TOROIDALIZATION OF
LOCALLY TOROIDAL MORPHISMS

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KRISHNA CHAITHANYA HANUMANTHU

Dr. Steven Dale Cutkosky, Dissertation Supervisor

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The undersigned, appointed by the Dean of the Graduate School, have examined the dissertation entitled

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presented by Krishna Chaithanya Hanumanthu

a candidate for the degree of Doctor of Philosophy

and hereby certify that in their opinion it is worthy of acceptance.

Professor Steven Dale Cutkosky

Professor Hema Srinivasan

Professor Zhenbo Qin

Professor Qi Zhang

Professor Kannappan Palaniappan

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Krishna Chaithanya Hanumanthu

Dr. Steven Dale Cutkosky, Dissertation Supervisor

ABSTRACT

Let X and Y be nonsingular varieties over an algebraically closed field k of characteristic zero. A *toroidal structure* on X is a simple normal crossing divisor D_X on X.

Suppose that D_X and D_Y are toroidal structures on X and Y respectively. A dominant morphism $f : X \to Y$ is *toroidal (with respect to the toroidal structures D_X and D_Y)* if for all closed points $p \in X$, f is isomorphic to a toric morphism of toric varieties specified by the toric charts at p and $f(p)$.

A dominant morphism $f : X \to Y$ of nonsingular varieties is *toroidalizable* if there exist sequences of blow ups with nonsingular centers $\pi : Y_1 \to Y$ and $\pi_1 : X_1 \to X$ so that the induced map $f_1 : X_1 \to Y_1$ is toroidal.

Let $f : X \to Y$ be a dominant morphism. Suppose that there exist finite open covers $\{U_i\}$ and $\{V_i\}$ of X and Y respectively such that $f(U_i) \subset V_i$ and the restricted morphisms $f : U_i \to V_i$ are toroidal for all i. f is then called *locally toroidal.*

It is proved that a locally toroidal morphism from an arbitrary variety to a surface is toroidalizable.

Chapter 1

Introduction

Fix an algebraically closed field k of characteristic 0. A variety is an open subset of an irreducible proper k-scheme.

A *simple normal crossing* (SNC) divisor on a nonsingular variety is a divisor D on X, all of whose irreducible components are nonsingular and whenever r irreducible components $Z_1, ..., Z_r$ of D meet at a point p, then local equations $x_1, ..., x_r$ of Z_i form part of a regular system of parameters in $\mathcal{O}_{X,p}$.

A *toroidal structure* on a nonsingular variety X is a SNC divisor D_X.

The divisor D_X specifies a *toric* chart (V_p, σ_p) at every closed point $p \in X$ where $p \in V_p \subset X$ is an open neighborhood and $\sigma_p : V_p \to X_p$ is an étale morphism to a toric variety X_p such that under σ_p the ideal of D_X at p corresponds to the ideal of the complement of the torus in X_p.

The idea of a toroidal structure is fundamental to algebraic geometry. It is developed in the classic book "Toroidal Embeddings I" [10] by G. Kempf, F. Knudsen, D. Mumford and B. Saint-Donat.

Definition 1.1. ([10], [1]) Suppose that D_X and D_Y are toroidal structures on X and Y respectively. Let $p \in X$ be a closed point. A dominant morphism $f : X \to Y$

is *toroidal at* p *(with respect to the toroidal structures* D_X *and* D_Y*)* if the germ of f at p is formally isomorphic to a toric morphism between the toric charts at p and $f(p)$. f is *toroidal* if it is toroidal at all closed points in X.

A nonsingular subvariety V of X is a *possible center* for D_X if $V \subset D_X$ and V intersects D_X transversally. That is, V makes *SNCs* with D_X, as defined before Lemma 2.3. The blowup $\pi : X_1 \to X$ of a possible center is called a possible blowup. $D_{X_1} = \pi^{-1}(D_X)$ is then a toroidal structure on X_1.

Let $Sing(f)$ be the set of points p in X where f is not smooth. It is a closed set.

The following "toroidalization conjecture" is the strongest possible general structure theorem for morphisms of varieties.

Conjecture 1.2. *Suppose that* $f : X \longrightarrow Y$ *is a dominant morphism of nonsingular varieties. Suppose also that there is a SNC divisor* D_Y *on* Y *such that* $D_X = f^{-1}(D_Y)$ *is a SNC divisor on* X *which contains the singular locus,* $Sing(f)$*, of the map* f*.*

Then there exists a commutative diagram of morphisms

$$\begin{array}{ccc} X_1 & \xrightarrow{f_1} & Y_1 \\ \downarrow{\scriptstyle \pi_1} & & \downarrow{\scriptstyle \pi} \\ X & \xrightarrow{f} & Y \end{array}$$

where π, π_1 *are possible blowups for the preimages of* D_Y *and* D_X *respectively, such that* f_1 *is toroidal with respect to* $D_{Y_1} = \pi^{-1}(D_Y)$ *and* $D_{X_1} = {\pi_1}^{-1}(D_X)$

A slightly weaker version of the conjecture is stated in the paper [2] of D. Abramovich, K. Karu, K. Matsuki, and J. Wlodarczyk.

When Y is a curve, this conjecture follows easily from embedded resolution of hypersurface singularities, as shown in the introduction of [5]. The case when X and Y are surfaces has been known before (see Corollary 6.2.3 [2], [3], [7]). The case when X has dimension 3 is completely resolved by Dale Cutkosky in [5] and [6]. A special case of $\dim(X)$ arbitrary and $\dim(Y) = 2$ is done in [8].

For detailed history and applications of this conjecture, see [6].

A related, but weaker question asked by Dale Cutkosky is the following Question 1.4.

To state the question we need the following definition.

Definition 1.3. Let $f : X \to Y$ be a dominant morphism of nonsingular varieties. Suppose that the following are true.

1. There exist open coverings $\{U_1, ..., U_m\}$ and $\{V_1, ..., V_m\}$ of X and Y respectively such that the morphism f restricted to U_i maps into V_i for all $i = 1, ..., m$.

2. There exist simple normal crossings divisors D_i and E_i in U_i and V_i respectively such that $f^{-1}(E_i) \cap U_i = D_i$ and $Sing(f|_{U_i}) \subset D_i$ for all $i = 1, ..., m$.

3. The restriction of f to U_i, $f|_{U_i} : U_i \to V_i$, is toroidal with respect to D_i and E_i for all $i = 1, ..., m$.

Then we say that f is *locally toroidal* with respect to the open coverings U_i and V_i and SNC divisors D_i and E_i.

For the remainder when we say "f is locally toroidal", it is to be understood that f is locally toroidal with respect to the open coverings U_i and V_i and SNC divisors D_i and E_i as in the definition. We will usually not mention U_i, V_i, D_i and E_i.

We have the following.

Question 1.4. *Suppose that $f : X \longrightarrow Y$ is locally toroidal. Does there exist a commutative diagram of morphisms*

$$\begin{tikzcd} X_1 \arrow[r, "f_1"] \arrow[d, "\pi_1"] & Y_1 \arrow[d, "\pi"] \\ X \arrow[r, "f"] & Y \end{tikzcd}$$

where π, π_1 are blowups of nonsingular varieties such that there exist SNC divisors E, D on Y_1 and X_1 respectively such that $Sing(f_1) \subset D$, ${f_1}^{-1}(E) = D$ and f_1 is toroidal with respect to E and D?

The aim of this paper is to give a positive answer to this question when Y is a surface and X is arbitrary. The result is proved in Theorem 4.2.

Chapter 2

Permissible Blowups

Let $f : X \longrightarrow Y$ be a locally toroidal morphism from a nonsingular n-fold X to a nonsingular surface Y with respect to open coverings $\{U_1, ..., U_m\}$ and $\{V_1, ..., V_m\}$ of X and Y respectively and SNC divisors D_i and E_i in U_i and V_i respectively. Then we have the following

Lemma 2.1. *Let $p \in D_i$. Then there exist regular parameters $x_1, ..., x_n$ in $\hat{\mathcal{O}}_{X,p}$ and regular parameters u, v in $\mathcal{O}_{Y,q}$ such that one of the following forms holds:*

$1 \leq k \leq n-1$: *$u = 0$ is a local equation of E_i, $x_1...x_k = 0$ is a local equation of D_i and*

$$u = {x_1}^{a_1}...{x_k}^{a_k}, \quad v = x_{k+1}, \tag{2.1}$$

where $a_1, ..., a_k > 0$.

$1 \leq k \leq n-1$: *$uv = 0$ is a local equation for E_i, $x_1...x_k = 0$ is a local equation of D_i and*

$$u = ({x_1}^{a_1}...{x_k}^{a_k})^m, \; v = ({x_1}^{a_1}...{x_k}^{a_k})^t(\alpha + x_{k+1}), \tag{2.2}$$

where $a_1, ..., a_k, m, t > 0$ and $\alpha \in K - \{0\}$.

