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## SEMISTABLE $K3$ -SURFACES WITH ICOSAHEDRAL SYMMETRY

by Jan STEVENS<sup>\*</sup>)

ABSTRACT. In a Type III degeneration of  $K3$ -surfaces the dual graph of the central fibre is a triangulation of  $S^2$ . We realise the tetrahedral, octahedral, and especially the icosahedral triangulation in families of  $K3$ -surfaces, preferably with the associated symmetry groups acting.

### INTRODUCTION

A degeneration of surfaces is a 1-parameter family with general fibre a smooth complex surface. The case of  $K3$ -surfaces has attracted a great deal of attention. A nice discussion is contained in the introductory first paper [F-M] of the bundle [SAGS]. One usually allows base change and modifications to obtain good models. After a ramified cover of the base and resolution of singularities we may assume that the degeneration  $f: \mathcal{X} \rightarrow S \ni 0$  is *semistable*: the zero fibre  $X = f^{-1}(0)$  is a reduced divisor with (simple) normal crossings in the smooth manifold  $\mathcal{X}$ . Further modifications of a  $K3$ -degeneration lead to a minimal model, which falls into one of three types.

In a Type III degeneration of  $K3$ -surfaces the dual graph of the central fibre is a triangulation of  $S^2$ . In this paper I construct an example with my favourite triangulation, the icosahedral one. A substantial part is taken up by the tetrahedral case, which is easier to handle and allows more explicit results. A second purpose of this paper is to link general theory with concrete computations.

There are two obvious ways to realise a semistable degeneration with prescribed combinatorial type. The first is to start with a singular total space,

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but correct central fibre. An example is the coordinate tetrahedron  $T = x_0x_1x_2x_3$  in  $\mathbf{P}^3$ , where we get a degeneration  $f: \mathcal{X} \rightarrow \mathbf{P}^1 \ni 0$  by blowing up the base locus of the pencil spanned by  $T$  and a generic quartic. The total space then has 24  $A_1$ -singularities. This is a minimal model in the Mori category, but one has to take a small resolution to get a smooth total space. We can arrange that each plane of the tetrahedron is blown up in 6 points. The dual graph of the central fibre remains the same.

The second method is to try to smooth the putative central fibre. For the tetrahedron this can be done directly. We glue together four cubic surfaces along triangles. This normal crossings variety satisfies the topological conditions to be a central fibre (the triple point formula), but one also needs a more subtle analytic condition ( $d$ -semistability), which translates into equations on the coefficients in the equations. The necessary deformation theory in general has been developed by Friedman [F2]. The central result is that smoothing is always possible in the  $K3$ -case. This holds both for abstract and embedded deformations. One typically obtains different degenerations from the two constructions, which fill up 19 dimensional families in a 20 dimensional deformation space of the normal crossings  $K3$ .

For the octahedron both methods can again be applied. We find the correct space as anticanonical divisor in the toric threefold given by a cube. In his monograph Ulf Persson invites the reader 'to find a degeneration into a dodecahedron of rational surfaces' [P, p. 126]. For a construction according to the first method the double curve must be an anti-canonical divisor on each component. The most natural choice for a rational surface is then a Del Pezzo of degree five. This makes that the dodecahedron itself has degree 60, and it is exactly such a dodecahedron, obtained by gluing twelve Del Pezzo surfaces, which the second method smoothes. Unfortunately the computations are too difficult to give explicit formulas. The same holds for a related problem in fewer variables, smoothing the Stanley-Reisner ring of the icosahedron. A semistable model of such a degeneration has as central fibre a complexified football. The extra components come from singularities of the total space.

The last example suggests that one can get a dodecahedron out of a central fibre with fewer than 12 components. This requires a breaking of the symmetry. By combining the first and the second method I obtain in 5.12 an explicit degeneration, whose general fibre is a smooth  $K3$ -surface of degree 12 in  $\mathbf{P}^7$ , with special fibre consisting of 6 planes with triangles as double curves and 3 quadric surfaces with rectangular double curve. Its total space has three singularities, which are isomorphic to cones over Del Pezzo surfaces of degree 5, and 18  $A_1$  points. The dual graph of the central fibre on a suitable

smooth model is the icosahedron.

This paper is organised as follows. In the first section I recall the results on degenerations of  $K3$ -surfaces, in particular that one can always realise a particularly nice model, the  $(-1)$ -form. Section 2 brings as illustration detailed computations for tetrahedra. The results fit in with the general deformation theory, which is treated in the third section, with special emphasis on degenerations in  $(-1)$ -form. A short fourth section introduces the combinatorial tools to handle large systems of equations: the definitions of Stanley-Reisner rings and Hodge algebras are reviewed. The final section contains the dodecahedral degenerations.

## 1. SEMISTABLE DEGENERATIONS OF $K3$ -SURFACES

1.1. The name  $K3$  has been explained by André Weil: «en l'honneur de Kummer, Kähler, Kodaira et de la belle montagne  $K2$  au Cachemire» [W, p.546]. He calls any surface a  $K3$ , if it has the differentiable structure of a smooth quartic surface in  $\mathbf{P}^3(\mathbf{C})$ . A Kummer surface is a quartic with 16  $A_1$ -singularities. As these singularities admit simultaneous resolution, the minimal resolution of a Kummer surface deforms into a smooth quartic and is therefore a  $K3$ -surface. A quartic surface  $X$  is simply connected, so in particular  $b_1(X) = 0$  and has trivial canonical sheaf by the adjunction formula:  $X$  is an anti-canonical divisor in  $\mathbf{P}^3$ . The modern definition of a  $K3$ -surface:  $b_1(X) = 0$  and  $K_X = 0$ , is equivalent with Weil's definition because all  $K3$ -surfaces form one connected family.

1.2. Let  $f: \mathcal{X} \rightarrow S \ni 0$  be a proper surjective holomorphic map of a 3-dimensional complex manifold  $\mathcal{X}$  to a (germ of a) curve  $S$  such that the zero fibre  $X = f^{-1}(0)$  is a reduced divisor with (simple) normal crossings; then the degeneration  $f$  is called *semistable*.

In the  $K3$  case the following holds (see [F-M] for exact references):

1.3. THEOREM (Kulikov). *Let  $f: \mathcal{X} \rightarrow S$  be a semistable degeneration of  $K3$ -surfaces. If all components of  $X = f^{-1}(0)$  are Kähler, then there exists a modification  $\mathcal{X}'$  of  $\mathcal{X}$  such that  $K_{\mathcal{X}'} \equiv 0$ .*

A degeneration as in the conclusion of the theorem ( $K_{\mathcal{X}} \equiv 0$ ) is called a *Kulikov model*.

1.4. THEOREM (Persson, Kulikov). *Let  $f: \mathcal{X} \rightarrow S$  be a Kulikov model of a degeneration of K3-surfaces with all components of  $X = f^{-1}(0)$  Kähler. Then either*

- (I)  *$X$  is smooth, or*
- (II)  *$X$  is a chain of elliptic ruled components with rational surfaces at the ends and all double curves are smooth elliptic curves, or*
- (III)  *$X$  consists of rational surfaces meeting along rational curves which form cycles on each component. The dual graph is a triangulation of  $S^2$ .*

According to the case division in the theorem one speaks of degenerations of type I, II, or III. Without the Kähler assumption it is not always possible to arrange that  $K_{\mathcal{X}} \equiv 0$  [K, N]. Even under the assumption  $K_{\mathcal{X}} \equiv 0$  the list becomes longer (see [N, Thm. 2.1]). In particular it is possible that the central fibre contains surfaces of type  $VII_0$ . The case that the central fibre contains an Inoue-Hirzebruch surface is relevant for the deformation of cusp singularities [L].

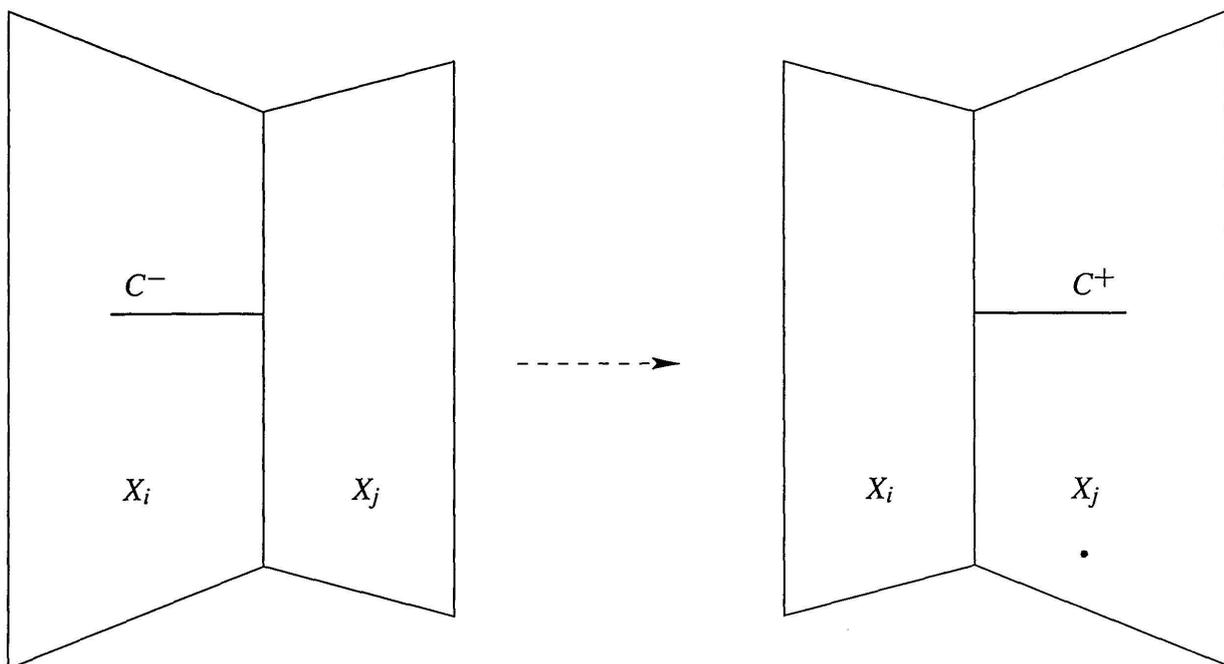


FIGURE 1.1

Elementary modification of type I

A Kulikov model is not unique. The central fibre can be modified with flops. If  $C^-$  is a smooth rational curve in  $X$  with self intersection  $-1$ , lying in a component  $X_i$  and intersecting the double curve transversally in one point lying in  $X_j$ , then after the flop the curve  $C^+$  lies in  $X_j$ . This operation is

also called an elementary modification of type I along  $C^-$ . An elementary modification of type II is a flop in a curve  $C^-$ , which is a component of the double curve and has self intersection  $-1$  on both components  $X_i, X_j$  on which it lies. There are two triple points on  $C^-$  involving the components  $X_k$  and  $X_l$ . After the flop  $C^+$  is a double curve lying in the components  $X_k$  and  $X_l$ . Note that we might lose projectivity by using elementary transformations.

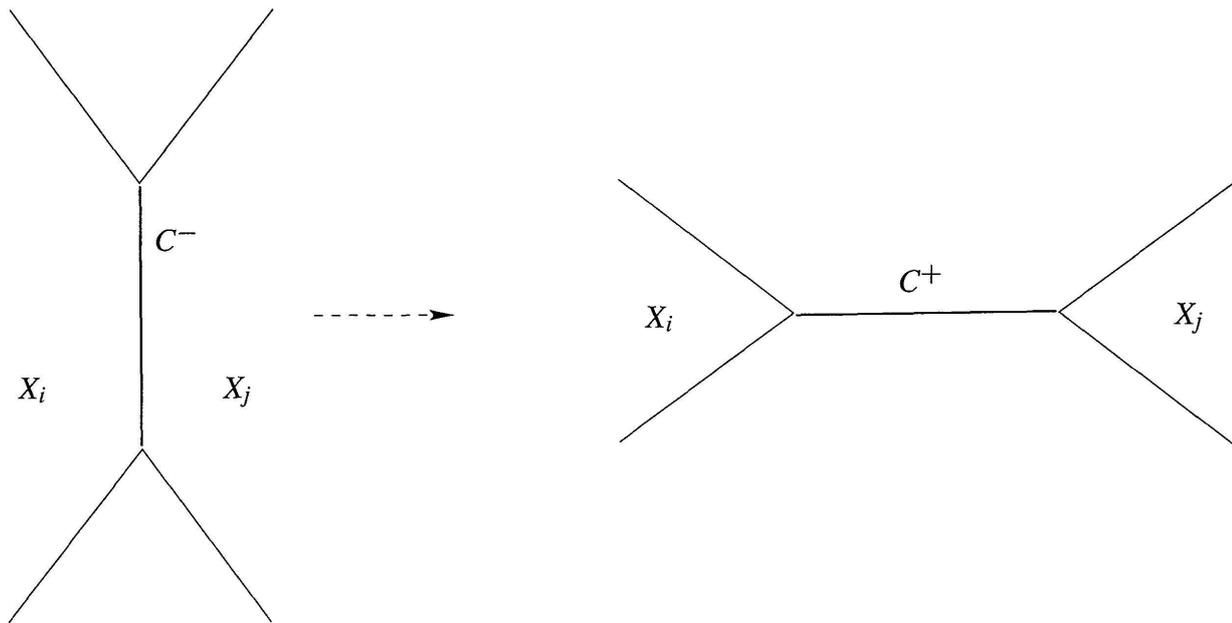


FIGURE 1.2

Elementary modification of type II

1.5. THE MINUS ONE THEOREM [M-M]. *By modifications of type I and II one can achieve that every component of the double curve of the special fibre has self intersection  $-1$  on both components on which it lies.*

1.6. Let  $X = \bigcup X_i$  be a normal crossings surface with double locus  $D$ . If  $X$  is a divisor in a smooth 3-fold  $M$  then one can define the infinitesimal normal bundle  $\mathcal{O}_D(X)$  as  $\mathcal{O}_D(X) = \mathcal{O}_M(X)|_D$ . It can be defined independently of  $M$ . To this end, let  $I_{X_i}$  be the ideal sheaf of  $X_i$  in  $X$ . It is locally generated by one generator  $z_i$ , but is not invertible as  $z_i$  is a zero divisor in  $\mathcal{O}_X$ . However  $I_{X_i}|_D$  is locally free [F2, (1.8)]. Following Friedman one makes the following definitions.

