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**SIMULTANEOUS CUBIC HYPER-RESOLUTIONS  
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AND COHOMOLOGICAL DESCENT**

SHOJI TSUBOI AND FRANCISCO GUILLÉN

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**Introduction**

In [10] the notion of *cubic hyper-resolutions* of algebraic varieties has been introduced, and its cohomological descent property together with several applications has been shown. For example, the mixed Hodge structure on the cohomology of an algebraic variety can be described by use of its cubic hyper-resolution. In this paper we shall consider *simultaneous cubic hyper-resolutions* of *locally trivial* analytic families of complex projective varieties, and prove that they have also cohomological descent property. This might be considered as a relative analogue of the second author's result in [10, Exposés I, III]. The motivation of this generalization is to describe the variations of mixed Hodge structure arising from *locally trivial* families of complex projective varieties with *ordinary singularities* (for terminology see Definition 1.10 and Definition 2.2 below) by use of simultaneous cubic hyper-resolutions of their fibers. We shall treat the *infinitesimal mixed Torelli problem* for algebraic surfaces with ordinary singularities in a forthcoming paper, using the result of this paper.

Throughout this paper, we shall always work over the complex number field. Our method is basically complex analytic and we shall always regard algebraic manifolds and algebraic varieties over the complex number field as complex manifolds and complex analytic varieties. Here we use the term of complex analytic varieties in the sense of reduced complex spaces (possibly not irreducible).

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### §1 Simultaneous cubic hyper-resolutions of locally trivial analytic families of complex projective varieties

First, we refer to some terminology and notation from [10]. We denote by  $\mathbb{Z}$  the integer ring. For a non-negative integer  $n$ , let  $\square_n^+$  the *augmented  $n$ -cubic category*, i.e., the category whose objects  $\text{Ob}(\square_n^+)$  and the set of homomorphisms  $\text{Hom}_{\square_n^+}(\alpha, \beta)$  ( $\alpha = (\alpha_0, \alpha_1, \dots, \alpha_n)$ ,  $\beta = (\beta_0, \beta_1, \dots, \beta_n) \in \text{Ob}(\square_n^+)$ ) are given as follows:

$$\text{Ob}(\square_n^+) := \{\alpha = (\alpha_0, \alpha_1, \dots, \alpha_n) \in \mathbb{Z}^{n+1} \mid 0 \leq \alpha_i \leq 1 \text{ for } 0 \leq i \leq n\},$$

$$\text{Hom}_{\square_n^+}(\alpha, \beta) := \begin{cases} \alpha \rightarrow \beta \text{ (an arrow from } \alpha \text{ to } \beta) & \text{if } \alpha_i \leq \beta_i \text{ for } 0 \leq i \leq n \\ \emptyset & \text{otherwise.} \end{cases}$$

For  $n = -1$  we define  $\square_{-1}^+$  to be the punctual category  $\{*\}$ , i.e., the category consisting of a single point. For  $n \geq 0$  the  *$n$ -cubic category*, denoted by  $\square_n$ , is defined to be the full subcategory of  $\square_n^+$  with  $\text{Ob}(\square_n) = \text{Ob}(\square_n^+) - \{(0, \dots, 0)\}$ . Notice that  $\text{Ob}(\square_n^+)$  and  $\text{Ob}(\square_n)$  can be considered as finite ordered sets whose order are defined by  $\alpha \leq \beta \iff \alpha \rightarrow \beta$  for  $\alpha, \beta \in \text{Ob}(\square_n^+)$ .

**1.1 Definition.** A  $\square_n^+$ -object (resp.  $\square_n$ -object) of a category  $\mathcal{C}$  is a contravariant functor  $X_\bullet^+$  (resp.  $X_\bullet$ ) from  $\square_n^+$  (resp.  $\square_n$ ) to  $\mathcal{C}$ . It is also called an *augmented  $n$ -cubic object of  $\mathcal{C}$*  (resp. an  *$n$ -cubic object of  $\mathcal{C}$* ).

**1.2 Definition.** Let  $X_\bullet, Y_\bullet$  be  $\square_n^+$ -objects (resp.  $\square_n$ -objects) of a category  $\mathcal{C}$ . We define a morphism  $\Phi_\bullet : X_\bullet \rightarrow Y_\bullet$  to be a natural transformation from the functor  $X_\bullet$  to the one  $Y_\bullet$  over the identity functor  $\text{id} : \square_n^+ \rightarrow \square_n^+$  (resp.  $\text{id} : \square_n \rightarrow \square_n$ ).

**1.3 Definition.** Let  $X_\bullet$  be an  $n$ -cubic object of  $\mathcal{C}$  ( $n \geq 0$ ),  $X$  an object of  $\mathcal{C}$ . An *augmentation of  $X_\bullet$  to  $X$*  is a natural transformation from the functor

$X_\bullet$  to the one  $X$  over the trivial functor  $\square_n \rightarrow \square_{-1}^+$ , where we consider  $X$  as a  $\square_{-1}^+$ -object of  $\mathcal{C}$ .

**1.4 Remark.** Notice that we may think of an  $n$ -cubic object of  $\mathcal{C}$  with an augmentation to  $X$  as an augmented  $n$ -cubic object of  $\mathcal{C}$ . Conversely, an augmented  $n$ -cubic object  $X_\bullet^+ : (\square_n^+)^{\circ} \rightarrow \mathcal{C}$  of  $\mathcal{C}$  can be identified with an  $n$ -cubic object  $X_\bullet := X_{\bullet|\square_n}^+ : (\square_n^+)^{\circ} \rightarrow \mathcal{C}$  of  $\mathcal{C}$  with an augmentation to  $X_{(0,\dots,0)}^+$ , where  $\circ$  denotes the dual category.

In what follows we shall interchangeably use an augmented  $n$ -cubic object of  $\mathcal{C}$  and an  $n$ -cubic object of  $\mathcal{C}$  with an augmentation.

**1.5 Definition.** A  $\square_n^+$ -complex projective variety (resp.  $\square_n^+$ -complex analytic variety) is defined to be a  $\square_n^+$ -object of the category of complex projective varieties ( $\text{Proj}/\mathbb{C}$ ) (resp. complex analytic varieties ( $\text{An}/\mathbb{C}$ )). It is also called an augmented  $n$ -cubic complex projective variety (resp. augmented  $n$ -cubic complex analytic variety).

**1.6 Example.** Let  $X$  be a complex projective variety and  $\{X_r\}_{0 \leq r \leq n}$  all of irreducible components of  $X$ . For each  $\alpha = (\alpha_0, \dots, \alpha_n) \in \square_n$  we define

$$X_\alpha := \bigcap \{X_i \mid \alpha_i = 1\}.$$

If  $\alpha \leq \beta$  in  $\square_n$ , then there is the natural inclusion map  $X_\beta \subseteq X_\alpha$ . Hence the correspondence  $\alpha \in \square_n \rightarrow X_\alpha \in (\text{Proj}/\mathbb{C})$  defines an  $n$ -cubic complex projective variety  $X_\bullet : (\square_n)^{\circ} \rightarrow (\text{Proj}/\mathbb{C})$ . We consider  $X$  as a  $\square_{-1}^+$ -complex projective variety. Then there exists naturally an augmentation  $X_\bullet \rightarrow X$ , which can be considered as an augmented  $n$ -cubic complex projective variety (cf. Remark 1.4)

**1.7 Definition.** For a  $\square_n^+$ -complex projective variety  $X_\bullet$ , a contravariant functor  $Y_\bullet$  from  $\square_1^+$  to the category of  $\square_n^+$ -complex projective varieties is called a 2-resolution of  $X_\bullet$  if  $Y_\bullet$  is defined by a cartesian square of morphisms of  $\square_n^+$ -complex projective varieties

$$(1.1) \quad \begin{array}{ccc} Y_{11\bullet} & \longrightarrow & Y_{01\bullet} \\ \downarrow & & \downarrow f \\ Y_{10\bullet} & \longrightarrow & Y_{00\bullet}, \end{array}$$

which satisfies the following conditions:

- (i)  $Y_{00\bullet} = X_\bullet$ ,
- (ii)  $Y_{01\bullet}$  is a smooth  $\square_n^+$ -complex projective variety, i.e., a contravariant functor from  $\square_n^+$  to the category of smooth complex projective varieties,
- (iii) the horizontal arrows are closed immersions of  $\square_n^+$ -complex projective varieties,
- (iv)  $f$  is a proper morphism between  $\square_n^+$ -complex projective varieties, and
- (v)  $f$  induces an isomorphism from  $Y_{01\beta} - Y_{11\beta}$  to  $Y_{00\beta} - Y_{10\beta}$  for any  $\beta \in \text{Ob}(\square_n^+)$ .

We think of the cartesian square in (1.1) as a morphism from the  $\square_{n+1}^+$ -complex projective variety  $Y_{1\bullet\bullet}$  to the one  $Y_{0\bullet\bullet}$  and write it as  $Y_{1\bullet\bullet} \rightarrow Y_{0\bullet\bullet}$ . For a 2-resolution  $Z_\bullet$  of  $Y_{1\bullet\bullet}$ , we define the  $\square_{n+3}^+$ -complex projective variety  $rd(Y_\bullet, Z_\bullet)$  by

$$rd(Y_\bullet, Z_\bullet) := \begin{array}{ccc} Z_{11\bullet} & \longrightarrow & Z_{01\bullet} \\ \downarrow & & \downarrow \\ Z_{10\bullet} & \longrightarrow & Y_{0\bullet\bullet} \end{array}$$

and call it the *reduction* of  $\{Y_\bullet, Z_\bullet\}$ .

**1.8 Definition.** Let  $X$  be a complex projective variety and let  $\{X_\bullet^1, X_\bullet^2, \dots, X_\bullet^n\}$  be a sequence of  $\square_r^+$ -complex projective varieties  $X_\bullet^r$  ( $1 \leq r \leq n$ ) such that

- (i)  $X_\bullet^1$  is a 2-resolution of  $X$ ,
- (ii)  $X_\bullet^{r+1}$  is a 2-resolution of  $X_\bullet^r$  for every  $r$  with  $1 \leq r \leq n-1$ .

Then, by induction on  $n$ , we define

$$Z_\bullet := rd(X_\bullet^1, X_\bullet^2, \dots, X_\bullet^n) := rd(rd(X_\bullet^1, X_\bullet^2, \dots, X_\bullet^{n-1}), X_\bullet^n).$$

With this notation, if  $Z_\alpha$  are smooth for all  $\alpha \in \text{Ob}(\square_n)$ , we call  $Z_\bullet$  an *augmented  $n$ -cubic hyper-resolution* of  $X$ .

**1.9 Example.** A 2-dimensional complex projective variety is said to be *with ordinary singularities* if it is locally isomorphic to one of the following germs of hypersurfaces of the complex 3-space  $\mathbb{C}^3$ :

$$\left\{ \begin{array}{ll} (i) \ z = 0 \text{ (simple point),} & (ii) \ yz = 0 \text{ (ordinary double point),} \\ (iii) \ xyz = 0 \text{ (ordinary triple point),} & (iv) \ xy^2 - z^2 = 0 \text{ (cuspidal point),} \end{array} \right.$$

where  $(x, y, z)$  is the coordinate on  $\mathbb{C}^3$ . We fix notation as follows:

Let  $S$  be a complex projective surface with ordinary singularities. We denote by  $D_S$  the singular locus of  $S$ , and call it the *double curve* of  $S$ .  $D_S$  is a singular curve with triple points. We denote by  $\Sigma t_S$  the triple point locus of  $S$ , and by  $\Sigma c_S$  the cuspidal point locus of  $S$ . Let  $f : X \rightarrow S$  be the normalization. Note that  $X$  is non-singular. We put  $D_X := f^{-1}(D_S)$  and  $\Sigma t_X := f^{-1}(\Sigma t_S)$ .  $D_X$  is a singular curve with nodes and  $\Sigma t_X$  coincides with the set of nodes of  $D_X$ . We denote by  $n_S : D_S^* \rightarrow D_S$  and  $n_X : D_X^* \rightarrow D_X$  the normalizations of  $D_S$  and  $D_X$ , respectively. We denote by  $g : D_X^* \rightarrow D_S^*$  the lifting of the map  $f|_{D_X} : D_X \rightarrow D_S$ . We put  $\Sigma t_S^* := n_S^{-1}(\Sigma t_S)$ ,  $\Sigma c_S^* := n_S^{-1}(\Sigma c_S)$  and  $\Sigma t_X^* := n_X^{-1}(\Sigma t_X)$ . With this notation, we have a *2-cubic hyper-resolution* of  $S$  as follows:

$$\begin{array}{ccccc}
 & & X_{111} := \sum t_X^* & \xrightarrow{\delta_0^{(2)}} & D_X^* := X_{011} \\
 & \delta_2^{(2)} \swarrow & \downarrow \delta_1^{(2)} & & \swarrow g =: \delta_1^{(1)} \\
 X_{110} := \sum t_S^* & \xrightarrow{\delta_0^{(1)}} & D_S^* := X_{010} & & \downarrow \nu_X =: \delta_0^{(1)} \\
 \downarrow \delta_1^{(1)} & & \downarrow \nu_S =: \delta^{(0)} & & \\
 & \delta_1^{(1)} \swarrow & X_{101} := \sum t_X & \xrightarrow{\delta_0^{(1)}} & X := X_{001} \\
 & & \downarrow \delta_1^{(1)} & & \swarrow f =: \delta^{(0)} \\
 X_{100} := \sum t_S & \xrightarrow{\delta^{(0)}} & S := X_{000} & & 
 \end{array}$$

where  $\nu_S$  and  $\nu_X$  are the composites of the normalizations  $n_S : D_S^* \rightarrow D_S$  and  $n_X : D_X^* \rightarrow D_X$  and the inclusion maps  $D_S \hookrightarrow S$  and  $D_X \hookrightarrow X$ , respectively, and the square on the left-hand side is the one induced from the square on the right-hand side.

The important property of a cubic hyper-resolution is *cohomological descent*. There are two sorts of *cohomological descent*; one is that of  $R$ -module sheaves ( $R$ : a commutative ring with identity element 1, especially  $R = \mathbb{Z}, \mathbb{Q}$  and  $\mathbb{C}$ ) ([10, p.41, Théorème 6.9]) and the second is that of de Rham complexes ([10, p.61, Théorème 1.3]).

Now we are going to give the definitions of *locally trivial* analytic families of complex projective varieties (resp. complex analytic varieties) and their *simultaneous cubic hyper-resolutions*.

**1.10 Definition.** By an analytic family of complex projective varieties (resp. complex analytic varieties), parametrized by a complex space  $M$ , we mean a triple  $(\mathfrak{X}, \pi, M)$  satisfying the following conditions:

- (i)  $\pi : \mathfrak{X} \rightarrow M$  is a flat surjective holomorphic map of complex spaces, and
- (ii)  $X_t := \pi^{-1}(t)$  is a complex projective variety (resp. complex analytic variety) for any  $t \in M$ .

Let  $(\mathfrak{X}, \pi, M)$  and  $(\mathfrak{X}', \pi', M)$  be analytic families of complex projective varieties (resp. complex analytic varieties) parametrized by the same complex space  $M$ .

**1.11 Definition.** By a morphism (resp. an isomorphism) for  $(\mathfrak{X}, \pi, M)$  to  $(\mathfrak{X}', \pi', M)$  we mean a holomorphic (resp. biholomorphic) map  $H : \mathfrak{X} \rightarrow \mathfrak{X}'$  such

that the diagram

$$\begin{array}{ccc} \mathfrak{X} & \xrightarrow{H} & \mathfrak{X}' \\ \pi \downarrow & & \downarrow \pi' \\ M & \xrightarrow{\text{id}_M} & M \end{array}$$

commutes, where  $\text{id}_M$  is the identity map on  $M$ .

