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## LOCAL EMBEDDINGS OF LINES IN SINGULAR HYPERSURFACES

by G. JIANG and D. SIERSMA

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### Introduction.

Simple surface singularities have been known for long time since they occur in several different situations. They have at least fifteen characterizations [4]. One often describes them by the normal forms of their defining equations in certain coordinate system. This has been done by Arnol'd [1] and Siersma [8], [9]. The idea is to classify all the surfaces that contain the origin 0 under the right equivalence defined by the group  $\mathcal{R}$ , consisting of all the coordinate transformations preserving 0. The equivalence classes without parameters in their normal forms are called the *simple surface singularities*, or the *A-D-E singularities*.

The observation by Gonzalez-Sprinberg and Lejeune-Jalabert [5] that on a singular surface  $X$  in  $\mathbb{C}^3$  one can not always find a smooth line passing through the singular point was our starting point for classifying functions  $f$ , where the corresponding hypersurface  $X = f^{-1}(0)$  contains a smooth curve.

We take the following set-up. Take a line  $L$  as the  $x$ -axis of the coordinate system in  $\mathbb{C}^{n+1}$ , classify all the hypersurfaces that contain  $L$  under the equivalence defined by the subgroup  $\mathcal{R}_L$  of  $\mathcal{R}$ , consisting of all the coordinate transformations preserving  $L$ . If we compare this with the usual  $\mathcal{R}$ -classification of surfaces, the result classifies the lines contained in  $X$ . Our work is in fact about the pair  $(X, L)$ .

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We obtain the following results:

- The  $\mathcal{R}_L$ -classification is finer than the  $\mathcal{R}$ -classification, *i.e.* there are different ‘positions’ of lines on the same hypersurface.
- There exist an  $\mathcal{R}_L$  invariant  $\lambda$ , which counts the maximal number of Morse points on the line over all Morsifications.
- $\lambda$  is invariant under sections with generic hyperplanes containing  $L$ .
- Another proof of the non-existence of lines on  $E_8$  surface.

We also introduce a sequence of higher order  $\mathcal{R}_L$  invariants which gives more information about lines on hypersurfaces. It turns out that our work tells how lines are embedded in a hypersurface.

What brought this problem to our attention was the study of functions with non-isolated singularities on singular spaces [7]. Natural questions are: given a singular hypersurface  $X$  with isolated singularity, does there exist smooth curves on  $X$  passing through the singular point of  $X$ ? If there exist smooth curves on  $X$ , how many of them?, *etc.*

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## 1. Lines contained in singular spaces.

**1.1.** — Let  $L$  be a smooth curve in  $\mathbb{C}^{n+1}$ . Since  $L$  is locally biholomorphic to a line, we often say that  $L$  is a line. Let  $X$  be a singular space embedded in  $\mathbb{C}^{n+1}$ . If for a singular point  $O \in X_{\text{sing}}$ , there exists a line (smooth curve)  $L$  in  $\mathbb{C}^{n+1}$  such that  $O \in L$  and  $L \setminus \{O\} \subset X_{\text{reg}}$ , we say that  $X$  *contains (or has) smooth curve* passing through  $O$ . Very often, we say that  $X$  *contains (or has) a line* passing through  $O$ .

**1.2.** — On a singular surface  $X$  in  $\mathbb{C}^3$  one can not always find a line passing through (not contained in) the singular locus of  $X$ . Gonzalez-Sprinberg and Lejeune-Jalabert [5], by using resolutions of singularities, have proved a criterion for the existence of lines on any (two dimensional) surface, and given a natural partition of the set of smooth curves on  $(X, 0)$  into families. Especially, on surfaces with  $A_k$ ,  $D_k$  ( $k \geq 4$ ),  $E_6$  or  $E_7$  type

singularity, there exist lines passing through the singular point. In fact one can find easily lines on this kind of surfaces simply by looking at the defining equations. But it is not easy to tell how many different lines there are on a surface, and what kind of invariants can be used to tell the differences. The hardest thing is to prove the non-existence of smooth curve on certain surfaces (e.g.  $E_8$  type surface *loc.cit.*). There exists similar question for hypersurfaces with other dimensions.

**1.3. Isolated hypersurface singularities.** — Let  $X$  be a hypersurface germ with isolated singularity at the origin. The singularity of  $X$  is *simple* if and only if  $X$  can be defined in a neighborhood of the origin in  $\mathbb{C}^{n+2}$  by the following equations (see [1] and [8], [9]):

$$\begin{aligned} A_k &: x^{k+1} + y^2 + z_1^2 + \cdots + z_n^2 = 0 \quad (k \geq 1), \\ D_k &: x^2y + y^{k-1} + z_1^2 + \cdots + z_n^2 = 0 \quad (k \geq 4), \\ E_6 &: x^4 + y^3 + z_1^2 + \cdots + z_n^2 = 0, \\ E_7 &: x^3y + y^3 + z_1^2 + \cdots + z_n^2 = 0, \\ E_8 &: x^5 + y^3 + z_1^2 + \cdots + z_n^2 = 0. \end{aligned}$$

The left hand sides of the equations are called the normal forms of the simple (or *A-D-E*) singularities.

The following equations define the *simple elliptic hypersurface singularities* (see [2] and [8], [9]):

$$\begin{aligned} \tilde{E}_6 &: x^2y + z_1^3 + \alpha y^2z_1 + \beta y^3 + z_2^2 + \cdots + z_n^2 = 0, & 4\alpha^3 + 27\beta^2 \neq 0; \\ \tilde{E}_7 &: x^4 + y^4 + \alpha x^2y^2 + z_1^2 + \cdots + z_n^2 = 0, & \alpha \neq \pm 2; \\ \tilde{E}_8 &: x^3 + \alpha xy^4 + \beta y^6 + z_1^2 + \cdots + z_n^2 = 0, & 4\alpha^3 + 27\beta^2 \neq 0. \end{aligned}$$

## 2. $\mathcal{R}_L$ -equivalence.

**2.1.** — Let  $\mathcal{O}_{n+1}$  (or  $\mathcal{O}$ ) be the stalk at 0 of the holomorphic structure sheaf  $\mathcal{O}_{\mathbb{C}^{n+1}}$ ,  $\mathfrak{m}$  be the maximal ideal of  $\mathcal{O}$ . Let  $\mathcal{R}$  be the group of all the holomorphic automorphisms of  $\mathbb{C}^{n+1}$  that preserve 0. Take  $L$  as the  $x$ -axis in  $\mathbb{C}^{n+1}$ , then the defining ideal of  $L$  is  $\mathfrak{g} := (y_1, \dots, y_n)$ , and

$$\mathcal{R}_L := \{ \phi \in \mathcal{R} \mid \phi^* \mathfrak{g} \subset \mathfrak{g} \}.$$

It has an action on  $\mathfrak{m}\mathfrak{g}$  from the right hand side. This defines an equivalence relation on  $\mathfrak{m}\mathfrak{g}$ .

