  $\mathbb{R}$ -divisors and  $p : X' \rightarrow X$  is a flat surjective proper morphism of relative dimension  $e$ .

For strongly pliant classes, we are able to prove the following generalization of (2).

**Theorem 3.** *Let  $X$  be a normal projective variety of dimension  $n$ . Then there exists a constant  $C > 0$  such that for any strongly pliant class  $\alpha \in \mathcal{C}^k(X)$ , for any big nef divisor  $\beta$ , one has in  $N^k(X)_{\mathbb{R}}$ :*

$$\alpha \leq C \frac{(\alpha \cdot \beta^{n-k})}{(\beta^n)} \times \beta^k. \quad (4)$$

Theorem 2 follows from (4) by observing that  $f^{\bullet,k} \mathcal{C}^k(X) \subset \text{Psef}^k(X)$ , so that the operator norm  $\|f^{\bullet,k}\|$  can be computed by evaluating  $f^{\bullet,k}$  only on strongly pliant classes.

In the singular case, the proof of Theorem 2 is completely similar but the spaces  $N^k(X)_{\mathbb{R}}$  and  $N_{n-k}(X)_{\mathbb{R}}$  are not necessarily isomorphic in general. As a consequence, several dual notions of positivity appear in  $N^k(X)_{\mathbb{R}}$  and  $N_k(X)_{\mathbb{R}}$  that make the arguments more technical.

Finally, using the techniques developed in this paper, we give a new proof of the product formula of Dinh, Nguyen, Truong ([DN11, Theorem 1.1],[DNT12, Theorem 1.1]) which they proved when  $\kappa = \mathbb{C}$  and which was later generalized by Truong ([Tru16, Theorem 1.1.(4)]) to normal projective varieties over any field.

The setup is as follows. Let  $q : X \rightarrow Y$  be any proper surjective morphism between normal projective varieties, and fix two big and nef divisors  $\omega_X, \omega_Y$  on  $X$  and  $Y$  respectively. Consider two dominant rational self-maps  $f : X \dashrightarrow X, g : Y \dashrightarrow Y$ , which are semi-conjugated by  $q$ , i.e. which satisfy  $q \circ f = g \circ q$ . To simplify notation we shall write  $X/qY \xrightarrow[-g]{f} X/qY$  when these assumptions hold true.

Recall that the  $k$ -th relative degree of  $X/qY \xrightarrow[-g]{f} X/qY$  is given by the intersection product

$$\text{reldeg}_k(f) := (\pi_1^*(\omega_X^{\dim X - \dim Y - k} \cdot q^* \omega_Y^{\dim Y}) \cdot \pi_2^* \omega_X^k),$$

where  $\pi_1$  and  $\pi_2$  are the projections from the graph of  $f$  in  $X \times X$  onto the first and the second component respectively. One can show a relative version of Theorem 1 (see Theorem 5.2.1), and define as in the absolute case, the  $k$ -th relative dynamical degree  $\lambda_k(f, X/Y)$  as the limit  $\lim_{p \rightarrow +\infty} \text{reldeg}_k(f^p)^{1/p}$ . It is also a birational invariant, and does not depend on the choices of  $\omega_X$  and  $\omega_Y$ . When  $q : X \dashrightarrow Y$  is merely rational and dominant, then we define (see Section 6) the  $k$ -th relative degree of  $f$  by replacing  $X$  with the normalization of graph of  $q$ . We prove the following theorem.

**Theorem 4.** *Let  $X, Y$  be normal projective varieties. For any dominant rational self-maps  $f : X \dashrightarrow X, g : Y \dashrightarrow Y$  which are semi-conjugated by a dominant rational map  $q : X \dashrightarrow Y$ , we have*

$$\lambda_k(f) = \max_{\max(0, k-l) \leq j \leq \min(k, e)} (\lambda_{k-j}(g) \lambda_j(f, X/Y)). \quad (5)$$

Observe that we are only able to relate the dynamical degrees of a rational map with the relative dynamical degrees and the dynamical degree on the base. Unfortunately, we do not know how

to control the degree growth of  $f$  with respect to the degree growth of  $g$  on the base  $Y$  and on the fibers of  $q : X \rightarrow Y$  except when  $e = 0$ , since in that case Theorem 1.(2) proves that  $1/C \leq \deg_{k,\omega_X}(f)/\deg_{k,\omega_Y}(g) \leq C$ .

Our proof follows closely Dinh and Nguyen's method from [DN11] and relies on a fundamental inequality (see Corollary 7.1.5 below) which follows from Künneth formula at least when  $\kappa = \mathbb{C}$ . To state it precisely, consider  $\pi : X' \rightarrow X$  a surjective generically finite morphism and  $q : X \rightarrow Y$  a surjective morphism where  $X', X$  and  $Y$  are normal projective varieties such that  $n = \dim X = \dim X'$  and such that  $l = \dim Y$ . We prove that for any pliant classes  $\alpha \in \mathcal{C}^k(X')$  and  $\beta \in \mathcal{C}^{n-k}(X')$ , one has:

$$(\beta \cdot \alpha) \leq C \sum_{\max(0,k-l) \leq j \leq \min(k,e)} U_j(\alpha) \times (\beta \cdot \pi^*(q^*\omega_Y \cdot \omega_X^j)), \quad (6)$$

where  $\omega_Y$  and  $\omega_X$  are big and nef divisors on  $Y$  and  $X$  respectively, and  $U_j(\alpha)$  is the intersection product given by  $U_j(\alpha) = (\pi^*(q^*\omega_Y^{l-k+j} \cdot \omega_X^{e-j}) \cdot \alpha)$ .

In the singular case, Truong has obtained this inequality using Chow's moving intersection lemma. We replace this argument by a suitable use of Siu's inequality and Theorem 3 in order to prove a positivity property for a class given by the difference between a strongly pliant class in  $X' \times X'$  and the fundamental class of the diagonal of  $X'$  in  $X' \times X'$  (see Theorem 7.1.1). Inequality (6) is a weaker version of [DN11, Proposition 2.3] proved by Dinh-Nguyen when  $Y$  is a complex projective variety, and was extended to a field arbitrary characteristic by Truong when  $Y$  is smooth ([Tru16, Lemma 4.1]).

**Organization of the paper.** In the first Sections 1 and 2, we review the background on the Chow groups and recall the definitions of the spaces of numerical cycles and provide their basic properties. In §3, we discuss the various notions of positivity of cycles and prove Theorem 3. In §4, we define relative numerical cycles and canonical morphisms which are the analogous to the Poincaré morphisms  $\psi_X$  in a relative setting. In §5, we prove Theorem 1, Theorem 2 and Theorem 4. Finally we give an alternate proof of Dinh-Sibony's theorem in the Kähler case ([DS05b, Proposition 6]) in §8 using Popovici [Pop16] and Xiao's inequality [Xia15]. Note that these inequalities allow us to avoid regularization techniques of closed positive currents but relies on a deep theorem of Yau. In Appendix A, we prove that our presentation and Fulton's definition of numerical cycles are equivalent, hence proving that any numerical cycles can be pulled back by a flat morphism.

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## 1. CHOW GROUP

**1.1. General facts.** Let  $X$  be a normal projective variety of dimension  $n$  defined over an algebraically closed field  $\kappa$  of arbitrary characteristic.

The space of cycles  $Z_k(X)$  is the free group generated by irreducible subvarieties of  $X$  of dimension  $k$ , and  $Z_k(X)_{\mathbb{Q}}, Z_k(X)_{\mathbb{R}}$  will denote the tensor products  $Z_k(X) \otimes_{\mathbb{Z}} \mathbb{Q}$  and  $Z_k(X) \otimes_{\mathbb{Z}} \mathbb{R}$ .

Let  $q : X \rightarrow Y$  be a morphism where  $Y$  is a normal projective variety. Since  $X$  and  $Y$  are respectively projective, the map  $q$  is proper. Following [Ful98], we define the proper pushforward

of the cycle  $[V] \in Z_k(X)$  as the element of  $Z_k(Y)$  given by:

$$q_*[V] = \begin{cases} 0 & \text{if } \dim(q(V)) < \dim V \\ [\kappa(\eta) : \kappa(q(\eta))] \times [q(V)] & \text{if } \dim V = \dim(q(V)), \end{cases}$$

where  $V$  is an irreducible subvariety of  $X$  of dimension  $k$ ,  $\eta$  is the generic point of  $V$  and  $\kappa(\eta)$ ,  $\kappa(q(\eta))$  are the residual fields of the local rings  $\mathcal{O}_\eta$  and  $\mathcal{O}_{q(\eta)}$  respectively. We extend this map by linearity and obtain a morphism of abelian groups  $q_* : Z_k(X) \rightarrow Z_k(Y)$ .

Let  $C$  be any subscheme of  $X$  of dimension  $k$  and denote by  $C_1, \dots, C_r$  its irreducible components. Then  $C$  defines a fundamental class  $[C] \in Z_k(X)$  by the following formula:

$$[C] := \sum_{i=1}^r l_{\mathcal{O}_{C_i, C}}(\mathcal{O}_{C_i, C})[C_i],$$

where  $l_A(M)$  denotes the length of an  $A$ -module  $M$  ([Eis95, section 2.4]).

For any flat morphism  $q : X \rightarrow Y$  of relative dimension  $e$  between normal projective varieties, we can define a flat pullback of cycles  $q^* : Z_k(Y) \rightarrow Z_{k+e}(X)$  (see [Ful98, section 1.7]). If  $C$  is any subscheme of  $Y$  of dimension  $k$ , the cycle  $q^*[C]$  is by definition the fundamental class of the scheme-theoretic inverse by  $q$ :

$$q^*[C] := [q^{-1}(C)] \in Z_{k+e}(X).$$

Let  $W$  be a subvariety of  $X$  of dimension  $k+1$  and  $\varphi$  be a rational map on  $W$ . Then we define a cycle on  $X$  by:

$$[\text{div}(\varphi)] := \sum \text{ord}_V(\varphi)[V],$$

where the sum is taken over all irreducible subvarieties  $V$  of dimension  $k$  of  $X$ . A cycle  $\alpha$  defined this way is rationally equivalent to 0 and in that case we shall write  $\alpha \sim 0$ .

The  $k$ -th Chow group  $A_k(X)$  of  $X$  is the quotient of the abelian group  $Z_k(X)$  by the free group generated by the cycles that are rationally equivalent to zero. We denote by  $A_\bullet(X)$  the abelian group  $\bigoplus A_k(X)$ .

We recall now the functorial operations on the Chow group, which results from the intersection theory developed in [Ful98].

**Theorem 1.1.1.** *Let  $q : X \rightarrow Y$  be a morphism between normal projective varieties. Then we have:*

- (1) *The morphism of abelian groups  $q_* : Z_k(X) \rightarrow Z_k(Y)$  induces a morphism of abelian groups  $q_* : A_k(X) \rightarrow A_k(Y)$ .*
- (2) *If the morphism  $q$  is flat of relative dimension  $e$ , then the morphism  $q^* : Z_k(Y) \rightarrow Z_{k+e}(X)$  induces a morphism of abelian groups  $q^* : A_k(Y) \rightarrow A_{k+e}(X)$ .*

Assertion (1) is proved in [Ful98, Theorem 1.4] and assertion (2) is given in [Ful98, Theorem 1.7].

*Remark 1.1.2.* Let  $q : X \rightarrow Y$  is a flat morphism of normal projective varieties. Suppose  $\alpha \in A_k(Y)$  is represented by an effective cycle  $\alpha \sim \sum n_i [V_i]$  where the  $n_i$  are positive integers. Then  $q^*\alpha$  is also represented by an effective cycle.

Any cycle  $\alpha \in Z_0(X)_\mathbb{Z}$  is of the form  $\sum n_i [p_i]$  with  $p_i \in X(\kappa)$  and  $n_i \in \mathbb{Z}$ . We define the degree of  $\alpha$  to be  $\text{deg}(\alpha) := \sum n_i$  and we shall write:

$$(\alpha) := \text{deg}(\alpha) = \sum n_i.$$

The morphism of abelian groups  $\text{deg} : Z_0(X)_\mathbb{Z} \rightarrow \mathbb{Z}$  induces a morphism of abelian groups  $\text{deg} : A_0(X) \rightarrow \mathbb{Z}$ .



**1.2. Intersection with Cartier divisors.** Let  $X$  be a normal projective variety and  $D$  be a Cartier divisor on  $X$ . Let  $V$  be a subvariety of of dimension  $k$  in  $X$  and denote by  $j : V \hookrightarrow X$  the inclusion of  $V$  in  $X$ . We define the intersection of  $D$  with  $[V]$  as the class:

$$D \cdot [V] := j_*[D'] \in A_{k-1}(X),$$

where  $D'$  is a Cartier divisor on  $V$  such that the line bundles  $j^*\mathcal{O}_X(D)$  and  $\mathcal{O}_V(D')$  are isomorphic. We extend this map by linearity into a morphism of abelian groups  $D \cdot : Z_k(X) \rightarrow A_{k-1}(X)$ .

**Theorem 1.2.1.** *Let  $X$  be a normal projective variety and  $D$  be a Cartier divisor on  $X$ . The map  $D \cdot : Z_k(X) \rightarrow A_{k-1}(X)$  induces a morphism of abelian groups  $D \cdot : A_k(X) \rightarrow A_{k-1}(X)$ . Moreover, the following properties are satisfied:*

(1) *For all Cartier divisors  $D$  and  $D'$  on  $X$ , for all class  $\alpha \in A_k(X)$ , we have:*

$$(D' + D) \cdot \alpha \sim D' \cdot \alpha + D \cdot \alpha.$$

(2) *(Projection formula) Let  $q : X \rightarrow Y$  be a morphism between normal projective varieties. Then for all class  $\beta \in A_k(X)$  and all Cartier divisor  $D$  on  $Y$ , we have in  $A_{k-1}(Y)$ :*

$$q_*(q^*D \cdot \beta) \sim D \cdot q_*(\beta).$$

**Definition 1.2.2.** *For all normal projective varieties  $X$ , the group  $\mathrm{IC}^k(X)$  is the free group generated by elements of the form  $D_1 \cdot \dots \cdot D_k$  where  $D_1, \dots, D_k$  are Cartier divisors on  $X$ .*

### 1.3. Characteristic classes.

**Definition 1.3.1.** *Let  $X$  be a normal projective variety of dimension  $n$  and  $L$  be a line bundle on  $X$ . There exists a Cartier divisor  $D$  on  $X$  such that the line bundles  $L$  and  $\mathcal{O}_X(D)$  are isomorphic. We define the first Chern class of  $L$  as:*

$$c_1(L) := [D] \in A_{n-1}(X).$$

**Definition 1.3.2.** *Let  $X$  be a normal projective variety and  $E$  be a vector bundle of rank  $e + 1$  on  $X$ . Given any vector bundle  $E$  on  $X$ , we shall denote by  $\mathbb{P}(E)$  the projective bundle of hyperplanes in  $E$  following the convention of Grothendieck. Let  $p$  be the projection from  $\mathbb{P}(E^*)$  to  $X$  and  $\xi = c_1(\mathcal{O}_{\mathbb{P}(E^*)}(1))$ . We define the  $i$ -th Segré class  $s_i(E)$  as the morphism  $s_i(E) \lrcorner \cdot : A_\bullet(X) \rightarrow A_{\bullet-i}(X)$  given by:*

$$s_i(E) \lrcorner \alpha := p_*(\xi^{e+i} \cdot p^*\alpha). \quad (7)$$

*Remark 1.3.3.* When  $X$  is smooth of dimension  $n$ , we can define an intersection product on the Chow groups  $A_k(X) \times A_l(X) \rightarrow A_{n-k-l}(X)$  (see [Ful98, Definition 8.1.1]) which is compatible with the intersection with Cartier divisors and satisfies the projection formula (see [Ful98, Example 8.1.7]). Applying the projection formula to (7), we get

$$s_i(E) \lrcorner \alpha = p_*(\xi^{e+i}) \cdot \alpha,$$

so that  $s_i(E)$  is represented by an element in  $A_{n-i}(X)$ . To simplify we shall also denote  $s_i(E)$  this element.

As Segré classes of vector bundles are operators on the Chow groups  $A_\bullet(X)$ , the composition of such operators defines a product.

**Theorem 1.3.4.** *(cf [Ful98, Proposition 3.1]) Let  $q : X \rightarrow Y$  be a morphism between normal projective varieties. For any vector bundle  $E$  and  $F$  on  $Y$ , the following properties hold.*

- (1) *For all  $\alpha \in A_k(Y)$  and all  $i < 0$ , we have  $s_i(E) \lrcorner \alpha = 0$ .*
- (2) *For all  $\alpha \in A_k(Y)$ , we have  $s_0(E) \lrcorner \alpha = \alpha$ .*
- (3) *For all integers  $i, j$ , we have  $s_i(E) \lrcorner (s_j(F) \lrcorner \alpha) = s_j(F) \lrcorner (s_i(E) \lrcorner \alpha)$ .*

- (4) (*Projection formula*) For all  $\beta \in A_k(X)$  and any integer  $i$ , we have  $q_*(s_i(q^*E) \lrcorner \beta) = s_i(E) \lrcorner q_*\beta$ .
- (5) If the morphism  $q : X \rightarrow Y$  is flat, then for all  $\alpha \in A_k(Y)$  and any integer  $i$ , we have  $s_i(q^*E) \lrcorner q^*\alpha = q^*(s_i(E) \lrcorner \alpha)$ .

The  $i$ -th Chern class  $c_i(E)$  of a vector bundle  $E$  on  $X$  is an operator  $c_i(E) : A_\bullet(X) \rightarrow A_{\bullet-i}$  defined formally as the coefficients in the inverse power series:

$$(1 + s_1(E)t + s_2(E)t^2 + \dots)^{-1} = 1 + c_1(E)t + \dots + c_{r+1}(E)t^{r+1}.$$

A direct computation yields for example  $c_1(E) = -s_1(E)$ ,  $c_2(E) = (s_1(E)^2 - s_2(E))$ .

**Definition 1.3.5.** Let  $X$  be a normal projective variety. The abelian group  $A^k(X)$  is the subgroup of  $\text{Hom}(A_\bullet(X), A_{\bullet-k}(X))$  generated by product of Chern classes  $c_{i_1}(E_1) \cdots c_{i_p}(E_p)$  where  $i_1, \dots, i_k$  are integers satisfying  $i_1 + \dots + i_p = k$  and where  $E_1, \dots, E_p$  are vector bundles over  $X$ . We denote by  $A^\bullet(X)$  the group  $\bigoplus A^k(X)$ .

Observe that by definition,  $A^k(X)$  contains  $\text{IC}^k(X)$ .

Recall that the Grothendieck group  $K^0(X)$  is the free group generated by vector bundles on  $X$  quotiented by the subgroup generated by relations of the form  $[E_1] + [E_3] - [E_2]$  where there is an exact sequence of vector bundles:

$$0 \longrightarrow E_1 \longrightarrow E_2 \longrightarrow E_3 \longrightarrow 0.$$

Moreover, the group  $K^0(X)$  has a structure of rings given by the tensor product of vector bundles.

Recall also that the Chern character is the unique morphism of rings  $\text{ch} : (K^0(X), +, \otimes) \rightarrow (A^\bullet(X), +, \cdot)$  satisfying the following properties (see [Ful98, Example 3.2.3]).

- (1) If  $L$  is a line bundle on  $X$ , then one has:

$$\text{ch}(L) = \sum_{i \geq 0} \frac{c_1(L)^i}{i!}.$$

- (2) For any morphism  $q : X' \rightarrow X$  and any vector bundle  $E$  on  $X$ , we have  $q^* \text{ch}(E) = \text{ch}(q^*E)$ .

For any vector bundle  $E$  on  $X$ , we will denote by  $\text{ch}_k(E)$  the term in  $A^k(X)$  of  $\text{ch}(E)$ .

We recall Grothendieck-Riemann-Roch's theorem for smooth varieties.

**Theorem 1.3.6.** (see [Ful98, Corollary 18.3.2]) Let  $X$  be a smooth variety. Then the Chern character induces an isomorphism:

$$\text{ch}_\lrcorner[X] : E \in K^0(X) \otimes \mathbb{Q} \rightarrow \text{ch}(E) \lrcorner[X] \in A_\bullet(X) \otimes \mathbb{Q}.$$

## 2. SPACE OF NUMERICAL CYCLES

**2.1. Definitions.** In all this section,  $X$  is a normal projective variety of dimension  $n$ , and all the varieties we consider are also normal and projective. Two cycles  $\alpha$  and  $\beta$  in  $Z_k(X)$  are said to be numerically equivalent and we will denote by  $\alpha \equiv \beta$  if for all flat morphisms  $p_1 : X_1 \rightarrow X$  of relative dimension  $e$  and all Cartier divisors  $D_1, \dots, D_{e+k}$  in  $X_1$ , we have:

$$(D_1 \cdots D_{e+k} \cdot q^*\alpha) = (D_1 \cdots D_{e+k} \cdot q^*\beta).$$

**Definition 2.1.1.** The group of numerical classes of dimension  $k$  is the quotient  $N_k(X) = Z_k(X) / \equiv$ .

By construction, the group  $N_k(X)$  is torsion free and there is a canonical surjective morphism  $A_k(X) \rightarrow N_k(X)$  for any integer  $k$ .

*Remark 2.1.2.* Observe also that for  $k = 0$ , two cycles are numerically equivalent if and only if they have the same degree. Since smooth points are dense in  $X$  (see [Dan94, Theorem II.4.7]) and are of degree 1, this proves that the degree realizes the isomorphism  $N_0(X) \simeq \mathbb{Z}$ .

We set  $N_k(X)_{\mathbb{Q}}$  and  $N_k(X)_{\mathbb{R}}$  the two vector spaces obtained by tensoring by  $\mathbb{R}$  and  $\mathbb{C}$  respectively.

*Remark 2.1.3.* This definition allows us to pullback numerical classes by any flat morphism  $q : X \rightarrow Y$  of relative dimension  $e$ . Our presentation is slightly different from the classical one given in [Ful98, Section 19.1]. We refer to Appendix A for a proof of the equivalence of these two approaches.

**Proposition 2.1.4.** *Let  $q : X \rightarrow Y$  a morphism. Then the morphism of groups  $q_* : Z_k(X) \rightarrow Z_k(Y)$  induces a morphism of abelian groups  $q_* : N_k(X) \rightarrow N_k(Y)$ .*

*Proof.* Let  $n$  be the dimension of  $X$  and  $l$  be the dimension of  $Y$ , and let  $\alpha$  be a cycle in  $Z_k(X)$  such that  $\alpha$  is numerically trivial. We need to prove that  $q_*\alpha$  is also numerically trivial.

Take  $p_1 : Y_1 \rightarrow Y$  a flat morphism of relative dimension  $e_1$ . Let  $X_1$  be the fibred product  $X \times_Y Y_1$  and let  $p'_1$  and  $q'$  be the natural projections from  $X_1$  to  $X$  and  $Y_1$  respectively.

$$\begin{array}{ccc} X_1 & \xrightarrow{p'_1} & X \\ \downarrow q' & & \downarrow q \\ Y_1 & \xrightarrow{p_1} & Y \end{array}$$

The morphism  $p'_1$  is flat and  $q'$  is proper. Pick any cycle  $\gamma$  whose class is in  $\text{IC}^{e_1+k}(Y_1)$ . We want to prove that  $(\gamma \cdot p_1^* q_* \alpha) = 0$ . By [Ful98, Proposition 1.7], we have that  $p_1^* q_* \alpha = q'_* p_1'^* \alpha$  in  $Z_{e_1+k}(Y_1)$ . Applying the projection formula, we get:

$$\gamma \cdot p_1^* q_* \alpha = \gamma \cdot q'_* p_1'^* \alpha \sim q'_*(q'^* \gamma \cdot p_1'^* \alpha).$$

Because  $p'_1$  is flat and  $q'^* \gamma \in \text{IC}^{e_1+k}(X_1)$ , we have  $(q'^* \gamma \cdot p_1'^* \alpha) = 0$  so that  $(\gamma \cdot p_1^* q_* \alpha) = 0$  as required.  $\square$

The numerical classes defined above are hard to manipulate, we want to define a pullback of numerical classes by any proper morphism. We proceed and define dual classes.

We denote by  $Z^k(X) = \text{Hom}_{\mathbb{Z}}(Z_k(X), \mathbb{Z})$  the space of cocycles. If  $p_1 : X_1 \rightarrow X$  is a flat morphism of relative dimension  $e_1$ , then any element  $\gamma \in \text{IC}^{e_1+k}(X_1)$  induces an element  $[\gamma]$  in  $Z^k(X)$  by the following formula:

$$[\gamma] : \alpha \in Z_k(X) \rightarrow (\gamma \cdot p_1^* \alpha) \in \mathbb{Z}. \quad (8)$$

**Definition 2.1.5.** *The abelian group  $N^k(X)$  is the subgroup of  $Z^k(X)$  generated by elements of the form  $[\gamma]$  where  $\gamma \in \text{IC}^{e_1+k}(X_1)$  and  $X_1$  is flat over  $X$  of relative dimension  $e_1$ .*

*Remark 2.1.6.* By definition, the map  $\text{deg} : Z_0(X) \rightarrow \mathbb{Z}$  is naturally an element of  $Z^0(X)$ . Moreover, one has using Theorem 1.3.4.(2) that:

$$z \in Z_0(X) \rightarrow (s_0(E) \lrcorner z) = \text{deg}(z) \in \mathbb{Z},$$

for any vector bundle  $E$  on  $X$ . Hence,  $\text{deg}$  defines an element of  $N^0(X)$  by definition of Segré classes (Definition 7).

