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Toroidal Embeddings and Desingularization

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TOROIDAL EMBEDDINGS AND DESINGULARIZATION

A Thesis
Presented to the
Faculty of
California State University,
San Bernardino

by
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June 2018

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Abstract

Algebraic geometry is the study of solutions in polynomial equations using objects and shapes. Differential geometry is based on surfaces, curves, and dimensions of shapes and applying calculus and algebra. Desingularizing the singularities of a variety plays an important role in research in algebraic and differential geometry. Toroidal Embedding is one of the tools used in desingularization. Therefore, Toroidal Embedding and desingularization will be the main focus of my project. In this paper, we first provide a brief introduction on Toroidal Embedding, then show an explicit construction on how to smooth a variety with singularity through Toroidal Embeddings.
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# Table of Contents

Abstract iii

Acknowledgements iv

List of Figures vi

1 Introduction 1
   1.1 Introduction .................................................. 1
   1.2 Definitions .................................................. 2
   1.3 Theorems ..................................................... 8

2 Toroidal Embeddings 9

3 Desingularization 12

Bibliography 30
### List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>$\sigma$</td>
<td>12</td>
</tr>
<tr>
<td>3.2</td>
<td>$\hat{\sigma}$</td>
<td>15</td>
</tr>
<tr>
<td>3.3</td>
<td>The sub-cones and their faces of $\sigma$</td>
<td>16</td>
</tr>
<tr>
<td>3.4</td>
<td>$\sigma_1$</td>
<td>17</td>
</tr>
<tr>
<td>3.5</td>
<td>$\hat{\sigma}_1$</td>
<td>18</td>
</tr>
<tr>
<td>3.6</td>
<td>$\sigma_2$</td>
<td>18</td>
</tr>
<tr>
<td>3.7</td>
<td>$\hat{\sigma}_2$</td>
<td>19</td>
</tr>
<tr>
<td>3.8</td>
<td>$\sigma_3$</td>
<td>20</td>
</tr>
<tr>
<td>3.9</td>
<td>$\hat{\sigma}_3$</td>
<td>21</td>
</tr>
<tr>
<td>3.10</td>
<td>$\tau_1$</td>
<td>21</td>
</tr>
<tr>
<td>3.11</td>
<td>$\hat{\tau}_1$</td>
<td>22</td>
</tr>
<tr>
<td>3.12</td>
<td>$\tau_2$</td>
<td>22</td>
</tr>
<tr>
<td>3.13</td>
<td>$\hat{\tau}_2$</td>
<td>23</td>
</tr>
<tr>
<td>3.14</td>
<td>$\tau_3$</td>
<td>23</td>
</tr>
<tr>
<td>3.15</td>
<td>$\hat{\tau}_3$</td>
<td>24</td>
</tr>
<tr>
<td>3.16</td>
<td>$\tau_4$</td>
<td>25</td>
</tr>
<tr>
<td>3.17</td>
<td>$\hat{\tau}_4$</td>
<td>26</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 Introduction

An affine variety is the zero set of a family of polynomials in $\mathbb{C}^n$. It often has singularities. To be able to desingularize the singularities of a variety is the key to many research in algebraic and differential geometry. There are different techniques in desingularization. Toroidal Embedding is one of them. In this paper, we will first introduce the Toroidal Embedding, then apply it to smooth a variety with singularity.

First, we introduce some definitions in algebraic and differential geometry, and recall some theorems we need. For the further details on these definitions and theorems, see [GH] and [H].
1.2 Definitions

Definition 1.1: Diffeomorphism

Let
\[ f(x_1, x_2, \ldots, x_n) = (f_1(x_1, x_2, \ldots, x_n), \ldots, f_n(x_1, x_2, \ldots, x_n)) \]
be a mapping between two open sets of \( \mathbb{R}^n \).

\( f \) is said to be a \( C^r \) mapping if each \( f_i \) can be differentiated up to \( r \) times,
\[ i = 1, 2, \ldots, n. \]

\( f \) is said to be \( C^\infty \)-differentiable if it is \( C^\infty \) mapping.

\( f \) is called a diffeomorphism if \( f \) is a bijection, and \( f \) and \( f^{-1} \) are both \( C^\infty \)-differentiable.

Definition 1.2: Holomorphism

Let \( f(z) : U \to \mathbb{C} \) be a function of one complex variable, where \( U \) is an open set of \( \mathbb{C} \),
\[ f(z) = u(x, y) + iv(x, y) \]
\( f(z) \) is said to be holomorphic, if \( f'(z) \) exists for every
\[ z_0 = (x_0, y_0) \in U, \]
Where
\[ f'(z_0) = \lim_{z \to z_0} \frac{f(z) - f(z_0)}{z - z_0} \]
\[ = \frac{\partial u(x_0, y_0)}{\partial x} + i \frac{\partial v(x_0, y_0)}{\partial x} \]
\[ = -i \frac{\partial u(x_0, y_0)}{\partial y} + \frac{\partial v(x_0, y_0)}{\partial y} \]

A function \( f(z_1, z_2, \ldots, z_n) \) of \( n \) complex variables is said to be holomorphic if \( f(z_1, z_2, \ldots, z_n) \) is holomorphic in each of variables.
Definition 1.3: Manifold

Let \( X \) be a topological space satisfying the Hausdorff separation axiom.

A differentiable structure on \( X \) of dimension \( n \) is a collection of open charts \( \{(U_i, \phi_i)\}, i \) is ranging in some index \( I \), satisfying the following conditions

(i) \( X = \bigcup_{i \in I} U_i \)

(ii) Each of \( \phi_i \) is a bijection of \( U_i \) onto an open set of \( \mathbb{R}^n \).

(iii) \( \phi_j \cdot \phi_i^{-1} : \phi_i(U_i \cap U_j) \rightarrow \phi_j(U_i \cap U_j) \) is a diffeomorphism.