We recall some notations from [10]. Two germs  $f, g \in \mathfrak{m}\mathfrak{g}$  are called  $\mathcal{R}_L$ -equivalent if there exists a  $\phi \in \mathcal{R}_L$  such that  $f = g \circ \phi$ . A germ  $f \in \mathfrak{m}\mathfrak{g}$  is called  $k$ - $\mathcal{R}_L$ -determined in  $\mathfrak{m}\mathfrak{g}$  if for each  $g \in \mathfrak{m}\mathfrak{g}$  with  $f - g \in \mathfrak{m}^{k+1} \cap \mathfrak{g} = \mathfrak{m}^k \mathfrak{g}$ ,  $f$  and  $g$  are  $\mathcal{R}_L$ -equivalent.

**2.2. THEOREM.** — *If*

$$\mathfrak{m}^k \mathfrak{g} \subset \mathfrak{m}\tau_{\mathfrak{g}}(f) + \mathfrak{m}^{k+1} \mathfrak{g},$$

then  $f$  is  $k$ - $\mathcal{R}_L$ -determined, where

$$\tau_{\mathfrak{g}}(f) := \mathfrak{m} \left( \frac{\partial f}{\partial x} \right) + \mathfrak{g} \left( \frac{\partial f}{\partial y_1}, \dots, \frac{\partial f}{\partial y_n} \right)$$

is the tangent space at  $f$  of the  $\mathcal{R}_L$ -orbit  $\mathcal{R}_L(f)$  of  $f$ .

*Proof.* — Since the proof is a standard argument in singularity theory and very similar to [10], we give a brief proof. For any function  $g \in \mathfrak{m}^k \mathfrak{g}$ , define a one parameter family of functions  $F := f + t(g - f)$ . Let  $\tilde{\tau}_{\mathfrak{g}}(F)$  be the collection of all the differentials of  $F$  by the one-parameter families of vector fields preserving 0 and  $L$ . By the assumption and Nakayama lemma, one finds that there exists a vector field  $\delta$  of the above mentioned type, such that  $g - f = \delta(F)$ . The flow of  $\delta$  gives an  $\mathcal{R}_L$ -equivalence between  $f$  and  $g$  by continuous induction. □

**2.3. Definitions.** — For a germ  $h \in \mathfrak{m}\mathfrak{g}$ , the  $\mathcal{R}_L$ -codimension of  $h$  is defined by

$$c_L = c_L(h) := \dim_{\mathbb{C}} \frac{\mathfrak{g}\mathfrak{m}}{\tau_{\mathfrak{g}}(h)}.$$

Moreover there exists the next  $\mathcal{R}_L$ -invariant

$$\lambda = \lambda(h) := \dim_{\mathbb{C}} \frac{\mathcal{O}}{J(h) + \mathfrak{g}},$$

where  $J(h)$  is the Jacobian ideal of  $h$ . Note that

$$1 \leq \lambda(h) \leq \mu(h),$$

where  $\mu(h)$  is the Milnor number of  $h$ . The number  $\lambda$  is equal to the torsion number defined in [7], see also § 2.4.

One can always write  $h$  in the following form:

$$h = \sum A_j x y_j + \sum B_{jk} y_j y_k,$$

where  $A_j$  are functions of one variable  $x$ :  $A_j \in \mathcal{O}_1$ , and  $B_{jk} \in \mathcal{O}$ . With this

notation we have the following simple formula:

$$\lambda = \dim_{\mathbb{C}} \frac{\mathcal{O}_1}{x(A_1, \dots, A_n)}.$$

**2.4. Torsion number.** — We recall the definition of the torsion number from [7]. This section plays no role in the rest of the paper.

Let  $L$  and  $X$  be analytic spaces in  $\mathbb{C}^{n+1}$  defined by the ideal  $\mathfrak{g}$  and  $\mathfrak{h}$  respectively. If  $L \subset X$ , then  $\mathfrak{h} \subset \mathfrak{g}$ . As a subspace,  $L$  can be defined by the ideal  $\bar{\mathfrak{g}}$ , the image of  $\mathfrak{g}$  in  $\mathcal{O}_X := \mathcal{O}/\mathfrak{h}$ . The  $\mathcal{O}_L := \mathcal{O}/\mathfrak{g}$ -module

$$M := \frac{\bar{\mathfrak{g}}}{\bar{\mathfrak{g}}^2} \cong \frac{\mathfrak{g}}{\mathfrak{g}^2 + \mathfrak{h}}$$

is called the conormal module of  $\bar{\mathfrak{g}}$ . Denote by  $T(M)$  the torsion submodule of  $M$ , and by  $N := M/T(M)$  the torsionless factored module. We have the following exact sequence:

$$0 \rightarrow T(M) \rightarrow M \rightarrow N \rightarrow 0.$$

In case  $L$  is a line on an isolated complete intersection singularity  $X$ , this sequence splits. The dimension of  $T(M)$ , as a  $\mathbb{C}$  vector space, is called the *torsion number* of  $L$  and  $X$ , denoted by

$$\varrho(L, X) := \dim_{\mathbb{C}} T(M).$$

When  $L$  is a line on a hypersurface  $X$  with isolated singularity, then  $\lambda = \varrho(L, X)$ . In fact, the defining equation  $h$  of  $X$  can be written in the form  $h \equiv xA_1(x)y_1 \pmod{\mathfrak{g}^2}$  by a coordinate transformation preserving  $L$ , which has been taken to be the  $x$ -axis. A calculation shows (see [7] for details) that

$$M = \frac{\mathfrak{g}}{(xA_1(x)y_1) + \mathfrak{g}^2}, \quad T(M) = \frac{(y_1)}{(xA_1(x)y_1) + (y_1^2) + y_1(y_2, \dots, y_n)}.$$

Hence

$$\dim T(M) = \dim \frac{\mathcal{O}_1}{(xA_1(x))} = \lambda.$$

**2.5. Semi-continuity of  $\lambda(h)$ .** — For  $h \in \mathfrak{gm}$  with isolated singularity at 0, there exist deformations of  $h$  in  $\mathfrak{gm}$  such that for generic parameters, the deformed function has only  $A_1$  type critical points. Is  $\lambda(h)$  a constant with respect to the deformation? The answer is negative in general, as easy examples show.