$2 \leq k \leq n$: $uv = 0$ *is a local equation of* E_i, $x_1 ... x_k = 0$ *is a local equation of* D_i *and*

$$u = {x_1}^{a_1} ... {x_k}^{a_k}, \quad v = {x_1}^{b_1} ... {x_k}^{b_k}, \tag{2.3}$$

where $a_1, ..., a_k, b_1, ..., b_k \geq 0, a_i + b_i > 0$ *for all* i *and*
rank $\begin{bmatrix} a_1 & . & . & a_k \\ b_1 & . & . & b_k \end{bmatrix} = 2.$

Proof. This follows from Lemma 4.2 in [8]. $\square$

Definition 2.2. Suppose that D is a SNC divisor on a variety X, and V is a nonsingular subvariety of X. We say that V makes SNCs with D at $p \in X$ if there exist regular parameters $x_1, ..., x_n$ in $\mathcal{O}_{X,p}$ and $e, r \leq n$ such that $x_1 ... x_e = 0$ is a local equation of D at p and $x_{\sigma(1)} = ... = x_{\sigma(r)} = 0$ is a local equation of V at p for some injection $\sigma : \{1, ..., r\} \to \{1, ..., n\}$.

We say that V makes SNCs with D if V makes SNCs with D at all points $p \in X$.

Let $q \in Y$ and let m_q be the maximal ideal of $\mathcal{O}_{Y,q}$.

Define $W_q = \{p \in X \mid m_q \mathcal{O}_{X,p}$ is not principal$\}$. Note that the closed subset $W_q \subset f^{-1}(q)$ and that $m_q \mathcal{O}_{X,p}$ is principal if and only if $m_q \hat{\mathcal{O}}_{X,p}$ is principal.

Lemma 2.3. *For all* $q \in Y$, W_q *is a union of nonsingular codimension 2 subvarieties of* X, *which make SNCs with each divisor* D_i *on* U_i.

Proof. Let us fix a $q \in Y$ and denote $W = W_q$. Let $\mathfrak{I}_W$ be the reduced ideal sheaf of W in X, and let $\mathfrak{I}_q$ be the reduced ideal sheaf of q in Y.

Since the conditions that W is nonsingular and has codimension 2 in X are both local properties, we need only check that for all $p \in W$, $\mathfrak{I}_{W,p}$ is an intersection of height 2 prime ideals which are regular.

Since X is nonsingular, $\mathfrak{I}_q \mathcal{O}_X = \mathcal{O}_X\ (-F)\mathcal{I}$ where F is an effective Cartier divisor on X and $\mathcal{I}$ is an ideal sheaf such that the support of $\mathcal{O}_X/\mathcal{I}$ has codimension at least 2 on X. We have $W = \mathrm{supp}(\mathcal{O}_X/\mathcal{I})$. The ideal sheaf of W is $\mathfrak{I}_W = \sqrt{\mathcal{I}}$.

Let $p \in W$. We have that $p \in U_i$ for some $1 \le i \le m$.

Suppose first that $q \notin E_i$. Then f is smooth at p because it is locally toroidal. This means that there are regular parameters u, v at q which form a part of a regular sequence at p. So we have regular parameters $x_1, ..., x_n$ in $\mathcal{O}_{X,p}$ such that $u = x_1, v = x_2$.

$\mathfrak{I}_q \mathcal{O}_{X,p} = (u, v)\mathcal{O}_{X,p} = (x_1, x_2)\mathcal{O}_{X,p}$. It follows that $\mathfrak{I}_{W,p} = (x_1, x_2)\mathcal{O}_{X,p}$. This gives us the lemma.

Suppose now that $q \in E_i$.

Since $p \in W_q$, there exist regular parameters $x_1, ..., x_n$ in $\hat{\mathcal{O}}_{X,p}$ and u, v in $\mathcal{O}_{Y,q}$ such that one of the forms (2.1) or (2.3) holds.

Suppose that (2.1) holds. Since D_j is a SNC divisor, there exist regular parameters $y_1, ..., y_n$ in $\mathcal{O}_{X,p}$ and some e such that $y_1...y_e = 0$ is a local equation of D_j.

Since $x_1...x_k = 0$ is a local equation for D_j in $\hat{\mathcal{O}}_{X,p}$, there exists a unit series $\delta \in \hat{\mathcal{O}}_{X,p}$ such that $y_1...y_e = \delta x_1...x_k$. Since the x_i and y_i are irreducible in $\hat{\mathcal{O}}_{X,p}$, it follows that $e = k$, and there exist unit series $\delta_i \in \hat{\mathcal{O}}_{X,p}$ such that $x_i = \delta_i y_i$ for $1 \le i \le k$, after possibly reindexing the y_i.

Note that $y_1, ..., y_k, x_{k+1}, y_{k+2}, ..., y_n$ is a regular system of parameters in $\hat{\mathcal{O}}_{X,p}$, after possibly permuting $y_{k+1}, ..., y_n$.

So the ideal $(y_1, ..., y_k, x_{k+1}, y_{k+2}, ..., y_n)\hat{\mathcal{O}}_{X,p}$ is the maximal ideal of $\hat{\mathcal{O}}_{X,p}$. Since $x_{k+1} = v \in \mathcal{O}_{X,p}$, $y_1, ..., y_k, x_{k+1}, y_{k+2}, ..., y_n$ generate an ideal J in $\mathcal{O}_{X,p}$. Since $\hat{\mathcal{O}}_{X,p}$ is faithfully flat over $\mathcal{O}_{X,p}$, and $J\hat{\mathcal{O}}_{X,p}$ is maximal, it follows that J is the maximal ideal of $\mathcal{O}_{X,p}$. Hence $y_1, ..., y_k, x_{k+1}, y_{k+2}, ..., y_n$ is a regular system of parameters in $\mathcal{O}_{X,p}$.

Rewriting (2.1), we have $u = {y_1}^{a_1} ... {y_k}^{a_k}\bar{\delta}$, where $\bar{\delta}$ is a unit in $\hat{\mathcal{O}}_{X,p}$.

Since $\bar{\delta} = \frac{u}{{y_1}^{a_1}...{y_k}^{a_k}}$, $\bar{\delta} \in \mathrm{QF}(\mathcal{O}_{X,p}) \cap \hat{\mathcal{O}}_{X,p}$, where $\mathrm{QF}(\mathcal{O}_{X,p})$ is the quotient field of $\mathcal{O}_{X,p}$. By Lemma 2.1 in [4], it follows that $\bar{\delta} \in \mathcal{O}_{X,p}$.

Since $\bar{\delta}$ is a unit in $\hat{\mathcal{O}}_{X,p}$, it is a unit in $\mathcal{O}_{X,p}$.

We have

$$\begin{aligned} \mathfrak{I}_{W,p} &= \sqrt{\mathfrak{I}_q \mathcal{O}_{X,p}} = \sqrt{(u,v)\mathcal{O}_{X,p}} = \sqrt{({y_1}^{a_1}...{y_k}^{a_k}, x_{k+1})} \\ &= (y_1, x_{k+1}) \cap (y_2, x_{k+1}) \cap ... \cap (y_k, x_{k+1}), \end{aligned}$$

as required.

We argue similarly when (2.3) holds at p. $\square$

Let Z be a nonsingular codimension 2 subvariety of X such that $Z \subset W_q$ for some q. Let $\pi_1 : X_1 \to X$ be the blowup of Z. Denote by $(W_1)_q$ the set $\{p \in X_1 \mid m_q\hat{\mathcal{O}}_{X_1,p} \text{ is not invertible}\}$.

Given any sequence of blowups $X_n \to X_{n-1} \to ... \to X_1 \to X$, we define $(W_i)_q$ for each X_i as above.

Definition 2.4. Let $q \in Y$. A sequence of blowups $X_k \to X_{k-1} \to ... \to X_1 \to X$ is called a *permissible sequence with respect to* q if for all i, each blowup $X_{i+1} \to X_i$ is centered at a nonsingular codimension 2 subvariety Z of X_i such that $Z \subset (W_i)_q$.

We will often write simply permissible sequence without mentioning q if there is no scope for confusion.

Lemma 2.5. *Let $f : X \to Y$ be a locally toroidal morphism. Let $\pi_1 : X_1 \to X$ be a permissible sequence with respect to a $q \in Y$.*

I *Suppose that $1 \le i \le m$ and $p \in (f \circ \pi_1)^{-1}(q) \cap {\pi_1}^{-1}(U_i)$ and $q \in E_i$. Then* **I.A** *and* **I.B** *as below hold.*

I.A. *There exist regular parameters $x_1, ..., x_n$ in $\hat{\mathcal{O}}_{X_1,p}$ and (u, v) in $\mathcal{O}_{Y,q}$ such that one of the following forms holds:*

$1 \le k \le n-1$: $u = 0$ is a local equation of E_i, $x_1...x_k = 0$ is a local equation of ${\pi_1}^{-1}(D_i)$ and

$$u = {x_1}^{a_1}...{x_k}^{a_k}, v = {x_1}^{b_1}...{x_k}^{b_k}x_{k+1}, \tag{2.4}$$

where $b_i \le a_i$.

