The geometry of cubic hypersurfaces

Daniel Huybrechts

1 Comments are very welcome at all times!
## Contents

<table>
<thead>
<tr>
<th>Category</th>
<th>Subcategory</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preface</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Abstracts</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>1 Basic facts</td>
<td>1 Numerical and cohomological invariants</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>2 Linear system and Lefschetz pencils</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>3 Automorphisms and deformations</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>4 Jacobian ring</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>5 Quadric fibrations and ramified covers</td>
<td>61</td>
</tr>
<tr>
<td>2 Moduli spaces</td>
<td>1 GIT-quotient</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>2 Stacks</td>
<td>73</td>
</tr>
<tr>
<td></td>
<td>3 Period approach</td>
<td>73</td>
</tr>
<tr>
<td>3 Fano varieties of lines</td>
<td>1 Construction and infinitesimal behaviour</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td>2 Global properties and a geometric Torelli theorem</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td>3 Cohomology and motives</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>4 The Fano correspondence</td>
<td>108</td>
</tr>
<tr>
<td>4 Cubic surfaces</td>
<td>1 Picard group</td>
<td>115</td>
</tr>
<tr>
<td></td>
<td>2 Representing cubic surfaces</td>
<td>122</td>
</tr>
<tr>
<td></td>
<td>3 Lines on cubic surfaces</td>
<td>128</td>
</tr>
<tr>
<td></td>
<td>4 Moduli space</td>
<td>134</td>
</tr>
<tr>
<td>5 Cubic threefolds</td>
<td>1 Lines on the cubic and curves on its Fano surface</td>
<td>137</td>
</tr>
<tr>
<td></td>
<td>2 Albanese of the Fano surface</td>
<td>145</td>
</tr>
<tr>
<td></td>
<td>3 Albanese, Picard, and Prym</td>
<td>151</td>
</tr>
</tbody>
</table>
Chapter 0. Contents

4 Global Torelli theorem and irrationality 158
6 Cubic fourfolds 159
   1 Geometry of special cubic fourfolds 161
   2 The Fano variety as a hyperkähler fourfold 174
References 180
Algebraic geometry starts with cubic polynomial equations. Everything of smaller degree, like linear maps or quadratic forms, fall in the realm of linear algebra. An important body of work, from the beginning of algebraic geometry to our days, has been devoted to cubic equations. In fact, cubic hypersurfaces of dimension one, so elliptic curves, are occupying a very special and central place in algebraic and arithmetic geometry and cubic surfaces with their 27 lines form one of the most studied classes of geometric objects.

These notes have their origin in a lecture course at the University of Bonn in the winter term 2017 - 2018. Since then, I have polished the text and added material. However, most parts are still in a preliminary form and will most certainly contain mistakes, typos, inaccuracies, and oversights. I will be most grateful for comments of any sort on these notes and will try to update them regularly on my webpage.

I have tried to give accurate references. If you spot any omissions, wrong attributions or simply want to point out references that have not been mentioned, please get in contact with me.

Be aware that not all ‘Proofs’ necessarily contain complete arguments. Often, I try to convey the basic idea, sometimes only in the special case of cubics, but (have to) refer for details to the literature.

Acknowledgements: Many people have made and continue to make comments on these notes. I am truly grateful for any kind of comments, suggestions, criticism, etc. My sincere thanks go to: Pieter Belmans, Robert Laterveer, and Samuel Stark.

Abstracts

1. Basic facts

H^n(X, Z) and π(X) via Lefschetz; hyperplane theorem resp. Bott vanishing; canonical bundle ω_X; Pic(X) = Z · O_X(1); motive b(X); Euler number e(X) and middle Betti number b_n(X); table for e(X), b_n(X), b_n(X)_{prim}, τ(X); χ_y-genus and Hodge numbers h^{p,q}(X); Hirzebruch formula \sum \chi_y(X_n) z^n + 1; table of Hodge numbers for n ≤ 10; intersection form on H^n(X, Z); connected sum decomposition X ≃ M # k (S^n × S^n); Hodge–de Rham spectral sequence and Zeta function Z(X, t) for k = F_q.

2. Linear system and Lefschetz pencils

Linear system |O(d)|; moduli space M(n); discriminant divisor D(d, n) ⊂ |O(d)|; dimensions of |O(d)|, M(n) and degree of D(n); examples of smooth cubic hypersurfaces; deg(D(d, n)); dual variety; resultant; explicit for (n, d) = (0, 3), (1, 3); Lefschetz pencil; monodromy representation; monodromy group Γ_n; orthogonal groups O^+(H^n(X, Z)); monodromy invariant cycles; vanishing cycles; Picard–Lefschetz; reflections s_δ; Weyl group; Diff^+(X).

3. Automorphisms and deformations

Smoothness via regularity of sequence \partial_i F; H^6(X, T_X) = 0; Aut(X, O_X(1) ⊂ Aut(X) finite; Def(X, O_X(1)) ⊂ Def(X); deformations of cubics remain cubics; Aut(X) = {1} for generic cubic; faithful action of Aut(X) on H^1(X, T_X) and H^n(X, Z).
4. Jacobian ring

Hessian $H(F)$; Jacobian ring $R(F)$; finite-dimensional Gorenstein; Poincaré series $P(R)$; Koszul complex $K_*(f_i)$; determinant $\det(H(F))$; generating socle; $R(X)$ for cubic curves; $R(X) \cong R(X')$ implies $X \cong X'$; $R_{\phi}(X) \cong H^{n+p}(X)_{\phi_i}$; $\Omega^*_X$; $\Omega^*_X(\log(X))$; $U_{p+1}$; $H^{n+1}(U, \mathbb{C})$; infinitesimal Torelli.

5. Quadric fibrations and ramified covers

Projection from linear subspace $P \subset X$; Blowing-up of $P \subset X$; smoothness of discriminant divisor $D_p \in |O(k+3)|$ of projection; quadric fibration $\text{Bl}_P(X) \to \mathbb{P}^2$; rationality for cubics containing disjoint $\mathbb{P}(W), \mathbb{P}(W') \subset X$; birational parametrization $\mathbb{P}(W) \times \mathbb{P}(W')X$; cyclic cover $X \to \mathbb{P}^{n+1}$ branched over $X \subset \mathbb{P}^{n+1}$.

2. Moduli spaces

1. GIT-quotient

Examples of non-stable hypersurfaces; GIT quotients of affine and projective varieties; good, categorical, and geometric quotients; semi-stable points; existence of good quotients; stability of smooth hypersurfaces; Hilbert–Mumford criterion; moduli functor; quasi-projective coarse moduli spaces; Luna’s étale slice theorem; non-existence of universal families; local universal families; field of moduli.

2. Stacks

3. Period approach

3. Fano varieties of lines

1. Construction and infinitesimal behaviour

Fano functor; Grassmann functor; Hilbert scheme; Fano variety of $m$-planes; Quot-scheme; Plücker embedding; universal sub- and quotient bundle; defining equation for $F(X, m) \subset \mathbb{G}(m, \mathbb{P})$; universal family $\to F(X, m)$; Plücker polarization; universal Fano scheme $F(X, m) \to |O(d)|$; as projective bundle over $\mathbb{G}(m, \mathbb{P})$; $\dim(F(X, m))$; tangent space; lines of the first and second type; $F_2(X) \subset F(X)$; $\dim F_2(X) = n - 2$ for generic $X$; $\dim(F(X)) = 2n - 4$; unirationality of cubics and $\dim(F(X, m))$. 

Abstracts
4. Cubic surfaces

115

2. Representing cubic surfaces

122

3. Lines on cubic surfaces

128

4. Moduli space

134

Chapter 0. Abstracts

2 Global properties and a geometric Torelli theorem

89

Canonical bundle \( \omega_F \simeq O_F(4-n) \); (anti-)ample; \( \text{Pic}(F) \simeq H^2(F, \mathbb{Z}) \); \( \text{Pic}^0(F) = 0 \); \( H^1(F, \mathbb{Z}) = 0 \); smoothness and irreducibility of \( F(X) \); \( \dim(F(X)) = 2n - 4 \); fibres of \( L \rightarrow X \); \( L \rightarrow F(T_X) \); \( F(X) \simeq F(X') \) if and only if \( X \cong X' \); \( \text{Aut}(F(X)) \) is finite; \( H^0(F(X), T) = 0 \).

3 Cohomology and motives

??

Grothendieck ring of varieties \( K_0(\text{Var}_k) \); Galkin–Shinder relation relating \( [F(X)] \) and \( [X^{2n}] \); \( h(F(X)) \in \text{Mot}(k) \); \( \text{deg}(F(X)) \); \( e(F(X)) \) and \( \sum e(F(X), i) \); category of Hodge structures \( \text{HS}_{2n} \); \( [H^0(F(X), \mathbb{Z})] \in K_0(\text{HS}_{2n}) \); Hodge conjecture for \( F(X) \) for general \( X \); \( \chi_2(F(X)) \); \( \text{Pic}^0(F(X)) = 0 \); \( F(X) \) is simply connected; \( \text{Pic}(F(X)) \simeq \mathbb{Z} \); \( H^{2n-2}(F(X), \mathbb{Q}) \) vs. \( H^n(X, \mathbb{Q}) \); Hodge numbers and structures for \( F(X, n) \), \( n = 2, 3, 4, 5 \); \( |\text{F}(X, \mathbb{F}_p)| \).

4 The Fano correspondence

108

Fano correspondence \( \varphi : H^n(X, \mathbb{Z}) \longrightarrow H^{n-2}(F(X), \mathbb{Z}) \); Plücker polarization \( \varphi(h^2) = g \); \( (a)^2 = -(1/6) \int \varphi(a^2) \cdot g \); degree of fibres of \( L \rightarrow X \); \( \psi : H^{3n-4}(F(X), \mathbb{Z}) \rightarrow H^n(X, \mathbb{Z}) \) dual to \( \varphi \); \( \psi \circ \varphi : \text{CH}(F(X)) \longrightarrow \text{CH}(X) \longrightarrow \text{CH}(F(X)) \) and compatibility with cycle class resp. Abel–Jacobi maps.

4 Cubic surfaces

115

1 Picard group

115

Riemann–Roch formula; \( \rho(S) \leq 7 \); Examples \( \rho(S) < 7 \); \( \text{Pic}^0(S) = 0 \); \( \text{Pic}(S) \simeq H^2(S, \mathbb{Z}) \); \( \text{Pic}(S) \simeq \mathbb{Z} \); \( h^2 \simeq E_8(-1) \); \( (-1) \)-curves and lines; six disjoint lines; ampleness of line bundles; \( \text{NE}(S) \) and \( \text{Amp}(S) \).

2 Representing cubic surfaces

122

Cubic surfaces and blow-ups of \( \mathbb{P}^3 \) and \( \mathbb{P}^3 \times \mathbb{P}^1 \); 27 lines in blow-up; cubic surfaces and double covers of \( \mathbb{P}^3 \); cubic surfaces as conic fibrations; TBC.

3 Lines on cubic surfaces

128

Every line can be blown-down under \( S \rightarrow \mathbb{P}^2 \); every two disjoint lines can be blown-down under \( S \rightarrow \mathbb{P}^2 \); every line is intersected by five disjoint pairs of lines; bases of \( \text{Pic}(S) \) consisting of lines; every two disjoint lines are intersected by five lines; configuration \( L(S) \) of lines; Schlafli graph and Schlafli double six; 27 lines versus 28 bitangents to quartic curve; Eckardt points; TBC.

4 Moduli space

134
5 Cubic threefolds

5.1 Lines on the cubic and curves on its Fano surface

Ramification surface \( R(q) \subset L \rightarrow X; R(q) = p^{-1}(R) \); curve of lines of second type \( R \in |\mathcal{O}_F|) \); \([L] \in R \) if and only if \( \exists \mathcal{P}_L \cong \mathbb{P}^2 \) tangent everywhere along \( L \); \( C_L \subset F(Y) \) curve of all lines intersecting \( L \); \( C_L \neq C_L \) algebraically equivalent; \( \mathcal{O}(3C_L) \cong \omega_Y; (C_L)^2 = 5 \); \( g(C_L) = 11 \); \((1/3) \) \( \in H^2(F(Y), \mathbb{Z}) \); discriminant curve \( D_L \) of conic fibration \( \mathcal{B}_L(Y) \rightarrow \mathbb{P}^2 \); \( \deg(D_L) = 5 \) and \( g(D_L) = 6 \); \( \mathcal{D}_L \cong C_L \); connectedness of \( C_L \); \( h^0(F(Y), \mathcal{O}(C_L)) = 1 \); \( F(Y) \) Picard-Fano surface.

6 Cubic fourfolds

?? ??
Basic facts

This first chapter collects general results on smooth hypersurfaces, especially those of relevance to cubic hypersurfaces. Results that are particular to any special dimension – cubic surfaces, threefolds, etc., behave all very differently – will be dealt with in subsequent parts of these notes.

1 Numerical and cohomological invariants

The goal of this first section is to compute the standard invariants, numerical and cohomological, of smooth cubic hypersurfaces $X \subset \mathbb{P}^{n+1}$. Essentially all results and arguments are valid for arbitrary degree, but specializing to the case of cubics often simplifies the formulae. Most of the results hold for hypersurfaces over arbitrary (algebraically closed) fields. However, to keep the discussion as geometric as possible, we often provide arguments relying on the ground field being the complex numbers and only indicate the general situation. See Section 1.6 for more specific comments.

1.1 Let us begin with recalling the Lefschetz hyperplane theorem, see e.g. [174, V.13] or, for the $\ell$-adic versions over arbitrary fields, [85, Exp. XIII], [1] Exp. XI, [58, IV]: Assume $X \subset Y$ is a smooth ample divisor of a smooth projective variety $Y$ of dimension $n + 1$. Then pull-back and push-forward yield natural maps between (co)homology and homotopy groups. They satisfy:

(i) $H^k(Y, \mathbb{Z}) \longrightarrow H^k(X, \mathbb{Z})$ is bijective for $k < n$ and injective for $k \leq n$.

(ii) $H_k(X, \mathbb{Z}) \longrightarrow H_k(Y, \mathbb{Z})$ is bijective for $k < n$ and surjective for $k \leq n$.

(iii) $\pi_k(X) \longrightarrow \pi_k(Y)$ is bijective for $k < n$ and surjective for $k \leq n$.

Combined with Poincaré duality $H^k(X, \mathbb{Z}) \cong H_{{2n-k}}(X, \mathbb{Z})$, these results provide information about the cohomology groups of $X$ in all degrees.
Using $H^k(\mathbb{P}^{n+1}, \mathbb{Z}) \cong \mathbb{Z}[h]/(h^{n+2})$ with $h := c_1(O(1)) \in H^2(\mathbb{P}^{n+1}, \mathbb{Z})$, yields the following result.

**Corollary 1.1.** Let $X \subset \mathbb{P}^{n+1}$ be a smooth hypersurface of degree $d$ and dimension $n > 1$. Then $X$ is simply connected and for $k \neq n$ one has

$$H^k(X, \mathbb{Z}) \cong \begin{cases} \mathbb{Z} & \text{if } k \text{ is even} \\ 0 & \text{if } k \text{ is odd} \end{cases}. \quad \square$$

**Remark 1.2.** According to the universal coefficient theorem, see e.g. [61, p. 186], there exist short exact sequences

$$0 \to \text{Ext}^1(H_{k-1}(X, \mathbb{Z}), \mathbb{Z}) \to H^k(X, \mathbb{Z}) \to \text{Hom}(H_k(X, \mathbb{Z}), \mathbb{Z}) \to 0.$$  

We apply this to the hypersurface $X \subset \mathbb{P}^{n+1}$ and $k = n$. As $H^{n-1}(X, \mathbb{Z}) \cong H_{n-1}(\mathbb{P}^{n+1}, \mathbb{Z})$ is trivial or isomorphic to $\mathbb{Z}$, one finds that $H^n(X, \mathbb{Z}) \cong \text{Hom}(H_n(X, \mathbb{Z}), \mathbb{Z}) \cong \mathbb{Z}^{\text{dim}(X)}$, i.e. $H^n(X, \mathbb{Z})$ is torsion free.

### 1.2 The Lefschetz hyperplane theorem (with coefficients in a field) has also an algebraic proof. For hypersurfaces the argument can be combined with Bott’s vanishing results to gain control over certain (twisted) Hodge numbers. As those will be frequently used in the sequel, we record them here.

We start with the classical Bott vanishing for $\mathbb{P} := \mathbb{P}^{n+1}$, which can be deduced from the (dual of the) Euler sequence

$$0 \to \Omega_p \to O(-1)^{\binom{n+2}{2}} \to O \to 0 \quad (1.1)$$

and the short exact sequences obtained by taking exterior products

$$0 \to \Omega_p^\wedge \to \bigwedge^p (O(-1)^{\binom{n+2}{2}}) \to \Omega_p^{n-1} \to 0.$$  

A closer inspection of the associated long exact sequences reveals that

$$H^q(\mathbb{P}, \Omega_p^\wedge(k)) = 0$$

unless:

(i) $0 \leq p = q \leq n$, $k = 0$, in which case $h^{p,q}(\mathbb{P}) = 1$,

(ii) $q = 0$, $k > p$, in which case $h^p(\mathbb{P}, \Omega_p^\wedge(k)) = \binom{n+1+k-p}{k} \cdot \binom{-1}{p}$, or

(iii) $q = n + 1$, $k < p - (n+1)$, in which case $h^{p+1}(\mathbb{P}, \Omega_p^\wedge(k)) = \binom{-k}{-k} \cdot \binom{-k-1}{p}$.

The last two cases are Serre dual to each other. The well known formula

$$h^p(\mathbb{P}, O(k)) = \binom{n+1+k}{k} \quad (1.2)$$

is a special case of (ii).
Chapter 1. Basic facts

To deduce vanishing for \(X\) one then uses the standard short exact sequences

\[
0 \longrightarrow \Omega^p_P(-d) \longrightarrow \Omega^p_P \longrightarrow \Omega^p_P|_X \longrightarrow 0,
\]

\[
0 \longrightarrow \mathcal{O}_X(-d) \longrightarrow \Omega^p_P|_X \longrightarrow \Omega^p_X \longrightarrow 0
\]

(1.3)

and the exterior powers of the latter

\[
0 \longrightarrow \Omega^{p-1}_X(-d) \longrightarrow \Omega^p_P|_X \longrightarrow \Omega^p_X \longrightarrow 0
\]

(1.4)

Note that as a special case of (1.4) one obtains the adjunction formula:

**Lemma 1.3.** The canonical bundle of a smooth hypersurface \(X \subset \mathbb{P}^{n+1}\) of degree \(d\) is

\[
\omega_X \cong \mathcal{O}_X(d - (n + 2)).
\]

(1.5)

It is ample for \(d > n + 2\), trivial for \(d = n + 2\), and anti-ample (i.e. \(\omega_X^*\) is ample) in all other cases. \(\Box\)

Applying cohomology and Bott vanishing to (1.3) and (1.4) then yields

**Corollary 1.4.** The natural map

\[
H^q(\mathbb{P}, \Omega^p_P(k)) \longrightarrow H^q(X, \Omega^p_X(k))
\]

is injective (bijective) if \(p + q \leq n\) \((p + q < n)\) and \(k < d\). \(\Box\)

Note that in particular, Kodaira vanishing holds (over any field!):

\[
H^1(X, \mathcal{O}_X) = 0
\]

for \(k > 0\) and \(p + q > n\), which is Serre dual to the vanishing for \(p + q < n\) and \(k < 0\).

**Remark 1.5.** For \(d = 3\) and \(n > 1\), the vanishing of \(H^1(X, \Omega^p_X) = 0\), \(p > 0\), can also be deduced (at least in characteristic zero) from the fact that cubic hypersurfaces are unirational, see Section 3.1.2.

**Corollary 1.6.** Let \(X \subset \mathbb{P}^{n+1}\) be a smooth hypersurface of degree \(d\). If \(n > 2\), then

\[
\text{Pic}(X) \cong \mathbb{Z} \cdot \mathcal{O}_X(1).
\]

If \(n = 2, d \leq n + 1 = 3, \text{and } k \equiv \mathbb{C}, \text{then one still has } \text{Pic}(X) \cong H^2(X, \mathbb{Z}).
\]

**Proof** Over \(\mathbb{C}\), the proof is a consequence of the exponential sequence (in the analytic topology) \(0 \longrightarrow \mathbb{Z} \longrightarrow \mathcal{O}_X \longrightarrow \mathcal{O}_X^* \longrightarrow 0\), which yields the exact sequence

\[
H^1(X, \mathcal{O}_X) \longrightarrow H^1(X, \mathcal{O}_X^*) \longrightarrow H^2(X, \mathbb{Z}) \longrightarrow H^2(X, \mathcal{O}_X).
\]

Now, by Lefschetz hyperplane theorem or Corollary 1.4 \(H^1(X, \mathcal{O}_X) = 0\) for \(n > 1\) and \(H^2(X, \mathcal{O}_X) = 0\) for \(n > 2\) or \(d \leq n + 1\) (using Serre duality).
Remark 1.7. For the motivated reader, the results shall be translated into motivic language, cf. \cite{144} for basic facts. For the pure motive $h(X)$ of a smooth hypersurface $X \subset \mathbb{P}^{n+1}$ of degree $d$ in the category of rational Chow motives $\text{Mot}(k)$ there exists a decomposition, cf. \cite{143},

\[ h(X) \cong h^0(X)_{\text{pr}} \oplus \bigoplus_{i=0}^{n} \mathbb{Q}(-i). \]

Here, $\mathbb{Q}(1)$ is the Tate motive $(\text{Spec}(k), \text{id}, 1)$ and the primitive part $h^0(X)_{\text{pr}}$ has cohomology concentrated in degree $n$. Moreover, $\text{CH}^n(h^0(X)_{\text{pr}})$ contains the homological trivial part of $\text{CH}^n(X)$. Note that not much more is known about the Chow ring of (cubic) hypersurfaces. However, according to Paranjape \cite{147}, see also \cite{162}, one knows $\text{CH}^{n-1}(X) \otimes \mathbb{Q} \cong \mathbb{Q}$ for smooth cubic hypersurfaces of dimension $n \geq 5$. The expectation however is that $\text{CH}^n(X) \otimes \mathbb{Q} \cong \mathbb{Q}$ for $i > (2n-1)/3$. See also Section \ref{5}.

1.3 Next, we would like to compute the remaining Betti number $b_i(X)$ of a smooth hypersurface $X \subset \mathbb{P} = \mathbb{P}^{n+1}$ and we approach this via the Euler number

\[ e(X) = \sum_{i=0}^{2n} (-1)^i b_i(X) = \sum_{i=0, \neq n}^{2n} (-1)^i b_i(X) + (-1)^n b_n(X). \]

Using $b_i(X) = b_i(\mathbb{P})$ for $i = 0, \ldots, 2n, \neq n$, one finds

\[ e(X) = \begin{cases} \frac{n + b_n(X)}{2} & \text{if } n \text{ is even} \\ \frac{n - b_n(X)}{2} & \text{if } n \text{ is odd.} \end{cases} \]

Rephrasing this in terms of the primitive Betti number $b_i(X)_{\text{pr}} := \dim_{\mathbb{Q}} H^i(X, \mathbb{Q})_{\text{pr}}$, which equals $b_i(X) - 1$ for even $n > 0$ and $b_n(X)$ for $n$ odd (use $b_{n-2}(X) = 1$ and 0, respectively), yields

\[ b_n(X)_{\text{pr}} = (-1)^n(e(X) - (n + 1)). \]

This reduces our task to the computation of $e(X) = \int c_n(X)$. Now, the total Chern character of $X$ can be computed by using the restriction of the Euler sequence \eqref{1.1} and the dual \eqref{1.3} of the normal bundle sequence:

\[ c(X) := \sum_{i=0}^{n} c_i(X) = c(T_{\mathbb{P}|X}) \cdot c(O_X(d))^{-1} = c(O_X(1))^{r+2} \cdot c(O_X(d))^{-1} \]

\[ = \left( \frac{(1 + h)^{n+2}}{(1 + dh)} \right) \left( 1 - dh + (dh)^2 \pm \cdots \right) \sum_{i=0}^{n} \binom{n + 2}{i} h^i, \]
where \( h := c_1(\mathcal{O}_X(1)) \). Hence,
\[
c_n(X) = \frac{1}{d^2} \left( (-1)^n \cdot d + \cdots + \binom{n + 2}{n} \cdot d \right) \cdot h^n
\]
\[
= \frac{1}{d^2} \left( (1 - d)^n + d \cdot (n + 2) - 1 \right) \cdot h^n,
\]
which combined with \( \int_X h^n = d \) leads to
\[
e(X) = \frac{1}{d} \left( (1 - d)^n + d \cdot (n + 2) - 1 \right).
\]
For \( d = 3 \) the right hand side becomes
\[
e(X) = \frac{1}{3} \left( (-2)^n + 3n + 5 \right). \tag{1.6}
\]

**Corollary 1.8.** The primitive middle Betti number of a smooth hypersurface \( X \subset \mathbb{P}^{n+1} \)
of degree \( d \) and dimension \( n > 0 \) is given by
\[
b_n(X)_{pr} = \frac{(-1)^n}{d} \left( d - 1 + (1 - d)^n \right),
\]
which for \( d = 3 \) becomes \( b_n(X)_{pr} = (-1)^n \cdot (2/3) \cdot \left( 1 + (-1)^n \cdot 2^{n+1} \right). \)

**Exercise 1.9.** For a smooth cubic hypersurface, its \( n \)-th Betti number itself can be expressed as
\[
b_n(X) = \frac{1}{6} \left( 2^{n+3} + 3 \cdot (-1)^n \cdot 7 \right).
\]

We record the result for cubics and small dimensions in the following table. Further information about the intersection form, to be discussed a little later, is also included.

<table>
<thead>
<tr>
<th>( n )</th>
<th>( e(X) )</th>
<th>( b_n(X)_{pr} )</th>
<th>( b_n(X) )</th>
<th>( \tau(X) )</th>
<th>( (b^+_n(X), b^-_n(X)) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>(3, 0)</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>-5</td>
<td>(1, 6)</td>
</tr>
<tr>
<td>2</td>
<td>-6</td>
<td>10</td>
<td>10</td>
<td>19</td>
<td>(21, 2)</td>
</tr>
<tr>
<td>3</td>
<td>27</td>
<td>22</td>
<td>23</td>
<td>-53</td>
<td>(17, 70)</td>
</tr>
<tr>
<td>4</td>
<td>-36</td>
<td>42</td>
<td>42</td>
<td>163</td>
<td>(253, 90)</td>
</tr>
<tr>
<td>5</td>
<td>93</td>
<td>86</td>
<td>87</td>
<td>682</td>
<td>(441, 926)</td>
</tr>
<tr>
<td>6</td>
<td>-162</td>
<td>170</td>
<td>170</td>
<td>-485</td>
<td>(441, 926)</td>
</tr>
</tbody>
</table>
1.4 After having computed all Betti numbers $b_i(X)$ of smooth hypersurfaces $X \subset \mathbb{P}^{n+1}$, we now aim at determining their Hodge numbers $h^{p,q}(X) := \dim H^p(X, \Omega^q_X)$.

They are encoded by the Hirzebruch $\chi_y$-genus, which for an arbitrary smooth projective variety $X$ of dimension $n$ is defined as the polynomial

$$\chi_y(X) := \sum_{p=0}^{n} \chi^p(X) y^p$$

with coefficients $\chi^p(X) := \chi(X, \Omega^p_X) = \sum_{q=0}^{n} (-1)^q h^{p,q}(X)$.

**Corollary 1.10.** For a smooth hypersurface $X \subset \mathbb{P}^{n+1}$ one has

$$\chi^p(X) = (-1)^{n-p} h^{p,n-p}(X) + \begin{cases} (-1)^p & \text{if } 2p \neq n \\ 0 & \text{if } 2p = n \end{cases}$$

and, therefore,

$$h^{p,n-p}(X) \neq 0 \text{ if and only if } \chi^p(X) \neq (-1)^p$$

$$h^{p,n-p}(X) = 1 \text{ if and only if } \chi^p(X) = (-1)^{n-p} + (-1)^p.$$  \(\square\)

This can be pictured by the Hodge diamonds for $n \equiv 0 \ (2)$ and $n \equiv 1 \ (2)$.
Chapter 1. Basic facts

This prompts certain natural questions: For which $d$ and $n$ is $h^{0,0}$ ≠ 0? Or, how to compute $\max\{p \mid h^{p,n-p} ≠ 0\}$, which encodes the level of the Hodge structure of $X$? By Corollary 1.4 one knows that $h^{0,0} = 0$ for cubic hypersurfaces of dimension $n > 1$.

In principle, $\chi_y(X)$ can be computed by the Hirzebruch–Riemann–Roch formula. Indeed,

$$\chi^p(X) = \int_X \text{ch}(\Omega^p_X) \cdot \text{td}(X),$$

which using Chern roots $\gamma_i$ of $T_X$ leads to

$$\chi_y(X) = \int_X \prod_{i=1}^n \frac{(1 - ye^{-\gamma_i}) \gamma_i}{1 - e^{-\gamma_i}}.$$

cf. [100, Cor. 5.1.4]. The characteristic classes of $\Omega^p_X$ and of $T_X$, the latter is needed for the computation of $\text{td}(X)$, can all be explicitly determined by using the Euler sequence and the conormal sequence. However, the computation is not particularly enlightening until everything is put in a generating series, cf. [96, Thm. 22.1.1].