In order to prove a semi-continuity result we consider a map

$$H: (\mathbb{C}^{n+1} \times \mathbb{C}^\sigma, 0) \longrightarrow (\mathbb{C} \times \mathbb{C}^\sigma, 0)$$

defined by  $H(z, s) = (h_s(z), s)$ , where  $h_s$  is a deformation of  $h$  in  $\mathfrak{mg}$ . The critical locus of  $H$  is the germ at 0 of

$$C_H := \left\{ (z, s) \in \mathbb{C}^{n+1} \times \mathbb{C}^\sigma \mid \frac{\partial h_s}{\partial z_j} = 0, j = 0, \dots, n \right\}.$$

Let  $\tilde{\mathcal{O}}$  be the stalk at 0 of the structure sheaf of  $\mathbb{C}^{n+1} \times \mathbb{C}^\sigma$ . We consider  $\mathcal{O}$  as a subring of  $\tilde{\mathcal{O}}$ . Denote

$$J(h_s) := \left( \frac{\partial h_s}{\partial z_0}, \dots, \frac{\partial h_s}{\partial z_n} \right) \tilde{\mathcal{O}}.$$

Obviously,  $C_H \cap (L \times \mathbb{C}^\sigma)$  can be defined by the ideal  $J(h_s) + \mathfrak{g}\tilde{\mathcal{O}}$ . Let

$$\tilde{\Lambda} := \frac{\tilde{\mathcal{O}}}{J(h_s) + \mathfrak{g}\tilde{\mathcal{O}}}, \quad \pi: (\mathbb{C}^{n+1} \times \mathbb{C}^\sigma, 0) \longrightarrow (\mathbb{C}^\sigma, 0), \quad \pi(z, s) = s.$$

Denote  $p := \pi|_{C_H \cap (L \times \mathbb{C}^\sigma)}$ .

**THEOREM.** — *Let  $h$  define an isolated singularity at 0.*

- 1)  $p$  is finite analytic map;
- 2) there exist representatives of all the germs considered such that for all  $s \in \mathbb{C}^\sigma$

$$\lambda(h) \geq \sum_{(P,s) \in p^{-1}(s)} \lambda(h_{s,P})$$

where  $h_{s,P}$  denotes the germ of  $h_s$  at point  $P$ .

**Proof.** — By [6], thm 5 (d) and  $\mu(h) < \infty$ ,  $p$  is finite.

Next we prove 2). Still we denote by  $\tilde{\Lambda}$  the sheaf defined by  $\tilde{\Lambda}$ . Since  $p$  is finite,  $p_*(\tilde{\Lambda})$  is again coherent. For any  $s \in \mathbb{C}^\alpha$ , we have

$$(p_*(\tilde{\Lambda}))_s \cong \bigoplus_{(P,s) \in p^{-1}(s)} \tilde{\Lambda}_P.$$

Note that  $p^{-1}(0) = \{0\}$  and the minimal generating set of  $\tilde{\Lambda}_0$  consists of  $\lambda(h)$  elements. For  $s$  near 0, let  $\lambda_s$  be the number of the elements in the minimal generating set of  $(p_*(\tilde{\Lambda}))_s$ . Then  $\lambda_s \leq \lambda(h)$ . Hence

$$\begin{aligned} \lambda(h) &= \dim \left( \frac{\tilde{\Lambda}_0}{p^*(\mathfrak{m}_{(\mathbb{C}^\sigma, 0)}\tilde{\Lambda}_0)} \right) \\ &\geq \sum_{(P,s) \in p^{-1}(s)} \dim \left( \frac{\tilde{\Lambda}_P}{p^*(\mathfrak{m}_{(\mathbb{C}^\sigma, s)}\tilde{\Lambda}_P)} \right) = \sum_{(P,s) \in p^{-1}(s)} \lambda(h_{s,P}). \quad \square \end{aligned}$$

Remark that there always exist deformations of  $h$  in  $\mathfrak{m}_g$  with only  $A_1$  points, called Morsifications. An easy calculation shows that there exist Morsifications  $h_s$  of  $h$  such that the number of  $A_1$  points of  $h_s$  sitting on  $L$  is exact  $\lambda(h)$ .

**Conclusion.** —  $\lambda(h)$  is semi-continuous under deformations and equal to the maximal number of  $A_1$  points of  $h_s$  sitting on  $L$ , where  $h_s$  is a Morsification of  $h$  in  $\mathfrak{m}_g$ . □

### 3. Classification of lines contained in hypersurfaces.

The aim of this section is to classify lines on surfaces in  $\mathbb{C}^3$  (see § 3.3), but first (for completeness) we classify the lines contained in curves in  $\mathbb{C}^2$ . The equivalence is defined by  $\mathcal{R}_L$ -action.

**3.1. THEOREM.** — *A curve  $X \subset \mathbb{C}^2$  with an isolated simple or elliptic simple singularity contains a line passing through its singular point if and only if it is of type*

$$A_{2k-1} (k \geq 1), \quad D_k (k \geq 4), \quad E_7, \tilde{E}_7 \text{ or } \tilde{E}_8.$$

*If we choose the singular point as the origin and the line as the  $x$ -axis of the local coordinate system, the defining equation of  $X$  is  $\mathcal{R}_L$ -equivalent to one of the equations in Table 1.*



Type of $X$	Equations	$\lambda$	Name	$c_L$
$A_{2k-1}$ ( $k \geq 1$ )	$x^k y + y^2 = 0$ ( $k \geq 1$ )	$k$	$A_{2k-1,k}$	$k - 1$
$D_k$ ( $k \geq 4$ )	$x^2 y + y^{k-1} = 0$ ( $k \geq 4$ ) $x^\ell y + xy^2 = 0$ ( $k = 2\ell, \ell \geq 3$ )	2 $\ell$	$D_{k,2}$ $D_{k,\ell}$	$k - 2$ $\ell$
$E_7$	$x^3 y + y^3 = 0$	3	$E_{7,3}$	4
$\tilde{E}_7$	$xy(x+y)(x+ty) = 0$ ( $t \neq 0, 1$ )	3	$\tilde{E}_{7,3}$	6
$\tilde{E}_8$	$x^2 y^2 + \alpha x^4 y + y^3 = 0$ ( $\alpha \neq 0, \frac{1}{4}$ )	4	$\tilde{E}_{8,4}$	6

Table 1. Curves containing  $x$ -axis

Sketch of the proof. — One considers the 2-jet  $j^2 h$  of a function  $h \in (xy, y^2)$ . Let  $r$  be the rank of the coefficient matrix of  $j^2 h$ .