1.7. DEFINITION. The *infinitesimal normal bundle*  $\mathcal{O}_D(X)$  is the line bundle dual to  $\mathcal{O}_D(-X)$ , where

$$\mathcal{O}_D(-X) = (I_{X_1}|_D) \otimes_{\mathcal{O}_D} \cdots \otimes_{\mathcal{O}_D} (I_{X_k}|_D).$$

If  $X$  is a divisor in  $M$  the bundle thus defined is equal to  $\mathcal{O}_M(X)|_D$ . In particular, if  $X$  is a central fibre in a semistable degeneration  $\mathcal{X} \rightarrow S$ , then  $\mathcal{O}_{\mathcal{X}}(X) \equiv \mathcal{O}_{\mathcal{X}}$  so  $\mathcal{O}_D(X) = \mathcal{O}_D$ . This gives a necessary condition for being a central fibre.

1.8. DEFINITION. The normal crossings surface  $X$  is *d-semistable* if  $\mathcal{O}_D(X) = \mathcal{O}_D$ .

A consequence is the triple point formula: let  $D_{ij} = X_i \cap X_j$  and denote by  $(D_{ij})_{X_i}^2$  the self intersection of  $D_{ij}$  on  $X_i$  and by  $T_{ij}$  the number of triple points on  $D_{ij}$ . Then (cf. [P, Cor. 2.4.2])

$$(D_{ij})_{X_i}^2 + (D_{ij})_{X_j}^2 + T_{ij} = 0.$$

1.9. DEFINITION. A compact normal crossings surface is a *d-semistable K3-surface of type III* if  $X$  is *d-semistable*,  $\omega_X = \mathcal{O}_X$  and each  $X_i$  is rational, the double curves  $D_i \subset X_i$  are cycles of rational curves and the dual graph triangulates  $S^2$ . If the conclusions of the Minus One Theorem hold, that every component of the double curve has self intersection  $-1$  on either component of  $X$  on which it lies, the surface  $X$  is said to be in *(-1)-form*.

## 2. TETRAHEDRA

2.1. To realise a tetrahedron we start out with four general planes in 3-space. They do not form a *d-semistable K3-surface*, but the dual graph is a tetrahedron. To write down a degeneration with this special fibre we just take the pencil spanned by  $T = x_0x_1x_2x_3$  and a smooth quartic. The symmetry group of the tetrahedron (including reflections) acts if we only take  $S_4$ -invariant quartics:

$$Q = a\sigma_1^4 + b\sigma_1^2\sigma_2 + c\sigma_2^2 + d\sigma_1\sigma_3,$$

where the  $\sigma_i$  are the elementary symmetric functions in the four variables  $x_i$  and  $a, b, c$  and  $d$  are constants.

To obtain a family  $f: \mathcal{X} \rightarrow S$  one has to blow up the base locus of the pencil. This can be done in several ways. Blowing up  $T = Q = 0$  gives a total space which is singular, with in general 24 ordinary double points coming from the 24 intersection points of  $Q$  with the double curve of the tetrahedron  $T$ . Arguably, this is the nicest model, and the best one can hope for in view of the theory of minimal models of 3-folds. A smooth model is

obtained by a suitable small resolution of the 24 singularities. The quartic intersects each edge of the tetrahedron in four points. To get the  $(-1)$ -form two of them have to be blown up in one face and the other two in the other face. The central fibre then consists of four Del Pezzo surfaces of degree 3.

Alternatively one can blow up the irreducible components of  $T = Q = 0$  one at a time. The advantage is that one has a projective model. However it is not in  $(-1)$ -form and furthermore the symmetry is not preserved. To achieve  $(-1)$ -form we have to apply modifications of type I; here we might lose projectivity.

2.2. THE TETRAHEDRON OF DEGREE 12. We glue together four Del Pezzo surfaces of degree 3. Take coordinates  $x_1, \dots, x_4, y_1, \dots, y_4$  on  $\mathbf{P}^7$ . Let  $\{i, j, k, l\} = \{1, 2, 3, 4\}$ . The Del Pezzo surface  $X_i$  lies in  $y_i = x_j = x_k = x_l = 0$  and has an equation of the form

$$y_j y_k y_l - x_i F_i(x_i, y_j, y_k, y_l) = 0,$$

where  $F_i$  is a quadratic form; more specifically,

$$F_i = \sum_{\alpha \neq i} f_i^{\alpha\alpha} y_\alpha^2 + \sum_{\alpha, \beta \neq i} f_i^{\alpha\beta} y_\alpha y_\beta + \sum_{\alpha \neq i} g_i^\alpha x_i y_\alpha + h_i x_i^2.$$

The condition that  $X_i$  be nonsingular in the vertices of the triangle  $x_i = y_j y_k y_l = 0$  is that the coefficients  $f_i^{\alpha\alpha}$  in  $F_i$  do not vanish.

The ideal of the tetrahedron  $X = \bigcup_i X_i$  has 14 generators, the 4 cubic Del Pezzo equations  $y_j y_k y_l - x_i F_i$  and 10 quadratic monomials: the six products  $x_i x_j$  and the four products  $x_i y_i$ . The relations among them are:

$$(2.1) \quad \begin{aligned} & (x_i x_j) x_k - (x_i x_k) x_j \\ & (x_i y_i) x_j - (x_i x_j) y_i \\ & (y_j y_k y_l - x_i F_i) x_l - (x_l y_l) y_j y_k + (x_i x_l) F_i \\ & (y_i y_j y_k - x_l F_l) y_l - (y_j y_k y_l - x_i F_i) y_i - (x_l y_l) F_l + (x_i y_i) F_i. \end{aligned}$$

2.3. PROPOSITION. *The tetrahedron  $X$  is  $d$ -semistable if and only if the four equations*

$$f_k^{jj} f_l^{kk} f_j^{ll} - f_j^{kk} f_k^{ll} f_l^{jj} = 0$$

*are satisfied.*

*Proof.* We look at the chart  $y_4 = 1$ . Then  $x_4 = 0$  and we have the equations  $x_i x_j$ ,  $x_i y_i$ ,  $y_1 y_2 y_3$  and  $y_i y_j - x_k F_k$ . In all points near the origin  $y_1 y_2 y_3 \mapsto 1$  is generator of the infinitesimal normal bundle  $\mathcal{O}_D(X)$ . We

now look on the  $y_2$ -axis. The equation  $y_2y_1 - x_3F_3$  shows that the section  $y_1y_2y_3 \mapsto 1$  has a pole in the zeroes of  $F_3$  restricted to the  $y_2$ -axis, and likewise in the zeroes of  $F_1$  (using the equation  $y_2y_3 - x_1F_1$ ).

This shows that the expression, given in homogeneous coordinates by

$$\frac{(f_1^{22}y_2^2 + f_1^{24}y_2y_4 + f_1^{44}y_4^2)(f_3^{22}y_2^2 + f_3^{24}y_2y_4 + f_3^{44}y_4^2)}{y_1y_2y_3y_4},$$

represents a non vanishing holomorphic section of  $\mathcal{O}_D(X)$  on the whole line  $y_1 = y_3$ . Similar expression can be found for the other edges of the tetrahedron. We get a global section if and only if we can find a quaternary form  $f$  of degree 4 which restricts to a multiple of the above denominator for each line.

For each face we find from the following lemma the condition that the 12 points in the corresponding hyperplane be cut out by a quartic. We obtain four equations, which in fact are not independent: under our assumption that all  $f_{ij}^i$  are different from 0 one can derive one equation from the remaining three. They give necessary and sufficient conditions for the existence of the quaternary quartic.  $\square$

2.4. LEMMA. Consider  $3n$  points  $P_{i,\alpha}$  with  $P_{i,1}, \dots, P_{i,n}$  smooth points of the triangle  $x_1x_2x_3 = 0$ , lying on the side  $x_i = 0$  and given by the binary form  $B_i(x_j, x_k) = \sum_{m=0}^n b_{im} x_j^m x_k^{n-m}$ , where  $(i, j, k)$  is a cyclic permutation of  $(1, 2, 3)$ . These points are cut out by a ternary form of degree  $n$  if and only if

$$b_{10}b_{20}b_{30} = b_{1n}b_{2n}b_{3n}.$$

*Proof.* Suppose  $A(x_1, x_2, x_3) = \sum_{l+m+p=n} a_{lmp} x_1^l x_2^m x_3^p$  cuts out the points. Then  $A(0, x_2, x_3)$  is proportional to  $B_1(x_2, x_3)$ , so  $(a_{0n0} : a_{00n}) = (b_{10} : b_{1n})$ . Likewise we have that  $(a_{00n} : a_{n00}) = (b_{20} : b_{2n})$  and that  $(a_{n00} : a_{0n0}) = (b_{30} : b_{3n})$ . Multiplying these ratios gives the condition.

Conversely, to find  $A$  we may suppose that  $b_{10} = b_{3n} \doteq 1 = a_{0n0}$  (as no point lies at one of the vertices). We put  $A(0, x_2, x_3) = B_1(x_2, x_3)$ ,  $A(x_1, x_2, 0) = B_3(x_1, x_2)$ . We also can take  $b_{20} = a_{00n}$ . As  $b_{1n} = a_{00n}$  the condition gives now  $b_{2n} = b_{30} = a_{n00}$  and we can set  $A(x_1, 0, x_3) = B_2(x_1, x_3)$ . The remaining monomials in  $A$  are divisible by  $x_1x_2x_3$  and do not matter.  $\square$

2.5. REMARK. It is not surprising that only the extremal coefficients  $b_{i0}$ ,  $b_{in}$  are involved, as they depend only on the product of the coordinates of the points. Ignoring the other coefficients we rename:  $b_{i0} =: b_{jk}$ ,  $b_{in} =: b_{kj}$ . The condition becomes  $b_{jk}b_{ki}b_{ij} = b_{ji}b_{ik}b_{kj}$ , which is the form used in the proposition above.

2.6. INFINITESIMAL DEFORMATIONS. We compute embedded deformations modulo coordinate transformations. To this end we look at the equations as defining the affine cone  $C(X)$  over  $X$ . We follow the standard procedure (see e.g. [S1]): given equations  $f_i$ , satisfying relations  $\sum f_i r_{ij} = 0$ , we have to lift the equations to  $F_i = f_i + \varepsilon f'_i$  and the relations to  $R_{ij} = r_{ij} + r'_{ij}$ , satisfying  $\sum F_i R_{ij} \equiv 0 \pmod{\varepsilon^2}$ . This means that we have to find  $f'_i$  such that  $\sum f'_i r_{ij}$  lies in the ideal generated by the  $f_i$ . Using undetermined coefficients this is a finite dimensional problem for each degree. The deformations of  $C(X)$  in degree 0 give embedded deformations of  $X$  in  $\mathbf{P}^7$ , while those in degree  $< 0$  have an interpretation in terms of extensions of  $X$ : they tell us of which varieties  $X$  is a hyperplane section. Our main interest lies in the degree 0 deformations, but as preparation we first compute those of negative degrees.

2.7. PROPOSITION. *The dimension of  $T_{C(X)}^1(-2)$  equals 4 and we have  $\dim T_{C(X)}^1(-1) = 16$ . In case  $X$  is  $d$ -semistable  $\dim T_{C(X)}^1(0) = 22$ , otherwise it is 21.*

*Proof.* Degree  $-2$ : we perturb the quadratic equations with constants and the cubic equations with linear terms. Write  $x_i x_j + a_{ij}$ . The first type of the relations (2.1) then gives  $a_{ij} x_k - a_{ik} x_j = 0 \in \mathcal{O}_{C(X)}$ , so  $a_{ik} = 0$ . Also the equation  $x_i y_i$  are not perturbed. Consider  $y_j y_k y_l - x_i F_i + \sum a_i^\alpha x_\alpha + \sum b_i^\alpha y_\alpha$ . The third relation gives  $a_i^j x_j^2 + \sum_{\alpha \neq j} b_i^\alpha x_j y_\alpha = 0$  so we conclude that all coefficients vanish, except the  $a_i^i$ , which we may choose arbitrary. The last type of relation is then also satisfied.

Degree  $-1$ : consider the perturbations

$$x_i x_j + \sum a_{ij}^\alpha x_\alpha + \sum b_{ij}^\alpha y_\alpha.$$

In the local ring we obtain the equation

$$a_{ij}^k x_k^2 + \sum_{\alpha \neq k} b_{ij}^\alpha x_k y_\alpha - a_{ik}^k x_j^2 + \sum_{\alpha \neq j} b_{ik}^\alpha x_j y_\alpha = 0,$$

from which we get  $b_{ij}^\alpha = 0$ ,  $a_{ij}^k = a_{ij}^l = 0$ . We now put

$$x_i y_i + \sum a_{ii}^\alpha x_\alpha + \sum b_{ii}^\alpha y_\alpha.$$

We find

$$a_{ii}^j x_j^2 + \sum_{\alpha \neq j} b_{ii}^\alpha x_j y_\alpha - a_{ij}^j x_j y_i = 0.$$

We conclude  $a_{ii}^j = 0$ ,  $b_{ii}^j = 0$  for all  $j \neq i$  and finally  $a_{ij}^j = b_{ii}^i$ . In particular  $a_{ij}^j$  is independent of  $j$ . We can use the coordinate transformation  $x_i \mapsto x_i - b_{ii}^i$

to get rid of the  $a_{ij}^j$ -term. So the equations  $x_i x_j$  are not perturbed at all. This means that  $x_i y_j$  is only perturbed with the term  $a_{ii}^i x_i$ , which can be made to vanish by coordinate transformations in the  $y_i$ -variables. As above we find that the only allowable perturbations of the cubic equation  $y_j y_k y_l - x_i F_i$  are those divisible by  $x_i$ . As we have used all coordinate transformations, all monomials  $x_i^2$ ,  $x_i y_j$  can occur. This makes the dimension of  $T^1(-1)$  into  $4 \times 4$ .

