

# Euler number of the compactified Jacobian and multiplicity of rational curves.

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## Abstract

In this paper we show that the Euler number of the compactified Jacobian of a rational curve  $C$  with locally planar singularities is equal to the multiplicity of the  $\delta$ -constant stratum in the base of a semi-universal deformation of  $C$ . In particular, the multiplicity assigned by Yau, Zaslow and Beauville to a rational curve on a K3 surface  $S$  coincides with the multiplicity of the normalisation map in the moduli space of stable maps to  $S$ .

## Introduction

Let  $C$  be a reduced and irreducible projective curve with singular set  $\Sigma \subset C$  and let  $n : \tilde{C} \rightarrow C$  be its normalisation. The generalised Jacobian  $JC$  of  $C$  is an extension of  $J\tilde{C}$  by an affine commutative group of dimension

$$\delta := \dim H^0(n_*(\mathcal{O}_{\tilde{C}})/\mathcal{O}_C) = \sum_{p \in \Sigma} \delta(C, p)$$

so that  $\dim JC = \dim J\tilde{C} + \delta = g(\tilde{C}) + \delta$  is equal to the arithmetic genus  $g_a(C)$  of  $C$ . The non-compact space  $JC$  is naturally an open subset of the *compactified Jacobian*  $\overline{JC}$  of  $C$ , whose points correspond to isomorphism classes of rank one torsion free sheaves  $\mathcal{F}$  of degree zero (i.e.  $\chi(\mathcal{F}) = 1 - g_a(C)$ ) on  $C$ . The space  $\overline{JC}$  is irreducible if and only if  $C$  has planar singularities; then  $\overline{JC}$  is in fact a compactification of  $JC$ , i.e.,  $JC$  is dense in  $\overline{JC}$ . If moreover  $C$  is rational and unibranch, then  $\overline{JC}$  is topologically the product of compact spaces  $M(C, p)$  for every  $p \in \Sigma$ . The space  $M(C, p)$  only depends on the analytic singularity  $(C, p)$ ; it can be defined as  $\overline{JD}$  for any rational curve  $D$  having  $(C, p)$  as unique singularity.

Let  $B = B(C, p)$  be the base of a semi-universal deformation of the singularity  $(C, p)$ . Inside  $B$  let  $B^\delta = B^\delta(C, p)$  be the locus of points for which  $\delta$  remains constant. This means that

$$t \in B^\delta \Leftrightarrow \sum_{p \in C_t} \delta(C_t, p) = \delta(C).$$

The codimension of  $B^\delta$  is  $\delta(C, p)$ ; its multiplicity  $m(C, p)$  at  $[(C, p)]$  is by definition equal to the number of intersection points with a generic  $\delta$ -dimensional smooth subspace of  $B$ . The  $\delta$ -constant stratum can be defined in a similar way for a semi-universal

deformation of a projective curve with only planar singularities. In this paper we show the following theorem.

**Theorem 1.** *Let  $(C, p)$  be a reduced plane curve singularity. Then the Euler number of  $M(C, p)$  is equal to the multiplicity of the  $\delta$ -constant stratum:*

$$e(M(C, p)) = m(C, p).$$

*Let  $C$  be a projective, reduced rational curve with only planar singularities. Then  $e(\overline{\mathcal{J}}C) = m(C)$ , the multiplicity of the  $\delta$ -constant stratum  $B^\delta$  at 0.*

Note that this gives an independent proof of the following result of Beauville: Let  $C$  be an irreducible and reduced rational curve with planar singularities. Then  $e(\overline{\mathcal{J}}C)$  can be written as a product over the singularities of  $C$  of a number only depending on the type of the singularity, and it is the same for  $C$  and its minimal unibranch partial normalisation.

Theorem 1 has an application in the following situation. Let  $X$  be a (smooth) K3 surface with a complete (hence  $g$ -dimensional) linear system of curves of genus  $g$ . Under the assumption that all curves in the system are irreducible and reduced, it was shown in [Y-Z] and [B] that the “number”  $n(g)$  of rational curves occurring in the linear system, is equal to the  $g^{\text{th}}$  coefficient of the 24<sup>th</sup> power of the partition function, i.e:

$$\sum_{g \geq 0} n(g)q^g = \frac{q}{\Delta(q)}$$

where  $\Delta(q) = q \prod_{n \geq 1} (1 - q^n)^{24}$ . In this counting, a rational curve  $C$  in the linear system contributes  $e(\overline{\mathcal{J}}C)$  to  $n(g)$ :

$$n(g) = \sum_C e(\overline{\mathcal{J}}C).$$

If  $C$  is a rational curve with only nodes as singularities, then  $e(\overline{\mathcal{J}}C) = 1$ , so that  $e(\overline{\mathcal{J}}C)$  seems to be a reasonable notion of multiplicity. Theorem 1 implies that  $e(\overline{\mathcal{J}}C)$  is always positive, and in principle allows an explicit computation of it (see section G).

In fact, we prove a more precise statement. For any projective scheme  $Y$  and  $d \in H_2(Y, \mathbf{Z})$  let  $M_{0,0}(Y, d)$  be the moduli space of genus zero stable maps  $f : \mathbf{P}^1 \rightarrow Y$  with  $f_*([\mathbf{P}^1]) = d$ . Under the above assumptions on the K3 surface  $X$  and the linear system corresponding to  $d$ , the space  $M_{0,0}(X, d)$  is a zero-dimensional scheme. If  $C \xrightarrow{i} X$  is a rational curve in  $X$  (always assumed to be irreducible and reduced),  $n : \mathbf{P}^1 \rightarrow C$  its normalisation, then  $f = i \circ n : \mathbf{P}^1 \rightarrow X$  is a point of  $M_{0,0}(X, d)$ . The moduli space  $M_{0,0}(X, d)$  contains naturally as a closed subscheme  $M_{0,0}(C, [C])$ , the submoduli space of maps whose scheme theoretic image is  $C$ ; the latter scheme is of course defined for any projective reduced curve  $C$ , and it is zero-dimensional if the curve is rational. More generally,  $M_{g,0}(C, [C])$  is zero dimensional, where  $g$  denotes the genus of the normalisation of  $C$ . The following theorem gives another interpretation

of  $e(\bar{J}C)$  in terms of the length of such zero-dimensional schemes.