- If  $r = 2$ , then  $h$  is  $\mathcal{R}_L$ -equivalent to  $A_{1,1}$ .
- If  $r = 1$ , one finds that  $h$  is  $\mathcal{R}_L$ -equivalent to  $A_{2k-1,k}$  ( $k > 1$ ) or  $y^2$ .
- If  $r = 0$ , one needs to consider  $j^3 h = ax^2 y + bxy^2 + cy^3$ .
  - ▷ In case  $a \neq 0$ ,  $j^3 h$  is  $\mathcal{R}_L$ -equivalent to  $D_{4,2}$  if  $b^2 - 4ac \neq 0$  and to  $x^2 y$  if  $b^2 - 4ac = 0$ . In the latter case, one considers the higher jets and finds the  $D_{k,2}$  singularities.
  - ▷ In case  $a = 0, b \neq 0$ , one finds the  $D_{2\ell,\ell}$ 's by considering the higher jets of  $h$ .
  - ▷ In case  $a = b = 0, c \neq 0$ , one finds that  $j^4 h$  is  $\mathcal{R}_L$ -equivalent to  $E_{7,3}$  or  $y^3 + x^2 y^2$  or  $y^3$ . If  $j^4 h \overset{\mathcal{R}_L}{\rightsquigarrow} y^3 + x^2 y^2$  (where  $\overset{\mathcal{R}_L}{\rightsquigarrow}$  means "to be  $\mathcal{R}_L$ -equivalent to"), then  $j^5 h \overset{\mathcal{R}_L}{\rightsquigarrow} y^3 + x^2 y^2 + \alpha x^4 y \overset{\mathcal{R}_L}{\rightsquigarrow} \tilde{E}_{8,4}$  ( $\alpha \neq 0, \frac{1}{4}$ ). One stops here since the singularity of  $h$  is neither simple nor elliptic simple if  $j^4 h \overset{\mathcal{R}_L}{\rightsquigarrow} y^3$  or  $j^5 h \overset{\mathcal{R}_L}{\rightsquigarrow} y^3 + x^2 y^2 + \alpha x^4 y$  ( $\alpha = 0, \frac{1}{4}$ ).
  - ▷ It remains to study the case  $j^3 h = 0$ . In the generic case,  $j^4 h$  is  $\mathcal{R}_L$ -equivalent to  $\tilde{E}_{7,3}$ . In the non-generic case, the singularity of  $h$  is neither simple nor elliptic simple.  $\square$

PROPOSITION. — If  $h \in \mathfrak{mg}$  defines an isolated singularity and  $n = 1$ , then  $c_L = \mu - \lambda$ .

*Proof.* — It is an easy exercise in algebra to show that

- for any  $n \geq 1$ ,  $c_L = \mu - \lambda + \nu$  where  $\nu = \dim \frac{(\mathfrak{m}J(h)) \cap \mathfrak{m}\mathfrak{g}}{\tau_{\mathfrak{g}}(h)}$ ;
- if  $n = 1$ , we have  $\nu = 0$ . □

**3.2.** — A class of singularities  $S$  (with respect to an equivalence) is *adjacent* to a class  $T$  (notation  $T \leftarrow S$ ) if every function  $f \in S$  can be deformed into a function of  $T$  by an arbitrarily small perturbation (cf. [3]).

For example,  $x^2y + y^6 + cy^5$  is  $\mathcal{R}_L$ -equivalent to  $D_{6,2}$ , hence

$$D_{6,2} \leftarrow D_{7,2}.$$

In the following diagram, we record some adjacencies from the proof of the theorem above, called the classification tree. Note that it does not contain all the adjacencies.

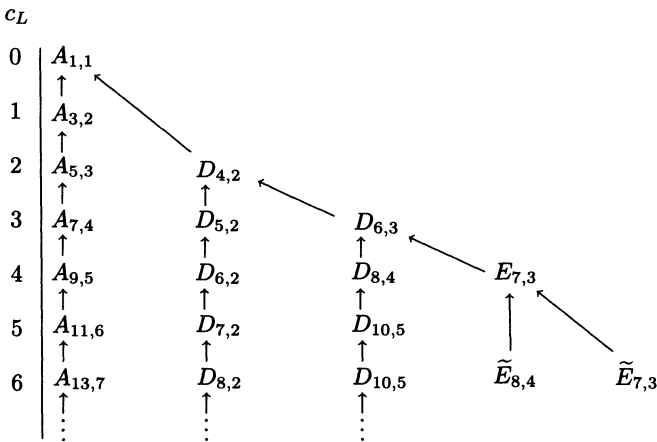


Diagram 1. Classification tree 1

**3.3. THEOREM.** — A surface  $X \subset \mathbb{C}^3$  with a simple isolated singularity contains a line passing through its singular point if and only if it is of type :

$$A_k \ (k \geq 1), \quad D_k \ (k \geq 4), \quad E_6, \text{ or } E_7.$$

Moreover, if we choose the singular point of  $X$  as the origin and the line  $L$  on  $X$  as the  $x$ -axis in  $\mathbb{C}^3$ , that is,  $L$  is defined by the ideal  $\mathfrak{g} = (y, z)$ , then the defining equation of  $X$  is  $\mathcal{R}_L$ -equivalent to one of the equations in Table 2.