**Theorem 1.11 (Hirzebruch).** For smooth hypersurfaces $X_n \subset \mathbb{P}^{n+1}$ of degree $d$ one has

$$\sum_{n=0}^{\infty} \chi(X_n) z^{n+1} = \frac{1}{(1 + y)(1 - z)} \cdot \frac{(1 + yz)^d - (1 + z)^d}{(1 + y)^d + y(1 - z)^d}.$$

A variant of this formula for the primitive Hodge numbers $h^{p,q}(X)_{\text{pr}} := \dim H^{p,q}(X)_{\text{pr}} = h^{p,q}(X) - \delta_{p,q}$ has been worked out in [1 Exp. XI]:

$$\sum_{p,q \geq 0, n \geq 0} h^{p,q}(X_n) y^p z^q = \frac{1}{(1 + y)(1 + z)} \cdot \left[ \frac{(1 + y)^d - (1 + z)^d}{(1 + z)y + (1 + y)^d z} - 1 \right].$$

We consider the usual specializations of the $\chi_y$-genus for cubic hypersurfaces ($d = 3$):

(i) $y = 0$. So, we consider $\chi_{y=0}(X) = \chi^0(X) = \chi(X, \mathcal{O}_X)$. The left hand side of (1.7) can be readily computed as

$$\sum_{n=0}^{\infty} \chi(X_n, \mathcal{O}_X) z^{n+1} = 3 + 0 z^2 + 3 z^3 + z^4 + \cdots.$$

Indeed, the first coefficient is $\chi(X_0 = \{x_1, x_2, x_3\}, \mathcal{O}_{\mathbb{P}^3}) = 3$ and the second $\chi(X_1 = E, \mathcal{O}_E) = 0$ with $E$ an elliptic curve. For $n > 1$ use Bott vanishing and the short exact sequence $0 \rightarrow \mathcal{O}_{\mathbb{P}}(-3) \rightarrow \mathcal{O}_{\mathbb{P}} \rightarrow \mathcal{O}_X \rightarrow 0$ to compute $\chi(X, \mathcal{O}_X) = \chi(\mathbb{P}, \mathcal{O}_\mathbb{P}) - \chi(\mathbb{P}, \mathcal{O}_\mathbb{P}(-3)) = 1.$
To confirm (1.7) in this case, we compute its right hand side and find
\[
\frac{1}{1-z} \left( 1 - (1-z)^3 \right) = \frac{1}{1-z} - (1-z)^2 \\
= (1+z + z^2 + \cdots) - (1-2z + z^2) \\
= 3z + 0z^3 + z^4 + \cdots.
\]
(ii) \( y = -1 \). Observe that \( \chi_{y=-1}(X) = e(X) \). In this case (1.7) taken literally yields
\[
\sum_{n=0}^{\infty} e(X_n) z^{n+1} = \frac{1}{(1-z)^2} \cdot \frac{(1-z)^3 - (1-z)^3}{(1-z)^3 - (1-z)^3},
\]
which is of course not very useful. Only when the right hand side of (1.7) for \( y = -1 \) is computed as the limit for \( y \to -1 \) via L'Hôpital's rule, one obtains the useful formula
\[
\sum_{n=0}^{\infty} e(X_n) z^{n+1} = \frac{3z}{(1-z)^2 (1+2z)} \\
= 3z \cdot (1+z + z^2 + \cdots)^2 \cdot (1-2z + (2z)^2 - \cdots) \\
= 3z + 0z^3 + 9z^3 + \cdots,
\]
which sheds a new light on (1.6). The reader may want to check that one indeed gets the same answer.

(iii) \( y = 1 \). This is the most interesting case. According to the Hirzebruch signature theorem [96, Thm. 15.8.2]
\[
\chi_{y=1}(X) = \tau(X).
\]
Recall that for \( n \equiv 0 \ (2) \) the intersection pairing
\[
\mathcal{H}^p(X, \mathbb{R}) \times \mathcal{H}^q(X, \mathbb{R}) \to \mathbb{R}
\]
is a non-degenerate symmetric bilinear form which, of course, can be diagonalized to become diag(+1, \ldots, +1, -1, \ldots, -1). Now, by definition,
\[
\tau(X) = b_n^+(X) - b_n^-(X),
\]
where \( b_n^\pm(X) \) is the number of \( \pm 1 \). Then the Hodge–Riemann bilinear relations imply \( \tau(X) = \sum_{p,q} (-1)^p \cdot h^{p,q}(X) \), cf. [100, Cor. 3.3.18]. Note that, although the definition of the signature only involves the middle cohomology, indeed all Hodge numbers \( h^{p,q}(X) \), also for \( p+q \neq n \), enter the sum.

As a side remark, observe that the right hand side of (1.7) for \( y = 1 \) reads
\[
\frac{1}{(1-z)^2} \cdot \frac{(1+z)^d - (1-z)^d}{(1+z)^d + (1-z)^d},
\]
which is anti-symmetric in \( z \). Hence, only \( X_n \) with \( n \equiv 0 \ (2) \) enter the computation.
Chapter 1. Basic facts

so that one need not worry about defining an analogue of the signature for alternating intersection forms. In any case, (1.7) yields for \( d = 3 \) the intriguing formula

\[
\sum_{n=0}^{\infty} \tau(X_n) z^{n+1} = \frac{6z + 2z^3}{(1-z)(2+6z^2)}
\]

= \( z \cdot (3 + z^2) \cdot (1 + z^2 + z^4 + \cdots) \cdot (1 - 3z^2 + (3z^2)^2 - (3z^2)^3 + \cdots) \)

= \( z \cdot (3 - 5z^2 + 19z^4 - 53z^6 + 163z^8 - 485z^{10} + \cdots) \).

Maybe more instructive is the closed formula for the signature of an even dimensional smooth cubic hypersurface

\[
\tau(X_{2m}) = (-1)^m \cdot 2 \cdot 3^m + 1.
\]

In principle, we have now computed all Hodge numbers of smooth (cubic) hypersurfaces, but decoding (1.7) is not always easy. For later use, we record the middle Hodge numbers of smooth cubic hypersurfaces of dimension \( \leq 10 \).

<table>
<thead>
<tr>
<th>( n )</th>
<th>( b_n(X)_{pr} )</th>
<th>( H^p_{pr} )</th>
<th>( h^{p,q}_{pr} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>( H^{1,0} \oplus H^{0,1} )</td>
<td>1 1</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>( H^{1,1} )</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>42</td>
<td>( H^{1,2} \oplus H^{1,2} \oplus H^{1,3} )</td>
<td>5 5</td>
</tr>
<tr>
<td>4</td>
<td>86</td>
<td>( H^{1,2} \oplus H^{2,2} \oplus H^{1,3} )</td>
<td>1 20 1</td>
</tr>
<tr>
<td>5</td>
<td>170</td>
<td>( H^{1,3} \oplus H^{1,3} \oplus H^{2,2} )</td>
<td>21 21</td>
</tr>
<tr>
<td>6</td>
<td>342</td>
<td>( H^{2,2} \oplus H^{2,3} \oplus H^{2,4} )</td>
<td>8 70 8</td>
</tr>
<tr>
<td>7</td>
<td>682</td>
<td>( H^{3,2} \oplus H^{3,3} \oplus H^{3,4} \oplus H^{2,5} )</td>
<td>1 84 84 1</td>
</tr>
<tr>
<td>8</td>
<td>1366</td>
<td>( H^{3,3} \oplus H^{4,4} \oplus H^{3,5} \oplus H^{4,6} \oplus H^{3,7} )</td>
<td>11 330 330 11</td>
</tr>
<tr>
<td>9</td>
<td>220</td>
<td>( H^{4,4} \oplus H^{4,5} \oplus H^{4,6} \oplus H^{3,7} )</td>
<td>924 220 220 1</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Remark 1.12. Later, in Section 4.4, we will see that for a smooth cubic hypersurface \( X \subset \mathbb{P}^{n+1} \) the Hodge numbers are given by

\[
h^{p,n-p}(X)_{pr} = \binom{n+2}{2n+1-3p}.
\]

These numbers are reasonable in the sense that they satisfy complex conjugation \( h^{p,n-p} = h^{n-p,p} \), but the combinatorial consequence of combining \( \sum_{p=0}^{n} h^{p,n-p}(X)_{pr} = b_n(X)_{pr} \) with Corollary 1.8 seems less clear, see Exercise 4.13. From this description we
1 Numerical and cohomological invariants

will eventually be able to read off easily properties of Hodge numbers. For example, one finds:

(i) \( h^{p,p}(X) \neq 0 \) if and only if \( n - 1 \leq 3p \leq 2n + 1 \) and

(ii) \( h^{p,n-p}(X) = 1 \) if and only if \( 3p = 2n + 1 \) or \( 3p = n - 1 \).

(iii) The level of the Hodge structure \( \ell = \ell(H^n(X)) := \max\{|p - q| \mid H^{p,q}(X) \neq 0\} \)

satisfies \( \ell > 1 \) for \( n > 5 \) and \( \ell > 2 \) for \( n > 8 \). The first computations of this sort were done in [152].

Note that the two cases in (ii) are Serre dual to each other.

1.5 Our next goal is to determine the intersection form on \( H^n(X, \mathbb{Z}) \) for a smooth cubic hypersurface \( X \subset \mathbb{P} = \mathbb{P}^{n+1} \). Recall from Section 1.1 that \( H^n(X, \mathbb{Z}) \) is torsion free, i.e. \( H^n(X, \mathbb{Z}) \cong \mathbb{Z}^{b_n(X)} \). The non-degenerate intersection pairing

\[
H^n(X, \mathbb{Z}) \times H^n(X, \mathbb{Z}) \to H^{2n}(X, \mathbb{Z}) \cong \mathbb{Z}
\]

is symplectic for \( n \equiv 1 (2) \) and symmetric for \( n \equiv 0 (2) \). In the first case, \( H^n(X, \mathbb{Z}) \) admits a basis \( \gamma_1, \ldots, \gamma_{b_n=2m} \) for which the intersection matrix has the standard form

\[
\begin{pmatrix}
0 & 1 & \cdots & 1 \\
-1 & 0 & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
-1 & 0 & \cdots & 0
\end{pmatrix}
\]

For \( n \equiv 0 (2) \) the intersection pairing on \( H^n(X, \mathbb{Z}) \) defines a unimodular lattice. In other words, the determinant of the intersection matrix (with respect to any integral basis), i.e. the discriminant of the lattice, is \( \pm 1 \). The classification of unimodular lattices is a classical topic. It distinguishes between even lattices \( \Lambda \), i.e. those for which \( (\alpha) = (\alpha, \alpha) \equiv 0 (2) \) for all \( \alpha \in \Lambda \), and odd lattices.

Assume that \( \Lambda \) is an odd lattice, i.e. that there exists \( \alpha \in \Lambda \) with \( (\alpha)^2 \equiv 1 (2) \), unimodular, and indefinite, then

\[
\Lambda \cong \mathbb{I}_{1,1} := \mathbb{Z}(1)^{b_0} \oplus \mathbb{Z}(-1)^{b_1},
\]

where \( \mathbb{Z}(a) \) is the lattice of rank one with intersection form given by \( (1)^2 = a \), see [159, V. Thm. 4]. This can be applied to the middle cohomology of any even-dimensional, smooth hypersurface of odd degree, as \( (h^{n/2}, h^{n/2}) = \int_X h^{n/2} \cdot h^{n/2} = d \). That the intersection pairing on \( H^n(X, \mathbb{Z}) \) is indeed indefinite can be deduced easily (at least for cubic hypersurfaces) from a comparison of \( \tau(X) \) and \( b_n(X) \), cf. Corollary 1.8 and 1.9.
Corollary 1.13. Let \( X \subset \mathbb{P}^{n+1} \) be a smooth cubic hypersurface of even dimension. Then the intersection form on its middle cohomology yields a lattice isomorphic to
\[
H^n(X, \mathbb{Z}) \cong \mathbb{Z}(1)^{\delta_{bc}} \oplus \mathbb{Z}(-1)^{\delta_{bc}} \cong I_{b^+_n, b^-_n}.
\]
Here, \( b^+_n := b^+_n(X) \) are determined by \( b^+_n + b^-_n = b_n(X) = (1/3)(2^{n+2} + 5) \), see Corollary 1.8 and \( b^+_n - b^-_n = \tau(X) = (-1)^{n/2} \cdot 2 \cdot 3^{n/2} + 1 \), see 1.9.

More interesting, however, is the primitive cohomology \( H^p(X, \mathbb{Z})_{pr} \). The intersection form is still non-degenerate there, but not necessarily unimodular, and, as it turns out, not odd. By definition and using that \( b^{p-2} = 1 \) for even \( n > 0 \), it is the orthogonal complement \((h^{p/2})^+ \subset H^p(X, \mathbb{Z})\). However, note that
\[
H^p(X, \mathbb{Z})_{pr} \oplus \mathbb{Z} \cdot h^{p/2} \subset H^p(X, \mathbb{Z})
\]
is not an equality. It describes a finite index subgroup. The square of the index is
\[
\text{ind}^2 = \pm \text{disc}(\mathbb{Z} \cdot h^{p/2}) \cdot \text{disc}(H^p(X, \mathbb{Z})_{pr}) = \pm 3 \cdot \text{disc}(H^p(X, \mathbb{Z})_{pr}),
\]
where we use that \( H^p(X, \mathbb{Z}) \) is unimodular and \( \mathbb{Z} \cdot h^{p/2} \cong \mathbb{Z}(3) \), see [103, Ch. 14.0.2] for the general statement and references. This also shows that the discriminant of the intersection form on \( H^p(X, \mathbb{Z})_{pr} \) is at least divisible by three and, therefore, \( H^p(X, \mathbb{Z})_{pr} \) is not unimodular.

The following is a folklore result for cubics (in dimension four, cf. [92]) and has been generalized to other degrees and complete intersections in [20]. For the definition of the lattices \( A_2, E_6, E_8, \) and \( U \) see [103, Ch. 14] and the references therein.

Proposition 1.14. Let \( X \subset \mathbb{P}^{n+1} \) be a smooth cubic hypersurface of even, positive dimension. Then the intersection form on its middle primitive cohomology \( H^p(X, \mathbb{Z})_{pr} \) is described as follows:

(i) For \( n = 2 \) one has \( H^p(X, \mathbb{Z})_{pr} \cong E_6(-1) \).

(ii) For \( n > 2 \) one has \( H^p(X, \mathbb{Z})_{pr} \cong A_2 \oplus E_8^\oplus \oplus U^\oplus \). Here, \( b := \min\{b^+_n(X), b^-_n(X)\} \) and
\[
a := \begin{cases} 
\frac{b^+_n - b^-_n - 3}{8} = \frac{\tau(X) - 3}{8} = \frac{3^{p/2} - 1}{4} & \text{if } n \equiv 0 (4) \\
\frac{b^-_n - b^+_n + 3}{8} = \frac{3 - \tau(X)}{8} = \frac{3^{p/2} + 1}{4} & \text{if } n \equiv 2 (4).
\end{cases}
\]
In particular, \( \text{disc}(H^p(X, \mathbb{Z})_{pr}) = 3 \) and the inclusion (1.10) has index three.

Note that \( n \equiv 0 (4) \) if and only if \( b^+_n \geq b^-_n \), see (1.9). Also, observe that \( b \geq (1/3)(2^{n+1} - 3^{n/2+1} - 1) \), which is rather large for \( n \geq 4 \), i.e. \( H^p(X, \mathbb{Z})_{pr} \) contains many copies of the hyperbolic plane \( U \). This often simplifies lattice theoretic arguments.
Proof Assume $n > 2$, so that $b^+_n(X) > 3$, and consider the odd, unimodular lattice
\[ \Lambda := \mathbb{Z}^{n^3} \oplus E_8^{\text{odd}} \oplus U^{\text{odd}}. \]

It has rank $\text{rk}(\Lambda) = b_n(X)$ and signature $\tau(\Lambda) = \tau(X)$\footnote{Note that $\tau \equiv 3 \pmod{8}$ is a general fact for unimodular lattices containing a characteristic element $\alpha$ with $\langle \alpha \rangle^2 \equiv 3 \pmod{8}$, cf. [159, V. Thm. 2]). In our situation, $\tau(X) \equiv 3 \pmod{8}$ can be deduced from [1].}. Therefore, $\Lambda$ and $H^n(X, \mathbb{Z})$ are odd, indefinite, unimodular lattices of the same rank and signature and hence isomorphic to each other (and to $1_{b_n^+, b_n^+}$), cf. [159] V. Thm. 6.

Recall that a primitive vector $\alpha \in \Lambda$ in an odd unimodular lattice $\Lambda$ is called characteristic if $\langle \alpha, \beta \rangle \equiv \langle \beta \rangle^2 \pmod{2}$ for all $\beta \in \Lambda$. Obviously, the orthogonal complement $\alpha^\perp \subset \Lambda$ of a characteristic class is always even. The converse also holds, cf. [127] Lem. 3.3. Indeed, for any primitive $\alpha \in \Lambda$ in the unimodular lattice $\Lambda$ there exists $\beta_0 \in \Lambda$ with $\langle \alpha \beta_0 \rangle = 1$. Then for all $\beta \in \Lambda$ the class $\beta - (\alpha, \beta)\beta_0$ is contained in $\alpha^\perp$ and in particular of even square if $\alpha^\perp$ is assumed to be even. Hence, $\langle \beta \rangle^2 \equiv \langle \alpha \rangle^2 (\beta_0)^2 \pmod{2}$. As $\Lambda$ is odd, there exists a $\beta$ with $\langle \beta \rangle^2$ odd and hence $(\beta_0)^2$ must be odd. Altogether this proves $\langle \beta \rangle^2 \equiv \langle \alpha \rangle^2 (\beta_0)^2 \pmod{2}$ for all $\beta$, i.e. $\alpha$ is characteristic.

For example, $(1,1,1) \in \mathbb{Z}^{n^3}$ is characteristic, for its orthogonal complement is $A_2$.

One now applies a general result for unimodular lattices from [177] Thm. 3: Two primitive vectors $\alpha, \beta \in \Lambda$ are in the same $\text{O}(\Lambda)$-orbit if and only if $\langle \alpha \rangle^2 = \langle \beta \rangle^2$ and are either both characteristic or both not.

Therefore, to prove the assertion, it suffices to show that $h^{n/2} \in H^n(X, \mathbb{Z})$ is characteristic or, equivalently, that $H^n(X, \mathbb{Z})_{\text{pr}}$ is even. We postpone the proof of this statement to Corollary [244], where it fits more naturally in the discussion of Picard–Lefschetz theory and of the monodromy action of the universal family of hypersurfaces. A more topological argument is given in [127].

It remains to deal with the case $n = 2$, where we have $H^2(X, \mathbb{Z}) \cong 1_{6,6}$. It is easy to check that $\alpha := (3,1,\ldots,1) \in 1_{6,6}$ is characteristic with $\langle \alpha \rangle^2 = 3$ and its orthogonal complement turns out to be $E_6(-1) \cong \alpha^\perp \subset 1_{6,6}$. Indeed a computation shows that $e_1 := (0,1,-1,0,0,0,0)$, $e_2 := (0,0,1,-1,0,0,0)$, $e_3 := (0,0,0,1,-1,0,0)$, $e_4 := (1,0,0,0,1,1,1)$, $e_5 := (0,0,0,0,1,-1,0)$, and $e_7 := (0,0,0,0,1,-1)$ span $\alpha^\perp$ and that their intersection matrix is just $E_6(-1)$.

Now consider the class of the hyperplane section $h \in H^2(X, \mathbb{Z})$. As in this case $\text{Pic}(X) \cong H^2(X, \mathbb{Z})$, one can argue algebraically, using the Hirzebruch–Riemann–Roch formula, to prove that $h$ is characteristic. Indeed,
\[ \chi(X, L) = \frac{(L \cdot L) + (L \cdot h)}{2} + 1 \]
implies \((L.h) \equiv (L.L) \equiv 0 (2)\). Hence, using \cite[Thm. 3]{177} again, \(H^2(X, \mathbb{Z})_{pt} \cong a^+ \cong E_6(-1)\).

Later we will describe the isomorphisms \(H^2(X, \mathbb{Z})_{pt} \cong E_6(-1)\) from a more geometric perspective and, in particular, write down bases of both lattices in terms of lines, see Sections\cite{41113}.

\[\square\]

**Remark 1.15.** In \cite[Thm. 11.1]{119} it is shown that the purely lattice theoretic description in Corollary \cite[1.13]{11} of the intersection product on \(H^n(X, \mathbb{Z})\) can be realized geometrically in the following sense: For \(n \equiv 0 (4)\) a smooth cubic hypersurface \(X \subset \mathbb{P}^n\) is diffeomorphic to a connected sum of the form \(M\# k(S^n \times S^n)\) with \(k = b_n(X)\) and, therefore, \(b_n^s(M) = b_n(M) = \tau(M) = \tau(X)\). For \(n \equiv 2 (4), n \geq 4\) the hypersurface is diffeomorphic to a connected sum of the form \(M\# k(S^n \times S^n)\) with \(k = b_n(X) - 1\) and, therefore, \(b_n^s(M) = b_n^s(M) + 1 = \tau(M) + 2 = -\tau(X) + 2\).

For \(n \equiv 1 (2), a smooth cubic hypersurface \(X\) is diffeomorphic to \(M\# k(S^n \times S^n)\), with \(k = b_n(X)/2 - 1\) and, hence, \(b_n^s(M) = 2\). For \(n = 1, 3, or 7\) this can be improved to \(k = b_n(X)/2\) and \(b_n^s(M) = 0\).

The remaining case of smooth cubic surfaces \(X \subset \mathbb{P}^3\) is slightly different. Viewing \(X\) as the blow-up of \(\mathbb{P}^2\) in six points (see Section \cite[4.2.2]{12}) reveals that it is diffeomorphic to the connected sum \(\mathbb{P}^2 \# 6\mathbb{P}^2\).

**1.6** We conclude with a number of comments on (cubic) hypersurfaces over arbitrary fields and notably in positive characteristics. Most of the subtleties and pathologies that usually occur for varieties over fields of positive characteristic can safely be ignored for hypersurfaces. In the following, let \(X \subset \mathbb{P}^n_{k}\) be a smooth hypersurface over an arbitrary field \(k\).

\[(i)\] The Hodge–de Rham spectral sequence

\[E_1^{p,q} = H^p(X, \Omega^q_X) \Rightarrow H^{p+q}_{dR}(X/k)\]

degenerates, cf. Section \cite[4.6]{11}. For \(\text{char}(k) = 0\) or \(\text{char}(k) > \dim(X)\), this follows from \cite{59}. Indeed, smooth hypersurfaces over fields of positive characteristic can of course be lifted to characteristic zero.

More directly and avoiding the assumption \(\text{char}(k) > \dim(X)\), one can argue as follows. The computations above show in particular that the Hodge numbers \(h^{p,q}(X) = \dim(E_1^{p,q})\) of smooth hypersurfaces only depend on \(d\) and \(n\), but not on \(\text{char}(k)\). From \cite[1.11]{11} one deduces that \(\sum_{p+q=n} h^{p,q}(X) \geq \dim H_{dR}^n(X/k)\). Moreover, equality holds if and only if the spectral sequence degenerates. On the other hand, \(\dim H_{dR}^n(X/k)\) is upper semi-continuous. Hence, the degeneration of the spectral sequence in characteristic zero implies the degeneration in positive characteristic.

\[(ii)\] The Kodaira vanishing \(H^p(X, \Omega^n_X \otimes L) = 0\) for \(p + q > n\) and \(L \in \text{Pic}(X)\) ample holds. This can either be seen as a consequence of \cite{59} for large enough characteristic.
or read off from Corollaries 1.4 and 1.6. In particular, all numerical assertions on Hodge numbers remain valid over arbitrary fields. Also, for algebraically closed fields, the étale Betti numbers equal the ones computed in characteristic zero. The only case not covered by these comments is the case of cubic surfaces in characteristic two.

(iii) Assume \( k = \mathbb{F}_q \). Then the Weil conjectures show that

\[
Z(X, t) := \exp \left( \sum_{r=1}^{\infty} \frac{|X(\mathbb{F}_q^r)| t^r}{r} \right) = \frac{P(t)^{q^{n+1}}}{\prod_{i=0}^{n}(1-q^i t)}
\]

with \( P(t) = \prod (1-\alpha_i t) \) of degree \( b_n(X) \) and \( \alpha_i \) algebraic integers of absolute value \( |\alpha_i| = q^{n/2} \). This was established by Bombieri and Swinnerton-Dyer [28] for cubic threefolds and by Dwork [66] for arbitrary hypersurfaces, prior to the proof of the general Weil conjectures by Deligne. Of course, as cubic surfaces are rational, the Weil conjectures follow from the Weil conjectures for \( \mathbb{P}^2 \) and for curves.

2 Linear system and Lefschetz pencils

This section discusses the linear system of (cubic) hypersurfaces. Basic facts concerning the discriminant divisor are reviewed and, in particular, its degree is computed. We describe the monodromy group of the family of smooth hypersurfaces as a subgroup of the orthogonal group of the middle cohomology and complement the results with a comparison of the action of the group of diﬀeomorphisms.

Hypersurfaces \( X \subset \mathbb{P} = \mathbb{P}^{n+1} \) of degree \( d \) are parametrized by the projective space

\[
|\mathcal{O}_{\mathbb{P}}(d)| \cong \mathbb{P}^{N(d,n)},
\]

where \( N = N(d,n) = h^0(\mathbb{P}^{n+1}, \mathcal{O}_{\mathbb{P}}(d)) - 1 = \binom{n+1+d}{d} - 1 \). The universal hypersurface shall be denoted

\[
\mathcal{X} \subset \mathbb{P}^N \times \mathbb{P}.
\]  
(2.1)

It is of bidegree \((1, d)\), i.e. a divisor contained in the linear system \( |\mathcal{O}_{\mathbb{P}}(1) \boxtimes \mathcal{O}_{\mathbb{P}}(d)| \), and the fibre of the (flat) first projection \( \mathcal{X} \longrightarrow \mathbb{P}^N \) over the point corresponding to \( X \subset \mathbb{P} \) is indeed just \( X \).

More explicitly, \( \mathcal{X} \) can be described as the zero set of the universal equation \( G = \sum a_I x^I \), where \( a_I \in H^0(\mathbb{P}^N, \mathcal{O}_{\mathbb{P}}(1)) \) are the linear coordinates corresponding to the monomials \( x^I \in H^0(\mathbb{P}, \mathcal{O}_{\mathbb{P}}(d)) \). In other words, if one writes \( \mathbb{P} \) as \( \mathbb{P} = \mathbb{P}(V) \) for some vector space \( V \) of dimension \( n+2 \), then \( H^0(\mathbb{P}, \mathcal{O}_{\mathbb{P}}(d)) = S^d(V^*) \) and \( \mathbb{P}^N = \mathbb{P}(S^d(V^*)) \). Hence, \( H^0(\mathbb{P}^N, \mathcal{O}_{\mathbb{P}}(1)) = S^d(V) \) and then \( G \) corresponds to the identity in \( \text{End}(S^d(V)) \cong S^d(V) \otimes S^d(V^*) \) and \( H^0(\mathbb{P}^N \times \mathbb{P}, \mathcal{O}_{\mathbb{P}}(1) \boxtimes \mathcal{O}_{\mathbb{P}}(d)) \).
24

Chapter 1. Basic facts

The universal hypersurface $\mathcal{X}$ is smooth. For this observe that the second projection $\mathcal{X} \to \mathbb{P}$ is the projective bundle $\mathbb{P}^*(\text{Ker}(ev)) \to \mathbb{P}$, where $ev$ is the evaluation map 

$$ev : H^0(\mathbb{P}, \mathcal{O}_\mathbb{P}(d)) \otimes \mathcal{O} \to \mathcal{O}_\mathbb{P}(d).$$

2.1 The natural $\text{SL}(n + 2)$-action on $H^0(\mathbb{P}, \mathcal{O}_\mathbb{P}(d))$ descends to an action of $\text{SL}(n + 2)$ and $\text{PGL}(n + 2)$ on $|\mathcal{O}_\mathbb{P}(d)|$. Both are linearized in the sense that they are obtained by composing homomorphisms $\text{SL}(n + 2) \to \text{SL}(N + 1)$ and $\text{PGL}(n + 2) \to \text{PGL}(N + 1)$ with the natural actions of $\text{SL}(N + 1)$ and $\text{PGL}(N + 1)$ on $H^0(\mathbb{P}^N, \mathcal{O}_{\mathbb{P}^N}(1))$ and $|\mathcal{O}_{\mathbb{P}^N}(1)|$.

The following table records the dimensions of the linear system of cubic hypersurfaces of small dimensions. It also contains information about the moduli space

$$M_n := |\mathcal{O}_\mathbb{P}(3)|_{\text{sm}}/\text{PGL}(n + 2)$$

and the discriminant divisor $D(n) := D(3, n) \subset |\mathcal{O}_\mathbb{P}(3)|$, both to be discussed below, see Sections 2.3 and 2.1.3. We write $N(n) := N(3, n)$.

\[
\begin{array}{|c|c|c|c|c|}
\hline
n & N(n) & \dim(\text{PGL}(n + 2)) & \dim(M_n) & \deg(D(n)) \\
\hline
0 & 3 & 3 & 0 & 4 \\
1 & 9 & 8 & 1 & 12 \\
2 & 19 & 15 & 4 & 32 \\
3 & 34 & 24 & 10 & 80 \\
4 & 55 & 35 & 20 & 192 \\
5 & 83 & 48 & 35 & 448 \\
\hline
\end{array}
\]

The closed formula for the dimension of the moduli space is

$$\dim(M_n) = \left(\frac{n + 2}{3}\right) = \frac{n^3 + 3n^2 + 2n}{6}.$$  \hspace{1cm} (2.2)

2.2 We are mostly interested in smooth hypersurfaces. They are parametrized by a Zariski open subset which shall be denoted

$$U(n, d) := |\mathcal{O}_\mathbb{P}(d)|_{\text{sm}} := \{ X \in |\mathcal{O}_\mathbb{P}(d)| \mid X \text{ smooth} \} \subset |\mathcal{O}_\mathbb{P}(d)|.$$

For an algebraically closed ground field $k$, Bertini’s theorem shows that there exists a smooth hypersurface of the given degree $d$. Hence, $U(n, d)$ is non-empty and, therefore, dense. In fact, if $\text{char}(k) = 0$ or at least $\text{char}(k) \nmid d$, then the Fermat hypersurface

$$X = V \left( \sum_{i=0}^{n+1} x_i^d \right) \subset \mathbb{P}$$
is always smooth, as it is easy to check using the Jacobian criterion. In [112, p. 333] one finds the following explicit equations for smooth hypersurfaces over arbitrary fields

\[
\begin{align*}
\sum_{i=0}^{m-1} x_{i} x_{i+m} & \quad \text{if } d = 2, n + 2 = 2m \\
\sum_{i=0}^{m-1} x_{i} x_{i+m} + x_{i}^{2} & \quad \text{if } d = 2, n + 1 = 2m \\
\sum_{i=0}^{n+1} x_{i}^{d} & \quad \text{if } d \geq 3, \text{char}(k) \nmid d \\
\sum_{i=0}^{n} x_{i} x_{i+1}^{d-1} + x_{0}^{d} & \quad \text{if } d \geq 3, \text{char}(k) \mid d.
\end{align*}
\]

(2.3)

Hence, the set of $k$-rational points of $U(n, d) = |\mathcal{O}_P(d)|_{\text{sm}}$ is always non-empty.