**Theorem 2.** *Let  $C$  be a reduced, irreducible projective curve with only planar singularities, and let  $g$  be the genus of its normalisation. Then  $m(C) = l(M_{g,0}(C, [C]))$ . If moreover  $C$  is rational and contained in a smooth K3 surface  $X$ , then  $e(\bar{J}C) = l(M_{0,0}(X, d), f)$  (length of the zero-dimensional component supported at  $f$ ).*

We now sketch briefly the idea of the proof of Theorem 1.

Let  $\mathcal{C} \rightarrow B$  be a semi-universal family of deformations of a curve  $C$  with planar singularities. We prove that the relative compactified Jacobian  $\bar{J}\mathcal{C}$  is smooth; moreover, given any deformation  $\mathcal{C}' \rightarrow S$  of  $C$  with a smooth base,  $\bar{J}\mathcal{C}'$  is smooth if and only if the image of  $TS$  is transversal in  $TB$  to the  $\delta$ -codimensional vector space  $V$ , the support of the tangent cone to the  $\delta$ -constant stratum  $B^\delta$ .

Assume now  $C$  is rational and has  $p$  as unique singularity. We have to show that  $e(\bar{J}C) = m(C, p)$ . Choose a one-parameter family  $W_t$  of smooth  $\delta$ -dimensional subspaces of  $B$  such that  $0 \in W_0$ ,  $T_{W_0,0} \cap V = \{0\}$ , and for general  $t$  the intersection  $W_t \cap B^\delta$  is a set of  $m(C, p)$  distinct points corresponding to nodal curves.

Let  $\mathcal{C}_t \rightarrow W_t$  be the induced families. Then  $\bar{J}\mathcal{C}_t$  is a family of smooth compact varieties, hence  $e(\bar{J}\mathcal{C}_t)$  does not depend on  $t$ . Arguing as in [Y-Z] and [B], we prove that  $e(\bar{J}\mathcal{C}_0) = e(\bar{J}C)$ , while  $e(\bar{J}\mathcal{C}_t) = m(C, p)$  for  $t$  general.

**Conventions.** In this paper we will always work over the complex numbers, and open will mean open in the strong (euclidean) topology (unless of course we specify Zariski open).

**Preliminaries.** We will use the language of deformation functors; we recall a few facts about them for the reader's convenience.

A deformation functor  $D$  will always be a covariant functor from local artinian  $\mathbf{C}$ -algebras to sets, satisfying Schlessinger's conditions (H1), (H2), (H3), hence admitting a hull (see [Sch]). In particular  $D$  admits a finite-dimensional tangent space, which we denote by  $TD$ , functorial in  $D$ . A functor is smooth if its hull is. The dimension of the functor will be equal to the dimension of the hull. We will need the following elementary result.

**Lemma.** *Let  $X \rightarrow Y$  and  $Z \rightarrow Y$  be morphisms of smooth deformation functors. Then  $X \times_Y Z$  is smooth of dimension  $\dim X + \dim Z - \dim Y$  if and only if the images of  $TX$  and  $TZ$  span  $TY$ .*

**Proof.** Base change considerations reduce the problem to the case of prorepresentable functors, where it is obvious.  $\diamond$

It would be possible to replace deformation functors with contravariant functors on the category of germs of complex spaces, and the hull with the base of a semi-universal family of deformations. The two viewpoints correspond to working with formal versus

convergent power series.

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## A. Deformations of curves and sheaves.

Let  $C$  be a reduced projective curve, with singular set  $\Sigma$ . Any deformation  $\mathcal{C} \rightarrow S$  of  $C$  over a base  $S$  induces a deformation of its singularities. More precisely, one can introduce the *functor of local deformations* by letting  $D^{loc}(C)(T)$  be the set of isomorphism classes of data  $(U_i, U_i^T)_{i \in I}$ , where  $(U_i)_{i \in I}$  is an affine open cover of  $C$  and, for each  $i$ ,  $U_i^T$  is a deformation of  $U_i$  over  $T$ ; we require that the induced deformations of  $U_{ij} := U_i \cap U_j$  be the same. There is a natural transformation of functors  $loc : D(C) \rightarrow D^{loc}(C)$ ; the induced map of tangent spaces can be identified with the edge homomorphism

$$\mathbf{T}_C^1 \rightarrow H^0(\mathcal{T}_C^1)$$

of the local-to-global spectral sequence for the  $\mathcal{T}^i$ . The kernel of this map is  $H^1(\Theta_C)$ , the cokernel injects in  $H^2(\Theta_C)$  which is zero. The obstruction space  $\mathbf{T}_C^2$  sits in an exact sequence

$$0 \rightarrow H^1(\mathcal{T}_C^1) \rightarrow \mathbf{T}_C^2 \rightarrow H^0(\mathcal{T}_C^2) \rightarrow 0.$$

As  $C$  is reduced,  $\mathcal{T}_C^1$  is supported on a finite set of points, hence  $H^1(\mathcal{T}_C^1) = 0$ . If  $C$  has locally complete intersection singularities, then also  $\mathcal{T}_C^2 = 0$ , so that in that case  $\mathbf{T}_C^2 = 0$ . Hence in such a situation, and in particular when  $C$  is a reduced curve with only planar singularities, the functors  $D(C)$  and  $D^{loc}(C)$  are smooth and  $loc$  is a smooth map.

Let  $\mathcal{F}$  be a torsion free coherent sheaf on  $C$ . Analogously, we denote by  $D(C, \mathcal{F})$  the functor of deformations of the pair, and define the functor of local deformations by letting  $D^{loc}(C, \mathcal{F})(T)$  be the set of isomorphism classes of data  $(U_i, U_i^T, F_i^T)_{i \in I}$  where  $(U_i)_{i \in I}$  is an affine open cover of  $C$ , and for each  $i$ ,  $(U_i^T, F_i^T)$  is a  $T$ -deformation of  $(U_i, \mathcal{F}|_{U_i})$  such that the induced deformations on  $U_{ij}$  are the same.

Again we have a localisation map  $D(C, \mathcal{F}) \rightarrow D^{loc}(C, \mathcal{F})$ . The four functors introduced sit in a natural commutative diagram

$$\begin{array}{ccc} D(C, \mathcal{F}) & \longrightarrow & D^{loc}(C, \mathcal{F}) \\ \downarrow & & \downarrow \\ D(C) & \longrightarrow & D^{loc}(C) \end{array}$$

with horizontally localisation maps and vertically forget maps. Note that this diagram in general is *not* cartesian.