$1 \le k \le n-1$: $u = 0$ is a local equation of E_i, $x_1...x_kx_{k+1} = 0$ is a local equation of ${\pi_1}^{-1}(D_i)$ and

$$u = {x_1}^{a_1}...{x_k}^{a_k}{x_{k+1}}^{a_{k+1}}, v = {x_1}^{b_1}...{x_k}^{b_k}{x_{k+1}}^{b_{k+1}}, \tag{2.5}$$

where $b_i \le a_i$ for $i = 1, ..., k$ and $b_{k+1} < a_{k+1}$.

$1 \le k \le n-1$: $u=0$ is a local equation of E_i, $x_1 ... x_k = 0$ is a local equation of ${\pi_1}^{-1}(D_i)$ and

$$u = {x_1}^{a_1} ... {x_k}^{a_k}, v = {x_1}^{b_1} ... {x_k}^{b_k}(x_{k+1} + \alpha), \tag{2.6}$$

where $b_i \le a_i$ for all i and $0 \ne \alpha \in K$.

$1 \le k \le n-1$: $uv = 0$ is a local equation for E_i, $x_1 ... x_k = 0$ is a local equation of ${\pi_1}^{-1}(D_i)$ and

$$u = ({x_1}^{a_1} ... {x_k}^{a_k})^m, v = ({x_1}^{a_1} ... {x_k}^{a_k})^t(\alpha + x_{k+1}), \tag{2.7}$$

where $a_1, ..., a_k, m, t > 0$ and $\alpha \in K - \{0\}$.

$2 \le k \le n$: $uv = 0$ is a local equation of E_i, $x_1 ... x_k = 0$ is a local equation of ${\pi_1}^{-1}(D_i)$ and

$$u = {x_1}^{a_1} ... {x_k}^{a_k}, v = {x_1}^{b_1} ... {x_k}^{b_k}, \tag{2.8}$$

where $a_1, ..., a_k, b_1, ..., b_k \ge 0$, $a_i + b_i > 0$ for all i and
rank $\begin{bmatrix} a_1 & . & . & a_k \\ b_1 & . & . & b_k \end{bmatrix} = 2$.

I.B. *Suppose that $p_1 \in (W_1)_q$. There exist regular parameters $x_1, ..., x_n$ in $\hat{\mathcal{O}}_{X_1,p}$ and (u, v) in $\mathcal{O}_{Y,q}$ such that one of the following forms holds:*

$1 \le k \le n-1$: $u = 0$ is a local equation of E_i, $x_1 ... x_k = 0$ is a local equation of ${\pi_1}^{-1}(D_i)$ and

$$u = {x_1}^{a_1} ... {x_k}^{a_k}, v = {x_1}^{b_1} ... {x_k}^{b_k} x_{k+1}, \tag{2.9}$$

where $b_i \le a_i$ and $b_i < a_i$ for some i. Moreover, the local equations of $(W_1)_q$ are $x_i = x_{k+1} = 0$ where $b_i < a_i$.

$2 \le k \le n$: $uv = 0$ is a local equation of E_i, $x_1 ... x_k = 0$ is a local equation of ${\pi_1}^{-1}(D_i)$ and

$$u = {x_1}^{a_1} ... {x_k}^{a_k}, v = {x_1}^{b_1} ... {x_k}^{b_k}, \tag{2.10}$$

where $a_1, ..., a_k, b_1, ..., b_k \ge 0$, $a_i + b_i > 0$ for all i, u does not divide v, v does not divide u, and rank $\begin{bmatrix} a_1 & . & . & a_k \\ b_1 & . & . & b_k \end{bmatrix} = 2$. Moreover, the local equations of $(W_1)_q$ are $x_i = x_j = 0$ where $(a_i - b_i)(b_j - a_j) > 0$.

II *Suppose that $1 \le i \le m$ and $p \in (f \circ \pi_1)^{-1}(q) \cap {\pi_1}^{-1}(U_i)$ and $q \notin E_i$. Then* **II.A** *and* **II.B** *as below hold.*

II.A *There exist regular parameters $x_1, ..., x_n$ in $\hat{\mathcal{O}}_{X_1,p}$ and (u, v) in $\mathcal{O}_{Y,q}$ such that one of the following forms holds:*

$$u = x_1, v = x_2 \tag{2.11}$$

$$u = x_1, v = x_1(x_2 + \alpha) \text{ for some } \alpha \in K. \tag{2.12}$$

$$u = x_1 x_2, v = x_2. \tag{2.13}$$

II.B *Suppose that* $p_1 \in (W_1)_q$. *There exist regular parameters* $x_1, ..., x_n$ *in* $\hat{\mathcal{O}}_{X_1,p}$ *and* (u, v) *in* $\mathcal{O}_{Y,q}$ *such that the following form holds:*

$$u = x_1, v = x_2. \tag{2.14}$$

The local equations of $(W_1)_q$ *are* $x_1 = x_2 = 0$.

III $(W_1)_q$ *is a union of nonsingular codimension 2 subvarieties of* X_1.

Proof.

I We prove this part by induction on the number of blowups in the sequence $\pi_1 : X_1 \to X$. In X the conclusions hold because of Lemma 2.3 and f is locally toroidal. Suppose that the conclusions of the lemma hold after any sequence of l permissible blowups where $l \geq 0$.

Let $\pi_1 : X_1 \to X$ be a permissible sequence (with respect to q) of l blowups. Let $\pi_2 : X_2 \to X_1$ be the blowup of a nonsingular codimension 2 subvariety Z of X_1 such that $Z \subset (W_1)_q$.

Let $p \in {\pi_2}^{-1}({\pi_1}^{-1}(U_i)) \cap (f \circ \pi_1 \circ \pi_2)^{-1}(q)$ for some $1 \leq i \leq m$.

If $p_1 = \pi_2(p) \notin Z$ then π_2 is an isomorphism at p and we have nothing to prove. Suppose then that $p_1 \in {\pi_1}^{-1}(U_i) \cap Z \subset {\pi_1}^{-1}(U_i) \cap (W_1)_q$.

Then by induction hypothesis (**I.B**) p_1 has the form (2.9) or (2.10). Suppose first that it has the form (2.9).

Then the local equations of Z at p_1 are $x_i = x_{k+1} = 0$ for some $1 \leq i \leq k$. Note that $b_i < a_i$.

As in the proof of Lemma 2.3, there exist regular parameters $y_1, ..., y_k, x_{k+1}, y_{k+2}, ..., y_n$ in $\mathcal{O}_{X_1,p_1}$ and unit series $\delta_i \in \hat{\mathcal{O}}_{X_1,p_1}$ such that $y_i = \delta_i x_i$ for $1 \leq i \leq k$.

Then $\mathcal{O}_{X_2,p}$ has one of the following two forms:

(a) $\mathcal{O}_{X_2,p} = \mathcal{O}_{X_1,p_1}[\frac{x_{k+1}}{y_i}]_{(y_i, \frac{x_{k+1}}{y_i} - \alpha)}$ for some $\alpha \in K$, or

(b) $\mathcal{O}_{X_2,p} = \mathcal{O}_{X_1,p_1}[\frac{y_i}{x_{k+1}}]_{(x_{k+1}, \frac{y_i}{x_{k+1}})}$

In case(a), set $\bar{y}_{k+1} = \frac{x_{k+1}}{y_i} - \alpha$. Then $y_1, ..., y_k, \bar{y}_{k+1}, y_{k+2}, ..., y_n$ are regular parameters in $\mathcal{O}_{X_2,p}$ and so $\hat{\mathcal{O}}_{X_2,p} = k[[y_1, ..., y_k, \bar{y}_{k+1}, y_{k+2}, ..., y_n]]$.

Let $c \neq 0$ be the constant term of the unit series δ_i.

Then evaluating δ_i in the local ring $\mathcal{O}_{X_2,p}$ we get,

$$\begin{aligned} \delta_i(y_1, ..., y_k, x_{k+1}, y_{k+2}, ..., y_n) &= \delta_i(y_1, ..., y_k, y_i(\bar{y}_{k+1} + \alpha), y_{k+1}, ..., y_n) \\ &= c + \Delta_1 y_1 + ... + \Delta_k y_k + \Delta_{k+2} y_{k+2} + ... + \Delta_n y_n \end{aligned}$$

for some $\Delta_i \in \mathcal{O}_{X_2,p}$.

Set $\bar{\alpha} = c\alpha$. Note that $\frac{x_{k+1}}{x_i} - \bar{\alpha} = \delta_i \frac{x_{k+1}}{y_k} - c\alpha = \delta_i(\bar{y}_{k+1} + \alpha) - c\alpha = \delta_i \bar{y}_{k+1} + (\delta_i - c)\alpha$.

Since $y_1, ..., y_k, \bar{y}_{k+1}, y_{k+2}, ..., y_n$ are regular parameters in $\hat{\mathcal{O}}_{X_2,p}$ the above calculations imply that $x_1, ..., x_k, \frac{x_{k+1}}{x_i} - \bar{\alpha}, y_{k+2}, ..., y_n$ are regular parameters in $\hat{\mathcal{O}}_{X_2,p}$.