**1.12 Definition.** An analytic family of complex projective varieties (resp. complex analytic varieties)  $(\mathfrak{X}, \pi, M)$  is said to be *locally trivial* if it satisfies the following condition: for every point  $p \in \mathfrak{X}$ , there exist open neighborhoods  $\mathcal{U}$  of  $p$  in  $\mathfrak{X}$ ,  $V$  of  $\pi(p)$  in  $M$  with  $\pi(\mathcal{U}) = V$ , and a biholomorphic map  $\phi : \mathcal{U} \rightarrow U \times V$ , where we define  $U := \mathcal{U} \cap X_{\pi(p)}$ , such that;

(a) the diagram

$$\begin{array}{ccc} \mathcal{U} & \xrightarrow{\phi} & U \times V \\ \pi|_{\mathcal{U}} \searrow & & \swarrow \text{Pr}_V \\ & V & \end{array}$$

commutes,

(b)  $\phi|_U := \text{id}_U$ .

We denote by  $\mathcal{F}_M(\text{Proj}/\mathbb{C})$  (resp.  $\mathcal{F}_M(\text{An}/\mathbb{C})$ ) the category of analytic families of complex projective (resp. analytic) varieties, parametrized by a complex space  $M$ .

**1.13 Definition.** We call a  $\square_n^+$ -object (resp.  $\square_n$ -object) of  $\mathcal{F}_M(\text{Proj}/\mathbb{C})$ , or of  $\mathcal{F}_M(\text{An}/\mathbb{C})$ , an *analytic family of augmented  $n$ -cubic (resp.  $n$ -cubic) complex projective varieties, or complex analytic varieties, parametrized by a complex space  $M$ .*

Let  $b_\bullet : X_\bullet \rightarrow X$  be an augmented  $n$ -cubic complex projective (resp. analytic) variety and  $M$  a complex space. Then  $X_\alpha \times M$  ( $\alpha \in \square_n$ ),  $X \times M$ ,  $a_\alpha := b_\alpha \times \text{id}_M : X_\alpha \times M \rightarrow X \times M$  and  $\pi := \text{Pr}_M : X \times M \rightarrow M$ , the projection to  $M$  constitute an analytic family of augmented  $n$ -cubic complex projective (resp. analytic) varieties, parametrized by a complex space  $M$ , which we denote by

$$X_\bullet \times M \xrightarrow{a_\bullet := b_\bullet \times \text{id}_M} X \times M \xrightarrow{\pi := \text{Pr}_M} M$$

and call the *product family of augmented  $n$ -cubic complex projective (resp. analytic) varieties, parametrized by a complex space  $M$* . Let  $\mathfrak{X}_\bullet^+ = \{a_\bullet : \mathfrak{X}_\bullet \rightarrow \mathfrak{X}\}$  be an analytic family of augmented  $n$ -cubic complex projective (resp. analytic) varieties (for notation see Remark 1.4 above), parametrized by a complex space  $M$ . Whenever we wish to express its parameter space  $M$  explicitly, we write

$$(1.2) \quad \mathfrak{X}_\bullet \xrightarrow{a_\bullet} \mathfrak{X} \xrightarrow{\pi} M.$$

For  $t \in M$ ,  $X_{\alpha t} := (\pi \circ a_\alpha)^{-1}(t)$  ( $\alpha \in \square_n$ ),  $X_t := \pi^{-1}(t)$  and  $a_{\alpha t} := a_\alpha|_{X_{\alpha t}} : X_{\alpha t} \rightarrow X_t$  constitute an augmented  $n$ -cubic complex projective (resp. analytic) variety, which we denote by  $X_{\bullet t} \xrightarrow{a_{\bullet t}} X_t$  and call the fiber at  $t \in M$  of an analytic family of augmented  $n$ -cubic complex projective (resp. analytic) varieties in (1.2). For an open subset  $U$  of  $\mathfrak{X}$ , we form an analytic family

$$a_{\bullet}^{-1}(\mathcal{U}) \xrightarrow{a_{\bullet}|_{a_{\bullet}^{-1}(\mathcal{U})}} \mathcal{U} \xrightarrow{\pi} \pi(\mathcal{U})$$

of augmented  $n$ -cubic *analytic varieties*, parametrized by a complex space  $\pi(\mathcal{U})$ . With these notions, we define a *simultaneous cubic hyper-resolution* of a locally trivial analytic family of complex projective varieties, parametrized by a complex space as follows:

**1.14 Definition.** Let  $\pi : \mathfrak{X} \rightarrow M$  be a *locally trivial* analytic family of complex projective varieties, parametrized by a complex space  $M$ . A *simultaneous ( $n$ -) cubic hyper-resolution* of the family  $\pi : \mathfrak{X} \rightarrow M$  is defined to be an analytic family  $\mathfrak{X}_{\bullet} \xrightarrow{a_{\bullet}} \mathfrak{X} \xrightarrow{\pi} M$  of augmented  $n$ -cubic complex projective varieties with a certain non-negative integer  $n$ , parametrized by the complex space  $M$ , which satisfies the following conditions:

(i) for any point  $t \in M$ ,  $a_{\bullet t} : X_{\bullet t} \rightarrow X_t$  is an augmented  $n$ -cubic hyper-resolution of  $X_t$ ,

(ii)(analytical "local triviality") for any point  $p \in \mathfrak{X}$ , there exists an open neighborhood  $\mathcal{U}$  of  $p$  in  $\mathfrak{X}$  such that  $a_{\bullet}^{-1}(\mathcal{U}) \xrightarrow{a_{\bullet}|_{a_{\bullet}^{-1}(\mathcal{U})}} \mathcal{U} \xrightarrow{\pi} \pi(\mathcal{U})$  is analytically isomorphic to

$$(a_{\bullet}^{-1}(\mathcal{U}) \cap X_{\bullet \pi(p)}) \times \pi(\mathcal{U}) \rightarrow (\mathcal{U} \cap X_{\pi(p)}) \times \pi(\mathcal{U}) \xrightarrow{\text{Pr}_{\pi(\mathcal{U})}} \pi(\mathcal{U})$$

over the identity map  $\text{id}_{\pi(\mathcal{U})} : \pi(\mathcal{U}) \rightarrow \pi(\mathcal{U})$

If the parameter space  $M$  of a locally trivial analytic family  $\pi : \mathfrak{X} \rightarrow M$  of complex projective varieties is smooth, we have the following theorems.

**1.15 Theorem.** Let  $\pi : \mathfrak{X} \rightarrow M$  be a *locally trivial analytic family* of complex projective varieties, parametrized by a complex manifold  $M$ , and  $a_{\bullet} : \mathfrak{X}_{\bullet} \rightarrow \mathfrak{X}$  the *canonical cubic hyper-resolution* of  $\mathfrak{X}$ . Here "canonical" means in the sense of Bierstone-Millman ([2]). Then  $\mathfrak{X}_{\bullet} \xrightarrow{a_{\bullet}} \mathfrak{X} \xrightarrow{\pi} M$  is a *simultaneous cubic hyper-resolution* of  $\pi : \mathfrak{X} \rightarrow M$ .

*Proof.* The construction of the canonical hyper-resolution of  $\mathfrak{X}$  is obtained, using the canonical process of desingularisation in the proof of the existence of the resolution of a diagram of complex projective varieties (or compact complex analytic varieties) (cf. [10, Théorème 2.6]). Then, because of the hypothesis of local triviality of  $\pi : \mathfrak{X} \rightarrow M$ , the fibre  $X_{\bullet t} \rightarrow X_t$  for each  $t \in M$  is also the canonical hyper-resolution. Hence  $\mathfrak{X}_{\bullet} \xrightarrow{a_{\bullet}} \mathfrak{X} \xrightarrow{\pi} M$  is a simultaneous cubic hyper-resolution of the family  $\pi : \mathfrak{X} \rightarrow M$  in the sense of Definition 1.14.



Q.E.D.

**1.16 Theorem.** *Let  $\mathfrak{X}_\bullet \xrightarrow{a_\bullet} \mathfrak{X} \xrightarrow{\pi} M$  be a simultaneous  $n$ -cubic hyper-resolution of locally trivial analytic family  $\pi : \mathfrak{X} \rightarrow M$  of complex projective varieties, parametrized by a complex manifold  $M$ . Then the  $\square_n$ -object  $\pi_\bullet : \mathfrak{X}_\bullet \rightarrow M(\pi_\bullet := \pi \circ a_\bullet)$  of smooth families of complex manifolds, parametrized by  $M$  is  $C^\infty$  trivial at any point of  $M$ ; that is, for any point  $t_0 \in M$ , there exist an open neighborhood  $N$  of  $t_0$  in  $M$  and a diffeomorphism  $\Phi_\bullet : (\pi_\bullet^{-1})(N) \rightarrow X_{\bullet, t_0} \times N$  of  $\square_n$ -objects of complex manifolds over the identity map  $\text{id}_N : N \rightarrow N$ . Furthermore,  $\mathfrak{X}_\bullet \xrightarrow{a_\bullet} \mathfrak{X} \xrightarrow{\pi} M$  is topologically trivial at any point of  $M$ .*

*Proof.* Let  $N_1$  be a coordinate neighborhood of  $t_0$  in  $M$  with a holomorphic local coordinate system  $(t_1, \dots, t_m)$ , and  $N$  a relatively compact open subset of  $N_1$  with  $\overline{N} \subset N_1$ . Let  $t_i = x_i + \sqrt{-1}x_{m+i}$  ( $1 \leq i \leq m$ ) be the expression of  $t_i$  in real local coordinate functions  $x_i, y_i$ . To prove the theorem it suffices to show that for every  $\partial/\partial x_i$  ( $1 \leq i \leq 2m$ ) and every  $\alpha \in \square_n$  there exists its liftings  $v_i^\alpha$  to  $\pi_\alpha^{-1}(N)$ , i.e., a  $C^\infty$  vector field on  $\pi_\alpha^{-1}(N)$  with the property

$$(d\pi_\alpha)(v_i^\alpha) = \pi_\alpha^*\left(\frac{\partial}{\partial x_i}\right),$$

subject to the requirement

$$(1.3) \quad dE_{\alpha\beta}(v_i^\beta) = E_{\alpha\beta}^*(v_i^\alpha)$$

in  $E_{\alpha\beta}^* \Theta_{\mathfrak{X}_\alpha}$  for every pair  $(\alpha, \beta)$  of elements of  $\text{Ob}(\square_n)$  with  $\alpha \leq \beta$  in the category  $\square_n$ , where  $E_{\alpha\beta} : \mathfrak{X}_\beta \rightarrow \mathfrak{X}_\alpha$  denotes a holomorphic map corresponding to an arrow  $\alpha \rightarrow \beta$  in  $\square_n$  and  $\Theta_{\mathfrak{X}_\alpha}$  the sheaf of germs of holomorphic vector fields on  $\mathfrak{X}_\alpha$ . In fact, if such liftings  $\{v_i^\alpha\}_{\alpha \in \square_n}$  exist, integrating  $v_i^\alpha$ , we have a  $C^\infty$ -trivialization of the family  $\pi_\alpha : \mathfrak{X}_\alpha \rightarrow N$  along the  $x_i$ -axis in  $N$  for all  $\alpha \in \square_n$  such that those trivializations commute with the maps  $E_{\alpha\beta} : \mathfrak{X}_\beta \rightarrow \mathfrak{X}_\alpha$  for every pair  $(\alpha, \beta)$  of elements of  $\text{Ob}(\square_n)$  with  $\alpha \rightarrow \beta$  in the category  $\square_n$  due to the requirement (1.3). Arguing inductively on the dimension of  $M$ , we finally get the trivialization asserted in the proposition (cf. for more precise argument we refer to Theorem 3.3 in [8]). Now we are going to prove the existence of the liftings  $v_i^\alpha$  to  $\pi_\alpha^{-1}(N)$  of  $\partial/\partial x_i$  subject to the requirement (1.3).

We take open coverings  $\mathcal{V} = \{\mathcal{V}_\lambda\}_{\lambda \in \Lambda_0}$  and  $\mathcal{V}' = \{\mathcal{V}'_\lambda\}_{\lambda \in \Lambda_0}$  of  $\pi^{-1}(\overline{N})$  in  $\mathfrak{X}$  that satisfy the following conditions:

for every  $\lambda \in \Lambda_0$ ,

- (i)  $\overline{\mathcal{V}_\lambda}$  is a compact subset of  $\mathcal{V}'_\lambda$ ,
- (ii) there exists an embedding  $\varphi_\lambda : \mathcal{V}'_\lambda \rightarrow \mathbb{C}^{n_\lambda}$ , and
- (iii)  $a_\bullet^{-1}(\mathcal{V}'_\lambda) \xrightarrow{a_\bullet} \mathcal{V}'_\lambda \xrightarrow{\pi} \pi(\mathcal{V}'_\lambda)$  is analytically trivial.

We are allowed to put the condition (iii) due to the analytical “local triviality” of the family  $\mathfrak{X}_\bullet \xrightarrow{a_\bullet} \mathfrak{X} \xrightarrow{\pi} M$  (cf. Definition 1.14 (ii)). By this condition there exist liftings  $v_{\lambda_i}^\alpha$  of  $\partial/\partial x_i$  to  $a_\alpha^{-1}(\mathcal{V}'_\lambda)$  for every  $\alpha \in \square_n$  and every  $\lambda \in \Lambda_0$ , subject to the requirement (1.3). We take a  $C^\infty$  partition of unity  $\{\rho_\lambda\}_{\lambda \in \Lambda_0}$  on  $\mathfrak{X}' := \bigcup_{\lambda \in \Lambda_0} \mathcal{V}'_\lambda$  subordinate to the covering  $\mathcal{V} = \{\mathcal{V}_\lambda\}_{\lambda \in \Lambda_0}$ , i.e.,  $\rho_\lambda$ 's are “ $C^\infty$  functions” on  $\mathfrak{X}' := \bigcup_{\lambda \in \Lambda_0} \mathcal{V}'_\lambda$  satisfying the following conditions:

- (i)  $0 \leq \rho_\lambda \leq 1$  for  $\lambda \in \Lambda_0$ ,
- (ii)  $\text{Supp } \rho_\lambda \subset \mathcal{V}_\lambda$  for  $\lambda \in \Lambda_0$ ,
- (iii)  $\sum_{\lambda \in \Lambda_0} \rho_\lambda \equiv 1$  on  $\mathfrak{X}'$ .

Notice that  $\mathfrak{X}'$  is a singular space. We use here the term “ $C^\infty$  functions” in the sense of that they are locally pull-backs of  $C^\infty$  functions on  $\mathbb{C}^{n_\lambda}$  via embeddings  $\varphi_\lambda : \mathcal{V}'_\lambda \rightarrow \mathbb{C}^{n_\lambda}$ . The existence of  $C^\infty$ -partition of unity  $\{\rho_\lambda\}_{\lambda \in \Lambda_0}$  as above is guaranteed by the fact that the proof of the existence of  $C^\infty$ -partition of unity subordinate to a countably indexed open covering of a  $C^\infty$ -manifold is also applicable in our case (cf.[8, Chapter I, Theorem 4.6]). We define

$$v_i^\alpha := \sum_{\lambda \in \Lambda_0} a_\alpha^*(\rho_\lambda) v_{\lambda_i}^\alpha$$

for  $\alpha \in \square_n$ . Then we can easily check that

$$(d\pi_\alpha)(v_i^\alpha) = \pi_\alpha^*\left(\frac{\partial}{\partial x_i}\right) \quad \text{and}$$

$$(dE_{\alpha\beta})(v_i^\beta) = E_{\alpha\beta}^*(v_i^\alpha)$$

for every pair  $(\alpha, \beta)$  of elements of  $Ob(\square_n)$  with  $\alpha \leq \beta$  in the category  $\square_n$ .