**Proposition 2.1.7.** *By definition of the numerical equivalence relation, any element of  $N^k(X)$  induces an element of the dual  $\text{Hom}_{\mathbb{Z}}(N_k(X), \mathbb{Z})$ . Hence, we can define a natural pairing between  $N^k(X)$  and  $N_k(X)$ . For any normal projective variety, the pairing  $N^k(X) \times N_k(X) \rightarrow \mathbb{Z}$  is non degenerate.*

*Proof.* It follows directly from the definition of  $N^k(X)$  and  $N_k(X)$ . □

A priori, an element of  $N^k(X)$  is a combination of elements  $[\gamma_1] + [\gamma_2] + \dots + [\gamma_i]$ . The following proposition proves one can always take  $i = 1$  at least if we tensor all spaces by  $\mathbb{Q}$ .

**Proposition 2.1.8.** *Any element of  $N^k(X)$  is induced by  $\gamma \in \text{IC}^{e_1+k}(X_1)_{\mathbb{Q}}$  where  $p_1 : X_1 \rightarrow X$  is a flat morphism of relative dimension  $e_1$ .*

*Proof.* By an immediate induction argument, we are reduced to prove the assertion for the sum of two elements  $[\gamma_1] + [\gamma_2]$  where  $\gamma_i \in \text{IC}^{e_i+k}(X_i)_{\mathbb{Q}}$  and  $p_i : X_i \rightarrow X$  are flat morphisms of relative dimension  $e_1$  and  $e_2$  respectively.

Let us consider  $X'$  the fibre product  $X_1 \times X_2$  and  $p'_i$  the flat projections from  $X'$  to  $X_i$  for  $i = 1, 2$ . By linearity, this amounts to show that there exists an element  $\gamma'_1 \in \text{IC}^{e_1+e_2+k}(X')$  such that  $[\gamma'_1] = [\gamma_1]$  in  $N^k(X)$ .

$$\begin{array}{ccc}
 & X_1 \times X_2 & \\
 & \swarrow p'_2 \quad \searrow p'_1 & \\
 X_1 & & X_2 \\
 & \searrow p_1 \quad \swarrow p_2 & \\
 & X & 
 \end{array}$$

Take an ample Cartier divisor  $\omega_{X_2}$  on  $X_2$  and  $\lambda_2$  an integer such that  $p_{2*}\omega_{X_2}^{e_2} \sim \lambda_2[X]$ . Setting  $\gamma'_1 = \frac{1}{\lambda_2} p_1^* \omega_{X_2}^{e_2} \cdot p_2^* \gamma_1$ , we need to prove that for any  $\alpha \in Z_k(X)$ , one has  $(\gamma_1 \cdot p_1^* \alpha) = (\gamma'_1 \cdot p_2^* p_1^* \alpha)$ . By [Ful98, Proposition 1.7], we have the equality  $p'_{2*} p_1^* \omega_{X_2}^{e_2} = p_1^* p_{2*} \omega_{X_2}^{e_2}$  in  $Z^{e_2}(X_2)$ , hence:

$$p'_{2*} p_1^* \omega_{X_2}^{e_2} = \lambda_2 p_1^*[X].$$

Since  $X_1$  is reduced and  $p_1^*[X]$  is a cycle of codimension 0 in  $X_1$ , we have  $p_1^*[X] = [X_1]$ . Hence by the projection formula, we have:

$$\begin{aligned}
 \frac{1}{\lambda_2} p'_{2*} (p_2^* (\gamma_1 \cdot p_1^* \alpha) \cdot p_1^* \omega_{X_2}^{e_2}) &\sim \frac{1}{\lambda_2} (p_1^* \alpha \cdot \gamma_1) \cdot p_{2*} p_1^* \omega_{X_2}^{e_2} \\
 &\sim \frac{1}{\lambda_2} (p_1^* \alpha \cdot \gamma_1) \cdot \lambda_2 [X_1] \\
 &\sim p_1^* \alpha \cdot \gamma_1.
 \end{aligned}$$

In particular, the degrees are equal and  $[\gamma_1] = [\gamma'_1] \in N^k(X)$  as required. □

**Definition 2.1.9.** *We define  $N_{\bullet}(X)$  (resp.  $N^{\bullet}(X)$ ) by  $\bigoplus_k N_k(X)$  (resp.  $\bigoplus_k N^k(X)$ ).*

**2.2. Algebra structure on the space of numerical cycles.** We now define a structure of algebra on  $N^{\bullet}(X)$ , and prove that  $N_{\bullet}(X)$  has a structure of  $N^{\bullet}(X)$  module.

Pick  $\gamma \in \text{IC}^{e_1+k}(X_1)_{\mathbb{Q}}$  where  $p_1 : X_1 \rightarrow X$  is a flat morphism of relative dimension  $e_1$ . The element  $\gamma$  induces a morphism in the Chow group:

$$\gamma_{\perp} \cdot : \alpha \in A_l(X) \rightarrow p_{1*}(\gamma \cdot p_1^* \alpha) \in A_{l-k}(X). \quad (9)$$

The morphism  $\gamma_{\perp} \cdot : A_l(X) \rightarrow A_{l-k}(X)$  induces a morphism of abelian groups from  $N_l(X)$  to  $N_{l-k}(X)$ .

**Proposition 2.2.1.** *Any element  $\alpha \in N^k(X)$  induces a morphism  $\alpha_{\perp} \cdot : N_{\bullet}(X) \rightarrow N_{\bullet-k}(X)$  such that the following conditions are satisfied.*

- (1) If  $\alpha$  is induced by  $\gamma \in \text{IC}^{e_1+k}(X_1)$  where  $p_1 : X_1 \rightarrow X$  is a flat morphism of relative dimension  $e_1$ , then for any integer  $l$  and any  $z \in N_l(X)$ , one has in  $N_{l-k}(X)$ :

$$\alpha \lrcorner z = \gamma \lrcorner z.$$

- (2) For any  $\alpha, \beta \in N^k(X)$  and any  $z \in N_l(X)$ , we have:

$$(\alpha + \beta) \lrcorner z = \alpha \lrcorner z + \beta \lrcorner z.$$

Hence, the space  $N_\bullet(X)$  has a structure of  $N^\bullet(X)$ -module.

*Proof.* Let us consider  $\alpha \in N^k(X)$  and suppose it is induced by  $\gamma_1 \in \text{IC}^{e_1+k}(X_1)_\mathbb{Q}$  where  $p_1 : X_1 \rightarrow X$  is a flat morphism of relative dimension  $e_1$ . We define the map  $\alpha \lrcorner \cdot$  as :

$$\alpha \lrcorner z = \gamma_1 \lrcorner z,$$

for any  $z \in N_l(X)$ . We show that the morphism does not depend on the choice of the class  $\gamma_1$  and (1) is follows from Proposition 2.1.8. Once (1) is satisfied, then (2) follows directly from the linearity of the intersection product.

Suppose that  $[\gamma_1] = [\gamma_2] \in N^k(X)$  where  $\gamma_2 \in \text{IC}^{e_2+k}(X_2)_\mathbb{Q}$  and  $p_2 : X_2 \rightarrow X$  is a flat morphism of relative dimension  $e_2$ , then we need to prove that:

$$p_{1*}(\gamma_1 \cdot p_1^* z) \equiv p_{2*}(\gamma_2 \cdot p_2^* z),$$

for any fixed  $z \in Z_l(X)$ . Take  $\beta \in \text{IC}^{e_3+l-k}(X_3)$  where  $p_3 : X_3 \rightarrow X$  is flat morphism of relative dimension  $e_3$ , we only need to show that:

$$(\beta \cdot p_3^* p_{1*}(\gamma_1 \cdot p_1^* z)) = (\beta \cdot p_3^* p_{2*}(\gamma_2 \cdot p_2^* z)).$$

Let  $X'_1$  and  $X'_2$  the fibre products  $X_1 \times X_3$  and  $X_2 \times X_3$ , and  $p'_1 : X'_1 \rightarrow X_3$ ,  $p'_3 : X'_1 \rightarrow X_1$ ,  $q_2 : X'_2 \rightarrow X_3$ ,  $q_3 : X'_2 \rightarrow X_2$  be the corresponding flat projection morphisms such that we obtain the following commutative diagrams:

$$\begin{array}{ccc} & X'_1 & \\ & \swarrow \quad \searrow & \\ X_1 & & X_3 \\ & \searrow \quad \swarrow & \\ & X & \end{array} \quad \begin{array}{ccc} & X'_2 & \\ & \swarrow \quad \searrow & \\ X_2 & & X_3 \\ & \searrow \quad \swarrow & \\ & X & \end{array}$$

As above, we have  $p_3^* p_{1*} = p'_{1*} p'^*_3$ , hence:

$$\begin{aligned} (\beta \cdot p_3^* p_{1*}(\gamma_1 \cdot p_1^* z)) &= (\beta \cdot p'_{1*} p'^*_3(\gamma_1 \cdot p_1^* z)) \\ &= (p'^*_1 \beta \cdot p'^*_3(\gamma_1 \cdot p_1^* z)) \\ &= (p'^*_3 \gamma_1 \cdot p'^*_1 p'^*_3 z \cdot p'^*_1 \beta) \\ &= (\gamma_1 \cdot p'^*_3 p'^*_1(p'^*_3 z \cdot \beta)) \\ &= (\gamma_1 \cdot p'^*_1 p_{3*}(p'^*_3 z \cdot \beta)) \\ &= (\gamma_2 \cdot p_2^* p_{3*}(p'^*_3 z \cdot \beta)). \end{aligned}$$

By a similar argument, we show that  $(\beta \cdot p_3^* p_{2*}(\gamma_2 \cdot p_2^* z)) = (\gamma_2 \cdot p_2^* p_{3*}(p'^*_3 z \cdot \beta))$  which implies the desired equality:

$$(\beta \cdot p_3^* p_{1*}(\gamma_1 \cdot p_1^* z)) = (\beta \cdot p_3^* p_{2*}(\gamma_2 \cdot p_2^* z)).$$

□

**Proposition 2.2.2.** *There exists a unique structure of commutative graded ring with unit  $(\text{deg})$  on  $N^\bullet(X)$  compatible with the action  $\lrcorner$  on  $N_\bullet(X)$ .*

*Proof.* Take  $\alpha_1 \in N^k(X)$  and  $\alpha_2 \in N^l(X)$  and define  $\varphi \in Z^{k+l}(X)$  by the formula:

$$\varphi : z \in Z_{k+l}(X) \rightarrow (\alpha_1 \frown (\alpha_2 \frown z)).$$

We prove that  $\varphi$  is an element of  $N^{k+l}(X)$ .

By linearity, we can suppose that  $\alpha_i$  is induced by  $\gamma_i \in \text{IC}^{k+e_i}(X_i)$  where  $p_i : X_i \rightarrow X$  is a flat morphism of relative dimension  $e_i$  for  $i = 1, 2$ . Let  $X' = X_1 \times_X X_2$  be the fibre product, let  $p'_1$  and  $p'_2$  be the projections from  $X'$  to  $X_1$  and  $X_2$  respectively such that we have the commutative diagram:

$$\begin{array}{ccc} & X' & \\ & \swarrow p'_2 \quad \searrow p'_1 & \\ X_1 & & X_2 \\ & \searrow p_1 \quad \swarrow p_2 & \\ & X & \end{array}$$

By the projection formula, we obtain for all  $z \in Z_{k+l}(X)$ :

$$\varphi(z) = (p_1'^* \gamma_2 \cdot p_2'^* \gamma_1 \cdot p_2'^* p_1^* z). \quad (10)$$

In particular, we have shown that  $\varphi$  is induced by  $p_1'^* \gamma_2 \cdot p_2'^* \gamma_1 \in \text{IC}^{e_1+e_2+k+l}(X')$ , hence  $\varphi$  is an element of  $N^{k+l}(X)$ . Moreover, the commutativity of the intersection product in (10) proves that  $(\alpha_2 \frown (\alpha_1 \frown z)) = (\alpha_1 \frown (\alpha_2 \frown z))$  for any  $z \in N_{k+l}(X)$ , hence  $\alpha_1 \cdot \alpha_2 = \alpha_2 \cdot \alpha_1$ .

Pick a vector bundle  $E$  on  $X$ . As the element  $\text{deg} \in N^0(X)$  is equal to  $z \rightarrow (s_0(E) \frown z)$  in  $N^0(X)$  (see Remark 2.1.6), we get using Theorem 1.3.4.(2) that:

$$(\alpha \frown z) = (\alpha \frown (s_0(E) \frown z)) = (s_0(E) \frown (\alpha \frown z)) = ((\alpha \cdot \text{deg}) \frown z) = (\text{deg} \cdot \alpha) \frown z,$$

for any  $z \in N_l(X)$  and any  $\alpha \in N^l(X)$ . Hence,  $\text{deg}$  is a unit of  $N^\bullet(X)$ . □

**2.3. Pullback on dual numerical classes.** Let us consider  $q : X \rightarrow Y$  a proper morphism. We define for any integer  $k$  the pullback  $q^* : N^k(Y) \rightarrow N^k(X)$  as the dual of the pushforward operation  $q_* : N_k(X) \rightarrow N_k(Y)$  with respect to the pairing  $N^k(X) \times N_k(X) \rightarrow \mathbb{Z}$  defined in Proposition 2.1.7.

**Proposition 2.3.1.** *Let  $q : X \rightarrow Y$  be a proper morphism. The morphism  $q^* : N^\bullet(Y) \rightarrow N^\bullet(X)$  is a morphism of graded rings which satisfies the projection formula:*

$$\forall \alpha \in N^k(Y), \forall z \in N_l(X), q_*(q^* \alpha \frown z) = \alpha \frown q_* z.$$

*Proof.* We only need to prove the projection formula as it directly implies that  $q^* : N^\bullet(Y) \rightarrow N^\bullet(X)$  is a morphism of rings since:

$$(\alpha \cdot \beta) \frown q_* z = q^*(\alpha \cdot \beta) \frown z = \alpha \frown q_*(q^* \beta \frown z) = (q^* \alpha \cdot q^* \beta) \frown z,$$

for any  $\alpha \in N^k(Y)$ ,  $\beta \in N^l(Y)$  and any  $z \in N_{k+l}(X)$ .

Consider a class  $\alpha \in N^k(Y)$  which is induced by  $\gamma \in \text{IC}^{e_1+k}(Y_1)$  where  $p_1 : Y_1 \rightarrow Y$  is a flat proper morphism of relative dimension  $e_1$ . Setting  $X_1$  to be the fibre product  $Y_1 \times Y$  and  $p'_1, q'$  the projections from  $X_1$  to  $X$  and  $Y_1$  respectively, one remarks using the equality  $q'_* p_1'^* = p_1^* q_*$  ([Ful98, Proposition 1.7]) that  $q^* \alpha$  is induced by  $q'^* \gamma$ . And the projection formula follows easily from the projection formula on divisors (Theorem 1.2.1.(2)). □

Let us sum up all the properties on numerical classes proven so far :

**Theorem 2.3.2.** *Let  $q : X \rightarrow Y$  be a proper morphism. For any integer  $0 \leq k \leq n$ :*

- (1) *The pushforward morphism  $q_* : Z_k(X) \rightarrow Z_k(Y)$  induces a morphism of abelian groups  $q_* : N_k(X) \rightarrow N_k(Y)$ .*
- (2) *The dual morphism  $q^* : Z^k(Y) \rightarrow Z^k(X)$  maps  $N^k(Y)$  into  $N^k(X)$ .*
- (3) *The induced morphism  $q^* : N^\bullet(Y) \rightarrow N^\bullet(X)$  preserves the structure of graded rings.*
- (4) *(Projection formula) For all  $\alpha \in N^k(Y)$  and all  $z \in N_l(X)$ , we have  $q_*(q^*\alpha \frown z) \equiv \alpha \frown q_*z$  in  $N_{l-k}(Y)$ .*

## 2.4. Canonical morphism.

**Theorem 2.4.1.** *There exists a canonical morphism  $\psi_X : N^k(X) \rightarrow N_{n-k}(X)$  which satisfies the following properties.*

- (1) *The image of the morphism  $\deg : Z_0(X) \rightarrow \mathbb{Z}$  seen as an element of  $Z^0(X)$  is given by  $\psi_X(\deg) = [X]$ .*
- (2) *The morphism  $\psi_X$  is  $N^k(X)$ -equivariant, i.e for all  $\alpha \in N^k(X)$  and all  $\beta \in N^l(X)$ , we have:*

$$\psi_X(\alpha \cdot \beta) = \alpha \frown \psi_X(\beta).$$

- (3) *Suppose  $q : X \rightarrow Y$  is a generically finite morphism where  $Y$  is of dimension  $n$ , then we have the following identity:*

$$q_* \circ \psi_X \circ q^* = \deg(q) \times \psi_Y.$$

*Proof.* We define  $\psi_X$  for any  $\alpha \in N^k(X)$  by setting:

$$\psi_X(\alpha) = \alpha \frown [X].$$

By construction, we have that  $\psi_X(\deg) = [X]$  and (2) follows directly from the definition and Proposition 2.2.2.

Assertion (3) is then a consequence of the projection formula (see Theorem 2.3.2.(4)) and the fact that  $q_*[X] = \deg(q)[Y]$ . □

Now we prove some properties of  $\psi_X$  in some particular cases.

**Theorem 2.4.2.** *The following properties are satisfied.*

- (1) *If  $X = X'/G$  is the quotient of a smooth variety  $X'$  by a finite group  $G$ , then for all integer  $0 \leq k \leq n$ , the induced morphism  $\psi_X : N^k(X)_{\mathbb{Q}} \rightarrow N_{n-k}(X)_{\mathbb{Q}}$  is an isomorphism.*
- (2) *If  $X$  is smooth and  $q : X \rightarrow Y$  is a surjective generically finite morphism where  $Y$  is a normal projective variety. Then we have for all integer  $k$ :*

$$q^*(\psi_Y(N^{n-k}(Y)_{\mathbb{Q}})^\perp) = q^*(N^k(Y)_{\mathbb{Q}}) \cap \text{Ker}(q_* \circ \psi_X : N^k(X)_{\mathbb{Q}} \rightarrow N_{n-k}(Y)_{\mathbb{Q}}). \quad (11)$$

*Proof.* (1) Suppose that  $X$  is smooth. Let us show that  $\psi_X$  is surjective. By Grothendieck-Riemann-Roch's theorem (Theorem 1.3.6), the Chern character induces an isomorphism:

$$\text{ch}_\frown [X] : E \in K^0(X) \otimes \mathbb{Q} \rightarrow \text{ch}(E) \frown [X] \in A_\bullet(X) \otimes \mathbb{Q}.$$

This implies that the morphism  $\psi_X : N^k(X)_{\mathbb{Q}} \rightarrow N_{n-k}(X)_{\mathbb{Q}}$  is surjective because any Chern class is the image of a product of Cartier divisors by a flat map (see Remark 1.3.3).

We now prove that  $\psi_X : N^k(X)_{\mathbb{Q}} \rightarrow N_{n-k}(X)_{\mathbb{Q}}$  is injective. Take  $\alpha_1 \in N^k(X)_{\mathbb{Q}}$  such that  $\psi_X(\alpha_1) = 0$ . By Proposition 2.1.8, the class  $\alpha_1$  is induced by  $\gamma_1 \in \text{IC}^{e_1+k}(X_1)_{\mathbb{Q}}$  where  $p_1 : X_1 \rightarrow X$  is a flat morphism of relative dimension  $e_1$ . The condition  $\psi_X(\alpha_1) = 0$  is equivalent to the equality

$p_{1*}\gamma_1 \equiv 0$ . We need to show that  $(\gamma_1 \cdot p_1^*z) = 0$  for any cycle  $z \in Z_k(X)$ . As  $X$  is smooth, we may compute intersection products inside the Chow group  $A_\bullet(X)$  directly by Remark 1.3.3 and we get:

$$(\gamma_1 \cdot p_1^*z) = (p_{1*}(\gamma_1 \cdot p_1^*z)) = (p_{1*}\gamma_1 \cdot z) = 0$$

as the class  $z \in N_k(X)$  is the image of an element of  $N^{n-k}(X)_\mathbb{Q}$  by surjectivity of  $\psi_X$ .

Let us consider  $X$  the quotient of  $X'$  by  $G$  where  $X'$  is a smooth projective variety and  $G$  is a finite group. We prove that  $\psi_X$  is surjective. Pick  $\beta \in N_{n-k}(X)_\mathbb{Q}$ , we only need to find a vector bundle  $E$  on  $X$  such that  $\text{ch}_k(E)_\perp[X] = \beta$ . Since the projection map  $q : X' \rightarrow X$  from  $X'$  to  $X$  is finite, the class  $\beta \in N_{n-k}(X)_\mathbb{Q}$  is the image by  $q$  of a class  $\alpha' \in N_{n-k}(X')_\mathbb{Q} \simeq N^k(X')_\mathbb{Q}$ . Applying Grothendieck-Riemann-Roch's theorem, there exists a vector bundle  $E'$  such that  $\text{ch}_k(E') = \alpha'$ . Setting  $E = \sum_{g \in G} g^*E'$  where any element  $g$  acts on  $X'$  by multiplication. By construction,  $\text{ch}_k(E) = |G| \times \alpha$  where  $|G|$  is the cardinal of the group  $G$  and the vector bundle  $E$  is  $G$ -equivariant, hence descends to a vector bundle  $E|_X$  on  $X$ . We have then  $\text{ch}_k(E|_X)_\perp[X] = |G| \times \beta$  as required. The injectivity of  $\psi_X$  is a consequence of the surjectivity of  $\psi_X$  since  $\ker(\psi_X|_{N^k(X)_\mathbb{Q}}) \subset \text{Im}(\psi_X|_{N^{n-k}(X)_\mathbb{Q}})^\perp = \{0\}$  where the orthogonal is taken with respect to the non-degenerate pairing  $N^k(X)_\mathbb{Q} \times N_k(X)_\mathbb{Q} \rightarrow \mathbb{Z}$ .

(3) We have the following series of equivalence:

$$\begin{aligned} \beta \in \psi_Y(N^{n-k}(Y)_\mathbb{Q})^\perp &\Leftrightarrow \forall \alpha \in N^{n-k}(Y)_\mathbb{Q}, (\beta \lrcorner \psi_Y(\alpha)) = 0 \\ &\Leftrightarrow \forall \alpha \in N^{n-k}(Y)_\mathbb{Q}, (\beta \lrcorner (q_*\psi_X q^*\alpha)) = 0 \\ &\Leftrightarrow \forall \alpha \in N^{n-k}(Y)_\mathbb{Q}, (q^*\beta \cdot q^*\alpha) = 0 \\ &\Leftrightarrow \forall \alpha \in N^{n-k}(Y)_\mathbb{Q}, (\alpha \lrcorner q_*\psi_X q^*\beta) = 0 \\ &\Leftrightarrow q^*\beta \in \text{Ker}(q_* \circ \psi_X : N^k(X)_\mathbb{Q} \rightarrow N_{n-k}(Y)_\mathbb{Q}), \end{aligned}$$

where the second equivalence follows from Theorem 2.4.2.(3), the third and the fourth equivalence from the projection formula, and the last equivalence is a consequence of the fact that  $\psi_X$  is self-adjoint :

$$(\beta \lrcorner \psi_Y(\alpha)) = (\beta \lrcorner (\alpha \lrcorner [Y])) = (\alpha \lrcorner (\beta \lrcorner [Y])) = (\alpha \lrcorner \psi_Y(\beta)),$$

where  $\alpha \in N^k(Y)$  and  $\beta \in N^{n-k}(Y)$ . □

*Remark 2.4.3.* The proof of Theorem 2.4.2.(1) shows that when  $X$  is smooth,  $N_k(X)_\mathbb{Q}$  is the quotient of  $Z_k(X)_\mathbb{Q}$  by cycles  $z \in Z_k(X)_\mathbb{Q}$  such that for any cycle  $z' \in Z_{n-k}(X)_\mathbb{Q}$ , one has  $(z \cdot z') = 0$ .

*Remark 2.4.4.* When  $X$  is smooth and when  $\kappa = \mathbb{C}$ , denote by  $\text{Alg}^k(X)$  the subgroup of the de Rham cohomology  $H^{2k}(X, \mathbb{C})$  generated by algebraic cycles of dimension  $k$  in  $X$ . Then there is a surjective morphism  $\text{Alg}^k(X) \rightarrow N^k(X)_\mathbb{Q}$

## 2.5. Numerical spaces are finite dimensional.

**Theorem 2.5.1.** *Both  $\mathbb{Q}$ -vector spaces  $N_k(X)_\mathbb{Q}$  and  $N^k(X)_\mathbb{Q}$  are finite dimensional.*

*Proof.* If  $X$  is smooth, then using Remark 2.4.3,  $N_k(X)_\mathbb{Q}$  is the quotient of  $Z_k(X)_\mathbb{Q}$  by the equivalence relation which identifies cycles  $\alpha$  and  $\beta$  in  $Z_k(X)_\mathbb{Q}$  if for any cycle  $z \in Z_{n-k}(X)_\mathbb{Q}$ ,  $(z \cdot \alpha) = (z \cdot \beta)$ . In particular, the vector-space  $N_k(X)_\mathbb{Q}$  is finitely generated (see [Mil13, Theorem 23.6] for a reference), and so is  $N^k(X)_\mathbb{Q}$  using Theorem 2.4.2.(1).

If  $X$  is not smooth, by DeJong's alteration theorem (cf [Jon96, Theorem 4.1]), there exists a smooth projective variety  $X'$  and a generically finite surjective morphism  $q : X' \rightarrow X$ . We only need to show that the pushforward  $q_* : N_k(X')_\mathbb{Q} \rightarrow N_k(X)_\mathbb{Q}$  is surjective. Indeed this first implies that  $N_k(X)_\mathbb{Q}$  is finite dimensional. Since the natural pairing  $N^k(X)_\mathbb{Q} \times N_k(X)_\mathbb{Q} \rightarrow \mathbb{Q}$  is non



degenerate we get an injection of  $N^k(X)_{\mathbb{Q}}$  onto  $\text{Hom}_{\mathbb{Q}}(N_k(X)_{\mathbb{Q}}, \mathbb{Q})$  which is also finite dimensional.

