Basepoint Free Theorem on Positive Characteristic

This section refers to [Kee99], [Art70] and [Fan+05]. Throughout this section, all schemes are of finite type over a base scheme S with S noetherian. we assume that the base field $\mathbf{k}$ is algebraically closed and of positive characteristic p.

1 Preliminaries

Theorem 1 (Serre vanishing in relative setting, ref. [Laz04, Theorem 1.7.6])**.** Let $f : X \to S$ be a proper morphism of schemes, $\mathcal{L}$ a line bundle and $\mathcal{F}$ a coherent sheaf on X. Suppose that $\mathcal{L}$ is relatively ample. Then there exists $n_0 \in \mathbb{N}$ such that for all $n \geq n_0$, the higher direct image sheaves $R^i f_* \mathcal{F} \otimes \mathcal{L}^{\otimes n}$ are zero for all $i > 0$.

Definition 2. Let X be a proper variety and $\mathcal{L}$ a nef line bundle on X. A closed subvariety $Z \subseteq X$ is called the *exceptional* for $\mathcal{L}$ if $\mathcal{L}^{\dim Z} \cdot Z = 0$. The *exceptional locus* of $\mathcal{L}$, denoted by $\operatorname{Exc} \mathcal{L}$, is defined as the closure of the union of all exceptional subvarieties of $\mathcal{L}$.

If $\mathcal{L}$ is semiample, then $\operatorname{Exc} \mathcal{L} = \operatorname{Exc} \varphi$ for the fibration $\varphi : X \to Y$ induced by $\mathcal{L}$.

Definition 3. Let X be a proper scheme and $\mathcal{L}$ a nef line bundle on X. We say that $\mathcal{L}$ is *endowed with a map (EWM)* if there is a proper morphism $\varphi : X \to Y$ to a proper algebraic space such that $\dim Z > \dim f(Z)$ if and only if Z is an exceptional subvariety of $\mathcal{L}$. If such a morphism is a fibration, then it is unique, called the *fibration associated to* $\mathcal{L}$.

Proposition 4. Let X be a proper variety and $\mathcal{L}$ a nef line bundle on X endowed with a map. Let $\varphi : X \to Y$ be the associated fibration. Then the $\mathcal{L}$ is semiample iff there is line bundle $\mathcal{L}_Y$ and $m \in \mathbb{Z}_{>0}$ such that $\mathcal{L}^{\otimes m} = \varphi^* \mathcal{L}_Y$.

Proof. Yang: To be completed. □

Definition 5. A morphism $f : X \to Y$ of schemes is called a *universal homeomorphism* if for every Y-scheme Y', the base change $X \times_Y Y' \to Y'$ is a homeomorphism between the underlying topological spaces.

Example 6. Let X be a scheme of finite type over $\mathbf{k}$. Then the natural morphism $X_{\mathrm{red}} \to X$ is a universal homeomorphism.

Let X be a scheme over S of characteristic p. Then the absolute and relative Frobenius morphisms are universal homeomorphisms. Yang: To be completed.

The morphism $\operatorname{Spec} \mathbb{C} \to \operatorname{Spec} \mathbb{R}$ is not a universal homeomorphism.

Lemma 7. Let X be a projective scheme over $\mathbf{k} = \overline{\mathbb{F}_p}$. Then $\operatorname{Pic}^0(X)$ is a torsion group.

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Proof. Yang: To be completed. □

2 Algebraic space

Definition 8. Let $\mathbf{C}$ be a category. A *Grothendieck topology* on $\mathbf{C}$ is a collection of sets of arrows $\{U_i \to U\}_{i\in I}$, called *covering*, for each object U in $\mathbf{C}$ such that:

(a) if $V \to U$ is an isomorphism, then $\{V \to U\}$ is a covering;

(b) if $\{U_i \to U\}_{i\in I}$ is a covering and $V \to U$ is a arrow, then the fiber product $U_i \times_U V \to V$ exists and $\{U_i \times_U V \to V\}$ is a covering of V;

(c) if $\{U_i \to U\}_{i\in I}$ and $\{U_{ij} \to U_i\}_{j\in J_i}$ are coverings, then the collection of composition $\{U_{ij} \to U_i \to U\}_{i\in I, j\in J_i}$ is a covering.

A *site* is a pair $(\mathbf{C}, \mathcal{J})$ where $\mathbf{C}$ is a category and $\mathcal{J}$ is a Grothendieck topology on $\mathbf{C}$.