*Degree 0:* we proceed in the same way by first considering the perturbations

$$x_i x_j + \sum a_{ij}^\alpha x_\alpha^2 + \sum b_{ij}^{\alpha\beta} x_\alpha y_\beta + \sum c_{ij}^\alpha y_\alpha^2 + \sum d_{ij}^{\alpha\beta} y_\alpha y_\beta.$$

Multiplied with  $x_k$  this gives the following terms in the local ring:

$$a_{ij}^k x_k^3 + \sum_{\beta \neq k} b_{ij}^{k\beta} x_k^2 y_\beta + \sum_{\alpha \neq k} c_{ij}^\alpha x_k y_\alpha^2 + \sum_{\alpha, \beta \neq k} d_{ij}^{\alpha\beta} x_k y_\alpha y_\beta.$$

We conclude that all coefficients occurring here vanish. In particular  $a_{ij}^k = 0$ . Using the coordinate transformations  $x_j \mapsto x_j - a_{ij}^i x_i$  we may suppose that all  $a_{ij}^\alpha$  vanish. We are left with

$$x_i x_j + \sum b_{ij}^{i\beta} x_i y_\beta + \sum b_{ij}^{j\beta} x_j y_\beta + d_{ij}^{kl} y_k y_l.$$

With the perturbations

$$x_i y_i + \sum_{\alpha \neq i} a_{ii}^\alpha x_\alpha^2 + \sum_{\alpha \neq i} b_{ii}^{\alpha\beta} x_\alpha y_\beta + \sum_{\alpha \neq i} c_{ii}^\alpha y_\alpha^2 + \sum_{\alpha, \beta \neq i} d_{ii}^{\alpha\beta} y_\alpha y_\beta,$$

where we used coordinate transformations  $x_i \mapsto x_i - c_{ii}^i y_i$ ,  $x_i \mapsto x_i - d_{ii}^{ij} y_j$ ,  $y_i \mapsto y_i - a_{ii}^i x_i$  and  $y_i \mapsto y_i - b_{ii}^{ij} y_j$  to remove some coefficients, we now get (using the  $j$ th Del Pezzo equation)

$$a_{ii}^j x_j^3 + \sum_{\alpha \neq i} b_{ii}^{j\beta} x_j^2 y_\beta + \sum_{\alpha \neq i} c_{ii}^\alpha x_j y_\alpha^2 + \sum_{\alpha, \beta \neq i} d_{ii}^{\alpha\beta} x_j y_\alpha y_\beta - \sum b_{ij}^{j\beta} x_j y_i y_\beta - d_{ij}^{kl} x_j F_j = 0.$$

Using the explicit expression for  $F_j$  we obtain the equations

$$\begin{aligned} a_{ii}^j &= d_{ij}^{kl} h_j, & b_{ii}^{j\beta} &= d_{ij}^{kl} g_j^\beta, & c_{ii}^\alpha &= d_{ij}^{kl} f_j^{\alpha\alpha}, \\ -b_{ij}^{ji} &= d_{ij}^{kl} f_j^{ii}, & d_{ii}^{kl} &= d_{ij}^{kl} f_j^{kl}, & -b_{ij}^{j\beta} &= d_{ij}^{kl} f_j^{i\beta}. \end{aligned}$$

We can determine all coefficients, but because  $c_{ii}^\alpha$  does not depend on  $j$ , we get two equations for it:

$$d_{ij}^{kl} f_j^{ll} = c_{ii}^l = d_{ik}^{jl} f_k^{ll}.$$

We view these as one linear equation for the unknowns  $d_{ij}^{kl}$ . The coefficient matrix of the resulting linear system is

$$\begin{pmatrix} 0 & f_k^{jj} & -f_l^{jj} & 0 & 0 & 0 \\ -f_j^{kk} & 0 & f_l^{kk} & 0 & 0 & 0 \\ f_j^{ll} & -f_k^{ll} & 0 & 0 & 0 & 0 \\ f_i^{kk} & 0 & 0 & 0 & -f_l^{kk} & 0 \\ -f_i^{ll} & 0 & 0 & f_k^{ll} & 0 & 0 \\ 0 & 0 & 0 & -f_k^{ii} & f_l^{ii} & 0 \\ 0 & f_i^{ll} & 0 & -f_j^{ll} & 0 & 0 \\ 0 & -f_i^{jj} & 0 & 0 & 0 & f_l^{jj} \\ 0 & 0 & 0 & f_j^{ii} & 0 & -f_l^{ii} \\ 0 & 0 & f_i^{jj} & 0 & 0 & -f_k^{jj} \\ 0 & 0 & -f_i^{kk} & 0 & f_j^{kk} & 0 \\ 0 & 0 & 0 & 0 & -f_j^{ii} & f_k^{ii} \end{pmatrix}$$

It has a nontrivial solution if all  $6 \times 6$  minors vanish. Among those are

$$f_j^{kk} f_k^{ll} f_l^{jj} (f_k^{jj} f_l^{kk} f_j^{ll} - f_j^{kk} f_k^{ll} f_l^{jj})$$

from which we obtain that the square of

$$f_k^{jj} f_l^{kk} f_j^{ll} - f_j^{kk} f_k^{ll} f_l^{jj}$$

lies in the ideal of the minors. This is one of the four conditions for  $d$ -semistability. There are three more equations

$$f_k^{jj} f_l^{ll} f_i^{kk} f_j^{kk} - f_j^{kk} f_l^{jj} f_i^{ll} f_k^{ii}$$

in the reduction of the ideal of minors, which do not give new conditions if the  $f_i^{jj} \neq 0$ , as

$$\begin{aligned} & f_l^{kk} (f_k^{jj} f_j^{ll} f_l^{ii} f_i^{kk} - f_j^{kk} f_l^{jj} f_i^{ll} f_k^{ii}) \\ &= f_l^{ii} f_i^{kk} (f_k^{jj} f_l^{kk} f_j^{ll} - f_j^{kk} f_k^{ll} f_l^{jj}) + f_j^{kk} f_l^{jj} (f_l^{ii} f_i^{kk} f_k^{ll} - f_i^{ll} f_k^{ii} f_l^{kk}). \end{aligned}$$

Under the  $d$ -semistability conditions the rank of the matrix is 5, and we obtain one infinitesimal deformation, where the quadratic equations are perturbed. Furthermore one has the perturbations of the cubic equations alone, which as before have to be divisible by  $x_i$ . We have already used 44 coordinate transformations. The coefficient of  $x_i y_\alpha y_\beta$  can be made to vanish with a transformation of the type  $y_\gamma \mapsto y_\gamma - \varepsilon x_i$ . So we have 28 coefficients left and the diagonal coordinate transformations, giving dimension 21.  $\square$

The computations in negative degree show that the tetrahedron  $X$  is only a hyperplane section of threefolds with two-dimensional singular locus, obtained by gluing together four cubic threefolds.

2.8. We want to describe an explicit deformation in the  $d$ -semistable case. We use the coordinate transformation  $x_i \mapsto (f_4^{ii}/f_i^{44})x_i$ ,  $i = 1, 2, 3$ , which gives  $f_i^{jj}f_4^{ii}/f_i^{44}$  as coefficient of  $y_j^2$  in the new  $F_i$ . The  $d$ -semistability conditions yield that the new coefficients satisfy  $f_i^{jj} = f_j^{ii}$ . We will denote them by  $f_{ij}$ . A solution to the linear equations above is then  $d_{ij} = df_{kl}$ , with  $d$  a new deformation variable. Furthermore we use coordinate transformations to remove the  $y_\alpha y_\beta$  terms from the  $F_i$ .

We set  $H_i = g_i^j y_j + g_i^k y_k + g_i^l y_l + h_i x_i$ . With this notation we get the following infinitesimal deformation:

$$\begin{aligned} & x_i x_j + df_{kl} y_k y_l - df_{ij} f_{kl} (x_i y_j + x_j y_i), \\ & x_i y_i + d(f_{kl} x_j H_j + f_{jl} x_k H_k + f_{jk} x_l H_l + f_{jk} f_{jl} y_j^2 + f_{kl} f_{kj} y_k^2 + f_{ij} f_{lk} y_l^2), \\ & y_j y_k y_l - x_i (f_{ij} y_j^2 + f_{ik} y_k^2 + f_{il} y_l^2) - x_i^2 H_i \\ & + dy_i ((f_{ik} f_{jl} + f_{il} f_{jk}) f_{ij} y_j^2 + (f_{ij} f_{kl} + f_{il} f_{kj}) f_{ik} y_k^2 + (f_{ij} f_{lk} + f_{ik} f_{lj}) f_{il} y_l^2) \\ & + df_{ij} f_{ik} f_{il} y_i^3 + dy_i (f_{ik} f_{il} x_j H_j + f_{ij} f_{il} x_k H_k + f_{ij} f_{ik} x_l H_l). \end{aligned}$$

If we try to lift to higher order complicated formulas arise, and it is not clear whether the computation is finite. It does stop if we restrict ourselves to the case of tetrahedral symmetry. Then  $f_{ij}$  does not depend on  $(i, j)$ , and we call the common value  $f$ ; likewise  $g$  is the value of all  $g_i^j$ , and  $h$  that of the  $h_i$ . We retain the notation  $H_i = g(y_j + y_k + y_l) + h x_i$ . By a coordinate transformation  $x_i \mapsto x_i + df^2 y_i$  we simplify the expression for the first 6 equations. We write  $t$  for the deformation parameter.

2.9. PROPOSITION. *The following set of equations defines a degeneration of K3-surfaces with special fibre a tetrahedron of degree 12:*

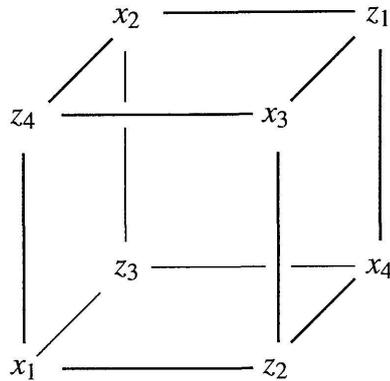
$$\begin{aligned} & x_i x_j + tf(y_k - tfH_k)(y_l - tfH_l), \\ & x_i y_i + tf(x_j H_j + x_k H_k + x_l H_l) + tf^2(y_i^2 + y_j^2 + y_k^2 + y_l^2), \\ & y_j y_k y_l - fx_i(y_i^2 + y_j^2 + y_k^2 + y_l^2) - x_i^2 H_i \\ & - t^2 f^2 (y_j H_k H_l + y_k H_j H_l + y_l H_j H_k) + 2t^3 f^3 H_j H_k H_l. \end{aligned}$$

*The general fibre is a smooth K3-surface lying on  $\mathbf{P}^1 \times \mathbf{P}^1 \times \mathbf{P}^1$ .*

*Proof.* We suppress the computation. For  $t \neq 0$  the cubic equations lie in the ideal of the quadrics. We can write three independent equations

$$x_i (y_i - tfH_i) - x_j (y_j - tfH_j)$$

which together with the first six define  $\mathbf{P}^1 \times \mathbf{P}^1 \times \mathbf{P}^1$ : each square in the following picture gives an equation, where we put  $z_i := \sqrt{-tf}(y_i - tfH_i)$ .



We obtain the  $K3$  by taking the complete intersection with the quadric  $\sum_i(x_i y_i + 3tfx_i H_i + 4tf^2 y_i^2)$ .  $\square$

2.10. THE RELATION WITH QUARTICS. We can construct a degree 12 tetrahedron from four planes in  $\mathbf{P}^3$  by first blowing up each plane in 6 points and then gluing them back together. Therefore we first describe the blow up in a way adapted to our situation.

Let two points lie on each side of the coordinate triangle in  $\mathbf{P}^2$  with coordinates  $(z_1 : z_2 : z_3)$ . We describe them by  $z_k = z_i^2 + a_{ij}z_i z_j + b_{ij}z_j^2 = 0$ , where  $(ijk)$  is a cyclic permutation of  $(123)$  (this means that we choose an orientation on the triangle). As cubics through the six points we take the coordinate triangle and three cubics, each consisting of a side and a quadric passing through the remaining four points. More precisely, we take

$$\begin{aligned} x_0 &= z_1 z_2 z_3, \\ y_i &= z_i(z_k^2 - a_{ki}z_k z_i + b_{ki}(z_i^2 - a_{ij}z_i z_j + b_{ij}z_j^2)). \end{aligned}$$

One computes the relations

$$z_k y_j - b_{ij} z_j y_k - ((1 - b_{ij} b_{jk} b_{ki}) z_i - a_{ij} z_j + b_{ij} b_{jk} a_{ki} z_k) x_0 = 0.$$

By the Hilbert-Burch theorem the maximal minors of the relation matrix

$$\begin{pmatrix} 0 & z_3 & -b_{12} z_2 & -(1 - b_{12} b_{23} b_{31}) z_1 + a_{12} z_2 - b_{12} b_{23} a_{31} z_3 \\ -b_{23} z_3 & 0 & z_3 & -(1 - b_{12} b_{23} b_{31}) z_2 + a_{23} z_3 - b_{23} b_{31} a_{12} z_1 \\ z_2 & -b_{31} z_1 & 0 & -(1 - b_{12} b_{23} b_{31}) z_3 + a_{31} z_1 - b_{31} b_{12} a_{23} z_2 \end{pmatrix}$$

give the cubics, up to a common factor  $1 - b_{12} b_{23} b_{31}$ . By Lemma 2.4 this factor vanishes exactly when the 6 points lie on a conic.