We take  $V$  an irreducible subvariety of codimension  $k$  in  $X$ . If  $\dim q^{-1}(V) = \dim V$ , then the class  $q_*[q^{-1}(V)]$  in  $N_{\dim V}(X)_{\mathbb{Q}}$  is represented by a cycle of dimension  $\dim V$  which is included in  $V$ . As  $V$  is irreducible, we have  $q_*[q^{-1}(V)] \equiv \lambda[V]$  for some  $\lambda \in \mathbb{N}^*$ .

If the dimension of  $q^{-1}(V)$  is strictly greater than  $V$ , we take  $W$  an irreducible component of  $q^{-1}(V)$  such that its image by  $q|_W : W \rightarrow V$  is dominant. We write the dimension of  $W$  as  $\dim V + r$  where  $r > 0$  is an integer. Fix an ample divisor  $\omega_X$  on  $X$ . The class  $\omega_X^r \lrcorner [W] \in N_{\dim V}(X)_{\mathbb{Q}}$  is represented by a cycle of dimension  $\dim V$  in  $W$ . So the image of the class  $q_*(\omega_X^r \lrcorner [W]) \in N_{\dim V}(X)_{\mathbb{Q}}$  is a multiple of  $[V]$  which implies the surjectivity of  $q_*$ .  $\square$

**Corollary 2.5.2.** *For any integer  $0 \leq k \leq n$ , the pairing  $N^k(X)_{\mathbb{R}} \times N_k(X)_{\mathbb{R}} \rightarrow \mathbb{R}$  is perfect.*

**Corollary 2.5.3.** *Suppose that the dimension of  $X$  is  $2n$ , then the morphism  $\psi_X : N^n(X)_{\mathbb{Q}} \rightarrow N_n(X)_{\mathbb{Q}}$  is an isomorphism.*

*Proof.* We apply (11) to an alteration  $X'$  of  $X$  where  $q : X' \rightarrow X$  is a proper surjective morphism and where  $X'$  is a smooth projective surface. This proves that  $\psi_X : N^n(X)_{\mathbb{Q}} \rightarrow N_n(X)_{\mathbb{Q}}$  is surjective. By duality, this gives that  $\psi_X : N^n(X)_{\mathbb{Q}} \rightarrow N_n(X)_{\mathbb{Q}}$  is injective. As a consequence, we have that  $\psi_X : N^n(X)_{\mathbb{Q}} \rightarrow N_n(X)_{\mathbb{Q}}$  is an isomorphism.  $\square$

**Corollary 2.5.4.** *Let  $X$  be a complex normal projective variety with at most rational singularities. We suppose that  $X$  is numerically  $\mathbb{Q}$ -factorial in the sense of [BdFFU15]. Then the morphisms  $\psi_X : N^1(X)_{\mathbb{Q}} \rightarrow N_{n-1}(X)_{\mathbb{Q}}$  and  $\psi_X : N^{n-1}(X)_{\mathbb{Q}} \rightarrow N_1(X)_{\mathbb{Q}}$  are isomorphisms.*

*Proof.* Using [BdFFU15, Theorem 5.11], then any Weil divisor which is numerically  $\mathbb{Q}$ -Cartier is  $\mathbb{Q}$ -Cartier. In particular,  $\psi_X : N^1(X)_{\mathbb{Q}} \rightarrow N_{n-1}(X)_{\mathbb{Q}}$  is surjective. Using (11) to an alteration of  $X'$  applied to  $k = 1$ , we have that  $\psi_X : N^1(X)_{\mathbb{Q}} \rightarrow N_{n-1}(X)_{\mathbb{Q}}$  is injective. Hence  $N^1(X)_{\mathbb{Q}}$  and  $N_{n-1}(X)_{\mathbb{Q}}$  are isomorphic and by duality  $N^{n-1}(X)_{\mathbb{Q}}$  and  $N_1(X)_{\mathbb{Q}}$  are also isomorphic.  $\square$

*Example 2.5.5.* When  $X = X(\Delta)$  be a toric variety associated to a complete fan  $\Delta$ . The map  $\psi_X : N^1(X)_{\mathbb{Q}} \rightarrow N_{n-1}(X)_{\mathbb{Q}}$  is an isomorphism if and only if  $\Delta$  is a simplicial fan using [Ful93, exercise p65 section 3.4].

### 3. POSITIVITY

The notion of positivity is relatively well understood for cycles of codimension 1 and of dimension 1. For cycles of intermediate dimension this situation is however more subtle and was only recently seriously considered (see [DELV11], [CC15], [CLO16] and the recent series of papers by Fulger and Lehmann ([FL14a], [FL14b])).

For our purpose, we will first review the notions of pseudo-effectivity and numerically effective classes. Then we will focus on the strongly pliant cone, which is a cone which have the same properties as the pliant cone introduced by [FL14b] but which is more suitable for stating generalized Siu's inequalities (see Section 3.3).

**3.1. Pseudo-effective and numerically effective cones.** As in the previous section,  $X$  is a normal projective variety of dimension  $n$ . To ease notation we shall also write  $N^k(X)$  and  $N_k(X)$  for the real vector spaces  $N^k(X)_{\mathbb{R}}$  and  $N_k(X)_{\mathbb{R}}$ .

**Definition 3.1.1.** *A class  $\alpha \in N_k(X)$  is pseudo-effective if it is in the closure of the cone generated by effective classes. This cone is denoted  $\text{Psef}_k(X)$ .*

When  $k = 1$ ,  $\text{Psef}_1(X)$  is the Mori cone (see e.g [KM98, Definition 1.17]), and when  $k = n - 1$ ,  $\text{Psef}_{n-1}(X)$  is the classical cone of pseudo-effective divisors, its interior being the big cone.

**Definition 3.1.2.** A class  $\beta \in N^k(X)$  is numerically effective (or nef) if for any class  $\alpha \in \text{Psef}_{n-k}(X)$ ,  $(\beta \perp \alpha) \geq 0$ . We denote this cone by  $\text{Nef}^k(X)$ .

When  $k = 1$ , the cone  $\text{Nef}^1(X)$  is the cone of numerically effective divisors, its interior is the ample cone.

We can define a notion of effectivity in the dual  $N^k(X)$ .

**Definition 3.1.3.** A class  $\alpha \in N^k(X)$  is pseudo-effective if  $\psi_X(\alpha) \in \text{Psef}_{n-k}(X)$ . We will write this cone as  $\text{Psef}^k(X)$ .

**Definition 3.1.4.** A class  $z \in N_k(X)$  is numerically effective if for any class  $\alpha \in \text{Psef}^k(X)$ , one has  $(\alpha \perp z) \geq 0$ . This cone is denoted  $\text{Nef}_k(X)$ .

By convention, we will write  $\alpha \leq \beta$  (resp.  $\alpha \leq \beta$ ) for any  $\alpha, \beta \in N_k(X)$  (resp.  $\alpha, \beta \in N^k(X)$ ) if  $\beta - \alpha \in \text{Psef}_k(X)$  (resp.  $\beta - \alpha \in \text{Psef}^k(X)$ ).

When  $X$  is smooth, the morphism  $\psi_X$  induces an isomorphism between  $N^k(X)$  and  $N_{n-k}(X)$ , and we can identify these cones:

$$\begin{aligned} \text{Nef}^k(X) &= \text{Nef}_{n-k}(X), \\ \text{Psef}^k(X) &= \text{Psef}_{n-k}(X). \end{aligned}$$

### 3.2. Strongly pliant classes.

**Definition 3.2.1.** The strongly pliant cone  $\mathcal{C}^k(X)$  is the closure of the convex cone in  $N^k(X)_{\mathbb{R}}$  generated by products of the form  $[\gamma_1] \cdot \dots \cdot [\gamma_l]$  where each  $\gamma_i$  is a product of  $e_i + k_i$  ample Cartier divisors on a normal projective variety  $X_i$  which is flat over  $X$  of relative dimension  $e_i$  and where  $k_i$  are integers satisfying  $k_1 + \dots + k_l = k$ .

*Remark 3.2.2.* By definition, the cone  $\mathcal{C}^k(X)$  contains the products of ample Cartier divisors and Segre classes of anti-ample vector bundles.

*Remark 3.2.3.* Recall the definition of pliant classes introduced in [FL14b, Definition 3.1]. The pliant cone is defined as the convex cone generated by product of Schur polynomials of globally generated vector bundle. We conjecture that the pliant cone and the strongly pliant cone are equal.

**Theorem 3.2.4.** The strongly pliant cone satisfies the following properties.

- (1) The cone  $\mathcal{C}^k(X)$  is a salient, closed, convex cone with non-empty interior in  $N^k(X)_{\mathbb{R}}$ .
- (2) The cone  $\mathcal{C}^k(X)$  contains products of ample Cartier divisors in its interior.
- (3) For all integer  $k$  and  $l$ , we have  $\mathcal{C}^k(X) \cdot \mathcal{C}^l(X) \subset \mathcal{C}^{k+l}(X)$ .
- (4) For any proper surjective morphism  $q : X \rightarrow Y$ , we have  $q^* \mathcal{C}^k(Y) \subset \mathcal{C}^k(X)$ .
- (5) For any integer  $k$ , we have  $\mathcal{C}^k(X) \subset \text{Nef}^k(X) \cap \text{Psef}^k(X)$ .
- (6) In codimension 1, one has  $\mathcal{C}^1(X) = \text{Nef}^1(X)$ .

*Proof.* We prove successively the items (3), (5), (6), (4), (2) and (1).

(3) This follows from the definition of  $\mathcal{C}^k(X)$ .

(5) It is sufficient to prove that for any effective cycle  $z \in Z_{n-l}(X)$  and any strongly pliant class  $\alpha \in \mathcal{C}^k(X)$ , then  $\alpha \perp z \in \text{Psef}_{n-k-l}(X)$ . Indeed, apply this successively to  $z = [X]$  and  $z \in \text{Psef}_k(X)$  give the inclusions  $\mathcal{C}^k(X) \subset \text{Psef}^k(X)$  and  $\mathcal{C}^k(X) \subset \text{Nef}^k(X)$ . By definition of strongly pliant classes and by linearity, we can suppose that  $\alpha$  is equal to a product  $[\gamma_1] \cdot \dots \cdot [\gamma_p]$  where  $\gamma_i \in \text{IC}^{e_i+k_i}(X_i)_{\mathbb{R}}$  are products of ample Cartier divisors on  $X_i$  where  $p_i : X_i \rightarrow X$  is a flat

proper morphism of relative dimension  $e_i$  and where  $k_i$  are integers such that  $k_1 + \dots + k_p = k$ . By definition, one has  $[\gamma_1] \lrcorner z = p_{1*}(\gamma_1 \cdot p_1^* z)$ . Because the cycle  $z$  is pseudo-effective, the cycle  $p_1^* z$  remains pseudo-effective as  $p_1$  is a flat morphism. As  $\gamma_1$  is a positive combination of products of ample Cartier divisors, we deduce that the cycle  $\gamma_1 \cdot p_1^* z$  is pseudo-effective. Hence,  $[\gamma_1] \lrcorner z \in \text{Psef}_{n-l_1-l}(X)$ . Iterating the same argument, we get that  $\alpha \lrcorner z \in \text{Psef}_{n-k-l}(X)$  as required.

(6) The interior of  $\text{Nef}^1(X)$  is equal to the ample cone of  $X$  so by definition:

$$\text{Int}(\text{Nef}^1(X)) \subset \mathcal{C}^1(X).$$

As the closure of the ample cone is the nef cone by [Laz04, Theorem 1.4.21.(i)], one gets  $\text{Nef}^1(X) \subset \mathcal{C}^1(X)$ . Conversely, the cone  $\mathcal{C}^1(X)$  is included in the cone  $\text{Nef}^1(X)$ , so we get  $\mathcal{C}^1(X) = \text{Nef}^1(X)$ .

(4) By linearity and stability by products, we are reduced to treat the case of a class  $[D]$  induced by an ample Cartier divisor on  $Y_1$  where  $p_1 : Y_1 \rightarrow Y$  is a flat proper morphism, and prove that  $q^*[D]$  is a limit of ample Cartier divisors on a flat variety over  $X$ . Let  $X_1$  be the fibre product of  $Y_1$  and  $X$  and let  $q'$  be the natural projection from  $X_1$  to  $Y_1$ , observe that  $q^*[D]$  is induced by  $q'^*D$  which remains nef on  $X_1$  as  $q'$  is proper. In particular, it is the limit of ample divisors on  $N^1(X_1)$ .

(1) Take  $\alpha \in \mathcal{C}^k(X)$  such that  $-\alpha \in \mathcal{C}^k(X)$ . Then for all  $z \in \text{Psef}_k(X)$ , one has that  $(\alpha \lrcorner z) = 0$  as  $\alpha$  is nef by (5). Since effective classes of dimension  $k$  generate  $Z_k(X)$ , it follows that  $(\alpha \lrcorner z) = 0$  for any  $z \in N_k(X)_{\mathbb{R}}$  which implies by definition that  $\alpha = 0$ . This shows  $\mathcal{C}^k(X)$  is salient.

(2) We show now that  $\mathcal{C}^k(X)$  contains product of ample divisors in its interior.

Let  $h_1, \dots, h_k, h$  be  $k+1$  ample Cartier divisors on  $X$ . Pick  $m$  large enough such that the divisor  $mh_i - h$  is very ample for all  $i \leq k$ . We thus have  $m^k h_1 \cdot h_2 \cdot \dots \cdot h_k = h^k + R$  where  $R$  is an element of  $\mathcal{C}^k(X)$ . So we just need to prove that  $h^k$  is in the interior of  $\mathcal{C}^k(X)$  for any ample Cartier divisor  $h$ . We shall prove by induction on  $k$  that  $h^k$  is in the interior of  $\mathcal{C}^k(X)$  for any  $k \leq n$ .

For  $k = 1$ ,  $\mathcal{C}^1(X) = \text{Nef}^1(X)$ , and by definition, the divisor  $h$  is ample so it is in the interior of the nef cone and we are done. Now suppose that the product of ample divisors  $h^i$  lies in the interior of  $\mathcal{C}^i(X)$  for  $i < k$ .

Take a class  $\alpha \in N^k(X)_{\mathbb{R}}$ , by Proposition 2.1.8, the class  $\alpha$  is induced by an element  $\gamma \in \text{IC}^{e_1+k}(X_1)_{\mathbb{R}}$  where  $p_1 : X_1 \rightarrow X$  is a flat morphism of relative dimension  $e_1$ . Let us fix an ample Cartier divisor  $\omega_{X_1}$  on  $X_1$ . It is sufficient to prove that the induced class  $[M\omega_{X_1}^{e_1} \cdot p_1^* h^k - \gamma] \in \mathcal{C}^k(X)$  for  $M$  large enough. This amounts to prove that there is an  $M$  large enough such that the class  $M\omega_{X_1}^{e_1} \cdot p_1^* h^k - \omega_{X_1}^{e_1+k}$  induces an element of  $\mathcal{C}^k(X)$ . Indeed, we can write  $\gamma_1 = \omega_{X_1}^{e_1+k} - R'$  where  $R'$  is a positive combination of products of products of ample divisors. By the induction hypothesis, there is an integer  $m$  such that  $[m\omega_{X_1}^{e_1} \cdot p_1^* h^i - \omega_{X_1}^{e_1+i}] \in \mathcal{C}^i(X)$  for any  $i < k$ . We can suppose by replacing  $\omega_{X_1}$  by a multiple of itself that  $\omega_{X_1} + p_1^* h$  is an ample divisor on  $X_1$ . We set  $U = \omega_{X_1}^{e_1} \cdot (\omega_{X_1} + p_1^* h)^k$ . By definition of  $U$ , its induced class is strongly pliant  $[U] \in \mathcal{C}^k(X)$ , and we have.

$$U = \sum_{1 \leq i \leq k-1} \binom{k}{i} p_1^* h^i \cdot \omega_{X_1}^{e_1+(k-i)} + p_1^* h^k \cdot \omega_{X_1}^{e_1+k}$$

For  $i > k$ , for any cycle  $z \in A^{n-k}(X)$ ,  $h^i \cdot z \in A^{n-k+i}(X)$ , so we have  $h^i \cdot z = 0$  for any  $z \in A^{n-k}(X)$ . We have thus:

$$[U] - [\omega_{X_1}^{e_1+k}] + \sum_{i \leq k-1} \binom{k}{i} [p_1^* h^i \cdot (m\omega_{X_1}^{e_1} \cdot p_1^* h^{k-i} - \omega_{X_1}^{e_1+(k-i)})] = M \times [p_1^* h^k \cdot \omega_{X_1}^{e_1}] - [\omega_{X_1}^{e_1+k}],$$

where  $M = 1 + m \sum_{i \leq k-1} \binom{k}{i}$ . As  $[U] - [\omega_{X_1}^{e_1+k}] \in \mathcal{C}^k(X)$ , because it is a linear combination of products of strongly pliant classes, we deduce that  $M[p_1^* h^k \cdot \omega_{X_1}^{e_1}] - [\omega_{X_1}^{e_1+k}] \in \mathcal{C}^k(X)$ , which proves that  $[h^k]$  is in the interior of  $\mathcal{C}^k(X)$ .  $\square$

We give here a detailed proof of the fact that the pseudo-effective cone is salient (see also [FL14b, Corollary 3.17]). The proof uses a useful proposition that we will use later on.

**Proposition 3.2.5.** *Let  $\alpha \in \text{Psef}_{n-k}(X)$  be a pseudo-effective class on  $X$  and  $\gamma \in \mathcal{C}^{n-k}(X)$  be class lying in the interior of the strongly pliant cone. Then we have  $(\gamma \lrcorner \alpha) = 0$  if and only if  $\alpha = 0$ .*

*Proof.* Let us fix two strongly pliant classes  $\beta$  and  $\gamma$  in  $\mathbb{N}^{n-k}(X)$ , and a norm  $\|\cdot\|$  on  $\mathbb{N}^{n-k}(X)_{\mathbb{R}}$ . As  $\gamma$  is in the interior of  $\mathcal{C}^{n-k}(X)$  by Theorem 3.2.4.(2), there exists a positive constant  $C > 0$  such that for any  $\beta \in \mathcal{C}^{n-k}(X)$ , one has:

$$C \|\beta\|_{\mathbb{N}^{n-k}(X)_{\mathbb{R}}} \gamma - \beta \in \mathcal{C}^{n-k}(X).$$

Intersecting with  $\alpha \in \text{Psef}_{n-k}(X)$  and using Theorem 3.2.4.(5), we have that  $(\beta \cdot \alpha) = 0$ . Since the strongly pliant cone  $\mathcal{C}^{n-k}(X)$  generates all  $\mathbb{N}^{n-k}(X)_{\mathbb{R}}$  by Theorem 3.2.4.(1), we have proved that  $(\beta' \lrcorner \alpha) = 0$  for any  $\beta' \in \mathbb{N}^{n-k}(X)$ , hence  $\alpha = 0$  as required.  $\square$

**Corollary 3.2.6.** *The pseudo-effective cone  $\text{Psef}_{n-k}(X)$  is a closed, convex, full dimensional salient cone in  $\mathbb{N}_{n-k}(X)_{\mathbb{R}}$ .*

*Proof.* We take  $u \in \text{Psef}_{n-k}(X)$  such that  $-u \in \text{Psef}_{n-k}(X)$ , then for any ample Cartier divisor  $\omega_X$  on  $X$ , the products  $(\omega_X^{n-k} \cdot u)$  and  $(-u \cdot \omega_X^{n-k})$  are non-negative hence  $(u \cdot \omega_X^{n-k}) = 0$ . This implies that  $u = 0$  by Proposition 3.2.5.  $\square$

**3.3. Siu's inequality in arbitrary codimension.** We recall Siu's inequality:

**Proposition 3.3.1.** ([Laz04, Theorem 2.2.13]) *Let  $V$  be a closed subscheme of dimension  $r$  in  $X$  and let  $A, B$  be two  $\mathbb{Q}$ -divisors nef on  $X$  such that  $A|_V$  is big, then we have in  $\mathbb{N}_{k-1}(X)$ ,*

$$B \lrcorner [V] \leq \frac{r((A^{r-1} \cdot B) \lrcorner [V])}{(A^r \lrcorner [V])} A \lrcorner [V].$$

*Remark 3.3.2.* The case  $V = X$  is a consequence of the bigness criterion given in [Laz04, Theorem 2.2.13].

*Remark 3.3.3.* The proof of the previous proposition implies that  $B|_V \leq r(A^{r-1} \cdot B \lrcorner [V]) / (A^r \lrcorner [V]) \times A|_V$  in the Chow group  $A^1(V)$ . However, since we want to work in the numerical group, we compare these classes in  $X$  (we look at their pushforward by the inclusion of  $V$  in  $X$ ).

*Proof.* The proof is the same as in [Laz04, Theorem 2.2.13], that is to find a section of the line bundle  $\mathcal{O}_V(m(A - B))$ . We choose  $m$  general elements  $E_i$  of  $|B|$  and consider the exact sequence:

$$0 \quad \mathcal{O}_V(mA - mB) \quad \mathcal{O}_V(mA) \quad \oplus \mathcal{O}_{E_i}(mA) \quad 0.$$

Taking long exact sequence associated, one obtains the minoration:

$$h^0(V, \mathcal{O}_V(mA - mB)) \geq h^0(V, \mathcal{O}_V(mA)) - \sum_{i \leq m} h^0(E_i, \mathcal{O}_{E_i}(mA)).$$

Applying [GGJ<sup>+</sup>16, Corollary 3.6.3] to the nef divisor  $A$ , we get  $h^0(V, \mathcal{O}_V(mA)) = m^r / (r!)(A^r \lrcorner [V]) + o(m^r)$ . Hence,

$$h^0(V, \mathcal{O}_V(mA - mB)) \geq \frac{m^r}{r!}(A^r - rA^{r-1} \cdot B) \lrcorner [V] + o(m^r).$$

In particular, this implies the required inequality.  $\square$

The next result is a key for our approach to controlling degrees of dominant rational maps.

**Theorem 3.3.4.** *Let  $k$  be an integer and  $V$  be a closed subscheme of dimension  $r$  in  $X$ . For any Cartier divisors  $\alpha_1, \dots, \alpha_k$  and  $b$  which are big and nef on  $V$ , then there exists a constant  $C > 0$  depending only on  $r$  and  $k$  such that:*

$$(\alpha_1 \cdot \dots \cdot \alpha_k) \lrcorner [V] \leq (r - k + 1)^k \frac{(\alpha_1 \cdot \dots \cdot \alpha_k \cdot b^{r-k} \lrcorner [V])}{(b^r \lrcorner [V])} \times b^k \lrcorner [V] \in N_{r-k}(X).$$

*Remark 3.3.5.* Observe that  $(b^n) > 0$  since  $b$  is big.

*Proof.* By continuity, we can suppose that  $\alpha_i$  and  $b$  are ample Cartier divisors. We apply successively Siu's inequality by restriction to subschemes representing the classes  $\alpha_2 \cdot \dots \cdot \alpha_k \lrcorner [V]$ ,  $b \cdot \alpha_3 \cdot \dots \cdot \alpha_k \lrcorner [V]$ ,  $\dots$ ,  $b^{k-1} \cdot \alpha_k \lrcorner [V]$ :

$$\begin{aligned} \alpha_1 \cdot \alpha_2 \cdot \dots \cdot \alpha_k \lrcorner [V] &\leq (r - k + 1) \frac{(\alpha_1 \cdot \dots \cdot \alpha_k \cdot b^{r-k} \lrcorner [V])}{(b^{r-k+1} \cdot \alpha_2 \cdot \dots \cdot \alpha_k \lrcorner [V])} \times b \cdot \alpha_2 \cdot \dots \cdot \alpha_k \lrcorner [V], \\ b \cdot \alpha_2 \cdot \dots \cdot \alpha_k \lrcorner [V] &\leq (r - k + 1) \frac{(b^{r-k+1} \cdot \alpha_2 \cdot \dots \cdot \alpha_k \lrcorner [V])}{(b^{r-k+2} \cdot \alpha_3 \cdot \dots \cdot \alpha_k \lrcorner [V])} \times b^2 \cdot \alpha_3 \cdot \dots \cdot \alpha_k \lrcorner [V], \\ \dots &\dots \\ b^{k-1} \cdot \alpha_k \lrcorner [V] &\leq (r - k + 1) \frac{(b^{r-1} \cdot \alpha_k \lrcorner [V])}{(b^r \lrcorner [V])} \times b^k \lrcorner [V]. \end{aligned}$$

This gives the required inequality:

$$\alpha_1 \cdot \dots \cdot \alpha_k \lrcorner [V] \leq (n - k + 1)^k \frac{(\alpha_1 \cdot \dots \cdot \alpha_k \cdot b^{r-k} \lrcorner [V])}{(b^r \lrcorner [V])} \times b^k \lrcorner [V].$$

$\square$

**Corollary 3.3.6.** *Let  $k$  be an integer, then for any  $a \in \mathcal{C}^k(X)$  and any big nef Cartier divisor  $b$  on  $X$ , one has:*

$$a \leq (n - k + 1)^k \frac{(a \cdot b^{n-k})}{(b^n)} \times b^k.$$

*Proof.* By linearity and stability by product, we just need to prove the inequality for  $a = D_1 \cdot \dots \cdot D_{e_1+k} \in \text{IC}^{e_1+k}(X_1)$ , where  $D_i$  are ample Cartier divisors  $X_1$ , where  $p_1 : X_1 \rightarrow X$  is a flat proper morphism of relative dimension  $e_1$ . We apply Theorem 3.3.4 to  $a' = D_{e_1+1} \cdot \dots \cdot D_{e_1+k} \cdot Z$  and  $b' = b|_Z$  where  $Z = D_1 \cdot \dots \cdot D_{e_1}$ . We obtain:

$$a \leq (n - k + 1)^k \frac{(a \cdot b^{n-k})}{(b^n \cdot Z)} \times b^k \cdot Z.$$

As the restriction of  $p_1$  on  $Z$  is generically finite, by the projection formula, we get:

$$a \leq (n - k + 1)^k \frac{(a \cdot b^{n-k})}{(b^n)} \times b^k.$$

$\square$

The previous inequality can be applied when we have positivity hypothesis on a birational model as follows.