**Proposition A.1.** *The canonical map*

$$D(C, \mathcal{F}) \longrightarrow D(C) \times_{D^{loc}(C)} D^{loc}(C, \mathcal{F})$$

*is smooth.*

**Proof.** We have to show the following: Let  $\mathcal{F}_T, C_T$  be flat deformations of  $C$  and  $\mathcal{F}$  over  $T$ ,  $\xi_T \in D^{loc}(C, \mathcal{F})(T)$  the induced local deformation. If we are given lifts  $C_{T'}$  and  $\xi_{T'}$  over a small extension  $T'$  of  $T$ , then we can lift  $\mathcal{F}_T$  to a deformation  $\mathcal{F}_{T'}$  of  $\mathcal{F}$  over  $C_{T'}$  inducing  $\xi_{T'}$ . This can be done as follows: choose an affine open cover  $U_i$  of  $C$  such that  $\xi_{T'}$  is defined by coherent sheaves  $F'_i$  on the induced cover  $U_{i,T'}$  of  $C_{T'}$ . Assume also that  $U_{ij} := U_i \cap U_j$  is smooth for every  $i \neq j$ .

Let  $F_i$  be the restriction of  $F'_i$  to  $U_{i,T}$ . The fact that  $\mathcal{F}$  induces  $\xi_T$  means that we can find isomorphisms  $\phi_i : \mathcal{F}_T|_{U_{i,T}} \rightarrow F_i$ . The  $\phi_i$  induce isomorphisms  $\phi_{ij} : F_i \rightarrow F_j$  over  $U_{ij,T}$ , satisfying the cocycle condition. What we need to prove is that the  $\phi_{ij}$  can be lifted to  $\phi'_{ij} : F'_i \rightarrow F'_j$ , again satisfying the cocycle condition; then the  $\phi'_{ij}$  can be used to glue together the  $F'_i$ 's to a coherent sheaf  $\mathcal{F}_{T'}$  as required. But on  $U_{ij}$  all the sheaves under consideration are line bundles, hence the obstruction to the existence of such a lifting is an element in  $H^2(C, \mathcal{O}_C)$ , which is zero as  $C$  has dimension 1.  $\diamond$

If  $R$  is a ring and  $M$  is an  $R$ -module, we denote by  $D(R)$ , respectively  $D(R, M)$  the corresponding deformation functors.

**Lemma A.2.** *Let  $C$  be a reduced projective curve,  $\mathcal{F}$  a torsion free module on  $C$ . Let  $\Sigma$  denote the singular locus. Then the natural morphisms of functors*

$$D^{loc}(C) \rightarrow \prod_{p \in \Sigma} D(\mathcal{O}_{C,p}) \quad \text{and} \quad D^{loc}(C, \mathcal{F}) \rightarrow \prod_{p \in \Sigma} D(\mathcal{O}_{C,p}, \mathcal{F}_p)$$

*are isomorphisms.*

**Proof.** Both morphisms are clearly injective. On the other hand, surjectivity is obvious since on the smooth open locus, every infinitesimal deformation is locally trivial and every torsion free sheaf is locally free.  $\diamond$

**Proposition A.3.** *Let  $P$  be a regular local ring of dimension 2,  $f \in P$  a nonzero element, and  $R = P/(f)$ ; assume that  $R$  is reduced. Let  $M$  be a finitely generated, torsion free  $R$ -module of rank 1. Then  $D(R, M)$  is a smooth functor.*

**Proof.** As it is torsion free, the module  $M$  has depth 1. By the Auslander-Buchsbaum theorem (see e.g. [Ma]),  $M$  has a free resolution of length 1 as a  $P$ -module, so is represented as the cokernel of some  $n \times n$  matrix  $A$  with entries from  $P$ :

$$0 \longrightarrow P^n \xrightarrow{A} P^n \longrightarrow M \longrightarrow 0$$

As  $M$  is an  $R$ -module of rank 1, the determinant ideal ( $\det(A)$ ) is equal to  $(f)$ .

Any flat deformation  $M_T$  of  $M$  over  $T$  (as  $P$ -module) is obtained by deforming the

matrix  $A$  to a matrix  $A_T$  with entries from  $P_T := T \otimes_{\mathbf{C}} P$ , so that  $M_T$  has a presentation

$$0 \longrightarrow P_T^n \xrightarrow{A_T} P_T^n \longrightarrow M_T \longrightarrow 0.$$

There is a unique deformation  $R_T$  of  $R$  over  $T$  such that  $M_T$  is a flat  $R_T$ -module, given by the ideal  $(\det(A_T))$ . It follows that the natural transformation

$$D(A) \longrightarrow D(R, M) \quad A_T \mapsto (P_T/\det(A_T), \text{Coker}(A_T))$$

is *smooth*. As  $D(A)$ , the functor of deformations of the matrix  $A$ , is clearly smooth, the functor  $D(R, M)$  is also smooth.  $\diamond$

Note that in the assumption of A.3, although both functors  $D(R, M)$  and  $D(R)$  are smooth, the forgetful morphism  $D(R, M) \rightarrow D(R)$  is not smooth in general.

**Remark A.4.** Let  $R$  be a one-dimensional local  $\mathbf{C}$ -algebra, and let  $M$  be a finitely generated torsion free  $R$ -module. Let  $\hat{R}$  be the completion of  $R$ , and  $\hat{M} = M \otimes_R \hat{R}$ . The natural morphism  $D(R, M) \rightarrow D(\hat{R}, \hat{M})$  is smooth and induces an isomorphism on tangent spaces, and the same is true for  $D(R) \rightarrow D(\hat{R})$ . In fact it is easy to see that the induced morphisms of tangent and obstruction spaces are isomorphisms.

## B. Relative compactified Jacobians.

For any flat projective family of curves  $\mathcal{C} \rightarrow S$  we let  $\overline{\mathcal{C}} \rightarrow S$  be the relative compactified Jacobian (see [R]). For every closed point  $s \in S$  the fiber over  $s$  of  $\overline{\mathcal{C}}$  is canonically isomorphic to the compactified Jacobian  $\overline{\mathcal{C}}_s$ ; in particular, its points correspond to isomorphism classes of torsion free rank 1 degree zero sheaves on  $C_s$ .