Viewing the relations as holding between the  $z_i$  gives the coefficient matrix

$$\begin{pmatrix} (1 - b_{12}b_{23}b_{31})x_0 & b_{12}y_3 - a_{12}x_0 & b_{12}b_{23}a_{31}x_0 - y_2 \\ b_{23}b_{31}a_{12}x_0 - y_3 & (1 - b_{12}b_{23}b_{31})x_0 & y_1b_{23} - a_{23}x_0 \\ b_{31}y_2 - a_{31}x_0 & b_{12}b_{31}a_{23}x_0 - y_1 & (1 - b_{12}b_{23}b_{31})x_0 \end{pmatrix}.$$

Its determinant is the equation of the surface. After dividing by  $b_{12}b_{23}b_{31} - 1$  it equals

$$\begin{aligned} & y_1y_2y_3 - x_0(b_{12}y_3^2 + b_{23}y_1^2 + b_{31}y_2^2) \\ & - x_0^2(a_{12}a_{23}b_{31}y_2 + a_{23}a_{31}b_{12}y_3 + a_{31}a_{12}b_{23}y_1 - (a_{12}y_3 + a_{23}y_1 + a_{31}y_2)(1 + b_{12}b_{23}b_{31})) \\ & - x_0^3((1 - b_{12}b_{23}b_{31})^2 + (1 + b_{12}b_{23}b_{31})a_{12}a_{23}a_{31} + b_{12}b_{23}a_{31}^2 + b_{23}b_{31}a_{12}^2 + b_{12}b_{31}a_{23}^2). \end{aligned}$$

This last formula also works if the 6 points lie on a conic, but then it is easier to take the  $y_i$  as product of a side and the conic through the 6 points; this means adding a multiple of  $x_0$  to each  $y_i$ . The equation then becomes  $y_1y_2y_3 - x_0Q(y)$  with  $Q(z)$  the conic.

Now we apply this to our tetrahedron. We choose an orientation and orient the faces with the induced orientation. We get variables  $x_i$  and  $y_i$ . For the face  $i$  we take  $x_i = z_jz_kz_l$  as before, but we multiply  $y_j$  by a factor  $\lambda_{ij}$  to be determined later. So we set  $y_j = \lambda_{ij}z_j(z_j^2 + \dots)$ . We look at the line  $z_3 = z_0 = 0$ , with coordinates  $(z_1 : z_2)$ . Via the coordinates of face 0 we get the embedding  $(y_1 : y_2) = (\lambda_{01}b_{31}z_1 : \lambda_{02}z_2)$  whereas face 3 gives  $(y_1 : y_2) = (\lambda_{31}z_1 : \lambda_{32}b_{02}z_2)$ . The condition that the Del Pezzo surfaces are glued in the same way as the planes yields the equations  $\lambda_{01}\lambda_{32}b_{31}b_{02} = \lambda_{02}\lambda_{31}$ . By even permutations of (0123) we get in total six equations. They are solvable if and only if

$$b_{01}b_{10}b_{02}b_{20}b_{03}b_{30}b_{12}b_{21}b_{13}b_{31}b_{23}b_{32} = 1,$$

a condition obtained by multiplying the six equations.

The  $d$ -semistability conditions  $f_k^{jj}f_l^{kk}f_j^{ll} - f_j^{kk}f_k^{ll}f_l^{jj} = 0$  give for the cubic above, using  $(jkl) = (123)$ :

$$\frac{b_{30}}{\lambda_{21}^2} \frac{b_{10}}{\lambda_{32}^2} \frac{b_{20}}{\lambda_{13}^2} = \frac{b_{03}}{\lambda_{12}^2} \frac{b_{01}}{\lambda_{23}^2} \frac{b_{02}}{\lambda_{31}^2}.$$

Using the fact that the  $\lambda_{ij}$  satisfy the equations  $\lambda_{32}b_{02}/\lambda_{31} = \lambda_{02}/(\lambda_{01}b_{31})$  we see that this condition is equivalent to  $b_{21}^2b_{32}^2b_{13}^2 = b_{12}^2b_{23}^2b_{31}^2$ , which is one of the conditions that the 24 points be cut out by a quartic.

We can ask which choices of 24 points give our symmetric tetrahedron. The condition  $\prod b_{ij} = 1$  limits the possibilities. In particular, if all  $b_{ij} = 1$ , the six points in each face lie on a conic, giving a singular tetrahedron. If we take the quartic  $Q = (a\sigma_1^2 + b\sigma_2)^2$  then each element of the pencil has 12 singular

points. We can blow them up and blow down the six conics in the faces by embedding the pencil in  $\mathbf{P}^7 \times \mathbf{P}^1$  with the linear system of cubics in  $\mathbf{P}^3$  with as base points the 12 singular points. We set

$$\begin{aligned} x_i &= z_j z_k z_l, \\ y_i &= z_i (a\sigma_1^2 + b\sigma_2). \end{aligned}$$

We obtain a symmetric tetrahedron with  $g = h = 0$ .

We get nonsingular Del Pezzo surfaces by taking all  $b_{ij} = -1$ , and  $a_{ij} = a$ . Then  $f = -1$ ,  $g = -a^2$  and  $h = a^2 + 4$ . The points on the side of the tetrahedron are given by

$$(z_i^2 + az_i z_j - z_j^2)(-z_i^2 + az_i z_j + z_j^2) = (-z_i^4 + (2 + a^2)z_i^2 z_j^2 - z_j^4).$$

In particular, we obtain different smoothings of the same tetrahedron, those embedded in  $\mathbf{P}^7$  and others where the general fibre is embeddable in  $\mathbf{P}^3$ . They belong to different 19-dimensional hypersurfaces in the 20-dimensional subspace of the versal deformation whose general fibre is a smooth  $K3$ -surface.

### 3. DEFORMATION THEORY

3.1. Let  $X = \bigcup X_i$  be a normal crossings surface with normalisation  $\tilde{X} = \coprod X_i$ . The components of the double locus  $D$  are  $D_{ij} = X_i \cap X_j$ . The divisor  $D_i := \bigcup_j D_{ij}$  is a normal crossings divisor in  $X_i$ . We set  $\bar{D} = \coprod D_i$ .

As  $X$  is locally a hypersurface in a 3-fold  $M$ , its cotangent cohomology sheaves  $\mathcal{T}_X^i$  vanish for  $i \geq 2$  and

$$0 \longrightarrow \mathcal{T}_X^0 \longrightarrow \Theta_M|_X \longrightarrow N_{X/M} \longrightarrow \mathcal{T}_X^1 \longrightarrow 0.$$

There is a canonical isomorphism  $\mathcal{T}_X^1 \cong \mathcal{O}_D(X)$  and in particular, if  $X$  is  $d$ -semistable, then  $\mathcal{T}_X^1 \cong \mathcal{O}_D$  [F2, Prop. 2.3].

3.2. LEMMA. *There is an exact sequence*

$$0 \longrightarrow \mathcal{T}_X^0 \longrightarrow n_* \Theta_{\tilde{X}}(\log \bar{D}) \longrightarrow \mathcal{T}_D^0 \longrightarrow 0.$$

*Proof.* This is a local computation. The sheaf  $\Theta_M(\log X)$  of vector fields on  $M$  which preserve  $z_1 z_2 z_3 = 0$  is generated by the  $z_i \frac{\partial}{\partial z_i}$ . Restricted to a component  $X_i: z_i = 0$  we get sections of  $\Theta_{X_i}(\log D_i)$ . The restrictions to different components satisfy the obvious compatibility condition.  $\square$

Sections of  $\mathcal{T}_D^0$  are given by vector fields on each component, which vanish in the triple points. We study  $\Theta_{X_i}(\log D_i)$  with the exact sequence

$$0 \longrightarrow \Theta_{X_i}(\log D_i) \longrightarrow \Theta_{X_i} \longrightarrow \bigoplus_j N_{D_{ij}/X_i} \longrightarrow 0.$$

For a  $d$ -semistable  $K3$ -surface  $X$  in  $(-1)$ -form,

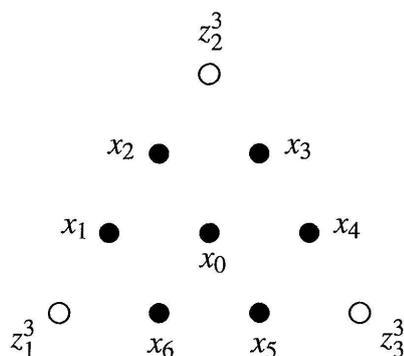
$$H^0(D_{ij}, N_{D_{ij}/X_i}) = H^1(D_{ij}, N_{D_{ij}/X_i}) = 0.$$

Each component  $X_i$  is  $\mathbf{P}^2$  blown up in  $k \geq 3$  points and  $H^2(\Theta_{X_i}) = 0$ ,  $h^0(\Theta_{X_i}) = \max(0, 8 - 2k)$ ,  $h^1(\Theta_{X_i}) = \max(0, 2k - 8)$ .

So  $H^0(\Theta_{X_i}) \neq 0$  only in the case that  $k = 3$  and the double curve  $D_i$  is a hexagon. We then call  $X_i$  a hexagonal component, or hexagon for short.

3.3. LEMMA [F1, Cor. 3.5]. *For a  $d$ -semistable  $K3$ -surface  $X$  of type III in  $(-1)$ -form,  $H^0(X, \mathcal{T}_X^0) = 0$ .*

*Proof.* We first describe the sections of  $H^0(\Theta_{X_i})$  for a hexagonal component. We blow up  $\mathbf{P}^2$  in the vertices of the coordinate triangle. As basis for the linear system of cubics we take the monomials given by black dots in the picture below.



A vector field  $\vartheta$  on  $X_i$  comes from a vector field on  $\mathbf{P}^2$  which vanishes in the points blown up. We can give it homogeneously by  $a_1 z_1 \frac{\partial}{\partial z_1} + a_2 z_2 \frac{\partial}{\partial z_2} + a_3 z_3 \frac{\partial}{\partial z_3}$ , subject to the relation  $z_1 \frac{\partial}{\partial z_1} + z_2 \frac{\partial}{\partial z_2} + z_3 \frac{\partial}{\partial z_3} = 0$ . In the  $x_j$  coordinates we get

$$\begin{aligned} (a_1 + a_2 + a_3) x_0 \frac{\partial}{\partial x_0} &+ (2a_1 + a_2) x_1 \frac{\partial}{\partial x_1} + (2a_2 + a_1) x_2 \frac{\partial}{\partial x_2} \\ &+ (2a_2 + a_3) x_3 \frac{\partial}{\partial x_3} + (2a_3 + a_2) x_4 \frac{\partial}{\partial x_4} \\ &+ (2a_3 + a_1) x_5 \frac{\partial}{\partial x_5} + (2a_1 + a_3) x_6 \frac{\partial}{\partial x_6}. \end{aligned}$$

We restrict to the line  $(x_{j-1} : x_j)$  and take as generator of  $\mathcal{T}_D^0|_{D_{ij}}$  the vector field  $\vartheta_j = \frac{1}{2}(x_j \frac{\partial}{\partial x_j} - x_{j-1} \frac{\partial}{\partial x_{j-1}})$ . On the  $(x_6 : x_1)$ -line  $\vartheta = (a_2 - a_3)\vartheta_1$  and on the  $(x_1 : x_2)$ -line  $\vartheta = (a_2 - a_1)\vartheta_2$ . The remaining coefficients  $\vartheta = \beta_j \vartheta_j$  are found by cyclic permutation. They satisfy  $\beta_j = \beta_{j-1} + \beta_{j+1}$ . In particular, two adjacent coefficients determine all the others and opposite coefficients add up to zero.

Let  $\vartheta \in H^0(X, \mathcal{T}_X^0)$  be a non-vanishing global section. As the dual graph is a triangulation of  $S^2$  one has  $\sum_i (6 - e_i) = 12$ , where  $e_i$  is the number of components of the double curve  $D_i$ . So there exist non-hexagonal components, and  $\vartheta$  vanishes on them. Suppose  $\vartheta$  vanishes on  $X_0$  and not on the adjacent hexagon  $X_1$ . We are going to look at the restriction of  $\vartheta$  to other components, as illustrated in Figure 3.1.

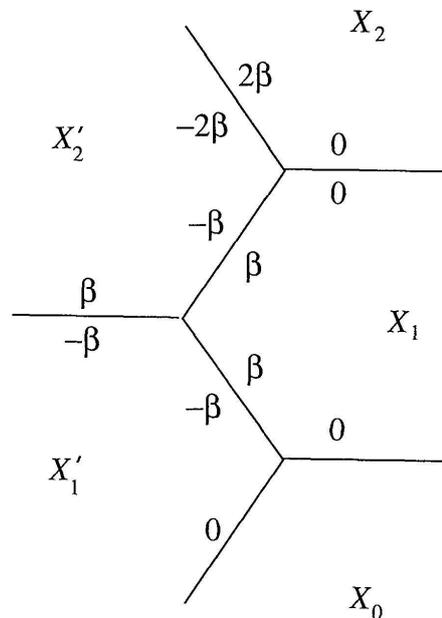


FIGURE 3.1

Coefficients of a vector field

Let  $T = X_0 \cap X_1 \cap X'_1$  be a triple point. We know that  $\vartheta$  vanishes on  $X_1 \cap X_0$ . If it also vanishes on  $X_1 \cap X'_1$ , then it vanishes altogether, contrary to the assumption. Therefore  $X'_1$  is also hexagonal. Let  $\vartheta = \beta \vartheta_0$  on  $D_{11'} = X_1 \cap X'_1 \subset X_1$ . Considered on  $X'_1$  the restriction of  $\vartheta$  is  $-\beta$  times the generator. The other triple point on  $D_{11'}$  involves a hexagon  $X'_2$ , which contains also the triple point  $X_1 \cap X'_2 \cap X_2$ . Considered on  $X'_2$ , the coefficient of the restriction of  $\vartheta$  to  $X'_2 \cap X'_1$  is  $\beta$ , to  $X'_2 \cap X_1$  it is  $-\beta$ , so to  $X'_2 \cap X_2$  it is  $-2\beta$ . Therefore on  $X_2$ ,  $\vartheta$  has adjacent coefficients  $0, 2\beta$ . Inductively we find components  $X'_n, X_n$  with the coefficient  $n\beta$  occurring. As there are only finitely many components, this is impossible.  $\square$

3.4. THEOREM. Let  $X = \bigcup_{i=1}^k X_i$  be a  $d$ -semistable  $K3$ -surface of type III in  $(-1)$ -form, with  $k$  components. Then

$$\dim H^1(X, \mathcal{T}_X^0) = k + 18,$$

$$\dim H^0(X, \mathcal{T}_X^1) = 1,$$

$$\dim H^1(X, \mathcal{T}_X^1) = k - 1.$$

So  $\dim T_X^1 = k + 19$ ,  $\dim T_X^2 = k - 1$ .