**Corollary 3.3.7.** *Let  $X, Y$  be two normal projective varieties of dimension  $n$ . Let  $\beta$  be a class in  $\mathcal{C}^k(Y)$ , we suppose there exists a birational morphism  $q : X \rightarrow Y$  and an ample Cartier divisor  $A$  on  $X$  such that  $A^k \leq q^*\beta$ . Then there exists a class  $\beta^* \in N_k(X)_{\mathbb{R}} \cap \text{Psef}_k(X)$  such that for any class  $\alpha \in \mathcal{C}^k(X)$ , we have:*

$$\alpha \leq (\alpha \perp \beta^*) \times \beta.$$

*Proof.* We just have to set  $\beta^* = \frac{(n-k+1)^k}{(A^n)} q_* \psi_X(A^{n-k})$ . □

*Remark 3.3.8.* We conjecture that for any strongly pliant class  $a \in \mathcal{C}^k(X)$  and any big nef divisor  $b$ , one has

$$a \leq \binom{n}{k} \frac{(a \cdot b^{n-k})}{(b^n)} b^k. \quad (12)$$

One can show that this inequality (if true) is optimal since equality can happen when  $X$  is an abelian variety.

**3.4. Norms on numerical classes.** In this section, the positivity properties combined with Siu's inequality allows us to define some norms on  $N_k(X)_{\mathbb{R}}$  and on  $N^k(X)_{\mathbb{R}}$ .

**3.4.1. Norms on  $N_k(X)_{\mathbb{R}}$ .** Let  $k \leq n$  be an integer and let  $\gamma \in \mathcal{C}^k(X)$  be a strongly pliant class on  $X$ . Any cycle  $z \in N_k(X)_{\mathbb{R}}$  can be written  $z = z^+ - z^-$  where  $z^+$  and  $z^-$  are pseudo-effective. We define :

$$F_{\gamma}(z) := \inf_{\substack{z = z^+ - z^- \\ z^+, z^- \in \text{Psef}_k(X)}} \{(\gamma \perp z^+) + (\gamma \perp z^-)\}. \quad (13)$$

**Proposition 3.4.1.** *For any class  $\gamma \in \mathcal{C}^k(X)$  lying in the interior of the strongly pliant cone, the function  $F_{\gamma}$  defines a norm on  $N_k(X)_{\mathbb{R}}$ . In particular, if we fix a norm  $\|\cdot\|_{N_k(X)_{\mathbb{R}}}$  on  $N_k(X)_{\mathbb{R}}$ , there exists a constant  $C > 0$  such that for any pseudo-effective class  $z \in \text{Psef}_k(X)$ , one has:*

$$\frac{1}{C} \|z\|_{N_k(X)_{\mathbb{R}}} \leq (\gamma \perp z) \leq C \|z\|_{N_k(X)_{\mathbb{R}}}. \quad (14)$$

*Proof.* The only point to clarify is that  $F_{\gamma}(z) = 0$  implies  $z = 0$ . Observe that Proposition 3.2.5 implies the result for  $z \in \text{Psef}_k(X)$ . In general, pick any two sequences  $(z_p^+)_{p \in \mathbb{N}}$  and  $(z_p^-)_{p \in \mathbb{N}}$  in  $\text{Psef}_k(X)$  such that  $z = z_p^+ - z_p^-$  and such that  $\gamma \cdot z_p^+ + \gamma \cdot z_p^- \rightarrow 0$ . Since  $z_p^+$  and  $z_p^-$  are pseudo-effective and  $\gamma$  is strongly pliant, it follows from Theorem 3.2.4.(5) that

$$\lim_{p \rightarrow +\infty} (\gamma \cdot z_p^+) = \lim_{p \rightarrow +\infty} (\gamma \cdot z_p^-) = 0.$$

As  $\gamma$  lies in the interior of  $\mathcal{C}^k(X)$ , given any  $\beta$  in  $\mathcal{C}^k(X)$ , one has that  $C\gamma - \beta$  is still in  $\mathcal{C}^k(X)$  for some sufficiently large constant  $C > 0$ . Intersecting with the pseudo-effective classes  $z_p^+$  and  $z_p^-$  and using Theorem 3.2.4.(5), we have  $\lim_{p \rightarrow \infty} (\beta \perp z_p^+) = \lim_{p \rightarrow \infty} (\beta \perp z_p^-) = 0$ , thus  $(\beta \perp z) = 0$ . Since the strongly pliant cone  $\mathcal{C}^k(X)$  generates all  $N^k(X)$  by Theorem 3.2.4.(1), we conclude that  $z = 0$  as required. □

### 3.4.2. Norms on $N^k(X)_{\mathbb{R}}$ .

**Definition 3.4.2.** We define the subcone  $\mathcal{C}_0^k(X)$  of  $\mathcal{C}^k(X)$  as the classes  $\alpha \in \mathcal{C}^k(X)$  such that for any birational map  $q : X' \rightarrow X$ , there exists an ample Cartier divisor  $A$  on  $X'$  such that  $q^*\alpha \geq A^k$ .

**Proposition 3.4.3.** The following assertions are satisfied.

- (1) Let  $\alpha \in N^k(X)$  be a strongly pliant class in  $X$ . Suppose there exists a normal projective variety  $X'$  and a birational map  $q : X' \rightarrow X$  such that  $q^*\alpha \geq A^k$  for an ample Cartier divisor  $A$  on  $X'$ , then  $\alpha \in \mathcal{C}_0^k(X)$ .
- (2) Let  $q : X' \rightarrow X$  be a generically finite surjective morphism. Then  $q^*\mathcal{C}_0^k(X) \subset \mathcal{C}_0^k(X')$ .
- (3) When  $X$  is smooth, the cone  $\mathcal{C}_0^1(X)$  is equal to the big nef cone. In particular  $\mathcal{C}_0^k$  is neither closed nor open in general.

*Proof.* (1) and (2) follow immediately from Theorem 3.3.4.

(3) Any big and nef divisor is by definition in  $\mathcal{C}_0^1(X)$  and the converse holds using again Theorem 3.3.4.  $\square$

**Proposition 3.4.4.** The cone  $\mathcal{C}_0^k(X)$  is a convex open subset of  $\mathcal{C}^k(X)$  that contains the classes induced by products of big nef divisors.

*Proof.* The cone  $\mathcal{C}_0^k(X)$  contains the products of big and nef Cartier divisors. The fact that  $\mathcal{C}_0^k(X)$  is convex is a consequence of Siu's inequality. We take two elements  $\alpha$  and  $\beta$  in  $\mathcal{C}_0^k(X)$  and any birational map  $q : X' \rightarrow X$ . By definition, there exists some ample Cartier divisors  $A$  and  $B$  on  $X'$  such that  $q^*\alpha \geq A^k$  and  $q^*\beta \geq B^k$ . As  $A$  and  $B$  are ample, there is a constant  $C > 0$  such that  $A^k \geq CB^k$  using the generalization of Siu's inequality (Theorem 3.3.4). This proves that  $q^*(t \times \alpha + (1-t) \times \beta) \geq (tC + (1-t)) \times B^k$  for any  $t \in [0, 1]$ . Hence  $t \times \alpha + (1-t) \times \beta \in \mathcal{C}_0^k(X)$  and the cone  $\mathcal{C}_0^k(X)$  is convex.

We prove that  $\mathcal{C}_0^k(X)$  is an open subset of  $\mathcal{C}^k(X)$ . We take  $\alpha \in \mathcal{C}_0^k(X)$ . We take any ample Cartier divisor  $\omega_X$  on  $X$  such that  $\alpha - t\omega_X^k$  is in  $\mathcal{C}^k(X)$  for small  $t > 0$ . We just need to show that  $\alpha - t\omega_X^k$  stays in  $\mathcal{C}_0^k(X)$  when  $t$  is small enough. Let  $q : X' \rightarrow X$  be a birational map where  $X'$  is projective and normal. By definition of  $\alpha$ , there exists an ample Cartier divisor  $A$  on  $X'$  such that  $q^*\alpha \geq A^k$ . By Siu's inequality, there exists a constant  $C$  such that:

$$q^*\omega_X^k \leq C \frac{(A^k \cdot q^*\omega_X^{n-k})}{(\omega_X^n)} \times A^k.$$

This implies the inequality:

$$q^*\beta - tq^*\omega_X^k \geq \left(1 - tC \frac{A^k \cdot \omega_X^{n-k}}{\omega_X^n}\right) \times A^k. \quad (15)$$

As  $A^k \leq q^*\alpha$ , we have the following upper bound:

$$(A^k \cdot \omega_X^{n-k}) \leq (q^*\alpha \cdot q^*\omega_X^{n-k}).$$

We get the following minoration which depends only on  $\alpha$  and  $\omega_X$ :

$$1 - t \frac{C(\alpha \cdot \omega_X^{n-k})}{(\omega_X^n)} \leq 1 - t \frac{C(A^k \cdot \omega_X^{n-k})}{(\omega_X^n)}. \quad (16)$$

Using (15) and (16), one gets that for  $t < \frac{(\omega_X^n)}{C(\alpha \cdot \omega_X^{n-k})}$ , the class  $\alpha - t\omega_X^k$  is in  $\mathcal{C}_0^k(X)$ .  $\square$

*Remark 3.4.5.* The cone  $\mathcal{C}_0^k(X)$  is not always equal to the cone generated by complete intersections. Following [LX15, Example 9.6], there exists a smooth toric threefold such that the cone generated by complete intersections in  $N_1(X)_{\mathbb{R}}$  is not convex, so it cannot be equal to  $\mathcal{C}_0^2(X)$  using the following proposition.

Let  $X$  be a normal projective variety of dimension  $n$ . Any class  $\alpha \in N^k(X)_{\mathbb{R}}$  can be decomposed as  $\alpha^+ - \alpha^-$  where  $\alpha^+$  and  $\alpha^-$  are strongly pliant classes. For any  $\gamma \in \mathcal{C}_0^{n-k}(X)$ , we define the function:

$$G_{\gamma}(\alpha) := \inf_{\substack{\alpha = \alpha^+ - \alpha^- \\ \alpha^+, \alpha^- \in \mathcal{C}^k(X)}} \{(\gamma \cdot \alpha^+) + (\gamma \cdot \alpha^-)\}. \quad (17)$$

**Proposition 3.4.6.** *For any  $\gamma \in \mathcal{C}_0^{n-k}(X)$ , the function  $G_{\gamma}$  defines a norm on  $N^k(X)_{\mathbb{R}}$ . In particular, for any norm  $\|\cdot\|_{N^k(X)_{\mathbb{R}}}$  on  $N^k(X)_{\mathbb{R}}$ , there is a constant  $C > 0$  such that for any class  $\alpha \in \mathcal{C}^k(X)$ :*

$$\frac{1}{C} \|\alpha\|_{N^k(X)_{\mathbb{R}}} \leq (\gamma \cdot \alpha) \leq C \|\alpha\|_{N^k(X)_{\mathbb{R}}}.$$

*Proof.* The only fact which is not immediate is the fact that  $G_{\gamma}(\alpha) = 0$  implies  $\alpha = 0$ .

Up to taking an alteration of  $X$ , we can suppose that  $X$  smooth as  $\mathcal{C}_0^k(X)$  is stable by generically finite morphisms (using Proposition 3.4.3.(2)). Moreover, we are reduced to treat the case where  $\alpha \in \mathcal{C}^k(X)$  as the strongly pliant cone is stable by pullback by generically finite morphism using Theorem 3.2.4.(4). Take an ample Cartier divisor  $\omega_X$  on  $X$  such that  $\gamma \geq \omega_X^{n-k}$ , as the class  $\alpha$  is nef, one has:

$$0 = G_{\gamma}(\alpha) = (\gamma \cdot \alpha) \geq (\omega_X^{n-k} \cdot \alpha) \geq 0.$$

As the class  $\alpha$  is pseudo-effective, we have that  $\alpha = 0$  using Proposition 3.2.5. □

*Remark 3.4.7.* In fact, the above proof gives a stronger statement: for any generically finite morphism  $q : X' \rightarrow X$  and any  $\gamma \in \mathcal{C}_0^{n-k}(X)$ , the function  $G_{q^*\gamma}$  defines a norm on  $N^k(X')_{\mathbb{R}}$ .

#### 4. RELATIVE NUMERICAL CLASSES

**4.1. Relative classes.** In this section, we fix  $q : X \rightarrow Y$  a surjective proper morphism between normal projective varieties where  $\dim X = n$ ,  $\dim Y = l$  and we denote by  $e = \dim X - \dim Y$  the relative dimension of  $q$ .

**Definition 4.1.1.** *The abelian group  $N_k(X/Y)$  is the subgroup of  $N_k(X)$  generated by classes of subvarieties  $V$  of  $X$  such that the image  $q(V)$  is a union of points in  $Y$ .*

Observe that by definition, there is a natural injection from  $N_k(X/Y)$  into  $N_k(X)$ :

$$0 \longrightarrow N_k(X/Y) \longrightarrow N_k(X).$$

**Definition 4.1.2.** *The abelian group  $N^k(X/Y)$  is the quotient of  $Z^k(X)$  by the equivalence relation  $\equiv_Y$  where  $\alpha \equiv_Y 0$  if for any cycle  $z \in Z_k(X)$  whose image by  $q$  is a collection of points in  $Y$ , we have  $(\alpha \cdot z) = 0$ .*

Therefore, one has the following exact sequence:

$$N^k(X) \longrightarrow N^k(X/Y) \longrightarrow 0.$$

As before, we write  $N_k(X/Y)_{\mathbb{R}} = N_k(X/Y) \otimes_{\mathbb{Z}} \mathbb{R}$ ,  $N^k(X/Y)_{\mathbb{R}} = N^k(X/Y) \otimes \mathbb{R}$ ,  $N_{\bullet}(X/Y) = \bigoplus N_k(X/Y)$  and  $N^{\bullet}(X/Y) = \bigoplus N^k(X/Y)$ .



**Proposition 4.1.3.** *The abelian groups  $N_k(X/Y)$  and  $N^k(X/Y)$  are torsion free and of finite type. Moreover, the pairing  $N_k(X/Y)_{\mathbb{Q}} \times N^k(X/Y)_{\mathbb{Q}} \rightarrow \mathbb{Q}$  induced by the pairing  $N_k(X)_{\mathbb{Q}} \times N^k(X)_{\mathbb{Q}} \rightarrow \mathbb{Q}$  is perfect.*

*Proof.* Since  $N_k(X/Y)$  is a subgroup of  $N_k(X)$ , it is torsion free and of finite type. The group  $N^k(X/Y)$  is also torsion free. Indeed pick  $\alpha \in Z^k(X)$  such that  $p\alpha \equiv_Y 0$  for some integer  $p$ , then for any cycle  $z$  whose image by  $q$  is a union of points, we have  $(p\alpha \lrcorner z) = p(\alpha \lrcorner z) = 0$  hence  $\alpha \equiv_Y 0$ . Finally, since there is a surjection from  $N^k(X)$  to  $N^k(X/Y)$ , the group  $N^k(X/Y)$  is also of finite type.

Let us show that the pairing is well defined and non degenerate. Take a cycle  $z \in Z_k(X)_{\mathbb{Q}}$  such that  $q(z)$  is a finite number of points in  $Y$ , then if  $\alpha \in N^k(X)$  such that its image is 0 in  $N^k(X/Y)$ , then  $(\alpha \lrcorner z) = 0$  and the pairing  $N^k(X/Y) \times N_k(X/Y) \rightarrow \mathbb{Z}$  is well-defined. Let us suppose that for any  $\alpha \in N^k(X/Y)_{\mathbb{Q}}$ ,  $(\alpha \lrcorner z) = 0$ . This implies that for any  $\beta \in N^k(X)$ , the intersection product  $(\beta \lrcorner z) = 0$ , thus  $z \equiv 0$ . Conversely, suppose that  $(\alpha \lrcorner z) = 0$  for any  $z \in N_k(X/Y)$ , then by definition  $\alpha \equiv_Y 0$ . □

*Example 4.1.4.* When  $Y$  is a point, we have  $N_k(X/Y) = N_k(X)$  and  $N^k(X/Y) = N^k(X)$ .

*Example 4.1.5.* If the morphism  $q : X \rightarrow Y$  is finite, then we have  $N^0(X/Y) = N_0(X/Y) = \mathbb{Z}$  and  $N^k(X/Y) = N_k(X/Y) = \{0\}$  for  $k \geq 1$ .

*Example 4.1.6.* When  $k = 1$ , the group  $N_1(X/Y)$  is generated by curves contracted by  $q$  so that  $N^1(X/Y)$  is the relative Neron-Severi group and its dimension is the relative Picard number.

*Remark 4.1.7.* When  $k$  is greater than the relative dimension, the relative classes might not be trivial. For example if  $q : X \rightarrow Y$  is a birational map, then  $e = 0$  but the space  $N^1(X/Y)_{\mathbb{R}}$  is generated by classes of exceptional divisors of  $q$ .

**Proposition 4.1.8.** *The intersection product on  $N^{\bullet}(X)$  induces a structure of algebra on  $N^{\bullet}(X/Y)$ . Moreover, the action from  $N^{\bullet}(X)$  on  $N_{\bullet}(X)$  induces an action from  $N^{\bullet}(X/Y)$  on  $N_{\bullet}(X/Y)$ , so that the vector space  $N_{\bullet}(X/Y)_{\mathbb{R}}$  becomes a  $N^{\bullet}(X/Y)_{\mathbb{R}}$ -module.*

*Proof.* Observe that if  $z \in Z_k(X)$  such that  $q(z)$  is a union of points in  $Y$  and  $\alpha \in N^l(X)$ , then  $\alpha \lrcorner z$  lies in  $N_{k-l}(X/Y)$ . Indeed, by definition, the class  $\alpha \lrcorner z$  is represented by a cycle supported in  $z$ , so its image by  $q$  is a collection of points in  $Y$ .

Let us now prove that the product is well-defined in  $N^{\bullet}(X/Y)$ . Take  $\alpha \in N^k(X)$  such that  $\alpha = 0$  in  $N^k(X/Y)$  and  $\beta \in N^l(X)$ , we must prove that  $\alpha \cdot \beta = 0$  in  $N^k(X/Y)$ . Pick a cycle  $z \in Z_{k+l}(X)$  whose image by  $q$  is a collection of points, by the properties of the intersection product,  $((\alpha \cdot \beta) \lrcorner z) = (\alpha \lrcorner (\beta \lrcorner z))$ . As  $\beta \lrcorner z$  is in  $N_k(X/Y)$ , we get that  $((\alpha \cdot \beta) \lrcorner z) = 0$  as required. □

As an illustration, we give an explicit description of these groups in a particular example.

**Proposition 4.1.9.** *Suppose  $q : X = \mathbb{P}(E) \rightarrow Y$  where  $E$  is a vector bundle of rank  $e + 1$  on  $Y$ . Then for any integer  $0 \leq k \leq e$ , one has:*

$$N_k(X/Y) = \mathbb{Z} \xi^{e-k} \lrcorner q^*[pt],$$

$$N^k(X/Y) = \mathbb{Z} \xi^k,$$

where  $\xi = c_1(\mathcal{O}_{\mathbb{P}(E)}(1))$ .

*Proof.* Since the pairing  $N^k(X/Y) \times N_k(X/Y) \rightarrow \mathbb{Z}$  is non degenerate and since  $(\xi^k \frown (\xi^{e-k} \frown q^*[pt])) = 1$ , the second equality is an immediate consequence of the first one. We suppose first that  $k > 0$ . Pick  $\alpha \in Z_k(X)$  which defines a class in  $N_k(X/Y)$ . Using [Ful98, Theorem 3.3.(b)],  $\alpha$  is rationally equivalent to  $\sum_{e-k \leq i \leq e} \xi^i \frown q^* \alpha_i$  where  $\alpha_i$  is an element of the Chow group  $A_{k-e+i}(Y)$ . Since the image of  $\alpha$  by  $q$  is a union of points in  $Y$ , we have that  $q_* \alpha = 0$  in  $A_k(Y)$  hence  $\alpha_e = 0$  in  $A_k(Y)_{\mathbb{Q}}$  using Theorem 1.3.4. Since  $\xi^i \frown \alpha$  defines also a class in  $N_{k-i}(X/Y)$ , this implies also that  $\alpha_{e-i} = 0$  in  $A_{k-e+i}(Y)$  for any  $i < k$ . We have finally that in  $N_k(X/Y)$ :

$$\alpha = \xi^{e-k} \frown q^* \alpha_{e-k}.$$

Since  $\alpha_{e-k}$  belongs to  $A_0(Y)$  and  $N_0(Y) = \mathbb{Z}[pt]$ , the  $\mathbb{Z}$ -module  $N_k(X/Y)$  is generated by  $\xi^{e-k} \frown q^*[pt]$  for  $k > 0$ .

For  $k = 0$ , the groups  $N_0(X)$  and  $N_0(X/Y)$  are isomorphic to  $\mathbb{Z}$ , so we get the desired conclusion.  $\square$

**4.2. Pullback and pushforward.** In this section, we fix any two proper surjective morphisms  $q_1 : X_1 \rightarrow Y_1$ ,  $q_2 : X_2 \rightarrow Y_2$ . To simplify the notation, we write  $X_1/q_1 Y_1 \xrightarrow[f]{g} X_2/q_2 Y_2$  when we have two regular maps  $f : X_1 \rightarrow X_2$  and  $g : Y_1 \rightarrow Y_2$  such that  $q_2 \circ f = g \circ q_1$ . When  $f : X_1 \dashrightarrow X_2$  and  $g : Y_1 \dashrightarrow Y_2$  are merely rational maps, then we write  $X_1/q_1 Y_1 \xrightarrow[-f]{g} X_2/q_2 Y_2$ .

**Proposition 4.2.1.** *Let  $X_1/q_1 Y_1 \xrightarrow[f]{g} X_2/q_2 Y_2$  be a morphism. Then the morphism of abelian groups  $f_* : N_k(X_1) \rightarrow N_k(X_2)$  induces a morphism of abelian groups  $f_* : N_k(X_1/Y_1) \rightarrow N_k(X_2/Y_2)$ .*

*Proof.* Take a cycle  $z \in Z_k(X_1)$  such that  $q_1(z)$  is a union of points of  $Y_1$ . Then the image of the cycle  $z$  by  $q_2 \circ f$  is also a union of points of  $Y_2$  due to the fact that  $q_2 \circ f = g \circ q_1$ . Hence  $f_*$  maps  $N_k(X_1/Y_1)$  to  $N_k(X_2/Y_2)$ .  $\square$

**Proposition 4.2.2.** *Let  $X_1/q_1 Y_1 \xrightarrow[f]{g} X_2/q_2 Y_2$  be a morphism. Then the morphism of graded rings  $f^* : N^\bullet(X_1) \rightarrow N^\bullet(X_2)$  induces a morphism of graded rings  $f^* : N^\bullet(X_1/Y_1) \rightarrow N^\bullet(X_2/Y_2)$ .*

*Proof.* This results follows immediately by duality from the previous proposition since the pairing  $N^k(X_i/Y_i) \times N_k(X_i/Y_i) \rightarrow \mathbb{Z}$  is non degenerate.  $\square$

**4.3. Restriction to a general fiber and relative canonical morphism.** Recall that  $\dim X = n$ ,  $\dim Y = l$  and that the relative dimension of  $q : X \rightarrow Y$  is  $e$ .

**Proposition 4.3.1.** *There exists a unique class  $\alpha_{X/Y} \in N^l(X)_{\mathbb{Q}}$  satisfying the following conditions.*

- (1) *The image  $\psi_X(\alpha_{X/Y})$  belongs to the subspace  $N_e(X/Y)_{\mathbb{Q}}$  of  $N_e(X)_{\mathbb{Q}}$ .*
- (2) *For any class  $\beta \in N_l(X)_{\mathbb{Q}}$ ,  $q_* \beta = (\alpha_{X/Y} \frown \beta) [Y]$ .*

*Moreover, for any open subset  $V$  of  $Y$  such that the restriction  $q$  to  $U = q^{-1}(V)$  is flat, and for all  $y \in V$  and any irreducible subvariety  $F$  of the scheme-theoretic fiber  $X_y$ , we have:*

$$\psi_X(\alpha_{X/Y}) = [X_y] = k[F],$$

*where  $k$  is a rational number which only depends on  $F$  and where  $[X_y]$  (resp.  $[F]$ ) denote the fundamental class of  $X_y$  (resp.  $F$ ).*

*Remark 4.3.2.* Recall that by generic flatness (see [FGI<sup>+</sup>05, Theorem 5.12]), one can always find an open subset  $V$  of  $Y$  such that the restriction of  $q$  to  $q^{-1}(V)$  is flat over  $V$ .

*Proof.* Fix an ample Cartier divisor  $\omega_Y$  on  $Y$ , we set

$$\alpha_{X/Y} := \frac{1}{(\omega_Y^l)} q^* \omega_Y^l \in N^l(X)_{\mathbb{Q}}.$$

By definition, it satisfies (1) and (2) follows from the projection formula (Theorem 2.3.2.(4)). Let us show that any class satisfying (1) and (2) is unique. Suppose there is another one  $\alpha' \in N^l(X)_{\mathbb{Q}}$ . Then for any class  $\beta \in N_l(X)_{\mathbb{Q}}$ ,  $((\alpha_{X/Y} - \alpha') \lrcorner \beta) = 0$  so that  $\alpha = \alpha'$  since the pairing  $N^l(X)_{\mathbb{Q}} \times N_l(X)_{\mathbb{Q}} \rightarrow \mathbb{Q}$  is non degenerate.