Type of $X$	Equations	$\lambda$	Name	$c_L$
$A_k$ ( $k \geq 1$ )	$xy + z^{k+1} = 0$	1	$A_{k,1}$	$k - 1$
	$x^\ell y + x^s z^2 + yz = 0$ ( $k = 2\ell + s - 1, \ell \geq 2, s \geq 0$ )	$\ell$	$A_{k,\ell}$	$k - 1$
$D_k$ ( $k \geq 4$ )	$x^2y + y^{k-1} + z^2 = 0$	2	$D_{k,2}$	$k - 1$
	$x^2y + xz^2 + y^2 = 0$	2	$D_{5,2}^*$	4
	$x^\ell y + xy^2 + z^2 = 0$ ( $k = 2\ell, \ell \geq 3$ )	$\ell$	$D_{k,\ell}$	$k - 1$
	$x^\ell y + xz^2 + y^2 = 0$ ( $k = 2\ell + 1, \ell \geq 3$ )	$\ell$	$D_{k,\ell}$	$k - 1$
$E_6$	$x^2z + y^3 + z^2 = 0$	2	$E_{6,2}$	5
$E_7$	$x^3y + y^3 + z^2 = 0$	3	$E_{7,3}$	6

Table 2. Simple surface singularities passing through  $x$ -axis

Sketch of the proof. — It is just classifying the functions in  $(y, z)\mathfrak{m}$  by choosing all the coordinate transformations in  $\mathcal{R}_L$ . One starts from the 2-jet of  $h \in (y, z)\mathfrak{m}$ :

$$j^2h = 2a_{12}xy + 2a_{13}xz + a_{22}y^2 + 2a_{23}yz + a_{33}z^2, \quad a_{ij} = a_{ji}.$$

Let  $r$  be the rank of the coefficient matrix  $(a_{ij})$  of  $j^2h$ .

- If  $r = 3$ , then  $(a_{12}, a_{13}) \neq 0$ . We can assume  $a_{12} \neq 0$ . Then

$$j^2h \overset{\mathcal{R}_L}{\rightsquigarrow} xy + az^2 \overset{\mathcal{R}_L}{\rightsquigarrow} xy + z^2 \overset{\mathcal{R}}{\rightsquigarrow} A_1$$

where we still denote by  $x, y, z$  the new coordinates by abuse of notations.

- Suppose  $r = 2$ . If  $(a_{12}, a_{13}) \neq 0$ , then  $j^2h \overset{\mathcal{R}_L}{\rightsquigarrow} xy$ . The higher order jet  $j^{k+1}h \overset{\mathcal{R}_L}{\rightsquigarrow} xy + az^{k+1}$  which, by Theorem 3.2, is  $(k + 1)$ - $\mathcal{R}_L$ -determined in  $(y, z)\mathfrak{m}$ , and  $\mathcal{R}_L$ -equivalent to  $xy + z^{k+1}$  if  $a \neq 0$ .

If  $(a_{12}, a_{13}) = 0$ ,  $j^2h \overset{\mathcal{R}_L}{\rightsquigarrow} yz$ . For  $\ell \geq 2$ ,  $j^{\ell+1}h \overset{\mathcal{R}_L}{\rightsquigarrow} yz + ax^\ell y + bx^\ell z$ .

▷  $ab \neq 0$ :  $j^{\ell+1}h \overset{\mathcal{R}_L}{\rightsquigarrow} yz + x^\ell y + z^2$ , which is  $A_{2\ell-1,\ell}$ .

▷  $ab = 0, a \neq 0$ :  $j^{\ell+1}h \overset{\mathcal{R}_L}{\rightsquigarrow} yz + x^\ell y$  which is not finitely  $\mathcal{R}_L$ -determined in  $(y, z)\mathfrak{m}$ . But  $j^{\ell+s+1}h \overset{\mathcal{R}_L}{\rightsquigarrow} yz + x^\ell y + \alpha x^s z$  which, if  $\alpha \neq 0$ , is  $(\ell + s + 1)$ - $\mathcal{R}_L$ -determined in  $(y, z)\mathfrak{m}$ ,  $\mathcal{R}_L$ -equivalent to  $yz + x^\ell y + x^s z$ .

- Suppose  $r = 1$ . We may assume  $j^2h = z^2$ . A calculation shows that

$$j^3h \overset{\mathcal{R}_L}{\rightsquigarrow} z^2 + axy^2 + bx^2y + cx^2z + ey^3$$

which is  $\mathcal{R}_L$ -equivalent to  $z^2 + x^2y + ey^3$  if  $b \neq 0$ . Further study of this case, gives  $D_{k,2}$  ( $k \geq 4$ ). If  $b = 0$ , we have

- ▷  $ac \neq 0$ :  $h$  is  $\mathcal{R}_L$ -equivalent to  $D_{5,2}^*$ .
  - ▷  $a \neq 0, c = 0$ : by studying the higher jet of  $h$ , we obtain  $D_{2\ell,\ell}$  and  $D_{2\ell+1,\ell}$  ( $\ell \geq 3$ ).
  - ▷  $a = 0, ce \neq 0$ : we obtain  $E_{6,2}$ .
  - ▷  $a = c = 0, e \neq 0$ : we can write  $j^3 = z^2 + y^3$ , and  $j^4h \overset{\mathcal{R}_L}{\rightsquigarrow} z^2 + y^3 + \alpha x^3y + \beta x^3z + \gamma x^2y^2$ . A calculation shows that  $h$  is  $\mathcal{R}_L$ -equivalent to  $E_{7,3}$  if  $\alpha \neq 0$ . And in case  $\alpha = 0$ , there are no simple germs with 4-jet  $\mathcal{R}_L$ -equivalent to  $z^2 + y^3 + \beta x^3z + \gamma x^2y^2$ .
  - ▷  $a = e = 0$ : there are no simple germs with 3-jet  $\mathcal{R}_L$ -equivalent to  $z^2 + cx^2z$ .
- If  $r = 0$ , there are no simple germs with 2-jet  $\mathcal{R}_L$ -equivalent to 0.

$E_8$  does not appear in the list. An intuitive reason for this is that one can bring the 4-jet of the  $E_k$  ( $k \geq 7$ ) singularities into the normal form:  $z^2 + y^3 + ax^3y$ . In case  $a \neq 0$ , one has  $E_7$ , otherwise, there is no term  $x^4$ , so one can never get  $E_8$ .