*Proof.* As the dual graph triangulates  $S^2$  we have  $V - E + F = 2$ , where  $V = k$ , the number of components of  $X$ ,  $E$  is the number of double curves and  $F$  is the number of triple points. Each double curve contains two triple points, so  $F = 2/3E$ , which makes  $E = 3k - 6$ . A component  $X_i$ , which is  $\mathbf{P}^2$  blown up in  $\delta_i$  points, has  $e_i = 9 - \delta_i$  double curves. Observe that  $\sum_i e_i = 2E$ . The exact sequence above gives  $\dim H^1(X, \mathcal{T}_X^0) = \sum_i 2(5 - e_i) + E = 10V - 3E = k + 18$ .

We have  $h^0(X, \mathcal{T}_X^1) = h^0(D, \mathcal{O}_D) = 1$  and  $h^1(X, \mathcal{T}_X^1) = h^1(D, \mathcal{O}_D) = 1 - \chi = 1 - (E - 2F) = k - 1$ .  $\square$

3.5. Locally trivial deformations of a  $d$ -semistable  $K3$ -surface  $X$  are unobstructed and fill up a codimension one smooth subspace of the base of the versal deformation with tangent space  $H^1(X, \mathcal{T}_X^0)$ . This means that every equation of the base is divisible by the equation of this hypersurface. As one obtains the base space as fibre of a map  $T^1 \rightarrow T^2$ , we look at the map

$$\text{Ob}: H^1(\mathcal{T}_X^0) \times H^0(\mathcal{T}_X^1) \rightarrow H^1(\mathcal{T}_X^1).$$

Let  $\xi$  be a global generator of  $\mathcal{T}_X^1$ . The existence of a second smooth component (of dimension 20) follows, if one can show that the linear map  $\text{Ob}(\cdot, \xi): H^1(\mathcal{T}_X^0) \rightarrow H^1(\mathcal{T}_X^1)$  is surjective. To describe it we start with the map  $\text{Ob}(\cdot, \xi): \mathcal{T}_X^0 \rightarrow \mathcal{T}_X^1$ . Locally  $X$  is a hypersurface given by an equation  $f = 0$  and elements of  $\mathcal{T}_X^0$  come from ambient vector fields satisfying  $\vartheta(f) = cf$ . We can choose coordinates such that  $\xi$  acts as  $f \mapsto 1$ . Then  $\text{Ob}(\vartheta, \xi) = -c\xi$ . In the normal crossings situation the map  $\text{Ob}(\cdot, \xi)$  is surjective and we get an exact sequence

$$0 \longrightarrow \mathcal{S} \longrightarrow \mathcal{T}_X^0 \longrightarrow \mathcal{T}_X^1 \longrightarrow 0.$$

The kernel of the map  $\text{Ob}(\cdot, \xi): H^1(\mathcal{T}_X^0) \rightarrow H^1(\mathcal{T}_X^1)$  can be characterised in a different way ([F-S]). If  $X = \bigcup_{i=1}^k X_i$  occurs as central fibre in a degeneration  $\mathcal{X} \rightarrow S$ , we define  $k$  line bundles  $L_i := \mathcal{O}_{\mathcal{X}}(X_i)|_X$ . On a  $d$ -semistable  $X$  they can be defined by

$$\begin{aligned} L_i|_{X_i} &= \mathcal{O}_{X_i}(-D_i), \\ L_i|_{X_j} &= \mathcal{O}_{X_j}(X_i \cap X_j), \quad j \neq i, \end{aligned}$$

with appropriate gluings, using the global section of  $\mathcal{O}_D(X)$ . The bundle  $L_i$  defines a class  $\xi_i$  in

$$H^1(X, \mathcal{O}_X^*) \cong \ker \{H^2(X, \mathbf{Z}) \rightarrow H^2(\mathcal{O}_X) = \mathbf{C}\},$$

which therefore lies in  $H^1(\Omega^1/\tau^1)$ , where  $\Omega^1/\tau^1$  are the Kähler differentials modulo torsion [F2, Sect. 1]. The condition that  $L_i$  lifts to line bundles on a locally trivial deformation with tangent vector  $\vartheta \in H^1(\mathcal{T}_X^0)$  is that  $\langle \vartheta, \xi_i \rangle = 0$  with  $\langle -, - \rangle$  the perfect pairing  $H^1(\mathcal{T}_X^0) \otimes H^1(\Omega^1/\tau^1) \rightarrow H^2(\mathcal{O}_X) = \mathbf{C}$  [F2, (2.10)]. The surjectivity of the map  $\text{Ob}(\cdot, \xi)$  follows from the following lemma.

3.6. LEMMA. *The classes  $\xi_i$  span a  $(k-1)$ -dimensional subspace of  $H^2(X, \mathbf{Z})$ .*

*Proof.* We compute  $H^2(X, \mathbf{Z})$  as the kernel of the map

$$\bigoplus H^2(X_i, \mathbf{Z}) \rightarrow \bigoplus H^2(D_{ij}, \mathbf{Z}).$$

Each  $\xi_i$  gives rise to a divisor  $\sum_m a_{lm} D_{lm}$  on  $X_l$ ,  $l = 1, \dots, k$ , with coefficients satisfying  $a_{lm} + a_{ml} = 0$  (and  $a_{lm} \neq 0$  only if  $i = l$  or  $i = m$ ). The relation  $\sum \xi_i = 0$  holds.

Let now  $\sum b_i \xi_i = 0 \in H^2(X, \mathbf{Z})$ . It gives rise to a divisor  $\sum_m \beta_{lm} D_{lm}$  on  $X_l$ . If the classes  $D_{lm}$  are independent in  $H^2(X_l, \mathbf{Z})$ , then  $\beta_{lm} = 0$  for all  $m$ . This condition is not satisfied if  $X_l$  is a hexagon. Then we can only conclude that  $\beta_{l,m-1} + \beta_{l,m+1} = \beta_{lm}$ . With the same argument as in the proof of Theorem 3.3, illustrated by Figure 3.1, we infer that even in this case  $\beta_{lm} = 0$  for all  $m$ .

Therefore  $b_i = b_j$  for all pairs  $(i, j)$  such that  $X_i \cap X_j \neq \emptyset$ . This implies that  $\sum b_i \xi_i$  is a multiple of  $\sum \xi_i$ .  $\square$

We summarise:

3.7. THEOREM [F2, (5.10)]. *A  $d$ -semistable K3-surface  $X$  of type III is smoothable. Its versal base space is the union  $V_1 \cup V_2$ , where  $V_1$  is a smooth hypersurface corresponding to locally trivial deformations of  $X$ , which meets transversally a 20-dimensional smooth subspace  $V_2$ , with  $V_2 \setminus V_1$  parametrising smooth K3-surfaces and  $V_2 \cap V_1$  locally trivial deformations of  $X$  for which  $\mathcal{O}_D(X)$  remains trivial.*

3.8. EMBEDDED DEFORMATIONS. We relate the above results to direct computations with generators and relations for the cone over  $X$ , as for the tetrahedron. The case of cones over non-singular varieties is treated in [S2]. We suppose that the affine cone  $C(X)$  over  $X$  is Cohen-Macaulay. The starting point is the exact sequence

$$(3.1) \quad 0 \longrightarrow T_{C(X)}^0 \longrightarrow \Theta_{\mathbf{C}^{n+1}|C(X)} \longrightarrow N_{C(X)} \longrightarrow T_{C(X)}^1 \longrightarrow 0,$$

which we shall relate to exact sequences of sheaves on  $X$ . We set  $U = C(X) \setminus 0$ ; then  $\pi: U \rightarrow X$  is a  $\mathbf{C}^*$ -bundle over  $X$ . For a reflexive sheaf  $\mathcal{F}$  on  $C(X)$  we have  $H^0(C(X), \mathcal{F}) = H^0(U, \mathcal{F})$ . All sheafs  $\mathcal{F}$  considered here have a natural  $\mathbf{C}^*$ -action, so  $\pi_* \mathcal{F}$  decomposes into the direct sum of eigenspaces. In particular, the degree 0 part is the sheaf of  $\mathbf{C}^*$ -invariants. With homogeneous coordinates  $x_i$  the  $\mathbf{C}^*$ -invariant sections  $x_j \frac{\partial}{\partial x_i}$  of  $H^0(U, \Theta_{\mathbf{C}^{n+1}|C(X)})$  can be considered as elements of  $H^0(X, V^* \otimes_{\mathbf{C}} \mathcal{O}_X(1))$ , where  $V = H^0(X, \mathcal{O}_X(1))$ . We get the degree zero part  $T_{C(X)}^1(0)$  as  $\text{coker } H^0(X, V^* \otimes_{\mathbf{C}} \mathcal{O}_X(1)) \rightarrow H^0(X, N_{X/\mathbf{P}^n})$ . We factorise this map corresponding to a splitting of the exact sequence (3.1):

$$(3.2) \quad 0 \longrightarrow T_{C(X)}^0 \longrightarrow \Theta_{\mathbf{C}^{n+1}|C(X)} \longrightarrow G \longrightarrow 0,$$

$$(3.3) \quad 0 \longrightarrow G \longrightarrow N_{C(X)} \longrightarrow T_{C(X)}^1 \longrightarrow 0.$$

Denoting by  $\mathcal{G}_X$  the sheaf of  $\mathbf{C}^*$  invariants associated to  $G$  we obtain

$$H^0(X, V^* \otimes_{\mathbf{C}} \mathcal{O}_X(1)) \longrightarrow H^0(X, \mathcal{G}_X) \longrightarrow H^0(X, N_{X/\mathbf{P}^n}).$$

On  $X$  we have the exact sequence

$$0 \longrightarrow \mathcal{G}_X \longrightarrow N_{X/\mathbf{P}^n} \longrightarrow \mathcal{T}_X^1 \longrightarrow 0.$$

The short exact sequence (3.2) gives

$$0 \longrightarrow \text{Diff}_X \longrightarrow V^* \otimes_{\mathbf{C}} \mathcal{O}_X(1) \longrightarrow \mathcal{G}_X \longrightarrow 0$$

with  $\text{Diff}_X$  the sheaf of differential operators on  $X$ , which is related to  $\mathcal{T}_X^0$  by the exact sequence

$$0 \longrightarrow \mathcal{O}_X \longrightarrow \text{Diff}_X \longrightarrow \mathcal{T}_X^0 \longrightarrow 0.$$

3.9. PROPOSITION. *Let  $X$  be a  $d$ -semistable K3 of type III in  $(-1)$ -form. The space of infinitesimal locally trivial embedded deformations is  $H^1(X, \mathcal{D}iff_X)$ , of dimension  $k + 17$ . It has codimension one in  $T_{C(X)}^1(0)$ .*

*Proof.* From the computation of  $h^i(\mathcal{T}_X^0)$  in 3.4 and the exact sequence for  $\mathcal{D}iff_X$  we conclude that  $h^0(\mathcal{D}iff_X) = h^0(\mathcal{O}_X) = 1$ . As  $h^1(\mathcal{O}_X) = 0$  and  $h^2(\mathcal{O}_X) = 1$  we get the exact sequence

$$0 \longrightarrow H^1(\mathcal{D}iff_X) \longrightarrow H^1(\mathcal{T}_X^0) \longrightarrow H^2(\mathcal{O}_X) \longrightarrow H^2(\mathcal{D}iff_X) \longrightarrow 0.$$

The line bundle  $\mathcal{O}(1)$  determines a class  $h \in H^1(\Omega^1/\tau^1)$ , which lifts to a deformation  $\vartheta \in H^1(X, \mathcal{T}_X^0)$  if and only if  $\langle \vartheta, h \rangle = 0$  with  $\langle -, - \rangle$  the perfect pairing  $H^1(\mathcal{T}_X^0) \otimes H^1(\Omega^1/\tau^1) \rightarrow H^2(\mathcal{O}_X) = \mathbf{C}$ . This accounts for the non-algebraic deformation direction. So  $\dim H^1(\mathcal{D}iff_X) = k + 17$  and  $H^2(\mathcal{D}iff_X) = 0$ . We then obtain

$$H^1(X, \mathcal{D}iff_X) = \text{coker} \{ H^0(X, V^* \otimes_{\mathbf{C}} \mathcal{O}_X(1)) \longrightarrow H^0(X, \mathcal{G}_X) \}$$

and  $h^1(\mathcal{G}_X) = 0$ , as  $h^i(X, \mathcal{O}_X(1)) = 0$  for  $i > 0$ . Finally we get  $H^1(N_{X/\mathbf{P}^n}) = H^1(\mathcal{T}_X^1)$  and the exact sequence

$$0 \longrightarrow H^0(X, \mathcal{G}_X) \longrightarrow H^0(X, N_{X/\mathbf{P}^n}) \longrightarrow H^0(X, \mathcal{T}_X^1) \longrightarrow 0. \quad \square$$

3.10. For  $T_{C(X)}^2(0)$  we can argue as in the smooth case [S2, (1.25)] to obtain the exact sequence

$$0 \longrightarrow T_{C(X)}^2(0) \longrightarrow H^1(X, N_{X/\mathbf{P}^n}) \longrightarrow \bigoplus H^1(X, \mathcal{O}_X(d_j))$$

with the  $d_j$  the degrees of the generators of the ideal of  $C(X)$  (or of  $X$ ). In particular, in our situation  $T_{C(X)}^2(0) = H^1(N_{X/\mathbf{P}^n}) = H^1(\mathcal{T}_X^1)$ .