Let us prove the last assertion. By generic flatness [FGI<sup>+</sup>05, Theorem 5.12], Let  $V$  be an open subset of  $Y$  such that the restriction  $q|_{q^{-1}(V)} : q^{-1}(V) \rightarrow V$  is flat and such that the dimension of every fiber is  $e$ . Since  $\omega_Y$  is ample, we can find some hyperplanes of  $H_i \subset Y$  such that  $H_1 \cap \dots \cap H_l$  represents the class  $\omega_Y^l$  and such that  $H_1 \cap \dots \cap H_l \subset V$ . In particular, by [Ful98, Proposition 2.3.(d)], the pullback  $q^* \omega_Y^l$  is represented by a cycle in the fiber of  $H_1 \cap \dots \cap H_l$ . Denote by  $i : V \rightarrow Y$  and  $j : U \rightarrow X$  the inclusion maps of  $V$  and  $U$  into  $Y$  and  $X$  respectively. The morphisms  $j$  and  $i$  are open embedding hence are flat. Moreover we have the following commutative diagram.

$$\begin{array}{ccc} U & \xrightarrow{i} & X \\ \downarrow q|_U & & \downarrow q \\ V & \xrightarrow{j} & Y \end{array}$$

As the class  $\omega_Y^l$  is equal in  $A_0(Y)$  to:

$$\omega_Y^l = \sum a_i [p_i] \quad (18)$$

where  $p_i \in V(\kappa)$  are points in  $V$  and  $a_i$  are positive integers satisfying  $\sum a_i = (\omega_Y^l)$ . Using [Ful98, Example 2.4.2], one has that for any  $\beta \in A_l(X)$ :

$$(q^* \omega_Y^l \lrcorner \beta) = (q|_U j^* (\omega_Y^l) \lrcorner i^* \beta).$$

Using (18), one obtains in  $A_e(X)$ :

$$q|_U j^* \omega_Y^l = q|_U j^* (\sum a_i [p_i]) = \sum a_i [q^{-1}(p_i)],$$

which is well-defined since the restriction of  $q$  on  $U$  is flat. By [Ful98, Theorem 10.2], we have that  $[X_{p_i}] = [X_y] \in N_e(X)$  for any  $p_i, y \in V$ . In particular, we have:

$$\psi_X(q^* \omega_Y^l) = (\sum a_i) [X_y] = (\omega_Y^l) [X_y] \in N_e(X),$$

where  $y$  is a point in  $V$ , which proves that  $\psi_X(\alpha_{X/Y}) = [X_y]$  in  $N_e(X)_{\mathbb{Q}}$  for any point  $y$  in  $V$ . By the Stein factorization theorem, there exists a morphism  $q' : X \rightarrow Y'$  with connected fibres and a finite morphism  $f : Y' \rightarrow Y$  such that  $q = q' \circ f$ .  $\square$

The class previously constructed allows us to define a restriction morphism.

**Definition 4.3.3.** *Suppose that  $\dim Y = l$  and that  $\omega_Y$  is an ample Cartier divisor on  $Y$ , then we define  $\text{Res}_{X/Y} : N_{\bullet}(X)_{\mathbb{Q}} \rightarrow N_{\bullet-l}(X/Y)_{\mathbb{Q}}$  by setting:*

$$\text{Res}_{X/Y}(\beta) := \alpha_{X/Y} \lrcorner \beta.$$

We shall denote by  $\text{Res}_{X/Y}^* : \beta \in N^{\bullet}(X/Y)_{\mathbb{Q}} \rightarrow \alpha_{X/Y} \cdot \beta \in N^{\bullet+l}(X)_{\mathbb{Q}}$  the dual morphism induced by  $\text{Res}_{X/Y}$ .

**Proposition 4.3.4.** *Recall that  $\dim Y = l$ . The following properties are satisfied.*

(1) For any class  $\alpha \in N^\bullet(X)_\mathbb{Q}$ , one has:

$$\psi_X \circ \text{Res}_{X/Y}^*(\alpha) = \text{Res}_{X/Y} \circ \psi_X(\alpha).$$

(2) For any morphism  $X'/_q Y' \xrightarrow[f]{g} X/_q Y$  where  $\dim X' = \dim X = n$  and  $\dim Y' = \dim Y = l$  such that the topological degree of  $g$  is  $d$ , we have for any  $\alpha \in N^{k-l}(X/Y)_\mathbb{Q}$ :

$$d \times \text{Res}_{X'/Y'}^* \circ f^* \alpha = f^* \circ \text{Res}_{X/Y}^* \alpha.$$

The definition of the restriction morphism gives a natural way to generalize the definition of the canonical morphism  $\psi_X : N^k(X) \rightarrow N_{n-k}(X)$  to the relative case.

**Definition 4.3.5.** Recall that the relative dimension of the morphism  $q : X \rightarrow Y$  is  $e$ . For any integer  $k \geq 0$ , we define the canonical morphism  $\psi_{X/Y}$  by:

$$\psi_{X/Y} := \psi_X \circ \text{Res}_{X/Y}^* : \beta \in N^k(X/Y)_\mathbb{Q} \rightarrow \psi_X(\alpha_{X/Y} \cdot \beta) \in N_{e-k}(X/Y)_\mathbb{Q}.$$

*Remark 4.3.6.* When  $k > e$  by convention the map  $\psi_{X/Y}$  is zero.

We give here a situation where this map is an isomorphism.

**Proposition 4.3.7.** Suppose  $q : X \rightarrow Y$  is a flat morphism of relative dimension  $e$  and that every fiber of  $q$  is smooth, then for any integer  $0 \leq k \leq e$ , the map  $\psi_{X/Y} : N^k(X/Y)_\mathbb{Q} \rightarrow N_{e-k}(X/Y)_\mathbb{Q}$  is an isomorphism.

*Proof.* Since the pairing  $N^k(X/Y)_\mathbb{Q} \times N_k(X/Y)_\mathbb{Q} \rightarrow \mathbb{Q}$  is perfect by Proposition 4.1.3, we have that the dual morphism  $\psi_{X/Y}^* : N^{e-k}(X/Y)_\mathbb{Q} \rightarrow N_k(X/Y)_\mathbb{Q}$  of  $\psi_{X/Y}$  is surjective whenever  $\psi_{X/Y} : N^k(X/Y)_\mathbb{Q} \rightarrow N_{e-k}(X/Y)_\mathbb{Q}$  is injective. We are thus reduced to prove the injectivity of  $\psi_{X/Y} : N^k(X/Y)_\mathbb{Q} \rightarrow N_{e-k}(X/Y)_\mathbb{Q}$ . Take  $a \in N^k(X/Y)_\mathbb{Q}$  such that  $\psi_{X/Y}(a) = 0$ , and choose a class  $\alpha \in N^k(X)_\mathbb{Q}$  representing  $a$ . We fix a subvariety  $V$  of dimension  $k$  in a fiber  $X_y$  of  $q$  where  $y$  is a point in  $Y$ . We need to prove that  $(\alpha \lrcorner [V]) = 0$ .

By Proposition 4.3.1, the condition  $\psi_{X/Y}(\alpha) = 0$  implies that:

$$\alpha \lrcorner [X_y] = 0 \in N_{e-k}(X)_\mathbb{Q}.$$

Since  $X_y$  is smooth, by Theorem 2.4.2, there exists a class  $\beta \in N^{e-k}(X_y)_\mathbb{Q}$  such that:

$$\beta \lrcorner [X_y] = [V].$$

In particular, we get:

$$(\alpha \lrcorner [V]) = (\alpha \lrcorner (\beta \lrcorner [X_y])) = (\beta \lrcorner (\alpha \lrcorner [X_y])) = 0$$

as required.  $\square$

*Example 4.3.8.* If  $X = \mathbb{P}(E)$  where  $E$  is a vector bundle on  $Y$ , then Proposition 4.1.9 implies that  $\psi_{X/Y} : N^k(X/Y)_\mathbb{Q} \rightarrow N_{e-k}(X/Y)_\mathbb{Q}$  is an isomorphism for any integer  $0 \leq k \leq e$ .

*Example 4.3.9.* If  $X$  is the blow-up of  $\mathbb{P}^1 \times \mathbb{P}^1$  at a point and  $q$  is the projection from  $\mathbb{P}^1 \times \mathbb{P}^1$  to the first component  $Y = \mathbb{P}^1$  composed with the blow-down from  $X$  to  $\mathbb{P}^1 \times \mathbb{P}^1$ . Then the morphism  $\psi_{X/Y} : N^0(X/Y)_\mathbb{Q} \rightarrow N_1(X/Y)_\mathbb{Q}$  is not surjective and  $\psi_{X/Y} : N^1(X/Y)_\mathbb{Q} \rightarrow N_0(X/Y)_\mathbb{Q}$  is not injective.

## 5. APPLICATION TO DYNAMICS

In this section, we shall consider various normal projective varieties  $X_i$  and  $Y_i$  respectively of dimension  $n$  and  $l$  and we write  $e = n - l$ . Recall from Section 4.2 that the notation  $X_i/q_i Y_i$  means that  $q_i : X_i \rightarrow Y_i$  is a regular surjective morphism of relative dimension  $e$  and that  $X/q Y \xrightarrow[f]{g} X'/q' Y'$  means that  $f : X \dashrightarrow X'$  and  $g : Y \dashrightarrow Y'$  are dominant rational maps such that  $q' \circ f = g \circ q$ . We shall also fix  $\omega_{X_i}$  and  $\omega_{Y_i}$  big and nef Cartier divisors on  $X_i$  and  $Y_i$  respectively.

In this section we prove Theorem 1 and Theorem 2. They will follow from Theorem 5.2.1 and Theorem 5.3.2 respectively.

## 5.1. Degrees of rational maps.

**Definition 5.1.1.** *Let us consider a rational map  $X_1/q_1 Y_1 \xrightarrow[f]{g} X_2/q_2 Y_2$  and let  $\Gamma_f$  (resp.  $\Gamma_g$ ) be the normalization of the graph of  $f$  (resp.  $g$ ) in  $X_1 \times X_2$  (resp.  $Y_1 \times Y_2$ ) such that we have the following diagram.*

$$\begin{array}{ccccc}
 & & \Gamma_f & & \\
 & \swarrow \pi_1 & & \searrow \pi_2 & \\
 X_1 & \overset{f}{\dashrightarrow} & & \dashrightarrow & X_2 \\
 \downarrow q_1 & & \varpi & & \downarrow q_2 \\
 Y_1 & \overset{g}{\dashrightarrow} & & \dashrightarrow & Y_2 \\
 & \swarrow \pi'_1 & & \searrow \pi'_2 & \\
 & & \Gamma_g & & 
 \end{array}$$

The  $k$ -th relative degree of  $f$  is defined by the formula:

$$\text{reldeg}_k(f) := (\pi_1^*(\omega_{X_1}^{e-k} \cdot (q_1^* \omega_{Y_1})^l) \cdot \pi_2^*(\omega_{X_2})^k).$$

When  $Y_1$  and  $Y_2$  are reduced to a point, we simply write  $\text{deg}_k(f) = \text{reldeg}_k(f)$ .

*Remark 5.1.2.* If  $e = 0$ , then  $\text{reldeg}_k(f) = (q_1^* \omega_{Y_1}^l)$  if  $k = 0$  and  $\text{reldeg}_k(f) = 0$  for  $k > 0$ .

Note that the degrees always depend on the choice of the big nef divisors, but to simplify the notations, we deliberately omit it.

We now explain how to associate to any rational map  $X_1/q_1 Y_1 \xrightarrow[f]{g} X_2/q_2 Y_2$  a pullback operator  $(f, g)^{\bullet, k}$ .

**Definition 5.1.3.** *Let  $X_1/q_1 Y_1 \xrightarrow[f]{g} X_2/q_2 Y_2$  be a rational map and let  $\pi_1$  and  $\pi_2$  be the projections from the graph of  $f$  in  $X_1 \times X_2$  onto the first and the second factor respectively. We define the linear morphisms  $(f, g)^{\bullet, k}$  and  $(f, g)_{\bullet, k}$  by the following formula:*

$$(f, g)^{\bullet, k} : \alpha \in N^k(X_2/Y_2)_{\mathbb{R}} \longrightarrow (\pi_{1*} \circ \psi_{\Gamma_f/\Gamma_g} \circ \pi_2^*)(\alpha) \in N_{e-k}(X_1/Y_1)_{\mathbb{R}}.$$

$$(f, g)_{\bullet, k} : \beta \in N^k(X_1/Y_1)_{\mathbb{R}} \longrightarrow (\pi_{2*} \circ \psi_{\Gamma_f/\Gamma_g} \circ \pi_1^*)(\beta) \in N_{e-k}(X_2/Y_2)_{\mathbb{R}}.$$

*Remark 5.1.4.* When  $Y_1$  and  $Y_2$  are reduced to a point, then we simply write  $f^{\bullet, k}(\alpha) := (f, \text{Id}_{\{pt\}})^{\bullet, k}(\alpha)$  and  $f_{\bullet, k}(\beta) := (f, \text{Id}_{\{pt\}})_{\bullet, k}(\beta)$ .

*Remark 5.1.5.* Since  $\psi_{\Gamma_f/\Gamma_g} : N^k(X/Y) \rightarrow N_{e-k}(X) = 0$  when  $k > e$ , it implies that  $(f, g)^{\bullet, k}$  and  $(f, g)_{\bullet, k}$  are identically zero for any  $k > e$ .

## 5.2. Sub-multiplicativity.

**Theorem 5.2.1.** *Let us consider the composition  $X_1/q_1 Y_1 \xrightarrow[g_2]{f_1} X_2/q_2 Y_2 \xrightarrow[g_2]{f_2} X_3/q_3 Y_3$  of dominant rational maps. Then for any integer  $0 \leq k \leq e$ , there exists a constant  $C > 0$  which depends only on the choice of  $\omega_{X_2}$ ,  $\omega_{Y_2}$ ,  $k$ ,  $l$  and  $e$  such that:*

$$\text{reldeg}_k(f_2 \circ f_1) \leq C \text{reldeg}_k(f_1) \text{reldeg}_k(f_2).$$

More precisely,  $C = (e - k + 1)^k / (\omega_{X_2}^e \cdot q_2^* \omega_{Y_2}^l)$ .

*Proof.* We denote by  $\Gamma_{f_1}$  (resp.  $\Gamma_{f_2}, \Gamma_{g_1}, \Gamma_{g_2}$ ) the normalization of the graph of  $f_1$  (resp.  $f_2, g_1, g_2$ ) and  $\pi_1, \pi_2$  (resp.  $\pi_3, \pi_4, \pi'_1, \pi'_2$  and  $\pi'_3, \pi'_4$ ) the projections onto the first and the second factor respectively. We set  $\Gamma$  as the graph of the rational map  $\pi_3^{-1} \circ f_1 \circ \pi_1 : \Gamma_{f_1} \dashrightarrow \Gamma_{f_2}$ ,  $u$  and  $v$  the projections from  $\Gamma$  onto  $\Gamma_{f_1}$  and  $\Gamma_{f_2}$  and  $\varpi_i$  the restriction on  $\Gamma_{f_i}$  of the projection from  $X_i \times X_{i+1}$  to  $Y_i \times Y_{i+1}$  for each  $i = 1, 2$ . We have thus the following diagram.

$$\begin{array}{ccccc} & & \Gamma & & \\ & & \swarrow u & \searrow v & \\ & \Gamma_{f_1} & & & \Gamma_{f_2} \\ & \swarrow \pi_1 & & \swarrow \pi_3 & \searrow \pi_4 \\ X_1 & \dashrightarrow f_1 & X_2 & \dashrightarrow f_2 & X_3 \\ q_1 \downarrow & & q_2 \downarrow & & q_3 \downarrow \\ Y_1 & \dashrightarrow g_1 & Y_2 & \dashrightarrow g_2 & Y_3 \\ & \swarrow \pi'_1 & \searrow \pi'_2 & \swarrow \pi'_3 & \searrow \pi'_4 \\ & \Gamma_{g_1} & & & \Gamma_{g_2} \end{array} \quad (19)$$

By Proposition 4.3.1 applied to  $q_2 \circ \pi_2 \circ u : \Gamma \rightarrow Y_2$ , the class  $\psi_\Gamma(u^* \pi_2^* q_2^* \omega_{Y_2}^l)$  is represented by the fundamental class  $[V]$  where  $V$  is a subscheme of dimension  $e$  in  $\Gamma$  which is a general fiber of  $q_2 \circ \pi_2 \circ u$ . We apply Theorem 3.3.4 by restriction to  $V$  to the class  $a = v^* \pi_4^* \omega_{X_3}^k \lrcorner [V]$  and  $b = u^* \pi_2^* \omega_{X_2} \lrcorner [V]$ . We obtain:

$$v^* \pi_4^* \omega_{X_3}^k \lrcorner [V] \leq (e - k + 1)^k \frac{(v^* \pi_4^* \omega_{X_3}^k \cdot u^* \pi_2^* \omega_{X_2}^{e-k} \lrcorner [V])}{(u^* \pi_2^* \omega_{X_2}^e \lrcorner [V])} u^* \pi_2^* \omega_{X_2}^k \lrcorner [V] \in N_{e-k}(\Gamma). \quad (20)$$

Let us simplify the right hand side of inequality (20). Since  $\pi_2 \circ u = \pi_3 \circ v$ ,  $\psi_\Gamma(u^* \pi_2^* q_2^* \omega_{Y_2}^l) = [V] \in N_e(\Gamma)$  and since the morphism  $v$  is generically finite, one has that:

$$(v^* \pi_4^* \omega_{X_3}^k \cdot u^* \pi_2^* \omega_{X_2}^{e-k} \lrcorner [V]) = (v^* (\pi_4^* \omega_{X_3}^k \cdot \pi_3^* \omega_{X_2}^{e-k} \cdot \pi_3^* q_2^* \omega_{Y_2}^l)) = d \times \text{reldeg}_k(f_2), \quad (21)$$

where  $d$  is the topological degree of  $v$ . The same argument gives:

$$(u^* \pi_2^* \omega_{X_2}^e \lrcorner [V]) = d \times (\omega_{X_2}^e \cdot q_2^* \omega_{Y_2}^l). \quad (22)$$

Using (21), (22), inequality (20) can be rewritten as:

$$u^* \pi_2^* q_2^* \omega_{Y_2}^l \cdot v^* \pi_4^* \omega_{X_3}^k \leq C \text{reldeg}_k(f_2) u^* \pi_2^* \omega_{X_2}^k \cdot u^* \pi_2^* q_2^* \omega_{Y_2}^l \in N^{l+k}(\Gamma),$$

where  $C = (e - k + 1)^k / (\omega_{X_2}^e \cdot q_2^* \omega_{Y_2}^l)$ . Since the class  $u^* \pi_1^* \omega_{X_1}^{e-k} \in N^{e-k}(\Gamma)$  is nef, we can intersect this class in the previous inequality to obtain:

$$(u^* (\pi_1^* \omega_{X_1}^{n-l-k} \cdot \pi_2^* q_2^* \omega_{Y_2}^l) \cdot v^* \pi_4^* \omega_{X_3}^k) \leq C' \text{reldeg}_k(f_2) (u^* \pi_2^* \omega_{X_2}^k \cdot u^* \pi_2^* q_2^* \omega_{Y_2}^l \cdot u^* \pi_1^* \omega_{X_1}^{n-l-k}). \quad (23)$$

Let us simplify the expressions in inequality (23). Because  $\pi_2^* q_2^* \omega_{Y_2}^l = \varpi_1^* \pi_2'^* \omega_{Y_2}^l$  and  $\deg_l(g_1) = (\pi_2'^* \omega_{Y_2}^l)$ , we deduce that:

$$\pi_2^* q_2^* \omega_{Y_2}^l = \frac{\deg_l(g_1)}{(\omega_{Y_1}^l)} \varpi_1^* \pi_1'^* \omega_{Y_1}^l = \frac{\deg_l(g_1)}{(\omega_{Y_1}^l)} \pi_1^* q_1^* \omega_{Y_1}^l. \quad (24)$$

Applying (24), the inequality (23) can be translated as:

$$\frac{\deg_l(g_1)}{(\omega_{Y_1}^l)} (u^* \pi_1^* (\omega_{X_1}^{n-l-k} \cdot q_1^* \omega_{Y_1}^l) \cdot v^* \pi_4^* \omega_{X_3}^k) \leq C \frac{\deg_l(g_1)}{(\omega_{Y_1}^l)} \text{reldeg}_k(f_2) (u^* (\pi_2^* \omega_{X_2}^k \cdot \pi_1^* q_1^* \omega_{Y_1}^l \cdot \pi_1^* \omega_{X_1}^{n-l-k})).$$

We obtain thus:

$$\frac{\deg_l(g_1)}{(\omega_{Y_1}^l)} \text{reldeg}_k(f_2 \circ f_1) \leq C \frac{\deg_l(g_1)}{(\omega_{Y_1}^l)} \text{reldeg}_k(f_1) \text{reldeg}_k(f_2).$$

This concludes the proof of the inequality after dividing by  $\deg_l(g_1)/(\omega_{Y_1}^l)$ .  $\square$

**5.3. Norms of operators associated to rational maps.** The proof of Theorem 2 relies on an easy but crucial lemma which is as follows.

**Lemma 5.3.1.** *Let us consider  $(V, \|\cdot\|)$  a finite dimensional normed  $\mathbb{R}$ -vector space and let  $\mathcal{C}$  be a closed convex cone with non-empty interior in  $V$ . Then there exists a constant  $C > 0$  such that any vector  $u \in V$  can be decomposed as  $v = v^+ - v^-$  where  $u^+$  and  $u^-$  are in  $\mathcal{C}$  such that:*

$$\|v^{+/-}\| \leq C \|v\|.$$

*Proof.* Let us define the map  $f : V \rightarrow \mathbb{R}^+$  given by:

$$f(v) = \inf\{\max(\|v'\|, \|v' - v\|) \mid v' \in V, v' - v \in \mathcal{C}\}.$$

Since  $\mathcal{C}$  has a non-empty interior, the function  $f$  is well-defined (the intersection of the affine cones  $\mathcal{C}$  and  $v + \mathcal{C}$  is always non-empty). Moreover,  $f$  is continuous, hence it is bounded by a constant  $C > 0$  on the sphere  $\{v \in V \mid \|v\| = 1\}$ . And we have proved the lemma since we can always divide by  $\|v\|$  to reduce to the case where  $\|v\| = 1$ .  $\square$

**Theorem 5.3.2.** *Let  $X/qY \xrightarrow[f]{g} X/qY$  be a rational map. We fix an integer  $k \leq e$ , some norms on  $N^k(X/Y)_{\mathbb{R}}$ , on  $N_{e-k}(X/Y)_{\mathbb{R}}$ . Then there is a constant  $C > 0$  such that for any rational map  $X/qY \xrightarrow[f]{g} X/qY$ , we have:*

$$\frac{1}{C} \leq \frac{\|(f, g)^{\bullet, k}\|}{\text{reldeg}_k(f)} \leq C.$$

*In particular, the  $k$ -th relative dynamical degree of  $f$  satisfies the following equality:*

$$\lambda_k(f, X/Y) = \lim_{p \rightarrow +\infty} \|(f^p, g^p)^{\bullet, k}\|^{1/p}.$$

*Moreover, when  $Y$  is reduced to a point, we obtain:*

$$\lambda_k(f) = \lim_{p \rightarrow +\infty} \|(f^p)^{\bullet, k}\|^{1/p}.$$

*Remark 5.3.3.* The proof of Theorem 2 follows directly from Theorem 5.3.2 since  $N^k(X/Y) = N^k(X)$  and  $N_{e-k}(X/Y) = N_{e-k}(X)$  when  $Y$  is reduced to a point.

*Proof.* We denote by  $\pi_1$  and  $\pi_2$  the projections from the graph  $\Gamma_f$  of  $f$  onto the first and the second component respectively. Since we want to control the norm of  $f^{\bullet,k}$  by the  $k$ -th relative degree of  $f$ , we first find an appropriate norm to relate the norm on  $N_{e-k}(X)_{\mathbb{R}}$  with an intersection product. As  $N_{e-k}(X/Y)_{\mathbb{R}}$  is a subspace of  $N_{e-k}(X)_{\mathbb{R}}$ , we can extend the norm  $\|\cdot\|_{N_{e-k}(X/Y)_{\mathbb{R}}}$  into a norm on  $N_{e-k}(X)_{\mathbb{R}}$ . As  $N_{e-k}(X)_{\mathbb{R}}$  is a finite dimensional vector space and since  $\omega_X^{e-k}$  is a class in the interior of the strongly pliant cone  $\mathcal{C}^{e-k}(X)$ , we can suppose by equivalence of norms that the norm on  $N_{e-k}(X)_{\mathbb{R}}$  given by

$$\|z\| = \inf_{\substack{z=z^+-z^- \\ z^+, z^- \in \text{Psef}_{e-k}(X)}} \{(\omega_X^{e-k} \frown z^+) + (\omega_X^{e-k} \frown z^-)\}$$

as in Proposition 3.4.1.

Let us prove that the lower bound of  $\|(f, g)^{\bullet,k}\|/\text{reldeg}_k(f)$  is 1. We denote by  $\varphi : N^k(X) \rightarrow N^k(X/Y)$  the canonical surjection. Since  $\omega_X^k$  is strongly pliant, it implies that the class  $(f, g)^{\bullet,k}(\varphi(\omega_X^k)) \in N_{e-k}(X/Y)_{\mathbb{R}} \subset N_{e-k}(X)_{\mathbb{R}}$  is pseudo-effective. In particular, this implies that its norm is exactly  $\text{reldeg}_k(f)$ . We have thus by definition:

$$\frac{\|(f, g)^{\bullet,k}\|}{\text{reldeg}_k(f)} = \left( \frac{\|(f, g)^{\bullet,k}\|}{\|(f, g)^{\bullet,k}(\varphi(\omega_X^k))\|} \right) \geq 1,$$

as required.