The list of  $\mathcal{R}$ -simple singularities is now exhausted.

One can easily calculate  $\lambda(h) = 1, 2$ , up to  $\lfloor \frac{1}{2}(k + 1) \rfloor$  when  $h$  defines an  $A_k$  surface,  $\lambda(h) = 2$  or  $\lfloor \frac{1}{2}k \rfloor$  when  $h$  defines a  $D_k$  surface, and so on. □

**3.4. COROLLARY.**

- 1) *There does not exist smooth curves on surface with  $E_8$  type isolated singularity.*
- 2) *All the normal forms of the germs in table 2 are also  $\mathcal{R}_L$ -simple. And all the  $\mathcal{R}_L$  simple germs of  $(y, z)\mathfrak{m}$  are contained in Table 2.*

*Proof.* — 1) follows from the proof of the theorem in § 3.3.

2) A germ  $h \in (y, z)\mathfrak{m}$  is  $\mathcal{R}_L$ -simple if  $c_L(h) < \infty$  and any small deformation  $\tilde{h}$  of  $h$  in  $(y, z)\mathfrak{m}$  cuts only finite number of the  $\mathcal{R}_L$ -orbits of  $(y, z)\mathfrak{m}$ . It follows from the classification procedure that all the germs

in Table 2 are  $\mathcal{R}_L$ -simple and that they are the only ones. All  $\mathcal{R}_L$ -simple germs in  $(y, z)m$  are also  $\mathcal{R}$ -simple germs, which are all contained in Table 2 except  $E_8$ .  $\square$

**3.5. Remarks.** — For a hypersurface  $X$  defined by  $h = 0$ , two lines  $L_1$  and  $L_2$  in  $X$  are in one class if there exists a  $\varphi \in \mathcal{R}$  such that  $\varphi(L_1) = L_2$  and  $h \circ \varphi = h$ .

The results of [5] say that there exist  $k$ , 3, 2 and 1 families of smooth curves on  $A_k$  ( $k \geq 1$ ),  $D_k$  ( $k \geq 4$ ),  $E_6$  and  $E_7$  surfaces respectively. In our classification of smooth curves on  $A$ - $D$ - $E_6$ - $E_7$  surfaces above, there exist  $\lceil \frac{1}{2}(k+1) \rceil$ , 2, 1 and 1 class(es) smooth curves on  $A_k$  ( $k \geq 1$ ),  $D_k$  ( $k \geq 4$ ),  $E_6$  and  $E_7$  surfaces respectively. The reason for this is the symmetry property of the simple singularities. Especially, there is only one class of smooth curves on  $A_1$ ,  $A_2$ ,  $D_4$ ,  $E_6$  and  $E_7$  surface. There exist two different classes of smooth curves on  $D_5$  surface with the same  $\lambda = 2$ . On  $A_k$  ( $k \geq 3$ ) and  $D_k$  ( $k \geq 6$ ) surfaces the number  $\lambda$  tells the differences of the smooth curves on these surfaces.

**3.6. The classification tree.** — We record some adjacencies in the proof of the theorem in § 3.3 in the classification tree 2 (Diagram 2). Note that this table contains only some of the adjacencies (cf. § 3.2)

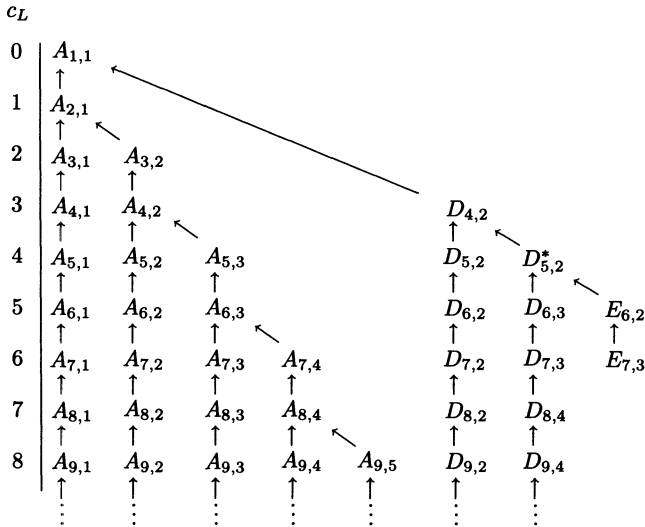


Diagram 2. The classification tree 2

**3.7. Lines on surfaces with simple elliptic singularities.** — If we continue the calculations for the case  $r = 1, 0$  in the proof of Theorem 3.3 and record the adjacencies appeared, we obtain the following theorem and classification tree.

**THEOREM.** — *A surface  $X$  with simple elliptic singularity at  $O$  has a line  $L$  passing through  $O$ . And if one chooses  $L$  as the  $x$ -axis of the local coordinate system, the defining equation of  $X$  is  $\mathcal{R}_L$ -equivalent to one of the equations in Table 3.*

We give the explanation of the notations in Table 3.

Type of $X$	Equations	$\lambda$	Name	$c_L$
$\tilde{E}_6$	$x^2y + d_0xz^2 + d_1y^3 + d_2y^2z + d_3yz^2 + d_4z^3 = 0$ (for generic $d_i$ ( $0 \leq i \leq 4$ ), especially $\Delta_1 \neq 0$ )	2	$\tilde{E}_{6,2}$	7
$\tilde{E}_7$	$x^2z + x^3y + bx^2y^2 + cxy^3 + dy^4 + z^2 = 0$ ( $\theta \neq 0, 1, \Delta_2 \neq 0$ )	2	$\tilde{E}_{7,2}$	8
	$xy(x - y)(x - \nu y) + z^2 = 0$ ( $\nu \neq 0, 1$ )	3	$\tilde{E}_{7,3}$	8
$\tilde{E}_8$	$x^3z + \gamma x^2y^2 + \delta x^4y + y^3 + z^2 = 0$ ( $D \neq 0$ )	3	$\tilde{E}_{8,3}$	9
	$\alpha x^4y + x^2y^2 + y^3 + z^2 = 0$ ( $\alpha \neq 0, \frac{1}{4}$ )	4	$\tilde{E}_{8,4}$	9