\( X \) is called a \( \mathbb{R} \)-manifold of dimension \( n \) if \( X \) admits a differentiable structure of \( \text{dim } n \), \( \{(U_i, \phi_i), i \in I\} \).

Definition 1.4: Complex Manifold

A complex manifold \( M \) is a differentiable manifold admitting an open covering \( \{U_\alpha\} \) and coordinate maps \( \phi_\alpha : U_\alpha \rightarrow \mathbb{C}^n \) such that \( \phi_\alpha \cdot \phi_\beta^{-1} \) a biholomorphism from \( \phi_\beta(U_\alpha \cap U_\beta) \) to \( \phi_\alpha(U_\alpha \cap U_\beta) \).

Example 1.1 Real Manifold

Let \( X = \{(x, y) : x^2 + y^2 = 1\} \), a subset of \( \mathbb{R}^2 \)

\[
U_1 = \{(x, y) : -1 < x < 1, y = \sqrt{1 - x^2}\},
\]

\[
U_2 = \{(x, y) : -1 < x < 1, y = -\sqrt{1 - x^2}\},
\]

\[
U_3 = \{(x, y) : -1 < y < 1, x = \sqrt{1 - y^2}\},
\]

\[
U_4 = \{(x, y) : -1 < y < 1, x = -\sqrt{1 - y^2}\}
\]

\( \phi_1 : U_1 \rightarrow \mathbb{R}, \)

defined by \( \phi_1(x, y) = x \)
\[ \phi_3 : U_3 \rightarrow \mathbb{R}, \]
defined by \[ \phi_3(x, y) = y \]

\(\phi_2\) and \(\phi_4\) can be defined similarly. Then

\[ \phi_1 \cdot \phi_1^{-1} : \phi_1(U_1), \rightarrow \phi_1(U_1), \]

\[ (\phi_1 \cdot \phi_1^{-1})(t) = t \]

\[ \phi_3 \cdot \phi_1^{-1} : \phi_1(U_1 \cap U_3) \rightarrow \phi_3(U_1 \cap U_3) \]

\[ (\phi_3 \cdot \phi_1^{-1})(t) = \phi_3(\phi_1^{-1}(t)) = \phi_3(t, \sqrt{1-t^2}) = \sqrt{1-t^2}, \]

where \(0 < t < 1\)

\(\{(U_i, \phi_i), i = 1, 2, 3, 4\}\) is a differential structure on \(X\).

Therefore, \(X\) is a \(\mathbb{R}\)-manifold of dimension 1.

**Example 1.2** Complex Manifold The unit two-sphere \(S^2\), which is the subset of \(\mathbb{R}^3\), defined by

\[ x^2 + y^2 + z^2 = 1 \]
is a complex manifold. One can use stereographic projection from the North Pole to the real plane \(\mathbb{R}^2\) with coordinates \(X, Y\) given by

\[ (X, Y) = \left( \frac{x}{1-\bar{z}}, \frac{y}{1-\bar{z}} \right). \]

This can be done for any point except the North Pole itself (corresponding to \(z = 1\)).

To include the North Pole, we introduce a second chart, in which we stereographically project from the South Pole:

\[ (U, V) = \left( \frac{x}{1+z}, \frac{y}{1+z} \right), \]
which holds for any point on $S^2$ except for the South Pole (at $z = -1$). In both patches, we can now define complex coordinates

$$Z = X + iY, \quad \bar{Z} = X - iY, \quad W = U - iV, \quad \bar{W} = U + iV,$$

and show that on the overlap of the two patches, the transition function is holomorphic. Indeed, on the overlap we compute that

$$W = \frac{1}{Z}.$$

This expression relates the coordinates $W$ to $Z$ in a holomorphic way. Hence the two-sphere is a complex manifold which can be identified with $\mathbb{C} \cup \infty$.

**Definition 1.5: Jacobian**

(i). **Holomorphic Jacobian**

Let $U \subset \mathbb{C}^n$ be an open set of $\mathbb{C}^n$ and let $f : U \rightarrow \mathbb{C}^n$ be a holomorphic mapping, that is, $f = (f_1, f_2, \ldots, f_n)$ with each $f_j$ holomorphic. Let $w_j = f_j(z)$, where $z = (z_1, \ldots, z_n)$. The Holomorphic Jacobian of $f$ is the matrix

$$J_{\mathbb{C}} f = \frac{\partial (w_1, \ldots, w_n)}{\partial (z_1, \ldots, z_n)} = \begin{bmatrix} \frac{\partial w_1}{\partial z_1} & \cdots & \frac{\partial w_1}{\partial z_n} \\ \cdots & \cdots & \cdots \\ \frac{\partial w_n}{\partial z_1} & \cdots & \frac{\partial w_n}{\partial z_n} \end{bmatrix}$$

**Recall:** For a complex valued function $f(z) = u + iv$ of a complex variable $z = x + iy$

$$\frac{\partial f}{\partial z} = \frac{1}{2} \left( \frac{\partial f}{\partial x} - i \frac{\partial f}{\partial y} \right) = \frac{1}{2} \left[ \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) + i \left( \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) \right]$$

and

$$\frac{\partial f}{\partial \bar{z}} = \frac{1}{2} \left( \frac{\partial f}{\partial x} + i \frac{\partial f}{\partial y} \right).$$
(ii). Real Jacobian

Let

\[ z_j = x_j + iy_j, \]
\[ w_k = u_k + iv_k, \]
\[ j = 1, \ldots, n, \]
\[ k = 1, \ldots, n. \]