Fix a point  $\mathcal{F} \in \overline{\mathcal{C}}$  over  $s \in S$ , and denote again by  $(\overline{\mathcal{C}}, \mathcal{F})$  and  $(S, s)$  the deformation functors induced by the respective germs of complex spaces. Let  $C = C_s$ . Remark that if  $\mathcal{C} \rightarrow S$  is a semi-universal family of deformations of  $C$ , then we have an isomorphism of functors

$$(\overline{\mathcal{C}}, \mathcal{F}) \simeq D(C, \mathcal{F})$$

For a general flat family one has a natural commutative diagram

$$\begin{array}{ccc} (\overline{\mathcal{C}}, \mathcal{F}) & \longrightarrow & D^{loc}(C, \mathcal{F}) \\ \downarrow & & \downarrow \\ (S, s) & \longrightarrow & D^{loc}(C) \end{array}$$

and analogous to **A.1.** one has:

**Proposition B.1.** *The canonical map*

$$(\overline{\mathcal{C}}, \mathcal{F}) \longrightarrow (S, s) \times_{D^{loc}(C)} D^{loc}(C, \mathcal{F})$$

*is smooth.*

We omit the proof, which is almost identical to that of **A.1.**

**Corollary B.2.** *Let  $C$  be a reduced curve with only plane curve singularities. If  $\mathcal{C} \rightarrow S$  is a versal family of deformations of  $C$ , then  $\overline{\mathcal{J}\mathcal{C}}$  is smooth along  $\overline{\mathcal{J}\mathcal{C}}$ , and  $\overline{\mathcal{J}\mathcal{C}}$  has local complete intersection singularities.*

**Proof.** The family is versal if and only if the natural map  $S \rightarrow D(C)$  is smooth. This in turn implies that  $S \rightarrow D^{loc}(C)$  is smooth, hence the first claim follows from Proposition B.1. On the other hand, all fibres of  $\overline{\mathcal{J}\mathcal{C}} \rightarrow S$  have the same dimension  $g_a(C)$ , therefore each of them has local complete intersection singularities.  $\diamond$

**Corollary B.3.** *With the same assumptions as B.2, let  $\mathcal{C}' \rightarrow S'$  be any deformation of  $C$  with smooth base  $S'$ . Let  $\mathcal{F}$  be a torsion free rank 1 degree zero coherent sheaf on  $C$ . Then the relative compactified Jacobian  $\overline{\mathcal{J}\mathcal{C}'}$  is smooth at  $[\mathcal{F}]$  if and only if the image of  $T\mathcal{S}'$  in  $TD^{loc}(C)$  is transversal to the image of  $TD^{loc}(C, \mathcal{F})$ .*

**Proof.** We keep the notation of B.2. The dimension of  $\overline{\mathcal{J}\mathcal{C}'}$  is equal to  $\dim S' + g_a(C)$ . As  $\overline{\mathcal{J}\mathcal{C}'}$  is equal to the fibred product of  $\overline{\mathcal{J}\mathcal{C}}$  and  $S'$  over  $S$ , it follows that  $\overline{\mathcal{J}\mathcal{C}'}$  is smooth at  $[\mathcal{F}]$  if and only if the image of  $T\mathcal{S}'$  in  $TS$  is transversal to that of  $T(\overline{\mathcal{J}\mathcal{C}}, \mathcal{F})$ . Proposition B.1 implies that the image of  $T(\overline{\mathcal{J}\mathcal{C}}, \mathcal{F})$  is the inverse image of the image of  $TD^{loc}(C, \mathcal{F})$  in  $TD^{loc}(C)$ .  $\diamond$

## C. The canonical sub-space $V$

Let  $C$  be a reduced curve with only planar singularities. In this section we study the map

$$D^{loc}(C, \mathcal{F}) \rightarrow D^{loc}(C)$$

at the level of tangent spaces. As both functors are products corresponding to the singularities of  $C$  (Lemma A.2) and the tangent spaces only depend on the formal structure of the singularity (Remark A.4), it suffices to analyse what happens for

$$D(R, M) \rightarrow D(R)$$

where  $P = \mathbf{C}[[x, y]]$ ,  $R = P/(f)$ ,  $f$  a non-zero element of the maximal ideal such that  $R$  is reduced, and  $M$  a torsion free rank one  $R$ -module given by a presentation

$$0 \longrightarrow P^n \xrightarrow{A} P^n \longrightarrow M \longrightarrow 0.$$

**Proposition C.1.** *The image of the map  $TD(R, M) \rightarrow TD(R)$  is the image of the first Fitting ideal  $F_1(M)$  in the quotient ring  $TD(R) = P/(f, \partial_x f, \partial_y f)$ .*

**Proof.** Let  $E_{i,j}$  be the  $n \times n$  matrix which has entry  $(i, j)$  equal to 1 and all other entries equal to zero. If  $\epsilon^2 = 0$ , then  $\det(A + \epsilon \cdot E_{i,j}) = \det(A) + \epsilon \wedge^{n-1}(A)_{i,j}$ , therefore we see that by perturbing the matrix  $A$  to first order, we generate precisely the ideal of  $(n-1) \times (n-1)$  minors of the matrix  $A$  as first order perturbations of  $f$ . This is by definition the first Fitting ideal of  $F_1(M)$ .  $\diamond$

Another description of the ideal  $F_1(M)$  is the following

**Proposition C.2.**  $F_1(M)$  is the set of elements  $r \in R$  such that  $r = \varphi(m)$  for some  $m \in M$ ,  $\varphi \in \text{Hom}_R(M, R)$ .

**Proof.** As  $M$  is maximal Cohen-Macaulay, a resolution of  $M$  as an  $R$ -module will be 2-periodic of the form

$$\dots \longrightarrow R^n \xrightarrow{\bar{B}} R^n \xrightarrow{\bar{A}} R^n \longrightarrow M \longrightarrow 0$$

for some  $n \times n$  matrix with  $P$ -coefficients  $B$  with the property that

$$AB = BA = f\mathbf{1}$$

and  $\bar{A}, \bar{B}$  are the induced matrices with  $R$  coefficients (see [E] or [Yo]).

From the 2-periodicity it follows that there is an exact sequence

$$0 \longrightarrow M \longrightarrow R^n \xrightarrow{\bar{A}} R^n \longrightarrow M \longrightarrow 0,$$

where  $M = \ker A = \text{im } B$ . We split this sequence into

$$\begin{aligned} 0 &\longrightarrow M \longrightarrow R^n \longrightarrow N \longrightarrow 0 \\ 0 &\longrightarrow N \longrightarrow R^n \longrightarrow M \longrightarrow 0. \end{aligned}$$

As  $N$  is also torsion free and  $R$  is Gorenstein,  $\text{Ext}_R^1(N, R) = 0$  by local duality. Hence we see from the first sequence that the map  $\text{Hom}_R(R^n, R) \longrightarrow \text{Hom}_R(M, R)$  is surjective.