Table 3. Simple elliptic surface singularities containing  $x$ -axis

$$\Delta_1 := \det \begin{bmatrix} 2d_4 & 0 & 0 & -4d_0d_1 & -3d_0d_2 & -2d_0d_3 \\ c & 0 & -6d_1 & -4d_2 & -2d_3 & 0 \\ 0 & -12d_1 & -8d_2 & -4d_3 & 0 & -c^2 \\ 0 & 0 & 4d_1 & 3d_2 & 2d_3 & d_4 \\ 0 & d_2 & 2d_3 & 3d_4 & -c^2 & 0 \\ 0 & 0 & d_2 & 2d_3 & 3d_4 & -c^2 \end{bmatrix},$$

$$\Delta_2 := \det \begin{bmatrix} 2 & 3 & 2b & c & 0 & 0 \\ c & -1 & 3 & 2b & c & 0 \\ 0 & 0 & 3 + 2b & 2b + 3c & c + 4d & 0 \\ 0 & 3 + 2b & 2b + 3c & c + 4d & 0 & 0 \\ 0 & 0 & -1 & 3 & 2b & c \\ 0 & 0 & 0 & 3 + 2b & 2b + 3c & c + 4d \end{bmatrix}.$$

$\theta$  is the cross ratio of the four lines defined by

$$-\frac{1}{4}x^4 + x^3y + bx^2y^2 + cxy^3 + dy^4 = 0$$

and

$$D := \frac{9}{4} \pm 6\gamma\delta - \frac{4}{3}\gamma^3 + \frac{16}{3}\delta^3 - \frac{4}{3}\gamma^2\delta^2.$$

**3.8. Remark.** — For  $\tilde{E}_{6,2}$ , there are two  $\mathcal{R}_L$  moduli.  $\tilde{E}_{7,2}$ ,  $\tilde{E}_{7,3}$ ,  $\tilde{E}_{8,3}$  and  $\tilde{E}_{8,4}$  are one  $\mathcal{R}_L$  modular.

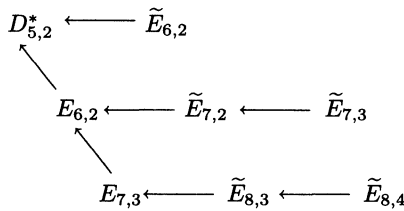


Diagram 3. Classification tree 3

**3.9. Invariance of  $\lambda$  under sections with hyperplanes through  $L$ .** — Let  $L$  be a line contained in a hypersurface  $X \subset \mathbb{C}^{n+1}$  with isolated singularity,  $H$  a generic hyperplane in the pencil of hyperplanes passing through  $L$ . Then  $X \cap H$  has also isolated singularity and contains  $L$ . A straightforward computation shows:

PROPOSITION. —  $\lambda(X \cap H) = \lambda(X)$ .

In fact we can continue cutting until we are in the curve case. If we apply this on the surfaces defined by the equation in Table 2, we have

$X$	$A_{k,\ell}$	$D_{k,\ell}$	$D_{5,2}^*$	$E_{6,2}$	$E_{7,3}$
$X \cap H$	$A_{2\ell-1,\ell}$	$A_{2\ell-1,\ell}$	$A_{3,2}$	$A_{3,2}$	$A_{5,3}$

Obviously we have in these examples  $\mu(X \cap H) = 2\lambda - 1$ . This reminds very much to Milnor’s double point formula

$$\mu = 2\delta + 1 - r,$$

where  $\delta$  is the maximal number of double points on a deformed curve, and  $r$  is the number of the branches of the curve. But this is a coincidence, which holds since  $X \cap H$  is of type  $A_{\text{odd}}$ . According to the above proposition

$$\lambda = \lambda(X) = \lambda(X \cap H) \leq \delta(X \cap H).$$

Inspection shows  $\lambda(A_{\text{odd}}) = \delta(A_{\text{odd}})$ . However for  $X$  with  $\tilde{E}_{6,2}$  type singularity, this is not the case.  $X \cap H$  is of  $D_{4,2}$  type singularity and  $\delta = 3, \lambda = 2$  and  $r = 3$ .

**3.10. Remark.** — For all the germs in Tables 2 and 3, we have  $c_L = \mu - 1$ , especially  $c_L(h)$  does not depend on  $\lambda$ . This means that for those surfaces we can not move from one position of a line into another position. This was a surprise to us; in other dimensions this is different (see also Question 4.4).

### 4. Lines on hypersurfaces in $\mathbb{C}^4$ .

About the existence of lines on hypersurfaces in  $\mathbb{C}^4$ , we mention first that on corank 2 singularities there always exist lines due to the suspension  $xy + g(z, w)$ . This gives lines on, for example, the  $E_8$  hypersurface in  $\mathbb{C}^4$ . And  $\lambda = 1$  all the time. For corank 3 singularities one can consider the suspension  $g(x, y, z) + w^2$ . If  $g$  contains the  $x$ -axis, so does this suspension with the same  $\lambda$ . But there are examples of corank 3 singularities which do not contain any lines. Here is one of them:

$$h = w^2 + x^{11} + y^{13} + z^{15} = 0.$$

It is natural to consider the above classifications with four variables. We give here the beginning of the classification for simple singularities. The proof is very similar to the cases considered in § 3. Also here we record some of adjancencies in the classification tree. We distinguish between  $\lambda = 1$  and  $\lambda > 1$ .

**4.1. THEOREM.** — *Let  $X \subset \mathbb{C}^4$  be hypersurfaces with isolated simple singularity. If  $X$  contains  $x$ -axis and  $\lambda = 1$ , then the defining equation of  $X$  is  $\mathcal{R}_L$ -equivalent to one of the equations in Table 4. □*



Type of $X$	Equations	$\lambda$	Name	$c_L$
$A_k$ ( $k \geq 1$ )	$xy + z^{k+1} + w^2 = 0$	1	$A_{k,1}$	$k - 1$
$D_k$ ( $k \geq 4$ )	$xy + z^2w + w^{k-1} = 0$	1	$D_{k,1}$	$k - 1$
$E_6$	$xy + z^4 + w^3 = 0$	1	$E_{6,1}$	5
$E_7$	$xy + z^3w + w^3 = 0$	1	$E_{7,1}$	6
$E_8$	$xy + z^5 + w^3 = 0$	1	$E_{8,1}$	7

Table 4

**4.2. THEOREM.** — *Let  $X \subset \mathbb{C}^4$  be hypersurfaces with simple isolated singularity. If  $X$  contains  $x$ -axis,  $\lambda > 1$  and  $c_L(X) \leq 8$ , then the defining equation of  $X$  is  $\mathcal{R}_L$  equivalent to one of the equations in Table 5.  $\square$*

**4.3. Remarks.**

1) One may compare table 4 with the list of simple hypersurface singularities in § 1.3.