Finally, we shall show that the  $C^\infty$  triviality of the family  $\pi_\bullet : \mathfrak{X}_\bullet \rightarrow M$  implies the topological triviality of the family  $\mathfrak{X}_\bullet \xrightarrow{a_\bullet} \mathfrak{X} \xrightarrow{\pi} M$ . For a fiber  $X_{\bullet,t}$  ( $t \in M$ ) of the family  $\pi_\bullet : \mathfrak{X}_\bullet \rightarrow M$ , we define an equivalence relation on the topological space  $\coprod_{\alpha \in \square_n} X_{\alpha t}$  (disjoint sum) by

$$p \sim q \text{ iff } p \in X_{\alpha t}, q \in X_{\beta t} \text{ such that } \begin{cases} \alpha \leq \beta & \text{and } e_{\alpha\beta}(q) = p \\ \text{or } \alpha > \beta & \text{and } e_{\beta\alpha}(p) = q, \end{cases}$$

where  $e_{\alpha\beta} : X_{\beta t} \rightarrow X_{\alpha t}$  (resp.  $e_{\beta\alpha} : X_{\alpha t} \rightarrow X_{\beta t}$ ) is the holomorphic map corresponding to an arrow  $\alpha \rightarrow \beta$  (resp.  $\beta \rightarrow \alpha$ ) in  $\square_n$ . Then the natural map from  $(\coprod_{\alpha \in \square_n} X_{\alpha t} / \sim)$  (the quotient topological space of  $\coprod_{\alpha \in \square_n} X_{\alpha t}$  by the equivalence relation  $\sim$  defined above) to  $X_t$  gives rise to a homeomorphism between these spaces, because  $X_{\bullet,t}$  is a cubic hyper-resolution of  $X_t$ . Therefore a diffeomorphism between different fibers  $X_{\bullet,t}$  and  $X_{\bullet,t'}$  ( $t, t' \in M$ ) gives rise to

a homeomorphism between different fibers  $X_{\bullet t} \rightarrow X_t$  and  $X_{\bullet t'} \rightarrow X_{t'}$  of the family  $\mathfrak{X}_{\bullet} \xrightarrow{\alpha_{\bullet}} \mathfrak{X} \xrightarrow{\pi} M$ .

*Q.E.D.*

## §2 Examples

In this section we shall show that we can obtain a simultaneous cubic hyper-resolution of a locally trivial family of complex projective varieties with *ordinary singularities* of dimension  $\leq 3$  as well as of a locally trivial family of complex projective varieties with normal crossing of any dimension by taking normalizations of their fibers successively. Though, using the local equations of ordinary singularities obtained in [15], we can prove that the same statement holds for locally trivial families of complex projective varieties with ordinary singularities of dimension 4 and 5, we omit its proof (for the case of dimension 4 see [19, Example 4.2.10]).

By definition a 1-dimensional complex projective variety with ordinary singularities is no more than a curve with nodes (possibly reducible). The definition of 2-dimensional complex projective varieties with ordinary singularities has been given in Example 1.7.

**2.1 Definition.** A 3-dimensional complex projective variety is said to be *with ordinary singularities* if it is locally isomorphic to one of the germs of hypersurfaces of the complex 4-space  $\mathbb{C}^4$  as follows:

$$(2.1) \quad \left\{ \begin{array}{ll} (i) \ w = 0 \text{ (simple point)}, & (ii) \ zw = 0 \text{ (ordinary double point)}, \\ (iii) \ yzw = 0 \text{ (ordinary triple point)}, & (iv) \ xyzw = 0 \text{ (ordinary quadruple point)}, \\ (v) \ xy^2 - z^2 = 0 \text{ (cuspidal point)}, & (vi) \ w(xy^2 - z^2) = 0 \text{ (stationary point)}, \end{array} \right.$$

where  $(x, y, z, w)$  is the coordinate on  $\mathbb{C}^4$ .

**2.2 Definition.** By a *locally trivial analytic family* of complex projective varieties with *ordinary singularities*, parametrized by a complex space  $M$ , we mean a *locally trivial analytic family*  $\pi : \mathfrak{X} \rightarrow M$  of complex projective varieties all of whose fibers  $X_t := \pi^{-1}(t)$  are complex projective varieties with *ordinary singularities*.

Now we are going to show that we can obtain a simultaneous cubic hyper-resolution of a locally trivial analytic family of complex projective varieties with *ordinary singularities* of dimension  $\leq 3$  by taking normalizations of their fibers successively. Our arguments in the subsequence are rather “set-theoretical” (not scheme-theoretic) and all complex analytic varieties and subvarieties are assumed to be reduced. First, we introduce a general notion and mention a fundamental fact on it, which will be needed later. Let  $I$  be a finite ordered set. Remember

that  $\text{Ob}(\square_n^+)$  and  $\text{Ob}(\square_n)$  can be considered as finite ordered sets. We think of  $I$  as a category. Let  $X_\bullet : I^\circ \rightarrow (\text{An}/\mathbb{C})$  be an  $I$ -object of complex analytic varieties, that is, a contravariant functor from the category  $I$  to the category  $(\text{An}/\mathbb{C})$  of complex analytic varieties. We shortly call an  $I$ -object of complex analytic varieties an  $I$ -complex analytic variety.

**2.3 Definition.** A morphism of  $I$ -complex analytic varieties  $f_\bullet : X_\bullet \rightarrow Y_\bullet$  is defined to be a *normalization* of  $Y_\bullet$  if  $f_i : X_i \rightarrow Y_i$  is the normalization for every  $i \in I$ .

For an  $I$ -complex analytic variety  $X_\bullet$ , we denote by  $e_{ij} : X_j \rightarrow X_i$  the corresponding holomorphic map to  $i, j \in I$  with  $i \leq j$ , and by  $N(X_i)$  the non-normal locus of  $X_i$  for each  $i \in I$ .

**2.4 Lemma.** *With the same notation as above, for an  $I$ -complex analytic variety  $X_\bullet$  we assume that  $e_{ij}^{-1}(N(X_i))$  is analytically rare in  $X_j$ , i.e., for any open subset  $U$  of  $X_j$  the restriction map  $\mathcal{O}_{X_j}(U) \rightarrow \mathcal{O}_{X_j}(U \setminus e_{ij}^{-1}(N(X_i)))$  is injective, for every  $i, j \in I$  with  $i \leq j$ . Then there exists a normalization  $\nu_\bullet : X'_\bullet \rightarrow X_\bullet$  of  $X_\bullet$  and it is unique up to isomorphisms in the category of  $I$ -complex analytic varieties over the identity map  $\text{id}_{X_\bullet} : X_\bullet \rightarrow X_\bullet$ .*

*Proof.* For any  $i \in I$  we take the normalization  $\nu_i : X'_i \rightarrow X_i$ . By the assumption, every  $e_{ij} : X_j \rightarrow X_i$  for  $i, j \in I$  with  $i < j$  can be uniquely lifted to  $e'_{ij} : X'_j \rightarrow X'_i$  ([6, p.121, Proposition 2.28]). Then  $\{X'_i, e'_{ij}\}$  constitutes an  $I$ -complex analytic variety due to the uniqueness of the liftings  $e'_{ij}$ , and by definition, this is a normalization of  $X_\bullet$ . The uniqueness of  $X'_\bullet$  up to isomorphisms over the identity map  $\text{id}_{X_\bullet} : X_\bullet \rightarrow X_\bullet$  results from the uniqueness of each  $X'_i$  up to isomorphisms over the identity map  $\text{id}_{X_i} : X_i \rightarrow X_i$  for every  $i \in I$ .

*Q.E.D.*

**2.5 Definition.** For a morphism of  $I$ -complex analytic varieties  $f_\bullet : X_\bullet \rightarrow Y_\bullet$ , the *discriminant* of  $f_\bullet$  is defined to be the smallest, closed  $I$ -complex analytic subvariety  $D_{f_\bullet}$  of  $Y_\bullet$  such that  $f_\bullet$  induces an isomorphism  $f_i : X_i - f_i^{-1}(D_{f_i}) \rightarrow Y_i - D_{f_i}$  for every  $i \in I$ .

**2.6 Remark.** Let  $f_\bullet : X_\bullet \rightarrow Y_\bullet$  be a proper morphism of  $I$ -complex analytic varieties, i.e.,  $f_i : X_i \rightarrow Y_i$  is proper for every  $i \in I$ . Then one has

$$D_{f_i} = \cup_{i \rightarrow j} \text{Im}(T_j \rightarrow Y_i) \quad (i \in I),$$

where  $T_j$  denotes the discriminant of  $f_j : X_j \rightarrow Y_j$  (cf. [10, p.9, Proposition 2.3]).

The notion of a *cubic hyper-resolution of a complex analytic variety being obtained by successive normalizations* is defined as follows:

Let  $X$  be a complex analytic variety. First, we define a  $\square_1^+$ -complex analytic variety  $X_\bullet^1$  to be

$$(2.2)_1 \quad \begin{array}{ccc} X_{11}^1 := D_{\nu_1}^* & \xrightarrow{j_1} & X^\nu :=: X_{01}^1 \\ \mu_1 \downarrow & & \downarrow \nu_1 \\ X_{10}^1 := D_{\nu_1} & \xrightarrow{i_1} & X :=: X_{00}^1, \end{array}$$

where  $\nu_1 : X^\nu \rightarrow X$  is the normalization of  $X$ ,  $D_{\nu_1}$  the discriminant of  $\nu_1$ ,  $D_{\nu_1}^* := \nu_1^{-1}(D_{\nu_1})$ , and  $\mu_1 := \nu_1|_{D_{\nu_1}^*} : D_{\nu_1}^* \rightarrow D_{\nu_1}$  the restriction of  $\nu_1$  to  $D_{\nu_1}^*$ . Inductively, for an integer  $r \geq 2$  we define  $\square_r^+$ -complex analytic variety  $X_\bullet^r$  to be

$$(2.2)_r \quad \begin{array}{ccc} X_{11\bullet}^r := D_{\nu_r}^* & \xrightarrow{j_r} & (X_{1\bullet}^{r-1})^\nu :=: X_{01\bullet}^r \\ \mu_r \downarrow & & \downarrow \nu_r \\ X_{10\bullet}^r := D_{\nu_r} & \xrightarrow{i_r} & X_{1\bullet}^{r-1} :=: X_{00\bullet}^r, \end{array}$$

where  $X_{1\bullet}^{r-1}$  is the  $\square_{r-2}^+$ -complex analytic variety,  $\mu_{r-1} := \nu_{r-1}|_{D_{\nu_{r-1}}^*} : X_{11\bullet}^{r-1} := D_{\nu_{r-1}}^* \rightarrow X_{10\bullet}^{r-1} := D_{\nu_{r-1}}$  in  $(2.2)_{r-1}$ ,  $\nu_r : (X_{1\bullet}^{r-1})^\nu \rightarrow X_{1\bullet}^{r-1}$  is the normalization of  $X_{1\bullet}^{r-1}$ ,  $D_{\nu_r}$  is the discriminant of  $\nu_r$ ,  $D_{\nu_r}^* := \nu_r^{-1}(D_{\nu_r})$ , and  $\mu_r := \nu_r|_{D_{\nu_r}^*}$  is the restriction of  $\nu_r$  to  $D_{\nu_r}^*$ .

**2.7 Definition.** In the above procedure we assume that the normalization  $(X_{1\bullet}^{r-1})^\nu$  is always non-singular for every  $r \geq 1$ , where we understand  $X_{1\bullet}^0 = X$ . Then, after finite steps, say  $n$ -th step, the reduction

$$Z_\bullet := rd(X_\bullet^1, X_\bullet^2, \dots, X_\bullet^n)$$

of the sequence  $\{X_\bullet^1, X_\bullet^2, \dots, X_\bullet^n\}$  of  $\square_r^+$ -complex analytic varieties  $X_\bullet^r$  ( $1 \leq r \leq n$ ) gives an augmented  $n$ -cubic hyper-resolution of  $X$ . If this is the case, we say that a *cubic hyper-resolution of  $X$  is obtained by successive normalizations*.

**2.8 Definition.** We say a complex analytic variety  $Z$  is *with normal crossing* if, at each point of  $Z$ , it is locally isomorphic to the germ of a subvariety  $\{(z_0, \dots, z_n) \in \mathbb{C}^{n+1} | z_0 \cdots z_r = 0\}$  at the origin of  $\mathbb{C}^{n+1}$  for some  $r$  ( $0 \leq r \leq n$ ).

**2.9 Proposition.** *For a complex analytic variety with normal crossing its cubic hyper-resolution is obtained by successive normalizations.*

*Proof.* Since the problem is local, it suffices to show that, for the subvariety  $Z$  in  $\mathbb{C}^{n+1}$  defined by  $z_0 \cdots z_r = 0$  ( $0 \leq r \leq n$ ) its cubic hyper-resolution is obtained by successive normalizations. Furthermore, we may assume that  $r = n$ , because the subvariety  $\{(z_0, \dots, z_n) \in \mathbb{C}^{n+1} | z_0 \cdots z_r = 0\}$  is isomorphic to the product  $\{(z_0, \dots, z_r) \in \mathbb{C}^{r+1} | z_0 \cdots z_r = 0\} \times \mathbb{C}^{n-r}$ . In fact, we shall prove the following by double induction on  $n$  and  $k$ .

**Claim.** *For the analytic subvariety*

$$Z = \{(z_0, \dots, z_n) \in \mathbb{C}^{n+1} \mid z_0 \cdots z_n = 0\},$$

we define

$$Z_{(z_0 \cdots \check{z}_{i_0} \cdots \check{z}_{i_k} \cdots z_n)} := \{(z) \in \mathbb{C}^{n+1} \mid z_{i_0} = \cdots = z_{i_k} = 0\} \quad (0 \leq i_0 < \cdots < i_k \leq n)$$

and

$$Z_k^{(n)} := \bigcup_{0 \leq i_0 < \cdots < i_k \leq n} Z_{(z_0 \cdots \check{z}_{i_0} \cdots \check{z}_{i_k} \cdots z_n)} \quad (0 \leq k \leq n) \quad (\text{a subvariety of } \mathbb{C}^{n+1})$$

Then a cubic hyper-resolution of  $Z_k^{(n)}$  ( $0 \leq n, 0 \leq k \leq n$ ) is obtained by successive normalizations.

*Proof of the claim.*

(I) In the case of  $n = k = 0$ :  $Z_0^{(0)}$  is non-singular (a single point), so there is nothing to be proved.