Let us find an upper bound for  $\|(f, g)^{\bullet,k}\|/\|(f, g)^{\bullet,k}(\varphi(\omega_X^k))\|$ . First we fix a morphism  $s : N^k(X/Y)_{\mathbb{R}} \rightarrow N^k(X)_{\mathbb{R}}$  such that  $\varphi \circ s = \text{Id}$ . Take  $\alpha \in N^k(X/Y)_{\mathbb{R}}$  of norm 1, then the class  $u = s(\alpha) \in N^k(X)_{\mathbb{R}}$  is a representant of  $\alpha$ . By construction, the norm of  $u$  is bounded by  $\|u\|_{N^k(X)_{\mathbb{R}}} \leq C_1 \|\alpha\|_{N^k(X/Y)_{\mathbb{R}}} = C_1$  where  $C_1$  is the norm of the operator  $s$ . Since by Proposition 4.3.4.(2),  $\text{Res}_{\Gamma_f/\Gamma_g}^* \circ \pi_2^* = (1/\text{deg}_i(g)) \times \pi_2^* \circ \text{Res}_{X/Y}^*$ , we have therefore:

$$(f, g)^{\bullet,k} \alpha = \frac{1}{\text{deg}_i(g)} \times \pi_{1*} \circ \psi_{\Gamma_f} \circ \pi_2^* \circ \text{Res}_{X/Y}^*(\alpha) = \text{Res}_{X/Y} f^{\bullet,k} u.$$

By Theorem 3.2.4, the pliant cone  $\mathcal{C}^k(X)$  has a non-empty interior in  $N^k(X)_{\mathbb{R}}$  and we can apply Lemma 5.3.1. There exists a constant  $C_2 > 0$  which depends only on  $\mathcal{C}^k(X)$  and the choice of the norm on  $N^k(X)_{\mathbb{R}}$  such that the class  $u$  can be decomposed as  $u = u_1 - u_2$  where  $u_i \in \mathcal{C}^k(X)$  such that  $\|u_i\|_{N^k(X)_{\mathbb{R}}} \leq C_2 \|u\|_{N^k(X)_{\mathbb{R}}}$  for  $i = 1, 2$ . We set  $\alpha_i = \varphi(u_i)$  for all  $i \in \{1, 2\}$ . By the triangular inequality, we have:

$$\frac{\|(f, g)^{\bullet,k} \alpha\|_{N_{e-k}(X/Y)_{\mathbb{R}}}}{\|(f, g)^{\bullet,k}(\varphi(\omega_X^k))\|} \leq \frac{\|(f, g)^{\bullet,k} \alpha_1\|_{N_{e-k}(X)_{\mathbb{R}}}}{\|(f, g)^{\bullet,k}(\varphi(\omega_X^k))\|} + \frac{\|(f, g)^{\bullet,k} \alpha_2\|_{N_{e-k}(X)_{\mathbb{R}}}}{\|(f, g)^{\bullet,k}(\varphi(\omega_X^k))\|}.$$

We have to find an upper bound of  $\|(f, g)^{\bullet,k} \alpha_i\|_{N_{e-k}(X)_{\mathbb{R}}}$  for each  $i = 1, 2$ . Applying Corollary 3.3.6 to  $a = \pi_2^* u_i$  and  $b = \pi_2^* \omega_X$  and then composing with  $\text{Res}_{X/Y} \circ \pi_{1*} \circ \psi_{\Gamma_f}$  gives

$$\text{Res}_{X/Y}(f^{\bullet,k}(u_i)) \leq C_3 \frac{\|u_i\|_{N^k(X)_{\mathbb{R}}}}{(\omega_X^n)} \times \text{Res}_{X/Y}(f^{\bullet,k}(\omega_X^k)),$$

where  $C_3$  is a positive constant which depends only on the choice of big nef divisors. This implies by intersecting with  $\omega_X^{e-k}$  the inequality:

$$\|((f, g)^{\bullet,k}(\alpha_i))\|_{N_{e-k}(X/Y)_{\mathbb{R}}} \leq C_3 \frac{\|u_i\|_{N^k(X)_{\mathbb{R}}}}{(\omega_X^n)} \|(f, g)^{\bullet,k}(\varphi(\omega_X^k))\|_{N_{e-k}(X/Y)_{\mathbb{R}}}.$$

In particular we have shown that:

$$1 \leq \frac{\|(f, g)^{\bullet,k} \alpha\|_{N_{e-k}(X/Y)_{\mathbb{R}}}}{\|(f, g)^{\bullet,k}(\varphi(\omega_X^k))\|_{N_{e-k}(X/Y)_{\mathbb{R}}}} \leq \frac{2C_1 C_2 C_3}{(\omega_X^n)},$$



which concludes the proof. □

## 6. SEMI-CONJUGATION BY DOMINANT RATIONAL MAPS

In this section, we consider a more general situation than in the previous section. We still suppose that the varieties  $X_i$  and  $Y_i$  are of dimension  $n$  and  $l$  respectively such that the relative dimension is  $e = n - l$ , but we suppose the maps  $q_i : X_i \dashrightarrow Y_i$  merely *rational* and dominant: they may exhibit indeterminacy points. Recall also that  $\omega_{X_i}$  and  $\omega_{Y_i}$  are again big and nef Cartier divisors on  $X_i$  and  $Y_i$  respectively.

**Definition 6.0.4.** *Let  $f : X_1 \dashrightarrow X_2$ ,  $g : Y_1 \dashrightarrow Y_2$ ,  $q_1 : X_1 \dashrightarrow Y_1$  and  $q_2 : X_2 \dashrightarrow Y_2$  be four dominant rational maps such that  $q_2 \circ f = g \circ q_1$ . We define the  $k$ -th relative dynamical degree of  $f$  (still denoted  $\text{reldeg}_k(f)$ ) as the relative degree  $\text{reldeg}_k(\tilde{f})$  with respect to the rational map  $\Gamma_{q_1}/Y_1 \xrightarrow{\tilde{f}} \Gamma_{q_2}/Y_2$  where  $\Gamma_{q_i}$  are the normalization of the graphs of  $q_i$  in  $X_i \times Y_i$  for each integer  $i \in \{1, 2\}$  respectively and  $\tilde{f} : \Gamma_{q_1} \dashrightarrow \Gamma_{q_2}$  is the rational map induced by  $f$ .*

**Theorem 6.0.5.** (1) *Consider now the following commutative diagram:*

$$\begin{array}{ccccc} X_1 & \xrightarrow{f_1} & X_2 & \xrightarrow{f_2} & X_3 \\ \downarrow q_1 & & \downarrow q_2 & & \downarrow q_3 \\ Y_1 & \xrightarrow{g_1} & Y_2 & \xrightarrow{g_2} & Y_3 \end{array}$$

where  $f_i : X_i \dashrightarrow X_{i+1}$ ,  $g_i : Y_i \dashrightarrow Y_{i+1}$ ,  $q_1 : X_1 \dashrightarrow Y_1$ ,  $q_2 : X_2 \dashrightarrow Y_2$ ,  $q_3 : X_3 \dashrightarrow Y_3$  are dominant rational maps for any integer  $i \in \{1, 2, 3\}$  such that  $q_{i+1} \circ f_i = g_i \circ q_i$  for any integer  $i \in \{1, 2\}$ . Then there exists a constant  $C > 0$  which depends only  $e, k$  and the choice of big nef Cartier divisors such that:

$$\text{reldeg}_k(f_2 \circ f_1) \leq C \text{reldeg}_k(f_2) \text{reldeg}_k(f_1).$$

(2) *Consider now the following commutative diagram:*

$$\begin{array}{ccccc} & & X'_1 & \xrightarrow{\tilde{f}} & X'_2 \\ & \swarrow \phi_1 & \downarrow & \swarrow \phi_2 & \downarrow \\ X_1 & \xrightarrow{f} & X_2 & & \\ \downarrow q_1 & & \downarrow q_2 & & \downarrow \\ Y_1 & \xrightarrow{g} & Y_2 & & \\ & \swarrow \phi_1 & \downarrow & \swarrow \phi_2 & \downarrow \\ & & Y'_1 & \xrightarrow{\tilde{g}} & Y'_2 \end{array}$$

where  $f : X_1 \dashrightarrow X_2$ ,  $g : Y_1 \dashrightarrow Y_2$ ,  $q_1 : X_1 \dashrightarrow Y_1$ ,  $q_2 : X_2 \dashrightarrow Y_2$  are four dominant rational maps such that  $q_2 \circ f = g \circ q_1$ . We consider some birational maps  $\varphi_i : X'_i \dashrightarrow X_i$  and  $\phi_i : Y'_i \dashrightarrow Y_i$  for  $i = 1, 2$  such that  $\tilde{f} = \varphi_2^{-1} \circ f \circ \varphi_1$  and  $\tilde{g} = \phi_2^{-1} \circ g \circ \phi_1$ . Then for any integer  $0 \leq k \leq e$ , there exists a constant  $C > 0$  which depends on  $e, k$  and on the choice of big nef Cartier divisors such that:

$$\frac{1}{C} \text{reldeg}_k(f) \leq \text{reldeg}_k(\tilde{f}) \leq C \text{reldeg}_k(f). \quad (25)$$

*Proof.* (1) Let  $\tilde{f}_i : \Gamma_{q_i} \dashrightarrow \Gamma_{q_{i+1}}$  be the rational maps induced by  $f_i$  on the graph  $\Gamma_{q_i}$  of  $q_i$  for  $i \in \{1, 2\}$  respectively. Then (1) results directly from Theorem 5.2.1 applied to the composition  $\Gamma_{q_1}/Y_1 \xrightarrow[g_1]{\tilde{f}_1} \Gamma_{q_2}/Y_2 \xrightarrow[g_2]{\tilde{f}_2} \Gamma_{q_3}/Y_3$ .

(2) Let us suppose first that the maps  $q_i : X_i \rightarrow Y_i$  and  $q'_i : X'_i \rightarrow Y'_i$  are all regular for  $i = 1, 2$ . Let us apply successively Theorem 5.2.1 to the composition  $X'_1/q'_1 Y'_1 \xrightarrow[\phi_1]{\varphi_1} X_1/q_1 Y_1 \xrightarrow[g]{f} X_2/q_2 Y_2 \xrightarrow[\phi_2^{-1}]{\varphi_2^{-1}} X'_2/q'_2 Y'_2$ . We obtain :

$$\text{reldeg}_k(\varphi_2^{-1} \circ f \circ \varphi_1) \leq C_2 \text{reldeg}_k(f \circ \varphi_1) \text{reldeg}_k(\varphi_2^{-1}) \leq C_1 C_2 \text{reldeg}_k(f) \text{reldeg}_k(\varphi_1) \text{reldeg}_k(\varphi_2^{-1}), \quad (26)$$

where  $C_1 = (e - k + 1)^k / (\omega_{X_1}^e \cdot q_1^* \omega_{Y_1}^l)$  and  $C_2 = (e - k + 1)^k / (\omega_{X_2}^e \cdot q_2^* \omega_{Y_2}^l)$ . This proves that:

$$\text{reldeg}_k(\varphi_2^{-1} \circ f \circ \varphi_1) \leq C \text{reldeg}_k(f),$$

where

$$C = \frac{(e - k + 1)^{2k} \text{reldeg}_k(\varphi_1) \text{reldeg}_k(\varphi_2^{-1})}{(\omega_{X_1}^e \cdot q_1^* \omega_{Y_1}^l)(\omega_{X_2}^e \cdot q_2^* \omega_{Y_2}^l)}.$$

The proof follows easily from the regular case since the maps  $\Gamma_{q'_i} \dashrightarrow \Gamma_{q_i}$  and  $\Gamma_{q'_2} \dashrightarrow \Gamma_{q_2}$  are birational where  $\Gamma_{q'_i}$  are the graphs of  $q'_i$  in  $X'_i \times Y'_i$  for  $i = 1, 2$ .  $\square$

*Proof of Theorem 1:* (1) We apply Theorem 5.2.1 to  $Y_1 = Y_2 = Y_3 = \text{Spec}(\kappa)$ ,  $X_1 = X_2 = X_3 = X$  and  $\omega_{X_1} = \omega_{X_2} = \omega_{X_3} = \omega_X$ , we get thus the desired conclusion:

$$\text{deg}_k(g \circ f) \leq \frac{(n - k + 1)^k}{(\omega_X^n)} \text{deg}_k(f) \text{deg}_k(g).$$

(2) Applying Theorem 6.0.5.(2) to the varieties  $X'_1 = X'_2 = X_1 = X_2 = X$ ,  $Y'_1 = Y'_2 = Y_1 = Y_2 = \text{Spec}(\kappa)$ , to the choice of big nef divisors  $\omega_{X'_1} = \omega_{X'_2} = \omega'_X$ ,  $\omega_{Y'_1} = \omega_{Y'_2} = \omega'_Y$ ,  $\omega_{X_1} = \omega_{X_2} = \omega_X$  and to the rational maps  $\varphi_1 = \varphi_2 = \text{Id}_X$ ,  $\phi_1 = \phi_2 = g = \text{Id}_{\text{Spec}(\kappa)}$ ,  $f : X \dashrightarrow X$  yields the desired result.

## 7. MIXED DEGREE FORMULA

Let us consider three dominant rational maps  $f : X \dashrightarrow X$ ,  $q : X \dashrightarrow Y$ ,  $g : Y \dashrightarrow Y$  such that  $g \circ f = g \circ q$ . Theorem 6.0.5.(1) implies that for any integer  $k \leq e$  the sequence  $\text{reldeg}_k(f^n)$  is submultiplicative. Define  $k$ -th relative dynamical degree as follows.

$$\lambda_k(f, X/Y) := \lim_{p \rightarrow +\infty} (\text{reldeg}_k(f^p))^{1/p}.$$

When  $Y$  is reduced to a point, then we simply write  $\lambda_k(f) := \lambda_k(f, X/\{pt\})$ .

*Remark 7.0.6.* Since  $\text{reldeg}_k(f^p) \in \mathbb{N}$  is an integer, one has that  $\lambda_k(f, X/Y) \geq 1$ .

*Remark 7.0.7.* Theorem 6.0.5.(2) implies that  $\lambda_k(f, X/Y)$  does not depend on the choice of big nef Cartier divisors and on any choice of varieties  $X'$  and  $Y'$  which are birational to  $X$  and  $Y$  respectively.

Our aim in this section is to prove Theorem 4. To that end, we follow the approach from [DNT12]. The main ingredient (Corollary 7.1.5) is an inequality relating strongly pliant classes which generalizes to arbitrary fields (see [DN11, Proposition 2.3] and [DNT12, Proposition 2.5]). This inequality is a direct consequence of Theorem 7.1.1 which estimates the positivity of the diagonal in a quite general setting. After this, we prove in Theorem 7.2.3 the submultiplicativity formula for the mixed degrees. Once the submultiplicativity of these mixed degrees holds, the proof follows from a linear algebra argument.

**7.1. Positivity estimate of the diagonal.** In this section, we prove the following theorem.

**Theorem 7.1.1.** *Let  $q : X \rightarrow Y$  be a surjective morphism such that  $\dim Y = l$  and such that  $q$  is of relative dimension  $e$ . There exists a constant  $C > 0$  such that for any surjective generically finite morphism  $\pi : X' \rightarrow X$  and any class  $\gamma \in \mathcal{C}^{l+e}(X' \times X')$ :*

$$(\gamma \lrcorner [\Delta_{X'}]) \leq C \times (\gamma \cdot (\pi \times \pi)^*(\Omega_X^e \cdot \Omega_Y^l)), \quad (27)$$

where  $p_1$  and  $p_2$  are the projections from  $X' \times X'$  to the first and the second factor respectively,  $\Omega_X = p_1^*\omega_X + p_2^*\omega_X$  and  $\Omega_Y = p_1^*q^*\omega_Y + p_2^*q^*\omega_Y$ , and where  $\Delta_{X'}$  (resp.  $\Delta_X$ ) is the diagonal of  $X'$  (resp. of  $X$ ) in  $X' \times X'$  (resp. in  $X \times X$ ).

*Remark 7.1.2.* The fact that the constant  $C > 0$  does not depend on  $\pi$  but only on  $\Omega_X, \Omega_Y$  is crucial in the applications. Moreover, we believe that the following conjecture, which is a stronger version of (27), should be true:

$$[\Delta_{X'}] \leq C \psi_{X' \times X'}((\pi \times \pi)^*(\Omega_X^e \cdot \Omega_Y^l)) \in N_{l+e}(X' \times X')_{\mathbb{R}}. \quad (28)$$

We shall use several times the following lemma.

**Lemma 7.1.3.** *Let  $X_1/q_1 Y_1 \xrightarrow[f]{g} X_2/q_2 Y_2$  be two dominant rational maps where  $\dim Y_1 = \dim Y_2 = l$  and  $\dim X_1 = \dim X_2 = e + l$ . We denote by  $\Gamma_f$  and  $\Gamma_g$  the normalizations of the graph of  $f$  and  $g$  in  $X_1 \times X_2$  and  $Y_1 \times Y_2$  respectively,  $\pi_1, \pi_2, \pi'_1, \pi'_2$  are the projections from  $\Gamma_f$  and  $\Gamma_g$  on the first and the second factor respectively. Then there exists a constant  $C > 0$  such that for any surjective generically finite morphism  $\pi : X' \rightarrow \Gamma_f$ , any integer  $0 \leq j \leq l$  and any class  $\beta \in \mathcal{C}^{e+l-j}(X')$ , one has:*

$$(\beta \cdot \pi^* \pi_2^* q_2^* \omega_{Y_2}^j) \leq C \frac{\deg_j(g)}{(\omega_{Y_1}^l)} \times (\beta \cdot \pi^* \pi_1^* q_1^* \omega_{Y_1}^j),$$

where  $\deg_j(g)$  is the  $j$ -th degree of the rational map  $g$  with respect to the divisors  $\omega_{Y_1}$  and  $\omega_{Y_2}$ .

*Proof of Theorem 7.1.1.* By Siu's inequality, we can suppose that both the classes  $\omega_X$  and  $\omega_Y$  are ample in  $X$  and  $Y$  respectively. We proceed in three steps. Fix  $\pi : X' \rightarrow X$ .

**Step 1:** We suppose first that  $X = \mathbb{P}^l \times \mathbb{P}^e$ ,  $Y = \mathbb{P}^l$  and  $q$  is the projection onto the first factor. Since  $X \times X$  is smooth, the pullback  $(\pi \times \pi)^*$  is well-defined in  $N_{l+e}(X \times X)_{\mathbb{R}}$  because the morphism  $\psi_{X \times X} : N^{l+e}(X \times X)_{\mathbb{R}} \rightarrow N_{l+e}(X \times X)_{\mathbb{R}}$  is an isomorphism. Our objective is to prove that there exists a constant  $C_1 > 0$  such that

$$[\Delta_{X'}] \leq C_1 \times \psi_{X' \times X'}((\pi \times \pi)^*(\Omega_X^e \cdot \Omega_Y^l)) \in N_{l+e}(X' \times X')_{\mathbb{R}}.$$

As  $X \times X$  is homogeneous, we apply the following lemma analogous to [Tru16, Lemma 4.4] which we prove at the end of the section.

**Lemma 7.1.4.** *Let  $X$  be a homogeneous projective variety of dimension  $n$  and let  $\pi : X' \rightarrow X$  be a surjective generically finite morphism. Then one has that :*

$$[\Delta_{X'}] \leq (\pi \times \pi)^*[\Delta_X] \in N_n(X' \times X')_{\mathbb{R}}.$$

We denote by  $p'_1, p'_2$  (resp.  $p''_1, p''_2$ ) the projections from  $Y \times Y$  (resp. from  $X \times X$ ) onto the first and the second factor respectively. Since the strongly pliant cone has a non-empty interior by Theorem 3.2.4.(1) and since the class  $p_1^*\omega_Y + p_2^*\omega_Y$  is ample on  $Y \times Y$ , there exists a constant  $C_2 > 0$  such that the class  $-[\Delta_Y] + C_2(p_1^*\omega_Y + p_2^*\omega_Y)^l \in N^l(Y \times Y)_{\mathbb{R}}$  is strongly pliant. Since  $\Delta_X = \Delta_Y \times \Delta_{\mathbb{P}^e}$  and by intersection and by pullback, we have that the class:

$$-[\Delta_X] + C_2 \times \Omega_Y^l \cdot p^*[\Delta_{\mathbb{P}^e}] \in N^{e+l}(X \times X)$$

is strongly pliant where  $p$  denotes the projection from  $X \times X$  to  $\mathbb{P}^e \times \mathbb{P}^e$ . By the same argument, there exists a constant  $C_3 > 0$  such that the class  $-p^*[\Delta_{\mathbb{P}^e}] + C_3\Omega_X^e \in N^e(X \times X)_{\mathbb{R}}$  is strongly pliant. We have proved that the class:

$$-[\Delta_X] + C_2C_3\Omega_Y^l \cdot \Omega_X^e \in N^{e+l}(X \times X)_{\mathbb{R}}$$

is strongly pliant. Since the strongly pliant cone is stable by pullback, we have thus:

$$[\Delta_{X'}] \leq (\pi \times \pi)^*[\Delta_X] \leq C_1 \times \psi_{X' \times X'}((\pi \times \pi)^*(\Omega_Y^l \cdot \Omega_X^e)) \in N_{l+e}(X' \times X')_{\mathbb{R}},$$

where  $C_1 = C_2 \times C_3$  as required.

**Step 2:** We now suppose that  $X = Y \times \mathbb{P}^e$ . Since  $Y$  is projective, there exists a dominant rational map  $\phi : Y \dashrightarrow \mathbb{P}^l$ . Let  $Y'$  be the normalization of the graph of  $\phi$  in  $X \times \mathbb{P}^e \times \mathbb{P}^l$  and we denote by  $\phi_1$  and  $\varphi_1$  the projections from  $Y'$  onto the first and the second factor respectively. Let  $\varphi_2 : Y' \times \mathbb{P}^e \rightarrow \mathbb{P}^l \times \mathbb{P}^e$  (resp.  $\phi_2 : Y' \times \mathbb{P}^e \rightarrow X$ ) the map induced by  $\varphi_1$  (resp.  $\phi_1$ ). Let  $X''$  be the fibred product of  $X'$  with  $Y' \times \mathbb{P}^e$  so that  $\phi_3, \pi'$  are the projections from  $X''$  onto  $X'$  and  $Y' \times \mathbb{P}^e$  respectively. We obtain the following commutative diagram:

$$\begin{array}{ccccc}
 X' & \xleftarrow{\phi_3} & X'' & & \\
 \downarrow \pi & & \downarrow \pi' & & \\
 Y \times \mathbb{P}^e & \xleftarrow{\phi_2} & Y' \times \mathbb{P}^e & \xrightarrow{\varphi_2} & \mathbb{P}^l \times \mathbb{P}^e \\
 \downarrow q & & \downarrow p_{Y'} & & \downarrow p_{\mathbb{P}^l} \\
 Y & \xleftarrow{\phi_1} & Y' & \xrightarrow{\varphi_1} & \mathbb{P}^l
 \end{array}$$

where  $p_{Y'}$  and  $p_{\mathbb{P}^l}$  are the projections from  $Y' \times \mathbb{P}^e$  and  $\mathbb{P}^l \times \mathbb{P}^e$  onto  $Y'$  and  $\mathbb{P}^l$  respectively and where the horizontal arrows are birational maps. Let us prove that there exists a constant  $C_4 > 0$  which does not depend on the morphism  $\pi : X' \rightarrow X$  such that for any strongly pliant class  $\gamma' \in \mathcal{C}^{e+l}(X'' \times X'')$ , one has:

$$(\gamma' \lrcorner [\Delta_{X''}]) \leq C_4(\gamma' \cdot (\phi_3 \times \phi_3)^*(\pi \times \pi)^*(\Omega_X^e \cdot \Omega_Y^l)).$$

Fix a class  $\gamma' \in \mathcal{C}^{e+l}(X'' \times X'')$ . We apply the conclusion of the first step to the surjective generically finite morphism  $\pi'' := \varphi_2 \circ \pi' : X'' \rightarrow \mathbb{P}^l \times \mathbb{P}^e$ . There exists a constant  $C_1 > 0$  such that

$$[\Delta_{X''}] \leq C_1 \psi_{X'' \times X''}((\pi'' \times \pi'')^*(\Omega_{\mathbb{P}^l}^l \cdot \Omega_{\mathbb{P}^l \times \mathbb{P}^e}^e)) \in N_{l+e}(X'' \times X'')_{\mathbb{R}}, \quad (29)$$

where  $\Omega_{\mathbb{P}^l \times \mathbb{P}^e}$  is an ample Cartier divisor in  $(\mathbb{P}^l \times \mathbb{P}^e)^2$  and  $\Omega_{\mathbb{P}^l}$  is the pullback by  $p_{\mathbb{P}^l} \times p_{\mathbb{P}^l}$  of an ample Cartier divisor in  $\mathbb{P}^l \times \mathbb{P}^l$ . Let us apply Theorem 3.3.4 to the class  $(\pi'' \times \pi'')^*\Omega_{\mathbb{P}^l \times \mathbb{P}^e}^e$  and to the class  $(\pi' \times \pi')^*(\phi_2 \times \phi_2)^*\Omega_X$ , there exists a constant  $C_5 > 0$  such that:

$$\begin{aligned}
 (\pi'' \times \pi'')^*\Omega_{\mathbb{P}^l \times \mathbb{P}^e}^e &\leq C_5 \frac{((\pi' \times \pi')^*((\phi_2 \times \phi_2)^*\Omega_X^{2l+e} \cdot (\varphi_2 \times \varphi_2)^*\Omega_{\mathbb{P}^l \times \mathbb{P}^e}^e))}{((\pi' \times \pi')^*(\phi_2 \times \phi_2)^*\Omega_X^{2(l+e)})} \\
 &\quad \times (\pi' \times \pi')^*(\phi_2 \times \phi_2)^*\Omega_X^e \in N^e(X'' \times X'')_{\mathbb{R}}.
 \end{aligned}$$