2) If we compare with the surface case, we find that on  $E_8$  hypersurface there exist two classes of lines. Also on other hypersurfaces, there exists more lines than in the case of surfaces in  $\mathbb{C}^3$ .

**4.4. Question.** — As claimed by the proposition in § 3.1, all the known examples show the following remarkable formulæ:

$$c_L = \mu + (n - 2)\lambda - n + 1.$$

Is it true for any hypersurfaces with isolated singularities in  $\mathbb{C}^{n+1}$ ?

**4.5. Higher order invariants.** — For  $h \in \mathfrak{m}_{\mathfrak{g}}$  defining an isolated singularity, there exists the following filtration:

$$J(h) + \mathfrak{g} \supset J(h) + \mathfrak{g}^2 \supset \cdots \supset J(h) + \mathfrak{g}^k \supset \cdots \supset J(h).$$

Define

$$\Lambda_k = \Lambda_k(h) := \frac{\mathcal{O}}{J(h) + \mathfrak{g}^k}, \quad k = 1, 2, \dots$$

Type of X	Equations	$\lambda$	Name	$c_L$
$A_k$ ( $k \geq 1$ )	$x^\ell y + x^s z^2 + yz + w^2 = 0$ ( $k = 2\ell + s - 1, \ell \geq 2, s \geq 0$ )	$\ell$	$A_{k,\ell}$	$3\ell + s - 3$
$D_k$ ( $k \geq 4$ )	$x^2 y + y^{k-1} + z^2 + w^2 = 0$	2	$D_{k,2}$	$k$
	$x^2 z + x^{\ell-3} w + xy^2 + wz = 0$ ( $\ell \geq 5$ )	2	$D_{\ell,2}^*$	$\ell$
	$x^\ell y + xy^2 + z^2 + w^2 = 0$ ( $\ell \geq 3$ )	$\ell$	$D_{2\ell,\ell}$	$3\ell - 2$
	$x^\ell z + xy^2 + z^2 + w^2 = 0$ ( $\ell \geq 3$ )	$\ell$	$D_{2\ell+1,\ell}$	$3\ell - 1$
$E_6$	$x^2 y + y^2 + z^3 + w^2 = 0$	2	$E_{6,2}$	6
$E_7$ {	$x^2 z + y^3 + xyw + zw = 0$	2	$E_{7,2}$	7
	$x^3 y + y^3 + z^2 + w^2 = 0$	3	$E_{7,3}$	8
$E_8$	$x^2 z + y^3 + xw^2 + zw = 0$	2	$E_{8,2}$	8

Table 5

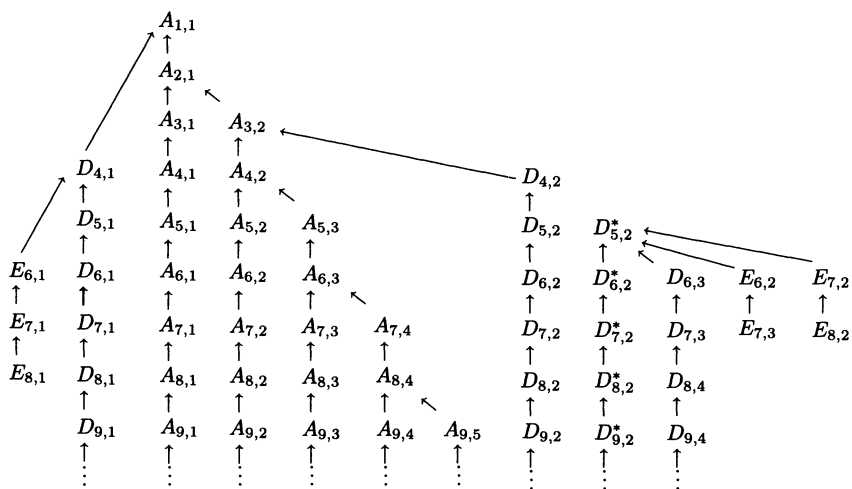


Diagram 4. Classification tree 4

and the higher order invariants:

$$\lambda_k = \lambda_k(h) := \dim_{\mathbb{C}} \Lambda_k, \quad k = 1, 2, \dots$$

Note that there exists a  $k_0$  such that

$$\lambda = \lambda_1 \leq \lambda_2 \leq \dots \leq \lambda_{k_0} = \mu.$$

Denote

$$\kappa = \kappa(h) = [\lambda_1, \lambda_2, \dots, \lambda_{k_0} = \mu],$$

where  $k_0$  is the minimal  $k$  such that  $\lambda_k = \mu$ , called the length of the sequence  $\kappa(h)$ .

The  $\kappa(h)$  give more information about how a line is embedded into a singular hypersurface. Recall that in Tables 2 and 5, we have  $D_{\ell,2}$  and  $D_{\ell,2}^*$  ( $\ell \geq 5$ ) with the same  $\lambda$ .

Easy calculations show the following:

For surfaces in  $\mathbb{C}^3$ ,

- $\kappa(D_{5,2}) = [2, 3, 4, 5]$  with length 4, and
- $\kappa(D_{5,2}^*) = [2, 4, 5]$  with length 3.

For the  $D_k$  type hypersurfaces in  $\mathbb{C}^4$ ,

- $\kappa(D_{\ell,2}) = [2, \dots, \ell]$  ( $\ell \geq 5$ ) with length  $\ell - 1$ ,
- $\kappa(D_{5,2}^*) = [2, 4, 5]$  with length 3,
- $\kappa(D_{2\ell,2}^*) = [2, 5, 7, \dots, 2\ell - 1, 2\ell]$  with length  $\ell \geq 3$ , and
- $\kappa(D_{2\ell+1,2}^*) = [2, 5, 7, \dots, 2\ell - 1, 2\ell + 1, ]$  with length  $\ell \geq 3$ .

So, higher order invariants  $\lambda_k$ 's distinguish  $D_{\ell,2}$  and  $D_{\ell,2}^*$ .

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