From this it follows that the ideal obtained by evaluating all homomorphisms  $\phi \in \text{Hom}_R(M, R)$  on all elements of  $M$  is the same as the ideal generated by the entries of the matrix  $\bar{B}$ .

As  $M$  has rank 1, it follows that  $\det(A) = f$ , and hence the matrix  $B$  is the Cramer matrix  $(\Lambda^{n-1}A)^{tr}$  of  $A$ . The claim follows.  $\diamond$

Locally, the normalisation  $\tilde{C} \longrightarrow C$  corresponds to the inclusion of  $R$  in its integral closure  $\bar{R}$

$$R \hookrightarrow \bar{R}.$$

Recall that the conductor is the ideal  $I = \text{Hom}_R(\bar{R}, R)$ . One has

$$I \subset R \subset \bar{R}$$

and  $\dim(R/I) = \dim(\bar{R}/R) = \delta(C, p)$ .

As an important corollary of Proposition C.2 we have

**Corollary C.3.**  $F_1(M) \supset I$ .

**Proof.** Write  $\bar{R} = \bigoplus \bar{R}_i$ , with  $\bar{R}_i$  a domain isomorphic to  $\mathbf{C}[[t]]$ . Let  $Q(\bar{R}_i)$  be the quotient field of  $\bar{R}_i$ , and let  $Q(R) = \bigoplus Q(\bar{R}_i)$  be the total quotient ring of  $R$ . As  $M$  has rank 1,  $M \otimes_R Q(R)$  is isomorphic to  $Q(R)$ ; as it is torsion-free, the natural map

$M \rightarrow M \otimes_R Q(R)$  is injective. Hence up to isomorphism we can assume that  $M$  is a submodule of  $Q(R)$ . Let  $m \in M$  be an element of minimal valuation (it exists as  $M$  is finitely generated). Then multiplication by  $m^{-1}$ , an isomorphism of  $Q(R)$  as an  $R$ -module, sends  $M$  to a submodule of  $\overline{R}$  containing 1.

So we can assume that  $R \subset M \subset \overline{R}$ . Let  $c$  be any element of  $I$ . Multiplication by  $c$  defines a homomorphism  $\phi \in \text{Hom}_R(M, R)$  with  $\phi(1) = c$  (note that  $1 \in R \subset M$ ). Hence

$$\{\phi(m) \mid m \in M, \phi \in \text{Hom}(M, R)\} \supset I.$$

◇

**Remark C.4.** From the above description one also sees that  $F_1(\overline{R}) = I$ . Hence the differential of the map  $D(R, M) \rightarrow D(R)$  has minimal rank for  $M = \overline{R}$ .

Let  $C$  be a reduced projective curve with only planar singularities,  $\Sigma$  its singular locus. For  $p \in \Sigma$ , let  $V_p$  be the subspace of codimension  $\delta(C, p)$  in  $TD(C, p)$  generated by the conductor, and put

$$V^{loc} = \prod_{p \in \Sigma} V_p \subset TD^{loc}(C) = \prod_{p \in \Sigma} TD(C, p).$$

Let  $V$  be the inverse image of  $V^{loc}$  in  $TD(C)$ ; note that  $V$  is a linear subspace of codimension  $\delta(C)$ . If  $B$  is the base space of a semi-universal family of deformations of  $C$ , then  $TB$  is identified with  $TD(C)$ .

**Proposition C.5.** *Let  $\mathcal{C} \rightarrow B$  be a semi-universal family of deformations of  $C$ . Then for any  $\mathcal{F} \in \overline{J}\mathcal{C}$  the image of the tangent map  $\overline{J}\mathcal{C} \rightarrow B$  at  $\mathcal{F}$  contains the subspace  $V$ , and there exists at least one such  $\mathcal{F}$  for which the image is exactly  $V$ .*

**Proof.** The first statement follows immediately from Proposition C.1 and Corollary C.3, by applying Proposition B.1 and Lemma A.2. The second statement follows in the same way from Remark C.4; e.g., we can take  $\mathcal{F} = n_*(\mathcal{O}_{\tilde{C}})$ , where  $n : \tilde{C} \rightarrow C$  is the normalisation map. ◇

## D. The $\delta$ -constant stratum.

Let  $C$  be a reduced curve with only planar singularities. We denote by  $B$  an appropriate representative of the semi-universal deformation of  $C$ . The stratum  $B^\delta$  is defined as the set of points where the geometric genus of the fibres is constant. This amounts to saying that

$$\sum_{x \in C_t} \delta(C_t, x)$$

is constant for  $t \in B^\delta$  and equal to  $g_a(C) - g(\tilde{C})$ , hence the name.

The analytic set  $B^\delta$  (we give it the reduced induced structure) is very singular in general, but its properties can be related directly to the local  $\delta$ -constant strata

$$B^\delta(C, p).$$

To be more precise,  $B^\delta$  is the pullback of  $B^{\delta,loc} = \coprod B^\delta(C, p)$  under the smooth map  $B \rightarrow B^{loc}$ . So let  $(C, p) \subset (\mathbf{C}^2, 0)$  be a reduced plane curve singularity, with normalisation

$$(\tilde{C}, q) \xrightarrow{n} (C, p), \quad q = n^{-1}(p).$$

Note that in general  $q$  will be a finite set of distinct points, one for each branch of  $C$  at  $p$ . We denote for brevity by  $D(n)$  the functor of deformations of  $n : (\tilde{C}, q) \rightarrow (C, p)$  (that is, we are allowed to deform  $C$  and  $\tilde{C}$  as well as the map).