Since  $((\pi' \times \pi')^*\alpha) = \deg(\pi')(\alpha)$  for any class  $\alpha \in N^{2l+2e}((Y' \times \mathbb{P}^e)^2)_{\mathbb{R}}$ , we have thus:

$$(\pi'' \times \pi'')\Omega_{\mathbb{P}^l \times \mathbb{P}^e}^e \leq C_6(\pi' \times \pi')^*(\phi_2 \times \phi_2)^*\Omega_X^e \in N^e(X'' \times X'')_{\mathbb{R}}, \quad (30)$$

where  $C_6 = C_5((\phi_2 \times \phi_2)^* \Omega_X^{2l+e} \cdot (\varphi_2 \times \varphi_2)^* \Omega_{\mathbb{P}^l \times \mathbb{P}^e}^e) / ((\phi_2 \times \phi_2)^* \Omega_X^{2l+2e}) > 0$  does not depend on  $\pi : X' \rightarrow X$ . Using (30) and (29), we obtain:

$$[\Delta_{X''}] \leq C_7 \times \psi_{X'' \times X''}((\pi'' \times \pi'')^* \Omega_{\mathbb{P}^l}^l \cdot (\phi_3 \times \phi_3)^*(\pi \times \pi)^* \Omega_X^e) \in N_{l+e}(X'' \times X'')_{\mathbb{R}}, \quad (31)$$

where  $C_7 = C_6 \times C_1$ . Since the strongly pliant cone is contained in the nef cone by Theorem 3.2.4.(5), we have thus:

$$(\gamma' \lrcorner [\Delta_{X''}]) \leq C_7 (\gamma' \cdot (\phi_3 \times \phi_3)^*(\pi \times \pi)^* \Omega_X^e \cdot (\pi'' \times \pi'')^* \Omega_{\mathbb{P}^l}^l). \quad (32)$$

Let us denote by  $X_1 = (Y \times \mathbb{P}^e)^2$ ,  $X_2 = (\mathbb{P}^l \times \mathbb{P}^e)^2$ ,  $Y_1 = Y \times Y$ ,  $Y_2 = \mathbb{P}^l \times \mathbb{P}^l$  and let  $f := (\varphi_2 \circ \phi_2^{-1} \times \varphi_2 \circ \phi_2^{-1}) : X_1 \dashrightarrow X_2$  and  $g := (\varphi_1 \circ \phi_1^{-1} \times \varphi_1 \circ \phi_1^{-1}) : Y_1 \dashrightarrow Y_2$  be the corresponding dominant rational maps. Let us apply Lemma 7.1.3 to the class  $(\pi' \times \pi')^* (\varphi_2 \times \varphi_2)^* \Omega_{\mathbb{P}^l}^l$  and to the class  $(\pi' \times \pi')^* (\phi_2 \times \phi_2)^* \Omega_Y^l$ , there exists a constant  $C_8 > 0$  which is independent of the morphism  $\pi' \times \pi' : X'' \times X'' \rightarrow (Y' \times \mathbb{P}^e)^2$  such that for any class  $\beta \in \mathcal{C}^{2e+l}(X'' \times X'')$ :

$$(\beta \cdot (\pi' \times \pi')^* (\varphi_2 \times \varphi_2)^* \Omega_{\mathbb{P}^l}^l) \leq C_8 \frac{\deg_l(g)}{(\Omega_Y^{2l})} (\beta \cdot (\phi_3 \times \phi_3)^*(\pi \times \pi)^* \Omega_Y^l). \quad (33)$$

Using (32) and (33) to the class  $\beta = \gamma' \cdot (\phi_3 \times \phi_3)^*(\pi \times \pi)^* \Omega_X^e \in \mathcal{C}^{l+2e}(X'' \times X'')$ , we obtain:

$$(\gamma' \lrcorner [\Delta_{X''}]) \leq C_4 (\gamma' \cdot (\phi_3 \times \phi_3)^*(\pi \times \pi)^*(\Omega_X^e \cdot \Omega_Y^l)),$$

where  $C_4 = C_4 \times C_8 (\deg_l(g)) / (\Omega_Y^{2l}) > 0$  does not depend on  $\pi$ . The conclusion of the theorem follows from the projection formula and from the fact that  $\phi_3 \times \phi_3$  is a birational map. Indeed, we apply the previous inequality to  $\gamma' = (\phi_3 \times \phi_3)^* \gamma$  where  $\gamma \in \mathcal{C}^{l+e}(X' \times X')$ , we obtain

$$(\gamma \lrcorner [\Delta_{X'}]) = ((\phi_3 \times \phi_3)^* \gamma \lrcorner [\Delta_{X''}]) \leq C_4 (\gamma \cdot (\pi \times \pi)^*(\Omega_X^e \cdot \Omega_Y^l))$$

as required.

**Step 3:** We prove the theorem in the general case. Suppose  $q : X \rightarrow Y$  is a surjective morphism of relative dimension  $e$  and fix a class  $\beta \in \mathcal{C}^{l+e}(X' \times X')$ . Since  $X$  is projective over  $Y$ , there exists a closed immersion  $i : X \rightarrow Y \times \mathbb{P}^N$  such that  $q = p'_Y \circ i$  where  $p'_Y$  is the projection of  $Y \times \mathbb{P}^N$  onto  $Y$ . Let us choose a projection  $Y \times \mathbb{P}^N \dashrightarrow Y \times \mathbb{P}^e$  so that the composition with  $i$  gives a dominant rational map  $f : X \dashrightarrow Y \times \mathbb{P}^e$ . Let us denote by  $\Gamma_f$  the normalization of the graph of  $f$  in  $X \times Y \times \mathbb{P}^e$  and  $\pi_1, \pi_2$  the projections of  $\Gamma_f$  onto the first and the second factor respectively. We set  $X''$  the fibred product of  $X'$  with  $\Gamma_f$  and we denote by  $\pi'$  and  $\phi$  the projection of  $X''$  to  $\Gamma_f$  and  $X'$  respectively. We get the following commutative diagram:

$$\begin{array}{ccc} X' & \longleftarrow & X'' \\ \downarrow \pi & & \downarrow \pi' \\ X & \xleftarrow{\pi_1} & \Gamma_f \\ \downarrow q & \dashrightarrow f & \downarrow \pi_2 \\ Y & \xleftarrow{p_Y} & Y \times \mathbb{P}^e \end{array}$$

where  $p_Y$  is the projection of  $Y \times \mathbb{P}^e$  onto  $Y$ . We apply the result of Step 2 to the class  $(\phi \times \phi)^* \beta \in \mathcal{C}^{l+e}(X'' \times X'')$  and to the diagonal of  $X''$ . There exists a constant  $C_4 > 0$  which does not depend on  $\pi$  such that:

$$((\phi \times \phi)^* \beta \lrcorner [\Delta_{X''}]) \leq C_4 ((\phi \times \phi)^*(\beta \cdot (\pi \times \pi)^* \Omega_Y^l) \cdot ((\pi_2 \circ \pi') \times (\pi_2 \circ \pi'))^* \Omega_{Y \times \mathbb{P}^e}^e). \quad (34)$$

Let us apply Theorem 3.3.4 to the class  $((\pi_2 \circ \pi') \times (\pi_2 \circ \pi'))^* \Omega_{Y \times \mathbb{P}^e}^e$  and to the class  $(\phi \times \phi)^*(\pi \times \pi) \Omega_X$ . There exists a constant  $C_9 > 0$  such that:

$$((\pi_2 \circ \pi') \times (\pi_2 \circ \pi'))^* \Omega_{Y \times \mathbb{P}^e}^e \leq C_9 \frac{((\pi' \times \pi')^*((\pi_2 \times \pi_2)^* \Omega_{Y \times \mathbb{P}^e}^e \cdot (\pi_1 \times \pi_1)^* \Omega_X^{2l+e}))}{((\pi' \times \pi')^*(\pi_1 \times \pi_1)^* \Omega_X^{2l+2e})} (\phi \times \phi)^*(\pi \times \pi) \Omega_X^e \in N^e(X'' \times X'')_{\mathbb{R}}.$$

Since  $((\pi' \times \pi')^*((\pi_2 \times \pi_2)^* \Omega_{Y \times \mathbb{P}^e}^e \cdot (\pi_1 \times \pi_1)^* \Omega_X^{2l+e}))/((\pi' \times \pi')^*(\pi_1 \times \pi_1)^* \Omega_X^{2l+2e}) = \deg_e(f \times f)/(\Omega_X^{2l+2e})$  and using (34), we obtain:

$$((\phi \times \phi)^* \beta \llcorner [\Delta_{X''}]) \leq C((\phi \times \phi)^*(\beta \cdot (\pi \times \pi)^*(\Omega_X^e \cdot \Omega_Y^l))),$$

where  $C = C_4 C_9 \deg_e(f \times f)/(\Omega_X^{2l+2e})$ . Since the morphism  $\pi_1 : \Gamma_f \rightarrow X$  is birational, the map  $\phi : X'' \rightarrow X'$  is also birational and we conclude using the projection formula and since  $(\phi \times \phi)_*[\Delta_{X''}] = [\Delta_{X'}]$ :

$$(\beta \llcorner [\Delta_{X'}]) \leq C(\beta \cdot (\pi \times \pi)^*(\Omega_X^e \cdot \Omega_Y^l)).$$

□

**Corollary 7.1.5.** *Let  $q : X \rightarrow Y$  be a surjective morphism of relative dimension  $e$  where  $\dim Y = l$ . Then there exists a constant  $C > 0$  such that for any surjective generically finite morphism  $\pi : X' \rightarrow X$  such that for any class  $\alpha \in \mathcal{C}^k(X')$  and any class  $\beta \in \mathcal{C}^{l+e-k}(X')$ , one has:*

$$(\beta \cdot \alpha) \leq C \sum_{\max(0, k-l) \leq j \leq \min(k, e)} U_j(\pi_* \psi_{X'}(\alpha)) \times (\beta \cdot \pi^*(q^* \omega_Y^{k-j} \cdot \omega_X^j)), \quad (35)$$

where  $U_j(\pi_* \psi_{X'}(\alpha)) = (\omega_X^{e-j} \cdot q^* \omega_Y^{l-k+j} \llcorner \pi_* \psi_{X'}(\alpha))$ .

*Remark 7.1.6.* Note that when  $k \leq e$ , then the inequality is already a consequence of Siu's inequality (Theorem 3.3.4). Indeed, the term on the right hand side of (35) with  $j = k$  corresponds exactly to the term  $C(\pi^* \omega_X^{n-k} \cdot \alpha) \times \pi^* \omega_X^k$ .

*Remark 7.1.7.* Equation (35) proves that the class

$$-\psi_{X'}(\alpha) + C \sum_{\max(0, k-l) \leq j \leq \min(k, e)} U_j(\pi_* \psi_{X'}(\alpha)) \times \psi_{X'}(\pi^*(q^* \omega_Y^{k-j} \cdot \omega_X^j)) \in N_{n-k}(X')_{\mathbb{R}}$$

is in the dual of the strongly pliant cone  $\mathcal{C}^{n-k}(X')$ . Moreover, if (28) is satisfied, then this class is pseudo-effective.

*Proof.* We apply Theorem 7.1.1 to the class  $\gamma = p_1^* \beta \cdot p_2^* \alpha \in \mathcal{C}^n(X' \times X')$ . There exists a constant  $C_1 > 0$  such that for any surjective generically finite morphism  $\pi : X' \rightarrow X$  and any class  $\gamma \in \mathcal{C}^n(X' \times X')$ , one has:

$$(\gamma \llcorner [\Delta_{X'}]) \leq C_1(\gamma \cdot (\pi \times \pi)^*(\Omega_X^e \cdot \Omega_Y^l)).$$

We denote by  $p_1$  and  $p_2$  the projections of  $X' \times X'$  onto the first and the second factors respectively. Fix  $\alpha \in \mathcal{C}^k(X')$  and  $\beta \in \mathcal{C}^{n-k}(X')$ . Let us apply the previous inequality to  $\gamma = p_1^* \beta \cdot p_2^* \alpha \in \mathcal{C}^n(X' \times X')$ . We obtain:

$$(\beta \cdot \alpha) = (p_1^* \beta \cdot p_2^* \alpha \llcorner [\Delta_{X'}]) \leq C_1(p_1^* \beta \cdot p_2^* \alpha \cdot (\pi \times \pi)^*(\Omega_X^e \cdot \Omega_Y^l)).$$

Since  $(p_1^* \pi^*(\omega_X^i \cdot q^* \omega_Y^j) \cdot p_2^*(\pi^*(q^* \omega_Y^{l-i} \cdot \omega_X^{e-j}) \cdot \gamma)) = 0$  when  $i + j \neq k$ , we obtain :

$$(\beta \cdot \alpha) \leq C \sum_{\max(0, k-l) \leq j \leq \min(e, k)} (\pi^*(q^* \omega_Y^{l-k+j} \cdot \omega_X^{e-j}) \cdot \alpha) (\pi^*(q^* \omega_Y^{k-j} \cdot \omega_X^j) \cdot \beta).$$

where  $C = C_1 \left( 1 + \max \left( \binom{e}{j} \binom{l}{k-j} \right) \right)$ . Hence by the projection formula, we have proved the required inequality:

$$(\beta \cdot \alpha) \leq C \sum_{\max(0, k-l) \leq j \leq \min(e, k)} U_j(\pi_* \psi_{X'}(\alpha)) \times (\beta \cdot \pi^*(q^* \omega_Y^{k-j} \cdot \omega_X^j)).$$

□

*Proof of Lemma 7.1.4:* (see [Tru16, Lemma 4.4]) Since  $X$  is homogeneous, it is smooth. Let  $G$  be the automorphism group of  $X \times X$ , we denote by  $\cdot$  the (transitive) action of  $G$  on  $X \times X$ . By generic flatness (see [FGI<sup>+</sup>05, Theorem 5.12]), there exists a non empty open subset  $V \subset X \times X$  such that the restriction of  $\pi \times \pi$  to  $U := (\pi \times \pi)^{-1}(V)$  is flat over  $V$ . Recall that two subvarieties  $V \subset X \times X$  and  $W \subset X \times X$  intersect properly in  $X \times X$  if  $\dim(V \cap W) = \dim V + \dim W - 2n$ . Since  $G$  acts transitively on  $X \times X$ , there exists by [Ful98, Lemma B.9.2] a Zariski dense open subset  $O \subset G$  such that for any point  $g \in O$ , the cycle  $g \cdot [\Delta_X]$  intersects properly every component of  $X \times X \setminus V$ . In particular, there exists a one parameter subgroup  $\tau : \mathbb{G}_m \rightarrow G$  such that  $\tau(1) = \text{Id} \in G$  and such that  $\tau$  maps the generic point of  $\mathbb{G}_m$  to a point in  $O$ . Let  $S$  be the closure in  $X' \times X' \times \mathbb{P}^1$  of the set  $\{(x', t) \in U \times \mathbb{G}_m \mid (\pi \times \pi)(x') \in \tau(t) \cdot \Delta_X\}$ . Let  $p : X' \times X' \times \mathbb{P}^1 \rightarrow X' \times X'$  be the projection onto  $X' \times X'$  and let  $f : S \rightarrow \mathbb{P}^1$  be the morphism induced by the projection of  $X' \times X' \times \mathbb{P}^1$  onto  $\mathbb{P}^1$ . As in [Ful98, Section 1.6], we denote by  $S_t := p_*[f^{-1}(t)] \in Z_n(X' \times X')$  for any  $t \in \mathbb{G}_m$ . By construction the cycle  $S_1 \in Z_n(X' \times X')$  is effective and its support contains the diagonal  $\Delta_{X'}$  in  $X' \times X'$ , hence:

$$[\Delta_{X'}] \leq S_1 \in N_n(X' \times X')_{\mathbb{R}}.$$

Let  $t \in \mathbb{G}_m$  such that  $\tau(t) \in O$ . Since  $S_1 = S_t \in A_n(X' \times X')$  for any  $t \in \mathbb{P}^1$ , we have thus:

$$[\Delta_{X'}] \leq S_t \in N_n(X' \times X')_{\mathbb{R}}.$$

Since the cycle  $\tau(t) \cdot [\Delta_X]$  intersects properly every component of  $X \times X \setminus V$ , we apply the result in [Ful98, Example 11.4.8.(b)] to the morphism  $\pi \times \pi : X' \times X' \rightarrow X \times X$  so that

$$S_t = \overline{[(\pi \times \pi)^{-1}_U(\tau(t) \cdot \Delta_X)]} = (\pi \times \pi)^*[\Delta_X] \in A_n(X' \times X').$$

We have thus proved:

$$[\Delta_{X'}] \leq (\pi \times \pi)^*[\Delta_X] \in N_n(X' \times X')_{\mathbb{R}}.$$

□

*Proof of Lemma 7.1.3.* Observe that one has the following commutative diagram:

$$\begin{array}{ccccc}
 & & X' & & \\
 & & \downarrow \pi & & \\
 & & \Gamma_f & & \\
 & \swarrow \pi_1 & & \searrow \pi_2 & \\
 X_1 & \overset{f}{\dashrightarrow} & X_2 & & \\
 \downarrow q_1 & & & & \downarrow q_2 \\
 Y_1 & \overset{g}{\dashrightarrow} & Y_2 & & \\
 \swarrow \pi'_1 & & \searrow \pi'_2 & & \\
 & & \Gamma_g & & 
 \end{array}$$

Fix a class  $\beta \in \mathcal{C}^{e+l-j}(X')$ . By linearity and by Proposition 2.1.8, we can suppose that the class  $\beta$  is induced by a product of nef divisors  $D_1 \cdots D_{e_1+e+l-j}$  where  $D_i$  are nef divisors on  $X'_1$  where  $p : X'_1 \rightarrow X'$  is a flat morphism of relative dimension  $e_1$ . The intersection  $(\beta \cdot \pi^* \pi_2^* q_2^* \omega_{Y_2}^j)$  is thus given by the formula:

$$(\beta \cdot \pi^* \pi_2^* q_2^* \omega_{Y_2}^j) = (D_1 \cdots D_{e_1+e+l-j} \cdot p^* \pi^* \pi_2^* q_2^* \omega_{Y_2}^j).$$

Take  $A$  an ample Cartier divisor on  $X'_1$  and set  $\alpha_\epsilon = (D_1 + \epsilon A) \cdots (D_{e_1+e} + \epsilon A) \in N^{e_1+e}(X'_1)_{\mathbb{R}}$  for any  $\epsilon > 0$ . Since the class  $\alpha_\epsilon$  is a complete intersection, there exists a cycle  $V_\epsilon \in Z_l(X'_1)_{\mathbb{R}}$  such that  $\psi_{X'_1}(\alpha_\epsilon) = \{V_\epsilon\} \in N_l(X'_1)_{\mathbb{R}}$  and such that the restrictions of the morphisms  $\pi_1 \circ \pi \circ p$  and  $\pi_2 \circ \pi \circ p$  to the support of  $V_\epsilon$  are surjective and generically finite onto  $Y_1$  and  $Y_2$  respectively. We apply Theorem 3.3.4 to the class  $(p^* \pi^* \pi_2^* q_2^* \omega_{Y_2}^j)_{|V_\epsilon}$  and to  $(p^* \pi^* \pi_1^* q_1^* \omega_{Y_1}^j)_{|V_\epsilon}$ , we get:

$$p^* \pi^* \pi_2^* q_2^* \omega_{Y_2}^j \cdot \alpha_\epsilon \leq C \frac{(p^* \pi^* (\pi_2^* q_2^* \omega_{Y_2}^j \cdot \pi_1^* \omega_{Y_1}^{l-j}) \llcorner \{V_\epsilon\})}{(p^* \pi^* \pi_1^* q_1^* \omega_{Y_1}^j \llcorner \{V_\epsilon\})} \times p^* \pi^* \pi_1^* q_1^* \omega_{Y_1}^j \cdot \alpha_\epsilon \in N^{j+e_1+e}(X'_1)_{\mathbb{R}}.$$

By the projection formula applied to the morphism  $\pi \circ p$ , we have that  $(p^* \pi^* (\pi_2^* q_2^* \omega_{Y_2}^j \cdot \pi_1^* \omega_{Y_1}^{l-j}) \llcorner \{V_\epsilon\}) / (p^* \pi^* \pi_1^* q_1^* \omega_{Y_1}^j \llcorner \{V_\epsilon\}) = \deg_j(g) / (\omega_{Y_1}^l)$ , hence:

$$p^* \pi^* \pi_2^* q_2^* \omega_{Y_2}^j \cdot \alpha_\epsilon \leq C \frac{\deg_j(g)}{(\omega_{Y_1}^l)} p^* \pi^* \pi_1^* q_1^* \omega_{Y_1}^j \cdot \alpha_\epsilon \in N^{j+e_1+e}(X'_1)_{\mathbb{R}}.$$

We intersect with the class  $(D_{e_1+e+1} \cdots D_{e_1+e+l-j}) \in N^{l-j}(X'_1)_{\mathbb{R}}$  and take the limit as  $\epsilon$  tends to zero. We obtain:

$$(\beta \cdot \pi^* \pi_2^* q_2^* \omega_{Y_2}^j) = (D_1 \cdots D_{e_1+e+l-j} \cdot p^* \pi^* \pi_2^* q_2^* \omega_{Y_2}^j) \leq C \frac{\deg_j(g)}{(\omega_{Y_1}^l)} (\beta \cdot \pi^* \pi_1^* q_1^* \omega_{Y_1}^j),$$

as required.  $\square$

## 7.2. Submultiplicativity of mixed degrees.

**Definition 7.2.1.** Let  $X_1/q_1 Y_1 \xrightarrow{f} X_2/q_2 Y_2$  be rational maps where  $e = \dim X_i - \dim Y_i$  and  $l = \dim Y_i$  for  $i = 1, 2$ . We fix some ample divisors  $\omega_{X_i}$  and  $\omega_{Y_i}$  on each variety respectively. We define for any integer  $0 \leq k \leq n$ :

$$a_{k,j}(f) := \begin{cases} ((\omega_{Y_1}^{l-j} \cdot \omega_{X_1}^{e+j-k}) \llcorner f^{\bullet,k}(\omega_{X_2}^k)) & \text{if } \max(0, k-e) \leq j \leq l, \\ 0 & \text{otherwise.} \end{cases}$$

*Remark 7.2.2.* For  $j = 0$ , it is the  $k$ -th relative degree  $a_{k,0}(f) = \text{reldeg}_k(f)$  and when  $j = l$ , it corresponds to the  $k$ -th degree of  $f$ ,  $a_{k,l}(f) = \text{deg}_k(f)$ .

**Theorem 7.2.3.** Let  $q_1 : X_1 \rightarrow Y_1$ ,  $q_2 : X_2 \rightarrow Y_2$ ,  $q_3 : X_3 \rightarrow Y_3$  be three surjective morphisms such that  $\dim X_i = e + l$  and  $\dim Y_i = l$  for all  $i \in \{1, 2, 3\}$ . Then there exists a constant  $C > 0$  such that for any rational maps  $X_1/q_1 Y_1 \xrightarrow{f_1} X_2/q_2 Y_2$ ,  $X_2/q_2 Y_2 \xrightarrow{f_2} X_3/q_3 Y_3$  and for all integers  $0 \leq j_0 \leq l$ :

$$a_{k,j_0}(f_2 \circ f_1) \leq C \sum_{\max(0, k-l) \leq j \leq \min(e, k)} \text{deg}_{k-j}(g_1) a_{k, k-j}(f_2) a_{j, j+j_0-k}(f_1).$$

*Proof.* Since we are in the same situation as Theorem 5.2.1, we can consider the diagram (19) and we keep the same notations. We denote by  $n = e + l$  the dimension of  $X_i$ .

Let us denote by  $d$  the topological degree of the map  $f_2$ . We apply Corollary 7.1.5 to the pliant class  $\alpha := (1/d) v^* \pi_4^* \omega_{X_3}^k \in \mathcal{C}^k(\Gamma)$ , to the class  $\beta := u^* \pi_1^* (\omega_{X_1}^{e-k+j_0} \cdot q_1^* \omega_{Y_1}^{l-j_0}) \in \mathcal{C}^{n-k}(\Gamma)$  and to the



morphism  $\pi = \varphi \circ \pi_3 \circ v$ . There exists a constant  $C_1 > 0$  which depends only on the choice of divisors  $\omega_{Y_2 \times \mathbb{P}^e}$  and  $\omega_{Y_2}$  such that:

$$a_{k,j_0}(f_2 \circ f_1) \leq C_1 \sum_{\max(0,k-l) \leq j \leq \min(e,k)} U_j(\pi_* \psi_\Gamma(\alpha))(\beta \cdot \pi^*(\omega_{X_2}^j \cdot q_2^* \omega_{Y_2}^{k-j})),$$

where  $U_j(\gamma) = (\omega_{X_2}^{e-j} \cdot q_2^* \omega_{Y_2}^{l-k+j} \lrcorner \gamma)$  for any class  $\gamma \in N_{n-k}(X_2)_\mathbb{R}$ . We observe that  $U_j(\pi_* \psi_\Gamma(\alpha)) = a_{k,k-j}(f_2)$ . We have thus:

$$a_{k,j_0}(f_2 \circ f_1) \leq C_1 \sum_{\max(0,k-l) \leq j \leq \min(e,k)} a_{k,k-j}(f_2) (u^*(\pi_1^*(\omega_{X_1}^{e-k+j_0} \cdot q_1^* \omega_{Y_1}^{l-j_0}) \cdot \pi_2^*(\omega_{X_2}^j \cdot q_2^* \omega_{Y_2}^{k-j}))). \quad (36)$$

Applying Lemma 7.1.3 to the class  $u^* \pi_2^* q_2^* \omega_{Y_2}^{k-j} \in \mathcal{C}^{k-j}(\Gamma)$  and to  $\beta' = \beta \cdot u^* \pi_2^* \omega_{X_2}^j \in \mathcal{C}^{n-k+j}(\Gamma)$ , there exists a constant  $C_2 > 0$  such that :

$$(\beta' \cdot u^* \pi_2^* q_2^* \omega_{Y_2}^{k-j}) \leq C_2 \deg_{k-j}(g_1) (u^*(\pi_1^*(\omega_{X_1}^{e-k+j_0} \cdot q_1^* \omega_{Y_1}^{l-j_0+k-j}) \cdot \pi_2^* \omega_{X_2}^j)).$$

Since the map  $u : \Gamma \rightarrow \Gamma_{f_1}$  is birational, we have that:

$$(u^*(\pi_1^*(\omega_{X_1}^{e-k+j_0} \cdot q_1^* \omega_{Y_1}^{l-j_0}) \cdot \pi_2^*(\omega_{X_2}^j \cdot q_2^* \omega_{Y_2}^{k-j}))) \leq C_2 \deg_{k-j}(g_1) a_{j,j_0+j-k}(f_1). \quad (37)$$

Finally, (36) and (37) imply:

$$a_{k,j_0}(f_2 \circ f_1) \leq C \sum_{\max(0,k-l) \leq j \leq \min(e,k)} a_{k,k-j}(f_2) a_{j,j_0+j-k}(f_1) \deg_{k-j}(g_1),$$

where  $C = C_2 C_1 > 0$  is a constant which is independent of  $f_1$  and  $f_2$  as required.  $\square$

**7.3. Proof of Theorem 4.** By definition of the relative degrees, we are reduced to prove the theorem when  $q : X \rightarrow Y$  is a proper surjective morphism. Recall that  $\dim X = n$  and  $\dim Y = l$  such that  $q : X \rightarrow Y$  has relative dimension  $e = n - l$ . Let us consider the following commutative diagram:

$$\begin{array}{ccccc} & & \Gamma_f & & \\ & \swarrow \pi_1 & & \searrow \pi_2 & \\ X & \overset{f}{\dashrightarrow} & & \overset{f}{\dashrightarrow} & X \\ \downarrow q & & \varpi & & \downarrow q \\ Y & \overset{g}{\dashrightarrow} & & \overset{g}{\dashrightarrow} & Y \\ & \swarrow \pi'_1 & & \searrow \pi'_2 & \\ & & \Gamma_g & & \end{array} \quad (38)$$

where  $f : X \dashrightarrow X$ ,  $g : Y \dashrightarrow Y$  are dominant rational maps,  $\Gamma_f, \Gamma_g$  are the normalization of the graph of  $f$  and  $g$  respectively,  $\pi_1, \pi_2, \pi'_1, \pi'_2$  are the projections from  $\Gamma_f$  and  $\Gamma_g$  onto the first and second factor respectively and  $\varpi : \Gamma_f \rightarrow \Gamma_g$  is the restriction of  $q \times q$  to  $\Gamma_f$ . The following lemma proves that  $\max_{j \leq k} (\lambda_j(f, X/Y) \lambda_{k-j}(g)) \leq \lambda_k(f)$ .