Set $\bar{x}_{k+1} = \frac{x_{k+1}}{x_k} - \bar{\alpha}$.

We get $u = {x_1}^{a_1} ... {x_k}^{a_k}$, $v = {x_1}^{b_1} ... {\bar{x}_i}^{b_i+1} ... {x_k}^{b_k}(\bar{x}_{k+1} + \alpha)$.

This is the form (2.6) if $\alpha \neq 0$ and form (2.4) if $\alpha = 0$.

In case (b), set $\bar{y}_{k+1} = \frac{y_i}{x_{k+1}}$. Then $y_1, ..., y_k, \bar{y}_{k+1}, y_{k+2}, ..., y_n$ are regular parameters in $\mathcal{O}_{X_2,p}$ and so $\hat{\mathcal{O}}_{X_2,p} = k[[y_1, ..., y_k, \bar{y}_{k+1}, y_{k+2}, ..., y_n]]$.

Then $x_1, ..., x_k, \frac{x_i}{x_{k+1}}, y_{k+2}, ..., y_n$ are regular parameters in $\hat{\mathcal{O}}_{X_2,p}$. Set $\bar{x}_i = \frac{x_i}{x_{k+1}}$.

$u = {x_1}^{a_1} ... {\bar{x}_i}^{a_i} ... {x_k}^{a_k} {x_{k+1}}^{a_i},\ v = {x_1}^{b_1} ... {\bar{x}_i}^{b_i+1} ... {x_k}^{b_k} x_{k+1}$.

This is the form (2.5).

By the above analysis, when $p_1 = \pi_2(p)$ has form (2.9), if $p \in (W_2)_q$, then it also has to be of the form (2.9).

Suppose now that p_1 has the form (2.10). Then the local equations of Z at p_1 are $x_i = x_j = 0$ for some $1 \leq i, j \leq k$.

Then as in the above analysis there exist regular parameters $y_1, ..., ..., y_n$ in $\mathcal{O}_{X_1,p_1}$ and unit series $\delta_i \in \hat{\mathcal{O}}_{X_1,p_1}$ such that $y_i = \delta_i x_i$ for $1 \leq i \leq k$.

Then $\mathcal{O}_{X_2,p}$ has one of the following two forms:

(a) $\mathcal{O}_{X_2,p} = \mathcal{O}_{X_1,p_1}[\frac{y_i}{y_j}]_{(y_j, \frac{y_i}{y_j} - \alpha)}$ for some $\alpha \in K$, or

(b) $\mathcal{O}_{X_2,p} = \mathcal{O}_{X_1,p_1}[\frac{y_j}{y_i}]_{(y_i, \frac{y_j}{y_j})}$

Arguing as above in case (a) we obtain regular parameters $x_1, ..., \bar{x}_i, ..., x_n$ in $\hat{\mathcal{O}}_{X_2,p}$ so that

$$u = {x_1}^{a_1} ... (\bar{x}_i + \alpha)^{a_i} ... {x_j}^{a_i+a_j} ... {x_k}^{a_k}, v = {x_1}^{b_1} ... (\bar{x}_i + \alpha)^{b_i} ... {x_j}^{b_i+b_j} ... {x_k}^{b_k}.$$

This is the form (2.8) if $\alpha = 0$.

If $\alpha \neq 0$, we obtain either the form (2.8) or the form (2.7) according as rank of $\begin{bmatrix} a_1 & . & . & a_i + a_j & . & . & a_{j-1} & a_{j+1} & . & . & a_k \\ b_1 & . & . & b_i + b_j & . & . & b_{j-1} & b_{j+1} & . & . & b_k \end{bmatrix}$ is $= 2$ or < 2.

Again arguing as above in case (b) we obtain regular parameters $x_1, ..., \bar{x}_j, ..., x_n$ in $\hat{\mathcal{O}}_{X_2,p}$ so that

$$u = {x_1}^{a_1} ... {x_i}^{a_i+a_j} ... {\bar{x}_j}^{a_j} ... {x_k}^{a_k}, v = {x_1}^{b_1} ... {x_i}^{b_i+b_j} ... {\bar{x}_j}^{b_j} ... {x_k}^{b_k}.$$

This is the form (2.8).

By the above analysis, when $p_1 = \pi_2(p)$ has the form (2.10), if $p \in (W_2)_q$, then it also has to be of the form (2.10).

This completes the proof of **I.A** for X_2. Now **I.B** is clear as the forms (2.9) and (2.10) are just the forms (2.4) and (2.8) from **I.A**.

II We prove this part by induction on the number of blowups in the sequence $\pi_1 : X_1 \to X$.

Since $q \notin E_i$ and f is locally toroidal, f is smooth at any point $p_1 \in f^{-1}(q)$. This means that the regular parameters at q form a part of a regular sequence at p. So we have regular parameters $x_1, ..., x_n$ in $\hat{\mathcal{O}}_{X,p_1}$ and u, v in $\mathcal{O}_{Y,q}$ such that $u = x_1, v = x_2$. This is the form (2.11). Thus the conclusions hold in X. Suppose that the conclusions of the lemma hold after any sequence of l permissible blowups where $l \geq 0$.

Let $\pi_1 : X_1 \to X$ be a permissible sequence (with respect to q) of l blowups. Let $\pi_2 : X_2 \to X_1$ be the blowup of a nonsingular codimension 2 subvariety Z of X_1 such that $Z \subset (W_1)_q$.

Let $p \in {\pi_2}^{-1}({\pi_1}^{-1}(U_i)) \cap (f \circ \pi_1 \circ \pi_2)^{-1}(q)$ for some $1 \leq i \leq m$.

If $p_1 = \pi_2(p) \notin Z$ then π_2 is an isomorphism at p and we have nothing to prove. Suppose then that $p_1 \in {\pi_1}^{-1}(U_i) \cap Z \subset {\pi_1}^{-1}(U_i) \cap (W_1)_q$.

Then by induction hypothesis (**II.B**) p_1 has the form (2.14). Then the local equations of Z at p_1 are $x_1 = x_2 = 0$.

There exist regular parameters $\bar{x}_1, \bar{x}_2$ in $\hat{\mathcal{O}}_{X_2,p}$ such that one of the following forms holds:

$x_1 = \bar{x}_1, x_2 = \bar{x}_1(\bar{x}_2 + \alpha)$ for some $\alpha \in K$ or $x_1 = \bar{x}_1\bar{x}_2, x_2 = \bar{x}_2$. These two cases give the forms (2.12) and (2.13).

Now **II.B** is clear as the form (2.14) is just the form (2.11) from **II.A**.

III Since $\{{\pi_1}^{-1}(U_i)\}$ for $1 \leq i \leq m$ is an open cover of X_1 and ${\pi_1}^{-1}(U_i) \cap (W_1)_q$ is a union of nonsingular codimension 2 subvarieties of X_1 for all i by **I** and **II**, $(W_1)_q$ is a union of nonsingular codimension 2 subvarieties of X_1. $\square$

Chapter 3

Principalization

Let $f : X \longrightarrow Y$ be a locally toroidal morphism from a nonsingular n-fold X to a nonsingular surface Y with respect to open coverings $\{U_1, ..., U_m\}$ and $\{V_1, ..., V_m\}$ of X and Y respectively and SNC divisors D_i and E_i in U_i and V_i respectively.

In this section we fix an i between 1 and m and a $q \in Y$.

Let $\pi_1 : X_1 \to X$ be a permissible sequence with respect to q. Our aim is to construct a permissible sequence $\pi_2 : X_2 \to X_1$ such that $\pi_2 \circ \pi_1 : X_2 \to X$ is a permissible sequence and ${\pi_2}^{-1}({\pi_1}^{-1}(U_i)) \cap (W_2)_q$ is empty.

First suppose that $q \notin E_i$. If $p \in {\pi_1}^{-1}(U_i)$, then by Lemma 2.5 one of the forms (2.11), (2.12) or (2.13) holds at p.

Theorem 3.1. *Let $\pi_1 : X_1 \to X$ be a permissible sequence with respect to $q \in Y$. Suppose that $q \notin E_i$. Then there exists a permissible sequence $\pi_2 : X_2 \to X_1$ with respect to q such that ${\pi_2}^{-1}({\pi_1}^{-1}(U_i)) \cap (W_2)_q$ is empty.*

Proof. If ${\pi_1}^{-1}(U_i) \cap (W_2)_q$ is empty, then there is nothing to prove. So suppose that ${\pi_1}^{-1}(U_i) \cap (W_2)_q \neq \emptyset$. By Lemma 2.3, it is a union of codimension 2 subvarieties of ${\pi_1}^{-1}(U_i)$.

Let $Z \subset {\pi_1}^{-1}(U_i) \cap (W_1)_q$ be a subvariety of ${\pi_1}^{-1}(U_i)$ of codimension 2.

Let $\pi_2 : X_2 \rightarrow X_1$ be the blowup of the Zariski closure $\bar{Z}$ of Z in X_1. Let $Z_1 \subset {\pi_2}^{-1}(Z)$ be a codimension 2 subvariety of ${\pi_2}^{-1}({\pi_1}^{-1}(U_i))$ such that $Z_1 \subset {\pi_2}^{-1}({\pi_1}^{-1}(U_i)) \cap (W_2)_q$.