3.11. THEOREM [F-S, (5.5)]. *A  $d$ -semistable K3-surface  $X$  of type III in  $\mathbf{P}^n$  is smoothable by embedded deformations. They form a 19-dimensional smooth component.*

*Proof.* In the embedded case the base space is also the fibre of a map between the relevant cotangent modules, and the locally trivial deformations are unobstructed. The map  $\text{Ob}: H^1(\mathcal{D}iff_X) \times H^0(\mathcal{T}_X^1) \rightarrow H^1(\mathcal{T}_X^1)$  is the restriction of the obstruction map in 3.5. We observe that  $H^1(\mathcal{D}iff_X)$  is transversal to  $\bigcap_i \ker \text{Ob}(\cdot, \xi_i)$ , as the class  $h$  satisfies  $h^2 > 0$  and is therefore independent of the classes of the  $\xi_i$ .  $\square$

3.12. THE TOPOLOGY OF THE SPECIAL FIBRE. One can compute the homology  $H_*(X, \mathbf{Z})$  with a Mayer-Vietoris spectral sequence [P, Prop. 2.5.1] with  $E^1$ -term  $E_{p,q}^1 = H_p(X^{[q]}, \mathbf{Z})$ , where  $X^{[0]} = \coprod X_i$ ,  $X^{[1]} = \coprod D_{ij}$  and  $X^{[2]}$  the set of triple points  $P_{ijk} = X_i \cap X_j \cap X_k$ .

3.13. PROPOSITION. Let  $X = \bigcup_{i=1}^k X_i$  be a  $d$ -semistable K3-surface of type III in  $(-1)$ -form, with  $k$  components. Then

$$\dim H_0(X, \mathbf{Z}) = 1,$$

$$\dim H_2(X, \mathbf{Z}) = k + 19,$$

$$\dim H_4(X, \mathbf{Z}) = k.$$

*Proof.* The  $E^1$ -term of the spectral sequence looks like:

$\bigoplus H_4(X_i, \mathbf{Z})$		
0		
$\bigoplus H_2(X_i, \mathbf{Z})$	$\bigoplus H_2(D_{ij}, \mathbf{Z})$	
0	0	
$\bigoplus H_0(X_i, \mathbf{Z})$	$\bigoplus H_0(D_{ij}, \mathbf{Z})$	$\bigoplus H_0(T_{ijk}, \mathbf{Z})$

To prove that the map  $\bigoplus H_2(D_{ij}, \mathbf{Z}) \rightarrow \bigoplus H_2(X_i, \mathbf{Z})$  is injective we observe that  $\bigoplus_j H_2(D_{ij}, \mathbf{Z}) \rightarrow H_2(X_i, \mathbf{Z})$  is injective unless  $X_i$  is a hexagonal component. We take care of those by arguing as in the proofs of Lemmas 3.3 and 3.6. If the component  $X_i$  is obtained by blowing up  $\mathbf{P}^2$  in  $\delta_i$  points, then  $b_2(X_i) = \delta_i + 1 = 10 - e_i$  with the notation of 3.3, so the cokernel of the map  $\bigoplus H_2(D_{ij}, \mathbf{Z}) \rightarrow \bigoplus H_2(X_i, \mathbf{Z})$  has dimension  $10V - 3E = k + 18$ . The dimension formulas now follow from the spectral sequence.  $\square$

3.14. We describe the non-algebraic homology class in more detail. Each double curve contains two triple points, which are homologous, so the boundary of an interval. On a component  $X_i$  these intervals make up a closed polygon (with  $e_i$  edges), which itself is the boundary of a topological disc. For the case of  $\mathbf{P}^2$  blown up in 4 points this is illustrated in Figure 5.1: after blowing up we have a pentagon, which is the boundary of the strict transform of the shaded area. With the given coordinates this strict transform consists of all points on the Del Pezzo surface with positive coordinates. Finally the discs glue together to a real polyhedron with the same dual graph as the complex surface  $X$ .

3.15. A nice construction for studying the homology of the general fibre is given by [A'C]. Let  $\sigma_i: \mathcal{Z}_i \rightarrow \mathcal{X}$  be the oriented real blow-up of  $X_i \subset \mathcal{X}$ . This is a manifold with boundary, whose boundary  $\partial\mathcal{Z}_i = \sigma_i^{-1}(X_i)$  is isomorphic to the boundary of a tubular neighbourhood of  $X_i$  in  $\mathcal{X}$ . The fibred product  $\sigma: \mathcal{Z} \rightarrow \mathcal{X}$  of the  $\sigma_i$  is a manifold with corners. Its boundary  $\mathcal{N} := \partial\mathcal{Z}$  comes with a map to  $X$ . It also fibres over  $S^1$ : the composed map  $\mathcal{Z} \rightarrow \mathcal{X} \rightarrow S \ni 0$  extends to a map from  $\mathcal{Z}$  to the real oriented blow-up of  $S$  in  $0$  (polar coordinates!). A fibre of  $\mathcal{N} \rightarrow S^1$  is then a topological model of the general fibre.

This model is not sufficient to describe the monodromy. One has first to replace  $X$  by the geometric realisation of the simplicial object  $X^{[1]}$ : one replaces each double point by an interval, and each triple point by a 2-simplex. A final fibred product then gives the new model. For details see [A'C, §2].

#### 4. HODGE ALGEBRAS

4.1. STANLEY-REISNER RINGS. Let  $\Delta$  be a simplicial complex with set of vertices  $V = \{v_1, \dots, v_n\}$ . A monomial on  $V$  is an element of  $\mathbf{N}^V$ . Each subset of  $V$  determines a monomial on  $V$  by its characteristic function. The support of a monomial  $M: V \rightarrow \mathbf{N}$  is the set  $\text{supp } M = \{v \in V \mid M(v) \neq 0\}$ . The set  $\Sigma_\Delta$  of monomials whose support is not a face is an ideal, generated by the monomials corresponding to minimal non-simplices.

Given a ring  $R$  and an injection  $\phi: V \rightarrow R$  we can associate to each monomial  $M$  on  $V$  the element  $\phi(M) = \prod_{v \in V} \phi(v)^{M(v)} \in R$ . We will usually identify  $V$  and  $\phi(V)$  and write  $M \in R$  for  $\phi(M)$ . This applies in particular to the polynomial ring  $K[V]$  over a field  $K$ . The ideal  $\Sigma_\Delta$  gives rise to the Stanley-Reisner ideal  $I_\Delta \subset K[V]$ . The *Stanley-Reisner ring* is  $A_\Delta = K[V]/I_\Delta$ .

Deformations of Stanley-Reisner rings are studied in [A-C].

4.2. EXAMPLE. Let  $\Delta$  be an octahedron. We map the set of vertices to  $\mathbf{C}[x_1, \dots, x_6]$  such that opposite vertices correspond to variables with index sum 7.

The Stanley-Reisner ring is minimally generated by the three monomials  $x_i x_{7-i}$ . The spaces smooths to a  $K3$ -surface, the complete intersection of three general quadrics. A general 1-parameter deformation is not semi-stable, because the total space has singularities at the six quadruple points of the special fibre.

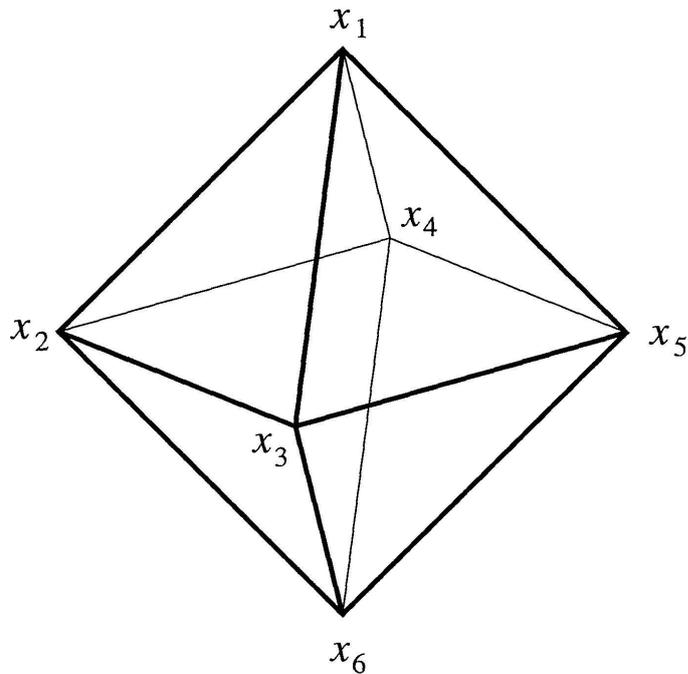


FIGURE 4.1  
Octahedron

4.3. REMARK. To get an octahedron as dual graph we need the incidence relations of a cube. The toric variety associated to a cube is  $\mathbf{P}^1 \times \mathbf{P}^1 \times \mathbf{P}^1$ . The general anticanonical divisor is a smooth  $K3$ , whereas the complement of the torus is the unions of six quadrics (each of the form  $\mathbf{P}^1 \times \mathbf{P}^1$ ) with dual graph the octahedron. A small resolution of a general pencil yields a semistable degeneration.

4.4. DEFINITION [D-E-P]. Let  $H$  be a finite partially ordered set and  $\Sigma$  an ideal of monomials on  $H$ . Let  $K$  be a commutative ring and  $R$  a commutative  $K$ -algebra. Suppose an injection  $\phi: H \rightarrow R$  is given. Then  $R$  is a *Hodge algebra* (or algebra with straightening law) *governed by*  $\Sigma$  if  
 H-1  $R$  is a free  $K$ -module admitting the set of monomials not in  $\Sigma$  as basis,  
 H-2 for each generator  $M$  of  $\Sigma$  in the unique expression

$$(*) \quad M = \sum_{N \notin \Sigma} k_{M,N} N, \quad k_{M,N} \in K,$$

guaranteed by H-1, for each  $x \in H$  dividing  $M$  and each  $N \notin \Sigma$  with  $k_{M,N} \neq 0$  there is a  $y_{M,N}$  dividing  $N$  and satisfying  $y_{M,N} < x$ .

The relations (\*) are called *straightening relations* for  $R$ .

4.5. If  $R$  is graded and the elements of  $\phi(H)$  are homogeneous the straightening relations give a presentation for  $R$  [D-E-P, p. 15].

We note that  $R$  is a deformation of the discrete Hodge algebra governed by  $\Sigma$ , whose ideal is generated by the monomials  $M$ .

4.6. EXAMPLE. The equations of the tetrahedron of degree 12 of 2.2 are straightening relations. We take  $\Sigma$  as Stanley-Reisner ideal  $\Sigma_\Delta$ , where  $\Delta$  is the stellation of the tetrahedron: in each top-dimensional face we take an additional vertex, which is joined to all vertices on the face. The partial order on the set of vertices is obtained by declaring the new vertices to be smaller. The discrete Hodge algebra then has equations  $x_i x_j$ ,  $x_i y_j$  and  $y_j y_k y_l$ .

## 5. THE DODECAHEDRON

5.1. To get an icosahedron as dual graph we need the incidence relations of a dodecahedron. Each side should be a rational surface and the intersection with the other surfaces should have a pentagon as dual graph. A pentagon occurs as hyperplane section of a Del Pezzo surface of degree 5. So we can realise our dodecahedron by gluing together 12 Del Pezzo surfaces.

We first describe the Del Pezzo surfaces. Each of those is an extension of its pentagonal hyperplane section. Its coordinate ring can be obtained as Stanley-Reisner ring of a pentagon as 1-dimensional simplicial complex. Introducing variables  $y_i$ , we get the equations  $y_{i-1} y_{i+1}$ . With an extra variable  $x$  the Del Pezzo surface has equations

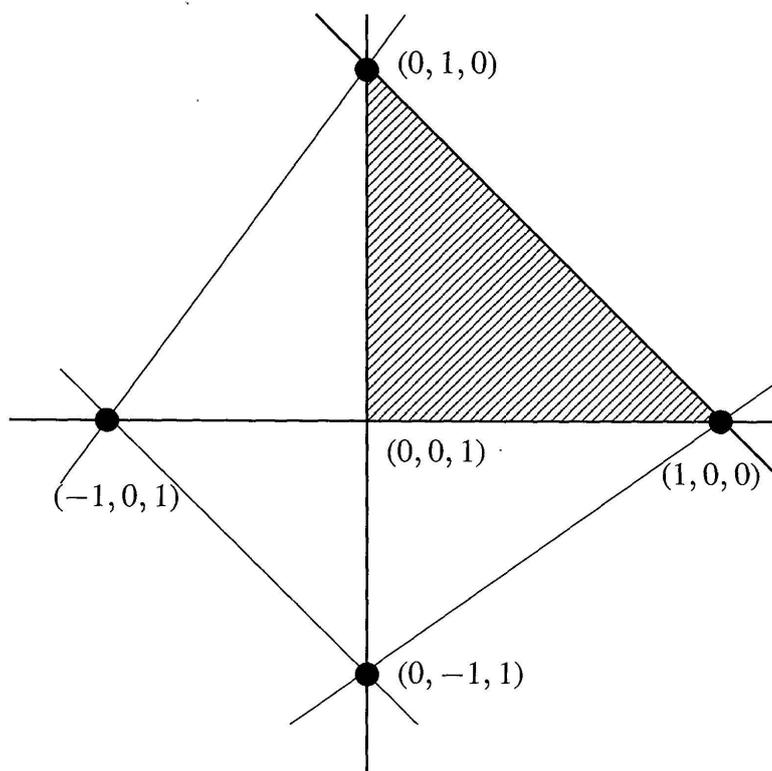
$$y_{i-1} y_{i+1} - x y_i - x^2.$$

These are the Pfaffians of the matrix

$$\begin{pmatrix} 0 & y_1 & x & -x & -y_5 \\ -y_1 & 0 & y_2 & x & -x \\ -x & -y_2 & 0 & y_3 & x \\ x & -x & -y_3 & 0 & y_4 \\ y_5 & x & -x & -y_4 & 0 \end{pmatrix}.$$

We can check that this is indeed a smooth Del Pezzo of degree 5 by giving an explicit birational map from  $\mathbf{P}^2$ , which blows up four points, see Figure 5.1.