**Definition 2.1.** The discriminant divisor $D(d, n) \subset |\mathcal{O}_P(d)|$ is the complement of the Zariski open (and dense) subset $U(d, n) \subset |\mathcal{O}_P(d)|$ of smooth hypersurfaces. Thus, $D(d, n)$ is closed and it will be viewed with its reduced induced scheme structure.

**Theorem 2.2.** The discriminant divisor $D(d, n) \subset |\mathcal{O}_P(d)|$ is an irreducible divisor. Its degree is $(d - 1)^{n+1}(n + 2)$, which for $d = 3$ reads

$$\deg(D(3, n)) = 2^{n+1}(n + 2).$$

**Proof** Consider the universal hypersurface $X' \subset \mathbb{P}^N \times \mathbb{P}$ as above and define

$$X_{\text{sing}} := X' \cap \bigcap_{i=0}^{n+1} V_i,$$

where the $V_i := V(\partial_i G)$ are the hypersurfaces of bidegree $(1, d - 1)$ defined by the derivatives of the equation of the universal hypersurface

$$\partial_i G := \sum_{a_i} a_i \frac{\partial G}{\partial x_i} \in H^0\left(\mathbb{P}^N \times \mathbb{P}, \mathcal{O}_P(1) \otimes \mathcal{O}_P(d - 1)\right).$$

By the Jacobian criterion, $X_{\text{sing}} \subset X \longrightarrow \mathbb{P}^N$ is the (non-flat) family of singular loci of the fibres $X_i$, i.e. $(X_{\text{sing}})_i = (X_i)_{\text{sing}}$.

As the Euler equation (see [30] Ch. 4]) holds in its universal form $\sum x_i \partial_i G = d \cdot G$, one has $X' \cap \bigcap V_i$ if $\text{char}(k) \nmid d$ (which we will tacitly assume, but see Remark 2.3). Hence, $X_{\text{sing}} = \bigcap V_i$ and, therefore, $\text{codim}(X_{\text{sing}}) \leq n + 2$. To prove that equality holds, consider the other projection $X_{\text{sing}} \longrightarrow \mathbb{P}$, which we claim is a $\mathbb{P}^{d-1}$-bundle with $k = N - n - 2$. To see this, observe that the homomorphism of sheaves on $\mathbb{P}$

$$\varphi: H^0\left(\mathbb{P}, \mathcal{O}_P(d)\right) \otimes \mathcal{O}_P \longrightarrow \mathcal{O}_P(d - 1)^{\oplus n+2}, \quad F \longrightarrow (\partial_i F)$$

is surjective, which can be checked e.g. at the point $z = [1 : 1 : \cdots : 1]$ by using that $(\partial_i x_j^d)(z) = d \cdot \delta_{ij}$, and

$$X_{\text{sing}} \approx \mathbb{P}(\text{Ker}(\varphi)) \longrightarrow \mathbb{P}.$$ 

This clearly proves $\text{codim}(X_{\text{sing}}) = n + 2$, but also that $X_{\text{sing}}$ is smooth and irreducible.
Chapter 1. Basic facts

To be precise, one needs to verify that $X_{\text{sing}} \cong \mathbb{P} (\text{Ker}(\varphi))$ as schemes and not only as sets, which is left to the reader.

Next, $D := D(d, n)$ is by definition the image of $X_{\text{sing}}$ under the projection

$$X_{\text{sing}} \subset X \subset \mathbb{P}^N \rightarrow \mathbb{P}^N.$$  

Let us denote the pull-backs of the hyperplane sections on $\mathbb{P}^N$ and $\mathbb{P}$ (both denoted by $h$) to $\mathbb{P}^N \times \mathbb{P}$ by $h_1$ and $h_2$. Suppose $D$ is of codimension $>1$. Then $(h^{N-1}.D) = 0$, which, however, would contradict

$$(h_1^{N-1}.X_{\text{sing}}) = (h_1^{N-1}.(h_1 + (d - 1) h_2)_{|\mathbb{P}^N}) = (n + 2)(d - 1)^{N-1}.$$  

Hence, $D \subset \mathbb{P}^N$ really is a divisor. The computation also shows that in order to prove the claimed degree formula for $D$, it suffices to prove that $X_{\text{sing}} \rightarrow D$ is generically injective or, in other words, that the generic singular hypersurface $X \in |\mathcal{O}_{\mathbb{P}^N}(d)|$ has exactly one singular point (which is in fact an ordinary double point). (Note that one needs to assume $\text{char}(k) = 0$ for the set-theoretic injectivity to imply that the morphism is of degree one.) One way of doing it would be to write down examples of hypersurfaces in each degree with exactly one ordinary double point\(^2\) or to argue geometrically (assuming $\text{char}(k) = 0$) by considering again the projective bundle $X_{\text{sing}} \rightarrow \mathbb{P}$. The fibre over a point $z$ can be thought of as a linear system with $z$ as its only base point. By Bertini’s theorem with base points, see e.g. [90, III. Rem. 10.9.2], the generic element will then be singular exactly at $z$.

To see that generically it has to be an ordinary double point, just write down one hypersurface with such a singular point at $z$ (but possibly other singular points), e.g. the union of $(d - 2)$ generic hyperplanes $\mathbb{P}^n \subset \mathbb{P}$ and of a cone with vertex $z$ over a quadric in some hyperplane.

Remark 2.3. In [1] Exp. XVII the discriminant divisor is viewed as the dual variety of the Veronese embedding $\nu_d : \mathbb{P} \hookrightarrow \mathbb{P}^{N_d}$, i.e. as the locus of hyperplanes (parametrized by $\mathbb{P}^N$) that are tangent to $\nu_d(\mathbb{P})$. It is also proved that the smooth locus of $D(d, n)$ is the maximal open subset over which $X_{\text{sing}} \rightarrow D(d, n)$ is an isomorphism and that it coincides with the set of those singular hypersurfaces with one ordinary double point as only singularity.

2.3 There is a classical and more algebraic approach to the discriminant divisor using resultants, cf. [34, 46, 60, 76]. Here are some general facts. Consider homogeneous polynomials in $k[x_0, \ldots, x_{n+1}]$ of degree $d_i > 0$, $i = 0, \ldots, m$. Then there exists a unique polynomial, the **resultant**, $R(y_{i,l}) = R_{d_i}(y_{i,l}) \in k[y_{i,l}], i = 0, \ldots, m, |l| = d_i$, such that:

Duco van Straten has provided me with examples in certain degrees. Note that writing down examples with just one singular point is easy, e.g. the cone over the smooth examples in (2.3) has only one singular point, which however is an ordinary double point only for $d = 2$. 

---

\(^2\) Duco van Straten has provided me with examples in certain degrees. Note that writing down examples with just one singular point is easy, e.g. the cone over the smooth examples in (2.3) has only one singular point, which however is an ordinary double point only for $d = 2$. 

---
Remark 2.4. The resultant is usually normalized to yield the discriminant for cubic polynomials $f$. Moreover, $R$ is homogeneous of degree $\prod d_i$ in the variables $y_{i,t}$ for fixed $i$ and so of total degree $\prod d_i \cdot \sum(1/d_i)$.

Consider $F \in k[y_0, \ldots, y_{n+1}]$ and apply the above to $f_i = \partial_i F$, $i = 0, \ldots, m = n + 2$, which are all homogeneous of degree $d_i = d - 1$. Then $X = V(F)$ is singular, i.e. $\cap V(f_i) \neq \emptyset$, if and only if $X \in |\mathcal{O}_2(d)|$ is in the zero locus of $R$.

Strictly speaking, $R$ defines a hypersurface in $\mathbb{P}^{N'} = \text{Proj}(k[y_{i,t}])$, $i = 0, \ldots, d = n + 1$, $|I| = d - 1$, so $N' = (n + 2)(d - 1) - 1$. Its pull-back via the linear embedding $\mathbb{P}^N \dashrightarrow \mathbb{P}^{N'}$ that maps $x^t$ to $[i_x x^t]_{i_0, \ldots, n+1}$, where for $I = (i_0, \ldots, i_{n+1})$ one sets $I_j := (i_0, \ldots, (i_j - 1), \ldots, i_{n+1})$, describes the image of $\mathcal{X}_{\text{sing}}$, i.e. the discriminant divisor. The irreducibility still holds, cf. [60] Sec. 5.6.

$$D(d, n) = V(R_{d,n}(\partial_0 G, \ldots, \partial_{n+1} G)) \subset \mathbb{P}^N = |\mathcal{O}_2(d)|.$$  

**Remark 2.4.** The resultant is usually normalized to yield the discriminant

$$\Delta_{d,n} := d^{c_{d,n}} \cdot R_{d,n}(\partial_1 G) \in H^{0} \left( \mathbb{P}^N, \mathcal{O}_{\mathbb{P}^N}(d - 1)^{n+1}(n + 2) \right), \tag{2.4}$$

where $c_{d,n} = (1/d) ((-1)^{n+1} - (d - 1)^{n+3})$. With this normalization, $\Delta_{d,n}$ becomes an irreducible polynomial in $\mathbb{Z}[y_{i,t}]$, which makes it unique up to $\pm 1$.

**Example 2.5.** The case $n = 0$ and $d = 3$, so three points in $\mathbb{P}^1$, leads to the classical discriminant for cubic polynomials $f(X)$. If $\alpha_1, \alpha_2, \alpha_3$ are the zeros of $f(X)$, then by definition $\Delta(f(X)) = ((\alpha_1 - \alpha_2)(\alpha_1 - \alpha_3)(\alpha_2 - \alpha_3))^2$. For $f(X) = X^3 + aX + b$ one has $\Delta(f(X)) = -4a^3 - 27b^2$.

The discriminant of a general polynomial $a_0 x_0^3 + a_1 x_0^2 x_1 + a_2 x_0 x_1^2 + a_3 x_1^3$ is the rather complicated polynomial of degree four

$$\Delta_{3,0} = a_1^2 a_2^5 - 4a_3 a_1^4 - 4a_2^3 a_0 - 27a_3^2 a_0^2 + 18a_0 a_1 a_2 a_3,$$

which thus defines the discriminant surface

$$D(3, 0) = V(\Delta_{3,0}) \subset \mathbb{P}^3.$$  

As an exercise, the reader may want to compare this with the normalization $R(x_0^2, x_1^2) = 1$, which in (2.4), using $c_{3,0} = -1$, yields $\Delta_{3,0}((1/3)(x_0^3 + x_1^3)) = (1/3)$.

To confirm Remark 2.3 the reader may want to verify that singular set of $D(3, 0) = V(\Delta_{3,0})$ is indeed the curve of triple points.
Example 2.6. For \( n = 1 \) and \( d = 3 \) the discriminant divisor
\[
D(3, 1) \subset \mathbb{P}^9
\]
is of degree 12 or, equivalently, the discriminant is an element of the vector space \( H^0(\mathbb{P}^9, \mathcal{O}_{\mathbb{P}^9}(12)) \), which is of dimension 293.930. Written as a linear combination of monomials, 12,894 of the coefficients are non-trivial, cf. [46] p. 99. If the partial derivatives \( \partial F \) are written as \( \partial F = a_{11}x_0^3 + a_{12}x_1^2 + a_{13}x_2^2 + a_{14}x_0x_1 + a_{15}x_0x_2 + a_{16}x_1x_2 \), etc., and one defines \( [t_1 t_2 t_3] := \det (a_{i,j}) \in H^0(\mathbb{P}^9, \mathcal{O}_{\mathbb{P}^9}(3)) \), with pairwise distinct \( t_i \), then \( \Delta \) is a polynomial of degree four in the \( [t_1 t_2 t_3] \) involving only 68 terms. In short, the discriminant is complicated.

Maybe just one word on the comparison between the discriminant introduced here and the discriminant of a plane cubic \( E \subset \mathbb{P}^2 \) in Weierstrass form \( y^2 = 4x^3 - g_2x - g_3 \) which is classically defined as \( \Delta(E) \). This is a rather simple polynomial of degree three in the coefficients, whereas the full discriminant of cubic plane curves is a polynomial of degree 12. The reason for this is that bringing a cubic polynomial in the variables \( x_0, x_1, x_2 \) into Weierstrass form involves non-linear transformations. More concretely, the coefficients \( g_2 \) and \( g_3 \) of the Weierstrass form are of degree four and six, respectively, in the coefficients of the original cubic equation, see e.g. [1] Ch. 3.

As a consequence of Theorem 2.2 and the discussion in its proof, we deduce the following.

Corollary 2.7. Assume \( k = \bar{k} \). Then for the generic line \( \mathbb{P}^1 \subset \mathbb{P}^2 \) the induced family \( \mathcal{X}_{\mathbb{P}^1} \to \mathbb{P}^1 \) has exactly \( (d - 1)n + 2 \) singular fibres \( \mathcal{X}_t, \mathcal{X}_t, \ldots \), each with exactly one singular point \( x_i \in \mathcal{X}_t \). Moreover, the \( x_i \) are all ordinary double points. \( \square \)

A pencil with these properties is called a Lefschetz pencil. Note that by Bertini’s theorem [90] III. Cor. 10.9], at least when \( \text{char}(k) = 0 \), the total space \( \mathcal{X}_{\mathbb{P}^1} \) is still smooth. See [1] Exp. XVII.

In more concrete terms, for generic choice of polynomials \( F_0, F_1 \in H^0(\mathbb{P}, \mathcal{O}_{\mathbb{P}}(d)) \) for exactly \( (d - 1)n + 2 \) values \( t = [t_0 : t_1] \) the hypersurface \( \mathcal{X}_t = V(t_0F_0 + t_1F_1) \) is singular. Each singular fibre \( \mathcal{X}_t \) has exactly one singular point \( x_i \), which, moreover, is an ordinary double point. Note that \( x_i \neq x_j \) for \( i \neq j \), as otherwise \( x_i \) would be a singular point of all the fibres.

Example 2.8. There are, of course, pencils \( \mathcal{X}_{\mathbb{P}^1} \to \mathbb{P}^1 \subset \mathbb{P}^2 \) with more singular fibres, e.g. with more or worse singularities. The Hesse pencil of plane cubics \( \mathcal{X}_t \subset \mathbb{P}^2 \) given by
\[
t_0 (x_0^3 + x_1^3 + x_2^3) + t_1 x_0 x_1 x_2
\]
is such an example. Here, the fibre \( \mathcal{X}_{[0:1]} \) consists of three lines yielding three singular
2 Linear system and Lefschetz pencils

The Hesse pencil is a special instance of the Dwork pencil (or Fermat pencil), see [24], defined by the equation
\[ t_0 \sum_{i=0}^{n+1} x_i^{n+2} - t_1 d \prod_{i=0}^{n+1} x_i \]
of hypersurfaces of degree \( d = n + 2 \).

Clearly, the number of singular fibres of any pencil is bounded by \((d - 1)^{n+1} (n + 2)\), unless all fibres are singular. Note that for general pencils the total space \( X_{\mathbb{P}^1} \) need not be smooth.

2.4 We now assume \( k = \mathbb{C} \). Let us consider the universal family of smooth hypersurfaces
\[ \pi: \mathcal{X} \longrightarrow U(d, n) \subset |O_{\mathbb{P}^n}(d)|. \]

Note the change in notation. If needed later, we will denote the universal family of all hypersurfaces by \( \tilde{\mathcal{X}} \). It is smooth and projective and contains \( \mathcal{X} \) as a dense open subset. Fix a point \( 0 \in U(d, n) \) and denote the fibre over it by \( \mathcal{X}_0 \). The monodromy representation
\[ \rho: \pi_1(U(d, n), 0) \longrightarrow \text{GL}(H^n(\mathcal{X}, \mathbb{Z})) \quad (2.5) \]
is the homomorphism obtained by parallel transport with respect to the Gauss–Manin connection. Equivalently, \( R^0 \pi_* \mathbb{Z} \) is a locally constant system on \( U(n, d) \) and (2.5) is the corresponding representation of the fundamental group. The monodromy group is by definition the image of the monodromy representation
\[ \Gamma(d, n) := \text{Im}(\rho: \pi_1(U(d, n), 0) \longrightarrow \text{GL}(H^n(\mathcal{X}, \mathbb{Z}))) \]
and it depends on \( 0 \in U(d, n) \) only up to conjugation.

The monodromy group has been determined in [17] in complete generality. We state the result for \( d = 3 \) and use the shorthand
\[ \Gamma_n := \Gamma(3, n) \subset \text{GL}(H^n(\mathcal{X}, \mathbb{Z})). \]

**Theorem 2.9.** The monodromy group \( \Gamma_n \) of the universal smooth cubic hypersurface \( \mathcal{X} \longrightarrow |O_{\mathbb{P}^n}(3)|_{\text{sm}} \) is the group
\[ \Gamma_n = \begin{cases} \tilde{\text{O}}^*(H^n(\mathcal{X}, \mathbb{Z})) & \text{if } n \equiv 0 \, (2) \\ \text{SpO}(H^n(\mathcal{X}, \mathbb{Z}), q) & \text{if } n \equiv 1 \, (2). \end{cases} \]

In fact, [17] shows that \( \Gamma(d, n) \) for \( n \) even and arbitrary \( d \) and for \( n \) odd and for all odd \( d \) admits the description. If \( n \) and \( d \) are both odd, then the monodromy group is the full symplectic group \( \text{SpO}(H^n(\mathcal{X}, \mathbb{Z})). \)

Before sketching the main steps of the proof in Section 2.5 let us explain the notation:
For $n$ even, one defines $\tilde{O}(H^k(X, \mathbb{Z})) \subset O(H^k(X, \mathbb{Z}))$ as the subgroup of all orthogonal transformations $g: H^k(X, \mathbb{Z}) \rightarrow H^k(X, \mathbb{Z})$ with $g(h^{k/2}) = h^{k/2}$. Via the induced action on $H^k(X, \mathbb{Z})_{pt}$ it can be identified with the subgroup (cf. [103, Prop. 14.2.6])
\[
\tilde{O}(H^k(X, \mathbb{Z})) = \left\{ g \in O(H^k(X, \mathbb{Z})_{pt}) \mid \text{id} = g \in O(A_{H^k(X, \mathbb{Z})_{pt}}) \right\}.
\]
Here, we use the notation $A_\Lambda \coloneqq \Lambda^*/\Lambda$ for the discriminant of a lattice $\Lambda$, which for the primitive cohomology of a smooth cubic hypersurface is just $\mathbb{Z}/3\mathbb{Z}$.

Another subgroup is given as
\[
O^*(H^k(X, \mathbb{Z})_{pt}) := \text{Ker} \left( s_n: \text{O}(H^k(X, \mathbb{Z})_{pt}) \rightarrow \{\pm 1\} \right).
\]
Here, the spinor norm $s_n(x)$ of a reflection in $\delta^\pm$ is defined as $(-1)^{n/2} \cdot (\delta^\pm | (\delta^\pm)^2]$. In other words, if $x$ is written as a product $\prod s_{\delta_i}$ of reflections with $\delta_i \in H^n(X, \mathbb{R})_{pt}$ (using the Cartan–Dieudonné theorem), then $s_n(x) = 1$ if the number of $\delta_i$ with $(\delta_i)^2 < 0$ for $n \equiv 0 \pmod{4}$ (respectively, of $\delta_i$ with $(\delta_i)^2 > 0$ for $n \equiv 2 \pmod{4}$) is even.

The orthogonal group in the theorem is the finite index subgroup of $O(H^k(X, \mathbb{Z})_{pt})$:
\[
O^*(H^k(X, \mathbb{Z})) :\tilde{O}(H^k(X, \mathbb{Z})) \cap O^*(H^k(X, \mathbb{Z})_{pt}).
\]
In fact, $O^*(H^k(X, \mathbb{Z})) = \tilde{O}(H^k(X, \mathbb{Z}))$ for $d = 3$ and $n \not\equiv 2$, see [?].

For $n$ odd, the intersection product on $H^k(X, \mathbb{Z}) = H^k(X, \mathbb{Z})_{pt}$ is alternating and can be put in the standard normal form. However, there exists an auxiliary rather subtle topological invariant, which is the quadratic form $q: H^n(X, \mathbb{Z}) \rightarrow \mathbb{Z}/2\mathbb{Z}$ (see [3, Sect. 1]) that enters the definition of the group $\text{SpO}(H^k(X, \mathbb{Z}), q)$ in the above theorem. Using that any $\alpha \in H^k(X, \mathbb{Z})$ can be represented by an embedded sphere $S^n \hookrightarrow X$, one has for $n \not\equiv 1, 3, 7$ that $q(\alpha) = 0$ if and only if the topological normal bundle of $S^n \hookrightarrow X$ is trivial. The definition for $n = 1, 3, 7$ is more involved. Then $\text{SpO}(H^k(X, \mathbb{Z}), q)$ is defined as the group of isomorphisms $g: H^k(X, \mathbb{Z}) \rightarrow H^k(X, \mathbb{Z})$ compatible with the alternating intersection form $(\cdot, \cdot)$ and the quadratic form $q$.

**Remark 2.10.** The appearance of the primitive cohomology in Theorem 2.9 is not a surprise. Indeed, the restriction of $h^{k/2} = c_1(\mathcal{O}_Y(1))^{n/2} \in H^n(\mathbb{P}^{n+1}, \mathbb{Z})$ to any of the fibres $\mathcal{X}$ defines a section of the locally constant system $R^k\pi_*\mathcal{Z}$. Hence, the primitive cohomology groups $H^k(\mathcal{X}, \mathbb{Z})_{pt}$ of the fibres glue to a locally constant subsheaf $R^k\pi_*\mathcal{Z} \subset H^k\pi_*\mathcal{Z}$. Equivalently, the monodromy representation (2.5) satisfies $\rho(\gamma)(h^{k/2}) = h^{k/2}$ for all $\gamma \in \pi_1(U(d, n))$, i.e. $h^{k/2}$ is monodromy invariant.

In fact, $h^{k/2}$ is the only monodromy invariant class up to scaling. Indeed, Deligne’s invariant cycle theorem [174, V. Thm. 16.24] shows that the monodromy invariant part

---

3 The Arf invariant of $q$, also called the Kervaire invariant of $X$, is often viewed as the analogue of the discriminant of the symmetric intersection form for $n$ even. Recall that the Arf invariant $A(q) \in \mathbb{F}_2$ of the binary quadratic form $q = ax^2 + xy + by^2$ is $ab$. For arbitrary $q$, which can be written as a direct sum of those, it is defined by additive extension, cf. [33, Ch. III]. Due to [119, Prop. 12.1], the Kervaire invariant is non-trivial for cubic hypersurfaces.
of $H^n(X, \mathbb{Q})'$ is the image of the restriction $H^n(\bar{X}, \mathbb{Q}) \to H^n(X, \mathbb{Q})$, where $\bar{X} \subset \mathbb{P}^N \times \mathbb{P}$ denotes the universal family of all hypersurfaces. Now writing $\bar{X}$ as a projective bundle over $\mathbb{P}$ shows that $H^n(\bar{X}, \mathbb{Q}) \cong \bigoplus H^{n-2i}(\mathbb{P}, \mathbb{Q}) \cdot c_1(\mathcal{O}_{\mathbb{P}^2}(1))^i$. As $c_1(\mathcal{O}_{\mathbb{P}^2}(1))$ restricts trivially to the fibres of the first projection $\bar{X} \to \mathbb{P}^N$, only $H^n(\mathbb{P}, \mathbb{Q})$ survives the map $H^n(\bar{X}, \mathbb{Q}) \to H^n(X, \mathbb{Q})$ and, therefore, its image is spanned by $h^{n/2}$.

Similarly, the monodromy representation preserves the intersection form on $H^n(X, \mathbb{Z})$. Therefore, $\text{Im}(\rho) \subset \text{O}(H^n(X, \mathbb{Z}))$ for $n$ even and $\text{Im}(\rho) \subset \text{Sp}(H^n(X, \mathbb{Z}))$ for $n$ odd.

Note that one can deduce from the theorem the well-known fact [174, Thm. 15.27] that $H^n(X, \mathbb{Q})_{pr}$ is an irreducible $\Gamma(\delta, n)$-module or, equivalently, that $R^m_{\nu!} \pi_* \mathbb{Q}$ cannot be written as a direct sum of non-trivial locally constant systems. See also Remark 2.11 and Corollary 2.12.

**Remark 2.11.** In the algebraic setting, where instead of working over $\mathbb{C}$ the ground field can be any algebraically closed field $k$, the geometric monodromy group is the Zariski closure $G$ of the image of the representation $\pi_*^{\text{ét}}(U) \to \text{GL}(H^n(X, \mathbb{Q}_\ell))$ or simply $G = \tilde{G}_n$ when working over $\mathbb{C}$. It has been determined in [58, Sec. 4.4]:

$$G = \begin{cases} \text{finite} & \text{if } n = 2 \\ \text{O}(H^n(X, \mathbb{Q}_\ell)) & \text{if } 2 < n \equiv 0 \pmod{2} \\ \text{Sp}(H^n(X, \mathbb{Q}_\ell, q)) & \text{if } n \equiv 1 \pmod{2}. \end{cases}$$

Instead of working with coefficients in $\mathbb{Q}_\ell$ one can as well use coefficients in $\mathbb{C}$. For $n$ even the proof comes down to the fact that an algebraic subgroup $G \subset \text{O}(V)$ of a complex vector space $V$ with a non-degenerate symmetric bilinear form is either finite or $\text{O}(V)$. The latter case holds as soon as there exists a $G$-orbit of classes $\delta$ with $(\delta)^2 = 2$ generating $V$ and such that $G$ contains all reflections $s_\delta$ induced by classes in that orbit, cf. [58, Lem. 4.4.2] or the account in [149].

For the following result, which for $n$ even strengthens Remark 2.10, recall that very general points in $|\mathcal{O}_\mathbb{P}(3)|$ are parametrized by the complement of a countable union of proper Zariski closed subsets and that the Hodge structure is $H^n(X, \mathbb{Q})_{pr}$ is irreducible if it cannot be written as a direct sum of non-trivial sub-Hodge structures or, equivalently, if it does not contain any non-trivial proper sub-Hodge structure. For the equivalence of the two characterizations use the existence of a polarization.

**Corollary 2.12.** Assume $X \in |\mathcal{O}_\mathbb{P}(3)|$ is a very general cubic hypersurface of dimension $n > 2$. Then $H^n(X, \mathbb{Q})_{pr}$ is an irreducible Hodge structure. In particular, the integral Hodge conjecture holds for the very general cubic hypersurface.

**Proof** We follow [139, Sec. 7]. The main input is that for $n > 2$ the identity component $G^0 \subset G$ of the geometric monodromy group acts irreducibly on $H^n(X, \mathbb{Q})_{pr}$, see Remark 2.11.
Chapter 1. Basic facts

Write the primitive cohomology of the very general cubic $X$ as direct sum $H^n(X, \mathbb{Q})_{pr} \cong \bigoplus_{i=1}^k V_i$ of irreducible Hodge structures. The projection $H^n(X, \mathbb{Q})_{pr} \longrightarrow V_1$ can be extended to a multivalued flat section of the local system $\text{End}(R^n_{pr}, \mathbb{Q})$ which is everywhere of type $(0, 0)$. As any polarizable variation of Hodge structures of type $(0, 0)$ has finite monodromy, this section becomes univalued after passing to a finite étale cover of $|O_3(3)|_{\text{sm}}$. In the process, the group $G^0$ does not change, so that it still acts irreducibly. The image of the flat section of $\text{End}(R^n_{pr}, \mathbb{Q})$ defines a locally constant sub-system of $R^n_{pr}, \mathbb{Q}$ with image $V_1$ at the point corresponding to $X$. However, as $G^0$ acts irreducibly this shows that $k = 1$, i.e. $H^n(X, \mathbb{Q})_{pr}$ is irreducible.

Concerning the Hodge conjecture, note that for an arbitrary smooth cubic hypersurface $X$ and $2p \neq n$, we have $H^{p,p}(X, \mathbb{Z}) = H^{2p}(X, \mathbb{Z}) = \mathbb{Z} \cdot h^p$. For a very general cubic hypersurface $X$ of even dimension $n = 2p$, the irreducibility of the Hodge structures $H^n(X, \mathbb{Q})_{pr}$ in particular says that $H^{p,p}(X, \mathbb{Q})_{pr} = 0$. Therefore, Hodge classes in $H^n(X)$ are again just integral multiples of $h^p$. \hfill \Box

Note that for $n = 2$, the identity component $G^0$ is trivial and indeed $H^2(S, \mathbb{Q})_{pr}$ is of type $(1, 1)$ for any cubic surface. As it is of dimension six, it is certainly not irreducible.

Remark 2.13. (i) The identity component $G^0 \subset G$ of the geometric monodromy group is contained in the Mumford–Tate group of the Hodge structure $H^n(X, \mathbb{Q})_{pr}$ of the very general $X$, see \cite{57} Prop. 7.5 or \cite{7} Lem. 4. By definition, the Mumford–Tate group of a Hodge structure determines the space of all Hodge classes in tensor products of the Hodge structure and of its dual. Thus, whenever the monodromy group is big, also the Mumford–Tate group is and, therefore, the various tensor products have only few Hodge classes. The argument in the proof make this philosophy explicit.

(ii) Arguments similar to the ones above also show that for the very general cubic $X$ of dimension $n > 2$ the Hodge structures $S^2H^n(X, \mathbb{Q})_{pr}$ for $n$ even and $\wedge^2 H^n(X, \mathbb{Q})_{pr}$ for $n$ odd split into the direct sum of two irreducible Hodge structures $\mathbb{Q} \cdot q_X \oplus q_X^*$. Here, $q_X$ denotes the symmetric resp. alternating bilinear form on $H^n(X, \mathbb{Q})_{pr}$. For this one uses the classical fact that the orthogonal group $O(V, q)$ resp. the symplectic group $Sp(V, q)$ of a vector space $V$ with a non-degenerate symmetric or alternating bilinear form $q$ acts irreducibly on the orthogonal complement $q^\perp$ in $S^2V$ resp. $\wedge^2 V$. For example, for symmetric forms $q^\perp$ is the space of harmonic polynomials, i.e. those that are killed by the Laplacian, which is an irreducible representation of $O(V)$, see \cite{77} Ch. 10.

2.5 The computation of the monodromy group $\Gamma_n$, or more generally of $\Gamma(d, n)$, proceeds in three steps.

(i) Show that $\Gamma(d, n)$ equals the monodromy group of the smooth part of a Lefschetz pencil $\mathcal{X}_{\delta} \longrightarrow \mathbb{P}^1$.