(II) In the case of  $n \geq 1$ : we assume that the claim is true for  $Z_\ell^{(m)}$  with  $0 \leq m \leq n - 1$  and  $0 \leq \ell \leq m$ .  $Z_n^{(n)}$  is non-singular (a single point), so there is nothing to be proved. Next we shall show that if the claim is true for  $Z_\ell^{(n)}$  with  $0 \leq k < \ell \leq n$ , then it is also true for  $Z_k^{(n)}$ . We consider the 2-resolution

$$\begin{array}{ccc} D_{\nu_1}^* & \xrightarrow{j_1} & (Z_k^{(n)})^\nu \\ \mu_1 \downarrow & & \downarrow \nu_1 \\ D_{\nu_1} & \xrightarrow{i_1} & Z_k^{(n)} \end{array}$$

in (2.2)<sub>1</sub> for  $Z_k^{(n)}$ . Then

$$(Z_k^{(n)})^\nu = \coprod_{0 \leq i_0 < \cdots < i_k \leq n} Z_{(z_0 \cdots \check{z}_{i_0} \cdots \check{z}_{i_k} \cdots z_n)} \quad (\text{disjoint sum})$$

$$D_{\nu_1} = Z_{k+1}^{(n)}, \quad \text{and}$$

$$D_{\nu_1}^* = \coprod_{0 \leq i_0 < \cdots < i_k \leq n} \bigcup_{\substack{i \neq i_0, \dots, i_k \\ 0 \leq i \leq n}} Z_{(z_0 \cdots \check{z}_{i_0} \cdots \check{z}_{i_k} \cdots \check{z}_i \cdots z_n)}.$$

Here we consider

$$(2.3) \quad \bigcup_{\substack{i \neq i_0, \dots, i_k \\ 0 \leq i \leq n}} Z_{(z_0 \cdots \check{z}_{i_0} \cdots \check{z}_{i_k} \cdots \check{z}_i \cdots z_n)}$$

as a subvariety of  $Z_{(z_0 \cdots \check{z}_{i_0} \cdots \check{z}_{i_k} \cdots z_n)}$ . By the induction hypothesis, a cubic hyper-resolution of  $D_{\nu_1} = Z_{k+1}^{(n)}$  is obtained by successive normalizations, which we denote by  $\nu_{1\bullet} : D_{\nu_{1\bullet}} \rightarrow D_{\nu_1}$  (an augmented  $\square_{n-k-1}^+$ -object of complex analytic

varieties). Since the complex analytic variety in (2.3) is isomorphic to  $Z_0^{(n-k-1)}$  for every  $(i_0, \dots, i_k)$  with  $0 \leq i_0 < \dots < i_k \leq n$ , by the induction hypothesis, a cubic hyper-resolution of  $D_{\nu_1}^*$  is also obtained by successive normalizations, which we denote by  $\nu_{1\bullet}^* : D_{\nu_{1\bullet}}^* \rightarrow D_{\nu_1}^*$  (an augmented  $\square_{n-k-1}^+$ -object of complex analytic varieties). Obviously, there naturally exists a homomorphism  $\mu_{1\bullet} : D_{\nu_{1\bullet}}^* \rightarrow D_{\nu_1}^*$  of  $\square_{n-k-1}$ -objects of complex analytic subvarieties such that the following diagram commutes:

$$\begin{array}{ccc} D_{\nu_{1\bullet}}^* & \xrightarrow{\nu_{1\bullet}^*} & D_{\nu_1}^* \\ \mu_{1\bullet} \downarrow & & \downarrow \mu_1 \\ D_{\nu_{1\bullet}} & \xrightarrow{\nu_{1\bullet}} & D_{\nu_1}, \end{array}$$

of which we think as a  $\square_{n-k+1}$ -object of complex analytic varieties. This is nothing but the cubic hyper-resolution of the  $\square_0^+$ -complex analytic variety  $\mu_1 : D_{\nu_1}^* \rightarrow D_{\nu_1}$  by successive normalizations. Therefore,

$$\begin{array}{ccc} D_{\nu_{1\bullet}}^* & \xrightarrow{j_1 \circ \nu_{1\bullet}^*} & (Z_k^{(n)})^\nu \\ \mu_1 \downarrow & & \downarrow \nu_1 \\ D_{\nu_{1\bullet}} & \xrightarrow{i_1 \circ \nu_{1\bullet}} & Z_k^{(n)}, \end{array}$$

is the cubic hyper-resolution of  $Z_k^{(n)}$  by successive normalizations. This completes the proof of the claim.

Since  $Z = Z_0^{(n)}$ , the proposition follows from this claim.

*Q.E.D.*

**2.10 Proposition.** *A cubic hyper-resolution of a complex analytic variety with ordinary singularities of dimension  $\leq 3$  is obtained by successive normalizations.*

*Proof.* The proof is straightforward calculation in terms of local coordinates. We shall show only in the case of dimension 3. First we fix notation as follows:

- $T$  : a threefold with ordinary singularities,
- $S$  : the singular locus of  $T$ ,
- $\Delta$  : the singular locus of  $S$ ,
- $\Sigma q$  : the set of ordinary quadruple points of  $T$ ,
- $\Sigma s$  : the set of stationary points of  $T$ .

Notice that  $\Delta$  is non-singular outside  $\Sigma q$  and that, at each point of  $\Sigma q$ ,  $\Delta$  is isomorphic to the union of four coordinate axes of  $\mathbb{C}^4$  at the origin. It suffices to prove the proposition for each hypersurface in  $\mathbb{C}^4$  in (2.1). The proofs for the hypersurfaces (ii), (iii), (iv) in (2.1) are included in Proposition 2.9.

(v) In the case of  $xy^2 - z^2 = 0$  (cuspidal point):

Let us take the 2-resolution of  $T$  by normalization in (2.2)<sub>1</sub>:

$$(2.4) \quad \begin{array}{ccc} D_{\nu_1}^* & \xrightarrow{j_1} & T^\nu \\ \mu_1 \downarrow & & \downarrow \nu_1 \\ D_{\nu_1} & \xrightarrow{i_1} & T. \end{array}$$

Then  $T^\nu \simeq \mathbb{C}^3$  and the normalization  $\nu_1 : T^\nu \rightarrow T \subset \mathbb{C}^4$  is given by  $(r, s, t) \rightarrow (r^2, s, rs, t) = (x, y, z, w)$ , where  $(r, s, t)$  is the coordinate on  $\mathbb{C}^3$  and  $(x, y, z, w)$  is that on  $\mathbb{C}^4$ . Hence  $D_{\nu_1} = S : y = z = 0$  and  $D_{\nu_1}^* : s = 0$ , which are non-singular. Therefore the 2-resolution of  $T$  by normalization in (2.4) gives a cubic hyper-resolution of  $T$ .

(vi) In the case of  $w(xy^2 - z^2) = 0$  (stationary point):

$T$  and  $S$  have the following irreducible decompositions:

$$\begin{aligned} T &= T_0 + T_c, \quad T_0 : w = 0, \quad T_c : xy^2 - z^2 = 0, \\ S &= S_d + S_c, \quad S_d : y = z = 0, \quad S_c : w = xy^2 - z^2 = 0. \end{aligned}$$

Notice that  $S_d$  is the singular locus of  $T_c$ ,  $S_c = T_0 \cap T_c$  and  $\Delta = S_d \cap S_c = S_d \cap T_0 : y = z = w = 0$ . The reduced ideal of  $S$  is  $(xy^2 - z^2, wy, wz)$ . The 2-resolution of  $T$  by normalization in (2.2)<sub>1</sub> is explicitly described as follows:

$$\begin{aligned} X_{11}^1 &:= D_{\nu_1}^* := S_{0c}^* \amalg (S_{1c}^* + S_d^*) \xrightarrow{j_1} T_0^\nu \amalg T_c^\nu =: X_{01}^1 \\ &\quad \mu_1 \downarrow \qquad \qquad \qquad \downarrow \nu_1 \\ X_{10}^1 &:= D_{\nu_1} := S = S_d + S_c \xrightarrow{i_1} T = T_0 + T_c =: X_{00}^1 \\ \nu_{1|T_0^\nu} &: T_0^\nu \simeq \mathbb{C}^3 \rightarrow T_0 \subset \mathbb{C}^4; (r, s, t) \rightarrow (r, s, t, 0) = (x, y, z, w), \\ \nu_{1|T_c^\nu} &: T_c^\nu \simeq \mathbb{C}^3 \rightarrow T_c \subset \mathbb{C}^4; (r', s', t') \rightarrow (r'^2, s', r's', t') = (x, y, z, w). \\ S_{0c}^* &:= \{rs^2 - t^2 = 0\} \subset T_0^\nu, \\ S_{1c}^* &:= \{t' = 0\} \subset T_c^\nu, \quad S_d^* := \{s' = 0\} \subset T_c^\nu. \end{aligned}$$

The 2-resolution of a  $\square_0^+$ -complex analytic variety  $\mu_1 : D_{\nu_1}^* \rightarrow D_{\nu_1}$  by normalization in (2.2)<sub>2</sub>



$$\begin{array}{ccccc}
& & D_{\nu_{21}}^* := X_{111}^2 & \xrightarrow{j_{21}} & X_{011}^2 \\
& \swarrow \tilde{\lambda}_1 & \downarrow & & \swarrow \tilde{\mu}_1 \\
D_{\nu_{20}}^* := X_{110}^2 & \xrightarrow{j_{20} \quad \mu_{21}} & X_{010}^2 & & \\
\downarrow \mu_{20} & & \downarrow & & \downarrow \nu_{21} \\
& & D_{\nu_{21}} := X_{101}^2 & \xrightarrow{i_{21} \quad \nu_{20}} & X_{001}^2 := X_{11}^1 := D_{\nu_1}^* \\
& \swarrow \lambda_1 & \downarrow & & \swarrow \mu_1 \\
D_{\nu_{20}} := X_{100}^2 & \xrightarrow{i_{20}} & X_{000}^2 = X_{10}^1 := D_{\nu_1} & & 
\end{array}$$

is explicitly described as follows:

$$\begin{array}{ccc}
\text{(I)} & X_{010}^2 := S_d \amalg S_c^\nu \xleftarrow{\tilde{\mu}_1} (S_{0c}^*)^\nu \amalg (S_{1c}^* \amalg S_d^*) := X_{011}^2 & \\
& \nu_{20} \downarrow & \downarrow \nu_{21} \\
& X_{000}^2 := S = S_d + S_c \xleftarrow{\mu_1} S_{0c}^* \amalg (S_{1c}^* + S_d^*) := X_{001}^2 & 
\end{array}$$

$$(S_{0c}^*)^\nu \simeq S_c^\nu \simeq S_{1c}^* \simeq \mathbb{C}^3, \quad S_d \simeq S_d^* \simeq \mathbb{C}^3;$$

$$\nu_{20}|_{S_d} : S_d \rightarrow S_d \subset S : \text{identity map,}$$

$$\nu_{20}|_{S_c^\nu} : S_c^\nu \rightarrow S_c \subset S : \text{normalization map,}$$

$$\nu_{21}|_{(S_{0c}^*)^\nu} : (S_{0c}^*)^\nu \rightarrow S_{0c}^* \subset X_{001}^2 : \text{normalization map,}$$

$$\nu_{21}|_{S_{1c}^*} : S_{1c}^* \rightarrow S_{1c}^* \subset X_{001}^2 : \text{identity map,}$$

$$\nu_{21}|_{S_d^*} : S_d^* \rightarrow S_d^* \subset X_{001}^2 : \text{identity map;}$$

$$\begin{array}{ccc}
T_0^\nu & \simeq & T_0 \subset \mathbb{C}^4 \\
\cup & & \cup \\
\mu_1|_{S_{0c}^*} : S_{0c}^* & \xrightarrow{\simeq} & S_c : \text{identity map,}
\end{array}$$

$$\begin{array}{ccc}
T_c^\nu & \rightarrow & T_c \subset \mathbb{C}^4 \\
\cup & & \cup \\
\mu_1|_{S_{1c}^*} : S_{1c}^* & \rightarrow & S_c, \quad (r', s', 0) \rightarrow (r'^2, s', r's', 0) = (x, y, z, w): \\
& & \text{normalization map,}
\end{array}$$

$$\begin{array}{c}
 T_c^\nu \rightarrow T_c \subset \mathbb{C}^4 \\
 \cup \quad \cup \\
 \mu_{1|S_d^*} : S_d^* \rightarrow S_d, (r', 0, t') \rightarrow (r'^2, 0, 0, t') = (x, y, z, w): \\
 \text{double covering}
 \end{array}$$

$$\tilde{\mu}_{1|(S_{0c}^*)^\nu} : (S_{0c}^*)^\nu \xrightarrow{\cong} S_c^\nu : \text{natural isomorphism,}$$

$$\tilde{\mu}_{1|S_{1c}^*} : S_{1c}^* \xrightarrow{\cong} S_c^\nu : \text{natural isomorphism,}$$

$$\tilde{\mu}_{1|S_d^*} : S_d^* \rightarrow S_d : \text{the same double covering as } \mu_{1|S_d^*} : S_d^* \rightarrow S_d;$$

$$\begin{array}{c}
 \text{(II)} \quad \begin{array}{ccccc}
 S_d & S_c^\nu & (S_{0c}^*)^\nu & S_{1c}^* & S_d^* \\
 \cup & \cup & \cup & \cup & \cup \\
 X_{110}^2 := \Delta \amalg \Delta^* & \xleftarrow{\tilde{\lambda}_1} & (\Delta^* \amalg (\Delta^* \amalg \Delta^*)) & =: & X_{111}^2 \\
 \mu_{20} \downarrow & & \downarrow \mu_{21} & & \\
 X_{100}^2 := \Delta & \xleftarrow{\lambda_1} & \Delta \amalg \Delta^* & =: & X_{101}^2 \\
 \cap & & \cap & \cap & \\
 S = S_c + S_d & & S_{0c}^* & S_{1c}^* + S_d^* &
 \end{array}
 \end{array}$$

Here  $\Delta^*$  are the inverse images of  $\Delta$  by the normalization maps  $\nu_{20|S_c^\nu} : S_c^\nu \rightarrow S_c$ ,  $\nu_{21|(S_{0c}^*)^\nu} : (S_{0c}^*)^\nu \rightarrow S_{0c}^* \simeq S_c$ ,  $\mu_{1|S_{1c}^*} : S_{1c}^* \rightarrow S_c$ , respectively, which are non-singular. This shows that a cubic hyper-resolution is obtained by successive normalizations for a stationary point.

*Q.E.D.*

By Proposition 2.9 and Proposition 2.10 we obtain the following theorem.