By the proof of Lemma 2.5 it follows that $Z_1 \cap (W_2)_q = \emptyset$.

The theorem now follows by induction on the number of codimension 2 subvarieties Z in ${\pi_1}^{-1}(U_i) \cap (W_1)_q$. $\square$

Now we suppose that $q \in E_i$.

Remark 3.2. *Suppose that $\pi_1 : X_1 \rightarrow X$ is a permissible sequence with respect to some $q \in E_i$. Let $\pi_2 : X_2 \rightarrow X_1$ be a permissible blowup with respect to q. Let $p_1 \in {\pi_2}^{-1}({\pi_1}^{-1}(U_i)) \cap (W_2)_q$. Then clearly $p = \pi_2(p_1) \in {\pi_1}^{-1}(U_i) \cap (W_1)_q$.*

Suppose that p_1 is a 1 point. Then the analysis in the proof of Lemma 2.5 shows that p also is a 1 point.

Suppose that p_1 is a 2 point where the form (2.10) holds. Then the analysis in the proof of Lemma 2.5 shows that p is a 2 or 3 point where the from (2.10) holds.

Suppose that $\pi_1 : X_1 \rightarrow X$ is a permissible sequence with respect to $q \in E_i$.

Let $p \in {\pi_1}^{-1}(U_i) \cap (W_1)_q$ be a 1 point. By Lemma 2.5, there exist regular parameters $x_1, ..., x_n$ in $\hat{\mathcal{O}}_{X_1,p}$ and u, v in $\mathcal{O}_{Y,q}$ such that $u = {x_1}^a,\ v = {x_1}^b x_2$ where $a > b$.

Define $\Omega_i(p) = a - b > 0$.

Let $Z \subset {\pi_1}^{-1}(U_i) \cap (W_1)_q$ be a codimension 2 subvariety of ${\pi_1}^{-1}(U_i)$.

Define $\Omega_i(Z) = \Omega_i(p)$ if there exists a 1 point $p \in Z$. This is well defined because $\Omega_i(p) = \Omega_i(p')$ for any two points $p, p' \in Z$.

If Z contains no 1 points, we define $\Omega_i(Z) = 0$.

Finally define

$$\Omega_i(f \circ \pi_1) = max\{\Omega_i(Z) | Z \subset {\pi_1}^{-1}(U_i) \cap (W_1)_q \text{ is an irreducible subvariety of } {\pi_1}^{-1}(U_i) \text{ of codimension } 2\}$$

Example: Let $p \in {\pi_1}^{-1}(U_i) \cap (W_1)_q$ be a 1 point.

Suppose that f has the forms $u = {x_1}^5,\ v = {x_1}^2 x_2$ where $x_1, ..., x_n$ are regular parameters in $\hat{\mathcal{O}}_{X_1,p}$ and u, v are regular parameters in $\mathcal{O}_{Y,q}$.

Then $\Omega_i(p) = 5 - 2 = 3$.

Note that, by Lemma 2.5, in a neighborhood of p the local equations of $(W_1)_q$ are $x_1 = x_2 = 0$. This is a codimension 2 subvariety of ${\pi_1}^{-1}(U_i) \cap (W_1)_q$, say Z. Then we also have $\Omega_i(Z) = 3$.

On the other hand, let $p' \in {\pi_1}^{-1}(U_i) \cap (W_1)_q$ be a 2 point.

Suppose that f has the forms $u' = {x_1}' {x_2}'^4,\ v' = {x_1}'^2 {x_2}'$ where ${x_1}', ..., {x_n}'$ are regular parameters in $\hat{\mathcal{O}}_{X_1,p'}$ and u', v' are regular parameters in $\mathcal{O}_{Y,q}$.

Then in a neighborhood of p', the local equations of $(W_1)_q$ are ${x_1}' = {x_2}' = 0$. This is again a codimension 2 subvariety of ${\pi_1}^{-1}(U_i) \cap (W_1)_q$, say Z'. Now we have $\Omega_i(Z') = 0$.

Theorem 3.3. *Let $\pi_1 : X_1 \to X$ be a permissible sequence with respect to $q \in E_i$. There exists a permissible sequence $\pi_2 : X_2 \to X_1$ with respect to q such that $\Omega_i(f \circ \pi_1 \circ \pi_2) = 0$.*

Proof. Suppose that $\Omega_i(f \circ \pi_1) > 0$. Let $Z \subset {\pi_1}^{-1}(U_i) \cap (W_1)_q$ be a subvariety of

${\pi_1}^{-1}(U_i)$ of codimension 2 such that $\Omega_i(f\circ\pi_1)=\Omega_i(Z)$.

Let $\pi_2 : X_2 \rightarrow X_1$ be the blowup of the Zariski closure $\bar{Z}$ of Z in X_1. Let $Z_1 \subset {\pi_2}^{-1}(Z)$ be a codimension 2 subvariety of ${\pi_2}^{-1}({\pi_1}^{-1}(U_i))$ such that $Z_1 \subset {\pi_2}^{-1}({\pi_1}^{-1}(U_i)) \cap (W_2)_q$. We claim that $\Omega_i(Z_1) < \Omega_i(Z)$.

If there are no 1 points of Z_1 then we have nothing to prove. Otherwise, let $p_1 \in Z_1$ be a 1 point. Then $\pi_1(p_1) = p$ is a 1 point of Z by Remark 3.2.

There are regular parameters $x_1, ..., x_n$ in $\hat{\mathcal{O}}_{X_1,p}$ and u, v in $\mathcal{O}_{Y,q}$ such that $u = {x_1}^a, v = {x_1}^b x_2$. There exist regular parameters $x_1, \bar{x}_2, ..., x_n$ in $\hat{\mathcal{O}}_{X_2,p_1}$ such that $x_2 = x_1(x_2+\alpha)$.

$u = {x_1}^a, v = {x_1}^{b+1}(x_2+\alpha)$. Since $p_1 \in (W_2)_q$, $\alpha = 0$.

$\Omega_i(Z_1) = \Omega_i(p_1) = a-b-1 < a-b = \Omega_i(Z)$.

The theorem now follows by induction on the number of codimension 2 subvarieties Z in ${\pi_1}^{-1}(U_i) \cap (W_1)_q$ such that $\Omega_i(f\circ\pi_1) = \Omega_i(Z)$ and induction on $\Omega_i(f\circ\pi_1)$. $\square$

Let $\pi_1 : X_1 \rightarrow X$ be a permissible sequence with respect to $q \in E_i$.

Let $Z \subset {\pi_1}^{-1}(U_i)) \cap (W_1)_q$ be a codimension 2 subvariety of ${\pi_1}^{-1}(U_i)$. Let $p \in Z$ be a 2 point where the form (2.10) holds.

There exist regular parameters $x_1, ..., x_n$ in $\hat{\mathcal{O}}_{X_1,p}$ and u, v in $\mathcal{O}_{Y,q}$ such that $u = {x_1}^{a_1}{x_2}^{a_2}$ and $v = {x_1}^{b_1}{x_2}^{b_2}$.

Define $\omega_i(p) = (a_1-b_1)(b_2-a_2)$. Then since $p \in (W_1)q$, $\omega_i(p) > 0$.

Now define $\omega_i(Z) = \omega_i(p)$ if $p \in Z$ is a 2 point where the form (2.10) holds. If there are no 2 points of the form (2.10) in Z define $\omega_i(Z) = 0$. Then $\omega_i(Z)$ is well-defined.

Finally define

$$\omega_i(f \circ \pi_1) = max\{\omega_i(Z) | Z \subset {\pi_1}^{-1}(U_i) \cap (W_1)_q \text{ is an irreducible}$$
$$\text{subvariety of } {\pi_1}^{-1}(U_i) \text{ of codimension } 2\}$$

Theorem 3.4. *Let $\pi_1 : X_1 \to X$ be a permissible sequence with respect to $q \in E_i$. Suppose that $\Omega_i(f \circ \pi_1) = 0$. There exists a permissible sequence $\pi_2 : X_2 \to X_1$ with respect to q such that $\Omega_i(f \circ \pi_1 \circ \pi_2) = 0$ and $\omega_i(f \circ \pi_1 \circ \pi_2) = 0$.*

Proof. Since $\Omega_i(f \circ \pi_1) = 0$, there are no 1 points in ${\pi_1}^{-1}(U_i) \cap (W_1)_q$. Let $X_2 \to X_1$ be any permissible blowup. Then by Remark 3.2 it follows that ${\pi_2}^{-1}({\pi_1}^{-1}(U_i)) \cap (W_2)_q$ has no 1 points. Hence $\Omega_i(f \circ \pi_1 \circ \pi_2) = 0$.

Suppose that $\omega_i(f \circ \pi_1) > 0$. Let $Z \subset {\pi_1}^{-1}(U_i) \cap (W_1)_q$ be a codimension 2 irreducible subvariety of ${\pi_1}^{-1}(U_i)$ such that $\omega_i(f \circ \pi_1) = \omega_i(Z)$.