(ii) Assume $\mathcal{X} \longrightarrow \Delta$ is a family of hypersurfaces over a disk with $\mathcal{X}$ and $\mathcal{X}_{\delta=0}$ smooth
and such that the central fibre $X_0$ has one ordinary double point as its only singularity. Let $\gamma$ be the simple loop around $0 \in \Delta$. Describe the induced monodromy operation $\rho(\gamma) : H^n(X, \mathbb{Z}) \rightarrow H^n(X, \mathbb{Z})$, where $X = X_\varepsilon$ is a distinguished smooth fibre, as a reflection $s_\delta$.

(iii) Let $X_0 : \mathbb{P}^1 \rightarrow \mathbb{P}^1$ be a Lefschetz pencil with nodal singular fibres over $t_1, \ldots, t_\ell \in \mathbb{P}^1 \setminus \infty$. Describe the sub-group $(s_{\delta}) \subset \text{GL}(H^n(X, \mathbb{Z}))$ generated by the monodromy operations around all the nodal fibres $X_{t_1}, \ldots, X_{t_\ell}$.

To give at least a rough idea, here are a few more details for all three steps. For details of the statements and proofs we have to refer to the literature, cf. [174].

(i) Similar to the Lefschetz hyperplane theorem for smooth hyperplane sections of smooth projective varieties, cf. Section 1.1, a result of Zariski, see [86] or [174, V. Thm. 15.22], shows that for a very general line $P^1 \subset P^n = |O_\ell(d)|$ the induced map

$$\pi_1(P^1 \setminus D) \longrightarrow \pi_1(P^n \setminus D) \quad (2.6)$$

is surjective. (From now on we suppress the base point in $P^1 \subset P^n$ in the notation.) The restriction of $R^\ell \pi_* \mathbb{Z}$ to $P^1 \setminus D$, which is isomorphic to the higher direct image for the restriction of the family to $P^1 \setminus D$, corresponds to the representation

$$\pi_1(P^1 \setminus D) \longrightarrow \pi_1(P^n \setminus D) \longrightarrow \text{GL}(H^n(X, \mathbb{Z}))$$

obtained by composing (2.5) with (2.6). Hence, $\Gamma(d, n)$ can be computed as the monodromy group of an arbitrary Lefschetz pencil $X_0 : \mathbb{P}^1 \rightarrow \mathbb{P}^1$, i.e. as the image of

$$\rho_{P^1} : \pi_1(P^1 \setminus D) \longrightarrow \text{GL}(H^n(X, \mathbb{Z})). \quad (2.7)$$

By Theorem 2.2 $P^1 \setminus D \cong P^1 \setminus \{t_1, \ldots, t_\ell\}$ with $\ell = (d - 1)n+1 (n + 2)$. Therefore, $\pi_1(P^1 \setminus D)$ is isomorphic to a quotient of the free group $\pi_1(\mathbb{C} \setminus \{t_1, \ldots, t_\ell\}) \cong \mathbb{Z}^\ell$ with free generators given by the simple loops $\gamma_i$ around the points $t_i \in \mathbb{C}$. Thus, in order to describe the image of (2.7), we need to compute the monodromy operators $\rho_{P^1}(\gamma_i)$ and the group they generate. (In our discussion the details concerning the base point and the dependence on the path connecting it to circles around the critical values are suppressed.)

(ii) Let $x \in X_0$ be the ordinary double point of the central fibre of a family $\mathcal{X} \longrightarrow \Delta$ obtained from the above by restriction to a small disk $\Delta \longrightarrow \mathbb{P}^1$, $0 \longrightarrow t_\ell$. Intersecting a ball $B(x) \subset \mathcal{X}$ around $x$ with the nearby smooth fibre $X = X_{t_\ell}$ retracts to a sphere $S^n \subset B(x) \cap X \subset X$. It is called the vanishing sphere and its cohomology class $\delta = [S^n] \in H^n(X, \mathbb{Z})$ is the vanishing class. Its main property, responsible for its name and verified by a local computation, is that it generates the kernel of the push-forward map, cf. [174, V. Cor. 14.17]:

$$H^n(X, \mathbb{Z}) = H_n(X, \mathbb{Z}) \longrightarrow H_n(\mathcal{X}, \mathbb{Z}).$$
Chapter 1. Basic facts

The self intersection \((\delta)^2\), determined by the normal bundle of \(S^n \subset X\), is given by

\[
(\delta)^2 = \begin{cases} 
0 & \text{if } n \equiv 1 \ (2) \\
-2 & \text{if } n \equiv 2 \ (4) \\
2 & \text{if } n \equiv 0 \ (4).
\end{cases}
\]

Of course, the vanishing for odd \(n\) follows from the fact that in this case the intersection pairing on the middle cohomology is alternating. The other two cases are obtained by an explicit computation, see [174, IV.15.2].

The crucial input is the description of the monodromy operation \(\rho(\gamma)\) induced by a simple loop around \(0 \in \Delta\). It is described by the Picard–Lefschetz formula:

\[
\rho(\gamma) = s_\delta: \alpha \mapsto \alpha + \epsilon_n(\alpha.\delta)\delta, \quad (2.8)
\]

where

\[
\epsilon_n = \begin{cases} 
1 & \text{if } n \equiv 2, 3 \ (4) \\
-1 & \text{if } n \equiv 0, 1 \ (4),
\end{cases}
\]

i.e. \(\epsilon_n = (-1)^{n(n-1)/2}\). Note that the sign is such that for \(n\) even \(s_\delta\) is a reflection in \(\delta^\perp\) and so, in particular, \(s_\delta(\delta) = -1\) and \(s_\delta^2 = \text{id}\). For \(n\) odd, the monodromy is not of finite order, as \(s_k\delta\) is associated with the corresponding classes \(\delta_i\). They are reflections for even \(n\) and of infinite order if \(n\) is odd.

(iii) We have computed the images \(\rho_P(\gamma_i)\) of the free loops around the singular fibres \(X^i, \ i = 1, \ldots, \ell = \deg D(d, n)\), as the operators \(s_\delta\) associated with the corresponding classes \(\delta_i\). They are reflections for even \(n\) and of infinite order if \(n\) is odd.

Consider now families \(X^i \rightarrow \Delta^i\) around each \(t_i \in \mathbb{P}^1\) as in (ii). We may assume that the smooth reference fibre is \(X^i\) for all of them. Note that all vanishing classes \(\delta_i \in H^n(X, \mathbb{Z})\) are contained in the primitive cohomology. This follows from describing the composition as the product with the hyperplane class

\[
H^n(X, \mathbb{Z}) \cong H_n(X, \mathbb{Z}) \rightarrow H_n(X^i, \mathbb{Z}) \rightarrow H_n(\mathbb{P}, \mathbb{Z}) \cong H^{n+2}(\mathbb{P}, \mathbb{Z}) \rightarrow H^{n+2}(X, \mathbb{Z}).
\]

In fact, the vanishing cohomology \(H^n(X, \mathbb{Z})_{\text{van}} := \ker(H^n(X, \mathbb{Z}) \rightarrow H^{n+2}(\mathbb{P}, \mathbb{Z}))\), which in our situation coincides with the primitive cohomology, is generated over \(\mathbb{Z}\) by the vanishing classes, see [174, V. Lem. 14.26] or for the algebraic treatment [58, Sec. 4.3]. This has the following consequence.

**Corollary 2.14.** The primitive cohomology \(H^n(X, \mathbb{Z})_{\text{pr}}\) of a smooth hypersurface \(X \subset \mathbb{P}^{n+1}\) is generated by classes \(\delta\) with \((\delta)^2\) even and, in fact, \((\delta)^2 = -2, 0, 2\) for \(n \equiv 2 \ (4),\ n \equiv 1 \ (2),\ \text{and } n \equiv 0 \ (4)\), respectively. In particular, for \(n \equiv 0 \ (2)\), the lattice \(H^n(X, \mathbb{Z})_{\text{pr}}\) is even. □

\(^4\) Note that in [17] the sign of the intersection form is changed for \(n \equiv 3 \ (4)\), so that in this case as well \(s_\delta(\alpha) = \alpha + (\alpha.\delta)\delta\).
Note that the fact that $H^n(X,Z)_{pr}$ is generated by the vanishing classes $\delta_i$ in particular shows that $b_n(X)_{pr} \leq \deg D(d,n)$, which is confirmed by a quick comparison of Corollary 1.8 with Theorem 2.2.

For even $n$ the Weyl group

$$W \subset O(H^n(X,Z)_{pr})$$

is by definition the subgroup generated by the reflections $s_{\delta_i}$. For $n$ odd the Weyl group $W \subset Sp(H^n(X,Z))$ is defined analogously. It turns out, that in both cases it acts transitively on the set of vanishing classes $\Delta \subset \{\delta_i\}$, cf. [128, Prop. 7.5] or [174, Prop. 15.23].

A lattice $\Lambda$ (symmetric or alternating) with a class of vectors $\Delta \subset \Lambda$ generating $\Lambda$ and with the associated Weyl group acting transitively on $\Delta$ is called a vanishing lattice, see [67, 111]. By our discussion so far we have

$$\Gamma(d,n) = \text{Im}(\rho) = \text{Im}(\rho_{pr}) = W.$$ 

The proof of Theorem 2.9 for even $n > 2$ is in [17] reduced to a purely lattice theoretic result in [67] describing the Weyl group of a complete vanishing lattice as this particular subgroup of the orthogonal group of the lattice. The lattice $H^n(X,Z)_{pr}$ is complete, which means that $\Delta$ contains a certain configuration of six vanishing classes. The fact that for $n > 2$, in accordance with Proposition 1.14, the lattice contains $A_2 \oplus U^2$ is part of the picture. The case of cubic surfaces is well known classically and is usually stated as

$$\Gamma(3,2) \cong W(E_6).$$

This is the only case of cubic hypersurfaces in which the monodromy group is actually finite. Indeed, it is an index two subgroup of the finite orthogonal group $O(H^2(X,Z)_{pr})$ of the definite lattice $H^2(X,Z)_{pr}$. We shall come back to it in Section 4.1.3. For $n$ odd the result is deduced from [111].

**Exercise 2.15.** Consider the case $n = 0$ for which the universal smooth hypersurface $X \longrightarrow \mathbb{P}^3 \setminus S$, defined over the complement of a quartic surface $S$ with the explicit equation given in Example 2.5, is an étale cover of degree three. Show that the monodromy group $\Gamma(0,3)$ is in fact $A_3$. It equals the Galois group of the field extension $K(\mathbb{P}^3) \subset K(X)$. See [87] for further information.

**2.6** As any monodromy transformation is induced by a diffeomorphism, the monodromy group $\Gamma_n$ is a subgroup of the image of the natural representation

$$\tau: \text{Diff}^+(X) \longrightarrow O(H^n(X,Z))$$

of the group of orientation preserving diffeomorphisms. It turns out that $\text{Im}(\tau)$ is slightly larger than $\Gamma_n$. Details have been worked out in [17]. Here are the main steps.
Let us first consider the case that $n$ is even and $n > 2$. Clearly, $\text{Diff}^+(X)$ also acts on $H^2(X, \mathbb{Z}) = \mathbb{Z} \cdot h$ and, therefore, sends $h$ to $h$ or to $-h$, where the latter is realized by complex conjugation defined on any $Y$ defined by an equation with coefficients in $\mathbb{R}$. As a consequence, $\text{Diff}^+(X)$ respects the direct sum decomposition $H^n(X, \mathbb{Q}) = H^n(X, \mathbb{Q})_{\text{pr}} \oplus \mathbb{Q} \cdot h^{n/2}$. This eventually leads to

$$\text{Im}(\tau) \cong \begin{cases} \hat{O}(H^n(X, \mathbb{Z})) & \text{if } n \equiv 0 \mod{4} \\ \text{O}(H^n(X, \mathbb{Z})_{\text{pr}}) & \text{if } n \equiv 2 \mod{4}. \end{cases}$$

To prove this note that $\hat{O}(H^n(X, \mathbb{Z})) \subset \text{Im}(\tau)$ and that for $n \equiv 2 \mod{4}$ complex conjugation induces an element in $\text{Im}(\tau)$ the restriction of which to $H^n(X, \mathbb{Z})_{\text{pr}}$ acts non-trivially on the discriminant $A_{\text{pr}} \cong A_{\text{pr}: 2} \cong \mathbb{Z}/3\mathbb{Z}$. Hence, it is enough to find an orientation preserving diffeomorphism $g$ which acts with spinor norm $s_n(\tau(g)) = -1$ on $H^n(X, \mathbb{Z})$ and fixes $h^{n/2}$. For this, one uses the connected sum decomposition of $X$ as $M' \# (S^n \times S^n)$, cf. Remark 1.15, and the diffeomorphism $g$ obtained by gluing the identity on $M'$ with the product $\iota \times \iota$ of the diffeomorphism $\iota: S^n \to S^n, (x_1, \ldots, x_{n+1}) \mapsto (x_1, \ldots, x_n, -x_{n+1})$. It acts on the induced orthogonal decomposition $H^n(X, \mathbb{Z}) = H^n(M', \mathbb{Z}) \oplus H^n(S^n \times S^n, \mathbb{Z})$, for which we may assume that $h^{n/2} \in H^n(M', \mathbb{Z})$, by $-\text{id}$ on $H^n(S^n \times S^n, \mathbb{Z}) \cong U$ and by $\text{id}$ on $U^\perp = H^n(M', \mathbb{Z})$. Write $-\text{id} = s_{e,f} \circ s_{e,e}$, with $e, f \in U$ the standard basis, to see that indeed $s_n(\tau(g)) = -1$ and $\tau(g)(h^{n/2}) = h^{n/2}$.

For cubic surfaces, there is no reason for a diffeomorphism to respect the hyperplane class (up to sign) and indeed $\text{Im}(\tau) = \text{O}(H^2(X, \mathbb{Z}))$, cf. [178] and Section 4.1.3.

For $n$ odd the result reads

$$\text{Im}(\tau) \cong \begin{cases} \text{Sp}(H^n(X, \mathbb{Z}), q) & \text{if } n \neq 1, 3, 7 \\ \text{Sp}(H^n(X, \mathbb{Z})) & \text{if } n = 1, 3, 7. \end{cases}$$

Indeed, the description of $q((S^n)^\perp)$ for $n \neq 1, 3, 7$ in terms of the topological normal bundle of $S^n \subset X$ is invariant under diffeomorphisms. In the other cases one proves that $s_d$ is realized by a diffeomorphism for any primitive $\delta \in H^n(X, \mathbb{Z})$. As those generate the symplectic group, this is enough to prove the claim for $n = 1, 3, 7$. Concretely, for a given $\delta$, there exist $\delta'$ with $(\delta, \delta') = 1$ and a decomposition $X \cong M' \# (S^n \times S^n)$ with $H^n(S^n \times S^n, \mathbb{Z})$ spanned by $\delta, \delta'$. In [17] it is then observed that the reflection $s_d$ is realized by gluing the identity on $M'$ with the diffeomorphism $(x, y) \mapsto (x, x \cdot y)$, where $x \cdot y$ is the multiplication in $C, \mathbb{H}$, or $\mathcal{O}$ for the three cases $n = 1, 3, 7$.

\footnote{In [17] the result for $n \equiv 2 \mod{4}$ is stated as $\text{Im}(\tau) = \hat{O}(H^n(X, \mathbb{Z})) \times \{ \pm 1 \}$. Indeed, complex conjugation defines an element of order two in $\text{Im}(\tau)$ that acts non-trivially on the discriminant of $H^n(X, \mathbb{Z})_{\text{pr}}$. Moreover, it commutes with the index two subgroup $G_{\delta} = \hat{O}(H^n(X, \mathbb{Z}))$, as the universal family is defined over $\mathbb{R}$, and hence monodromy commutes with complex conjugation. However, that complex conjugation also commutes with the additional diffeomorphism $g$ seems to need an additional argument.}
3 Automorphisms and deformations

Smooth hypersurfaces behave nicely in many respects. For example, for most of them the deformation theory is easy to understand, not showing any of the pathological features to be reckoned with for arbitrary smooth projective varieties. Similarly, their group of automorphisms are usually finite and generically even trivial. We will assume $d \geq 3$ throughout this section. The only slightly exotic cases that need special care are $(n,d) = (1,3)$ and $(n,d) = (2,4)$, i.e. plane cubic (elliptic) curves and quartic K3 surfaces.

3.1 First order information about the group of automorphisms of a smooth hypersurface $X \subset \mathbb{P}^{n+1}$ and about its deformations are encoded by the cohomology groups $H^0(X,T_X)$ and $H^1(X,T_X)$, respectively. Those can be computed in terms of the standard exact sequences. We begin, however, with the following well-known fact.

**Lemma 3.1.** Assume $\text{char}(k) \nmid d$. Then the hypersurface $X \subset \mathbb{P}^{n+1}$ defined by $F \in k[x_0,\ldots,x_{n+1}]_d$ is smooth if and only if the partial derivatives $\partial F$ form a regular sequence in $k[x_0,\ldots,x_{n+1}]$.

**Proof** A standard result in commutative algebra shows that a sequence $a_i \in A$, $i = 1,\ldots,\dim(A)$, in a regular local ring $A$ is regular if and only if $\text{ht}((a_i)) = \dim(A)$, cf. [134] Thm. 16.B]. Hence, $(\partial F)$ is a regular sequence if and only if the affine intersection $V((\partial F)) = \bigcap V(\partial_i F) \subset A^{n+2}$ is zero-dimensional. However, as the polynomials $\partial_i F$ are homogeneous, $V((\partial_i F))$ is $\mathbb{G}_m$-invariant. Hence, $(\partial F)$ is a regular sequence if and only if the projective intersection $V((\partial_i F)) \subset \mathbb{P}^{n+1}$ is empty. This implies that also $X \cap V((\partial_i F))$ is empty and, by the Jacobian criterion, that $X$ is smooth.

Conversely, if $X$ is smooth and $\text{char}(k) \nmid d$, the Euler equation $d \cdot F = \sum_{i=0}^{n+1} x_i \partial_i F$. shows that $V((\partial_i F)) = X_{\text{sing}} = \emptyset$, i.e. $(\partial_i F)$ is a regular sequence. \hfill $\square$

**Example 3.2.** The assumption on the characteristic is needed, as shown by the example $F = x_0^3 x_1 - x_0 x_1^2$ with $\text{char}(k) = 3$. Indeed, in this case $X = [0,\infty,[1:1]]$ is smooth, but $\partial_0 F = -x_1 (x_0 + x_1)$ and $\partial_1 F = x_0 (x_0 + x_1)$ have a common zero in $[1:-1]$.

**Corollary 3.3.** Let $X \subset \mathbb{P} = \mathbb{P}^{n+1}$ be a smooth hypersurface of degree $d$.

(i) If $n \geq 0$ and $d \geq 3$ but $(n,d) \neq (1,3)$, then $H^0(X,T_X) = 0$.
(ii) If $n > 2$ or $d \leq 3$, then $H^1(X,T_X) = 0$ and the normal bundle sequence induces a surjection

$$H^0(X,\mathcal{O}_X(d)) \longrightarrow H^1(X,T_X).$$

**Proof** We shall give a proof under the additional assumption that $\text{char}(k) \nmid d$ and refer to [172] Sec. 11.7] for the general case.
Combining the Euler sequence \(0 \rightarrow \mathcal{O}_P \rightarrow \mathcal{O}_P(1)\)\(^{\text{gen}}\) \(-2\) \(\rightarrow \mathcal{T}_P \longrightarrow 0\) and the normal bundle sequence \(0 \rightarrow \mathcal{T}_X \rightarrow 
abla_{\mathcal{T}_X} \mathcal{O}_X(d) \longrightarrow 0\), we obtain a diagram:

\[
\begin{array}{c}
\mathcal{H}^0(T_{\mathcal{P}|X}) \rightarrow \mathcal{H}^0(\mathcal{O}_X(d)) \rightarrow \mathcal{H}^1(T_X) \rightarrow \mathcal{H}^1(T_{\mathcal{P}|X}) \rightarrow 0 \quad (3.1)
\end{array}
\]

Here, as before, \(\partial_i F \in \mathcal{H}^0(P, \mathcal{O}_P(d - 1))\) are the \(n + 2\) partial derivatives of the homogeneous polynomial \(F \in \mathcal{H}^0(P, \mathcal{O}_P(d))\) defining \(X\). The quotient of the vertical map is contained in \(\mathcal{H}^1(\mathcal{O}_X)\), which is trivial for \(n \neq 1\).

Now, for the first assertion, observe that \(\mathcal{H}^0(X, T_X) = 0\) if and only if the kernel of the composition

\[(\partial_i F): \mathcal{H}^0(X, \mathcal{O}_X(1))^{\text{gen}} \rightarrow \mathcal{H}^0(X, \mathcal{O}_X(d))
\]

is spanned by \((x_0, \ldots, x_{n+1})\). Assume \(\sum h_i \partial_i F\) vanishes on \(X\) for some \(h_i \in \mathcal{H}^0(P, \mathcal{O}_P(1))\). Then, after rescaling, \(\sum h_i \partial_i F = d \cdot F = \sum x_i \partial_i F\) and, therefore, \(\sum (h_i - x_i) \partial_i F = 0\). Using that \((\partial_i F)\) is a regular sequence, see Lemma [3.7] and \(d \geq 3\), this yields \(h_i = x_i\).

The remaining case \(n = 1, d > 3\) follows from the fact that \(\mathcal{H}^0(C, \omega_C) = 0\) for a smooth curve of genus \(g(C) > 1\).

For the second assertion observe that \(\mathcal{H}^1(X, T_{\mathcal{P}|X}) = 0\), whenever \(\mathcal{H}^1(X, \mathcal{O}_X(1)) = 0 = \mathcal{H}^2(X, \mathcal{O}_X)\), which holds as soon as \(n > 2\), see Corollary [1.4] We leave it to the reader to complete the argument in the cases \(n = 1, 2\) and \(d = 1, 2, 3\).

\[\square\]

3.2 Let \(X\) be a smooth projective variety and assume \(\mathcal{O}_X(1)\) is an ample line bundle. We are interested in the two groups:

\[\text{Aut}(X, \mathcal{O}_X(1)) \subset \text{Aut}(X)\]

Here, \(\text{Aut}(X)\) is the group of all automorphisms \(g: X \rightarrow X\) over \(k\). The subgroup \(\text{Aut}(X, \mathcal{O}_X(1))\) is the group of all such automorphisms with the additional property that \(g^* \mathcal{O}_X(1) = \mathcal{O}_X(1)\). These groups are in fact the groups of \(k\)-rational points of group schemes over \(k\), which we shall also denote by \(\text{Aut}(X, \mathcal{O}_X(1))\) and \(\text{Aut}(X)\).

\textbf{Remark 3.4.} Standard Hilbert scheme theory \([21]\) ensures that \(\text{Aut}(X, \mathcal{O}_X(1))\) is a quasi-projective variety and that \(\text{Aut}(X)\) is at least locally of finite type. Indeed, there exists an open embedding

\[\text{Aut}(X) \hookrightarrow \text{Hilb}(X \times X), \quad g \mapsto \Gamma_g\]

mapping an automorphism to its graph. The Hilbert scheme \(\text{Hilb}(X \times X)\) of \(X \times X\) is locally of finite type and in fact the disjoint union \([1]\) \(\text{Hilb}(X \times X), \quad P \in \mathbb{Q}[T]\), of projective varieties \(\text{Hilb}(X \times X)\) parametrizing subschemes \(Z \subset X \times X\) with Hilbert polynomial \(\chi(Z, (\mathcal{O}_X(m) \boxtimes \mathcal{O}_X(m))|_Z) = P(m)\), see \([71]\).
The Hilbert polynomial of the graph \( \Gamma_S \) of an arbitrary isomorphism is \( \chi(X, \mathcal{O}_X(m) \otimes g^* \mathcal{O}_X(m)) \). Thus, for \( P(m) := \chi(X, \mathcal{O}_X(2m)) \) one has a locally closed embedding

\[
\text{Aut}(X, \mathcal{O}_X(1)) \subseteq \text{Hilb}^p(X \times X).
\]

Note that it may fail to be open in general, as \( \chi(X, \mathcal{O}_X(m) \otimes g^* \mathcal{O}_X(m)) = \chi(X, \mathcal{O}_X(2m)) \) may not necessarily imply that \( g^* \mathcal{O}_X(1) \cong \mathcal{O}_X(1) \).

**Proposition 3.5.** The Zariski tangent spaces of \( \text{Aut}(X) \) and \( \text{Aut}(X, \mathcal{O}_X(1)) \) at the identity are given by

\[
T_{\text{id}}\text{Aut}(X, \mathcal{O}_X(1)) \subset T_{\text{id}}\text{Aut}(X) \cong H^0(X, \mathcal{T}_X).
\]

The inclusion is an equality if \( H^1(X, \mathcal{O}_X) = 0 \).

**Proof.** This follows from the description of the tangent space of the Hilbert scheme of closed subschemes of \( Y \) at the point \([Z] \in \text{Hilb}(Y)\) corresponding to \( Z \subset Y \) as

\[
T_{[Z]}\text{Hilb}(Y) \cong \text{Hom}(\mathcal{I}_Z, \mathcal{O}_Z),
\]

cf. [71] Thm. 6.4.9. For \( Z := \Gamma_{\text{id}} \subset Y := X \times X \) this becomes

\[
T_{\text{id}}\text{Aut}(X) \cong \text{Hom}(\mathcal{I}_{\Delta}, \mathcal{O}_{\Delta}) \cong H^0(\Delta, \mathcal{N}_{\Delta/X \times X}) \cong H^0(X, \mathcal{T}_X).
\]

As for our purposes the inclusion in (3.2) is all we need, we leave the second assertion to the reader. Hint: Use \( H^1(X, \mathcal{O}_X) \cong T_{[\mathcal{O}_X]}\text{Pic}(X) \). In fact, \( T_{\text{id}}\text{Aut}(X, \mathcal{O}_X(1)) \) is the kernel of the map \( H^0(X, \mathcal{T}_X) \twoheadrightarrow H^1(X, \mathcal{O}_X) \) induced by the contraction with the first Chern class \( c_1(L) \).

For a smooth hypersurface of dimension \( n \geq 2 \) and degree \( d \geq 3 \) the result immediately yields

\[
T_{\text{id}}\text{Aut}(X, \mathcal{O}_X(1)) = T_{\text{id}}\text{Aut}(X) \cong H^0(X, \mathcal{T}_X) = 0,
\]

which allows one to prove the following general finiteness result. The original proof in [135] is different. It avoids cohomological methods and relies on techniques from commutative algebra. See [146] Rem. 6 for historical remarks.

**Corollary 3.6.** Let \( X \subset \mathbb{P}^{n+1} \) be a smooth hypersurface of dimension \( n \geq 0 \) and degree \( d \geq 3 \), but \( (n, d) \neq (1, 3) \). Then \( \text{Aut}(X, \mathcal{O}_X(1)) \) is finite and \( \text{Aut}(X) \) is discrete. In fact, if \( (n, d) \neq (1, 3), (2, 4) \), then \( \text{Aut}(X, \mathcal{O}_X(1)) = \text{Aut}(X) \), and then both groups are finite.

**Proof.** As \( \text{Aut}(X) \) and \( \text{Aut}(X, \mathcal{O}_X(1)) \) are group schemes, all tangent spaces are isomorphic and in our case trivial by Corollary 3.3. Hence, \( \text{Aut}(X) \), which is locally of finite type, is a countable set of reduced isolated points. As \( \text{Aut}(X, \mathcal{O}_X(1)) \) is quasi-projective, it must be a finite set of reduced isolated points.

The equality \( \text{Aut}(X, \mathcal{O}_X(1)) = \text{Aut}(X) \) for \( n > 2 \) follows from Corollary 1.6. For \( n = 2 \)
Chapter 1. Basic facts

and \( d \neq 4 \), use that \( \omega_X \cong \mathcal{O}(d - (n + 2)) \) is preserved by all automorphisms and that Pic(X) is torsion free, see Remark 1.2.

\[ \square \]

**Remark 3.7.** (i) For \( n = 1 \) and \( d = 3 \) the result really fails, but not too badly. For a smooth plane cubic \( E \subset \mathbb{P}^2 \) and char(k) \( \neq 3 \), one has:

\[ 0 = \text{Id} \text{Aut}(E, \mathcal{O}_E(1)) \subset \text{Id} \text{Aut}(E) \cong H^0(E, \mathcal{T}_E) \cong H^0(E, \mathcal{O}_E) \cong k, \]

see [112, Sec. 11.7.5]. So, even in this case, Aut(E, \mathcal{O}_E(1)) is in fact finite, but Aut(E) certainly is not.

(ii) The finiteness of Aut(X) also fails for \( n = 2 \) and \( d = 4 \) in general. Indeed, there exist quartic K3 surfaces with infinite automorphism groups, see [103] for examples and references.

The groups of automorphisms of the universal smooth hypersurface \( X \rightarrow U = |\mathcal{O}(d)|_{\text{sm}} \) sit in a relative quasi-projective family

\[ \text{Aut} : \text{Aut}(X/U, \mathcal{O}_X(1)) \rightarrow U = |\mathcal{O}(d)|_{\text{sm}}. \] (3.3)

More precisely, there exist functorial bijections between Mor_U(T, \text{Aut}) and the set of automorphisms \( g : X_T \rightarrow X_T \) over \( T \) with \( g^* \mathcal{O}_X(1) = \mathcal{O}_X(1) \) modulo Pic(T). As in the absolute case, mapping \( g \) to its graph, yields a locally closed embedding \( \text{Aut} \subset \text{Hilb}(X \times_U X/U) \) into the relative Hilbert scheme.

According to Corollary 3.6, the fibres of \( \text{Aut} \rightarrow U \), i.e. the groups \( \text{Aut}(X, \mathcal{O}_X(1)) \), are finite and, therefore, Aut \rightarrow U is a quasi-finite morphism. In fact, it turns out to be finite, cf. Remark 2.17. This is a consequence of the GIT-stability of hypersurfaces. Note that the general result of [136] proving properness for families of non-ruled varieties is not applicable to cubic hypersurfaces of dimension at least two.