**2.11 Theorem.** *Taking successive normalizations fiberwise, we obtain a simultaneous cubic hyper-resolution of a locally trivial family of the following kinds of complex analytic varieties :*

- (i) *complex analytic varieties with ordinary singularities of dimension  $\leq 3$ ,*
- (ii) *complex analytic varieties with normal crossing of any dimension.*

*Proof.* Let  $\pi : \mathfrak{X} \rightarrow M$  be a locally trivial family of above kinds of complex analytic varieties, parametrized by a complex space  $M$ . Taking relative normalization  $\nu_1 : \mathfrak{X}^\nu \rightarrow \mathfrak{X}$  of  $\mathfrak{X}$  over  $M$  (cf. [16, Theorem 3.6]), we obtain the “relative 2-resolution” of the family  $\pi : \mathfrak{X} \rightarrow M$ , which we denote as follows:

$$(2.5) \quad \begin{array}{ccc} \mathfrak{X}_{11}^1 := \mathfrak{D}_{\nu_1/M}^* & \xrightarrow{j_1} & \mathfrak{X}^\nu =: \mathfrak{X}_{01}^1 \\ \mu_1 \downarrow & & \downarrow \nu_1 \\ \mathfrak{X}_{10}^1 := \mathfrak{D}_{\nu_1/M} & \xrightarrow{i_1} & \mathfrak{X} =: \mathfrak{X}_{00}^1, \end{array}$$

where  $\mathfrak{D}_{\nu_1/M}$  denotes the “relative discriminant” of the map  $\nu_1 : \mathfrak{X}^\nu \rightarrow \mathfrak{X}$  over  $M$  and  $\mathfrak{D}_{\nu_1/M}^* := \nu_1^{-1}(\mathfrak{D}_{\nu_1/M})$ . All maps in the diagram (2.5) are over  $M$ . Notice that  $\mathfrak{D}_{\nu_1/M}$  and  $\mathfrak{D}_{\nu_1/M}^*$  are locally trivial families of complex analytic varieties over  $M$ , since  $\pi : \mathfrak{X} \rightarrow M$  is locally trivial. Next, we take the “relative normalizations” of the families  $\mathfrak{D}_{\nu_1/M}$  and  $\mathfrak{D}_{\nu_1/M}^*$ , respectively, which we denote as follows:

$$(2.6) \quad \begin{array}{ccc} & \tilde{\mu}_1 & \\ (\mathfrak{D}_{\nu_1/M}^\nu)^\nu & \longleftarrow & (\mathfrak{D}_{\nu_1/M}^*)^\nu \\ \nu_{20} \downarrow & & \downarrow \nu_{21} \\ \mathfrak{D}_{\nu_1/M} & \xleftarrow{\mu_1} & \mathfrak{D}_{\nu_1/M}^*, \end{array}$$

where  $\tilde{\mu}_1$  stands for the “fiberwise” lifting of the map  $\mu_1$ . Here the “fiberwise” lifting means that, for every  $t \in M$ ,  $\tilde{\mu}_{1t} : (D_{\nu_1/M,t}^*)^\nu \rightarrow (D_{\nu_1/M,t})^\nu$  is the lifting of the map  $\mu_{1t} : D_{\nu_1/M,t}^* \rightarrow D_{\nu_1/M,t}$  between fibers of the families  $(\mathfrak{D}_{\nu_1/M}^*)^\nu$  and  $\mathfrak{D}_{\nu_1/M}^*$  over  $M$ . This is possible due to the fact that  $(\mathfrak{D}_{\nu_1/M}^\nu)^\nu$  and  $(\mathfrak{D}_{\nu_1/M}^*)^\nu$  are the “relative normalizations of  $\mathfrak{D}_{\nu_1/M}$  and  $\mathfrak{D}_{\nu_1/M}^*$ , respectively. In fact,  $\tilde{\mu}_1 := \{\tilde{\mu}_{1t}\}_{t \in M}$  is a holomorphic map from  $(\mathfrak{D}_{\nu_1/M}^*)^\nu$  to  $(\mathfrak{D}_{\nu_1/M}^\nu)^\nu$ , since the family  $\mu_1 : \mathfrak{D}_{\nu_1/M}^* \rightarrow \mathfrak{D}_{\nu_1/M}$  of holomorphic maps over  $M$  is locally trivial. Therefore we conclude that the diagram (2.6) gives a “relative normalization” of the  $\square_0^+$ -object  $\mathfrak{X}_{1\bullet}^1 := \{\mu_1 : \mathfrak{D}_{\nu_1/M}^* \rightarrow \mathfrak{D}_{\nu_1/M}\}$  of locally trivial families of complex analytic varieties over  $M$  in (2.5). Using this “relative normalization”, we obtain the “relative 2-resolution” of the  $\square_0^+$ -object  $\mathfrak{X}_{1\bullet}^1 := \{\mu_1 : \mathfrak{D}_{\nu_1/M}^* \rightarrow \mathfrak{D}_{\nu_1/M}\}$ , which we denote as follows:

$$\begin{array}{ccc} \mathfrak{X}_{11\bullet}^2 := \mathfrak{D}_{\nu_{2\bullet}/M}^* & \xrightarrow{j_2} & (\mathfrak{X}_{1\bullet}^1)^\nu =: \mathfrak{X}_{01\bullet}^2 \\ \mu_{2\bullet} \downarrow & & \downarrow \nu_{2\bullet} \\ \mathfrak{X}_{10\bullet}^2 := \mathfrak{D}_{\nu_{2\bullet}/M} & \xrightarrow{i_2} & \mathfrak{X}_{1\bullet}^1 =: \mathfrak{X}_{00\bullet}^2, \end{array}$$

where  $\nu_{2\bullet} : (\mathfrak{X}_{1\bullet}^1)^\nu \rightarrow \mathfrak{X}_{1\bullet}^1$  is the relative normalization of  $\mathfrak{X}_{1\bullet}^1$  in (2.6),  $\mathfrak{D}_{\nu_{2\bullet}/M}$  is the “relative discriminant” of the map  $\nu_{2\bullet} : (\mathfrak{X}_{1\bullet}^1)^\nu \rightarrow \mathfrak{X}_{1\bullet}^1$ ,  $\mathfrak{D}_{\nu_{2\bullet}/M}^* := \nu_{2\bullet}^{-1}(\mathfrak{D}_{\nu_{2\bullet}/M})$ , and  $\mu_{2\bullet}$  is the restriction of  $\nu_{2\bullet}$  to  $\mathfrak{D}_{\nu_{2\bullet}/M}^*$ . The procedure of taking this “relative normalization” can be continued similarly like the absolute

case and obtain a sequence  $\mathfrak{X}_\bullet^0 = \mathfrak{X}, \mathfrak{X}_\bullet^1, \mathfrak{X}_\bullet^2, \dots, \mathfrak{X}_\bullet^r, \dots$  of  $\square_r^+$ -objects  $\mathfrak{X}_\bullet^r$  of locally trivial analytic families of complex projective varieties, parametrized by  $M$ , such that  $\mathfrak{X}_\bullet^r$  is the 2-resolution of  $\mathfrak{X}_\bullet^{r-1}$  by “relative normalization” for every  $r \geq 0$ . Then, after finite steps, say  $n$ -th step, the reduction

$$\mathfrak{X}_\bullet^+ := rd(\mathfrak{X}_\bullet^1, \mathfrak{X}_\bullet^2, \dots, \mathfrak{X}_\bullet^n),$$

which can be defined in the same manner as in the absolute case, gives a “relative” cubic hyper-resolution of  $\mathfrak{X}$ , i.e., if we write  $\mathfrak{X}_\bullet^+$  as

$$(2.7) \quad \mathfrak{X}_\bullet \xrightarrow{a_\bullet} \mathfrak{X} \xrightarrow{\pi} M,$$

where  $\mathfrak{X}_\bullet$  is the “ $\square_n$ ”-part of  $\mathfrak{X}_\bullet^+$ , then the fiber  $a_{\bullet,t} : \mathfrak{X}_{\bullet,t} \rightarrow \mathfrak{X}_t$  is a cubic hyper-resolution of  $\mathfrak{X}_t$  for every  $t \in M$ . The analytical “local triviality” of the family in (2.7) is obvious, because the original family  $\pi : \mathfrak{X} \rightarrow M$  is so. That is, by definition, the family in (2.7) is a simultaneous cubic hyper-resolution of the family  $\pi : \mathfrak{X} \rightarrow M$ .

*Q.E.D.*

### §3 Cohomological descent

The relative version of “cohomological descent” holds for a simultaneous cubic hyper-resolution of a locally trivial analytic family of complex projective varieties. In order to state this fact we refer to some notation and terminology from [10]. Let  $\Phi_\bullet : X_\bullet \rightarrow X$  be an  $n$ -cubic topological space with an augmentation to a topological space  $X$ , i.e.,  $X_\bullet$  is a contravariant functor from the  $n$ -cubic category  $\square_n$  to the category of topological space (Top) and  $\Phi_\bullet$  is a natural transformation from the functor  $X_\bullet$  to the one  $X$  over the trivial functor  $\square_n \rightarrow \square_{-1}^+$ , where  $X$  is considered as a  $\square_{-1}^+$ -object of the category (Top) (cf. Definition 1.1, Definition 1.3 and Remark 1.4).

**3.1 Definition.** For a commutative ring  $R$  with identity element 1, an  $R$ -module presheaf  $F^\bullet$  on an  $n$ -cubic topological space  $X_\bullet : \square_n \rightarrow (\text{Top})$  is defined to be a contravariant functor from the total category  $\text{tot}(X_\bullet)$  to the category of  $R$ -modules, where we identify a topological space with the category of open subsets of it. We say an  $R$ -module presheaf  $F^\bullet$  on an  $n$ -cubic topological space  $X_\bullet$  is an  $R$ -module sheaf if the presheaves  $F^\alpha$  on  $X_\alpha$ , defined by  $F^\bullet$ , are sheaves for all  $\alpha \in \square_n$ . For  $R$ -module (pre)sheaves  $F^\bullet$  and  $G^\bullet$  on  $X_\bullet$ , a *morphism from  $F^\bullet$  to  $G^\bullet$*  is defined to be a natural transformation from  $F^\bullet$  to  $G^\bullet$ .

We denote by  $\mathcal{M}(X_\bullet, R)$  and  $\mathcal{M}(X, R)$  the categories of  $R$ -module sheaves on  $X_\bullet$  and  $X$ , respectively, where  $R$  is a commutative ring with identity element 1. For an  $R$ -module sheaf  $\mathcal{F}$  on  $X$  we define its inverse image  $\Phi_\bullet^* \mathcal{F} \in \mathcal{M}(X_\bullet, R)$  in a natural way. The functor  $\Phi_\bullet^* : \mathcal{M}(X, R) \rightarrow \mathcal{M}(X_\bullet, R)$  has a right adjoint  $\Phi_{\bullet*} : \mathcal{M}(X_\bullet, R) \rightarrow \mathcal{M}(X, R)$ . Since the functor  $\Phi_\bullet^*$  is exact, it defines a functor

$$(3.1) \quad \Phi_\bullet^* : D^+(X, R) \rightarrow D^+(X_\bullet, R),$$

where  $D^+(X, R)$  and  $D^+(X_\bullet, R)$  denote the derived categories of lower bounded complexes of  $R$ -module sheaves on  $X$  and  $X_\bullet$ , respectively. The functor in (3.1) has a right adjoint

$$\mathbb{R}\Phi_{\bullet*} : D^+(X_\bullet, R) \rightarrow D^+(X, R).$$

Let  $F^\bullet$  be a lower bounded complex of  $R$ -module sheaves on an  $n$ -cubic topological space  $X_\bullet$ . We take the factorization

$$(3.2) \quad X_\bullet \xrightarrow{\Phi_{1\bullet}} X \times \square_n \xrightarrow{\Phi_{2\bullet}} X$$

of  $\Phi_\bullet : X_\bullet \rightarrow X$ , where  $X \times \square_n$  is the  $n$ -cubic object of (Top) defined by  $(X \times \square_n)(\alpha) := X$  for  $\alpha \in \square_n$ ,  $\Phi_{1\bullet}$  is the natural transformation defined by  $\Phi_{1\alpha} := \Phi_\alpha$  for  $\alpha \in \square_n$ , and  $\Phi_{2\bullet}$  the one defined by  $\Phi_{2\alpha} := id_X$  for  $\alpha \in \square_n$ . By definition  $\Phi_{1\bullet*}F^\bullet = \{\Phi_{1\alpha*}F^\alpha\}_{\alpha \in \text{Ob}(\square_n)}$ , to which we associate a simple complex  $s(\Phi_{1\bullet*}F^\bullet)$  of  $R$ -module sheaves on  $X$ . To explain this we give the definition of an  $n$ -ple complex of an abelian category. Let  $A$  be an abelian category. We denote by  $C^+(A)$  the category of lower bounded complexes of  $A$ . Let  $n$  be an integer  $\geq 1$ . We denote by  $e_i$  the  $i$ -th vector of the canonical basis of  $\mathbb{Z}^n$ , i.e.,  $e_i = (0, \dots, 1, \dots, 0)$  (1 is at the  $i$ -th place) for  $1 \leq i \leq n$ .

**3.2 Definition.** With the notation above, an  $n$ -ple complex of  $A$  consists of the following entities:

- (i) a  $\mathbb{Z}^n$ -graded object  $\{K^\alpha\}_{\alpha \in \mathbb{Z}^n}$  of  $A$ , and
- (ii) a family  $\{d_i\}_{1 \leq i \leq n}$  of differentials of  $K^\bullet$  such that  $d_i$  is of degree  $e_i$  and they commute each other.

We denote by  $n\text{-}C^+(A)$  the category of  $n$ -ple complexes of an abelian category  $A$ .

**3.3 Definition.** For  $K \in n\text{-}C^+(A)$  its associated simple complex  $s(K) \in C^+(A)$  is defined to be as follows:

$$s(K)^p := \sum_{\sum p_i = p} K^{p_1 \cdots p_n}, \quad p \in \mathbb{Z} \text{ and}$$

the differential  $d$  of  $s(K)$  is defined by

$$d = \sum_{j=1}^n (-1)^{\varepsilon_j} d_j \text{ on } K^{p_1 \cdots p_n},$$

where  $\varepsilon_j = \sum_{i < j} p_i$ .

Let  $\mathcal{A}$  be a  $(\square_n^+)^{\circ}$ -object of lower bounded complexes of  $R$ -module sheaves on a topological space, say  $Y$ , i.e., a functor  $\mathcal{A} : (\square_n^+)^{\circ} \rightarrow C^+(Y, R)$ , where  $C^+(Y, R)$  is the category of lower bounded complexes of  $R$ -module sheaves on

$Y$ . We denote  $\mathcal{A}(\alpha) \in C^+(Y, R)$  by  $\mathcal{A}^{\alpha\bullet}$  for each  $\alpha \in \text{Ob}(\square_n^+)$ . We associate to such  $\mathcal{A}$  an object  $K(\mathcal{A})$  of  $(n+2)\text{-}C^+(Y, R)$ , i.e., an  $(n+2)$ -ple lower bounded complex of  $\mathcal{M}(Y, R)$  as follows:

$$K(\mathcal{A})^{\alpha_0 \cdots \alpha_n q} := \begin{cases} \mathcal{A}^{\alpha q} & \text{if } \alpha \in \text{Ob}(\square_n^+) \\ 0 & \text{if } \alpha \in \mathbb{Z}^{n+1} - \text{Ob}(\square_n^+); \end{cases}$$

the  $(i+1)$ -th differential is the one induced by the morphism  $\alpha \rightarrow \alpha + e_i$  in  $\square_n^+$  for  $0 \leq i \leq n$ , and  $(n+2)$ -th differential is the one of the complex  $\mathcal{A}^{\alpha\bullet}$ . For the sake of simplicity we denote  $s(K(\mathcal{A}))$  by  $s(\mathcal{A})$ .

We think of  $\Phi_{1\bullet\bullet} F^\bullet = \{a_{1\alpha\bullet} F^\alpha\}_{\alpha \in \text{Ob}(\square_n)}$  as a  $(\square_n^+)^{\circ}$ -object of lower bounded complexes of  $R$ -module sheaves on  $X$  by defining  $F^{(0, \dots, 0)} = \{0\}$  for  $(0, \dots, 0) \in \square_n^+$ , and form  $s(\Phi_{1\bullet\bullet} F^\bullet)$ . Then we have

$$\mathbb{R}\Phi_{2\bullet\bullet}(\Phi_{1\bullet\bullet} F^\bullet) \cong s(\Phi_{1\bullet\bullet} F^\bullet)[1]$$

in  $D^+(X, R)$ , where  $[1]$  stands for the shift of the degree of complexes to the left by 1, i.e.,  $s(\Phi_{1\bullet\bullet} F^\bullet)[1]^p = s(\Phi_{1\bullet\bullet} F^\bullet)^{p+1}$ . Then we have

$$(3.3) \quad \mathbb{R}\Phi_{\bullet\bullet} F^\bullet \cong s(\Phi_{1\bullet\bullet} F^\bullet)[1]$$

in  $D^+(X, R)$ . This description of  $\mathbb{R}\Phi_{\bullet\bullet} F^\bullet$  is necessary for our arguments in the following. For more details we refer to [10, Exposé I].

The following is the relative version of the cohomological descent for  $R$ -module sheaves.