**Lemma D.1.**  *$D(n)$  is smooth.*

**Proof.** The morphism  $D((C, p) \rightarrow (\mathbf{C}^2, 0)) \rightarrow D(n)$  (given by taking the image of the deformation of the map) is smooth. Hence it is enough to verify that  $D((C, p) \rightarrow (\mathbf{C}^2, 0))$  is smooth, and this is obvious.  $\diamond$

**Theorem D.2.** ([T], [D-H]). *Let  $(C, p) \subset (\mathbf{C}^2, 0)$  be a reduced plane curve singularity,  $n : (\tilde{C}, q) \rightarrow (C, p)$  its normalisation. Let  $B(C, p)$  be a semi-universal family for  $D(C, p)$  and*

$$B^\delta(C, p) \subset B(C, p)$$

the  $\delta$ -constant stratum. Then one has:

- (1) The normalisation  $\tilde{B}^\delta(C, p)$  of  $B^\delta(C, p)$  is a smooth space.
- (2) The pullback of the semi-universal family to  $\tilde{B}^\delta$  admits a simultaneous resolution of singularities. This makes  $\tilde{B}^\delta(C, p)$  into a semi-universal family for  $D(n)$ .
- (3) The codimension of  $B^\delta \subset B$  is  $\delta(C, p)$ . Over the generic point  $p \in B^\delta$ , the curve  $C_p$  has precisely  $\delta(C, p)$  double points as its only singularities.
- (4) The tangent cone to the  $\delta$ -constant stratum is supported on  $V_p$ , the vector subspace generated by the conductor ideal.  $\diamond$

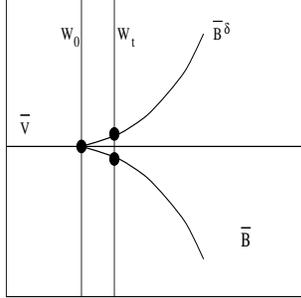
The second half of (2) is in fact not explicitly stated in either of [T], [D-H]; however it follows easily from Lemma D.1. A similar argument is presented in the proof of Proposition F.2, so we don't repeat it here.

## E. Proof of Theorem 1.

Let  $C$  be a reduced projective rational curve with only planar singularities. We want to show that  $e(\bar{J}C) = m(C)$ . In particular let  $(C, p)$  be a reduced plane curve singularity. Let  $C$  be a projective rational curve that has  $(C, p)$  as its only singular point. Then it follows that  $e(\bar{J}C) = m(C, p)$ .

Let  $\Phi : \mathcal{C} \rightarrow B$  be a semi-universal family of deformations of  $C$ ; we denote its fibres by  $C_s = \Phi^{-1}(s)$ ,  $C_0 = C$ . Let  $\pi : \bar{J}\mathcal{C} \rightarrow B$  be the corresponding family of compactified Jacobians. We always assume that we have chosen discs as representatives for the corresponding germs. We may also assume that the induced morphism  $j : B \rightarrow B^{loc}$  is smooth and has contractible fibres. We choose a section  $\sigma : B^{loc} \rightarrow B$  of  $j$  with  $\sigma(0) = 0$ . We will denote  $\bar{B} := \sigma(B^{loc})$ ,  $\bar{B}^\delta := \sigma(B^\delta)$  and  $\bar{V} := \sigma(V)$ .

Let  $(W, 0) \subset (\overline{B}, 0)$  be a smooth subspace of dimension  $\delta + 1$  containing the point  $(0, 0)$  together with a smooth map  $\lambda : (W, 0) \rightarrow (T, 0)$  to a disc  $(T, 0) \subset (\mathbf{C}, 0)$ .  $W$  is a one parameter family of  $\delta$ -dimensional subspaces  $W_t = \lambda^{-1}(t) \subset \overline{B}$ . We require in addition that  $W_0$  is transverse to  $V$ .



By Theorem D.2 we can choose  $W$  in such a way that for  $t \neq 0$  the fibre  $W_t$  intersects  $\overline{B}^\delta$  in  $\text{mult}(B^\delta)$  points, and for  $s \in W_t \cap \overline{B}^\delta$  the corresponding curve  $C_s$  has precisely  $\delta$  nodes as singularities. For  $s \in W_t \setminus \overline{B}^\delta$  the curve  $C_s$  will have positive genus. Let  $\overline{\Delta} \subset B$  be a closed disc, and let  $Z = W \cap \overline{\Delta}$ . We define the family  $\rho : \overline{\mathcal{J}}C_Z \rightarrow T$  by pullback:

$$\begin{array}{ccccc} & & \overline{\mathcal{J}}C_Z & \longrightarrow & \overline{\mathcal{J}}C \\ & \swarrow \rho & \downarrow \pi & & \downarrow \pi \\ T & \xleftarrow{\lambda} & Z & \longrightarrow & B \end{array}$$

As we have chosen  $W_0$  to be transversal to  $V$ , Proposition C.5 implies that  $\rho$  is smooth along  $\pi^{-1}(0)$ ; by making  $\overline{\Delta}$  and  $T$  smaller we can assume that  $\rho$  is smooth. As  $\rho$  is also proper, all the fibres  $\rho^{-1}(t)$  are diffeomorphic, in particular they all have the same Euler number.

The space  $\rho^{-1}(t)$  is the union, for  $s \in W_t$ , of  $\overline{\mathcal{J}}C_s$ . We know that if  $C_s$  has positive geometric genus, then  $e(\overline{\mathcal{J}}C_s)$  is zero; arguing as in [B], we obtain that

$$e(\rho^{-1}(t)) = \sum_{s \in W_t \cap \overline{B}^\delta} e(\overline{\mathcal{J}}C_s)$$

(note that if  $s \in W_t$ , then  $C_s$  is rational if and only if  $s \in \overline{B}^\delta$ ).

The intersection of  $W_0 \subset \overline{B}$  with  $\overline{B}^\delta$  consists only of the point 0 corresponding to the curve  $C$ . Therefore  $e(\rho^{-1}(0)) = e(\overline{\mathcal{J}}C)$ .