3.3 The first order description of the deformation behavior of a smooth projective variety \( X \) is similar. Firstly, there is a natural bijection between \( H^1(X, \mathcal{T}_X) \) and the set of flat morphisms \( X \rightarrow \text{Spec}(k[\varepsilon]) \) with closed fibre \( X_0 = X \), cf. [90] II. Ex. 9.13.2]. This can be extended to the following picture, cf. [71] Ch. 6]: If \( H^1(X, \mathcal{T}_X) = 0 \), then the functor

\[ F_X : (\text{Art}/k) \rightarrow (\text{Set}), \]

mapping a local Artinian \( k \)-algebra \( A \) to the set of flat morphisms \( X \rightarrow \text{Spec}(A) \) with the choice of an isomorphism \( X_0 \cong X \) for the closed fibre \( X_0 \) has a pro-representable hull, see [71] Def. 6.3.1]. This means that there exist a complete local \( k \)-algebra \( R \) and a ‘versal’ flat family \( X \rightarrow \text{Spf}(R) \), \( X_0 = X \), for which the induced transformation

\[ h_R = \text{Mor}_{\text{alg}}(R, \text{Set}) \rightarrow F_X \] (3.4)

is bijective for \( A = k[\varepsilon] \). We shall write Def(X) : \( \text{Spf}(R) \) with the closed point \( 0 \in \text{Def}(X) \) and the Zariski tangent space \( T_0\text{Def}(X) \cong H^1(X, \mathcal{T}_X) \).
3 Automorphisms and deformations

Similarly, one may consider the polarized version

\[ F_{X, \mathcal{O}_X(1)} : (\text{Art}/k) \longrightarrow (\text{Set}) \]

mapping \( A \) to the set of flat polarized families \( (\mathcal{X}, \mathcal{O}_\mathcal{X}(1)) \longrightarrow \text{Spec}(A) \) with closed fibre \( (\mathcal{X}, \mathcal{O}_\mathcal{X}(1)) \approx (X, \mathcal{O}_X(1)) \). Again, the functor \( F_{X, \mathcal{O}_X(1)} \) has a pro-representable hull \( R' \) with a ‘versal’ flat family \( (\mathcal{X}, \mathcal{O}_\mathcal{X}(1)) \longrightarrow \text{Def}(X, \mathcal{O}_X(1)) := \text{Spf}(R') \).

Only if \( \text{Aut}(X) \) is trivial, one can expect a universal family to exist, i.e. \([3.4]\) to be an isomorphism. Then \( F_X \) is said to be pro-representable (and similarly for \( F_{X, \mathcal{O}_X(1)} \)). This is the difference between a universal and a versal family.

The natural forgetful transformation \( F_{X, \mathcal{O}_X(1)} \longrightarrow F_X \) yields a morphism

\[ \text{Def}(X, \mathcal{O}_X(1)) \longrightarrow \text{Def}(X), \quad (3.5) \]

which in general is neither injective nor surjective. The first Chern class \( c_1(\mathcal{O}_X(1)) \in H^1(X, \mathcal{O}_X) \approx \text{Ext}^1(T_X, \mathcal{O}_X) \) interpreted as an extension class defines an exact sequence \( 0 \longrightarrow \mathcal{O}_X \longrightarrow D(\mathcal{O}_X(1)) \longrightarrow T_X \longrightarrow 0 \). Here, the sheaf \( D(\mathcal{O}_X(1)) \) can be thought of as the sheaf of differential operators of \( \mathcal{O}_X(1) \) of order \( \leq 1 \).

Then \( T_0\text{Def}(X, \mathcal{O}_X(1)) \approx H^1(X, D(\mathcal{O}_X(1))) \) and the tangent map of \((3.5)\) is part of a long exact sequence (see \([158]\) Sec. 3.3) for more details):

\[
\cdots \longrightarrow H^1(X, \mathcal{O}_X) \longrightarrow H^1(X, D(\mathcal{O}_X(1))) \longrightarrow H^1(X, T_X) \longrightarrow H^2(X, \mathcal{O}_X) \longrightarrow \cdots .
\]

\[ \approx T_0\text{Def}(X, \mathcal{O}_X(1)) \quad \approx T_0\text{Def}(X) \]

In fact, for most hypersurfaces the outer terms are trivial.

**Remark 3.8.** Over \( \mathbb{C} \), the formal spaces \( \text{Def}(X) \) and \( \text{Def}(X, \mathcal{O}_X(1)) \) can alternatively be thought of as germs of complex spaces. Standard deformation theory ensures that the universal families \( \mathcal{X} \longrightarrow \text{Def}(X) \) and \( (\mathcal{X}, \mathcal{O}_\mathcal{X}(1)) \longrightarrow \text{Def}(X, \mathcal{O}_X(1)) \) can in fact be extended from families over formal bases to families over some small complex spaces. While this remains true in the algebraic setting for \( (\mathcal{X}, \mathcal{O}_\mathcal{X}(1)) \longrightarrow \text{Def}(X, \mathcal{O}_X(1)) \), cf. \([21]\) Thm. 8.4.10, it fails for the unpolarized situation.

The universal family of smooth hypersurfaces \( \mathcal{X} \longrightarrow U = \{|\mathcal{O}_d|\}_\text{lim} \) induces a morphism \( (U, 0) \longrightarrow \text{Def}(X, \mathcal{O}_X(1)) \) of the formal neighbourhood of \( 0 : = [X] \in U \). We think of \(|\mathcal{O}_d|\) as a component of the Hilbert scheme \( \text{Hilb}(\mathbb{P}^{n+1}) \) and of \( \mathcal{O}_X(1) \) as the normal bundle \( \mathcal{N}_{X/\mathbb{P}^{n+1}} \). Then \( T_0U \approx H^0(X, \mathcal{O}_X(d)) \) and the tangent map of the composition \( (U, 0) \longrightarrow \text{Def}(X, \mathcal{O}_X(1)) \longrightarrow \text{Def}(X) \) is the boundary map of the normal bundle sequence \( H^0(X, \mathcal{O}_X(d)) \longrightarrow H^1(X, T_X) \). Conversely, for an arbitrary deformation \( (\mathcal{X}, \mathcal{O}_\mathcal{X}(1)) \longrightarrow \text{Spec}(A) \) of \( X \) over a local ring \( A \) there exists a relative embedding \( \mathcal{X} \subseteq \mathbb{P}_A^{n+1} \) extending the given one \( X \subset \mathbb{P}^{n+1} \). Here one uses that \( H^1(X, \mathcal{O}_X(1)) = 0 \), which ensures that all sections of \( \mathcal{O}_X(1) \) on \( X \) extend to sections of \( \mathcal{O}_X(1) \), see \([158]\) Sec. 3.3.
Proposition 3.9. Let $X \subset \mathbb{P}^{n+1}$ be a smooth hypersurface of degree $d$. Assume $n > 2$ or $n = 2$, $d \leq 3$. Then the natural map

$$H^0(X, \mathcal{O}_X(d)) \cong T_0[\mathcal{O}_P(d)] \xrightarrow{T_0\text{Def}(X, \mathcal{O}_X(1))} T_0\text{Def}(X) \cong H^1(X, T_X)$$

is surjective. Furthermore, the forgetful morphism (3.5) is an isomorphism

$$\text{Def}(X, \mathcal{O}_X(1)) \cong \text{Def}(X).$$

Proof. Most of the proposition is an immediate consequence of the preceding discussion and the vanishings $H^1(X, \mathcal{O}_X) = H^2(X, \mathcal{O}_X) = 0$. In order to see that the isomorphism $T_0\text{Def}(X, \mathcal{O}_X(1)) \cong T_0\text{Def}(X)$ between the tangent spaces is induced by an isomorphism $\text{Def}(X, \mathcal{O}_X(1)) \cong \text{Def}(X)$ it suffices to observe that both spaces are smooth and so isomorphic to $\text{Spf}(k[[z_1, \ldots, z_m]])$ with $m = \dim T_0$. This could either be deduced from the vanishing $H^2(X, D(\mathcal{O}_X(1))) = H^2(X, T_X) = 0$ for $n > 3$ [138, Thm. 3.3.11] or, simply, from the fact that $[\mathcal{O}_P(d)]$ is smooth. □

Remark 3.10. The kernel of $H^0(X, \mathcal{O}_X(d)) \longtwoheadrightarrow H^1(X, T_X)$ is a quotient of $H^0(X, T_P|_X)$ (and in fact equals it for $n \geq 2$). The latter should be thought of as the tangent space of the orbit through $[X] \in [\mathcal{O}_P(d)]$ of the natural $\text{GL}(n+2)$-action on $[\mathcal{O}_P(d)]$, see Section 2.1.3.

It may be worth pointing out the following consequence, which we will only state for cubic hypersurfaces.

Corollary 3.11. Any local deformation of a smooth cubic hypersurface $X \subset \mathbb{P}^{n+1}$ as a variety over $k$ is again a cubic hypersurface. □

For $n = 2$, so for cubic surfaces, it is easy to construct smooth projective global deformations that are not cubic surfaces any longer. However, for $n > 2$ the fact that $\rho(X) = 1$ allows one to prove that global smooth projective deformations of cubic hypersurfaces are again cubic hypersurfaces, cf. [109, Thm. 3.2.5]. The situation is more complicated when one is interested in non-projective or, equivalently, non-Kählerian global deformations.

3.4 In [135] it has also been observed that in fact for generic hypersurfaces the automorphism group is trivial. Generalizations for complete intersections have been proved more recently in [23, 40].

Theorem 3.12. Assume $n > 0$, $d \geq 3$, and $(n, d) \neq (1, 3)$. Then there exists a dense open subset $V \subset [\mathcal{O}_P(d)]_{\text{sm}}$ such that for all geometric points $[X] \in V$ one has

$$\text{Aut}(X) = \text{Aut}(X, \mathcal{O}_X(1)) = [\text{id}].$$

6 Thanks to J. Ottem for the reference. Compare this to the well-known fact that $\text{Def}(\mathbb{P}^1 \times \mathbb{P}^1)$ is a reduced point but yet $\mathbb{P}^1 \times \mathbb{P}^1$ can be deformed to any other Hirzebruch surface $\mathbb{P}_n = \mathbb{P}(\mathcal{O} \oplus \mathcal{O}(n))$ with $n$ even.
There are three proofs in the literature. The original due to Matsumura and Monsky [135] and two more recent ones by Poonen [151] and Chen, Pan, and Zhang [40]. In fact, Aut(X, O_X(1)) = {id} also holds for (n, d) = (1, 3) as long as char(k) ≠ 3. For simplicity we shall assume that (n, d) ≠ (1, 3), (2, 4) and so Aut(X) = Aut(X, O_X(1)), see Corollary 3.6.

In [151] the result is proved by writing down an explicit equation of one smooth hypersurface without any non-trivial polarized automorphisms. We will follow [40] adapting the arguments to our situation. We shall begin with the following result which is of independent interest.

**Proposition 3.13.** Assume X ⊂ P^{n+1} is a smooth hypersurface of degree d over a field of characteristic zero with n > 0, d ≥ 3, and (n, d) ≠ (1, 3). Then Aut(X) acts faithfully on H^1(X, T_X).

**Proof.** We may assume that k algebraically closed. Suppose g ∈ Aut(X) acts trivially on H^1(X, T_X). As an element g ∈ Aut(X) ⊂ PGL(n + 2) it can be lifted to an element in SL(n + 2) which we shall also call g. It is still of finite order and, after a linear coordinate change, can be assumed to act by g(x_i) = λ_i x_i for some roots of unities λ_i. This is where one needs char(k) = 0.

Let F ∈ H^0(ℙ^2, O_{ℙ^2}(d)) be a homogeneous polynomial defining X. As g(X) = X, the induced action of g on H^0(ℙ^2, O_{ℙ^2}(d)) satisfies g(F) = μ F for some root of unity μ. Moreover, changing g by μ^{-1/d} we may assume that μ = 1 (but possibly g is now only a finite order element in GL(n + 2)). For greater clarity, we rewrite (3.1) as the short exact sequence

\[ 0 \to H^0(X, O_X(d)) \to H^0(X, O_X(d)) \to H^1(X, T_X) \to 0, \]

with V = \langle x_0, \ldots, x_{n+1} \rangle and using H^0(X, T_X) = 0 = H^1(X, T_X|X) observed earlier. All maps are compatible with the action of g and, in fact, the isomorphism is GL-equivariant. Note that H^0(X, O_X(d)) is endowed with the action of g by interpreting O_X(d) as the normal bundle N_X/ℙ. The induced action is compatible with the natural one on H^0(ℙ^2, O(d)) under the isomorphism H^0(X, O_X(d)) ≅ H^0(ℙ^2, O(d))/k · F.

As g has finite order, any class v ∈ H^1(X, T_X) fixed by g can be lifted to a g-invariant section (1/|g|) \sum g^s v ∈ H^0(X, O_X(d)), where v is an arbitrary pre-image of v. Thus, in order to arrive at a contradiction, it suffices to show that the g-invariant part H^0(X, O_X(d))^g cannot map onto H^1(X, T_X). So it is enough to show that its dimension h^0(O_X(d))^g sat-

---

7 There is a technical subtlety for (n, d) = (2, 4) in positive characteristic which needs to be checked. The question is whether for the generic quartic K3 surface all automorphisms are polarized. This is clear in vanishing characteristic using transcendental techniques. In [135] the case is excluded but I believe that now one should be able to settle this one way or the other.

8 Thanks to O. Benoist for the reference.
Chapter 1. Basic facts

isfies

\[ h^{0}(O_{X}(d))^{\mathbb{F}} < h^{1}(X, T_{X}) + \dim(W^{\mathbb{F}}). \]

As \( h^{1}(X, T_{X}) = h^{0}(O_{X}(d)) - \dim(W) \), this reduces the task to proving

\[ \dim(W) - \dim(W^{\mathbb{F}}) < h^{0}(O_{X}(d)) - h^{0}(O_{X}(d))^{\mathbb{F}}. \] (3.6)

Note that the left hand side of (3.6) equals \( \dim(V \otimes V^{*}) - \dim(V \otimes V^{*})^{\mathbb{F}} \) and, as \( g(F) = F \), the right hand side is nothing but \( h^{0}(\mathbb{F}, O(d)) - h^{0}(\mathbb{F}, O(d))^{\mathbb{F}} \). The weak inequality in (3.6) follows from the obvious equality \( W^{\mathbb{F}} = W \cap H^{0}(X, O_{X}(d))^{\mathbb{F}} \).

The strict equality follows from purely combinatorial considerations for which we refer to [40]. The idea is to write \( V = \bigoplus V_{\lambda} \) with \( V_{\lambda} := \langle x_{1} \mid - x_{2} = \lambda \rangle \). Then, the left hand side is \( \dim(W) - \dim(W^{\mathbb{F}}) = (n+2)^{2} - \sum \dim(V_{\lambda})^{2} \). To compute the right hand side, one decomposes \( S^{n}(V) = S^{d} \bigoplus V_{\lambda} \) and shows that for \( d \geq 3 \) the dimension of the non-invariant part on the left exceeds the one on the right\(^9\). \( \square \)

**Exercise 3.14.** In order to gain a concrete understanding of the combinatorial part of the proof, consider the situation \( V = V_{1} \oplus V_{2}, A_{1} \neq A_{2} \) and \( d = 3 \). Then \( S^{3}V = S^{3}V_{1} \oplus (S^{2}V_{1} \otimes V_{2}) \oplus (V_{1} \otimes S^{2}V_{2}) \oplus S^{3}V_{2} \), and \( \dim(S^{3}V)^{\mathbb{F}} \) is maximal when \( \lambda_{1}^{3} = \lambda_{2}^{3} = 1 \). Show that in this case (3.6) holds, i.e. \((\binom{n_{i}+2}{n_{i-1}} + (n_{i}+2)^{2} < \binom{n+4}{n+1} + n_{1}^{2} + n_{2}^{2}\), where \( n_{i} = \dim V_{i} \) and \( n_{1} + n_{2} = n + 2 > 2 \).

**Corollary 3.15.** The group \( \text{Aut}(X) \) of a smooth hypersurface over \( \mathbb{C} \) of dimension \( n > 0 \) and degree \( d \geq 3 \) with \( n, d \neq (1, 3) \) acts faithfully on the middle cohomology \( H^{n}(X, \mathbb{Z}) \).

**Proof** The assertion follows from the proposition by using that the contraction map \( H^{1}(X, T_{X}) \rightarrow \text{End}(H^{n}(X, \mathbb{C})) \) is equivariant and injective, cf. Corollary 4.23. \( \square \)

For \( (n, d) = (1, 3) \), so elliptic curves, the subgroup \( \text{Aut}(X, O_{X}(1)) \) still acts faithfully on \( H^{1}(X, \mathbb{Z}) \).

**Proof of Theorem 3.12** As \( H^{0}(X, T_{X}) = 0 \), the morphism \( \text{Aut} \rightarrow U \) in (3.3) is unramified. After passing to a dense open subset \( V \subset U \), we may assume it is in fact étale. Fix \( [X] \in V \) and assume there exists \( \text{id} \neq g \in \text{Aut}(X) \). After base change to an open neighbourhood of \( [g] \in \text{Aut} \), considered as an étale open neighbourhood of \( [X] \in V \), we may assume that there exists a relative automorphism \( g : X \rightarrow X \), so \( \pi \circ g = g \), with \( g|_{X} = g \). The base change is suppressed in the notation.

The relative tangent sequence \( 0 \rightarrow T_{X} \rightarrow T_{X}|_{X} \rightarrow T_{X}| V \otimes O_{X} \rightarrow 0 \) induces an exact sequence \( H^{1}(X, T_{X}|_{X}) \rightarrow T_{X}| V \otimes O_{X} \rightarrow H^{1}(X, T_{X}). \) The surjectivity follows from

\(^9\) It is interesting to observe that the argument breaks down at this point for \( n = 0 \). And, indeed, the automorphism group of a cubic \( X \subset \mathbb{P}^{3} \) is never trivial. For \( n = 1 \) and \( d = 3 \) the arguments still show that \( \text{Aut}(X, O_{X}(1)) \) acts faithfully on \( H^{1}(X, T_{X}) \).
Proposition 3.9 and all maps are compatible with the action of $g$. However, as $\pi$ is $g$-invariant, the action on $T[\chi]V$ is trivial and, therefore, the action of $g$ on $H^1(X, T_X)$ is trivial as well. This contradicts Proposition 3.13. □

Remark 3.16. It is worth pointing out that [151] provides equations for smooth hypersurfaces $X$ defined over the prime field $k$, so $k = F_p$ or $k = \mathbb{Q}$, such that $\text{Aut}(\bar{X}, O_{\bar{X}}(1)) = \{\text{id}\}$ for $\bar{X} := X \times_k \bar{k}$. For cubic hypersurfaces the equations are of the form $c x^3_0 + \sum_{i=0}^{n} x_0 x_i x_{i+1}^3$, where $n > 2$ and $\text{char}(k) \neq 3$. The hard part of this approach is then the verification that the hypersurface given by this equation has really no polarized automorphisms.

Remark 3.17. Assume $n \geq 2$ and $d \geq 3$ as before. Then $|\text{Aut}(X)|$ is universally bounded, i.e. there is a constant $C(d, n)$ such that for all smooth $X \in |O(d)|$

$$|\text{Aut}(X)| < C(d, n).$$

This follows again from the fact that $\text{Aut}(X/U, O_X(1)) \to U$ is a finite morphism, see Remark 2.1.7.

The bound $C(d, n)$ can be made effective. In [97] it has been shown that $C(d, n)$ can be chosen of the form $C(d, n) = C(n) \cdot d^n$. The bound is unlikely to be optimal. See also Remark 4.7.

Question 3.18. Is there anything known about the codimension of the closed set of hypersurfaces $X \in |O(d)|$ for which $\text{Aut}(X, O_X(1)) \neq \{\text{id}\}$?

4 Jacobian ring

The Jacobian ring is a finite-dimensional quotient of the coordinate ring of a smooth hypersurface obtained by dividing out the partial derivatives of the defining equation. At first glance, it looks like a rather coarse invariant but it turns out to encode the isomorphism type of the hypersurface as an abstract variety. There are purely algebraic aspects of the Jacobian ring as well as Hodge theoretic ones, which shall be explained or at least sketched in this section.

4.1 We shall assume $\text{char}(k) = 0$ or, at least, that $\text{char}(k)$ is prime to the degree $d$ of the hypersurfaces under considerations and prime to $d - 1$. The ring $S := k[x_0, \ldots, x_{n+1}]$ is naturally graded $S = \bigoplus_{s \geq 0} S_s$, such that $F \in S_d$ for all homogeneous polynomials $F$ of degree $d$. We write $\partial F \in S_{d-1}$ for the partial derivatives $\partial F := \partial F / \partial x_i$. The Hessian of $F$ is the matrix of homogeneous polynomials of degree $d - 2$

$$H(F) := \left( \frac{\partial^2 F}{\partial x_i \partial x_j} \right)_{i,j}.$$
Chapter 1. Basic facts

For its determinant one has \( \det H(F) \in S_\sigma \), where here and throughout we will use the shorthand

\[
\sigma := (n + 2) \cdot (d - 2). \tag{4.1}
\]

The reader may want to compare this number to the much larger degree of the discriminant divisor \( \deg D(d,n) = (d - 1)^{n+1}(n + 2) \). For the case of interest to us, \( d = 3 \), one simply has

\[
\sigma = n + 2.
\]

Recall that the polynomial \( F \) can be recovered from its partial derivatives by means of the Euler equation

\[
d \cdot F = \sum_{i=0}^{n+1} x_i \partial_i F. \tag{4.2}
\]

**Definition 4.1.** The Jacobian ideal of a homogeneous polynomial \( F \in S_d \) of degree \( d \) is the homogeneous ideal

\[
J(F) := (\partial_i F) \subset S = k[x_0, \ldots, x_{n+1}]
\]

generated by the partial derivatives of \( F \). The Jacobian ring or Milnor ring of \( F \) is the quotient

\[
S \longrightarrow R(F) := S / J(F).
\]

An immediate consequence of (4.2) is that the quotient map factors through the coordinate ring of \( X \):

\[
S \longrightarrow S/\langle F \rangle \longrightarrow R(F).
\]

If \( X \subset \mathbb{P} := \mathbb{P}^{n+1} \) is the hypersurface defined by \( F \), then we shall also write \( J(X) \) and \( R(X) \) instead of \( J(F) \) and \( R(F) \). As \( F \) is determined by \( X \) up to scaling, there is no risk of ambiguity. If \( F \) or \( X \) are understood, we will abbreviate further to \( J = J(F) \) and \( R = R(F) \). Note that the Jacobian ring \( R \) is naturally graded.

As an immediate consequence of Lemma 3.1 one has

**Corollary 4.2.** For a smooth hypersurface \( X \subset \mathbb{P} \) defined by a homogeneous polynomial \( F \) the Jacobian ring \( R(X) = R(F) \) is a zero-dimensional local ring and a finite-dimensional \( k \)-algebra. \( \square \)

4.2 The content of the next result is to show that the Jacobian ring \( R \) is Gorenstein with its (one-dimensional) socle in degree \( \sigma = (n + 2) \cdot (d - 2) \) and to compute the dimensions of its graded pieces.
Proposition 4.3. Assume that the homogeneous polynomial \( F \in S_d \) defines a smooth hypersurface \( X \subset \mathbb{P} = \mathbb{P}^{n+1} \). Then the Jacobian ring \( R := R(X) = R(F) \) has the following properties:

(i) The ring \( R \) is an Artinian graded ring with \( R_i = 0 \) for \( i > \sigma \) and \( R_\sigma \) is generated by \( \det H(F) \).
(ii) Multiplication yields a perfect pairing \( R_i \times R_{\sigma-i} \rightarrow R_\sigma = k \).
(iii) The Poincaré polynomial of \( R \) is given by

\[
P(R) := \sum_{i=0}^{\sigma} \dim_k(R_i) t^i = \left( \frac{1 - t^{d-1}}{1-t} \right)^{n+2}.
\]

For \( d = 3 \) the dimensions of the graded pieces of the Jacobian ring \( R(F) \) are simply

\[
\dim_k(R_i) = \binom{n+2}{i}.
\]

Proof. We write \( f_i := \partial_i F \). Then, by Lemma 3.1, \( f_0, \ldots, f_{n+1} \in S \) is a regular sequence of homogeneous polynomials of degree \( d-1 \) and this is in fact all we need for the proof.

Let us begin by recalling basic facts about the Koszul complex of a regular sequence \( f_0, \ldots, f_{n+1} \in S \). As always, \( \mathbb{P}^{n+1} = \mathbb{P}(V) \) and so \( V^* = \langle x_0, \ldots, x_{n+1} \rangle \). Then the Koszul complex is the complex (concentrated in (homological) degree \( n+2, \ldots, 0 \))

\[
K_*(f_i): \left( \wedge^{n+2} V^* \longrightarrow \cdots \longrightarrow \wedge^4 V^* \longrightarrow \cdots \longrightarrow \wedge^2 V^* \longrightarrow V^* \longrightarrow k \right) \otimes_k S
\]

with differentials

\[
\partial_p(x_{i_1} \wedge \cdots \wedge x_{i_p}) = \sum (-1)^j f_{i_j} x_{i_1} \wedge \cdots \wedge \hat{x}_{i_j} \wedge \cdots \wedge x_{i_p}.
\]

Now, for a regular sequence \( (f_i) \) the Koszul complex is exact in degree \( \neq 0 \) with:

\[
H_0(K_*(f_i)) = \text{Coker}(V^* \otimes S \rightarrow S) \approx R := S/(f_i),
\]

see [160]. The exactness of the complex \( K_*(f_i) \rightarrow R \) and the fact that the differentials in the Koszul complex are homogeneous of degree \( d-1 \) shows

\[
\dim R_i = \dim(S_i) - (n+2) \dim(S_{i-(d-1)}) + \cdots
\]

\[
= \sum_{j=0}^{n+2} (-1)^j \binom{n+2}{j} \dim(S_{i-j-(d-1)}).
\]

Of course, \( \dim(S_{i-j-(d-1)}) = h^0(\mathbb{P}, \mathcal{O}(i-j(d-1))) = \binom{n+1+j(d-1)}{j} \), see [12]. This in principle allows one to compute the right hand side. The argument can be made more explicit by observing that in \( K_*(f_i) \) only the differentials depend on the sequence \( (f_i) \). Hence, \( \dim R_i \) can be computed by choosing a particular sequence, e.g. \( f_i = x_i^{d-1} \). In this
case, if a monomial $x^d = x_0^{i_0} \cdots x_{\sigma+1}^{i_{\sigma+1}}$ is not contained in the Jacobian ideal $(f_i = x_i^{d-1})$, then all $i_j \leq d - 2$ and hence $|\sigma| \leq (n + 2) \cdot (d - 2) = \sigma$. In other words, $R_i = 0$ for $i > \sigma$, which is not quite so obvious from the above dimension formula. Moreover, if $x^d \notin (f_i)$ for $|\sigma| = \sigma$, then $x^d = \prod x_i^{d-2}$, i.e. $R_{\sigma}$ is one-dimensional and generated by the Hessian determinant of $F = \sum x_i^d$. To compute the Poincaré polynomial completely, observe that

$$R \left(\sum x_i^d\right) = k[x_0]/(x_i^{d-1}) \otimes \cdots \otimes k[x_{\sigma+1}]/(x_{\sigma+1}^{d-1})$$

and hence

$$P(R \left(\sum x_i^d\right)) = P(k[x]/(x_i^{d-1}))^{n+2} = (1 + t + \cdots + t^{d-2})^{n+2} = \left(\frac{1 - t^{d-1}}{1 - t}\right)^{n+2}.$$ 

One can also argue without specializing to the case of a Fermat (or any other) hypersurface and without relying on the Koszul complex as follows. For an exact sequence

$$0 \rightarrow M^m \rightarrow \cdots \rightarrow M^0 \rightarrow 0$$

of graded $S$-modules, the additivity of the Poincaré polynomial implies $\sum (-1)^j P(M^j) = 0$. Now, define $R' \cong S/(f_0, \ldots, f_i)$ and consider the sequences

$$0 \rightarrow R \rightarrow R' \rightarrow R' \rightarrow 0.$$ 

They are exact due to the regularity of the sequence $(f_i)$. Then

$$P(R') = P(R') - t^{d-1} \cdot P(R') = (1 - t^{d-1}) \cdot P(R')$$

and by induction

$$P(R) = (1 - t^{d-1})^{n+2} \cdot P(S).$$

Using $P(S) = 1/(1 - t)^{n+2}$, this yields (iii) and, in particular, $R_i = 0$ for $i > \sigma$ and $R_{\sigma} = k$.