Let $\pi_2 : X_2 \to X_1$ be the blowup of the Zariski closure $\bar{Z}$ of Z in X_1. Let $Z_1 \subset {\pi_2}^{-1}(Z)$ be a codimension 2 subvariety of ${\pi_2}^{-1}({\pi_1}^{-1}(U_i))$ such that $Z_1 \subset {\pi_2}^{-1}({\pi_1}^{-1}(U_i)) \cap (W_2)_q$. We prove that $\omega_i(Z_1) < \omega_i(Z) = \omega_i(f \circ \pi_1)$.

If there are no 2 points of the form (2.10) in Z_1 then $\omega_i(Z_1) = 0$ and we have nothing to prove. Otherwise let $p_1 \in Z_1$ be a 2 point of the form (2.10).

By Remark 3.2, $p = \pi_2(p_1) \in Z$ is a 2 or 3 point of form (2.10).

Suppose that $p \in Z$ is a 2 point. There exist regular parameters $x_1, ..., x_n$ in $\hat{\mathcal{O}}_{X_1,p}$ and u, v in $\mathcal{O}_{Y,q}$ such that $u = {x_1}^{a_1}{x_2}^{a_2}$ and $v = {x_1}^{b_1}{x_2}^{b_2}$. Also the local equations of Z are $x_1 = x_2 = 0$.

Then there exist regular parameters $x_1, \bar{x_2}, x_3..., x_n$ in $\hat{\mathcal{O}}_{X_2,p_1}$ such that $x_2 =$

$x_1\bar{x_2}$ and $u = {x_1}^{a_1+a_2}\bar{x_2}^{a_2}$ and $v = {x_1}^{b_1+b_2}\bar{x_2}^{b_2}$.

$$
\begin{aligned}
\omega_i(Z_1) = \omega_i(p_1) &= (a_1 + a_2 - b_1 - b_2)(b_2 - a_2) \\
&= (a_1 - b_1)(b_2 - a_2) + (a_2 - b_2)(b_2 - a_2) \\
&< (a_1 - b_1)(b_2 - a_2) = \omega_i(p) = \omega_i(Z) = \omega_i(f \circ \pi_1).
\end{aligned}
$$

Suppose that $p \in Z$ is a 3 point. There exist regular parameters $x_1, ..., x_n$ in $\hat{\mathcal{O}}_{X_1,p}$ and u, v in $\mathcal{O}_{Y,q}$ such that $u = {x_1}^{a_1}{x_2}^{a_2}{x_3}^{a_3}$ and $v = {x_1}^{b_1}{x_2}^{b_2}{x_3}^{b_3}$. After permuting x_1, x_2, x_3 if necessary, we can suppose that the local equations of Z are $x_2 = x_3 = 0$.

Then there exist regular parameters $x_1, x_2, \bar{x_3}..., x_n$ in $\hat{\mathcal{O}}_{X_2,p_1}$ such that $x_3 = x_2(\bar{x_3} + \alpha)$ and $u = {x_1}^{a_1}{x_2}^{a_2+a_3}(\bar{x_3} + \alpha)^{a_3}$ and $v = {x_1}^{b_1}{x_2}^{b_2+b_3}(\bar{x_3} + \alpha)^{b_3}$.

Since p_1 is a 2 point, we have $\alpha \neq 0$ and $a_1(b_2+b_3)-b_1(a_2+a_3) \neq 0$. After an appropriate change of variables x_1, x_2 we obtain regular parameters $\bar{x_1}, \bar{x_2}, \tilde{x_3}, x_4, ..., x_n$ in $\hat{\mathcal{O}}_{X_2,p_1}$.

$u = \bar{x_1}^{a_1}\bar{x_2}^{a_2+a_3}$ and $v = \bar{x_1}^{b_1}\bar{x_2}^{b_2+b_3}$.

Since the local equations of $Z \subset {\pi_1}^{-1}(U_i) \cap (W_1)_q$ are $x_2 = x_3 = 0$, $b_2 - a_2$ and $b_3 - a_3$ have different signs. So $a_1 - b_1$ has the same sign as exactly one of $b_2 - a_2$ or $b_3 - a_3$. Without loss of generality suppose that $(a_1 - b_1)(b_2 - a_2) > 0$ and $(a_1 - b_1)(b_3 - a_3) < 0$.

Let Z' be the codimension 2 variety whose local equations are $x_1 = x_2 = 0$ defined in an appropriately small neighborhood in ${\pi_1}^{-1}(U_i)$. Then the closure $\bar{Z}'$ of Z' in ${\pi_1}^{-1}(U_i)$ is an irreducible codimension 2 subvariety contained in ${\pi_1}^{-1}(U_i)\cap$

$(W_1)_q$.

$$\begin{aligned}\omega_i(Z_1) = \omega_i(p_1) &= (a_1 - b_1)(b_2 + b_3 - a_2 - a_3) \\ &= (a_1 - b_1)(b_2 - a_2) + (a_1 - b_1)(b_3 - a_3) \\ &< (a_1 - b_1)(b_2 - a_2) = \omega_i(\bar{Z}') \leq \omega_i(f \circ \pi_1).\end{aligned}$$

The theorem now follows by induction on the number of codimension 2 subvarieties Z in ${\pi_1}^{-1}(U_i) \cap (W_1)_q$ such that $\omega_i(f \circ \pi_1) = \omega_i(Z)$ and induction on $\omega_i(f \circ \pi_1)$. $\square$

Remark 3.5. *Let $\pi_1 : X_1 \to X$ be a permissible sequence with respect to q. Let i be such that $1 \leq i \leq m$.*

If $q \notin E_i$ then by Theorem 3.1 there exists a permissible sequence $\pi_2 : X_2 \to X_1$ with respect to q such that $\sigma_i(f \circ \pi_1 \circ \pi_2) = 0$.

If $q \in E_i$ then it follows from Theorems 3.3 and 3.4 that there exists a permissible sequence with respect to q $\pi_2 : X_2 \to X_1$ such that $\Omega_i(f \circ \pi_1 \circ \pi_2) = 0$ and $\omega_i(f \circ \pi_1 \circ \pi_2) = 0$.

Theorem 3.6. *Let $f : X \longrightarrow Y$ be a locally toroidal morphism between a nonsingular n-fold X and a nonsingular surface Y. Let $q \in Y$.*

Then there exists a permissible sequence $\pi_1 : X_1 \to X$ with respect to q such that $(W_1)_q$ is empty.

Proof. First we apply the Remark 3.5 to X and $i = 1$.

Suppose that $q \notin E_1$. Then by Remark 3.5, there exists a permissible sequence $\pi_1 : X_1 \to X$ with respect to q such that $\sigma_1(f \circ \pi_1) = 0$. Hence ${\pi_1}^{-1}(U_1) \cap (W_1)_q = \emptyset$.

Now suppose that $q \in E_1$. It follows from Remark 3.5 that there exists a permissible sequence $\pi_1 : X_1 \to X$ with respect to q such that $\Omega_1(f \circ \pi_1) = 0$

and $\omega_1(f \circ \pi_1) = 0$. So there are no 1 points or 2 points of the form (2.10) in ${\pi_1}^{-1}(U_1) \cap (W_1)_q$. But if $Z \subset {\pi_1}^{-1}(U_1) \cap (W_1)_q$ is any codimension 2 irreducible subvariety of ${\pi_1}^{-1}(U_i)$, then a generic point of Z must either be a 1 point or a 2 point of the form (2.10). It follows then that ${\pi_1}^{-1}(U_1) \cap (W_1)_q$ is empty.

Now we apply Remark 3.5 to the permissible sequence $\pi_1 : X_1 \to X$ and $i = 2$.

If $q \notin E_2$ there exists a permissible sequence $\pi_2 : X_2 \to X_1$ such that $\sigma_2(f \circ \pi_1 \circ \pi_2) = 0$. Hence ${\pi_2}^{-1}({\pi_1}^{-1}(U_2)) \cap (W_2)_q = \emptyset$.

If $q \in E_2$ then as above there exists a permissible sequence $\pi_2 : X_2 \to X_1$ such that ${\pi_2}^{-1}({\pi_1}^{-1}(U_2)) \cap (W_2)_q$ is empty.

Notice that we also have ${\pi_2}^{-1}({\pi_1}^{-1}(U_1)) \cap (W_2)_q = \emptyset$.

Repeating the argument for $i = 3, 4, ..., m$ we obtain the desired permissible sequence. $\square$

Chapter 4

Toroidalization

Theorem 4.1. *Let $f : X \longrightarrow Y$ be a locally toroidal morphism from a nonsingular n-fold X to a nonsingular surface Y with respect to open coverings $\{U_1, ..., U_m\}$ and $\{V_1, ..., V_m\}$ of X and Y respectively and SNC divisors D_i and E_i in U_i and V_i respectively. Let $\pi : Y_1 \to Y$ be the blowup of a point $q \in Y$.*

Then there exists a permissible sequence $\pi_1 : X_1 \to X$ such that there is a locally toroidal morphism $f_1 : X_1 \to Y_1$ such that $\pi \circ f_1 = f \circ \pi_1$.