The Real Jacobian of \( f \) is the matrix

\[
J_R f = \frac{\partial (u_1, v_1, \ldots, u_n, v_n)}{\partial (x_1, y_1, \ldots, x_n, y_n)} = \begin{bmatrix}
\frac{\partial u_1}{\partial x_1} & \frac{\partial u_1}{\partial y_1} & \cdots & \frac{\partial u_1}{\partial x_n} & \frac{\partial u_1}{\partial y_n} \\
\frac{\partial v_1}{\partial x_1} & \frac{\partial v_1}{\partial y_1} & \cdots & \frac{\partial v_1}{\partial x_n} & \frac{\partial v_1}{\partial y_n} \\
\vdots & \vdots & \ddots & \vdots & \vdots \\
\frac{\partial u_n}{\partial x_1} & \frac{\partial u_n}{\partial y_1} & \cdots & \frac{\partial u_n}{\partial x_n} & \frac{\partial u_n}{\partial y_n} \\
\frac{\partial v_n}{\partial x_1} & \frac{\partial v_n}{\partial y_1} & \cdots & \frac{\partial v_n}{\partial x_n} & \frac{\partial v_n}{\partial y_n}
\end{bmatrix}
\]

One can prove that

\[ \det J_R f = \det J_C f \cdot \det J_C f. \]

**Definition 1.6: Variety over \( \mathbb{C} \)**

1. \( X \) is called an analytic variety if \( X \) is the common zero locus of a collection of holomorphic functions of \( n \) variables, i.e.

\[ X = \{(z_1, z_2, \ldots, z_n); f_1(z_1, \ldots, z_n) = 0, \ldots, f_k(z_1, \ldots, z_n) = 0\} \subset \mathbb{C}^n, k \leq n, \]

where each \( f_i \) is a holomorphic function.

\[ \tilde{z}_0 = (z_1, \ldots, z_n) \in X \]

is called a non-singular point if rank \([J_C(f)(\tilde{z}_0)] = k, \)

(i.e. there is a \( k \times k \) sub-matrix \( A \) of \( J_C(f)(z_0) \), such that \( \det A \neq 0 \).)
where
\[ f = (f_1, \ldots, f_k) \]

Otherwise, \( z_0 \) is called a singular point.

If \( X_{sig} = \{ \text{all singular point of } X \} \), then \( X_{sig} \) as a submanifold of \( \mathbb{C}^n \).

2. \( X \) is called affine variety if \( X \) is the common zero locus of a collection of polynomial in \( \mathbb{C}[z_1, \ldots, z_n] \).

3. \( X \) is called an algebraic variety (projective variety) if \( X \) is the common zero locus of a collection of homogenous polynomials.
1.3 Theorems

Theorem 1.1: Implicit Function Theorem
Let \((f_1, f_2, \ldots, f_k)\) be a holomorphic function of \(n\) complex variable \((z_1, \ldots, z_n)\), \(k \leq n\). If
\[
\det(J_C(f)_k(z_0)) \neq 0,
\]
where
\[
J_C(f)_k = \frac{\partial (f_1, \ldots, f_k)}{\partial (z_1, \ldots, z_k)}
\]
and
\[
z_0 = (z_1^0, z_2^0, \ldots, z_n^0)
\]
then there exist holomorphic function \(\phi_1, \ldots, \phi_k\) of \(n - k\) variables such that in a neighborhood of \(z_0\),
\[
f_1(z_1, \ldots, z_n) = f_2(z_1, \ldots, z_n) = \cdots = f_k(z_1, \ldots, z_n) = 0
\]
if and only if
\[
z_j = \phi_j(z_{k+1}, \ldots, z_n),
\]
\[
j = 1, \ldots, k.
\]

Theorem 1.2: Inverse Function Theorem
Let \(U \subset \mathbb{C}^n\) be an open set of \(\mathbb{C}^n\) and \(f : U \to \mathbb{C}^n\) be a holomorphic mapping with \(\det J_C f(z_0) \neq 0, z_0 \in U\). Then \(f\) is one-to-one in a neighborhood of \(z_0\), and \(f^{-1}\) is holomorphic at \(f(z_0)\).
Chapter 2

Toroidal Embeddings

We first give a brief introduction on toroidal embedding. For the further details on the subject, see [N].

Let $T$ be an $n$-dimensional complex torus, i.e., $T = (\mathbb{C}^*)^n$.

Definition.

(1) A torus embedding of $T$ is an algebraic variety $X$ such that

(a) $X$ contains $T$ as a Zariski open dense subset;

(b) $T$ acts on $X$ extending the natural action on itself defined by translation.

(2) A morphism between torus embedding $X$ and $X'$ is a map $f : X \rightarrow X'$ such that the following diagram commutes,

\[
\begin{array}{ccc}
T & \longrightarrow & X \\
\downarrow & & \downarrow f \\
X' & \longrightarrow & X'
\end{array}
\]

We can describe the torus embedding combinatorially.

Let $T = (\mathbb{C}^*)^n = \text{Spec}(\mathbb{C}[T_1, T_1^{-1}, \ldots, T_n, T_n^{-1}])$ as a scheme. For a commutative ring $R$, $\text{Spec}(R)$ is the set of all prime ideals of $R$. Let $M = \text{Hom}(T, \mathbb{C}^*)$. $M$ is called the character Group of $T$. Then $M \simeq \mathbb{Z}^n$ with the following mapping,

for $r = (r_1, r_2, \ldots, r_n) \in \mathbb{Z}^n$, $\chi^r \in M,$

where $\chi^r(t_1, t_2, \ldots, t_n) = t_1^{r_1} t_2^{r_2} \cdots t_n^{r_n}.$

Let $N = \text{Hom}(\mathbb{C}^*, T)$. $N$ is called the group of one-parameter subgroup in $T$. Then $N \simeq \mathbb{Z}^n$ with the following mapping,
for $a = (a_1, a_2, ..., a_n) \in \mathbb{Z}^n, \lambda_a \in N$, 
where $\lambda_a(t) = (t^{a_1}, t^{a_2}, ..., t^{a_n})$.

$M$ and $N$ are dual to each other under the pairing $\langle , \rangle : M \times N \to \mathbb{Z}$, 

$$\langle r, a \rangle = \sum_{i=1}^{n} r^{a_i}.$$ 

Notice that $\chi^r(\lambda_a(t)) = t^{\langle r, a \rangle}$ for $r \in M, a \in N$, and $t \in \mathbb{C}^\ast$.