Let us next show that the Hessian determinant $\det \left(\partial_i f_j\right)$ is not contained in the ideal $(f_i)$ and thus generates $R_{\sigma}$. For this consider the dual Koszul complex $K^*(f_i) = \text{Hom}_S(K_*(f_i), S)$, which quite generally satisfies the duality

$$H^p(K^*(f_i)) = H_{n+2-p}(K_*(f_i)).$$

see [129] Ch. 4. So, for a regular sequence $(f_i)$ the complex $K^*(f_i)$ is exact in degree $\neq n + 2$ and $H^{n+2}(K^*) = R$. This can also be checked directly, for example by using that $H^i(K^*(f_i)) = \text{Ext}^i_{S}(R, S)$. Suppose now that $H = \left(\delta_{ij}\right)$ is a matrix of homogeneous polynomials of degree $d - 2$ such that $H \cdot (x_j) = (f_i)$, i.e. $\sum h_{ij} x_j = f_i$. Then $H$ induces a morphism of complexes $\wedge^* H: K_*(f_i) \rightarrow K_*(f_i)$, the dual of which is a morphism $K^*(x_i) \rightarrow K^*(f_i)$. The latter induces in degree $n + 2$ the map

$$k \cong S/(x_i) \rightarrow H^{n+2}(K^*(x_i)) \rightarrow H^{n+2}(K^*(f_i)) = R, 1 \rightarrow \det(H),$$

which can also be interpreted as the map $\eta: \text{Ext}^i_{S}(k, S) \rightarrow \text{Ext}^i_{S}(R, S)$ induced by the short exact sequence $0 \rightarrow (x_i)/(f_i) \rightarrow R \rightarrow k \rightarrow 0$. As $(x_i)/(f_i)$ has zero-dimensional support and, thus, $\text{Ext}^i_{S}(x_i)/(f_i, S) = 0$, the map $\eta$ is injective. Therefore,
4 Jacobian ring

\[ \det(H) \neq 0 \text{ in } R. \] To relate this to our assertion, observe that the Euler equation \( \frac{1}{2\pi i} \int \frac{\det(H) \, dx_0 \wedge \ldots \wedge dx_{n+1}}{f_0 \cdot \ldots \cdot f_{n+1}} = \frac{1}{2\pi i} \int \frac{\det(f) \, dx_0 \wedge \ldots \wedge dx_{n+1}}{\zeta_0 \cdot \ldots \cdot \zeta_{n+1}} = \deg(f) \cdot \prod_{j=0}^{n+1} \frac{1}{\zeta_j} \]

It remains to prove that the pairing defined by multiplication is perfect. Evidence comes from the equation \( t' \cdot P(t)\) for the Poincaré polynomial computed above. This already shows that \( \dim R_\sigma = \dim R_{\sigma+1} \). Thus, to verify that the pairing is non-degenerate, it suffices to prove that for any homogeneous \( g \notin (f) \) there exists a homogeneous polynomial \( h \) with \( 0 \neq g \cdot h \in R_\sigma \) or, equivalently, such that the degree \( \sigma \) part \((\delta)_{\sigma}\) of the homogeneous ideal \((\delta)\) in \( R \) is not trivial. Let \( i \) be maximal with \((\delta)_{\sigma} \neq 0\) and pick \( 0 \neq G \in (\delta)_{\sigma} \). Suppose \( i < \sigma \). Then \( G \cdot (x_i) \in (f) \), which induces a non-trivial homomorphism of \( S \)-modules \( k \to R, \sigma \rightsquigarrow G \). Hence, \( \dim S, \hom_k(k, \sigma) > 1 \), but this is absurd. Indeed, splitting the Koszul complex \( K_\sigma(f) \) into short exact sequences and using that \( \Ext_S^i(k, \wedge^i V^* \otimes S) = 0 \) for \( i < n + 2 \), one finds a sequence of inclusions

\[ \hom_k(k, \sigma) \to \Ext_k^1(k, \sigma, \partial_0) \to \ldots \to \Ext_k^{n+2}(k, \wedge^{n+2} V^* \otimes S) \approx k. \]

This concludes the proof of (ii). \( \square \)

**Remark 4.4.** Let us add a more analytic argument for the fact that the Hessian determinant generates the socle, cf. [79]. For this we assume \( k = \mathbb{C} \) and define the residue of \( g \in \mathbb{C}[x_0, \ldots, x_{n+1}] \) with respect to \( F \) as

\[ \text{Res}(g) := \left( \frac{1}{2\pi i} \right)^{n+2} \int_\Gamma \frac{g \, dx_0 \wedge \ldots \wedge dx_{n+1}}{f_0 \cdot \ldots \cdot f_{n+1}}, \]

where as before \( f_i = \partial_i F \) and \( \Gamma := \{ x \in \mathbb{C}^{n+2} \mid |f_i(x)| = \epsilon_i \} \) with \( 0 < \epsilon_i \ll 1 \). Then one checks two things:

(i) If \( g \in (f) \), then \( \text{Res}(g) = 0 \). This follows from Stokes’s theorem. Indeed, for example for \( g = h f_0 \) one has

\[ (2\pi i)^{n+2} \text{Res}(g) = \int_\Gamma \frac{h \, dx_0 \wedge \ldots \wedge dx_{n+1}}{f_0 \cdot \ldots \cdot f_{n+1}} = \int_\Gamma d \left( \frac{h}{f_0 \cdot \ldots \cdot f_{n+1}} \right) \wedge dx_0 \wedge \ldots \wedge dx_{n+1} = 0, \]

as \( h/(f_0 \cdot \ldots \cdot f_{n+1}) \) is holomorphic around \( \Gamma_0 := \{ z \in \mathbb{C}^{n+2} \mid |f_0(z)| < \epsilon_0, |f_0(z)| = \epsilon_i \} \).

(ii) The residue of \( g = \det H(F) \) is non-zero. More precisely, \( \text{Res}(\det H(F)) = \deg(f) \).

Here, \( f : \mathbb{C}^{n+2} \to \mathbb{C}^{n+2} \) is the map \( x = (x_i) \to (f_i(x)) \), which is of degree \( \deg(f) = \dim \mathcal{O}_{\mathbb{C}^{n+2}, 0}/(f_i) \). Indeed,

\[ \left( \frac{1}{2\pi i} \right)^{n+2} \int_\Gamma \frac{\det(H) \, dx_0 \wedge \ldots \wedge dx_{n+1}}{f_0 \cdot \ldots \cdot f_{n+1}} = \left( \frac{1}{2\pi i} \right)^{n+2} \int_\Gamma f^* \left( \frac{dz_0}{\zeta_0} \wedge \ldots \wedge \frac{dz_{n+1}}{\zeta_{n+1}} \right) = \deg(f) \cdot \prod_{j=0}^{n+1} \frac{1}{\zeta_j}, \]

\[ = \deg(f). \]
Clearly, (i) and (ii) together imply \( \det H(F) \neq J(F) \).

In [156] one finds a proof of the above proposition that reduces the assertion to statements in local duality theory as in [89]. In [174] the results are deduced from global Serre duality on \( \mathbb{P}^{n+1} \).

Here is an immediate consequence of the perfectness of the pairing \( \mathcal{H} \times \mathcal{H} \rightarrow \mathcal{H} \).

Corollary 4.5. Assume \( i + j \leq r \). Then the natural map

\[
\mathcal{H} \rightarrow \text{Hom}(\mathcal{H}^i, \mathcal{H}^j)
\]

induced by multiplication is injective. \( \square \)

Remark 4.6. If \( X \subset \mathbb{P}^{n+1} \) is smooth cubic hypersurface of even dimension \( n = 2m \), then the injectivity \( \mathcal{H} \rightarrow \text{Hom}(\mathcal{H}^{2m}, \mathcal{H}^{2m+1}) \) translates into the injectivity of the map \( H^1(X,\mathcal{T}_X) \rightarrow \text{Hom}(H^{2m}(X), H^{2m+1}(X)) \), which geometrically can be interpreted by saying that the \((m,m)\)-part of the primitive cohomology does not stay \((m,m)\) under any first order deformation.

Remark 4.7. Let \( X = V(F) \subset \mathbb{P}^{n+1} \) be a smooth hypersurface of degree \( d \). Then its group of polarized automorphisms \( \text{Aut}(X,\mathcal{O}_X) \), which according to Corollary 3.6 is essentially always finite, acts on the finite dimensional Jacobian ring \( R = R(X) \). The action is graded and faithful. As a generalization of the Poincaré polynomial \( P(R) \) one considers for any \( g \in \text{Aut}(X,\mathcal{O}_X) \) the polynomial

\[
P(R, g) := \sum \text{tr}(g| R_i)_i.
\]

Then the Poincaré polynomial is recovered as \( P(R) = P(R, \text{id}) \). The equation (4.3) has been generalized by Bott–Tate and Orlik–Solomon [146] to

\[
P(R, g) = \frac{\det(1 - g t^{d-1} | V)}{\det(1 - g t | V)},
\]

where \( V = S_1 = \langle x_0,\ldots,x_{n+1} \rangle \). This can then be used to see that \( |\text{Aut}(X,\mathcal{O}_X)\rangle \) is bounded by a function only depending on \( d \) and \( n \), see [146, Cor. 2.7], which we have hinted at already in Remark 3.17.

4.3 As a graded version of a result of Mather and Yau [133], Donagi showed in [64] that the Jacobian ring of a hypersurface determines the hypersurface up to projective equivalence.

Example 4.8. To motivate Donagi’s result, let us discuss the case of smooth cubic curves \( E = X \subset \mathbb{P} \subset \mathbb{P}^2 \). The interesting information encoded by the Jacobian ring

\[
R = R_0 \oplus R_1 \oplus R_2 \oplus R_3
\]

is the perfect pairing \( R_1 \times R_2 \rightarrow R_3 = k \). We shall describe this for a plane cubic in
Weierstraß form $y^2 = 4x^3 - g_2x - g_3$, i.e. with $F = x_1^2x_2 - 4x_0^3 + g_2x_0x_2^2 + g_3x_2^3$. The partial derivatives are

$$\partial_0 F = -12x_0^2 + g_2x_2^2, \quad \partial_1 F = 2x_1x_2, \quad \text{and} \quad \partial_2 F = x_1^2 + 2g_2x_0x_2 + 3g_3x_2^2.$$

From this one deduces bases for $R_1$, $R_2$, and $R_3$, namely:

$$R_1 = \langle x_0, x_1, x_2 \rangle, \quad R_2 = \langle x_0^2, x_0x_1, x_0x_2 \rangle, \quad \text{and} \quad R_3 = \langle x_2^3 \rangle.$$  

With respect to these bases, the multiplication $R_1 \times R_2 \longrightarrow R_3$ is described by the matrix

$$\begin{pmatrix}
\bar{x}_0 \bar{x}_2^2 & \bar{x}_0^2 \bar{x}_1 & \bar{x}_0^2 \bar{x}_2 \\
\bar{x}_1 \bar{x}_2^2 & \bar{x}_1^2 \bar{x}_1 & \bar{x}_1 \bar{x}_2 \bar{x}_2 \\
\bar{x}_2^2 & \bar{x}_0 \bar{x}_1 \bar{x}_2 & \bar{x}_0^2 \bar{x}_2
\end{pmatrix} = \begin{pmatrix}
-3g_3/(2g_2) & 0 & \frac{g_2}{12} \\
0 & (27g_2^2 - 4g_3^3)/(6g_2) & 0 \\
1 & 0 & -3g_3/(2g_2)
\end{pmatrix}.$$  

Recall that the discriminant of an elliptic curve in Weierstraß form is by definition $\Delta(E) = g_2^3 - 27g_3^2$ and its $j$-function $j(E) = 1728\frac{g_2^3}{\Delta(E)}$, cf. [90, Sec. IV.4]. Hence, the perfect pairing $R_1 \times R_2 \longrightarrow R_3 \cong k$ determines $j(E)$ and, therefore (at least for $k$ algebraically closed), the isomorphism type of $E$. Note that already the determinant

$$\frac{\Delta(E)^2}{72g_2^4} = 24 \cdot 1728 \cdot g_2^3 \cdot j(E)^{-2}$$

of the above matrix almost remembers the isomorphism type of $E$.

**Proposition 4.9.** Let $X, X' \subset \mathbb{P} = \mathbb{P}^{n+1}$ be two smooth hypersurfaces such that there exists an isomorphism $R(X) \cong R(X')$ of graded rings. Then the two hypersurfaces are equivalent, i.e. there exists an automorphism $g \in \text{PGL}(n+2)$ of the ambient $\mathbb{P}$ with $g(X) = X'$.

**Proof.** We follow the proof in [174, Ch. 18]. Denote the polynomials defining $X$ and $X'$ by $F$ and $F'$. The given graded isomorphism $R(F) \longrightarrow R(F')$ can be lifted to an isomorphism $g : S \longrightarrow S$ with $g(J(F)) = J(F')$. Thus, we may reduce to the case $g = \text{id}$, i.e. $J(F) = J(F')$.

Consider the path $F_t := t \cdot F' + (1-t) \cdot F$ connecting $F$ and $F'$. Deriving with respect to $t$ yields $(d/dt)F_t = F' - F$ which is contained in the ideal $(F) + (F') \subset J(F) = J(F')$.

On the other hand, the tangent space of the $\text{GL}(n+2)$-orbit at $F_t$ is just $J(F_t)_{\text{id}} = J(F)_{\text{id}}$, which can be seen by computing for $A = (a_{ij}) \in M(n+2, \mathbb{C})$

$$\frac{d}{ds} F_t((\text{id} + s \cdot A)x)|_{s=0} = \sum_i \partial_i F_t \sum_j a_{ij} x_j.$$  

Hence, the path $F_t$ is tangent to all orbits and, therefore, stays inside the $\text{GL}(n+2)$-orbit through $F$. This proves the assertion.

Note that in general the given isomorphism between the Jacobian rings is not induced by any $g \in \text{PGL}(n+2)$ identifying $X$ and $X'$.  \[\square\]
Chapter 1. Basic facts

Remark 4.10. There exist examples of smooth projective varieties $X$ that can be embedded as hypersurfaces $X \hookrightarrow \mathbb{P}$ in non-equivalent ways. For example, the Fermat quartic $X \subset \mathbb{P}^3$ is known to admit exactly three equivalence classes of degree four polarizations \[56\]. The three Jacobian rings are therefore non-isomorphic.

Remark 4.11. In Proposition 4.9 it is enough to assume that there is a ring isomorphism $R(X) \cong R(X')$, not necessarily graded. Indeed, any ring isomorphism induces a graded isomorphism $\bigoplus \frac{m_R^i}{m_R^{i+1}} \cong \bigoplus \frac{m'_R^i}{m'_R^{i+1}}$, where $m_R \subset R(X)$ and $m'_R \subset R(X')$ are the maximal ideals. Then use that $R \cong \bigoplus \frac{m_R^i}{m_R^{i+1}}$ as graded $k$-algebras.\[10\]

4.4 For later use, we study the part of the Jacobian ring $R(X)$ which only takes into account the degrees

$$ t(p) := (n - p + 1) \cdot d - (n + 2). $$

Observe that these indices enjoy the symmetry

$$ t(p) + t(n - p) = (n + 2) \cdot (d - 2) = \sigma. $$

Therefore, multiplication yields perfect pairings

$$ R_{t(p)} \times R_{t(n-p)} \longrightarrow R_{\sigma} \cong k. $$

Let us first check for which $p$ one finds a non-trivial $R_{n(p)}$. This is the case if and only if $0 \leq t(p) \leq \sigma = (n + 2) \cdot (d - 2)$, i.e. for

$$ \frac{n + 2 - d}{d} \leq p \leq \frac{(n + 2) \cdot (d - 1) - 1}{d}. $$

For $d = 3$ this becomes

$$ \frac{n - 1}{3} \leq p \leq \frac{2n + 1}{3}. \quad (4.5) $$

Observe that $t(p) = \sigma$ if and only if $n - p + 1 = \frac{(n + 2)(d - 1)}{d}$, which leads to the next

Lemma 4.12. For given $n$ and $d$ the following conditions are equivalent:

(i) $d \mid (n + 2)$.
(ii) There exists $p \in \mathbb{Z}$ with $t(p) = 0$.
(iii) There exists $p \in \mathbb{Z}$ with $t(p) = \sigma$.
(iv) There exists $p \in \mathbb{Z}$ with $t(p) = d$.
(v) There exists $p \in \mathbb{Z}$ with $\dim R_{n(p)} = 1$.
(vi) $\bigoplus R_{n(p)} \cong \bigoplus R_{\text{aut}}$. \hfill \Box

We also record that for $d = 3$

$$ \dim_k(R_{n(p)}) = \binom{n + 2}{3(n - p + 1) - (n + 2)} = \binom{n + 2}{2n + 1 - 3p}. $$

Thanks to J. Rennemo for explaining this to me.
Exercise 4.13. Let $X \subset \mathbb{P}^{n+1}$ be a smooth hypersurface of degree $d$. Show that

$$\sum \dim_k(R_t(p)) = b_n(X)_{pr},$$

where $b_n(X)_{pr}$ was computed in Section 1.3. For $d = 3$ this becomes the mysterious formula

$$\sum \binom{n+2}{2n+1-3p} = (-1)^n \cdot \left(2/3 \cdot (1 + (-1)^n \cdot 2^{n+1})\right),$$

(cf. Remark 1.12) A geometric explanation will be given below.

4.5 There is a beautiful technique going back to [64] that, under certain numerical conditions, allows one to recover the full Jacobian ring $R_B(X)$ from just the multiplications $R_d \times R_{t(p)} \rightarrow R_{t(p)+d}$. This is useful as $R_d$ and the $R_{t(p)}$ can be described geometrically. We start with the geometric description of $R_d(X)$. We recommend [44] for an instructive brief discussion and [174] for a more detailed one.

Lemma 4.14. Let $X \subset \mathbb{P}^{n+1}$ be a smooth hypersurface of degree $d$. Assume $\dim(X) > 2$ or $d \leq 3$. Then there exists a natural isomorphism

$$R_d(X) \cong H^1(X, T_X).$$

Proof This follows from (3.1) in the proof of Corollary 3.3 and $H^1(X, T_{\mathbb{P}|X}) = 0$, which holds under the present assumptions. The case $n = 1, d = 3$ needs an additional argument which is left to the reader.

Example 4.15. Observe that the isomorphism confirms the dimension formula (2.2):

$$\dim(M_n) = \dim H^1(X, T_X) = \dim R_3(X) = \binom{n+2}{3}.$$ 

Before turning to the geometric interpretation of the spaces $R_{t(p)}(X)$, we present the following purely algebraic result. It was proved by Donagi [64] for generic polynomials and in [65] in general.

Proposition 4.16 (Symmetrizer lemma). Assume the following conditions are satisfied:

(i) $i < j$, (ii) $i + j \leq \sigma - 1$, and (iii) $d + \max\{i, j\} \leq \sigma + 3$. Then the image of the injection

$$R_{j-i} \hookrightarrow \text{Hom}(R_i, R_j)$$

(see Corollary 3.3) is the subspace of all linear maps $\varphi : R_i \rightarrow R_j$ such that for all $g, h \in R_i$ one has $g \cdot \varphi(h) = h \cdot \varphi(g) \in R_{i+j}.$

Proof The subspace described by the symmetry condition is the kernel of

$$\text{Hom}(R_i, R_j) \rightarrow \text{Hom}(\wedge^2 R_i, R_{i+j}), \varphi \mapsto (g \wedge h \mapsto g \cdot \varphi(h) - h \cdot \varphi(g)).$$
As \( R_{i-j} \) obviously maps into it, one has to prove the exactness of the sequence

\[
R_{j-i} \rightarrow \text{Hom}(R_i, R_j) \rightarrow \text{Hom}(\bigwedge^2 R_i, R_{i+j}).
\]

This is done by comparing it to a certain Koszul complex on \( \mathbb{P}^{n+1} \). See [174, Prop. 18.21] for details.

Note that for cubic hypersurfaces the discussion below makes use of the symmetrizer lemma only for \( i = 1, 2 \), but the proof does not seem to become any easier in these cases.

To recover large portions of \( R(X) \), the proposition is applied repeatedly. Suppose \( R_i \times R_j \rightarrow R_{i+j} \) is known. Then one recovers \( R_i \times R_j - i \rightarrow R_j \), for which in addition (ii) and (iii) still hold. However, it may happen that (i) no longer holds, i.e. that \( i \geq j - i \), but this can be remedied by swapping the factors, which does not effect the symmetry conditions (ii) and (iii). The procedure stops at some \( R_\ell \times R_\ell \rightarrow R_{2\ell} \) and a moment’s thought reveals that \( \ell = \gcd(i, j) \). Applied to \( i = d \) and \( j = t(p) \) (or, with reversed order) this procedure eventually yields the following result.

**Proposition 4.17.** Assume \((2n + 1)/n \leq d\). Fix \( p \) such that \( 0 < t(p) \leq \sigma - d - 1 \), and let \( \ell := \gcd(d, n+2) \). Then multiplication

\[
R_\ell \times R_\ell \rightarrow R_{2\ell}
\]

determines the multiplication \( R_\ell \times R_\ell \rightarrow R_{2\ell} \). (Note that in general \( \ell \) is not of the form \( t(p) \).)

The next result is a special case of a more general one, which beyond the cubic case is known for all smooth hypersurfaces except when \((d,n) = (4,4m)\) or \( d \mid (n+2) \). The argument is easier for cubic hypersurfaces and so we restrict to this case.

**Corollary 4.18.** Assume \( X = V(F) \subset \mathbb{P}^{n+1} \) is a smooth cubic hypersurface of dimension \( n > 2 \) with \( 3 \nmid (n+2) \). Then there exist integers \( p \) with \( 0 < t(p) \leq n - 2 \) and for each of them the graded algebra \( R = R(X) \), and hence by Proposition 4.9 also \( X \), is uniquely determined by the multiplication \( R_3 \times R_{n(p)} \rightarrow R_{3+n(p)} \).

**Proof** The condition \( 0 < t(p) \leq \sigma - d - 1 \) in Proposition 4.17 turns for \( d = 3 \) into (cf. (4.5))

\[
n + 3 \leq 3p < 2n + 1,
\]

which has integral solutions for all \( n > 2 \). For any such \( p \), multiplication \( R_3(X) \times R_{n(p)} \rightarrow R_{3+n(p)} \) determines \( R_1 \times R_1 \rightarrow R_2 \), as \( 3 \nmid (n+2) \) implies \( \gcd(3, t(p)) = 1 \).

Suppose this multiplication is isomorphic to another one \( R_1' \times R_1' \rightarrow R_2' \) associated with a cubic \( X' = V(F') \subset \mathbb{P}^{n+1} \). The isomorphism \( R_1 \simeq R_1' \) corresponds to a linear
coordinate change \( g: (x_0, \ldots, x_{n+1}) \rightarrow (x_0, \ldots, x_{n+1}) \) and the compatibility with the multiplication can be interpreted as an isomorphism
\[
\{ k[x_0, \ldots, x_{n+1}]_2 \simeq S^2(R_1) \longrightarrow R_2 \} = \{ k[x_0, \ldots, x_{n+1}]_2 \simeq S^2(R'_1) \longrightarrow R'_2 \}.
\]
Hence, under \( g \), their kernels are identified, which are spanned by the partial derivatives \( \partial_{F} \) and \( \partial_{F'} \), respectively. Thus, \( g \) induces a ring isomorphism \( k[x_0, \ldots, x_{n+1}] \rightarrow k[x_0, \ldots, x_{n+1}] \) that restricts to \( J(X) \rightarrow J(X') \) and, hence, \( R(X) \rightarrow R(X') \).

Note that under the assumptions of Corollary 4.18 there always exists \( p \) with \( t(p) = 1 \) or \( t(p) = 2 \). The result covers, for example, cubics of dimension \( n = 2, 3, 5, 6, 8, 9 \), for which we list the admissible \( t(p) \):

<table>
<thead>
<tr>
<th>( n )</th>
<th>( 0 &lt; t(p) \leq \sigma - 4 = n - 2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>( t(2) = 1 )</td>
</tr>
<tr>
<td>5</td>
<td>( t(2) = 5, t(3) = 2 )</td>
</tr>
<tr>
<td>6</td>
<td>( t(3) = 4, t(4) = 1 )</td>
</tr>
<tr>
<td>8</td>
<td>( t(3) = 8, t(4) = 5, t(5) = 2 )</td>
</tr>
<tr>
<td>9</td>
<td>( t(4) = 7, t(5) = 4, t(6) = 1 )</td>
</tr>
</tbody>
</table>

**Remark 4.19.** The result is sharp. For example, for \( n = 4 \), the only \( 0 \leq t(p) \leq \sigma = 6 \) are \( t(1) = 6, t(2) = 3, \) and \( t(3) = 0 \). But the pairing \( R_3 \times R_3 \longrightarrow R_6 \simeq k \) does certainly not determine the cubic nor does the identity \( R_3 \times R_0 \longrightarrow R_3 \).

**4.6** The next step is to describe the parts \( R_{\ell}(X) \) geometrically. This is the following celebrated result due to Carlson and Griffiths [36].

**Theorem 4.20** (Carlson–Griffiths). Let \( X \subset \mathbb{P}^{n+1} \) be a smooth hypersurface of degree \( d \). Assume \( n > 2 \) or \( d \leq 3 \). Then for all integers \( p \) there exists an isomorphism
\[
H^{\mu-p}(X)_{\text{pr}} \simeq R_{\ell}(X),
\]
with \( t(p) = (n - p + 1) \cdot d - (n + 2) \), compatible with the natural pairings on both sides, i.e. there exist commutative diagrams
\[
\begin{array}{ccc}
H^{\mu-p}(X)_{\text{pr}} & \times & H^{\mu-p}(X)_{\text{pr}} \\
\downarrow & \downarrow & \downarrow \\
R_{\ell}(X) & \times & R_{\ell}(X)
\end{array}
\]
Moreover, using the isomorphism \( H^1(X, \mathcal{T}_X) \simeq R_d(X) \), cf. Lemma 4.14 and the pairing
Chapter 1. Basic facts

\[ \Gamma_X \times \Omega_X^p \longrightarrow \Omega_{X}^{p-1}, \]

one obtains commutative diagrams

\[
\begin{array}{ccc}
H^1(X, \Gamma_X) \times H^{p,n-p}(X)_{\text{pr}} & \longrightarrow & H^{p-1,n-p+1}(X)_{\text{pr}} \\
\downarrow & & \downarrow \\
R_d(X) \times R_d(X) & \longrightarrow & R_{d-1}(X).
\end{array}
\]

(4.10)

The proof of the theorem is involved and we will not attempt to present it in full. However, we will outline the most important parts of the general theory that enter the proof and, in particular, explain how to establish a link between the Jacobian ring and the primitive cohomology at all. As we will restrict to the case of hypersurfaces in \( P^{n+1} \) throughout, certain aspects simplify. We refer to [35] and [174] for more details and some of the crucial computations.

(i) The de Rham complex of a (smooth) \( k \)-variety \( X \) of dimension \( n \) is the complex

\[ \Omega_X^\bullet : \mathcal{O}_X \longrightarrow \Omega_X^1 \longrightarrow \Omega_X^2 \longrightarrow \cdots \longrightarrow \Omega_X^n. \]

The \( \Omega_X^p \rightleftharpoons \bigwedge^p \Omega_X \) are coherent sheaves (here in the Zariski topology), but the differentials \( d : \Omega_X^p \longrightarrow \Omega_X^{p+1} \) are only \( k \)-linear. The de Rham cohomology of \( X \) is then defined as the hypercohomology of this complex:

\[ H^*_\text{dR}(X) := H^*(X, \Omega_X^\bullet), \]

which can be computed via the Hodge–de Rham spectral sequence

\[ E_1^{p,q} = H^q(X, \Omega_X^p) \Rightarrow H^{p+q}_\text{dR}(X/k). \]

(4.11)

Note that the \( E_1 \)-terms are just cohomology groups of coherent sheaves. The spectral sequence is associated with the Hodge filtration, which is induced by the complexes

\[ F^p \Omega_X^\bullet : \Omega_X^p \longrightarrow \cdots \longrightarrow \Omega_X^n \]

concentrated in degrees \( p, \ldots, n \) and the natural morphism \( F^p \Omega_X^\bullet \longrightarrow \Omega_X^\bullet \). Then one defines

\[ F^p H^*_\text{dR}(X/k) := \text{Im} \left( H^*(F^p \Omega_X^\bullet) \longrightarrow H^*(\Omega_X^\bullet) = H^*_\text{dR}(X/k) \right). \]

(4.12)

Remark 4.21. If \( X \) is smooth and projective over a field \( k \) satisfying \( \text{char}(k) = 0 \) or \( \text{char}(k) = p > \text{dim}(X) \) and \( X \) is liftable to \( W_2(k) \), then (4.11) degenerates [59]. This applies to smooth hypersurfaces \( X \subset P^{n+1} \), for which the assumption on the characteristic of \( k \) can be avoided, cf. Section 1.6. Once (4.11) is known to degenerate, the map in (4.12) is injective.

(ii) For open varieties the Hodge–de Rham spectral sequence does not necessarily degenerate, but a replacement is available. Consider the open complement \( j : U := \mathbb{P} \setminus \)
of a smooth hypersurface $X \subset \mathbb{P}$. There are quasi-isomorphisms (see the discussion following (4.20))

$$\Omega^*_p(\log(X)) \to \Omega^*_p(\log(X)^*) = j_* \Omega^*_U.$$  \hfill (4.13)

Here, $\Omega^*_p(\log(X)^*) := j_* \Omega^*_p(\log(X))$ (in the Zariski topology!) is the sheaf of meromorphic $p$-forms on $\mathbb{P}$ with poles (of arbitrary order) along $X$. Furthermore, $\Omega^1_p(\log(X)) \subset \Omega^1_p(\log(X)^*)$ is defined as the subsheaf locally generated by $d \log(f) = \frac{d f}{f}$, where $f$ is the local equation for $X$, and $\Omega^1_p(\log(X)^*) := \wedge^p (\Omega^1_p(\log(X))$. In our case, $X = V(F)$ and

$$\Omega^1_p(\log(X)) | U_j = d \log(F_j) \mathcal{O}_{U_j} = \frac{dF_j}{F_j} \mathcal{O}_{U_j}.$$  

on the standard open subset $U_j := \mathbb{P} \setminus V(x_j)$ with $F_j := F(x_0/x_j, \ldots, x_{n+1}/x_j)$. The differentials in both complexes are the usual ones. By construction, $\Omega^*_p(\log(X))$ is the subcomplex of forms $\alpha$ with $\alpha$ and $d \alpha$ having at most simple poles along $X$. The Hodge filtration in the open case is defined by

$$F^p \Omega^*_p(\log(X)) : \Omega^*_p(\log(X)) \to \cdots \to \Omega^{p+1}_p(\log(X))$$

(and not as the direct image of $F^p \Omega^*_U$) in degrees $p, \ldots, n+1$. It induces the spectral sequence

$$E^{p,q}_{1} = H^q(\mathbb{P}, \Omega^p(\log(X))) \Rightarrow H^{p+q}(\mathbb{P}, \Omega^*_p(\log(X))),$$  \hfill (4.14)

where the right hand side is isomorphic to

$$\mathbb{H}^*(\mathbb{P}, \Omega^*_p(\log(X))) \cong \mathbb{H}^*(\mathbb{P}, \Omega^*_p(\log(X)^*)) = H^*_{dR}(U/k).$$

Again due to [59], this spectral sequence degenerates under the assumptions of Remark 4.21 and so in particular for smooth hypersurfaces.