Note that sheaf is indeed defined on a site.

Definition 9. Let $(\mathbf{C}, \mathcal{J})$ be a site. A *sheaf* on $(\mathbf{C}, \mathcal{J})$ is a functor $\mathcal{F} : \mathbf{C}^{op} \to \mathbf{Set}$ satisfying the following condition: for every object U in $\mathbf{C}$ and every covering $\{U_i \to U\}_{i\in I}$ of U, if we have a collection of elements $s_i \in \mathcal{F}(U_i)$ such that for every i, j, the pullback $s_i|_{U_i\times_U U_j}$ and $s_j|_{U_i\times_U U_j}$ are equal, then there exists a unique element $s \in \mathcal{F}(U)$ such that for every i, the pullback $s|_{U_i} = s_i$.

Definition 10. Let X be a scheme. The *big étale site* of X, denoted by $(\mathbf{Sch}/X)_{\text{ét}}$, is the category of schemes over X with the Grothendieck topology generated by étale morphisms, that is, a collection of morphisms $\{U_i \to U\}_{i\in I}$ is a covering if and only if each U_i is étale over U and the union of their images is the whole U.

Let X be a scheme over S. By Yoneda's Lemma, it is equivalent to give a functor $h_X : \mathbf{Sch}_S^{op} \to \mathbf{Set}$ such that for any S-scheme T, $h_X(T) = \mathrm{Hom}_{\mathbf{Sch}_S}(T, X)$. Yang: Easy to check that h_X is a sheaf on the big étale site $(\mathbf{Sch}/S)_{\text{ét}}$.

Definition 11. Let U be a scheme over a base scheme S. An *étale equivalence relation* on U is a morphism $R \to U \times_S U$ between schemes over S such that:

(a) the projections in two factors $R \to U$ are étale and surjective;

(b) for every S-scheme T, $h_R(T) \to h_U(T) \times h_U(T)$ gives an equivalence relation on $h_U(T)$ set-theoretically.

Definition 12. An *algebraic space* X over a base scheme S is an S-scheme U together with an étale equivalence relation $R \to U \times_S U$.

Let $X = (U, R)$ be an algebraic space over S. We explain X as a sheaf on the big étale site $(\mathbf{Sch}/S)_{\text{ét}}$. For any scheme T over S, $h_R(T)$ is an equivalence relation on $h_U(T)$. The rule sending T to the set of equivalence classes of $h_R(T)$ gives a presheaf on the site $(\mathbf{Sch}/S)_{\text{ét}}$. The sheafification of this presheaf is the sheaf associated to the algebraic space X. Explicitly, we have

$$X(T) := \left\{ f = (f_i) \,\middle|\, \begin{array}{c} \{T_i \to T\} \text{ a covering, } f_i \in h_U(T_i) \text{ such} \\ \text{that } (f_i|_{T_i \times_T T_j}, f_j|_{T_i \times_T T_j}) \in h_R(T_i \times_T T_j) \end{array} \right\} \Big/ \sim,$$

where

$$\alpha \sim \beta \quad \text{if } \exists \{S_i \to T\} \text{ such that } (\alpha|_{S_i}, \beta|_{S_i}) \in h_R(S_i).$$

Definition 13. An *algebraic space* over a base scheme S is a sheaf F on the big étale site $(\mathbf{Sch}/S)_{\text{ét}}$ such that

(a) the diagonal morphism $F \to F \times_S F$ is representable;

(b) there exists a scheme U over S and a map $h_U \to F$ which is surjective and étale.

The *morphism between algebraic spaces* F_1, F_2 is defined as a natural transformation of functors F_1, F_2.

Remark 14. By Yoneda's Lemma, given a morphism $h_U \to F$ between sheaves is the same as giving an element of $F(U)$. We may abuse the notation.

Definition 15. Let $\mathcal{P}$ be a property of morphisms of schemes satisfying the following conditions:

(a) is preserved under any base change;

(b) is étale local on the base. Yang: In [Stacks], this requires that "fppf local".

Let $\alpha : F \to G$ be a representable morphism of sheaves on the big étale site $(\mathbf{Sch}/S)_{\text{ét}}$. We say that α has property $\mathcal{P}$ if for every $h_T \to G$, the base change $h_T \times_G F \to F$ has property $\mathcal{P}$.