**3.4 Theorem.** *Let  $\mathfrak{X}_\bullet \xrightarrow{a_\bullet} \mathfrak{X} \xrightarrow{\pi} M$  be a simultaneous  $n$ -cubic ( $n \geq 1$ ) hyper-resolution of a locally trivial analytic family of complex projective varieties, parametrized by a complex space  $M$ . Then, for an  $R$ -module sheaf  $\mathcal{A}$  on  $\mathfrak{X}$ , the adjunction map*

$$\mathcal{A} \longrightarrow \mathbb{R}a_{\bullet\bullet} a_{\bullet\bullet}^* \mathcal{A}$$

*is an isomorphism in  $D^+(\mathfrak{X}, R)$ .*

*Proof.* In order to prove the theorem, it suffices to show that for any point  $x \in \mathfrak{X}$ , the homomorphism

$$(3.4) \quad \mathcal{A}_x \longrightarrow (\mathbb{R}a_{\bullet\bullet} a_{\bullet\bullet}^* \mathcal{A})_x$$

is a quasi-isomorphism of complexes of  $R$ -modules. We put  $t := \pi(x)$ ,  $X_t := \pi^{-1}(t)$ ,  $X_{\bullet t} := \pi_{\bullet}^{-1}(t)$  and

$$b_{\bullet t} := a_{\bullet|X_{\bullet t}} : X_{\bullet t} \rightarrow X_t$$

Since  $b_{\bullet t} : X_{\bullet t} \rightarrow X_t$  is a cubic hyper-resolution by the assumption, it follows from its cohomological descent property that the homomorphism

$$(3.5) \quad (\mathcal{A}|_{X_t})_x \longrightarrow (\mathbb{R}b_{\bullet t} b_{\bullet t}^* \mathcal{A}|_{X_t})_x$$

is a quasi-isomorphism. Therefore, since  $\mathcal{A}_x = (\mathcal{A}|_{X_t})_x$ , it suffices to show that the canonical map

$$(3.6) \quad (\mathbb{R}a_{\bullet\bullet}a_{\bullet}^*\mathcal{A})_x \longrightarrow (\mathbb{R}b_{t\bullet}b_{t\bullet}^*\mathcal{A}|_{X_t})_x,$$

is a quasi-isomorphism in order to prove that the homomorphism in (3.5) is a quasi-isomorphism. We use the following lemma which is a consequence of the proper base change formula of Godement ([7, II.4.11]), and of [10, Exposé I,5.13]:

**3.5 Lemma.** *Let  $T_{\bullet}$  be a cubic paracompact topological space,  $S$  a paracompact space, and  $f_{\bullet} : T_{\bullet} \rightarrow S$  a proper augmentation. For all complex of sheaves  $F^{\bullet}$  on  $T_{\bullet}$  and all  $s \in S$ , the fibre at  $s$  of the complex of sheaves  $\mathbb{R}f_{\bullet\bullet}F^{\bullet}$  is quasi-isomorphic to the hypercohomology  $\mathbb{H}(T_{\bullet s}, F^{\bullet}|_{T_{\bullet s}})$  of the fiber  $T_{\bullet s} := f_{\bullet}^{-1}(s)$ .*

Then one obtains the following quasi-isomorphisms,

$$\begin{aligned} (\mathbb{R}a_{\bullet\bullet}a_{\bullet}^*\mathcal{A})_x &\cong \mathbb{H}(a_{\bullet}^{-1}(x), a_{\bullet}^*\mathcal{A}|_{a_{\bullet}^{-1}(x)}) \\ (\mathbb{R}b_{\bullet t}b_{\bullet t}^*\mathcal{A}|_{X_t})_x &\cong \mathbb{H}(b_{\bullet t}^{-1}(x), b_{\bullet t}^*(\mathcal{A}|_{X_t})|_{b_{\bullet t}^{-1}(x)}) \end{aligned}$$

and the obvious identity  $a_{\bullet}^{-1}(x) = b_{\bullet t}^{-1}(x)$ , from which one deduces that (3.6) is a quasi-isomorphism as required.

*Q.E.D.*

We are now going to define the *cohomological relative de Rham complex*  $DR_{\mathfrak{X}/M} \in D^+(\mathfrak{X}, \mathbb{C})$  for an analytic family  $\pi : \mathfrak{X} \rightarrow M$  of complex analytic varieties, parametrized by a complex space  $M$ . For this end we take a system of relative local embeddings  $\mathcal{U} := \{(\mathcal{U}'_i, \mathcal{U}_i), \varphi_i, (\mathcal{Y}'_i, \mathcal{Y}_i, \pi_i)\}$  of  $\pi : \mathfrak{X} \rightarrow M$  which consists of the following entities:

- (i)  $\{\mathcal{U}'_i\}, \{\mathcal{U}_i\}$  are open coverings of  $\mathfrak{X}$  with  $\mathcal{U}_i$  being a relatively compact open subset of  $\mathcal{U}'_i$  for every  $i$ ,
- (ii)  $\mathcal{Y}'_i = D_i \times \pi(\mathcal{U}'_i)$ , where  $D_i$  are polycylinders in complex number spaces  $\mathbb{C}^{n_i}$ ,
- (iii)  $\mathcal{Y}_i \xrightarrow{\pi_i} \pi(\mathcal{U}_i)$  are smooth families of complex manifolds, parametrized by  $\pi(\mathcal{U}_i)$  such that
  - (a)  $\mathcal{Y}_i$  are relatively compact open subsets of  $\mathcal{Y}'_i$ , and
  - (b) the following diagrams commute:

$$\begin{array}{ccc} \mathcal{Y}_i & \longrightarrow & \mathcal{Y}'_i \\ \pi_i \downarrow & & \downarrow \text{Pr}_{\pi(\mathcal{U}'_i)} \\ \pi(\mathcal{U}_i) & \longrightarrow & \pi(\mathcal{U}'_i), \end{array}$$

- (iv)  $\varphi_i : \mathcal{U}'_i \rightarrow \mathcal{Y}'_i$  are closed embeddings over  $\pi(\mathcal{U}'_i)$  such that  $\varphi_i(\mathcal{U}_i) = \mathcal{Y}_i$ .

For each  $(p+1)$ -tuple  $(i) = \{i_0 < i_1 < \cdots < i_p\}$  we consider an open set  $\mathcal{U}'_{(i)} = \mathcal{U}'_{i_0} \cap \cdots \cap \mathcal{U}'_{i_p}$  and a relative closed embedding

$$\begin{aligned} \mathcal{U}'_{(i)} &\rightarrow \mathcal{Y}'_{(i)} \\ &:= (D_{i_0} \times \pi(\mathcal{U}'_{(i)})) \times_{\pi(\mathcal{U}'_{(i)})} (D_{i_1} \times \pi(\mathcal{U}'_{(i)})) \times_{\pi(\mathcal{U}'_{(i)})} \cdots \\ &\quad \times_{\pi(\mathcal{U}'_{(i)})} (D_{i_p} \times \pi(\mathcal{U}'_{(i)})) \end{aligned}$$

over  $\pi(\mathcal{U}'_{(i)})$ , where  $\times_{\pi(\mathcal{U}'_{(i)})}$  denotes the fiber product over  $\pi(\mathcal{U}'_{(i)})$ ; and define

$$\Omega_{\mathcal{Y}'_{(i)}/\pi(\mathcal{U}'_{(i)})} \widehat{|\mathcal{U}'_{(i)}} := \varprojlim_k \Omega_{\mathcal{Y}'_{(i)}/\pi(\mathcal{U}'_{(i)})} / \mathcal{I}_{\mathcal{U}'_{(i)}}^k \Omega_{\mathcal{Y}'_{(i)}/\pi(\mathcal{U}'_{(i)})}$$

where  $\Omega_{\mathcal{Y}'_{(i)}/\pi(\mathcal{U}'_{(i)})}$  is the relative de Rham complex of the smooth family  $\text{Pr}_{\pi(\mathcal{U}'_{(i)})} : \mathcal{Y}'_{(i)} \rightarrow \pi(\mathcal{U}'_{(i)})$  of complex manifolds and  $\mathcal{I}_{\mathcal{U}'_{(i)}}$  is the ideal sheaf of  $\mathcal{U}'_{(i)}$  in the structure sheaf  $\mathcal{O}_{\mathcal{Y}'_{(i)}}$  of  $\mathcal{Y}'_{(i)}$ . We call  $\Omega_{\mathcal{Y}'_{(i)}/\pi(\mathcal{U}'_{(i)})} \widehat{|\mathcal{U}'_{(i)}}$  the completion of  $\Omega_{\mathcal{Y}'_{(i)}/\pi(\mathcal{U}'_{(i)})}$  along  $\mathcal{U}'_{(i)}$ . Then we consider a complex of sheaves of  $\mathbb{C}$ -vector spaces on  $\mathfrak{X}$

$$\mathcal{C}_{(i)}^\bullet := j_*(\Omega_{\mathcal{Y}'_{(i)}/\pi(\mathcal{U}'_{(i)})} \widehat{|\mathcal{U}'_{(i)}})|_{\mathcal{U}_{(i)}},$$

where  $j$  is the inclusion of  $\mathcal{U}'_{(i)}$  into  $\mathfrak{X}$  and  $\mathcal{U}_{(i)} = \mathcal{U}_{i_0} \cap \cdots \cap \mathcal{U}_{i_p}$ . Here, putting 0 outside  $\mathcal{U}_{(i)}$ , we consider  $\mathcal{C}_{(i)}^\bullet$  as a complex of sheaves of  $\mathbb{C}$ -vector spaces on  $\mathfrak{X}$ . Now for any  $0 \leq j \leq p$ , let  $(i') = \{i_0, \dots, \check{i}_j, \dots, i_p\}$  (omit  $i_j$ ). Then we have a natural inclusion  $\mathcal{U}'_{(i)} \rightarrow \mathcal{U}'_{(i')}$ , which maps  $\mathcal{U}_{(i)}$  into  $\mathcal{U}_{(i')}$ ; and a natural inclusion  $\mathcal{Y}'_{(i)} \rightarrow \mathcal{Y}'_{(i')}$  over  $\pi(\mathcal{U}'_{(i)}) \rightarrow \pi(\mathcal{U}'_{(i')})$ , which maps  $\mathcal{Y}_{(i)}$  into  $\mathcal{Y}_{(i')}$  over  $\pi(\mathcal{U}_{(i)}) \rightarrow \pi(\mathcal{U}_{(i')})$ . Hence there is a natural map

$$\Omega_{\mathcal{Y}'_{(i')}/\pi(\mathcal{U}'_{(i')})} \widehat{|\mathcal{U}'_{(i')}|_{\mathcal{U}'_{(i)}}} \rightarrow \Omega_{\mathcal{Y}'_{(i)}/\pi(\mathcal{U}'_{(i)})} \widehat{|\mathcal{U}'_{(i)}},$$

and a morphism of complexes on  $\mathfrak{X}$

$$\delta_{j,(i)} : \mathcal{C}_{(i')}^\bullet \rightarrow \mathcal{C}_{(i)}^\bullet$$

Notice that, by the construction, for two integers  $0 \leq j < k \leq p$ , the corresponding four  $\delta$  maps are compatible with each other. Hence we can define a double complex  $\mathcal{C}(\mathcal{U})$  by

$$\mathcal{C}(\mathcal{U})^p = \prod_{|i|=p} \mathcal{C}_{(i)}^\bullet$$

where  $|i|$  is defined to be  $p$  for  $i = (i_0, \dots, i_p)$ , and

$$\delta^{p-1} := \prod_{|i|=p} \sum_{j=0}^p (-1)^j \delta_{j,(i)} : \mathcal{C}(\mathcal{U})^{p-1} \rightarrow \mathcal{C}(\mathcal{U})^p$$



We denote by  $\widehat{\Omega}_{\mathfrak{X}/M}^\bullet(\mathcal{U})$  the associated single complex of  $\mathcal{C}(\mathcal{U})$ . If  $\mathcal{V} = \{(\mathcal{V}'_j, \mathcal{V}_j), \psi_j, (\mathcal{Z}'_j, \mathcal{Z}_j, \pi_j)\}$  is a refinement of a system of relative local embeddings  $\mathcal{U}$ , then there is a natural map of double complexes  $\varphi : \mathcal{C}(\mathcal{U}) \rightarrow \mathcal{C}(\mathcal{V})$  and, as in the absolute case, we can see that the map  $\widehat{\Omega}_{\mathfrak{X}/M}^\bullet(\mathcal{U}) \rightarrow \widehat{\Omega}_{\mathfrak{X}/M}^\bullet(\mathcal{V})$  of simple complexes associated to  $\varphi$  is a quasi-isomorphism (cf. [11, p.29]). Therefore we conclude that  $\widehat{\Omega}_{\mathfrak{X}/M}^\bullet(\mathcal{U})$  defines an element of  $D^+(\mathfrak{X}, \mathbb{C})$ , which is independent of the choice of  $\mathcal{U}$ .

**3.6 Definition.** We call such an element of  $D^+(\mathfrak{X}, \mathbb{C})$  determined by the  $\widehat{\Omega}_{\mathfrak{X}/M}^\bullet(\mathcal{U})$  the *cohomological relative de Rham complex* of the family  $\pi : \mathfrak{X} \rightarrow M$  and denote by  $DR_{\mathfrak{X}/M}^\bullet$ .

Let  $\mathfrak{X}_\bullet \xrightarrow{a_\bullet} \mathfrak{X} \xrightarrow{\pi} M$  be a simultaneous  $n$ -cubic hyper-resolution of a locally trivial analytic family of complex projective varieties, parametrized by a complex space  $M$ . For each  $\alpha \in \square_n$  we denote by  $\Omega_{\mathfrak{X}_\alpha/M}^\bullet$  the relative de Rham complex of a smooth family  $\pi \circ a_\alpha : \mathfrak{X}_\alpha \rightarrow M$  of complex manifolds. Then  $\Omega_{\mathfrak{X}_\bullet/M}^\bullet := \{\Omega_{\mathfrak{X}_\alpha/M}^\bullet\}_{\alpha \in \square_n}$  is obviously a complex of sheaves of  $\mathbb{C}$ -vector spaces on a  $\square_n$ -complex manifold  $\mathfrak{X}_\bullet$ . The rest of this section will be devoted to proving the following theorems and a corollary.

**3.7 Theorem.** (*Cohomological descent of relative de Rham complexes*) Under the same setting as above, there naturally exists an isomorphism

$$DR_{\mathfrak{X}/M}^\bullet \simeq \mathbb{R}a_{\bullet\bullet} \Omega_{\mathfrak{X}_\bullet/M}^\bullet$$

in  $D^+(\mathfrak{X}, \mathbb{C})$ .

**3.8 Theorem.** (*Relative formal analytic Poincaré lemma*) Under the same setting as above,  $\widehat{\Omega}_{\mathfrak{X}/M}^\bullet(\mathcal{U})$  yields a resolution of the sheaf  $\pi^*(\mathcal{O}_M)$  for a system of relative local embeddings  $\mathcal{U} = \{(\mathcal{U}'_i, \mathcal{U}_i), \varphi_i, (\mathcal{Y}'_i, \mathcal{Y}_i, \pi_i)\}$  of  $\pi : \mathfrak{X} \rightarrow M$ , where  $\pi^*(\mathcal{O}_M)$  denotes the topological inverse of the structure sheaf of  $M$  by the map  $\pi : \mathfrak{X} \rightarrow M$ .

**3.9 Corollary.** *There exist isomorphisms*

$$\begin{aligned} H^i(\mathfrak{X}, \pi^*(\mathcal{O}_M)) &\simeq H^i(\mathbb{R}\Gamma(\mathfrak{X}, s(a_{1\bullet\bullet} \Omega_{\mathfrak{X}_\bullet/M}^\bullet)[1])) \\ &\simeq H^i(\mathbb{R}\Gamma(\mathfrak{X}_\bullet, \Omega_{\mathfrak{X}_\bullet/M}^\bullet)[1]) \quad (1 \leq i \leq 2 \dim_{\mathbb{C}} \mathfrak{X}). \end{aligned}$$

(for the notation  $a_{1\bullet}$  see (3.2))

To prove these theorems the following two theorems are essential.