If we identify $\chi^r$ with the monomial $\prod_{i=1}^{n} T^{r_i}$, for a subsemigroup $S$ of $M$ containing 0, then $\mathbb{C}[\chi^r]_{r \in S}$ is a subring of $\mathbb{C}[M] = \mathbb{C}[T_1, T_n^{-1}, ..., T_n, T_n^{-1}]$. Let $N_c = N \otimes \mathbb{C}$, then $N_C \simeq \mathbb{C}^n$ and $T = Spec(\mathbb{C}[M]) = N_C/N$.

Let $\sigma$ be a convex rational polyhedral cone in $N_R = N \otimes \mathbb{R} = \mathbb{R}^n$ not containing a line. Then 

$$\sigma = \{ a \in N_R; \langle r_i, a \rangle \geq 0, i = 1, ..., k, r_i \in M \}.$$ 

The dual of $\sigma$,

$$\hat{\sigma} = \{ r \in M_R; \langle r, a \rangle \geq 0, \text{ for all } a \in \sigma \},$$

is the cone in $M_R$.

$X_{\sigma}$ is defined to be $Spec(\mathbb{C}[\hat{\sigma} \cap M])$. Then $X_{\sigma}$ is an affine normal torus embedding of $T$ through $Spec(\mathbb{C}[M]) \subset Spec(\mathbb{C}[\hat{\sigma} \cap M])$.

Let $\{ r_1, ..., r_m \}$ be a subset of $M$ which generates $\hat{\sigma} \cap M$, i.e.,

$$\hat{\sigma} \cap M = \mathbb{Z}^{+}r_1 + \cdots + \mathbb{Z}^{+}r_m.$$ 

($m \geq n$, since $\sigma$ does not contain a line)

Then 

$$X_{\sigma} = Spec(\mathbb{C}[\chi^{r_1}, ..., \chi^{r_m}]) \subset \mathbb{C}^m.$$ 

The embedding of $T$ into $X_{\sigma}$ is defined by 

$$i : T \to \mathbb{C}^m, i(t) = (\chi^{r_1}(t), ..., \chi^{r_m}(t)),$$

where $t = (t_1, ..., t_n) \in T$. 
$X_\sigma$ is the scheme-theoretic closure of $i(T)$ in $\mathbb{C}^m$. $T$ acts on $X_\sigma$ as

$$t \cdot x = (\chi^{r_1}(t)x_1, \ldots, \chi^{r_m}(t)x_m)$$

for $t \in T, x = (x_1, \ldots, x_m) \in X_\sigma$. $X_\sigma$ can be decomposed as the disjoint union of $T$-orbits under this action, and

$$\{T \text{-orbits in } X_\sigma\} \longleftrightarrow \{\text{all faces of } \sigma\}.$$

If $\tau$ is a face of $\sigma$ (we will write it as $\tau < \sigma$), let $N(\tau)$ be the subset $\{r_i; \langle r_i, r \rangle | \tau = 0\}$ of $\{r_1, \ldots, r_m\}$, and $O_\tau$ be the $T$-orbit in $X_\sigma$ corresponding to $\tau$. Then

$$O_\tau = \{(x_1, \ldots, x_m) \in X_\sigma; x_i \neq 0 \text{ iff } r_i \in N(\tau)\},$$

and

$$\dim \tau + \dim O_\tau = \dim T = n$$

$$O_0 = T.$$

A finite rational partial polyhedral decomposition of $N_\mathbb{R}$ is a finite collection $\Sigma = \{\sigma_i\}$ such that

(i) the face of $\sigma$ is in $\Sigma$ if $\sigma \in \Sigma$;
(ii) $\sigma_i \cap \sigma_j$ is a face of both $\sigma_i$ and $\sigma_j$ for $\sigma_i, \sigma_j \in \Sigma$.

For a finite rational partial polyhedral decomposition $\Sigma$, we can patch all $X_{\sigma_i}, \sigma_i \in \Sigma$ together to form a normal torus embedding of $T$, $X_\Sigma$, by the $T$-orbits. In fact, if $\tau < \sigma$, then $X_{\tau} \subset X_\sigma$ and the inclusion $X_{\tau} \to X_\sigma$ is an open immersion in the following diagram,

$$\begin{array}{ccc}
T & \longrightarrow & T \\
\downarrow & & \downarrow \\
X_\tau & \longrightarrow & X_\sigma.
\end{array}$$

$X_\Sigma$ is the disjoint union of all $T$-orbits in $X_\Sigma$.

$X_\sigma$ is smooth if and only if $\sigma$ is regular, i.e., $\sigma$ is generated by a part of a $\mathbb{Z}$-basis of $N$. $X_\Sigma$ is smooth if and only if each member $\sigma$ of $\Sigma$ is regular. For a non-regular $\sigma$, one can find a finite rational polyhedral decomposition $\Sigma$ of $\sigma$ such that each member of $\Sigma$ is regular. Then $X_\Sigma$ will be a smooth variety which is a blowing-up of $X_\sigma$ at its singularity.
Chapter 3

Desingularization

Consider $S = \{(x, y, z) \in \mathbb{C}^3; F(x, y, z) = z^3 - xy = 0\}$, then $S$ is an analytic hypersurface in $\mathbb{C}^3$. Since $J_{\mathbb{C}}F = [-y, -x, 3z^2]$. It is clear that $0 = (0, 0, 0)$ is the only singular point of $S$, i.e. $S_0 = S \{0\}$ is a complex manifold. $S$ is the natural completion of $S_0$ in $\mathbb{C}^3$, yet singular. In algebraic geometry, it is known that one can obtain a canonical smooth completion $\overline{S_0}$ of $S_0$ by blowing up the singular point $0$. In this project, we are going to explicitly construct $\overline{S_0}$, by using toroidal embeddings.

Let $\sigma = \{(x, y) \in \mathbb{R}^2; x - y \geq 0, -x + 4y \geq 0\}$. $\sigma$ is called a rational convex polyhedral cone.