To the variable  $x$  corresponds a new vertex at the centre of the pentagon. By joining it to all other vertices we obtain a 2-dimensional simplicial complex, and the homogeneous coordinate ring of the Del Pezzo surface is a graded Hodge algebra governed by the Stanley-Reisner ideal of the complex: to satisfy H-2 we take  $x$  to be less than all  $y_i$ .



$$\begin{aligned}
 y_1 &= v^2u \\
 y_2 &= vw(v+w) \\
 y_3 &= w^2(u+v+w) \\
 y_4 &= uw(u+w) \\
 y_5 &= u^2v \\
 x &= uvw
 \end{aligned}$$

FIGURE 5.1  
Blowing up  $\mathbf{P}^2$  in 4 points

5.2. To construct a normal crossings dodecahedron of degree 60 we glue twelve Del Pezzo surfaces. We get a simplicial complex  $\Delta$  by stellating a dodecahedron: we take in each face the centre of the pentagon as extra vertex. A non-convex realisation of this complex is the great stellated dodecahedron.

5.3. PROPOSITION. *The coordinate ring of the dodecahedron of degree 60 is a graded Hodge algebra governed by  $\Sigma_\Delta$ .*

We describe the equations for a dodecahedron  $X$  with icosahedral symmetry in more detail. We have 20 variables  $y_\alpha$ , one for each dodecahedral vertex and 12 variables  $x_i$  from the extra vertices in the faces. We will denote the vertices by  $\alpha$  and  $i$ . As two face vertices are not connected by an edge we have 66 equations  $x_i x_j = 0$ ,  $i \neq j$ . If  $\overline{i\alpha}$  is not an edge, we have  $x_i y_\alpha = 0$ ; there are 180 such equations. The non-edges  $\overline{\alpha\beta}$  come in two types: in 100 cases the line  $\overline{\alpha\beta}$  does not lie in a face of the original dodecahedron, leading to  $y_\alpha y_\beta = 0$ ; if it lies in such a face we get a Del Pezzo equation (in  $5 \times 12 = 60$  cases).

We summarise:

Type	Equation	Conditions	#
(1)	$x_i x_j$	$i \neq j$	66
(2)	$x_i y_\alpha$	$\overline{i\alpha}$ not an edge	180
(3)	$y_\alpha y_\beta$	$\overline{\alpha\beta}$ not in face	100
(4)	$y_\alpha y_\gamma - x_i y_\beta - x_i^2$	Del Pezzo	60

The relations follow from the relations between the generators of the Stanley-Reisner ideal of the great stellated dodecahedron, which have a particularly simple form: we get a relation for each pair of equations which have one variable in common.

This gives the following list of relations, where we suppress the conditions on the indices; they can be deduced from the list of equations.

Type	Relation	#
(1-1)	$(x_i x_j) x_k - (x_i x_k) x_j$	440
(2-1)	$(x_i y_\alpha) x_j - (x_i x_j) y_\alpha$	1980
(2-2)	$(x_i y_\alpha) y_\beta - (x_i y_\beta) y_\alpha$	1260
(3-2)	$(y_\alpha y_\beta) x_i - (x_i y_\alpha) y_\beta$	1200
(3-3)	$(y_\alpha y_\beta) y_\gamma - (y_\alpha y_\gamma) y_\beta$	780
(4-2)	$(y_\alpha y_\gamma - x_i y_\beta - x_i^2) x_j - (x_j y_\alpha) y_\gamma + (x_i x_j)(x_i + y_\beta)$	660
(4-3)	$(y_\alpha y_\gamma - x_i y_\beta - x_i^2) y_\delta - (y_\alpha y_\delta) y_\gamma + (x_i y_\delta)(x_i + y_\beta)$	860
(4-3)	$(y_\alpha y_\gamma - x_i y_\beta - x_i^2) y_\delta - (y_\alpha y_\delta - x_j y_\beta - x_j^2) y_\gamma$ $+ (x_i y_\delta)(x_i + y_\beta) - (x_j y_\gamma)(x_j + y_\beta)$	40
(4-4)	relations from matrices	60

We use the equations and relations to compute infinitesimal deformations. The computations are similar to the case of the tetrahedron of degree 12. To illustrate our methods we prove that the dodecahedron  $X$  has no nontrivial extensions. This statement means that  $X$  is only a hyperplane section of the projective cone over it. To prove this we have to show that the affine cone  $C(X)$  has no deformations of negative degree.

5.4. PROPOSITION.  $T_{C(X)}^1(-\nu) = 0$  for  $\nu > 0$ .

*Proof.* As all quadratic equations occur in linear relations we cannot perturb the equations with constants, so  $T^1(-2) = 0$ .

Now we consider deformations of degree  $-1$ . We start with equations of type (1), which we perturb as follows:

$$x_i x_j + \sum a_{ij}^m x_m + \sum b_{ij}^\alpha y_\alpha.$$

The relations (1-1) together with the equations give

$$a_{ij}^k x_k^2 + \sum_{\overline{k\alpha} \text{ edge}} b_{ij}^\alpha x_k y_\alpha = a_{ik}^j x_j^2 + \sum_{\overline{j\alpha} \text{ edge}} b_{ik}^\alpha x_j y_\alpha.$$

This shows that  $a_{ij}^k = 0$  for  $k \notin \{i, j\}$ . For each  $\alpha$  we can find a  $k \notin \{i, j\}$  such that  $\overline{k\alpha}$  is an edge, so  $b_{ij}^\alpha = 0$  and the deformation has the form

$$x_i x_j + a_{ij}^i x_i + a_{ij}^j x_j.$$

We now perturb equations of type (2):

$$x_i y_\alpha + \sum a_{i\alpha}^m x_m + \sum b_{i\alpha}^\beta y_\beta$$

and use the relations of type (2-1):

$$a_{i\alpha}^j x_j^2 + \sum_{\overline{j\beta} \text{ edge}} b_{i\alpha}^\beta x_j y_\beta = a_{ij}^j x_j y_\alpha$$

to conclude that  $a_{i\alpha}^j = 0$  for all  $j \neq i$ ,  $b_{i\alpha}^\beta = 0$  for all  $\beta \neq \alpha$  and  $b_{i\alpha}^\alpha = a_{ij}^j$  for all  $j$  such that  $\overline{j\alpha}$  is an edge. It follows that  $a_{ij}^j = a_{ik}^k$  for all  $j$  and  $k$ . Using the coordinate transformation  $\partial_{x_i}$  we may therefore assume that the equations of type (1) are not perturbed at all, while those of type (2) have the form  $x_i y_\alpha + a_{i\alpha}^i x_i$ .

Perturbing equations of type (3) in a similar manner as  $y_\alpha y_\beta + \sum a_{\alpha\beta}^m x_m + \sum b_{\alpha\beta}^\gamma y_\gamma$  we find from the relations (3-2) that

$$a_{\alpha\beta}^i x_i^2 + \sum_{\overline{i\gamma} \text{ edge}} b_{\alpha\beta}^\gamma x_i y_\gamma = a_{i\alpha}^i x_i y_\beta.$$

So  $a_{\alpha\beta}^i = 0$ ,  $b_{\alpha\beta}^\gamma = 0$  for  $\gamma \notin \{\alpha, \beta\}$  and  $b_{\alpha\beta}^\beta = a_{i\alpha}^i$ . The coordinate transformation  $\partial_{y_\alpha}$  can be used to eliminate the perturbation of the equations of type (2). Then those of type (3) are not perturbed either.

Finally we look at the Del Pezzo equations (4). From the relations (4-2) we conclude as before that the only possible perturbations have the form

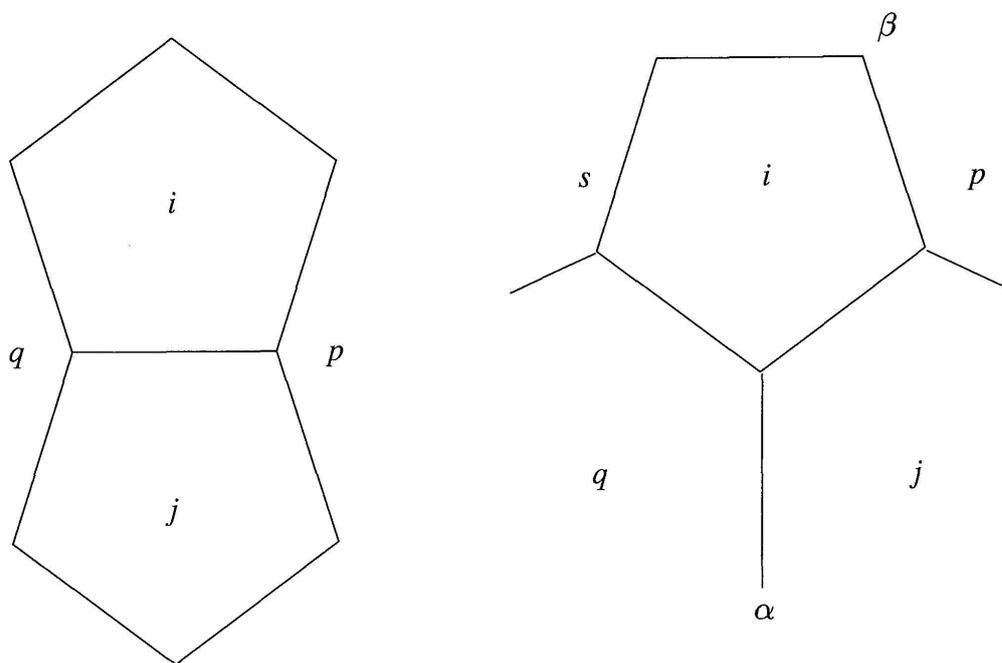
$$y_\alpha y_\gamma - x_i y_\beta - x_i^2 + a_{\alpha\gamma}^i x_i.$$

Here  $\overline{i\alpha}$ ,  $\overline{i\beta}$  and  $\overline{i\gamma}$  all are edges. This means that we can look at each Del Pezzo separately. From the matrix of relations we obtain that  $a_{\alpha\gamma}^i = 0$ .  $\square$

5.5. PROPOSITION. *The dodecahedron  $X$  with icosahedral symmetry is  $d$ -semistable. The space of locally trivial embedded deformations has dimension 29.*

*Proof.* We describe a global section of the sheaf  $\mathcal{T}_X^1$ , without proof. To formulate the result we use the alternative notation  $y_{ijk}$  for  $y_\alpha$ , if  $\overline{i\alpha}$ ,  $\overline{j\alpha}$  and  $\overline{k\alpha}$  are the edges involving  $\alpha$ .

The equations of type (1) are not deformed, unless  $\overline{ij}$  is an edge, in which case we have  $x_i x_j + d y_{ijp} y_{ijq}$ . An equation of type (2) is perturbed to  $x_i y_\alpha + d(x_j y_{ijp} + x_j y_{ijq} + x_j^2)$  if  $\alpha = (jkl)$  is opposite the edge  $[pq]$ ; if  $ijp$ ,  $ijq$  and  $\alpha = jqr$  are three consecutive vertices, as are  $\alpha = jqr$ ,  $ijq$  and  $iqs$ , we get  $x_i y_\alpha + d(x_j y_{ijq} + x_q y_{ijq} + y_{ijq}^2)$  and in all other cases the equation is not deformed.



All perturbations of the equations (3) vanish except when  $\alpha$  and  $\beta$  are nearest possible: one can reach  $\beta$  from  $\alpha$  by passing three edges. Suppose that the vertices on this path are  $\beta = ipo$ ,  $ijp$ ,  $ijq$ ,  $jqr = \alpha$ . Then we set  $y_\alpha y_\beta + d(x_i y_{ijq} + x_j y_{ijp} + y_{ijp} y_{ijq})$ . The Del Pezzo equations are not deformed.

We compute locally near a triple point and look at the chart  $y_\alpha = 1$ . All variables can be eliminated except  $y_\beta$ ,  $y_\gamma$  and  $y_\delta$  such that  $\overline{\alpha\beta}$ ,  $\overline{\alpha\gamma}$  and  $\overline{\alpha\delta}$  are edges, and  $x_i$ ,  $x_j$  and  $x_k$ , where  $\alpha$ ,  $\beta$  and  $\gamma$  lie on the face  $k$ , etc. We have nine equations left, of three types:  $x_i x_j + d y_\delta$ ,  $x_k y_\delta + d(1 + x_i + x_j)$  and the Del Pezzo equation  $y_\beta y_\gamma - x_k - x_k^2$ . The last one shows that even  $x_k$  can be eliminated, as the double curve lies in  $x_k = 0$ . By multiplying the Del Pezzo equation with  $y_\delta$  and using the other equations we get

$$y_\beta y_\gamma y_\delta + d(1 + x_i + x_j + x_k).$$

This shows that our  $d$ -deformation indeed represents the class  $[1] \in H^0(\mathcal{O}_D) = H^0(\mathcal{T}_X^1)$ .  $\square$

Proposition 3.9 gives the dimension of the space of locally trivial deformations, but it can also be computed directly. For each Del Pezzo we have 5 deformations by multiplying the  $x_i$  in a given column of the defining matrix with a unit of the form  $1 + \varepsilon_{ij}$ . These deformations are trivial and can also be obtained by multiplying the  $y_\alpha$  by suitable factors. In total we have 60 such deformations, but globally we have only 31 diagonal coordinate transformations (32 variables, but we have to subtract one for the Euler vector field).

5.6. THEOREM. *There exists a semistable degeneration of K3-surfaces of degree 60 with icosahedral symmetry, whose special fibre is our dodecahedron.*

5.7. The rotation group  $G_{60} \cong A_5$  of the icosahedron acts symplectically on the general fibre  $\mathcal{X}_t$  and the quotient  $\mathcal{X}_t/G_{60}$  is again a K3-surface, with 2  $A_4$ , 3  $A_2$  and 4  $A_1$  singularities [X]. The locus of such surfaces has dimension two in moduli, so together with a polarisation there is only a curve of such surfaces. It would be interesting to know this curve. A deformation computation as above only gives a parametrisation with power series; anyway, the computation is too complicated.