**3.10 Theorem.** (*Mayer-Vietories sequence for relative de Rham complexes*)

Let  $\pi : \mathfrak{Y} \rightarrow M$  be a flat family of analytic varieties, parametrized by a complex space  $M$ . Suppose that  $\pi : \mathfrak{Y} \rightarrow M$  is relatively embedded in a smooth family  $\pi' : \mathfrak{X} \rightarrow M$  of complex manifolds, parametrized by the same complex space  $M$ , and further suppose that  $\mathfrak{Y}$  is a union of two closed subvarieties  $\mathfrak{Y}_1$  and  $\mathfrak{Y}_2$  of  $\mathfrak{X}$ . Then there is an exact sequence of relative de Rham complexes

$$0 \rightarrow \Omega_{\mathfrak{X}/M}^\bullet \widehat{|\mathfrak{Y}} \rightarrow \Omega_{\mathfrak{X}/M}^\bullet \widehat{|\mathfrak{Y}}_1 \oplus \Omega_{\mathfrak{X}/M}^\bullet \widehat{|\mathfrak{Y}}_2 \rightarrow \Omega_{\mathfrak{X}/M}^\bullet \widehat{|\mathfrak{Y}}_1 \cap \mathfrak{Y}_2 \rightarrow 0,$$

where  $\Omega_{\mathfrak{X}/M}^\bullet \widehat{|\mathfrak{Y}}$  is the completion of the relative de Rham complex  $\Omega_{\mathfrak{X}/M}^\bullet$  along  $\mathfrak{Y}$  and so on.

**3.11 Theorem.** Let  $f : X' \rightarrow X$  be a proper morphism of analytic varieties.

Let  $Y$  be a closed analytic subvariety of  $X$ , and let  $Y' := f^{-1}(Y)$ . Assume that  $f$  maps  $X' - Y'$  isomorphically onto  $X - Y$ . Suppose we are given coherent sheaves  $\mathcal{F}$  on  $X$  and  $\mathcal{F}'$  on  $X'$ , and an injective map  $\mathcal{F} \rightarrow f_* \mathcal{F}'$ , whose restriction to  $X - Y$  is an isomorphism. Then the single complex associated to the  $\square_1^+$ -object of lower bounded complexes of sheaves of  $\mathbb{C}$ -vector spaces on  $X$

$$\begin{array}{ccc} \mathbb{R}(\widehat{\iota \circ f})_* \widehat{\mathcal{F}}' & \longleftarrow & \mathbb{R}f_* \mathcal{F}' \\ \uparrow & & \uparrow \\ \widehat{\iota}_* \widehat{\mathcal{F}} & \longleftarrow & \mathcal{F} \end{array}$$

is acyclic in  $D^+(X, \mathbb{C})$ , where  $\iota$  is the closed immersion  $Y \rightarrow X$  and  $\widehat{\phantom{x}}$  denotes the completion along  $Y$ , or  $Y'$ , respectively.

The proof of Theorem 3.10 for the absolute case, i.e.,  $M$  is a single point, can be found in [11, p.89, Proposition(1.4)]. Since  $\Omega_{\mathfrak{X}/M}^p$  are locally free sheaves over  $\mathcal{O}_{\mathfrak{X}}$ , and since all of  $\Omega_{\mathfrak{X}/M}^p \widehat{|\mathfrak{Y}}$ ,  $\Omega_{\mathfrak{X}/M}^p \widehat{|\mathfrak{Y}}_i$  ( $i = 1, 2$ ) and  $\Omega_{\mathfrak{X}/M}^p \widehat{|\mathfrak{Y}}_1 \cap \mathfrak{Y}_2$  are completions with respect to some ideal sheaves of  $\mathcal{O}_{\mathfrak{X}}$ , the same arguments as in the absolute case also go well for the relative case. Hence we obtain Theorem 3.10. Theorem 3.11 is an analytic analogue of Proposition(4.3) in [11]. The key point of the proof of Proposition(4.3) in [11] is “fundamental theorem of a proper morphism” ([9, 4.1.5]), which tells us that, with the same notation as in Theorem 3.11, though all things should be replaced by algebraic ones,

$$R^i f_* \widehat{\mathcal{F}}' \simeq (R^i f_* \mathcal{F}')^\wedge \quad (i \geq 0),$$

where  $(R^i f_* \mathcal{F}')^\wedge$  is the completion of  $R^i f_* \mathcal{F}'$  along  $Y$ , and  $R^i \widehat{f}_* \widehat{\mathcal{F}}'$  the  $i$ -th higher direct image sheaf of  $\widehat{\mathcal{F}}'$  by the morphism of formal schemes  $\widehat{f} : \widehat{X}' \rightarrow \widehat{X}$ , induced by  $f$ , from the completion  $\widehat{X}'$  of  $X'$  along  $Y'$  to that of  $X$  along  $Y$ . Fortunately, we have an analytic analogue of the “fundamental theorem of a

proper morphism" due to C. Bănică and O. Stănășilă ([1, p.225, VI, Cor.4.5]). Using this theorem, we can carry out the same arguments as in the proof of Proposition(4.3) in [11]. Hence we obtain Theorem 3.11.

To prove Theorem 3.7 we shall use the following theorem, which is an analytic analogue of Theorem(4.4) in [11, p.44].

**3.12 Theorem.** *Let  $\pi' : \mathfrak{X}' \rightarrow M$  and  $\pi : \mathfrak{X} \rightarrow M$  be two flat families of analytic varieties, parametrized by the same complex space  $M$ . Let  $f : \mathfrak{X}' \rightarrow \mathfrak{X}$  be a proper morphism of analytic varieties over  $M$ ,  $\mathfrak{Y}$  a closed subvariety of  $\mathfrak{X}$ ,  $\mathfrak{Y}' := f^{-1}(\mathfrak{Y})$ , and  $h := f|_{\mathfrak{Y}'} : \mathfrak{Y}' \rightarrow \mathfrak{Y}$  the restriction of  $f$  to  $\mathfrak{Y}'$ . We assume the following:*

- (i)  $f$  maps  $\mathfrak{X}' - \mathfrak{Y}'$  isomorphically onto  $\mathfrak{X} - \mathfrak{Y}$ ,
- (ii) there exist
  - (a) smooth families of complex manifolds  $\pi' : \mathfrak{Z}' \rightarrow M$  and  $\pi : \mathfrak{Z} \rightarrow M$ , parametrized by the complex space  $M$ ,
  - (b) closed immersions  $\mathfrak{X}' \rightarrow \mathfrak{Z}'$  and  $\mathfrak{X} \rightarrow \mathfrak{Z}$  over  $M$ , and
  - (c) a proper morphism  $g : \mathfrak{Z}' \rightarrow \mathfrak{Z}$  over  $M$
 such that  $g|_{\mathfrak{X}'} = f$  and  $g$  maps  $\mathfrak{Z}' - g^{-1}(\mathfrak{Y})$  isomorphically onto  $\mathfrak{Z} - \mathfrak{Y}$ .

Then the single complex associated to the following  $\square_1^+$ -object of lower bounded complexes of sheaves of  $\mathbb{C}$ -vector spaces on  $\mathfrak{X}$

$$\begin{array}{ccc}
 \mathbb{R}(\widehat{\iota} \circ \widehat{h})_* \Omega_{\mathfrak{Z}'/M}^\bullet \widehat{|\mathfrak{Y}'} & \longleftarrow & \mathbb{R}f_* \Omega_{\mathfrak{Z}'/M}^\bullet \widehat{|\mathfrak{X}'} \\
 \uparrow & & \uparrow \\
 \widehat{\iota}_* \Omega_{\mathfrak{Z}/M}^\bullet \widehat{|\mathfrak{Y}} & \longleftarrow & \Omega_{\mathfrak{Z}/M}^\bullet \widehat{|\mathfrak{X}}
 \end{array}$$

is acyclic in  $D^+(\mathfrak{X}, \mathbb{C})$ , where  $\iota : \mathfrak{Y} \rightarrow \mathfrak{X}$  is the inclusion map.

Since the proof of Theorem 3.12 is almost identical with that in the algebraic case ([11, p.44, Chapter II, Theorem(4.4)], we omit it, just mentioning that we essentially use Theorem 3.10 and Theorem 3.11 to prove it.

**3.13 Proposition.** *Let  $\pi : \mathfrak{Y} \rightarrow M$  be a flat family of analytic varieties, parametrized by a complex space  $M$ , which is relatively embedded in a smooth family  $\pi' : \mathfrak{X} \rightarrow M$  of complex manifolds, parametrized by the same complex space  $M$ . Suppose  $\mathfrak{Y}$  is a union of finite closed subvarieties  $\mathfrak{Y}_1, \dots, \mathfrak{Y}_n$  ( $n \geq 2$ ). Let  $\iota : \mathfrak{Y}_\bullet \rightarrow \mathfrak{Y}$  be the  $n$ -cubic object of analytic varieties, augmented to  $\mathfrak{Y}$ , effected by the finite closed cover  $\{\mathfrak{Y}_r\}_{1 \leq r \leq n}$  of  $\mathfrak{Y}$  (cf. Example 1.6). Then we have a quasi-isomorphism*

$$\Omega_{\mathfrak{X}/M}^\bullet \widehat{|\mathfrak{Y}} \rightarrow \iota_* \Omega_{\mathfrak{X}/M}^\bullet \widehat{|\mathfrak{Y}_\bullet},$$

where

$$\Omega_{\mathfrak{X}/M}^\bullet \widehat{\mathfrak{Y}}_\bullet := \{\Omega_{\mathfrak{X}/M}^\bullet \widehat{\mathfrak{Y}}_\alpha\}_{\alpha \in \square_n}$$

is a complex of sheaves of  $\mathbb{C}$ -vector spaces on  $\mathfrak{Y}_\bullet$  obtained by the completion of  $\Omega_{\mathfrak{X}/M}^\bullet$  along  $\mathfrak{Y}_\alpha$  for every  $\alpha \in \square_n$ .

*Proof.* We use induction on  $n$ . The case  $n=2$  is nothing but Theorem 3.10. In the case  $n \geq 3$ , the argument is almost identical with that of Proposition 1.4 in [10, p.61] for the absolute and algebraic case. Hence we omit it.

*Q.E.D.*

**3.14 Proposition.** *Let  $X$  be a complex projective variety embedded in a smooth complex projective variety  $Y$ , and let  $a_\bullet : X_\bullet \rightarrow X$  be an  $n$ -cubic hyper-resolution of  $X$  in the category of complex projective varieties. We denote by  $X_h$  and  $Y_h$  the corresponding complex analytic varieties, and by  $a_{h\bullet} : X_{h\bullet} \rightarrow X_h$  the corresponding  $n$ -cubic hyper-resolution of  $X_h$  in the category of complex analytic varieties. Let  $p$  be a point of  $X_h$ . We take an open neighborhood  $V$  of  $p$  in  $Y_h$  and define  $U := V \cap X_h$  and  $U_\alpha := a_\alpha^{-1}(U)$  for each  $\alpha \in \square_n$ . We consider an  $n$ -cubic object of the product families of complex analytic varieties*

$$a_\bullet \times \text{id}_M : U_\bullet \times M \rightarrow U \times M$$

where  $M$  is a complex space and  $\text{id}_M$  is the identity map on  $M$ . Then we have a quasi-isomorphism

$$(3.7) \quad \Omega_{V \times M/M}^\bullet \widehat{U \times M} \rightarrow \mathbb{R}(a_\bullet \times \text{id}_M)_* \Omega_{U_\bullet \times M/M}^\bullet.$$

*Proof.* By the same argument used in the proof for the absolute case of Theorem 3.1 (cf. [10, p.41, Théorème 6.9]), we can reduce the proof to the case of  $n=2$ . Hence it suffices to prove (3.7) for the following  $\square_1^+$ -object of complex analytic varieties:

$$\begin{array}{ccc} U_{11} \times M & \longrightarrow & U_{01} \times M \\ \downarrow & & \downarrow a_{01} \times \text{id}_M \\ U_{10} \times M & \longrightarrow & U_{00} \times M \\ & & \parallel \\ & & U \times M \subset V \times M, \end{array}$$

which is a cartesian square, where  $U_{01}$  is a smooth analytic variety,  $a_{01} : U_{01} \rightarrow U_{00}$  a proper morphism (hence so is  $a_{01} \times \text{id}_M : U_{01} \times M \rightarrow U_{00} \times M$ ),  $U_{11} \rightarrow U_{01}$  and  $U_{10} \rightarrow U_{00}$  are closed immersions, such that  $a_{01} \times \text{id}_M : (U_{10} \times M) \setminus (U_{11} \times M) \rightarrow (U_{00} \times M) \setminus (U_{10} \times M)$  is an isomorphism. Furthermore, using

Proposition 3.13, we can reduce the proof to that for the case where  $U_{01}$  and  $U_{00}$  are irreducible (for the details of this procedure we refer to the proof of Théorème 1.5 in [10, p.62]). Now we shall check the proof for this case.

We write  $X, X', Y, Y', Z$  and  $f$  instead of  $U_{00}, U_{01}, U_{10}, U_{11}, V$  and  $a_{01}$ , respectively. Since  $X, X'$  are open subsets of complex projective varieties, by the result of Hironaka (Elimination of points of indeterminacy of a rational mapping, [12]), there exists a commutative diagram

$$(3.8) \quad \begin{array}{ccccc} \overline{X'} & \xrightarrow{f_4} & \overline{X} & & \\ & \searrow f_3 & \downarrow f_2 & \searrow f_1 & \\ & & X' & \xrightarrow{f} & X \hookrightarrow Z \end{array}$$

such that (i)  $f_1, f_3$  are the composites of blowing-ups along non-singular centers, (ii)  $\overline{X}, \overline{X'}$  are non-singular, and (iii)  $f_2, f_4$  are proper morphisms. Blowing up  $Z$  along the same centers as those of  $f_1 : \overline{X} \rightarrow X$ , we have the following diagram

$$(3.9) \quad \begin{array}{ccccc} \overline{Y} & \xrightarrow{\bar{\iota}} & \overline{X} & \longrightarrow & \overline{Z} \\ \downarrow & & \downarrow f_1 & & \downarrow g_1 \\ Y & \xrightarrow{\iota} & X & \longrightarrow & Z \end{array}$$

where  $\overline{Y} := f_1^{-1}(Y)_{red}$ . Forming direct product of each term in the diagram (3.9) with  $M$ , we come to the same setting as in Theorem 3.12. Hence, by that theorem, we conclude that the simple complex associated to the following  $\square_1^+$ -object of lower bounded complex of sheaves of  $\mathbb{C}$ -vector spaces on  $X \times M$

$$\begin{array}{ccc} \mathbb{R}(h_1 \times \text{id}_M)_* \Omega_{\overline{Z} \times M}^\bullet \widehat{|\overline{Y}} \times M & \longleftarrow & \mathbb{R}(f_1 \times \text{id}_M)_* \Omega_{\overline{Z} \times M}^\bullet \widehat{|\overline{X}} \times M \\ \uparrow & & \uparrow \\ (\iota \times \text{id}_M)_* \Omega_{Z \times M}^\bullet \widehat{|Y} \times M & \longleftarrow & \Omega_{Z \times M}^\bullet \widehat{|X} \times M, \end{array}$$

where  $h_1 := f_1 \circ \bar{\iota}$ , is acyclic in  $D^+(X \times M, \mathbb{C})$ . If we define  $s(X \times M/Y \times M)$ ,  $s(\overline{X} \times M/\overline{Y} \times M)$  to be the single complexes associated to the morphisms of complexes

$$\begin{aligned} \Omega_{Z \times M}^\bullet \widehat{|X} \times M &\rightarrow (\iota \times \text{id}_M)_* \Omega_{Z \times M}^\bullet \widehat{|Y} \times M \text{ and} \\ \Omega_{\overline{Z} \times M}^\bullet \widehat{|\overline{X}} \times M &\rightarrow (\bar{\iota} \times \text{id}_M)_* \Omega_{\overline{Z} \times M}^\bullet \widehat{|\overline{Y}} \times M, \end{aligned}$$

respectively, then the above statement is equivalent to that the morphism  $(f_1 \times id_M)^* : s(X \times M/Y \times M) \rightarrow s(\overline{X} \times M/\overline{Y} \times M)$  induced by  $f_1 \times id_M$  is a quasi-isomorphism. Here we should notice that, since  $X', \overline{X}'$  are non-singular,  $s(X' \times M/Y' \times M)$  and  $s(\overline{X}' \times M/\overline{Y}' \times M)$  are defined as the single complexes associated to the morphisms of complexes

$$\begin{aligned} \Omega_{X' \times M/M}^\bullet &\rightarrow (\iota' \times id_M)_* \Omega_{X' \times M/M}^\bullet \widehat{Y}' \times M \quad \text{and} \\ \Omega_{\overline{X}' \times M/M}^\bullet &\rightarrow (\overline{\iota}' \times id_M)_* \Omega_{\overline{X}' \times M/M}^\bullet \widehat{\overline{Y}'} \times M, \end{aligned}$$

respectively, where  $\overline{Y}' := f_4^{-1}(\overline{Y})_{red} = f_3^{-1}(Y')_{red}$  and  $\iota' : Y' \rightarrow X', \overline{\iota}' : \overline{Y}' \rightarrow \overline{X}'$  are natural inclusions. We consider the following diagram derived from (3.8)