Figure 3.1: $\sigma$
Notice that $\sigma = \mathbb{R}^+ \{(4,1), (1,1)\}$, where $\mathbb{R}^+$ is the set of all non-negative real numbers. Let $\langle , \rangle$ denote the usual inner product in $\mathbb{R}^2$. The dual of $\sigma$ is defined as the following,

$$\hat{\sigma} = \{ r \in \mathbb{R}^2; \langle \vec{r}, \vec{a} \rangle \geq 0, \forall \vec{a} \in \sigma \}.$$ 

$$\hat{\sigma} = \{ \vec{r} = (r_1, r_2); r_1a_1 + r_2a_2 \geq 0, \forall \vec{a} = (a_1, a_2) \in \sigma \}.$$ 

Let

$$\vec{r}_1 = (1, -1)$$

and

$$\vec{r}_2 = (-1, 4)$$

Claim:

$$\hat{\sigma} = \mathbb{R}^+ \{\vec{r}_1, \vec{r}_2\}$$

Proof: We will prove it by showing two inclusions, $\mathbb{R}^+ \{\vec{r}_1, \vec{r}_2\} \subset \hat{\sigma}$ and $\hat{\sigma} \subset \mathbb{R}^+ \{\vec{r}_1, \vec{r}_2\}$.

(i) First, we prove $\mathbb{R}^+ \{\vec{r}_1, \vec{r}_2\} \subset \hat{\sigma}$

By the definition of $\sigma$, it is clear that

$$\vec{r}_1 \in \hat{\sigma}$$

and

$$\vec{r}_2 \in \hat{\sigma}.$$ 

Therefore,

$$\mathbb{R}^+ \{\vec{r}_1, \vec{r}_2\} \subset \hat{\sigma}$$

(ii) Second, we prove $\hat{\sigma} \subset \mathbb{R}^+ \{\vec{r}_1, \vec{r}_2\}$.

For any

$$\vec{r} = (r_1, r_2) \in \hat{\sigma},$$

then

$$\langle \vec{r}, \vec{a} \rangle \geq 0, \forall \vec{a} \in \sigma.$$
Since \( \{\vec{r}_1, \vec{r}_2\} \) forms a basis for \( \mathbb{R}^2 \), then

\[
\vec{r} = \alpha \vec{r}_1 + \beta \vec{r}_2,
\]

for some \( \alpha \in \mathbb{R} \), and \( \beta \in \mathbb{R} \).

For

\[
\vec{a}_1 = (1, 1) \in \sigma,
\]

\[
< \vec{r}_1, \vec{a}_1 > = 0,
\]

\[
< \vec{r}_2, \vec{a}_1 > = 3,
\]

therefore,

\[
< \vec{r}, \vec{a}_1 > = 3\beta \geq 0.
\]

It implies that

\[
\beta \geq 0.
\]

Similarly,

\[
\vec{a}_2 = (4, 1) \in \sigma,
\]

\[
< \vec{r}_1, \vec{a}_2 > = 3,
\]

\[
< \vec{r}_2, \vec{a}_2 > = 0,
\]

then

\[
< \vec{r}, \vec{a}_2 > = 3\alpha \geq 0.
\]

It implies that

\[
\alpha \geq 0
\]

Then

\[
\vec{r} \in \mathbb{R}^+\{\vec{r}_1, \vec{r}_2\}
\]

Therefore,

\[
\hat{\sigma} \subset \mathbb{R}^+\{\vec{r}_1, \vec{r}_2\}
\]

We have proved that

\[
\hat{\sigma} = \mathbb{R}^+\{\vec{r}_1, \vec{r}_2\}
\]
Let $\hat{\sigma}_Z$ denote the set of all integer points of $\hat{\sigma}$, i.e., $\hat{\sigma}_Z = \hat{\sigma} \cap \mathbb{Z}^2$, where $\mathbb{Z} = \text{the set of integers}$. Then

$$\hat{\sigma}_Z = \mathbb{Z}^+ \{ r_1 = (1, -1), r_2 = (-1, 4), r_3 = (0, 1) \},$$

i.e. $\{ r_1, r_2, r_3 \}$ forms a $\mathbb{Z}^+$-basis for $\hat{\sigma}_Z$.

Each $r_i$ corresponds to a monomial $m_{r_i}$ in $\mathbb{C}[T_1, T_1^{-1}, T_2, T_2^{-1}]$,

$$m_{r_1} = T_1 T_2^{-1}, m_{r_2} = T_1^{-1} T_2^4, m_{r_3} = T_2.$$

They induce a map

$$i_\sigma : T \to \mathbb{C}^3,$$

where, $T = (\mathbb{C}^*)^2$, the complex torus of dim 2.

$$i_\sigma(t_1, t_2) = (t_1 t_2^{-1}, t_1^{-1} t_2^4, t_2) =: (x, y, z).$$

It is clear that $i_\sigma(T) \subset S$. In fact,

$$S = \text{Spec}(\mathbb{C}[m_{r_1}, m_{r_2}, m_{r_3}]),$$
the Scheme-theoretic closure of $i_\sigma(T)$ in $\mathbb{C}^3$. We will denote $\text{Spec}(\mathbb{C}[m_{r_1}, m_{r_2}, m_{r_3}])$ by $X_\sigma$. It is called the Torus embedding associated with a rational convex polyhedral cone $\sigma$.

It is known that, from the general theory of Toroidal Embeddings, $X_\phi$ is smooth if and only if $\phi$ is regular, for any rational convex polyhedral cone $\phi$ of $\mathbb{R}^2$. $\phi$ is called regular if $\phi \cap \mathbb{Z}^2$ can be generated by a $\mathbb{R}^+$-basis of $\phi$.

The cone $\sigma$ above is not regular because the $\mathbb{R}^+$-basis $\{(4, 1), (1, 1)\}$ cannot generate $\sigma \cap \mathbb{Z}^2$.