Remark 16. The fiber product $F_1 \times_F F_2$ is just defined as $F_1 \times_F F_2(T) := F_1(T) \times_{F(T)} F_2(T)$ for any object $T \in \mathrm{Obj}(\mathbf{Sch}_S)$. We say that a morphism $f : F_1 \to F_2$ of sheaves is *representable* if for every $T \in \mathrm{Obj}(\mathbf{Sch}/S)$ and every $\xi \in F_2(T)$, the sheaf $F_1 \times_{F_2} h_T$ is representable as a functor. Here $h_T \to F_2$ is given by

$$h_T(U) \to F_2(U), \quad f \in \mathrm{Hom}(U, T) \mapsto F_2(f)(\xi) \in F_2(U).$$

In our case, given an arbitrary $h_U \to F \times F$ is equivalent to giving morphisms $h_{U_i} \to F$ for $i = 1, 2$. And the fiber product $F \times_{F \times F} (h_{U_1} \times h_{U_2})$ is just the fiber product $h_{U_1} \times_F h_{U_2}$. Hence the first condition in Definition 13 is equivalent to that $h_{U_1} \times_F h_{U_2}$ is representable for any U_1, U_2 over F. This implies that $h_U \to F$ is representable, whence the second condition in Definition 13 makes sense.

Definition 17. Let X be an algebraic space over a base scheme S. Two two morphisms form field $\operatorname{Spec} k_i \to X$ is called equivalent if there is a common extension $K \supset k_1, k_2$ such that we have $\operatorname{Spec} K \to \operatorname{Spec} k_i \to X$ are the same for $i = 1, 2$. The *underlying point set* of X, denote by $|X|$, is defined as the set of equivalence classes of morphisms $\operatorname{Spec} k \to X$ for all field k over the base field $\mathbf{k}$.

This definition coincides with the underlying set of a scheme. Let $\alpha : X \to Y$ be a morphism of algebraic spaces. It induces a map $|\alpha| : |X| \to |Y|$ by $x \mapsto \alpha \circ x$ (vertical composition).

Proposition 18 (ref. [Stacks, Lemma 66.4.6])**.** There is a unique topology on $|X|$ such that

(a) if X is a scheme, then the topology coincides with the usual topology.

(b) every morphism of algebraic spaces $f : X \to Y$ induces a continuous map $|f| : |X| \to |Y|$.

(c) if U is a scheme and $U \to X$ is étale, then the induced map $|U| \to |X|$ is open.

This topology is called the *Zariski topology* on $|X|$.

Definition 19. Let X be an algebraic space over a base scheme S. All étale morphisms $U \to X$ with U scheme form a small site $X_{\text{ét}}$. All étale morphisms $U \to X$ with U algebraic space form a small site $X_{\text{sp, ét}}$. The *structure sheaf* $\mathcal{O}_X$ of X is given by $U \mapsto \Gamma(U, \mathcal{O}_U)$ for every étale morphism $U \to X$ from a scheme. It extends to a sheaf on the site $X_{\text{sp, ét}}$ uniquely.

Example 20. Let $U = \mathbb{A}^1_{\mathbb{C}}$ and $R \subset U \times U$ given by $y = x + n, n \in \mathbb{Z}$. Then R is a disjoint union of lines in $U \times U$. Write $R = \coprod_{n\in\mathbb{Z}} R_n$ with $R_n = \{(x, x+n) : x \in \mathbb{C}\}$. Then the projection is given by

$$\pi_1|_{R_n} : R_n \to U, \quad (x, x+n) \mapsto x,$$
$$\pi_2|_{R_n} : R_n \to U, \quad (x, x+n) \mapsto x+n.$$

Easily see that the projection $\pi_i : R \to U$ is étale and surjective for $i = 1, 2$. Let $r_{ij} : R \times U \to U \times U \times U$ be the morphism which maps $((x, y), u)$ to (a_1, a_2, a_3) where $a_i = x$, $a_j = y$ and $a_k = u$ for $k \neq i, j$. Since $\Delta_U \to U \times U$ factors through R, $(\pi_1, \pi_2) = (\pi_2, \pi_1)$ and $r_{12} \times_{(U\times U\times U)} r_{23}$ factors through r_{13}, we have that $h_R(T)$ is an equivalence relation on $h_U(T)$ for all T over S. Then $X := (U, R)$ is an algebraic space.