Proof. By Theorem 3.6 there is a permissible sequence $\pi_1 : X_1 \to X$ such that there exists a morphism $f_1 : X_1 \to Y_1$ and $\pi \circ f_1 = f \circ \pi_1$.

Let $p \in X_1$. Suppose that $p \in {\pi_1}^{-1}(U_i)$ for some i such that $1 \leq i \leq m$. If $\pi_1(p) \notin f^{-1}(q)$ then we have nothing to prove. So we assume that $\pi_1(p) \in f^{-1}(q)$.

Suppose first that $q \notin E_i$. Then by Lemma 2.5 one of the forms (2.12) or (2.13) holds at p. So there exist regular parameters $x_1, ..., x_n$ in $\hat{\mathcal{O}}_{X_1,p}$ and u, v in $\mathcal{O}_{Y,q}$ such that

$$u = x_1,\ v = x_1(x_2 + \alpha) \text{ for some } \alpha \in K,\ \text{ or } u = x_1y_1, v = x_2.$$

Let $f_1(p) = q_1$. There exist regular parameters $u_1, v_1 \in \mathcal{O}_{Y_1,q_1}$ such that

$$u = u_1, v = u_1(v_1 + \alpha) \text{ or } u = u_1 v_1, v = v_1$$

according as the form (2.12) or the form (2.13) holds. In either case, we have $u_1 = x_1, v_1 = x_2$, and f_1 is smooth at p.

Now suppose that $q \in E_i$.

By Lemma 2.5 there exist regular parameters $x_1, ..., x_n$ in $\hat{\mathcal{O}}_{X_1,p}$ and u, v in $\mathcal{O}_{Y,q}$ such that one of the forms (2.4), (2.5), (2.6), (2.7), or (2.8) of Lemma 2.5 holds.

Suppose first that the form (2.4) holds. Then since $m_q \hat{\mathcal{O}}_{X_1,p}$ is invertible, there exist regular parameters $x_1, ..., x_n$ in $\hat{\mathcal{O}}_{X_1,p}$ and u, v in $\mathcal{O}_{Y,q}$ such that $u = {x_1}^{a_1} ... {x_k}^{a_k}$, $v = {x_1}^{a_1} ... {x_k}^{a_k} x_{k+1}$ for some $1 \le k \le n-1$.

Further $x_1 ... x_k = 0$ is a local equation of ${\pi_1}^{-1}(D_i)$ and $u = 0$ is a local equation for E_i.

Let $f_1(p) = q_1$. There exist regular parameters (u_1, v_1) in $\mathcal{O}_{Y_1,q_1}$ such that $u = u_1$ and $v = u_1 v_1$. Hence the local equation of $\pi^{-1}(E_i)$ at q_1 is $u_1 = 0$.

$$u_1 = {x_1}^{a_1} ... {x_k}^{a_k}, v_1 = x_{k+1}.$$

This is the form (2.1).

Suppose now that the form (2.5) holds at p for $f \circ \pi_1$. There exist regular parameters $x_1, ..., x_n$ in $\hat{\mathcal{O}}_{X_1,p}$ and u, v in $\mathcal{O}_{Y,q}$ and $1 \le k \le n-1$ such that $u = 0$ is a local equation of E_i, $x_1 ... x_k x_{k+1} = 0$ is a local equation of ${\pi_1}^{-1}(D_i)$ and

$$u = {x_1}^{a_1} ... {x_k}^{a_k} {x_{k+1}}^{a_{k+1}}, v = {x_1}^{b_1} ... {x_k}^{b_k} {x_{k+1}}^{b_{k+1}},$$

where $b_i \leq a_i$ for $i = 1, ..., k$ and $b_{k+1} < a_{k+1}$.

Let $f_1(p) = q_1$. There exist regular parameters u_1, v_1 in $\mathcal{O}_{Y_1,q_1}$ such that $u = u_1 v_1$ and $v = v_1$. Hence the local equation of $\pi^{-1}(E_i)$ at q_1 is $u_1 v_1 = 0$.

$$u_1 = {x_1}^{a_1 - b_1} ... {x_k}^{a_k - b_k} {x_{k+1}}^{a_{k+1} - b_{k+1}}, v_1 = {x_1}^{b_1} ... {x_k}^{b_k} {x_{k+1}}^{b_{k+1}}.$$

This is the form (2.3). Note that the rank condition follows from the dominance of the map f_1.

Suppose now that the form (2.6) holds. There exist regular parameters $x_1, ..., x_n$ in $\hat{\mathcal{O}}_{X_1,p}$ and u, v in $\mathcal{O}_{Y,q}$ and $1 \leq k \leq n-1$ such that $u = 0$ is a local equation of E_i, $x_1 ... x_k = 0$ is a local equation of ${\pi_1}^{-1}(D_i)$ and

$$u = {x_1}^{a_1} ... {x_k}^{a_k}, v = {x_1}^{b_1} ... {x_k}^{b_k}(x_{k+1} + \alpha),$$

where $b_i \leq a_i$ for all i and $0 \neq \alpha \in K$.

Let $f_1(p) = q_1$. There exist regular parameters u_1, v_1 in $\mathcal{O}_{Y_1,q_1}$ such that $u = u_1 v_1$ and $v = v_1$. Hence the local equation of $\pi^{-1}(E_i)$ at q_1 is $u_1 v_1 = 0$.

$$u_1 = {x_1}^{a_1 - b_1} ... {x_k}^{a_k - b_k}(x_{k+1} + \alpha)^{-1}, v_1 = {x_1}^{b_1} ... {x_k}^{b_k}(x_{k+1} + \alpha).$$

If rank $\begin{bmatrix} a_1 - b_1 & . & . & a_k - b_k \\ b_1 & . & . & b_k \end{bmatrix} = 2$ then there exist regular parameters $\bar{x_1}, ..., \bar{x_n}$ in $\hat{\mathcal{O}}_{X_1,p}$ such that $u_1 = \bar{x_1}^{a_1 - b_1} ... \bar{x_k}^{a_k - b_k}, v_1 = \bar{x_1}^{b_1} ... \bar{x_k}^{b_k}$. This is the form (2.3).

If rank $\begin{bmatrix} a_1 - b_1 & . & . & a_k - b_k \\ b_1 & . & . & b_k \end{bmatrix} < 2$ then there exist regular parameters $\bar{x_1}, ..., \bar{x_n}$ in $\hat{\mathcal{O}}_{X_1,p}$ such that $u_1 = (\bar{x_1}^{a_1} ... \bar{x_k}^{a_k})^m$, $v = (\bar{x_1}^{a_1} ... \bar{x_k}^{a_k})^t (x_{k+1} + \beta)$, with $\beta \neq 0$. This is the form (2.2).

Suppose that the form (2.7) holds. There exist regular parameters $x_1, ..., x_n$ in $\hat{\mathcal{O}}_{X_1,p}$ and u, v in $\mathcal{O}_{Y,q}$ and $1 \leq k \leq n-1$ such that $uv = 0$ is a local equation for

E_i, $x_1 ... x_k = 0$ is a local equation of ${\pi_1}^{-1}(D_i)$ and

$$u = ({x_1}^{a_1} ... {x_k}^{a_k})^m,\ v = ({x_1}^{a_1} ... {x_k}^{a_k})^t(\alpha + x_{k+1}),$$

where $a_1, ..., a_k, m, t > 0$ and $\alpha \in K - \{0\}$.

Suppose that $m \leq t$. There exist regular parameters u_1, v_1 in $\mathcal{O}_{Y_1,q_1}$ such that $u = u_1$ and $v = u_1(v_1 + \beta)$ for some $\beta \in K$.

$$u_1 = ({x_1}^{a_1} ... {x_k}^{a_k})^m,\ v_1 = ({x_1}^{a_1} ... {x_k}^{a_k})^{t-m}(\alpha + x_{k+1}) - \beta.$$

If $m < t$ then $\beta = 0$. So $u_1 v_1 = 0$ is a local equation of $\pi^{-1}(E_i)$ and we have the form (2.2). If $m = t$ then $\alpha = \beta \neq 0$ and u_1 is a local equation of $\pi^{-1}(E_i)$. In this case we have the form (2.1).

Suppose that $m > t$. Then there exist regular parameters u_1, v_1 in $\mathcal{O}_{Y_1,q_1}$ such that $u = u_1 v_1$ and $v = v_1$.

$$u_1 = ({x_1}^{a_1} ... {x_k}^{a_k})^{m-t}(\alpha + x_{k+1})^{-1},\ v_1 = ({x_1}^{a_1} ... {x_k}^{a_k})^t(\alpha + x_{k+1}).$$

We obtain the form (2.2).

Finally suppose that the form (2.8) holds. There exist regular parameters $x_1, ..., x_n$ in $\hat{\mathcal{O}}_{X_1,p}$ and u, v in $\mathcal{O}_{Y,q}$ and $2 \leq k \leq n$ such that $uv = 0$ is a local equation of E_i and $x_1 ... x_k = 0$ is a local equation of ${\pi_1}^{-1}(D_i)$ and $u = {x_1}^{a_1} ... {x_k}^{a_k}, v = {x_1}^{b_1} ... {x_k}^{b_k}$, where rank $\begin{bmatrix} a_1 & . & . & a_k \\ b_1 & . & . & b_k \end{bmatrix} = 2$.