Observe that the residue

$$\text{res} : \frac{df}{f} \mapsto h|_X$$

yields a short exact sequence $0 \to \Omega^1_p(\log(X)^*) \to i_* \mathcal{O}_X \to 0$. Taking exterior powers, one obtains an exact sequence of complexes

$$0 \to \Omega^*_p(\log(X)) \to \Omega^*_p(\log(X)^*) \to (i_* \Omega^*_X)[-1] \to 0$$

with $\text{res} \left( \frac{df}{f} \wedge \alpha \right) = \alpha|_X$. In fact, the sequence is compatible with the Hodge filtrations of all three complexes, which leads to exact sequences

$$0 \to F^0 \Omega^*_p(\log(X)) \to F^0 \Omega^*_p(\log(X)^*) \to (i_* F^{p-1} \Omega^*_X)[-1] \to 0.$$
Chapter 1. Basic facts

The induced long exact cohomology sequences read

\[ \cdots \to H^i_{dR}(\mathbb{P}/k) \to H^i_{dR}(U/k) \to H^{i+1}_{dR}(X/k) \to H^{i+1}_{dR}(\mathbb{P}/k) \to \cdots \quad (4.15) \]

and

\[ \cdots \to F^pH^i_{dR}(\mathbb{P}/k) \to F^pH^i_{dR}(U/k) \to F^{p+1}H^{i-1}_{dR}(X/k) \to F^pH^{i+1}_{dR}(\mathbb{P}/k) \to \cdots \quad (4.16) \]

Note that the Hodge filtration \( F^pH^\ast_{dR}(U/k) \) is defined as the image of

\[ H^\ast(P, F^p \Omega^\bullet_{\mathbb{P}}(\log(X))) \to H^\ast(P, \Omega^\bullet_{\mathbb{P}}(\log(X))) \cong H^\ast_{dR}(U/k) \quad (4.17) \]

and not via the Hodge filtration of \( \Omega^\bullet_{\mathbb{P}} \). The exactness of (4.16) relies on the injectivity of (4.12) and (4.17), which is equivalent to the degeneration of the spectral sequences (4.11) and (4.14).

If \( X \) is defined over \( k = \mathbb{C} \), there is an analytic version of the above for the associated complex manifold \( X^{an} \). The de Rham complex \( \Omega^\bullet_{X^{an}} \) is defined similarly (now in the analytic topology) and so is the Hodge–de Rham spectral sequence

\[ E^{p,q}_1 = H^p(X^{an}, \Omega^q_{X^{an}}) \Rightarrow H^{p+q}_{dR}(X^{an}). \quad (4.18) \]

The Poincaré lemma shows that in the analytic topology the inclusion \( \mathbb{C} \to \mathcal{O}_{X^{an}} \) yields a quasi-isomorphism \( \mathbb{C} \to \Omega^\ast_{X^{an}} \) and hence an isomorphism

\[ H^\ast(X^{an}, \mathbb{C}) \cong H^\ast_{dR}(X^{an}) = H^\ast(\Omega^\ast_{X^{an}}). \]

The natural morphism \( X^{an} \to X \) of ringed spaces provides a comparison map from the algebraic to the analytic de Rham cohomology. For \( X \) smooth and projective, GAGA shows that \( H^p(X, \Omega^q_{X^{an}}) \cong H^p(X^{an}, \Omega^q_{X^{an}}) \). Hence, the left hand sides of (4.11) and (4.18) coincide and, therefore, also the right hand sides do, i.e.

\[ H^\ast_{dR}(X/\mathbb{C}) \cong H^\ast_{dR}(X^{an}), \quad (4.19) \]

which is compatible with the Hodge filtration. In fact, (4.19) continues to hold for arbitrary smooth varieties without any projectivity assumption, see \([82, \text{Thm. 1}']\).

Also the open case can be cast in the analytic setting, where (4.13) is replaced by

\[ \Omega^\ast_{P^{an}}(\log(X^{an})) \to \Omega^\ast_{P^{an}}(*X^{an}) \to j_* A^\ast_U \to Rj_* \mathcal{C}_U. \quad (4.20) \]

Here, the complex \( A_U \) is the standard \( \mathcal{C}^{\infty} \)-de Rham complex.

The verification of the quasi-isomorphisms in (4.20), and, similarly, in (4.13), is read-
Lemma 4.22

This is usually not a quasi-isomorphism. However, using that sequence (4.15) becomes the classical Gysin isomorphisms (4.13) and (4.20) the two compare as follows

\[ \Omega^\bullet_p(\log(X)) : \Omega^\bullet_p(\log(X)) \to \bigoplus \Omega^{\bullet+1}(X) \to \cdots \]

The cohomology of all three satisfies \( H^i \cong \mathbb{C} \) for \( i = 0, 1 \) and \( H^i = 0 \) otherwise.

Also, there is an analytic version of (4.14) and there exists a natural isomorphism

\[ \mathbb{H}^i(\mathbb{F}, \Omega^\bullet_p(\log(X))) \cong \mathbb{H}^i(\mathbb{F}^an, \Omega^\bullet_p(\log(X)) \).

To simplify the notation, we will from now on also write \( X, U, \) and \( \mathbb{F} \) for the associated analytic varieties. Then the exact sequence (4.15) becomes the classical Gysin sequence

\[ \cdots \to H^i(U, \mathbb{C}) \to H^i(X, \mathbb{C}) \to H^{i+1}(\mathbb{F}, \mathbb{C}) \to \cdots \]

This is interesting only for \( i = 1 \). As the map \( H^k(X, \mathbb{C}) \to H^{k+2}(\mathbb{F}, \mathbb{C}) \) is surjective for \( k = n - 1, n \), simply because \( H^k(\mathbb{F}) \to H^k(X) \to H^{k+2}(\mathbb{F}) \) is multiplication with \([X] \in H^2(\mathbb{F}), \) one finds

\[ H^{n+1}(U, \mathbb{C}) \to H^n(X, \mathbb{C}) \]

\[ \bigcup \to \bigcup \to F^p H^{n+1}(U, \mathbb{C}) \to F^{p+1} H^n(X, \mathbb{C}) \]

\[ \text{for the associated analytic varieties. Then the exact sequence (4.15) becomes the classical Gysin sequence} \]

However, as it turns out, the Hodge filtration is difficult to compute and it is preferable to replace it by the pole filtration \( F^p \) of the complex \( \Omega_p^\bullet(\log(X)) \). Under the quasi-isomorphisms (4.13) and (4.20) the two compare as follows

\[ F^p \Omega^\bullet_p(\log(X)) : \bigcap \Omega^\bullet_p(\log(X)) \to \bigcap \Omega^\bullet_p(\log(X)) \to \cdots \]

\[ F^p \Omega^\bullet_p(\log(X)) \to \bigcap \Omega^\bullet_p(\log(X)) \to \cdots \to \Omega^\bullet_p((n - p + 2)X). \]

This is usually not a quasi-isomorphism. However, using that \( H^i(X, \mathbb{C}) \) is 0 and applying Bott vanishing, see Section 4.2, one finds

\[ F^p H^{n+1}(U, \mathbb{C}) \cong F^p H^{n+1}(U, \mathbb{C}). \]

The advantage of using the pole filtration comes from the following

**Lemma 4.22 (Griffiths).** Let \( X \subset \mathbb{P} = \mathbb{P}^{n+1} \) be a smooth hypersurface.

Then \( F^p H^{n+1}(U, \mathbb{C}) \cong F^p H^{n}(\mathbb{F}, \mathbb{C}) \) is isomorphic to

\[ F^p H^{n+1}(U, \mathbb{C}) \cong \frac{H^0(\mathbb{F}, \Omega^\bullet_p(\log(X)))}{dH^0(\mathbb{F}, \Omega^\bullet_p(\log(X)))} \]

(4.21)
and $F^{p+1}\mathcal{H}^{n+1}(U, \mathbb{C})/F^{p+2}\mathcal{H}^{n+1}(U, \mathbb{C}) \cong \mathcal{H}^{p,n-p}(X)_{pr}$ is isomorphic to

$$\frac{F_{\text{pol}}^{p+1}\mathcal{H}^{n+1}(U, \mathbb{C})}{F_{\text{pol}}^{p+2}\mathcal{H}^{n+1}(U, \mathbb{C})} \cong \mathcal{H}^{p}(\mathbb{P}, \mathcal{O}_{\mathbb{P}}^{n+1}((n-p+1)X)),$$

(4.22)

**Proof** By definition, the left hand side in (4.21) is the image of the map

$$\mathbb{H}^{n+1}(\mathbb{P}, F_{\text{pol}}^{p+1}\mathcal{H}^{n+1}(U, \mathbb{C})) \longrightarrow \mathbb{H}^{n+1}(\mathbb{P}, \mathcal{O}_{\mathbb{P}}^{n+1}(X)).$$

The natural map $\mathcal{O}_{\mathbb{P}}^{p+1}((n-p+1)X) \longrightarrow F_{\text{pol}}^{p+1}\mathcal{H}^{n+1}(U, \mathbb{C})$ induces

$$\mathcal{H}^{p}(\mathbb{P}, \mathcal{O}_{\mathbb{P}}^{n+1}((n-p+1)X)) \longrightarrow F_{\text{pol}}^{p+1}\mathcal{H}^{n+1}(U, \mathbb{C}).$$

It is rather straightforward to show that the map is surjective and that its kernel is the image of $d: \mathcal{H}^{p}(\mathbb{P}, \mathcal{O}_{\mathbb{P}}^{n+1}((n-p+1)X)) \longrightarrow \mathcal{H}^{p+1}(\mathbb{P}, \mathcal{O}_{\mathbb{P}}^{n+1}((n-p+1)X))$. The isomorphism in (4.22) follows.

Observe that

$$\mathcal{H}^{0}(\mathbb{P}, \mathcal{O}_{\mathbb{P}}^{n+1}((n-p+1)X)) \cong \mathcal{H}^{0}(\mathbb{P}, \mathcal{O}((n-p+1) \cdot d - (n + 2)))$$

$$\cong \mathcal{H}^{0}(\mathbb{P}, \mathcal{O}(t(p))).$$

Thus, in order to prove (4.8), it suffices to show that the image of

$$(\partial, F): \mathcal{H}^{0}(\mathbb{P}, \mathcal{O}((n-p) \cdot d - (n + 2))) \longrightarrow \mathcal{H}^{0}(\mathbb{P}, \mathcal{O}(t(p)))$$

equals $\mathcal{H}^{0}(\mathbb{P}, \mathcal{O}_{\mathbb{P}}^{n+1}((n-p)X)) + d\mathcal{H}^{0}(\mathbb{P}, \mathcal{O}_{\mathbb{P}}^{n+1}((n-p)X)).$ This is a rather unpleasant computation in terms of rational differential forms on $\mathbb{P}$ and $\mathbb{C}^{n+2}$. We omit this here and refer to [174] Thm. 18.10 or [35] Ch. 3.2.

To prove the commutativity of (4.9), one first needs to fix an appropriate isomorphism $\mathcal{H}^{n,n}(X)_{pr} \cong \mathcal{R}_{r}(X)$ which again involves rational forms. Also the commutativity of (4.10) is not straightforward. One has to argue that multiplication

$$\mathcal{H}^{0}(\mathbb{P}, \mathcal{O}(d)) \times \mathcal{H}^{0}(\mathbb{P}, \mathcal{O}(t(p))) \longrightarrow \mathcal{H}^{0}(\mathbb{P}, \mathcal{O}(t(p) - 1)))$$

is related to the contraction

$$\mathcal{H}^{1}(X, T_{X}) \times \mathcal{H}^{p-p}(X, \mathcal{O}_{X}^{p}) \longrightarrow \mathcal{H}^{p-p+1}(X, \mathcal{O}_{X}^{p-1})$$

via the surjection $\mathcal{H}^{0}(\mathbb{P}, \mathcal{O}(d)) \longrightarrow \mathcal{H}^{0}(\mathbb{P}, \mathcal{O}(d)) \longrightarrow \mathcal{H}^{1}(X, T_{X}).$ The multiplication takes

\[ One could try an alternative argument: Apply $\Lambda^{n+1}$ to the Euler sequence to obtain $0 \longrightarrow \mathcal{O}(-n+2) \longrightarrow \mathcal{O}(-n+1) \longrightarrow \mathcal{O} \longrightarrow 0$. Tensor with $\mathcal{O}(n-p) \cdot d$ and consider the composition $\mathcal{H}^{0}(\mathbb{P}, \mathcal{O}(n-p) \cdot d - (n+1)) \longrightarrow \mathcal{H}^{0}(\mathbb{P}, \mathcal{O}) \longrightarrow \mathcal{H}^{0}(\mathbb{P}, \mathcal{O}(n-p) \cdot d) \longrightarrow \mathcal{H}^{0}(\mathbb{P}, \mathcal{O}(n-p+1) \cdot d)$, which should be compared to the map given by $(\partial, F)$. However this attempt becomes quickly as technical as the standard approach. \]
place in the top degree \( n + 1 \) of \( F_{\text{pol}}^{p+1} \Omega_p^*(X) \), whereas the contraction applies to the lowest degree (from degree \( p \) to \( p - 1 \)). This finishes the discussion of the main ideas used to prove Theorem 4.20.

We conclude this section by a result that will later be used to prove that the period map is unramified. We state the result for cubic hypersurfaces only.

**Corollary 4.23** (Infinitesimal Torelli Theorem). Let \( X \subset \mathbb{P}^{n+1} \) be a smooth cubic hypersurface of dimension \( n > 2 \). Then the contraction \( T_X \times \Omega_p^X \rightarrow \Omega_p^{p-1} \) yields an injection

\[
H^1(X, T_X) \hookrightarrow \text{Hom} \left( \bigoplus_{p+q=n} H^{p,q}(X)_{pr}, \bigoplus_{p+q=n+1} H^{p-1,q+1}(X)_{pr} \right)
\]

**Proof** There exists a \( p \) such that \( 0 \leq t(p) \leq \sigma - 3 \). Then, by Corollary 4.5, multiplication in the Jacobian ring \( R(X) \) yields an injection

\[
R_3 \hookrightarrow \text{Hom}(R_{n,p}, R_{n,p+3}).
\]

Now use \( R_{n,p} \cong H^{p+p}(X)_{pr} \) and the compatibility of the multiplication in \( R(X) \) with the contraction map, cf. Theorem 4.20. \( \square \)

**Remark 4.24.** If \( X \subset \mathbb{P}^{n+1} \) is smooth cubic hypersurface of even dimension \( n = 2m \), then the injectivity \( R_3 \hookrightarrow \text{Hom}(R_{m,n}, R_{m,n+3}) \) translates into the injectivity of

\[
H^1(X, T_X) \hookrightarrow \text{Hom}(H^{m,m}(X)_{pr}, H^{m-1,m+1}(X)_{pr}),
\]

which geometrically can be interpreted as saying that the \((m,m)\)-part of the primitive cohomology does not stay of type \((m,m)\) under any first order deformation.

### 5 Quadric fibrations and ramified covers

This part is devoted to standard constructions for cubic hypersurfaces, for example using linear projection to view them as quadric fibrations or studying triple cover of the ambient projective space ramified along the cubic.

#### 5.1

Let \( P := \mathbb{P}(W) \subset \mathbb{P} := \mathbb{P}(V) \) be a linear subspace with \( \dim(V) = n + 2 \) and \( \dim(W) = k \). Furthermore, pick a generic linear subspace \( \mathbb{P}(U) \subset \mathbb{P}(V) \) of codimension \( k \). Here, generic means that the composition \( U \subset V \rightarrow V/W \) is an isomorphism or, equivalently, that \( U + W = V \).

The linear projection \( \mathbb{P} \dashrightarrow \mathbb{P}(U) \cong \mathbb{P}(V/W) \) from \( P \) is the rational map that sends \( x \in \mathbb{P} \setminus P \) to the unique point of intersection of the linear subspace \( x\mathbb{P} \cong \mathbb{P}^k \) with \( \mathbb{P}(U) \cong \mathbb{P}^{n+1-k} \). It is the rational map associated with the linear system \( |\mathcal{I}_P \otimes \mathcal{O}(1)| \subset |\mathcal{O}(1)| \).
with base locus $P \subset \mathbb{P}$, which is resolved by a simple blow-up. The resulting morphism

$\varphi: \text{Bl}_P(\mathbb{P}) \to \mathbb{P}(V/W)$

is associated with the complete linear system $|\tau^*\mathcal{O}(1) \otimes \mathcal{O}(-E)|$:

$$E = \mathbb{P}(\mathcal{N}_{P/\mathbb{P}}) \xrightarrow{\varphi} \text{Bl}_P(\mathbb{P})$$

$\tau$ $\mathbb{P}$ $\mathbb{P} \dashrightarrow \mathbb{P}(V/W)$.

The fibre $\varphi^{-1}(y), y \in \mathbb{P}(U) \simeq \mathbb{P}(V/W)$, is the strict transform of $\mathbb{P}^k \simeq \overline{yP} \subset \text{Bl}_P(\mathbb{P})$ which for dimension reasons is isomorphic to $\mathbb{P}^k$. To visualize the situation observe that $\tau: E \cap \varphi^{-1}(y) \dashrightarrow \mathbb{P}$ is a section of $\tau: E \to \mathbb{P}$ that over a point $x \in \mathbb{P}$ picks out the normal direction $v \in \mathbb{P}(\mathcal{N}_{P/\mathbb{P}}(x))$ given by the line $\overline{xy}$. All fibres of $\varphi: \text{Bl}_P(\mathbb{P}) \to \mathbb{P}(V/W)$ are projective spaces $\mathbb{P}^k$ and, indeed, $\text{Bl}_P(\mathbb{P}) \simeq \mathbb{P}(\mathcal{F}^*)$ for the locally free sheaf $\mathcal{F} := \varphi_*\tau^*\mathcal{O}(1)$ on $\mathbb{P}(V/W)$ which is of rank $k + 1$. To determine $\mathcal{F}$ explicitly, tensor the structure sequence of the exceptional divisor $E \subset \text{Bl}_P(\mathbb{P})$ with $\tau^*\mathcal{O}(1)$ to get the short exact sequence

$$0 \to \tau^*\mathcal{O}(1) \otimes \mathcal{O}(-E) \to \tau^*\mathcal{O}(1) \to \tau^*\mathcal{O}(1)|_E \to 0 \quad (5.1)$$

Here, we use that $\mathcal{N}_{P/\mathbb{P}} \simeq \mathcal{O}(1)$, which yields an isomorphism

$$E = \mathbb{P}(\mathcal{N}_{P/\mathbb{P}}) \simeq \mathbb{P} \times \mathbb{P}(V/W)$$

compatible with the two natural projections. This also shows that $\mathcal{O}(E)|_E \simeq \mathcal{O}(1, -1)$ on $E \simeq \mathbb{P} \times \mathbb{P}(V/W)$. In particular, $\varphi^*\mathcal{O}(1)|_E \simeq (\tau^*\mathcal{O}(1) \otimes \mathcal{O}(-E))|_E \simeq \mathcal{O}(0, 1)$. Therefore, $\varphi$ restricted to $E$ is the projection onto $\mathbb{P}(V/W)$. Thus, $\mathcal{F}$ is described by the direct image under $\varphi$ of $\mathcal{F}$

$$0 \to \mathcal{O}(1) \to \mathcal{F} \to H^0(\mathbb{P}, \mathcal{O}(1)) \otimes \mathcal{O}(V/W) \to 0.$$

The sequence splits, which yields a non-canonical isomorphism

$$\mathcal{F} \simeq \mathcal{O}(1) \otimes (W^* \otimes \mathcal{O}(V/W))$$

and, hence, $\det(\mathcal{F}) \simeq \mathcal{O}(1)$, which is all we shall use.

Let now $X \subset \mathbb{P} = \mathbb{P}(V)$ be a cubic hypersurface with equation $F \in H^0(\mathbb{P}, \mathcal{O}(3))$. The pull-back $\tau^* F$ is a section of $\tau^*\mathcal{O}(3)$, whose zero divisor $V(\tau^* F)$ is the total transform of $X$. If $P \subset \mathbb{P}$ is contained in $X$ (cf. Exercise 3.1.3), then the total transform has two components, the exceptional divisor $E$ and the strict transform $\text{Bl}_P(X)$ of $X \subset \mathbb{P}$. More precisely, in this case $F$ is contained in $H^0(\mathbb{P}, \mathcal{O}(3) \otimes \mathcal{I}_P) \subset H^0(\mathbb{P}, \mathcal{O}(3))$ and $\tau^* F$ in $H^0(\text{Bl}_P(\mathbb{P}), \tau^*\mathcal{O}(3) \otimes \mathcal{O}(-E)) \subset H^0(\text{Bl}_P(\mathbb{P}), \tau^*\mathcal{O}(3))$. Therefore,

$$\text{Bl}_P(X) = V(\tau^* F) \in |\tau^*\mathcal{O}(3) \otimes \mathcal{O}(-E)|$$
in $\text{Bl}_p(P)$. To describe $\text{Bl}_p(X)$ as a quadric fibration over $P(V/W)$, we compute the direct image of $\tau^*F$ under $\varphi$. First, observe that

$$
\tau^*O(3) \otimes O(-E) \simeq \tau^*O(2) \otimes (\tau^*O(1) \otimes O(-E)) \simeq O_\varphi(2) \otimes \varphi^*O(1).
$$

Hence,

$$
\varphi_*(\tau^*O(3) \otimes O(-E)) \simeq \varphi_*(O_\varphi(2) \otimes \varphi^*O(1)) \simeq S^2(F) \otimes O(1)
$$

and, therefore, $\tau^*F$ can be thought of as a section $q \in H^0(P(V/W), S^2(F) \otimes O(1))$ or as a homomorphism

$$
q: F^* \longrightarrow F \otimes O(1).
$$

Then the fibre of $\text{Bl}_p(X) \subset \text{Bl}_p(P) \simeq P(F^*)$ over $t \in P(V/W)$ is the quadric defined by $q \in S^2(F(t))$. In particular, the fibre is smooth if and only if this quadric is non-degenerate. Hence, the discriminant divisor $D_P$ of $\varphi$: $\text{Bl}_p(X) \longrightarrow P(V/W)$ is

$$
D_P = \text{det}(q) \subset P(V/W).
$$

Here, $\text{det}(q)$: $\text{det}(F^*) \longrightarrow \text{det}(F) \otimes O(k+1)$ is viewed as a section of $\text{det}(F)^2 \otimes O(k+1) \simeq O(k + 3)$. In other words, $D_P$ is the degeneracy locus $M_k(q) = \{ t \mid \text{rk}(q_t) \leq k \}$ and one would expect it to be singular along $M_{k-1}(q)$. The discussion is summarized by the following classical fact, see e.g. [28, Lem. 2] for $n = 3$ and [13, Ch. 4].

**Proposition 5.1.** Assume a smooth cubic hypersurface $X \subset \mathbb{P}^{n+1}$ contains a linear subspace $P = \mathbb{P}^{k-1}$. Then the linear projection from $P$ defines a morphism

$$
\varphi: \text{Bl}_p(X) \longrightarrow \mathbb{P}^{n+1-k}
$$

with a quadric hypersurface in $\mathbb{P}^k \simeq \mathbb{F}^k$ as the fibre over $y$. The fibres are singular exactly over the discriminant divisor $D_P \in |O(k+3)|$.

We will encounter more detailed descriptions in low dimensions in subsequent chapters, see e.g. Corollary [5.1.20]. The bigger $k$ or, equivalently, the smaller the dimension of the target space $\mathbb{P}(U)$ is, the more special is $X$. As $\text{Pic}(X) \simeq \mathbb{Z} \cdot O(1)$ for $n > 2$, we certainly have $k \leq n - 1$. Thus, the most special and, hence, the geometrically most revealing case is $\mathbb{P}(U) \simeq \mathbb{P}^2$.

**Corollary 5.2.** Assume $X \subset \mathbb{P}^{n+1}$ is a smooth cubic hypersurface containing a linear $P = \mathbb{P}^{n-2} \subset X \subset \mathbb{P}^{n+1}$. Linear projection from $P$ yields a quadric fibration $\text{Bl}_p(X) \longrightarrow \mathbb{P}^2$ with discriminant curve $D_P \in |O(n+2)|$.

**Remark 5.3.** Assume $\mathbb{P}^{n-2} \cong P \subset X \subset \mathbb{P} = \mathbb{P}^{n+1}$ are as above. The quadric fibration $\text{Bl}_p(X) \longrightarrow \mathbb{P}^2$ allows one to prove the unirationality (of degree two) of $X$. In fact, unirationality (of degree two) holds true for all cubics of dimension $n > 1$, cf. Corollary [3] 1.14. Indeed, pick a generic $\mathbb{P}^3 \subset \mathbb{P}$ and let $\tilde{S}$ be the intersection of $\tau^{-1}(\mathbb{P}^3) \subset \text{Bl}_p(\mathbb{P})$. 

which is the blow-up of \( \mathbb{P}^3 \) in the point of intersection \( x \) of \( \mathbb{P}^3 \) and \( P \), and \( \text{Bl}_p(X) \subset \text{Bl}_p(\mathbb{P}) \). Then \( \tilde{S} \) is the blow-up of the cubic hypersurface \( S := X \cap \mathbb{P}^3 \) in \( x \). The generic fibre of \( \varphi|_S : \tilde{S} \to \mathbb{P}^2 \) over \( y \in \mathbb{P}^2 \) is the intersection of the quadric \( \varphi^{-1}(y) \subset \overline{yP} \) with the line \( \mathbb{P}^1 = \mathbb{P}^1 \cap \overline{yP} \) and, therefore, consists of two points, i.e. \( \tilde{S} \to \mathbb{P}^2 \) is of degree two. The base change \( \text{Bl}_P(X) \times_{\mathbb{P}^2} \tilde{S} \to \tilde{S} \) is a quadric fibration with a section over the rational surface \( \tilde{S} \) and hence rational.

One can try to run the same argument for any linear subspace \( P \subset X \). For example, for a line \( \mathbb{P}^1 = L \subset X \), which always exists as we will see, one picks a generic \( \mathbb{P}^n \) and lets \( S := \mathbb{P}^n \cap X \), which is cubic hypersurface of dimension \( n - 1 \). The base change \( \text{Bl}_P(X) \times_{\mathbb{P}^2} \tilde{S} \to \tilde{S} \) is a conic fibration with a section but now, by induction, one only knows that \( \tilde{S} \) is unirational of degree two.

In fact, for \( n \geq 7 \) the existence of \( \mathbb{P}^{n-2} \subset X \) implies the rationality of \( X \), see [13 Cor. 4.2]. Indeed, the scheme theoretic generic fibre is a quadric over the \( C_2 \)-field \( K(\mathbb{P}^2) = K(S) \), cf. [121].

If the existence of a complementary linear space contained in the cubic hypersurface \( X \) is assumed, not only unirationality but in fact rationality of \( X \) can be proved.

**Corollary 5.4.** Assume that a smooth cubic hypersurface \( X \subset \mathbb{P}^{n+1} \) contains \( \mathbb{P}^{k-1} \cong \mathbb{P}(W) \subset X \) and a complementary \( \mathbb{P}^{n+1-k} \cong \mathbb{P}(W') \subset X \), i.e. such that \( W + W' = V \) or, equivalently, \( \mathbb{P}(W) \cap \mathbb{P}(W') = \emptyset \). Then the quadric fibration \( \mathbb{P}^{n+1-k} \) admits a section. In particular, \( X \) is rational.

**Proof** The section is of course given by the inclusion \( \mathbb{P}^{n+1-k} \cong \mathbb{P}(W') \subset X \), which under the linear projection yields \( \mathbb{P}(W') \to \mathbb{P}(U) \). As any quadric admitting a rational point is rational, the scheme-theoretic generic fibre \( \varphi^{-1}(\eta) \) is a rational quadric over \( K(\mathbb{P}^{n+1-k}) \). Hence, \( \text{Bl}_P(X) \) is rational and, therefore, \( X \) itself is. \( \square \)

**Example 5.5.** In fact, assuming the existence two complementary linear subspaces \( P := \mathbb{P}(W), P' := \mathbb{P}(W') \subset X \), i.e. such that \( W \oplus W' = V \), the rationality of \( X \) can also be deduced from the following construction. Consider the rational map

\[
\psi : P \times P' \dashrightarrow X
\]

that sends a pair \((x, x')\) to the residual point of intersection \( y \) of \( \{x, x'\} \subset \overline{xy} \cap X \). This is well defined for all \((x, x')\) such that the line \( \overline{xy} \) is not contained in \( X \), which describes a non-empty open subset of \( P \times P' \). Next observe that any point in the complement of \( P \cup P \) is contained in the image of \( \psi \). More concretely, \( y \in X \setminus (P \cup P) \) is the image of \((x, x')\), where \( x \) and \( x' \) are determined by \( \{x\} = P \cap \overline{yP} \) and \( \{x'\} = \overline{yP} \cap P' \). As any line through \( y \) that intersects both \( P \) and \( P' \) meets \( P \) and \( P' \) exactly in these points \( x \) and \( x' \), the argument also shows that \( \psi \) is also generically injective and, therefore, \( X \) is rational.

Typical examples include even-dimensional cubics \( X \subset \mathbb{P}^{n+1}, n = 2m \), containing
two disjoint linear subspaces $\mathbb{P}^n \subset X$. In this case, the construction yields a rational parametrization $\mathbb{P}^n \times \mathbb{P}^n \dashrightarrow X \subset \mathbb{P}^{2n+1}$.

A concrete example is provided by $X = V(F)$ with $F = x_1^3 x_1 - x_0 x_1^2 + x_1^3 x_3 - x_2^2 x_5 - x_4 x_3^2$ which contains the two disjoint planes $P = V(x_0, x_2, x_4)$ and $P' = V(x_1, x_3, x_5)$, cf. [92, Sec. 5] or [93, Sec. 1].

Rationality of $X$, for example in dimension four, can also be deduced from the existence of other types of surfaces. We recommend [93] for further information.

5.2 The generic hyperplane section of a smooth cubic hypersurface yields again a smooth cubic hypersurface of one less dimension. In Section ?? we shall discuss how many hypersurfaces can be obtained as hyperplane sections of a fixed hypersurfaces. But the procedure can also be reversed. There is an almost canonical way of associating with a smooth cubic hypersurface $X \subset \mathbb{P}^{n+1}$ a smooth cubic hypersurface $\tilde{X} \subset \mathbb{P}^{n+2}$. In fact, the construction works for hypersurfaces of any degree $d$.

Let $X = V(F) \subset \mathbb{P}^{n+1}$ be an arbitrary hypersurface of degree $d$ given by a polynomial $F = F(x_0, \ldots, x_{n+1}) \in H^0(\mathbb{P}^{n+1}, \mathcal{O}(d))$. Then $\tilde{F} := F - x_{n+2}^d \in H^0(\mathbb{P}^{n+2}, \mathcal{O}(d))$ describes a hypersurface $\tilde{X} := V(\tilde{F}) \subset \mathbb{P}^{n+2}$. Clearly, $X$ is a hyperplane section of $\tilde{X}$, namely

$$X = \tilde{X} \cap V(x_{n+2}).$$

Observe that $X$ is smooth if and only if $\tilde{X}$ is smooth.