We do not check the representability here but give an example. Let $U \to X$ be the natural morphism given by $\mathrm{id}_U \in X(U)$. For any scheme T over $\mathbb{C}$, we have

$$(U \times_X U)(T) = \{(f, g) \in h_{U\times U}(T) : \exists\{T_i \to T\} \text{ s.t. } (f_i, g_i) \in h_R(T_i)\} = h_R(T).$$

Hence the fiber product $h_U \times_X h_U$ is represented by R.

We show that $X \ncong \mathbb{C}^\times$ by computing the the global sections. Consider the covering $U \to X$, a section $s \in \mathcal{O}_X(X)$ is given by a section $s \in \Gamma(U, \mathcal{O}_U) = \mathbb{C}[t]$ such that $\pi_1^* s = \pi_2^* s$ in $\Gamma(R, \mathcal{O}_R)$. This means that $s(x+n) = s(x)$ for all $n \in \mathbb{Z}$. Hence s is a constant function. In particular, $\mathcal{O}_X(X) = \mathbb{C} \neq \mathbb{C}[t, t^{-1}]$.

The underlying set $|X|$ is union of the quotient set $\mathbb{C}/\mathbb{Z}$ and a generic point. Yang: The Zariski topology on $|X|$ is the quiotient topology induced by $|U| \to |X|$.

Definition 21. Let X be an algebraic space over a base scheme S. A *coherent sheaf* on X is a sheaf $\mathcal{F}$ on $X_{\text{ét}}$ such that for every covering $\{U_i \to X\}$ with U_i schemes, the sheaf $\mathcal{F}|_{U_i}$ is coherent for every i. It extends to a sheaf on the site $X_{\text{sp, ét}}$ uniquely.
An *ideal sheaf* on X is a coherent sheaf $\mathcal{I} \subset \mathcal{O}_X$. It defines a closed subspace $V(\mathcal{I}) \subset X$ by Yang: to be completed. And every closed subspace $Y \subset X$ is defined by an ideal sheaf $\mathcal{I}_Y$ such that $V(\mathcal{I}_Y) = Y$.

Definition 22. Let X be an algebraic space over a base scheme S and Y a closed subset of $|X|$. The *formal completion* of X along Y, denoted by $\mathfrak{X}$, is the functor defined as

$$(\mathbf{Sch}/S)_{\text{ét}} \to \mathbf{Set}, \quad U \mapsto \{f : U \to X : f(|U|) \subset |Y|\}.$$

Yang: to be completed.

Definition 23. Let X be an algebraic space and Y a closed subset of X. A *modification* of X along Y is a proper morphism $f : X' \to X$ and a closed subset $Y' \subset X'$ such that $X' \setminus Y' \to X \setminus Y$ is an isomorphism and $f^{-1}(Y) = Y'$.

Theorem 24 (ref. [Art70, Theorem 3.1])**.** Let Y' be a closed subset of an algebraic space X' of finite type over $\mathbf{k}$. Let $\mathfrak{X}'$ be the formal completion of X' along Y'. Suppose that there is a formal modification $\mathfrak{f} : \mathfrak{X}' \to \mathfrak{X}$. Then there is a unique modification

$$f : X' \to X, \quad Y \subset X$$

such that the formal completion of X along Y is isomorphic to $\mathfrak{X}$ and the induced morphism $\mathfrak{X}' \to \mathfrak{X}$ is isomorphic to $\mathfrak{f}$.

Theorem 25 (ref. [Art70, Theorem 6.2])**.** Let $\mathfrak{X}'$ be a formal algebraic space and $Y' = V(\mathcal{I}')$ with $\mathcal{I}'$ the defining ideal sheaf of $\mathfrak{X}'$. Let $f : Y' \to Y$ be a proper morphism. Suppose that

(a) for every coherent sheaf $\mathcal{F}$ on $\mathfrak{X}'$, we have

$$R^1 f_* \mathcal{I}'^n \mathcal{F} / \mathcal{I}'^{n+1} \mathcal{F} = 0, \quad \forall n \gg 0;$$

(b) for every n, the homomorphism

$$f_*(\mathcal{O}_{\mathfrak{X}'}/\mathcal{I}'^n) \otimes_{f_* \mathcal{O}_{Y'}} \mathcal{O}_Y \to \mathcal{O}_Y$$

is surjective.

Then there exists a modification $\mathfrak{f} : \mathfrak{X}' \to \mathfrak{X}$ and a defining ideal sheaf $\mathcal{I}$ of $\mathfrak{X}$ such that $V(\mathcal{I}) = Y$ and $\mathfrak{f}$ induces f on Y.