Hence, $X_\sigma = S$ has a singularity at $0 = (0, 0, 0)$

Now we consider the sub-cones and their faces of $\sigma$.

\[ \sigma_1 = \mathbb{R}^+ \{(2, 1), (1, 1)\} \]
\[ \sigma_2 = \mathbb{R}^+ \{(2, 1), (3, 1)\} \]
\[ \sigma_3 = \mathbb{R}^+ \{(3, 1), (4, 1)\} \]
\[ \tau_1 = \mathbb{R}^+ \{(1, 1)\} \]
\[ \tau_2 = \mathbb{R}^+ \{(2, 1)\} \]
\[ \tau_3 = \mathbb{R}^+ \{(3, 1)\} \]
\[ \tau_4 = \mathbb{R}^+ \{(4, 1)\} \]

Figure 3.3: The sub-cones and their faces of $\sigma$
They are all regular. $\Sigma = \{0, \tau_1, \tau_2, \tau_3, \tau_4, \sigma_1, \sigma_2, \sigma_3\}$ is called a regular rational convex polyhedral decomposition of $\sigma$.

For each cone in $\Sigma$, there is a Torus embedding of $T$ associated to it. We are going to construct some of them here in detail.

Considering the sub-cone $\sigma_1$

It can be verified that the dual

$\hat{\sigma}_1 =: \{r \in \mathbb{R}^2, \langle r, a \rangle \geq 0, \forall a \in \sigma_1 \}$

$= \mathbb{R}^+ \{(1, -1), (-1, 2)\}$.

$\hat{\sigma}_1 \cap \mathbb{Z}^2 = \mathbb{Z}^+ \{(1, -1), (-1, 2)\}$.

(So, $\sigma_1$ is regular.)

Therefore, the embedding $i_{\sigma_1} : T \to \mathbb{C}^2$ is given by

$i_{\sigma_1}(t_1, t_2) = (t_1 t_2^{-1}, 1 t_1^{-1} t_2^2)$. 

Figure 3.4: $\sigma_1$
Let $X_{\sigma_1}$ denote the closure of $i_{\sigma_1}(T)$ in $C^3$, then

$$X_{\sigma_1} = C^2.$$ 

Considering the sub-cone $\sigma_2$
It can be verified that the dual

\[ \hat{\sigma}_2 =: \{ r \in \mathbb{R}^2, < r, a > \geq 0, \forall a \in \sigma_2 \} \]

\[ = \mathbb{R}^+ \{(1, -2), (-1, 3)\}. \]

\[ \hat{\sigma}_2 \cap \mathbb{Z}^2 = \mathbb{Z}^+ \{(1, -2), (-1, 3)\}. \]

(So, \( \sigma_2 \) is regular.)

Therefore, the embedding \( i_{\sigma_2} : T \to \mathbb{C}^2 \) is given by

\[ i_{\sigma_2}(t_1, t_2) = (t_1 t_2^{-2}, t_1^{-1} t_2^3). \]

Let \( X_{\sigma_2} \) denote the closure of \( i_{\sigma_2}(T) \) in \( \mathbb{C}^3 \), then

\[ X_{\sigma_2} = \mathbb{C}^2. \]
Considering the sub-cone $\sigma_3$

It can be verified that the dual

$$\hat{\sigma}_3 = \{ r \in \mathbb{R}^2, < r, a > \geq 0, \forall a \in \sigma_3 \}$$

$$= \mathbb{R}^+\{(1, -3), (-1, 4)\}.$$  

$\hat{\sigma}_3 \cap \mathbb{Z}^2 = \mathbb{Z}^+\{(1, -3), (-1, 4)\}.$

(So, $\sigma_3$ is regular.)

Therefore, the embedding $\iota_{\sigma_3} : T \rightarrow \mathbb{C}^2$ is given by

$$\iota_{\sigma_3}(t_1, t_2) = (t_1 t_2^{-3}, t_1^{-1} t_2^4).$$

For the face $\tau_1 = \mathbb{R}^+\{(1, 1)\}$ of $\sigma$,

it is found that

$$\hat{\tau}_1 = \mathbb{R}^+\{(-1, 1), (1, -1), (0, 1)\},$$

(See Figure 3.8: $\sigma_3$.)
\( \hat{\tau}_1 \cap \mathbb{Z}^2 = \mathbb{Z}^+ \{(-1,1), (1,-1), (0,1)\} \),

and \( i_{\tau_1} \) defines an embedding of \( T \) into \( \mathbb{C}^3 \), where

\[
i_{\tau_1}(t_1, t_2) = (t_1^{-1}t_2^{-1}t_1, t_2).
\]

Hence, \( X_{\tau_1} = \{(x,y,z) \in \mathbb{C}^3, xy = 1\} \) is a smooth surface in \( \mathbb{C}^3 \).
For the face $\tau_2 = \mathbb{R}^+ \{(2, 1)\}$ of $\sigma$,

it is found that

$$\hat{\tau}_2 = \mathbb{R}^+ \{(-1, 2), (1, -2), (1, 0)\},$$

$$\hat{\tau}_2 \cap \mathbb{Z}^2 = \mathbb{Z}^+ \{(-1, 2), (1, -2), (1, 0)\},$$
and $i_{\tau_2}$ defines an embedding of $T$ into $\mathbb{C}^3$, where

$$i_{\tau_2}(t_1, t_2) = (t_1^{-1}t_2^2, t_1 t_2^{-2}, t_1).$$

Hence, $X_{\tau_2} = \{(x, y, z) \in \mathbb{C}^3, xy = 1\}$ is a smooth surface in $\mathbb{C}^3$.

For the face $\tau_3 = \mathbb{R}^+ \{ (3, 1) \}$ of $\sigma$,
it is found that

$$\hat{\tau}_3 = \mathbb{R}^+\{(-1, 3), (1, -3), (1, 0)\},$$

$$\hat{\tau}_3 \cap \mathbb{Z}^2 = \mathbb{Z}^+\{(-1, 3), (1, -3), (1, 0)\},$$

and $i_{\tau_3}$ defines an embedding of $T$ into $\mathbb{C}^3$, where

$$i_{\tau_3}(t_1, t_2) = (t_1^{-1}t_2^3, t_1t_2^{-3}, t_1).$$

Hence, $X_{\tau_3} = \{(x, y, z) \in \mathbb{C}^3, xy = 1\}$ is a smooth surface in $\mathbb{C}^3$.