(3.10)

$$\begin{array}{ccc} s(\overline{X}' \times M/\overline{Y}' \times M) & \xleftarrow{(f_4 \times id_M)^*} & s(\overline{X} \times M/\overline{Y} \times M) \\ & \swarrow (f_3 \times id_M)^* & \uparrow (f_2 \times id_M)^* \\ & & s(X' \times M/Y' \times M) \xleftarrow{f^*} s(X' \times M/Y' \times M) \\ & & \nwarrow (f_1 \times id_M)^* \end{array}$$

By the same reasoning as for  $(f_1 \times id_M)^*$ , we conclude that  $(f_3 \times id_M)^*, (f_4 \times id_M)^*$  are quasi-isomorphisms on  $X, X'$ , respectively. Hence by the commutativity of the diagram in (3.10), we conclude that  $(f_2 \times id_M)^*$  is a quasi-isomorphism on  $X'$  and so is  $(f \times id_M)^*$ . This completes the proof of the proposition.

*Q.E.D.*

We are now in a position to prove Theorem 3.7 and Theorem 3.8.

**Proof of Theorem 3.7:** By the assumption, we can take a system  $\mathcal{U} = \{(\mathcal{U}'_i, \mathcal{U}_i), \varphi_i, (\mathcal{Y}'_i, \mathcal{Y}_i, \pi_i)\}$  of relative local embeddings of  $\mathfrak{X}$  which satisfies the following conditions:

(3.11)

For each  $i$  there exists a point  $p_i \in \mathcal{U}_i$  and an embedding  $e_i : X_{\pi(p_i)} \rightarrow Y_{p_i}$  of  $X_{\pi(p_i)}$  (the fiber of  $\mathfrak{X}$  over  $\pi(p_i)$ ) into a smooth complex projective variety  $Y_{p_i}$  such that

$$\begin{aligned} \text{(i)} \quad a_{\bullet}^{-1}(\mathcal{U}'_i) &\xrightarrow{a_{\bullet} |_{a_{\bullet}^{-1}(\mathcal{U}'_i)}} \mathcal{U}'_i \xrightarrow{\pi|_{\mathcal{U}'_i}} \pi(\mathcal{U}'_i) \text{ is isomorphic to} \\ (a_{\bullet}^{-1}(\mathcal{U}'_i) \cap X_{\pi(p_i)}) \times \pi(\mathcal{U}'_i) &\xrightarrow{a_{\bullet} \times id_{\pi(\mathcal{U}'_i)}} (\mathcal{U}'_i \cap X_{\pi(p_i)}) \times \pi(\mathcal{U}'_i) \xrightarrow{\text{Pr}_{\pi(\mathcal{U}'_i)}} \pi(\mathcal{U}'_i) \end{aligned}$$

(for the notation see Definition 1.12)

- (ii)  $\mathcal{Y}'_i = D'_i \times \pi(\mathcal{U}'_i)$  and  $\mathcal{Y}_i = D_i \times \pi(\mathcal{U}_i)$ , where  $D'_i, D_i$  are open neighborhoods of the point  $e_i(p_i)$  in  $Y_{p_i}$  with  $D_i \subset D'_i$ , and
- (iii)  $\varphi_i(\mathcal{U}'_i) = (e_i(X_{\pi(p_i)}) \cap D'_i) \times \pi(\mathcal{U}'_i)$ . and  $\varphi_i(\mathcal{U}_i) = (e_i(X_{\pi(p_i)}) \cap D_i) \times \pi(\mathcal{U}_i)$ .

Then by Proposition 3.14 the natural map

$$\widehat{\Omega}_{\mathcal{U}'_i/\pi(\mathcal{U}'_i)}^\bullet \rightarrow \mathbb{R}a_{\bullet, |a_\bullet^{-1}(\mathcal{U}'_i)} * \Omega_{a_\bullet^{-1}(\mathcal{U}'_i)/\pi(\mathcal{U}'_i)}^\bullet = \mathbb{R}a_{\bullet, *} \Omega_{\mathfrak{X}_\bullet/M|\mathcal{U}'_i}^\bullet$$

is a quasi-isomorphism on  $\mathcal{U}'_i$ , hence

$$j_*(\widehat{\Omega}_{\mathcal{U}'_i/\pi(\mathcal{U}'_i)}^\bullet)|_{\mathcal{U}_i} \rightarrow j_*(\mathbb{R}a_{\bullet, *} \Omega_{\mathfrak{X}_\bullet/M|\mathcal{U}'_i}^\bullet)|_{\mathcal{U}_i}$$

is a quasi-isomorphism on  $\mathfrak{X}$  for every  $i$ , where  $j : \mathcal{U}'_i \rightarrow \mathfrak{X}$  is the inclusion map. From this it follows that for any  $(i) = \{i_0 < i_1 < \cdots < i_p\}$

$$C_{(i)} := j_*(\widehat{\Omega}_{\mathcal{U}'_{(i)}/\pi(\mathcal{U}'_{(i)})}^\bullet)|_{\mathcal{U}_{(i)}} \rightarrow D_{(i)} := j_*(\mathbb{R}a_{\bullet, *} \Omega_{\mathfrak{X}_\bullet/M|\mathcal{U}'_{(i)}}^\bullet)|_{\mathcal{U}_{(i)}}$$

is a quasi-isomorphism. Similarly as for  $C(\mathcal{U})$ , we define a double complex  $D(\mathcal{U})$ , using  $\{D_{(i)}\}$ , which is nothing but  $\mathbb{R}a_{\bullet, *} \Omega_{\mathfrak{X}_\bullet/M}^\bullet$ . Therefore we conclude that the natural map

$$\widehat{\Omega}_{\mathfrak{X}/M}^\bullet(\mathcal{U}) \rightarrow \mathbb{R}a_{\bullet, *} \Omega_{\mathfrak{X}_\bullet/M}^\bullet$$

is a quasi-isomorphism. Since any system of relative local embeddings of  $\mathfrak{X}$  has its refinement satisfying the conditions (i),(ii),(iii) in (3.11) we obtain the theorem.

**Proof of Theorem 3.8:** Since the problem is local, we may assume that  $\pi : \mathfrak{X} \rightarrow M$  is a product family, namely  $\pi := \text{Pr}_M : \mathfrak{X} = X \times M \rightarrow M$ , where  $X$  is a complex projective variety,  $M$  a complex space, and  $\pi := \text{Pr}_M$  the projection to  $M$ . Furthermore we may assume that  $X$  is embedded in a smooth complex projective variety  $Z$ . We define  $\mathfrak{Z} := Z \times M$  and  $\pi_1 := \text{Pr}_M : \mathfrak{Z} = Z \times M \rightarrow M$  the projection to  $M$ . Under this setting we shall prove that

$$(3.12) \quad \pi^* \mathcal{O}_M \rightarrow \Omega_{\mathfrak{Z}/M}^\bullet|_{\mathfrak{X}}$$

is a quasi-isomorphism on  $\mathfrak{X}$ . In the following we shall confuse complex algebraic objects and their associated analytic objects, and write them by the same letters. To prove (3.12) we proceed by induction on  $\dim_{\mathbb{C}} X$ . If  $\dim_{\mathbb{C}} X = 0$ , there is nothing to be proved. We assume that (3.12) holds for any  $X$  with  $0 \leq \dim_{\mathbb{C}} X < n$ . By the Hironaka resolution theorem ([12]) there is the following commutative diagram:

$$(3.13) \quad \begin{array}{ccccc} Y' & \xrightarrow{\iota'} & X' & \hookrightarrow & Z' \\ h \downarrow & & \downarrow g & & \downarrow f \\ Y & \xrightarrow{\iota} & X & \hookrightarrow & Z \end{array}$$

with the property  $g|_{X'-Y'} : X' - Y' \rightarrow X - Y$  is an isomorphism, where  $X'$  is a smooth complex projective variety,  $f : X' \rightarrow X$  a proper morphism,  $Y$  a proper closed subvariety of  $X$ ,  $Y' := f^{-1}(Y)_{red}$ , and  $\iota, \iota'$  closed immersions. Taking direct product of each term in (3.13) with  $M$ , we obtain the commutative diagram

$$(3.14) \quad \begin{array}{ccccc} \mathfrak{Y}' & \xrightarrow{I'} & \mathfrak{X}' & \hookrightarrow & \mathfrak{Z}' \\ H \downarrow & & \downarrow G & & \downarrow F \\ \mathfrak{Y} & \xrightarrow{I} & \mathfrak{X} & \hookrightarrow & \mathfrak{Z}, \end{array}$$

where  $\mathfrak{X} := X \times M$ ,  $\mathfrak{X}' := X' \times M$ ,  $F := f \times \text{id}_M$ , etc.. Then, by Theorem 3.12 it follows that

$$\begin{array}{ccc} \mathbb{R}(I \circ H)_* \Omega_{\mathfrak{X}'/M}^\bullet \widehat{|\mathfrak{Y}'} & \longleftarrow & \mathbb{R}G_* \Omega_{\mathfrak{X}'/M}^\bullet \\ \uparrow & & \uparrow \\ \mathbb{R}I_* \Omega_{\mathfrak{Z}/M}^\bullet \widehat{|\mathfrak{Y}} & \longleftarrow & \Omega_{\mathfrak{Z}/M}^\bullet \widehat{|\mathfrak{X}} \end{array}$$

is acyclic in  $D^+(\mathfrak{X}, \mathbb{C})$ . Therefore, for any relatively compact open subset  $\mathfrak{X}_0$  of  $\mathfrak{X}$ , we have the following long exact sequence of cohomology

$$(3.15) \quad \begin{aligned} & \rightarrow H^i(\mathfrak{X}_0, \Omega_{\mathfrak{Z}/M}^\bullet \widehat{|\mathfrak{X}}) \rightarrow H^i(\mathfrak{X}_0, \mathbb{R}I_* \Omega_{\mathfrak{Z}/M}^\bullet \widehat{|\mathfrak{Y}}) \oplus H^i(\mathfrak{X}_0, \mathbb{R}G_* \Omega_{\mathfrak{X}'/M}^\bullet) \\ & \rightarrow H^i(\mathfrak{X}_0, \mathbb{R}(I \circ H)_* \Omega_{\mathfrak{X}'/M}^\bullet \widehat{|\mathfrak{Y}'} ) \rightarrow H^{i+1}(\mathfrak{X}_0, \Omega_{\mathfrak{Z}/M}^\bullet \widehat{|\mathfrak{X}}) \rightarrow \\ & \dots \end{aligned}$$

On the other hand, applying Theorem 3.4 for  $\mathcal{A} = \pi_* \mathcal{O}_M$ , we derive from (3.14) that

$$\begin{array}{ccc} (I \circ H)_* \pi'_{|\mathfrak{Y}'} \mathcal{O}_M & \longleftarrow & G_* \pi' \mathcal{O}_M \\ \uparrow & & \uparrow \\ I_* \pi_{|\mathfrak{Y}} \mathcal{O}_M & \longleftarrow & \pi_* \mathcal{O}_M \end{array}$$

is acyclic in  $D^+(\mathfrak{X}, \mathbb{C})$ , where  $\pi' := \text{Pr}_M : \mathfrak{X}' = X' \times M \rightarrow M$ , the projection to  $M$ . Therefore we have the following long exact sequence of cohomology



$$\begin{aligned}
(3.16) \quad & \rightarrow H^i(\mathfrak{X}_0, \pi^* \mathcal{O}_M) \rightarrow H^i(\mathfrak{X}_0, I_* \pi'_* \mathcal{O}_M) \oplus H^i(\mathfrak{X}_0, G_* \pi'^* \mathcal{O}_M) \\
& \rightarrow H^i(\mathfrak{X}_0, (I \circ H)_* \pi'_* \mathcal{O}_M) \rightarrow H^{i+1}(\mathfrak{X}_0, \pi^* \mathcal{O}_M) \rightarrow \dots
\end{aligned}$$

There naturally exist homomorphisms from (3.16) to (3.15). Among these homomorphisms,

$$\begin{aligned}
& H^i(\mathfrak{X}_0, I_* \pi'_* \mathcal{O}_M) \rightarrow H^i(\mathfrak{X}_0, \mathbb{R} I_* \Omega_{3/M}^\bullet | \widehat{\mathfrak{Y}}), \\
& H^i(\mathfrak{X}_0, (I \circ H)_* \pi'_* \mathcal{O}_M) \rightarrow H^i(\mathfrak{X}_0, \mathbb{R} (I \circ H)_* \Omega_{\mathfrak{X}'/M}^\bullet | \widehat{\mathfrak{Y}'})
\end{aligned}$$

are isomorphisms on  $\mathfrak{X}_0$  by the induction hypothesis, and

$$H^i(\mathfrak{X}_0, G_* \pi'^* \mathcal{O}_M) \rightarrow H^i(\mathfrak{X}_0, \mathbb{R} G_* \Omega_{\mathfrak{X}'/M}^\bullet)$$

is also, because  $\pi' : \mathfrak{X}' \rightarrow M$  is a smooth family ([3, p.15, 2.23.2]). Hence we conclude that

$$H^i(\mathfrak{X}_0, \pi^* \mathcal{O}_M) \rightarrow H^i(\mathfrak{X}_0, \Omega_{3/M}^\bullet | \widehat{\mathfrak{X}})$$

is an isomorphism on  $\mathfrak{X}_0$ , which means  $\pi^* \mathcal{O}_M \rightarrow \Omega_{3/M}^\bullet | \widehat{\mathfrak{X}}$  is a quasi-isomorphism on  $\mathfrak{X}_0$  as required. This completes the proof of Theorem 3.8.

Corollary 3.9 follows from Theorem 3.7 and Theorem 3.8.

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