Theorem 26 (ref. [Art70, Theorem 6.1])**.** Let Y' be a closed algebraic subspace of an algebraic space X' and $f_0 : Y' \to Y$ a finite morphism. Then there exists a modification $f : X' \to X$ whose restriction to Y' is f_0. It is the amalgamated sum $X = X' \amalg_{Y'} Y$ in the category of algebraic spaces **AlgSp**.

Example 27. Let $X = \mathbb{A}^2 = \operatorname{Spec} \mathbf{k}[x, y]$ and $Y = V(y)$ be the x-axis. Let $f_0 : Y' = \mathbb{A}^1 \to Y, x \mapsto x^2$. Then there exists a modification $f : X' \to X$ such that the restriction $f|_{Y'} : Y' \to Y$ is f_0. Yang: To be completed.

Lemma 28. Let $f : X \to Y$ be a finite morphism of algebraic space and is a universal homeomorphism. Then there exists $q = p^n$ such that the relative Frobinius morphism $\mathrm{Frob}^n_{X/\mathbf{k}}$ factors as

$$\mathrm{Frob}^n_{X/\mathbf{k}} : X \xrightarrow{f} Y \to X^{(q)}.$$

Proof. Yang: To be completed. □

Corollary 29. Let $Z \to X$ be a finite universal homeomorphism of algebraic spaces and $Z \to Y$ any morphism of algebraic spaces. Suppose that X, Y, Z are all of finite type over $\mathbf{k}$. Then the amalgamated sum $X \amalg_Z Y$ exists in the category of algebraic spaces. Moreover, $Y \to X \amalg_Z Y$ is a finite universal homeomorphism.

Proof. Yang: To be completed. □

3 A sufficient and necessary condition for basepoint free

Proposition 30. Let $g : X' \to X$ be a proper, finite universal homeomorphism between algebraic spaces. Then a line bundle $\mathcal{L}$ on X is endowed with a map if and only if $g^*\mathcal{L}$ is endowed with a map.

Proof. Yang: To be completed. □

Proposition 31. Let X be a projective scheme and $\mathcal{L}$ a nef line bundle on X. Assume that $X = X_1 \cup X_2$ for closed subsets X_1 and X_2. Suppose that $\mathcal{L}|_{X_i}$ is endowed with a map $g_i : X_i \to Z_i$ for $i = 1, 2$. Assume that for all but finitely many points $x \in X$, the geometric fiber of $g_1|_{X_1 \cap X_2}$ are connected. Then $\mathcal{L}$ is endowed with a map $g : X \to Z$.

Proof. Yang: To be completed. □

Proposition 32. Let X be a proper variety and D a nef and big divisor on X. Then we can write $D = A + E$ where A is an ample divisor and E is an effective divisor. Then D is endowed with a map iff $D|_{E_{red}}$ is endowed with a map.

Proof. By Proposition 30, we may assume that $D|_E$ is endowed with a map $f : E \to Z$. Let $\mathcal{L} = \mathcal{O}_X(-E)$ be the ideal sheaf of E. note that $-E = D - A$ and D is f-numerically trivial. Hence $\mathcal{L}|_E$ is f-ample. By Serre's vanishing, for every coherent sheaf $\mathcal{F}$ on X, there exists $n_0 \in \mathbb{N}$ such that for all $n \geq n_0$, we have

$$R^i f_* \mathcal{F}|_E \otimes \mathcal{L}^{\otimes n} = R^i f_*(\mathcal{L}^n \mathcal{F}/\mathcal{L}^{n+1}\mathcal{F}) = 0$$

for all $i > 0$.

Yang: To be completed. □

Theorem 33. Let X be a proper variety and $\mathcal{L}$ a nef line bundle on X. Then $\mathcal{L}$ is basepoint free if and only if $\mathcal{L}|_{\mathrm{Exc}\,\mathcal{L}}$ is basepoint free.

Proof. Yang: To be completed. □

4 Basepoint free theorem on positive characteristic

Theorem 34. Let X be a normal projective $\mathbb{Q}$-factorial threefold and $B \in (0, 1)$ a $\mathbb{Q}$-divisor. Let $\mathcal{L}$ be a nef and big line bundle on X such that $\mathcal{L} - K_{(X,B)}$ is nef and big. Then $\mathcal{L}$ is endowed with a map. Moreover, if $\mathbf{k} = \overline{\mathbb{F}_p}$, $\mathcal{L}$ is basepoint free.

Proof. Yang: To be completed. □

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