For the face $\tau_4 = \mathbb{R}^+\{(4, 1)\}$ of $\sigma$,

it is found that

$$\hat{\tau}_4 = \mathbb{R}^+\{(-1, 4), (1, -4), (1, 0)\},$$
$\hat{\tau}_4 \cap \mathbb{Z}^2 = \mathbb{Z}^+ \{(-1, 4), (1, -4), (1, 0)\}$,

and $i_{\tau_4}$ defines an embedding of $T$ into $\mathbb{C}^3$, where

$$i_{\tau_4}(t_1, t_2) = (t_1^{-1} t_2^4, t_1 t_2^{-4}, t_1).$$

Hence, $X_{\tau_4} = \{(x, y, z) \in \mathbb{C}^3, xy = 1\}$ is a smooth surface in $\mathbb{C}^3$.

$X_{\tau_2}, X_{\tau_3}$ and $X_{\tau_4}$ will be the same type of surface as $X_{\tau_1}$.

We are now going to show how can these $X_{\tau_1}$ and $X_{\sigma_j}$ be patched together through the "orbit decompositions".

Consider the sub-cone $\sigma_1$ of $\sigma$ first. It is clear that

$$\hat{\sigma} \subset \hat{\sigma}_1$$

and

$$\hat{\sigma} \cap \mathbb{Z}^2 \subset \hat{\sigma}_1 \cap \mathbb{Z}^2.$$

Recall that

$$\hat{\sigma}_1 \cap \mathbb{Z}^2 = \mathbb{Z}^+ \{s_1, s_2\}$$

and
\[ \hat{\sigma} \cap \mathbb{Z}^2 = \mathbb{Z}^+ \{r_1, r_2, r_3\}, \]

where \( s_1 = (1, -1) \) and \( s_2 = (-1, 2) \). Therefore, the set \( \{s_1, s_2\} \) should generates the set \( \{r_1, r_2, r_3\} \) over \( \mathbb{Z}^+ \). In fact,

\[
\begin{align*}
    r_1 &= s_1, \\
    r_2 &= s_1 + 2s_2, \\
    r_3 &= s_1 + s_2.
\end{align*}
\]

Their monomials are related as in the following,

\[
\begin{align*}
    m_{r_1} &= m_{s_1}, \\
    m_{r_2} &= m_{s_1}m_{s_2}^2, \\
    m_{r_3} &= m_{s_1}m_{s_2}.
\end{align*}
\]

They induce a homomorphism \( \alpha_1 \) from \( X_{\sigma_1} \) to \( X_{\sigma} \).

\[
\alpha_1(u, v) = (u, uv^2, uv) =: (x, y, z).
\]

It can be verified that \( \alpha_1 \) is 1-1 on \( X_{\sigma} \cap \{ z \neq 0 \} \), and the following diagram
commutes.

\[
\begin{array}{c}
T \longrightarrow X_{\sigma_1} \\
\alpha \downarrow \downarrow \alpha_1 \\
X_\sigma \longrightarrow X_\sigma
\end{array}
\]

On the other hand, each \(X_\ast\) has a canonical decomposition in terms of all possible faces of the cone. For instance,

\[
X_\sigma = O_0 \cup O_{\tau_1} \cup O_{\tau_4} \cup O_\sigma,
\]

where

\[
O_0 = \{(x, y, z); z^3 = xy, xyz \neq 0\} \cong (\mathbb{C}^*)^2 = T
\]

\[
O_{\tau_1} = \{(x, 0, 0); x \neq 0\} \cong \mathbb{C}^*
\]

\[
O_{\tau_4} = \{(0, y, 0); y \neq 0\} \cong \mathbb{C}^*
\]

\[
O_\sigma = \{(0, 0, 0)\}
\]

This is called the orbits decompositions of \(X_\sigma\).

We explain in the following how the orbit associated to a face of \(\sigma\), for instance \(O_{\tau_1}\), is determined.

Recall that the embedding

\[
i_\sigma : T \to X_\sigma \subset \mathbb{C}^3
\]

is given by the monomials \(\{m_{r_1}, m_{r_2}, m_{r_3}\}\).

\[
i_\sigma(t_1, t_2) = (x, y, z)
\]

where

\[
x = m_{r_1}(t_1, t_2), y = m_{r_2}(t_1, t_2), z = m_{r_3}(t_1, t_2),
\]

and

\[
\{r_1 = (1, -1), r_2 = (-1, 3), r_3 = (0, 1)\} \subset \hat{\sigma}.
\]

Notice that \(r_1 = 0\) on \(\tau_1\), \(r_2\) and \(r_3\) are non-zero on \(\tau_1\). Hence, the orbit \(O_{\tau_1}\) is determined by the conditions

\[
x \neq 0, \quad y = z = 0.
\]

Similarly, \(X_{\sigma_1} = \mathbb{C}^2 = O_0^1 \cup O_{\tau_1}^1 \cup O_{\tau_2}^1 \cup O_{\sigma_1}\), where

\[
O_0^1 = \{(u, v); uv \neq 0\} \cong (\mathbb{C}^*)^2 = T
\]

\[
O_{\tau_1}^1 = \{(u, 0); u \neq 0\} \cong \mathbb{C}^*
\]

\[
O_{\tau_2}^1 = \{(0, v); v \neq 0\} \cong \mathbb{C}^*
\]

\[
O_{\sigma_1} = \{(0, 0)\}
\]
\( \sigma \) and \( \sigma_1 \) have common faces \( \tau_1 \) and \( 0 \) (the origin). The induced homomorphism \( \alpha_1 \) becomes an isomorphism when it is restricted to \( O^1_0 \) or \( O^1_{\tau_1} \). In the mean time, \( \alpha_1 \) will collapse \( O^1_{\tau_2} \cup O_{\sigma_1} \) into a single point \( O_\sigma \). This is illustrated in the following diagrams.