On the other hand, for  $t \neq 0$ ,  $W_t$  intersects  $\overline{B}^\delta$  in  $\text{mult}(B^\delta)$  points and for  $s \in \overline{B}^\delta \cap W_t$  the curve  $C_s$  has precisely  $\delta$  nodes as singularities. As for a nodal rational curve  $C_s$ , the Euler number  $e(\overline{\mathcal{J}}C_s)$  is equal to 1, we obtain

$$e(\rho^{-1}(t)) = \sum_{s \in W_t} e(\overline{\mathcal{J}}C_s) = \sum_{s \in W_t \cap \overline{B}^\delta} 1 = \text{mult}(B^\delta).$$

So we get

$$e(\overline{JC}) = e(\rho^{-1}(0)) = e(\rho^{-1}(t)) = \text{mult}(B^\delta).$$

◇

## F. The invariant as length of moduli of stable maps

Let  $C$  be a reduced projective curve with only plane curve singularities; let  $n : \tilde{C} \rightarrow C$  be its normalisation, and  $g$  the genus of  $\tilde{C}$ . Let  $m(C) = \prod m(C, p)$ . The scheme  $\overline{M}_{g,0}(C, [C])$  parametrizing stable birational maps from a genus  $g$  curve to  $C$  contains only one point, namely the normalisation of  $C$ . The aim of this section is to prove that its length is equal to  $m(C)$ . Note that if  $C$  is an isolated rational curve inside a smooth manifold  $Y$ ,  $\overline{M}_{g,0}(C, [C])$  is naturally a closed subscheme of  $\overline{M}_{g,0}(Y, [C])$ ; in particular,  $m(C)$  is a lower bound for the length of the corresponding component of  $M_{g,0}(Y, [C])$  (in case this scheme also has dimension zero).

Denote by  $D(n)$  the deformation functor of the triple  $(n : \tilde{C} \rightarrow C)$ , and by  $D^{loc}(n)$  the corresponding local deformation functor. As before  $D^{loc}(n)$  is the product over the singular points  $p$  of  $C$  of  $D(n, p)$ , the deformation functor of the triple  $n : (\tilde{C}, n^{-1}(p)) \rightarrow (C, p)$ .

If  $(C, p)$  is the germ of a planar reduced curve singularity, then  $D(n, p)$  is a smooth functor (see section D).

**Lemma F.1.** *The natural morphism of functors  $D(n) \rightarrow D^{loc}(n) \times_{D^{loc}(C)} D(C)$  is an isomorphism.*

**Proof.** Let  $C_T$  be an infinitesimal deformation of  $C$ , and let  $U_i$  be an open cover of  $C$  such that  $U_{ij}$  is smooth for each  $i \neq j$ . Let  $V_i = n^{-1}(U_i)$ . Let  $U_{i,T}$  be the deformation of  $U_i$  induced by  $C_T$ , and assume we are given a deformation  $n_{i,T} : V_{i,T} \rightarrow U_{i,T}$  of  $n_i := n|_{V_i}$ . Then to lift  $(C_T, n_{i,T})$  to a deformation of  $n$  we must choose gluing isomorphisms  $\psi_{ij} : V_{ij,T} \rightarrow V_{ji,T}$  satisfying the cocycle condition and compatible with the other data, namely the maps  $n_{i,T}$  and the gluing isomorphisms  $\phi_{ij} : U_{ij,T} \rightarrow U_{ji,T}$  induced by  $C_T$ . But  $U_{ij}$  is smooth, so that  $n|_{V_{ij}}$  is an isomorphism for each  $i \neq j$ ; hence the  $\psi_{ij}$  are univocally determined by the  $\phi_{ij}$  and automatically satisfy the cocycle condition. ◇

Let us now denote by  $B(\cdot)$  the germ of complex space being a hull for the functor  $D(\cdot)$ . Note that Lemma F.1 implies that there is a cartesian diagram

$$\begin{array}{ccc} B(n) & \longrightarrow & B(C) \\ \downarrow & & \downarrow \\ B^{loc}(n) & \longrightarrow & B^{loc}(C). \end{array}$$

**Proposition F.2.** *Let  $C$  be a reduced projective curve with planar singularities,  $n : \tilde{C} \rightarrow C$  be the normalisation,  $g = g(\tilde{C})$ . Let  $\pi : \mathcal{C} \rightarrow B(C)$  be a semi-universal deformation of  $C$ . Denote by  $M = M_{g,0}(\mathcal{C}, [C])$ ; then  $M$  is smooth at  $n$ , and the natural map  $M \rightarrow B^\delta := B^\delta(C)$  is the normalisation map.*

**Proof.** Write  $M$  for the germ of  $M$  at  $n$ . As the domain of  $n$  is a smooth curve, the same is true for all stable maps in a neighborhood of  $n$ . Hence  $M$  is isomorphic to  $B(n)$ . By Lemma F.1, together with Lemma D.1, we deduce that  $B(n)$  is smooth. By the definition of  $B^\delta$  the natural map  $M \rightarrow B(C)$  factors via  $B^\delta$ , hence, as  $M$  is smooth, via its normalisation  $\tilde{B}^\delta$ . On the other hand, we know that the family  $\tilde{C} \rightarrow \tilde{B}^\delta$  gotten by pullback admits a very weak simultaneous resolution of singularities [T], inducing a morphism  $\tilde{B}^\delta \rightarrow M$ . It is easy to check pointwise that these two morphisms are inverse to each other (both  $\tilde{B}^\delta$  and  $M$  just parametrize the normalisation maps of the fibres of  $\pi$ ). As both  $\tilde{B}^\delta$  and  $M$  are smooth, a bijective morphism must be an isomorphism.  $\diamond$

**Proof of Theorem 2.** The scheme  $M_{g,0}(C, [C])$  is the fibre over the point  $[C]$  of the morphism  $\tilde{B}^\delta \rightarrow B^\delta$ ; this is the multiplicity of  $B^\delta$  at  $[C]$ , as  $\tilde{B}^\delta$  is smooth. This proves the first equality.

Let now  $X$  be a smooth projective surface,  $C \subset X$  a reduced irreducible curve,  $n : \tilde{C} \rightarrow C$  the normalisation,  $g = g(\tilde{C})$ . Assume that  $n$  is an isolated point of  $\overline{M}_{g,0}(X, [C])$ , and let  $M_n$  be the connected component of  $n$ .  $M_n$  contains  $M_{g,0}(C, [C])$  as a closed subscheme, so we always have an inequality

$$l(M_n) \geq l(M_{g,0}(C, [C])) = m(C).$$

This inequality is an equality if and only if the natural morphism  $M_n \rightarrow \text{Hilb}(X)$  sending each map to its image factors scheme theoretically (and not only set-theoretically) via  $C$ .