We have either $a_i \geq b_i$ for all i or $a_i \leq b_i$ for all i. Without loss of generality, suppose that $a_i \leq b_i$ for all i.

Let $f_1(p) = q_1$. There exist regular parameters u_1, v_1 in $\mathcal{O}_{Y_1,q_1}$ such that $u = u_1$

and $v = u_1 v_1$. Hence the local equation of $\pi^{-1}(E_i)$ at q_1 is $u_1 v_1 = 0$.

$$u_1 = {x_1}^{a_1} ... {x_k}^{a_k}, v_1 = {x_1}^{b_1 - a_1} ... {x_k}^{b_k - a_k}.$$

Further, rank $\begin{bmatrix} a_1 & . & . & a_k \\ b_1 - a_1 & . & . & b_k - a_k \end{bmatrix} = 2$. This is the form (2.1). $\square$

Now we are ready to prove our main theorem.

Theorem 4.2. *Suppose that $f : X \longrightarrow Y$ is a locally toroidal morphism between a variety X and a surface Y. Then there exists a commutative diagram of morphisms*

$$\begin{tikzcd} X_1 \arrow[r, "f_1"] \arrow[d, "\pi_1"] & Y_1 \arrow[d, "\pi"] \\ X \arrow[r, "f"] & Y \end{tikzcd}$$

where π, π_1 are blowups of nonsingular varieties such that there exist SNC divisors E, D on Y_1 and X_1 respectively such that $Sing(f_1) \subset D$, ${f_1}^{-1}(E) = D$ and f_1 is toroidal with respect to E and D.

Proof. Let $E' = \bar{E_1} + ... + \bar{E_m}$ where $\bar{E_i}$ is the Zariski closure of E_i in Y. There exists a finite sequence of blowups of points $\pi : Y_1 \to Y$ such that $\pi^{-1}(E')$ is a SNC divisor on Y_1.

By Theorem 4.1, there exists a sequence of blowups $\pi_1 : X_1 \to X$ such that there is a locally toroidal morphism $f_1 : X_1 \to Y_1$ with $f \circ \pi_1 = \pi \circ f_1$.

Let $E = \pi^{-1}(E')$ and $D = {f_1}^{-1}(E)$.

We now verify that E and D are SNC divisors on Y_1 and X_1 respectively and that $f_1 : X_1 \to Y_1$ is toroidal with respect to D and E.

Let $p \in X_1$ and let $q = f_1(p)$.

Suppose that $p \notin D$, so that $q \notin E$. There exists i such that $1 \leq i \leq m$ and $p \in {\pi_1}^{-1}(U_i)$. Then $q \notin E = \pi^{-1}(E') \Rightarrow q \notin \pi^{-1}(E_i)$. So $p \notin {f_1}^{-1}(\pi^{-1}(E_i)) = {\pi_1}^{-1}(D_i)$. Then f_1 is smooth at p because $f_1|_{{\pi_1}^{-1}(U_i)}$ is toroidal.

Thus $Sing(f_1) \subset D$.

Suppose now that $p \in D$. Let $p \in {\pi_1}^{-1}(U_i)$ for some i between 1 and m. If $q \notin \pi^{-1}(E_i)$ then f_1 is smooth at p and then $D = {f_1}^{-1}(E)$ is a SNC divisor at p. We assume then that $q \in \pi^{-1}(E_i)$.

Case 1 $q \in E$ is a 1 point.

q is necessarily a 1 point of $\pi^{-1}(E_i)$.

Then $\pi^{-1}(E_i)$ and E are equal in a neighborhood of q. Hence ${\pi_1}^{-1}(D_i)$ and D are equal in a neighborhood of p. Since ${\pi_1}^{-1}(D_i)$ is a SNC divisor in a neighborhood of p, D is a SNC divisor in a neighborhood of p.

Since $f_1|_{{\pi_1}^{-1}(U_i)}$ is toroidal there exist regular parameters u, v in $\mathcal{O}_{Y_1,q}$ and regular parameters $x_1, ..., x_n$ in $\hat{\mathcal{O}}_{X_1,p}$ such that the the form (2.1) holds at p with respect to E and D.

Case 2 $q \in E$ is a 2 point.

q is either a 1 point or a 2 point of $\pi^{-1}(E_i)$.

Case 2(a) q is a 1 point of $\pi^{-1}(E_i)$.

There exists regular parameters u, v in $\mathcal{O}_{Y_1,q}$ and regular parameters $x_1, ..., x_n$ in $\hat{\mathcal{O}}_{X_1,p}$ such that the form (2.1) holds at p. There exists $\tilde{v} \in \mathcal{O}_{Y_1,q}$ such that $u, \tilde{v}$ are regular parameters in $\mathcal{O}_{Y_1,q}$, $u\tilde{v} = 0$ is a local equation for E at q, $u = 0$ is a local equation of $\pi^{-1}(E_i)$ at q, and

$$\tilde{v} = \alpha u + \beta v + \text{ higher degree terms in } u \text{ and } v,$$

for some $\beta \in K$ with $\beta \neq 0$.

Since ${\pi_1}^{-1}(D_i)$ is a SNC divisor in a neighborhood of p, there exist regular parameters $\bar{x}_1, ..., \bar{x}_n$ in $\mathcal{O}_{X_1,p}$ such that $\bar{x}_1 ... \bar{x}_k = 0$ is a local equation of ${\pi_1}^{-1}(D_i)$ at p. Since $x_1 ... x_k = 0$ is also a local equation of ${\pi_1}^{-1}(D_i)$ at p, there exist units $\delta_1, ..., \delta_k \in \hat{\mathcal{O}}_{X_1,p}$ such that, after possibly permuting the x_j, $x_j = \delta_j \bar{x}_j$ for $1 \leq j \leq k$.

$$\begin{aligned}
\tilde{v} &= \alpha u + \beta v + \text{ higher degree terms in } u \text{ and } v \\
&= \alpha {x_1}^{a_1} ... {x_k}^{a_k} + \beta x_{k+1} + \text{ higher degree terms in } u \text{ and } v \\
&= \alpha {\delta_1}^{a_1} ... {\delta_k}^{a_k} \bar{x}_1^{a_1} ... \bar{x}_k^{a_k} + \beta x_{k+1} + \text{ higher degree terms in } u \text{ and } v
\end{aligned}$$

Let $\mathfrak{m}$ be the maximal ideal of $\mathcal{O}_{X_1,p}$ and let $\hat{\mathfrak{m}} = \mathfrak{m} \hat{\mathcal{O}}_{X_1,p}$ be the maximal ideal of $\hat{\mathcal{O}}_{X_1,p}$.

Since $\beta \neq 0$, $\bar{x_1}, ..., \bar{x_k}, \tilde{v}$ are linearly independent in $\hat{\mathfrak{m}}/\hat{\mathfrak{m}}^2 \cong \mathfrak{m}/\mathfrak{m}^2$, so that they extend to a system of regular parameters in $\mathcal{O}_{X_1,p}$.

Say $\bar{x_1}, ..., \bar{x_k}, \tilde{v}, \tilde{x}_{k+2}, ..., \tilde{x}_n$.

$u\tilde{v} = \bar{x_1} ... \bar{x_k} \tilde{v} = 0$ is a local equation of D at p, so D is a SNC divisor in a neighborhood of p, and $u, \tilde{v}$ give the form (2.3) with respect to the formal parameters $x_1, ..., x_k, \tilde{v}, \tilde{x}_{k+2}, ..., \tilde{x}_n$.

Case 2(b) q is a 2 point of $\pi^{-1}(E_i)$.

Then $\pi^{-1}(E_i)$ and E are equal in a neighborhood of q. Hence ${\pi_1}^{-1}(D_i)$ and D are equal in a neighborhood of p. Since ${\pi_1}^{-1}(D_i)$ is a SNC divisor in a neighborhood of p, D is a SNC divisor in a neighborhood of p.

Since $f_1|_{{\pi_1}^{-1}(U_i)}$ is toroidal there exist regular parameters u, v in $\mathcal{O}_{Y_1,q}$ and regular parameters $x_1, ..., x_n$ in $\hat{\mathcal{O}}_{X_1,p}$ such that the one of the forms (2.2) or (2.3) holds at p with respect to E and D.

$\square$

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VITA

Krishna Hanumanthu was born March 23, 1981, in the state of Andhra Pradesh, India. After finishing high school in Andhra Pradesh in 1998, he went to Chennai Mathematical Institute in Chennai, India. There he received his Bachelors (1998-2001) and Masters (2001-2003) degrees in mathematical sciences. In Fall, 2003, he came to University of Missouri to pursue a doctorate in mathematics. He plans to graduate in May 2008. After that, he will join the Department of Mathematics at University of Kansas as a visiting assistant professor in mathematics.