We can take the quotient of the special fibre, which is our dodecahedron. Invariants for the icosahedral reflection group are

$$X = \sum x_i, \quad Y_1 = \sum y_\alpha, \quad Y_2 = \sum_{\overline{\alpha\beta} \text{ edge}} y_\alpha y_\beta,$$

and a skew invariant  $Z$  is obtained by taking the  $G_{60}$  orbit of  $x_i y_\alpha y_\beta (y_\alpha - y_\beta)$ . After a coordinate transformation  $X \mapsto \frac{1}{5}X$ ,  $Y_2 \mapsto Y_2 + \frac{1}{5}XY_1 + \frac{1}{5}X^2$  the quotient is given by the equation

$$0 = Z^2 + 5X^2 Y_2^2 (4Y_2 + 8X^2 + 12XY_1 - Y_1^2) \\ + (30Y_1 + 20X)Y_2 X^3 (X^2 + XY_1 - Y_1^2) + X^3 (3X + 4Y_1)(X^2 + XY_1 - Y_1^2)^2.$$

This is a surface of degree 8 in the weighted projective space  $\mathbf{P}(1, 1, 2, 4)$ . These numbers are in Reid's list of famous 95 and the general  $X_8 \subset \mathbf{P}(1, 1, 2, 4)$  is a K3-surface with 2  $A_1$  singularities. Our surface has a double line and two  $A_4$  singularities, at  $Y_2 = X^2 + XY_1 - Y_1^2 = 0$ .

5.8. Finite groups acting symplectically on K3-surfaces have been classified by Mukai [Mu], see also [X]. Mukai gives an example of a K3-surface with even an action of the symmetric group  $S_5$  :

$$\begin{aligned}x_1 + x_2 + x_3 + x_4 + x_5 &= 0, \\x_0^2 + x_1^2 + x_2^2 + x_3^2 + x_4^2 + x_5^2 &= 0, \\x_1^3 + x_2^3 + x_3^3 + x_4^3 + x_5^3 &= 0.\end{aligned}$$

An element of  $S_5$  acts by permuting the coordinates  $x_1, \dots, x_5$  and multiplying  $x_0$  by its sign. By changing the last equations to  $tx_0^3 + x_1^3 + x_2^3 + x_3^3 + x_4^3 + x_5^3 = 0$  we obtain a pencil of  $A_5$ -invariant surfaces. The semistable model of the degeneration at  $t = \infty$  is of type I.

5.9. THE STANLEY-REISNER RING OF THE ICOSAHEDRON. A different family of  $K3$ -surfaces with icosahedral symmetry is obtained by smoothing the Stanley-Reisner ring of the icosahedron. The infinitesimal deformations can be found from [A-C, Sect. 4] or computed directly with the methods above. All deformations are unobstructed ( $T_{C(X)}^2 = 0$ ). We have  $T_{C(X)}^1(\nu) = 0$  for  $\nu < 0$  and  $\dim T_{C(X)}^1(0) = 30$ . Furthermore the dimension of  $H^0(\Theta_X)$  equals 11, which fits with the fact that  $X$  deforms to smooth  $K3$ -surfaces ( $30 - 11 = 19$ ).

We number the vertices as in Figure 5.2.

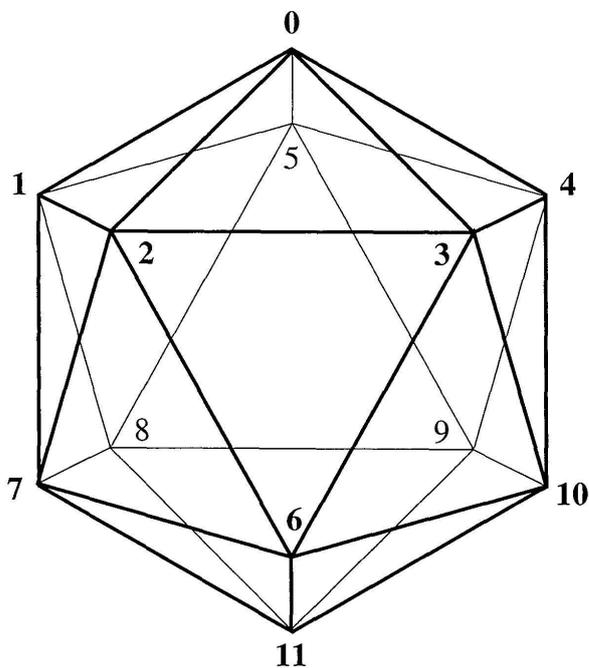


FIGURE 5.2  
Icosahedron

We have two types of equations, depending on the distance between vertices. On suitable representatives the infinitesimal deformations are

$$x_0x_6 + \varepsilon_{06}x_2x_3, \quad x_0x_{11}.$$

By taking all  $\varepsilon_{ij}$  equal we get an icosahedral invariant deformation. The lift to a one-parameter deformation seems to involve power series of the deformation variable (I computed up to order 7). Anyway, equations for a  $K3$  of degree 20 are not very illuminating.

As before, this deformation is not semistable, because the total space has singularities. Each vertex of the icosahedron gives a singularity, which is the cone over a pentagon. It is smoothed negatively, with total space the cone over a Del Pezzo of degree 5. We resolve these singularities by blowing up. We introduce 12 Del Pezzo surfaces. The sides are blown up in three points, giving hexagons. The dual graph of the central fibre is now a stellated dodecahedron. The object itself consists of pentagons and hexagons. It contains a real homology class, as described in 3.14, which looks like a football, so our special fibre is a complexified football.

5.10. A DEGENERATION OF DEGREE 12. The existence of the two type III degenerations above with icosahedral symmetry follows from a deformation argument, but it is too complicated to give explicit equations. In the football case pentagons arise because of the singularities of the total space. This suggests that one can get a degeneration of low degree by blowing down components of the special fibre. Blowing down means removing vertices from the dual graph.

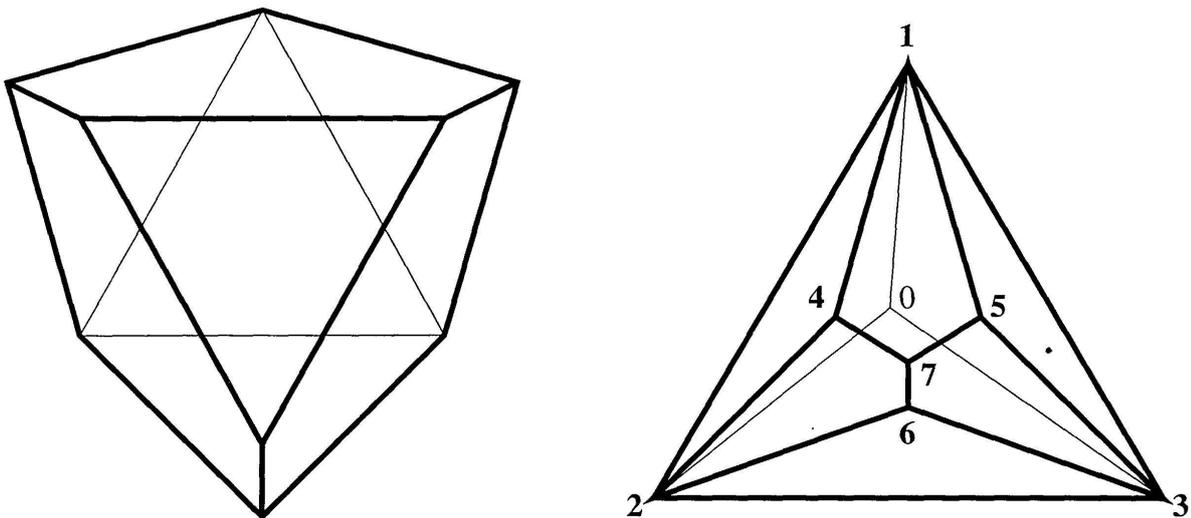


FIGURE 5.3

Dual graph and its realisation for  $X$  of degree 12

We start from the icosahedron (Figure 5.2) and remove non-adjacent vertices, say those numbered 0, 7 and 10. This means breaking the symmetry. The resulting dual graph is shown in Figure 5.3. Of the double curves on

the components, six are triangles and four are rectangles. We realise them on planes, resp. quadric surfaces. The picture also shows a realisation (as a real polyhedron). We cannot take the Stanley-Reisner ideal, as the realisation contains rectangles. For those we take an equation of the form  $xy - zt$ . One may think that a rectangle can be triangulated in two ways, each giving a monomial, which are forced to be equal. The result is a surface  $X \subset \mathbf{P}^7$  of degree 12. With the numbering in the figure we get the  $S_3$ -invariant ideal

$$\begin{aligned} & x_0x_7, \\ & x_0x_4, \quad x_0x_5, \quad x_0x_6, \\ & x_1x_6, \quad x_2x_6, \quad x_3x_4, \\ & x_1x_7 - x_4x_5, \quad x_2x_7 - x_4x_6, \quad x_3x_7 - x_5x_6, \\ & x_1x_2x_3. \end{aligned}$$

The next thing to do is to compute the  $T^1$  and  $T^2$  for the affine cone  $C(X)$  over  $X$ . This is conveniently done with a computer algebra program. A computation with *Macaulay* [B-S] gives the following result:

5.11. LEMMA. *As  $\mathcal{O}_{C(X)}$ -module  $T_{C(X)}^1$  is generated by eight elements, represented by the following perturbations of the equations:*

$$\begin{aligned} & x_0x_7, \\ & x_0x_4 - c_3x_1x_2, \quad x_0x_5 - c_2x_1x_3, \quad x_0x_6 - c_1x_2x_3, \\ & x_1x_6 + b_0x_7 + b_1x_6 + b_2x_5 + b_3x_6, \\ & x_2x_5 + b_0x_7 + b_1x_6 + b_2x_5 + b_3x_6, \\ & x_3x_4 + b_0x_7 + b_1x_6 + b_2x_5 + b_3x_6, \\ & x_1x_7 - x_4x_5, \quad x_2x_7 - x_4x_6, \quad x_3x_7 - x_5x_6, \\ & x_1x_2x_3 + ax_0 + b_1x_2x_3 + b_2x_1x_3 + b_3x_1x_2, \end{aligned}$$

and  $\dim T_{C(X)}^2 = 2$ , concentrated in degree  $-2$ .

The quadratic obstruction is given by  $a(c_1 - c_2) = a(c_1 - c_3) = 0$ . We conclude that the degree zero deformations are unobstructed. The base space for  $C(X)$  in non-positive degrees has two components. As we are mainly interested in  $S_3$ -invariant deformations we consider only the component with

$c_1 = c_2 = c_3$  ( $=: c$ ). The component will be obtained by substituting polynomials for the deformation variables  $a$ ,  $b_i$  and  $c$ . A computation gives the equations

$$\begin{aligned} & x_0x_7 + c(b_0x_7 + b_1x_6 + b_2x_5 + b_3x_6 + ac), \\ & x_0x_4 - cx_1x_2, \quad x_0x_5 - cx_1x_3, \quad x_0x_6 - cx_2x_3, \\ & x_1x_6 + b_0x_7 + b_1x_6 + b_2x_5 + b_3x_6 + ac, \\ & x_2x_5 + b_0x_7 + b_1x_6 + b_2x_5 + b_3x_6 + ac, \\ & x_3x_4 + b_0x_7 + b_1x_6 + b_2x_5 + b_3x_6 + ac, \\ & x_1x_7 - x_4x_5, \quad x_2x_7 - x_4x_6, \quad x_3x_7 - x_5x_6, \end{aligned}$$

$$x_1x_2x_3 + ax_0 + b_1x_2x_3 + b_2x_1x_3 + b_3x_1x_2 - b_0(b_0x_7 + b_1x_6 + b_2x_5 + b_3x_6 + ac).$$

For  $c \neq 0$  we derive the three equations  $x_0x_7 - cx_ix_{7-i}$ , which show that we have a hypersurface in the cone over  $\mathbf{P}^1 \times \mathbf{P}^1 \times \mathbf{P}^1$ .

5.12. PROPOSITION. *A general one-parameter deformation in degree 0 on the component described above has a minimal model in  $(-1)$ -form with the icosahedron as dual graph for the central fibre. In particular, this holds for*

$$\begin{aligned} a &= c(x_0^2 + x_0(x_1 + x_2 + x_3) + x_1^2 + x_2^2 + x_3^2), \\ b_0 &= cx_7, \\ b_1 &= c(x_2 + x_3 + x_6 + x_7), \\ b_2 &= c(x_1 + x_3 + x_5 + x_7), \\ b_3 &= c(x_1 + x_2 + x_4 + x_7). \end{aligned}$$

*Proof.* One first checks that the general fibre is a smooth  $K3$ -surface. For this it suffices to look at the hypersurface in  $\mathbf{P}^1 \times \mathbf{P}^1 \times \mathbf{P}^1$ .

In the particular example the total space has at the origin of the affine chart  $x_1 = 1$  a singularity, which is isomorphic to the cone over the Del Pezzo surface of degree 5, as it should be: the point to check is that we indeed have a generic local deformation. Furthermore there are 18 singularities of type  $A_1$ . On the  $(x_1, x_4)$ -line we have the point  $x_1 + x_4 = 0$ . On the  $(x_0, x_1)$ -line we have two points, given by  $x_0^2 + x_0x_1 + x_1^2$ , and on the  $(x_7, x_7)$ -line the two points  $x_6^2 + x_6x_7 + x_7^2$ . The other singular points are found by symmetry.

By blowing up the three singularities of multiplicity 5 and making a small resolution of the  $A_1$ -points we get a smooth total space. To obtain the  $(-1)$ -form one has to place one exceptional curve on either component in case

the double line contains two singularities. If there is only one, the exceptional curve should lie on the triangle component.  $\square$

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