Hence to complete the proof of Theorem 2, it is enough to show that this is the case if  $C$  is rational and  $X$  is a  $K3$  surface. Let  $S$  be the complete linear system defined by  $C$  on  $X$ , and let  $\mathcal{C} \rightarrow S$  be the universal curve. It is known that  $\bar{J}\mathcal{C}$  is smooth, see [Mu]; but this means precisely that  $S$  maps transverse to the  $\delta$ -constant stratum in  $B(C)$ , and we are done in view of Corollary B.3.  $\diamond$

## G. Examples.

**Example 1 (Beauville):** Let  $(C, o)$  be the singularity of equation  $x^q = y^p$ , with  $p < q$  and  $(p, q) = 1$ . Then

$$m(C, o) = \frac{1}{p+q} \binom{p+q}{p}.$$

**Proof.** We write for simplicity  $\overline{M}(X, \beta)$  instead of  $\overline{M}_{0,0}(X, \beta)$ ; if  $X$  is a curve and  $\beta = [X]$  we omit it. Let  $C$  be the plane curve of equation  $y^p z^{q-p} = x^q$ .  $C$  is a rational curve with two singular points,  $o = (0, 0, 1)$  and  $\infty = (1, 0, 0)$ . Let  $\alpha : C' \rightarrow C$  be the partial normalisation of  $C$  at  $\infty$ . By Theorem 2, it is enough to prove that

$$l(\overline{M}(C')) = \frac{1}{p+q} \binom{p+q}{p} =: N(p, q).$$

The natural map  $\overline{M}(C') \rightarrow \overline{M}(C)$  given by  $\mu \mapsto \alpha \circ \mu$  is a closed embedding, and the closed subscheme  $\overline{M}(C')$  is identified by requiring the deformation of the normalisation morphism to be locally trivial near  $\infty$ . On the other hand  $\overline{M}(C)$  is naturally a closed subset of  $\overline{M}(\mathbf{P}^2, q\ell)$ , where  $\ell$  is the class of a line.

Let  $n : \mathbf{P}^1 \rightarrow C$  be the normalisation map, and choose coordinates on  $\mathbf{P}^1$  such that  $n(s, t) = (t^p s^{q-p}, t^q, s^q)$ . A morphism in  $\overline{M}(\mathbf{P}^2, q\ell)$  near  $n$  has equations

$$(t^p s^{q-p} + x, t^q + y, s^q + z),$$

for suitable homogeneous polynomials  $x, y, z$  of degree  $q$ .

We impose the conditions that the image of the map be contained in  $C$  and that the deformation be locally trivial at  $\infty$ . Then we eliminate the indeterminacy generated by a reparametrization of  $\mathbf{P}^1$  and a rescaling of the coordinates on  $\mathbf{P}^2$ . We get that all deformations of  $n$  in  $\overline{M}(C)$  must be (in affine coordinates where  $z = 1$ ) of the form

$$t \mapsto (t^p + \sum_{i=0}^p x_i t^i, t^q + \sum_{i=0}^q y_i t^i).$$

Hence we are now left with the following problem: compute the length of the  $\mathbf{C}$ -algebra with generators  $x_0, \dots, x_{p-2}, y_0, \dots, y_{q-2}$  and relations given by the coefficients of the polynomial  $f^q - g^p$ , where  $f = t^p + \sum x_i t^i$  and  $g = t^q + \sum y_i t^i$ .

It is easy to check that the equation  $f^q = g^p$  is equivalent to  $qf'g = pg'f$  by taking  $d/dt \circ \log$  on both sides. The  $t$ -degree of  $qf'g - pg'f$  is  $p + q - 1$ , however we only get  $p + q - 2$  equations as the coefficients of  $t^{p+q-1}$  and  $t^{p+q-2}$  are zero anyway. Moreover, if we consider the variables  $x_i$  (resp.  $y_i$ ) as having degree  $p - i$  (resp.  $q - i$ ), the equations we obtain are homogeneous of degree  $2, \dots, p + q - 1$ .

Now we recall the weighted Bézout theorem, which says that if we have a zero-dimensional algebra given by  $N$  homogeneous equations of degrees  $e_j$  in  $N$  weighted variables of degree  $d_j$ , then the length of the algebra is  $\prod e_j / \prod d_j$ .

Applying the formula in our case, with  $N = p + q - 2$ ,  $(d_j) = (2, 3, \dots, p, 2, 3, \dots, q)$  and  $e_j = (2, 3, \dots, p + q - 1)$  gives

$$N(p, q) = \frac{\prod e_j}{\prod d_j} = \frac{(p + q - 1)!}{p!q!} = \frac{1}{p + q} \binom{p + q}{p}.$$

**Example 2.** We would like to outline an algorithm for the computation of  $m(C, p)$  for a planar, reduced and irreducible curve singularity  $(C, p)$ . Assume we know how to realize  $(C, p)$  as singularity of a rational curve. It is then easy to realize it as singularity of a plane rational curve  $C$ , whose other singularities are only nodes. Let  $d$  be the degree of the curve,  $F(x, y, z) = 0$  its equation, and  $\bar{n} = (\bar{x}, \bar{y}, \bar{z})$  an explicit normalisation given by homogeneous polynomials of degree  $d$  in  $s, t$ . Assume without loss of generality that  $\bar{z}$  contains the monomial  $s^d$  with nonzero coefficient.

Then we can describe the scheme  $M_{0,0}(C, [C])$  explicitly as follows. Choose three points  $p_i$  ( $i = 1, 2, 3$ ) in  $\mathbf{P}^1$  mapping via  $n$  to smooth points of  $C$ ; let  $L_i \subset \mathbf{P}^2$  be a line transversal to  $C$  at  $n(p_i)$ .

Choose variables  $x_i, y_i$  and  $z_i$  for  $i = 0, \dots, d$ , and let  $x$  be the polynomial  $\bar{x} + \sum_i x_i s^i t^{d-i}$ ; define  $y$  and  $z$  in a similar way.

Then  $M_{0,0}(C, [C])$  is naturally isomorphic to the subscheme of  $\text{Spec } \mathbf{C}[x_i, y_i, z_i]$  defined by the equations

$$\begin{aligned} z_d &= 0, \\ (x, y, z)(p_i) &\in L_i \quad i = 1, 2, 3, \\ F(x, y, z) &= 0. \end{aligned}$$

In fact, all deformations of  $\bar{n}$  are again morphisms of degree  $d$  from  $\mathbf{P}^1$  to  $\mathbf{P}^2$ , hence are given by polynomials of degree  $d$ . The first four equations, defining a linear subspace, correspond to choosing local coordinates near  $\bar{n}$  on  $M_{0,0}(\mathbf{P}^2, d)$ ; the last one, which is a system of  $d^2$  equations, imposes the condition that the scheme-theoretic image of the morphism be contained in  $C$ .

\*

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