**Lemma 7.3.1.** *For any integer  $\max(0, k-l) \leq j \leq \min(k, e)$ , we have that  $\lambda_j(f, X/Y) \lambda_{k-j}(g) \leq \lambda_k(f)$ .*

*Proof.* We are reduced to show that for any  $\max(0, k-l) \leq j \leq \min(k, e)$ , there exists a constant  $C > 0$  such that:

$$\deg_{k-j}(g) \operatorname{reldeg}_j(f) \leq C \deg_k(f).$$

For this, it suffices to consider the product  $(\pi_1^*(\omega_X^{e-j} \cdot q^* \omega_Y^{l-k+j}) \cdot \pi_2^*(\omega_X^j \cdot q^* \omega_Y^{k-j}))$ . Since  $\pi_i \circ q = \varpi \circ \pi'_i$  for  $i \in \{1, 2\}$ , we obtain:

$$(\pi_1^*(\omega_X^{e-j} \cdot q^* \omega_Y^{l-k+j}) \cdot \pi_2^*(\omega_X^j \cdot q^* \omega_Y^{k-j})) = (\varpi^*(\pi_1'^* \omega_Y^{l-k+j} \cdot \pi_2'^* \omega_Y^{k-j}) \cdot \pi_1^* \omega_X^{e-j} \cdot \pi_2^* \omega_X^j).$$

Moreover, one has that  $\pi_1'^* \omega_Y^{l-k+j} \cdot \pi_2'^* \omega_Y^{k-j} = (\pi_1'^* \omega_Y^{l-k+j} \cdot \pi_2'^* \omega_Y^{k-j}) [p_0] = \deg_{k-j}(g) [p_0]$  where  $p_0$  is a general point in  $\Gamma_g$ . We can hence apply Proposition 4.3.1 to the morphism  $\varpi : \Gamma_f \rightarrow \Gamma_g$  and obtain:

$$(\pi_1^*(\omega_X^{e-j} \cdot q^* \omega_Y^{l-k+j}) \cdot \pi_2^*(\omega_X^j \cdot q^* \omega_Y^{k-j})) = \deg_{k-j}(g) (\pi_1^* \omega_X^{e-j} \cdot \pi_2^* \omega_X^j \llcorner [\Gamma_{f_{p_0}}]).$$

Since  $\pi'_1$  is a birational morphism, a general fiber of  $\varpi$  is equal to a general fiber of  $\pi'_1 \circ \varpi$ . In other words, we have that  $\text{Res}_{\Gamma_f/\Gamma_g} = \text{Res}_{\Gamma_f/Y}$  and since  $\pi_1^* \omega_X^{e-j} \cdot \pi_2^* \omega_X^j \llcorner [\Gamma_{f_{p_0}}] = \text{Res}_{\Gamma_f/\Gamma_g} (\pi_1^* \omega_X^{e-j} \cdot \pi_2^* \omega_X^j)$ , we obtain:

$$(\pi_1^*(\omega_X^{e-j} \cdot q^* \omega_Y^{l-k+j}) \cdot \pi_2^*(\omega_X^j \cdot q^* \omega_Y^{k-j})) = \deg_{k-j}(g) \times \text{reldeg}_j(f).$$

As  $\omega_X$  is ample, we apply Theorem 3.2.4 to the classes  $\pi_2^* q^* \omega_Y$  and  $\pi_2^* \omega_X$ :

$$\pi_2^* q^* \omega_Y^{k-j} \leq (n - k + j + 1)^{k-j} \frac{(\pi_2^* q^* \omega_Y^{k-j} \cdot \pi_2^* \omega_X^{n-k+j})}{(\pi_2^* \omega_X^n)} \pi_2^* \omega_X^{k-j} = C_1 \pi_2^* \omega_X^{k-j} \in N^{k-j}(X)_{\mathbb{R}},$$

where  $C_1 = (n - k + j + 1)^{k-j} (q^* \omega_Y^{k-j} \cdot \omega_X^{n-k+j}) / (\omega_X^n)$  depends only on  $n, k$  and the choice of big nef Cartier divisors. Intersecting with  $\pi_1^* \omega_X^{n-k} \cdot \pi_2^* \omega_X^j$ , one obtains:

$$\deg_{k-j}(g) \cdot \text{reldeg}_j(f) \leq C_1 (\pi_2^* \omega_X^k \cdot \pi_1^* (\omega_X^{e-j} \cdot q^* \omega_Y^{l-k+j})).$$

By the same argument, there exists a constant  $C_2 > 0$  which depends only on  $\omega_Y, \omega_X$  and  $k$  such that:

$$\pi_1^* q^* \omega_Y^{l-k+j} \leq C_2 \pi_1^* \omega_X^{l-k+j}.$$

Hence, we obtain:

$$\deg_{k-j}(g) \text{reldeg}_j(f) \leq C \deg_k(f),$$

where  $C = C_1 C_2$ . □

Let us prove the converse inequality. We fix an integer  $0 \leq k \leq n$ . Let us apply Theorem 7.2.3 to  $f_1 = f, f_2 = f^p, g_1 = g$  and  $g_2 = g^p$ , we can rewrite the inequality as:

$$a_{k,j_0}(f^{p+1}) \leq C \sum_{\max(0, k-e) \leq j \leq \min(k, l)} \deg_j(g) a_{k-j, j_0-j}(f) a_{k,j}(f^p). \quad (39)$$

Let us denote by  $U_k(f)$  the column vector given by:

$$U_k(f) = (a_{k,i}(f))_{0 \leq i \leq l} = \begin{pmatrix} a_{k,0}(f) \\ \dots \\ a_{k,l}(f) \end{pmatrix}.$$

Let us also denote by  $M_k(f)$  the  $(l+1) \times (l+1)$  lower-triangular matrix given by:

$$M_k(f) := (\deg_j(g) a_{k-j, i-j}(f) \times \mathbb{1}_{[k-e, \min(k, l)]}(j))_{0 \leq i \leq l, 0 \leq j \leq l},$$

where  $\mathbb{1}_A$  denotes the characteristic function of the set  $A$ . Therefore, (39) can be rewritten as:

$$U_k(f^{p+1}) \leq C M_k(f) \cdot U_k(f^p),$$

where  $\cdot$  denotes the linear action on  $\mathbb{Z}^{l+1}$ . A simple induction proves:

$$U_k(f^p) \leq C^p (M_k(f))^{p-1} \cdot U_k(f)$$

Since the  $(l+1)$ -th entry of the vector  $U_k(f^p)$  corresponds to  $\deg_k(f^p)$ , we deduce that:

$$\deg_k(f^p)^{1/p} \leq C \langle e_l, (M_k(f))^p \cdot U_k(f) \rangle^{1/p}, \quad (40)$$

where  $(e_0, \dots, e_l)$  denotes the canonical basis of  $\mathbb{Z}^{l+1}$ . In particular,  $\deg_k(f^p)^{1/p}$  is controlled up to a constant by the eigenvalues of the matrix  $M_k(f)$  which are  $\deg_j(g) \operatorname{reldeg}_{k-j}(f)$  for  $\max(0, k-e) \leq j \leq \min(k, l)$  since  $M_k(f)$  is lower-triangular. Applying (40) to  $f^r$ , we get:

$$\deg_k(f^{pr})^{1/(pr)} \leq C^{1/r} \|U_k(f^r)\|^{1/pr} \max_{\max(0, k-e) \leq j \leq \min(k, l)} (\deg_j(g^r) \operatorname{reldeg}_{k-j}(f^r))^{1/r}.$$

We conclude by taking the lim sup as  $r \rightarrow +\infty, p \rightarrow +\infty$ :

$$\lambda_k(f) \leq \max_{\max(0, k-l) \leq j \leq \min(k, e)} \lambda_{k-j}(g) \lambda_j(f, X/Y).$$

*Remark 7.3.2.* Note that the previous theorem gives information only on the dynamical degrees of  $f$ . Lemma 7.3.1 provides a lower bound on the degree of  $f^p$ . However, one cannot find an upper bound for  $\deg_k(f^p)$  which would only depend on the relative degrees and the degree on the base. If  $X = E \times E$  is a product of two elliptic curves and if  $f : (z, w) \in E \times E \rightarrow (z, z + w)$  is an automorphism of  $X$ , then the degree growth of  $f^p$  is equivalent to  $p^2$  whereas the degree on the base and on any fiber are trivial.

## 8. KÄHLER CASE

We prove the submultiplicativity of the  $k$ -th degrees in the case where  $(X, \omega)$  is a complex compact Kähler manifold. For any closed smooth  $(p, q)$ -form  $\alpha$  on  $X$ , we denote by  $\{\alpha\}$  its class in the Dolbeault cohomology  $H^{p,q}(X)_{\mathbb{R}}$ .

**Definition 8.0.3.** *Let  $(X, \omega)$  be a compact Kähler manifold. A class  $\alpha \in H^{1,1}(X)_{\mathbb{R}}$  is nef if for any  $\epsilon > 0$ , the class  $\alpha + \epsilon\{\omega\}$  is represented by a Kähler metric.*

**Definition 8.0.4.** *Let  $(X, \omega)$  be a compact Kähler manifold of dimension  $n$ . A class  $\alpha$  of degree  $(k, k)$  is pseudo-effective if it can be represented by a closed positive current  $T$ . Moreover, one says that  $\alpha$  is big if there exists a constant  $\delta > 0$  such that  $T - \delta\omega^k$  is a closed positive current and we write  $T \geq \delta\omega^k$ .*

**Theorem 8.0.5.** *(cf [Xia15, Remark 3.1]) Let  $(X, \omega)$  be a compact Kähler manifold of dimension  $n$ . Let  $k$  be an integer and  $\alpha, \beta$  be two nef classes in  $H^{1,1}(X)$  such that  $\alpha^k \in H^{k,k}(X)$  is big and such that  $\int_X \alpha^n - \binom{n}{k} \int_X \alpha^{n-k} \wedge \beta^k > 0$ . Then the class  $\alpha^k - \beta^k$  is big.*

Recall that the degree of a meromorphic selfmap  $f : X \dashrightarrow X$  when  $(X, \omega)$  is given by:

$$\deg_k(f) := \int_{\Gamma_f} \pi_1^* \omega^{n-k} \wedge \pi_2^* \omega^k,$$

where  $\Gamma_f$  is the desingularization of the graph of  $f$  and  $\pi_i$  are the projections from  $\Gamma_f$  onto the first and the second factor respectively.

**Corollary 8.0.6.** *Let  $(X_1, \omega_{X_1})$ ,  $(X_2, \omega_{X_2})$  and  $(X_3, \omega_{X_3})$  be some compact Kähler manifolds of dimension  $n$ . Then there exists a constant  $C > 0$  which depends only on the choice of the Kähler classes  $\omega_{X_i}$  such that for any dominant meromorphic maps  $f_1 : X_1 \dashrightarrow X_2$  and  $f_2 : X_2 \dashrightarrow X_3$ , one has:*

$$\deg_k(f_2 \circ f_1) \leq C \deg_k(f_1) \deg_k(f_2).$$

Moreover, the constant  $C$  may be chosen to be equal to  $\binom{n}{k} / (\int_{X_2} \omega_{X_2}^n)$ .

*Proof.* The previous theorem gives that for any big nef class  $\beta^k \in H^{k,k}(X)$ , for any nef class  $\alpha \in H^{1,1}(X)$ , one has:

$$\alpha^k \leq \binom{n}{k} \frac{\int_X \alpha^k \wedge \beta^{n-k}}{\int_X \beta^n} \times \beta^k. \quad (41)$$

Then, the proof is formally the same as Theorem 5.2.1. Indeed, one only needs to consider the diagram (19) where  $Y_1 = Y_2 = Y_3$  are reduced to a point and where  $\Gamma_{f_1}, \Gamma_{f_2}, \Gamma$  are the desingularizations of the graph of  $f_1, f_2$  and  $\pi_3^{-1} \circ f_1 \circ \pi_1$  respectively. We apply (41) to  $\alpha = v^* \pi_4^* \omega_{X_3}$  and  $\beta = v^* \pi_3^* \omega_{X_2}$  to obtain:

$$v^* \pi_4^* \omega_{X_3}^k \leq \binom{n}{k} \frac{\deg_k(f_2)}{\int_{X_2} \omega_{X_2}^n} \times v^* \pi_3^* \omega_{X_2}^k.$$

By intersecting the previous inequality with the class  $u^* \pi_1^* \omega_{X_1}^{n-k}$ , we finally get:

$$\deg_k(f_2 \circ f_1) \leq \binom{n}{k} \frac{\deg_k(f_2) \deg_k(f_1)}{\int_{X_2} \omega_{X_2}^n}.$$

□

## APPENDIX A. COMPARISON WITH FULTON'S APPROACH

In [Ful98, Chapter 19], a cycle  $z \in Z_k(X)$  on a variety  $X$  is defined to be numerically trivial if  $(c \lrcorner z)$  for any product  $c = c_{i_1}(E_1) \cdot \dots \cdot c_{i_p}(E_p) \in A^k(X)$  of Chern classes  $c_{i_j}(E_j)$  where  $E_j$  is a vector bundle on  $X$  and  $i_1 + \dots + i_p = k$ . This appendix is devoted to the proof of the following result:

**Theorem A.1.** *Let  $X$  be a normal projective variety of dimension  $n$ . For any  $z \in Z_k(X)$ , the following conditions are equivalent:*

- (i) *For any product of Chern classes  $c = c_{i_1}(E_1) \cdot \dots \cdot c_{i_p}(E_p) \in A^k(X)_{\mathbb{R}}$  where  $E_j$  are vector bundles on  $X$  and  $i_1 + \dots + i_p = k$ , we have  $(c \lrcorner z) = 0$ .*
- (ii) *For any integer  $e$ , any flat morphism  $p_1 : X_1 \rightarrow X$  of relative dimension  $e$  between normal projective varieties and any Cartier divisors  $D_1, \dots, D_{e+k}$  on  $X_1$ , we have  $(D_1 \cdot \dots \cdot D_{e+k} \lrcorner p_1^* z) = 0$ .*

The implication (ii)  $\Rightarrow$  (i) follows immediately from the definition of Chern classes. For the converse implication (i)  $\Rightarrow$  (ii), we rely on the following proposition.

**Proposition A.2.** *Let  $q : X \rightarrow Y$  be a flat morphism of relative dimension  $e$  between normal projective varieties. For any Cartier divisors  $D_1, \dots, D_{e+k}$  be some ample Cartier divisors on  $X$ , there exist vector bundles  $E_j$ , and a homogeneous polynomial  $c = P(c_{i_1}(E_1), \dots, c_{i_p}(E_p))$  of degree  $k$  with respect to the weight  $(i_1, \dots, i_p)$ , with rational coefficients such that for any cycle  $z \in Z_k(X)$ ,  $(c \cdot z) = (D_1 \cdot \dots \cdot D_{e+k} \cdot q^* z)$ .*

*Proof.* We take some ample Cartier divisors  $D_1, \dots, D_{e+k}$  on  $X$ . We denote by  $\mathcal{L}_i$  the line bundle  $\mathcal{O}_X(D_i)$ . By Grauert's Theorem (cf [Har77, Corollary 12.9]), the sheaves  $R^i q_*(\mathcal{L}_1^{m_1} \otimes \dots \otimes \mathcal{L}_{e+k}^{m_{e+k}})$  are locally free. By [Har77, Theorem 8.8], we have that  $R^i q_*(\mathcal{L}_1^{m_1} \otimes \dots \otimes \mathcal{L}_{e+k}^{m_{e+k}}) = 0$  for  $i > 0$  and  $m_i$  large enough since the line bundle  $\mathcal{L}_i$  are ample. So the sheaf  $q_*(\mathcal{L}_1^{m_1} \otimes \dots \otimes \mathcal{L}_{e+k}^{m_{e+k}})$  is locally free and we have in  $K_0(Y)$ :

$$q_*[\mathcal{L}_1^{m_1} \otimes \dots \otimes \mathcal{L}_{e+k}^{m_{e+k}}] = \sum (-1)^i [R^i q_*(\mathcal{L}_1^{m_1} \otimes \dots \otimes \mathcal{L}_{e+k}^{m_{e+k}})] = [q_*(\mathcal{L}_1^{m_1} \otimes \dots \otimes \mathcal{L}_{e+k}^{m_{e+k}})]. \quad (42)$$

**Lemma A.3.** *For any  $j \leq k$ :*

- (1) *The function  $(m_1, \dots, m_{e+k}) \rightarrow \text{ch}_j(q_*(\mathcal{L}_1^{m_1} \otimes \dots \otimes \mathcal{L}_{e+k}^{m_{e+k}})) \in \mathbb{N}^j(Y)_{\mathbb{R}}$  is a polynomial of degree  $e + j$  with coefficients in  $\mathbb{N}^j(Y)$ .*

- (2) For any cycle  $z \in Z_j(Y)$ , the coefficient in  $m_1 \cdots m_{e+k}$  in  $(\text{ch}_j(q_*(\mathcal{L}_1^{m_1} \otimes \cdots \otimes \mathcal{L}_{e+k}^{m_{e+k}}))) \lrcorner z$  is  $((D_1 \cdots D_{e+k}) \lrcorner q^*z)$ .

*Proof.* Let us set  $\mathcal{F} = \mathcal{L}_1^{m_1} \otimes \cdots \otimes \mathcal{L}_{e+k}^{m_{e+k}}$ . We prove the result by induction on  $0 \leq j \leq k$ .

For  $j = 0$ , choosing a point  $y \in Y(\kappa)$ , the number  $\text{ch}_0(q_*(\mathcal{F}))$  is equal to  $h^0(X_y, \mathcal{F}_{X_y})$ . By asymptotic Riemann-Roch, for  $m_1, \dots, m_{e+k}$  large enough, it is a polynomial of degree  $\dim X_y = e$ . Moreover, Snapper's theorem (see [Deb01, Definition 1.7]) states that the coefficient in  $m_1 \cdots m_{e+k}$  is the number  $(D_1 \cdots D_{e+k} \lrcorner [X_y])$ .

We suppose by induction that  $\text{ch}_i(q_*(\mathcal{F}))$  is a polynomial of degree  $e + i$  for any  $i \leq j$  where  $j \leq k - 1$ . For any subvariety  $V$  of dimension  $j + 1$  in  $Y$ , we denote by  $W$  its scheme-theoretic preimage by  $q$ .

For any scheme  $V$ , let us denote by  $\tau_V$  the morphisms:

$$\tau_V : K_0(V) \otimes \mathbb{Q} \rightarrow A_\bullet(V) \otimes \mathbb{Q}.$$

We refer to [Ful98, Theorem 18.3] for the construction of this morphism and its properties. We apply Grothendieck-Riemann-Roch's theorem for singular varieties (see [Ful98, Theorem 18.3.(1)]) and using (42), we get in  $A_\bullet(Y)_{\mathbb{Q}}$ :

$$\text{ch}(q_*(\mathcal{L}_1^{m_1} \otimes \cdots \otimes \mathcal{L}_{e+k}^{m_{e+k}})) \lrcorner \tau_V(\mathcal{O}_V) = q_*(\text{ch}(\mathcal{L}_1^{m_1} \otimes \cdots \otimes \mathcal{L}_{e+k}^{m_{e+k}}) \lrcorner \tau_W(\mathcal{O}_W)). \quad (43)$$

The term in  $A_0(Y)_{\mathbb{Q}}$  in the left handside of the previous equation is equal to:

$$\text{ch}_{j+1}(q_*(\mathcal{F})) \lrcorner [V] + \sum_{i \leq j} \text{ch}_i(q_*(\mathcal{F})) \lrcorner \tau_{V,i}(\mathcal{O}_V),$$

where  $\tau_{V,i}(\mathcal{O}_V)$  is the term in  $A_i(Y)$  of  $\tau_V(\mathcal{O}_V)$ . By the induction hypothesis, every  $\text{ch}_i(q_*(\mathcal{F}))$  is a polynomial of degree  $e + i$ , and the right hand side of equation (43) is a polynomial of degree  $e + j + 1$ , so  $\text{ch}_{j+1}(q_*(\mathcal{L}_1^{m_1} \otimes \cdots \otimes \mathcal{L}_{e+k}^{m_{e+k}}))$  is also a polynomial of degree  $e + j + 1$ . Now we identify the coefficients in  $m_1 \cdots m_{e+k}$  of the term in  $N_0(Y)$  in equation (43). It follows from [Ful98, example 18.3.11] that  $\tau_W(\mathcal{O}_W) = [W] + R_W$  where  $R_W$  is a linear combination of cycles of dimension  $< e + k$ . Therefore, the coefficient in  $m_1 \cdots m_{e+k}$  of the right hand side of equation (43) in  $N_0(Y)$  is  $((D_1 \cdots D_{e+k}) \lrcorner [W])$  if  $j + 1 = k$  or 0 otherwise.

We have proved that the coefficient of  $\text{ch}_{j+1}(q_*(\mathcal{L}_1^{m_1} \otimes \cdots \otimes \mathcal{L}_{e+k}^{m_{e+k}})) \lrcorner [V]$  is  $((D_1 \cdots D_{e+k}) \lrcorner [W])$  if  $\dim V = k$  or 0 otherwise. Extending it by linearity, one gets the desired result.  $\square$

We have that  $\text{ch}_k(q_*(\mathcal{L}_1^{m_1} \otimes \cdots \otimes \mathcal{L}_{e+k}^{m_{e+k}}))$  is by definition a polynomial in Chern classes of vector bundles on  $Y$ . Using the previous lemma, the coefficient  $U(D_1, \dots, D_{e+k})$  in  $m_1 \cdots m_{e+k}$  of  $\text{ch}_k(q_*(\mathcal{L}_1^{m_1} \otimes \cdots \otimes \mathcal{L}_{e+k}^{m_{e+k}}))$  is equal to  $P(c_{i_1}(E_1), \dots, c_{i_p}(E_p))$  where  $P$  is a homogeneous polynomial with rational coefficients of degree  $k$  with respect to the weight  $(i_1, \dots, i_p)$  and  $E_i$  are vector bundles on  $Y$ . We have proven that for any cycle  $z \in Z_k(Y)$ :

$$(P(c_{i_1}(E_1), \dots, c_{i_p}(E_p)) \lrcorner z) = ((D_1 \cdots D_{e+k}) \lrcorner q^*z).$$

As any Cartier divisor can be written as a difference of ample Cartier divisors. The proposition provides a proof for the implication (i)  $\Rightarrow$  (ii) of Theorem A.1.  $\square$

*Remark A.4.* In codimension 1, the intersection product  $(D_1 \cdots D_{e+1} \lrcorner q^*z)$  is represented by Deligne's product  $I_X(\mathcal{O}_X(D_1), \dots, \mathcal{O}_X(D_{e+1})) \in N^1(X)_{\mathbb{R}}$  (see [Gar00] for a reference). Indeed, one has by [Gar00, Section 6] that for any cycle  $z \in N_1(X)$ :

$$c_1(I_X(\mathcal{O}_X(D_1), \dots, \mathcal{O}_X(D_{e+1}))) \lrcorner z = D_1 \cdots D_{e+1} \lrcorner q^*z.$$

This gives an answer to the question of numerical pullback formulated in [FL14b, section 1.2].

**Corollary A.5.** *Let  $q : X \rightarrow Y$  be a flat morphism of relative dimension  $e$  between normal projective varieties. Then the morphism  $q^* : A_{\bullet}(Y)_{\mathbb{Q}} \rightarrow A_{e+\bullet}(X)_{\mathbb{Q}}$  induces a morphism of abelian groups  $q^* : N_{\bullet}(Y)_{\mathbb{Q}} \rightarrow N_{e+\bullet}(X)_{\mathbb{Q}}$ .*

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