\[
\begin{align*}
X_{\sigma_1} & = O^1_0 \cup O^1_{\tau_1} \cup O^1_{\tau_2} \cup O_{\sigma_1} \\
\downarrow & \downarrow \downarrow \searrow \nearrow \\
X_\sigma & = O_0 \cup O_{\tau_1} \cup O_\sigma \cup O_{\tau_4}
\end{align*}
\]

The orbit decompositions for \( X_{\sigma_2} \) are stated in the following,

\[
X_{\sigma_2} = O^2_0 \cup O^2_{\tau_2} \cup O^2_{\tau_3} \cup O_{\sigma_2}.
\]

The induced homomorphism \( \alpha_2 \) from \( X_{\sigma_2} \) to \( X_\sigma \) will collapse \( O^2_{\tau_2} \cup O^2_{\tau_3} \cup O_{\sigma_2} \) into a single point \( O_\sigma \), while \( \{ \alpha_2 : O^2_0 \to O_0 \} \) is isomorphism.

\[
\begin{align*}
X_{\sigma_2} & = O^2_0 \cup O^2_{\tau_2} \cup O^2_{\tau_3} \cup O_{\sigma_2} \\
\downarrow & \downarrow \downarrow \nearrow \searrow \\
X_\sigma & = O_0 \cup O_{\tau_1} \cup O_\sigma \cup O_{\tau_4}
\end{align*}
\]

Each \( X_{\tau_i} \) has an orbit decompositions with two orbits only. For instance,

\[
X_{\tau_2} = O^\prime_0 \cup O^\prime_{\tau_2}.
\]

Since \( \tau_2 \) is a face of \( \sigma_1 \), there is an induced immersion from \( X_{\tau_2} \) into \( X_{\sigma_1} \) which will isomorphically map \( O^\prime_0 \) onto \( O^1_0 \), and \( O^\prime_{\tau_2} \) onto \( O^1_{\tau_2} \). Therefore, under the isomorphisms, we may write

\[
X_{\tau_2} = O^\prime_0 \cup O^\prime_{\tau_2}
\]

and

\[
X_{\sigma_1} = O^\prime_0 \cup O^\prime_{\tau_1} \cup O^\prime_{\tau_2} \cup O_{\sigma_1}.
\]

Similarly,

\[
X_{\sigma_2} = O^\prime_0 \cup O^\prime_{\tau_2} \cup O^\prime_{\tau_3} \cup O_{\sigma_2}.
\]

\[
X_{\sigma_3} = O^\prime_0 \cup O^\prime_{\tau_3} \cup O^\prime_{\tau_4} \cup O_{\sigma_3}.
\]

\[
X_{\tau_1} = O^\prime_0 \cup O^\prime_{\tau_1}.
\]
\[ X_{\tau_3} = O'_0 \cup O'_{\tau_3} \]

and
\[ X_{\tau_4} = O'_0 \cup O'_{\tau_4} \]

Let \( X_\Sigma = \bigsqcup_{i=1}^{3} X_{\sigma_i} \bigsqcup_{j=1}^{4} X_{\tau_j} \) be the union of \( X_{\sigma_i} \) and \( X_{\tau_j} \), patching through the orbits. Hence, \( X_\Sigma \) has an orbit decomposition as the following,
\[ X_\Sigma = O'_0 \cup O'_{\tau_1} \cup O'_{\tau_3} \cup O'_{\tau_2} \cup O'_{\tau_4} \cup O_{\sigma_1} \cup O_{\sigma_2} \cup O_{\sigma_3}. \]

\( X_\Sigma \) is a smooth variety, since \( \Sigma = \{0, \tau_1, \tau_2, \tau_3, \sigma_1, \sigma_2, \sigma_3\} \) is a regular rational convex polyhedral decomposition of \( \sigma \). There is a homomorphism \( \beta \) from \( X_\Sigma \) to \( X_\sigma \), which will be an isomorphism on \( O'_0, O'_{\tau_1} \) and \( O'_{\tau_4} \) respectively,
\begin{align*}
O'_0 &\cong O_0 \\
O'_{\tau_1} &\cong O_{\tau_1} \\
O'_{\tau_3} &\cong O_{\tau_4}.
\end{align*}

\( \beta \) will map \( O'_{\tau_2} \cup O'_{\tau_3} \cup O_{\sigma_1} \cup O_{\sigma_2} \cup O_{\sigma_3} \) into the single point \( O_\sigma \). Therefore, we have the following diagrams.
\[
\begin{array}{cccccc}
X_\Sigma & = & O'_0 & \cup & O'_{\tau_1} & \cup & O'_{\tau_3} \cup O'_{\tau_2} \cup O'_{\tau_4} \cup D \\
\downarrow & & \downarrow & & \downarrow & & \downarrow \\
X_\sigma & = & O_0 & \cup & O_{\tau_1} & \cup & O_{\tau_3} \cup O_{\tau_4} \cup O_{\sigma} \\
\end{array}
\]

where
\[ D = O'_{\tau_2} \cup O'_{\tau_3} \cup O_{\sigma_1} \cup O_{\sigma_2} \cup O_{\sigma_3}. \]

Notice that \( O_\sigma = \{0\} \), the singular point of \( S \).

We have constructed a smooth completion \( X_\Sigma \) of the surface \( S \) with a mapping
\[ \beta : X_\Sigma \rightarrow X_\sigma = S \]

\( \beta \) is the blowing-up of \( S \) at its singular point 0.

\[ \beta^{-1}(0) = O'_{\tau_2} \cup O'_{\tau_3} \cup O_{\sigma_1} \cup O_{\sigma_2} \cup O_{\sigma_3}, \]

is the exceptional divisor.
Bibliography