Note that $X \subset \mathbb{P}^{n+1}$ determines its defining equation $F$ only up to a scaling factor, i.e. $V(F) = V(\lambda F)$ for all $\lambda \in k^*$, and this does effect the equation $\tilde{F}$. However, at least if $k$ contains $d$ th roots, the two hypersurfaces $V(F - x_{n+2}^d)$ and $V(\lambda F - x_{n+2}^d)$ only differ by a linear coordinate change $[x_0 : \cdots : x_{n+1} : x_{n+2}] \mapsto [x_0 : \cdots : x_{n+1} : \lambda^{1/d} x_{n+2}]$.

It turns out that $X$ is not only a hyperplane section of $\tilde{X}$. The rational map given by the projection $\mathbb{P}^{n+2} \dashrightarrow \mathbb{P}^{n+1}$ that drops the last coordinate is regular along $X \subset \mathbb{P}^{n+2}$. It defines a finite morphism, and in fact a cyclic cover, of degree $d$

$$\pi: \tilde{X} \longrightarrow \mathbb{P}^{n+1}$$

branched over $X \subset \mathbb{P}^{n+1}$. More precisely, $\pi^{-1}(X) = dX$ as divisors in $\tilde{X}$ and

$$\pi: X = \tilde{X} \cap V(x_{n+2}) \longrightarrow X.$$

This basic construction has been successfully used to relate moduli spaces of cubic hypersurfaces of different dimensions. We shall come back to this in Section ??.
Moduli spaces

To study the geometry of a particular hypersurface \( X \subset \mathbb{P} = \mathbb{P}^{n+1} \) or to understand how a certain feature changes when \( X \) is deformed, the actual embedding of \( X \) into the projective space \( \mathbb{P} \) is often of no importance. This viewpoint leads to the notion of moduli spaces of varieties isomorphic to hypersurfaces of fixed degree and dimension. There are various ways to construct these moduli spaces and we will sketch the most fundamental ones.

1 GIT-quotient

The embeddings of a fixed \( X \) into \( \mathbb{P} \) are parametrized by the choice of a basis of \( H^0(X, \mathcal{O}_X(1)) \) up to scaling. So, instead of the linear system \(|\mathcal{O}_\mathbb{P}(d)|\) one is really interested in the quotient \(|\mathcal{O}_\mathbb{P}(d)|/\text{GL}(n+2)\). Ideally, one would like this quotient to exist in the category of varieties or schemes and to come with a universal family. However, as it turns out, this is too much to ask for.

Example 1.1. Consider the easiest case of interest to us: \( d = 3 \) and \( n = 0 \), i.e. three points in \( \mathbb{P}^1 \). Up to a linear coordinate change, there are only three possibilities: \( \{x_1, x_2, x_3\} \) (three distinct points), \( \{2 \cdot x_1, x_2\} \) (two distinct points of which one with multiplicity two), or \( \{3x\} \) (a triple point). Thus, the moduli space parametrizing all varieties isomorphic to hypersurfaces \( X \subset \mathbb{P}^1 \) of degree three should consist of three points. On the other hand, together with all possible embeddings they are parametrized by the projective space \(|\mathcal{O}_{\mathbb{P}^1}(3)|\), which is connected and, therefore, does not admit a morphism onto a disconnected space.

The same phenomenon can be described in terms of orbit closures. For example, the

---

1 For \( n \geq 2 \) and \( d \neq n + 2 \) the line bundle \( \mathcal{O}_X(1) \) itself does not depend on the embedding, as it is determined by the property that \( \mathcal{O}_X(d - (n + 2)) = \omega_X \). For \( n > 2 \) one can alternatively use that \( \mathcal{O}_X(1) \) is the ample generator of \( \text{Pic}(X) \).
limit of the one-parameter subgroup \( \text{diag}(t, 1/t) \) applied to the set \( V(x_0^2, x_1 - x_0 x_1^2) = [0, \infty, [1 : 1]] \) viewed as a point in \( |\mathcal{O}_3(3)| \) is \([2, 0, \infty] \) for \( t \to \infty \) and \([0, 2, \infty] \) for \( t \to 0 \). Hence, all these points should be identified under the quotient map to any moduli space with a reasonable geometric structure.

Similar phenomena occur in higher dimensions and for all \( d > 1 \). The way out is to allow only stable hypersurfaces. Those are parametrized by an open subset of \( |\mathcal{O}_d(d)| \) and include all smooth hypersurfaces. To obtain a projective moduli space one has to allow semi-stable hypersurfaces. This, however, leads to a moduli space that identifies certain orbits.

We briefly review the main features of GIT needed to understand moduli spaces of (smooth, cubic) hypersurfaces. We recommend [126, Ch. 6] for a quick introduction and the classic [140] or the textbooks [62, 137] for more details and references. Although we definitely want the moduli spaces to be defined over arbitrary fields, we usually assume that \( k \) is algebraically closed, just to keep the discussion geometric.

1.1 Let \( A \) be a finite type (say integral) \( k \)-algebra and \( G \) a linear algebraic group over \( k \) with an action on \( X = \text{Spec}(A) \) or, equivalently, an action on \( A \). If a quotient \( X \twoheadrightarrow X/G \) in the geometric sense exists, then \( X/G = \text{Spec}(A^G) \), where \( A^G \subset A \) is the invariant ring. In order for \( X/G \) to be a variety, the ring \( A^G \) needs to be again of finite type. This is Hilbert’s 14th problem which has been answered by Hilbert himself in characteristic zero for \( G = \text{SL} \) and in general by Nagata and Haboush, see [140] or the entertaining [139] for a historic account, references, and proofs:

If \( G \) is reductive, then \( A^G \) is again a finite type \( k \)-algebra.

This seems to settle the question in the affine case by just defining \( X/G \coloneqq \text{Spec}(A^G) \) with the quotient morphism \( X \twoheadrightarrow X/G \) induced by the inclusion \( A^G \subset A \). However, this is, in general, a quotient only in a weaker sense.

**Definition 1.2.** A morphism \( \pi : X \twoheadrightarrow Y \) is a categorical quotient for the action of a group \( G \) on \( X \) if it is \( G \)-invariant \footnote{\begin{itemize}
  \item i.e. the composition of \( \pi \) with two morphisms \( G \times X \twoheadrightarrow X \) defined by the second projection and by the group action coincide.
\end{itemize}} and if any other \( G \)-invariant morphism \( \pi' : X \twoheadrightarrow Y' \) factors uniquely through a morphism \( Y \twoheadrightarrow Y' \).

A \( G \)-invariant morphism \( \pi : X \twoheadrightarrow Y \) is a good quotient if it satisfies the following conditions: (i) \( \pi \) is affine and surjective; (ii) \( \pi(Z) \) of any closed \( G \)-invariant subset \( Z \subset X \) is closed; (iii) \( \pi(Z_1) \cap \pi(Z_2) = \pi(Z_1 \cap Z_2) \) for all closed \( G \)-invariant sets \( Z_1, Z_2 \subset X \); and (iv) \( \mathcal{O}_Y \) is the sheaf of \( G \)-invariant sections of \( \mathcal{O}_X \), i.e. \( \mathcal{O}_Y \cong (\pi^* \mathcal{O}_X)^G \) which means that \( \pi^* : \mathcal{O}_Y(U) \twoheadrightarrow \mathcal{O}_X(\pi^{-1}(U))^G \) for all open \( U \subset Y \).
A good quotient is geometric if in addition the pre-image of any closed point is an orbit.

By definition, any geometric quotient is a good quotient and, as proved in [140], any good quotient is also a categorical quotient:

geometric \Rightarrow \text{good} \Rightarrow \text{categorical}.

Note that a good quotient is equipped with the quotient topology and parametrizes the closed orbit of the action. Hence, a good quotient is geometric exactly when all orbits are closed, see [126, Prop. 6.1.7]. The main results on affine quotients is the following, cf. [140] or [126, Prop. 6.3.1]:

Assume $A$ is a finite type $k$-algebra and the reductive group $G$ acts on $X = \text{Spec}(A)$. Then $X \twoheadrightarrow X//G := \text{Spec}(A^G)$ is a good quotient.

In particular, it is a categorical quotient, but usually not a geometric one.

1.2 With certain modifications, the same recipe can be applied to projective varieties. Assume $A = \bigoplus_{i \geq 0} A_i$ is a graded $k$-algebra of finite type generated by $A_1$ and assume that the projective variety $X = \text{Proj}(A)$ is endowed with the action of a reductive linear algebraic group $G$. Note that, in contrast to the affine case, the action is not necessarily induced by an action of $G$ on $A$. However, we shall assume it is, in which case it is induced by a $G$-action on $A_1$. This is called a linearization. Geometrically it is realized by an embedding $X \hookrightarrow \text{Proj}(S^*(A_1)) = \mathbb{P}^m$ such that the action of $G$ on $X$ is the restriction of an action of $G$ on $\mathbb{P}^m$ induced by a linear representation $G \twoheadrightarrow \text{GL}(A_1)$.

One is tempted to imitate the affine case and define the quotient simply as $\text{Proj}(A^G)$. Note that $A^G$ is naturally graded and again of finite type, but possibly not generated in degree one. This can be easily remedied by passing to $\bigoplus_{i \geq 0} (A^G)_i$ for some $m > 0$. However, the graded inclusion $A^G \subset A$ does not define a morphism between the associated projective schemes. Indeed, a homogeneous prime or maximal ideal in $A$ may intersect $A^G$ in its inessential ideal $(A^G)_+ = \bigoplus_{i > 0} (A^G)_i$. In other words, there exists a morphism

$$X^s \longrightarrow X^s//G := \text{Proj}(A^G)$$

only on the open set $X^s := X \setminus V((A^G)_+) \subset X$. This naturally leads to the central definition in GIT.

Definition 1.3. A point $x \in X$ is semi-stable if it is contained in the open subset $X^s \subset X$, i.e. if there exists a homogeneous $G$-invariant $f \in A_i$, for some $i > 0$, with $f(x) \neq 0$. A point $x \in X$ is stable if $x$ is semi-stable and the induced morphism $G \cdot x \longrightarrow X^s$ is proper, i.e. the orbit $G \cdot x$ is closed in $X^s$ and the stabilizer $G_x$ is finite.

3 The exact definition of these notions varies from source to source. The subtle differences will be of no importance in our situation.
Exercise 1.4. For a linearized action of a reductive group $G$ on $\mathbb{P}(V)$, a point $[x] \in \mathbb{P}(V)$ is semi-stable if and only if $0 \notin \mathbb{G} \cdot x \subset V$. A point $[x] \in \mathbb{P}(V)$ is stable if and only if the morphism $G \longrightarrow V, g \longmapsto g \cdot x$ is proper.

Using open affine covers, the problem is reduced to the affine case which eventually leads to the following key result in GIT.

Theorem 1.5 (Mumford). Assume that a linearization of the action of a reductive linear algebraic group $G$ on $X = \text{Proj}(A)$ has been fixed. Then the natural morphism $X^{ss} \longrightarrow X^G/G$ is a good quotient.

1.3 Let us turn to the concrete GIT problem that concerns us. Consider $G := \text{SL}(n+2)$ with its natural action on $\mathbb{P}^{n+1}$ and the induced action on all complete linear systems $|\mathcal{O}(d)|$. Instead of $\text{SL}(n+2)$ one often considers $\text{PGL}(n+2)$. Both groups are reductive and the orbits of their actions on $|\mathcal{O}(d)|$ are of course the same. The advantage of working with $\text{SL}$ is that its action on $|\mathcal{O}(d)|$ comes with a natural linearization. The relevant result for us is the following, see [112, Sec. 11.8] for the arithmetic version over $\text{Spec}(\mathbb{Z})$.

Corollary 1.6. Every smooth hypersurface $X \subset \mathbb{P}$ of degree $d \geq 3$ defines a stable point $[X] \in |\mathcal{O}(d)|$ for the action of $G = \text{SL}(n+2)$, i.e.

$$U(d, n) = |\mathcal{O}(d)|_{\text{sm}} \subset |\mathcal{O}(d)|^s.$$ 

Proof The semi-stability is an immediate consequence of Theorem 1.2.2 and holds in fact for $d > 1$. Indeed, the complement of $U(d, n) \subset \mathbb{P}^N = |\mathcal{O}(d)|$ is the discriminant divisor $D = D(d, n)$, which is the zero set $V(\Delta)$ of the discriminant $\Delta = \Delta_{d, n} \in H^0(\mathbb{P}^N, \mathcal{O}(\ell))$, $\ell = (d - 1)^{n+1}(n + 2)$. As the smoothness of a hypersurface $X \subset \mathbb{P}$ does not depend on the embedding, the discriminant divisor $D$ is invariant under the action of $\text{GL}$. Hence, for all $g \in \text{GL}$ the induced action on $H^0(\mathbb{P}^N, \mathcal{O}(\ell))$, sending $\Delta$ to $g^*\Delta$, satisfies $D = V(\Delta) = V(g^*\Delta)$. Therefore, $g^*\Delta = \lambda_g \cdot \Delta$ for some $\lambda_g \in \mathbb{G}_m$. This in fact defines a morphism of algebraic groups $\text{GL} \longrightarrow \mathbb{G}_m, g \longmapsto \lambda_g$. However, the only characters of $\text{GL}$ are powers of the determinant, which by definition is trivial on $G = \text{SL}$. Hence, $\Delta$ is a $G$-invariant homogeneous polynomial that does not vanish at any point $[X] \in |\mathcal{O}(d)|$ that corresponds to a smooth hypersurface. In other words, $U \subset |\mathcal{O}(d)|^s$.

In order to show stability, one has to prove that for $X$ the morphism

$$G \longrightarrow |\mathcal{O}(d)|^s, g \longmapsto g[X]$$

is proper. Let us first prove that the stabilizer $G_{[X]}$ is finite. Clearly, any $g \in G_{[X]}$ induces an automorphism of the polarized variety $(X, \mathcal{O}_X(1))$. This yields a morphism $G_{[X]} \longrightarrow \text{Aut}(X, \mathcal{O}_X(1))$, the fibre of which is contained in the finite subgroup $\mu_{n+2} = \text{Ker}(\text{SL}(n+2) \longrightarrow \text{PGL}(n+2))$. Now use Corollary 1.3.6 and Remark 1.3.7.
To conclude one needs to show that the orbit $G \cdot [X]$ is closed in $|\mathcal{O}(d)|^{\text{ss}}$. Let us first show it is closed in the open subset $U = |\mathcal{O}(d)|_{\text{sm}} \subset |\mathcal{O}(d)|^{\text{ss}}$. Consider its closure $\overline{G \cdot [X]}$ in $U$ and pick a point $[X'] \in \overline{G \cdot [X]} \setminus G \cdot [X]$. Then $G \cdot [X'] \subset \overline{G \cdot [X]} \setminus G \cdot [X]$ and hence $\dim(G \cdot [X']) < \dim(G \cdot [X])$ which would imply $\dim(G_{[X']}) > 0$ contradicting the above discussion. Now, consider the morphism

$$\pi: |\mathcal{O}(d)|^{\text{ss}} \longrightarrow |\mathcal{O}(d)|^{\text{ss}} / G = \text{Proj} \left( k[H^0(\mathbb{P}^N, \mathcal{O}(1))^G \right).$$

Clearly, $U$ is the pre-image of the open non-vanishing locus of $\Delta \in H^0(\mathbb{P}^N, \mathcal{O}(f))^G \subset k[H^0(\mathbb{P}^N, \mathcal{O}(1))]^G$ and, therefore, $\pi^{-1}(\pi([X])) \subset U$ for all smooth $X$. As the subset $G \cdot [X]$ of $\pi^{-1}(\pi([X]))$ is closed in the bigger set $U$, it is also closed in $\pi^{-1}(\pi([X]))$. However, the fibre $\pi^{-1}(\pi([X]))$ as the pre-image of a closed point is closed in $|\mathcal{O}(d)|^{\text{ss}}$. Altogether this proves that $G \cdot [X] \subset |\mathcal{O}(d)|^{\text{ss}}$ is closed.

\begin{remark}

The techniques of the proof show that the morphism

$$\text{PGL}(n + 2) \times U \longrightarrow U \times U, \quad (g, [X]) \longmapsto ([X], g[X])$$

is proper. Now, the pre-image of the diagonal $\Delta \subset U \times U$ can be interpreted as the scheme $\textbf{Aut} = \text{Aut}(X/U, \mathcal{O}_X(1)) \longrightarrow U$ of polarized automorphisms of the universal family of smooth hypersurfaces $X \longrightarrow U \subset |\mathcal{O}(d)|$, cf. Section 13.2. So, in particular, the fibre over $[X] \in U$ is the finite group $\text{Aut}(X, \mathcal{O}_X(1))$. Note that as a consequence one finds that $\text{Aut}(X/U, \mathcal{O}_X(1)) \longrightarrow U$ is a finite morphism, cf. [112, Cor. 11.8.4].

\begin{example}

For $d = 1$, i.e. for hyperplanes, no $[X] \in |\mathcal{O}(1)|$ is semi-stable. Indeed, in this case, $U(1, n) = |\mathcal{O}(1)| = \mathbb{P}^n$ and $k[x_0, \ldots, x_{n+2}]^{\text{SL}} = k$.

Smooth quadrics, so $d = 2$, are semi-stable by the above, but they are not stable. Indeed, the stabilizer of a quadric, say of $\sum x_i^2$ and in fact every smooth quadric of this form after a linear coordinate change, is the special orthogonal group $\text{SO}(n + 2) \subset \text{SL}(n + 2)$, which is not finite.

\begin{exercise}

The above proof did not cover the case $n = 0, 1$. Verify that stability still holds in these cases. The only problematic case is $n = 1$ and $d = 3$.

Show that for $n = 0$ and $d = 3$ (semi-)stability is equivalent to smoothness.

The next question one should ask is whether the inclusion $|\mathcal{O}(d)|_{\text{sm}} \subset |\mathcal{O}(d)|^{\text{ss}}$ is strict. How can one interpret geometrically its complement? How big is $|\mathcal{O}(d)|^{\text{ss}} \setminus |\mathcal{O}(d)|^{\text{ss}}$?

\end{exercise}

\subsection{1.4}

For actual computations of stable and semi-stable points, the Hilbert–Mumford criterion is a powerful tool. It roughly says that it suffices to check one-parameter subgroups and gives a numerical criterion for those.

A one-parameter subgroup of a (reductive) group $G$ is a non-constant morphism $\lambda: \mathbb{G}_m \longrightarrow G$ of algebraic groups. If a linear action $\rho: G \longrightarrow \text{GL}(V)$ is given, then the induced action $\rho \circ \lambda: \mathbb{G}_m \longrightarrow \text{GL}(V)$ can be diagonalized, i.e. there exists a basis $(e_i)$ of $V$
such that \( \lambda(t)(e_i) = t^i \cdot e_i, r_i \in \mathbb{Z} \). The **Hilbert–Mumford weight** of a point \( x = \sum x_i e_i \in V \) with respect to this one-parameter subgroup is

\[
\mu(x, \lambda) := -\min \{ r_i \mid x_i \neq 0 \}.
\]

**Theorem 1.10** (Hilbert–Mumford criterion). For a linearized action of a reductive group \( G \) on \( \mathbb{P}(V) \) a point \([x] \in \mathbb{P}(V)\) is semi-stable if and only if \( \mu(x, \lambda) \geq 0 \) for all one-parameter subgroups \( \lambda : \mathbb{G}_m \rightarrow G \). The point \([x]\) is stable if and only if strict inequality holds for all non-trivial \( \lambda \).

Using Exercise [1.4] one direction is easy to prove. The difficulty lies in checking that it suffices to test one-parameter subgroups.

**Example 1.11.**

(i) A plane cubic curve \( C \subset \mathbb{P}^2 \) is stable if and only if it is smooth. It is semi-stable if and only if it has at most ordinary double points as singularities, cf. [137 Exa. 7.2] or [140].

(ii) The Hilbert–Mumford criterion allows one to prove that cubic surfaces \( S \subset \mathbb{P}^3 \) with at most ordinary double points as singularities are stable. Assume that \( S := V(F) \subset \mathbb{P}^3 \) is integral and defines a point \( x \in |O(3)| \) that is not stable, i.e. such that there exists a \( \lambda : \mathbb{G}_m \rightarrow \text{SL}(4) \) with \( \mu(x, \lambda) \leq 0 \). After a linear coordinate change we may assume that the action is diagonal and the induced action on the linear coordinates is given by \( \lambda(t)(x_j) = t^{i_j} \cdot x_j \) with \( r_0 \leq \cdots \leq r_3 \) and \( \sum r_j = 0 \). Then, on a cubic polynomial \( F = \sum a_i x^I \) the action is given by \( \lambda(t)(F) = \sum a_i t^{i_j} x^{I_j} \), where \( I = (i_0, \ldots, i_3) \), \( \sum i_j = 3 \), and \( rI := \sum r_j i_j \). By an elementary computation, see [19 Prop. 6.5], one shows that \( \mu(x, \lambda) \leq 0 \) implies that \([1 : 0 : 0 : 0] \in S\) is either a non-ordinary double point or a cusp.

There exist complete classification of (semi-)stable points in other linear systems \(|O_{\mathbb{P}^1}(d)|\) for other small values of \( d \) and \( n \). But even for \( d = 3 \), only the cases \( n \leq 4 \) have been studied in detail, see Sections ?? ??.

**Remark 1.12.** In [73] it is shown that a hypersurface \( X \subset \mathbb{P}^{n+1} \) defines a semi-stable point in \(|O_{\mathbb{P}^{n+1}}(d)|\) if and only if the subspace \( \langle \partial F \rangle \subset k[x_0, \ldots, x_{n+1}]_d \) defines a semi-stable point in \( \text{Gr}(n+2, k[x_0, \ldots, x_{n+1}]_d) \) with respect to the natural \( \text{SL}(n + 2) \)-action on the Grassmannian.

**1.5** Ideally, one would like the universal family \( \mathcal{X} \rightarrow |O(d)|_{\text{sm}} \) of smooth hypersurfaces to descend to a universal family \( \bar{\mathcal{X}} \rightarrow |O(d)|_{\text{sm}}/G \) (of varieties isomorphic to smooth hypersurfaces). The natural (and only) choice for such a family would be the quotient \( \bar{\mathcal{X}} := X/G \). However, over a point \([X] \in |O(d)|_{\text{sm}}/G\) the fibre of this family would be the quotient \( X/\text{Aut}(X, O_X(1)) \) of \( X \) by the finite group \( \text{Aut}(X, O_X(1)) \) and not \( X \) itself. This is the reason for

\[
M_{d,n} := |O(d)|_{\text{sm}}/G
\]

(1.1)
not representing the moduli functor
\[ \mathcal{M}_{d,n}: (\text{Sch}/k)^\circ \to \text{(Set)}. \]

By definition, \( \mathcal{M}_{d,n} \) sends a \( k \)-scheme \( T \) to the set \( \mathcal{M}_{d,n}(T) \) of equivalence classes of polarized smooth projective families \( (X, \mathcal{O}_X(1)) \to T \) with \( \mathcal{O}_X(1) \in \text{Pic}_X(T) \) such that all geometric fibres are isomorphic to a smooth hypersurface \( X \subset \mathbb{P}^{n+1} \) (over the appropriate field) of degree \( d \) with polarization given by the restriction \( \mathcal{O}_{\mathbb{P}^{n+1}}(1)|_X \).

However, \( \mathcal{M}_{d,n} \) is still a coarse moduli space which means the following.

**Corollary 1.13.** Assume \( d \geq 3 \). There exists a natural transformation \( \mathcal{M}_{d,n} \to \mathcal{M}_{d,n} \) such that

(i) The induced map \( \mathcal{M}_{d,n}(\text{Spec}(k')) \to \mathcal{M}_{d,n}(\text{Spec}(k')) \) is bijective for any algebraically closed field extension \( k'/k \).

(ii) Any natural transformation \( \mathcal{M}_{d,n} \to N \) to a \( k \)-scheme factorizes uniquely through a morphism \( \mathcal{M}_{d,n} \to N \) over \( k \).

The second condition is essentially a consequence of the fact that \( |\mathcal{O}(d)|_{\text{sm}} \to \mathcal{M}_{d,n} \) is a categorical quotient. The fact that \( |\mathcal{O}(d)|_{\text{sm}} \subset |\mathcal{O}(d)|^n \) and that \( |\mathcal{O}(d)|^n \to |\mathcal{O}(d)|^n/G \) is a geometric quotient implies the first one. For an outline of the details of the arguments see the discussion in [103, Sec. 5.2].

**Remark 1.14.** As some geometric arguments make use of actual families, one often has to find substitutes for it. The following techniques are the most frequent ones:

(i) Instead of working with a universal family over \( \mathcal{M}_{d,n} \), which does not exist, one uses the universal family \( \mathcal{X} \to |\mathcal{O}(d)|_{\text{sm}} \) and the fact that \( |\mathcal{O}(d)|_{\text{sm}} \to \mathcal{M}_{d,n} \) is a geometric quotient.

(ii) Assume \( n > 0 \), \( d \geq 3 \), and \( (n,d) \neq (1,3) \). Then, according to Theorem 1.3.12, there exists an open and dense subset \( \mathcal{V} \subset |\mathcal{O}(d)|_{\text{sm}} \) such that \( \text{Aut}(\mathcal{X}, \mathcal{O}_X(1)) = \{\text{id}\} \) for all \( [X] \in \mathcal{V} \). We may choose \( \mathcal{V} \) to be invariant under \( G \). Then there exists a universal family

\[ \tilde{\mathcal{X}} \to \mathcal{V} \subset \mathcal{M}_{d,n} \]

over the dense open subset \( \mathcal{V} := \mathcal{V}/G \subset \mathcal{M}_{d,n} \). Explicitly, set \( \tilde{\mathcal{X}} := \mathcal{X}/G \). It would be useful to have control over the closed set \( \mathcal{M}_{d,n} \setminus \mathcal{V} \), e.g. to know its codimension, cf. Remark 1.3.17.

(iii) Luna’s étale slice theorem can be applied and yields the following: For any point \( x := [X] \in |\mathcal{O}(d)|_{\text{sm}} \), there exists a \( G_x \)-invariant smooth locally closed subscheme \( [X] \in \mathcal{S} \subset |\mathcal{O}(d)|_{\text{sm}} \), the slice through \( [X] \), such that both natural morphisms

\[ S \times^{G_x} G \to |\mathcal{O}(d)|_{\text{sm}} \text{ and } S/G_x \to \mathcal{M}_{d,n} \]

are étale. The morphism \( S \to S/G_x \) is finite and over \( S \) a ‘universal’ family exists,
the pull-back of $\mathcal{X} \to |\mathcal{O}(d)|_{\text{sm}}$. In this sense, universal families exist étale locally over appropriate finite covers. See for example [118] for more on Luna’s étale slice theorem.

(iv) Universal family may not even exist in formal neighbourhoods of points $[X] \in M_{d,n}$. Using the notation in Section 1.3, for any $X$ the restriction of the moduli functor $\mathcal{M}_{d,n}$ to $(\text{Art}/k) \hookrightarrow \text{Sch}/k$, $A \to \text{Spec}(A)$, is the union of all

$$F_X \simeq F_{X,\mathcal{O}(1)}$$

(under the numerical assumptions of Proposition 1.39). This yields a finite morphism $\text{Def}(X, \mathcal{O}_X(1)) \to \text{Def}(X)$ onto the formal neighbourhood of $[X] \in M_{d,n}$, which is in fact the quotient by Aut$(X)$. Furthermore, over $\text{Def}(X, \mathcal{O}_X(1)) \simeq \text{Def}(X)$ there does exist a ‘universal’ family. This is a formal variant of (iii).

(v) Finally, using finite level structures, to be explained later, there exists a finite morphism $\tilde{M}_{d,n} \to M_{d,n}$ with a ‘universal’ family $\tilde{X} \to \tilde{M}_{d,n}$.

**Remark 1.15.** The non-existence of a universal family or, equivalently, the possibility of non-trivial automorphisms, is also responsible for the difference between the field of moduli and the (or, rather, a) field of definition. This is expressed by saying that for non-closed fields $k$ the map $\mathcal{M}_{d,n}(k) \to M_{d,n}(k)$ is usually not bijective.

To make this precise, let $X \subset \mathbb{P}^{n+1}_k$ be a hypersurface of degree $d$ and $[X] \in M_{d,n}(\bar{k})$ the corresponding closed point in the moduli space. The moduli space $M_{d,n}$ is defined over the ground field $k$ and so $[X] \in M_{d,n}$ has a residue field $k \subset k_{[X]} \subset \bar{k}$, the field of moduli of $X$, which is finite over $k$. However, $X$ may not be defined over its field of moduli $k_{[X]}$, but only over some finite extension $k_{[X]} \subset k$ of it (which is not necessarily unique), i.e. there exists a variety $X_0$ over $k_X \subset k$ such that $X \simeq X_0 \times_{k_X} \bar{k}$. Moreover, for all $\sigma \in \text{Aut}(k_{[X])}$ there exists a polarized automorphism $\varphi_\sigma: X_0^\sigma \to X_0$ over $k_X$. In fact, $k_{[X]}$ is the fixed field of all $\sigma \in \text{Aut}(\bar{k}/k)$ with $X^\sigma \simeq X$.

The isomorphisms $\varphi_\sigma$ do not necessarily define a descent datum, as $X_0$ may have non-trivial automorphisms. But if Aut$(X)$ is trivial, then indeed $k_{[X]}$ is a field of definition, which in this case is unique, and so $k_{[X]} = k_X$. As a consequence, one finds that for all $[X]$ in the open subset $\tilde{V} \subset M_{d,n}$ of hypersurfaces without automorphisms the field of definition and the field of moduli coincide, i.e. $X$ is defined over the residue field $k_{[X]}$ of $[X] \in M_{d,n}$.

2 **Stacks**

3 **Period approach**
With any (cubic) hypersurface $X \subset \mathbb{P}^{n+1}$ one associates its Fano variety of lines $F(X)$ or, more generally, of $m$-planes, contained in $X$. For a smooth cubic surface $S \subset \mathbb{P}^3$ the Fano variety $F(S)$ consists of 27 reduced points corresponding to the 27 lines contained in $S$. In higher dimensions, the Fano varieties $F(X)$ are even more interesting and have become a central topic of study in the theory of cubic hypersurfaces, especially in dimension three and four.

The classical references for Fano varieties of lines and planes are [5, 12]. For cubic hypersurfaces many arguments simplify dramatically and we will restrict to those whenever this is the case. For enumerative aspects we recommend [5, 69].

\section{Construction and infinitesimal behaviour}

We shall begin with an outline of the techniques that go into the construction of the Fano variety of linear subspaces $\mathbb{P}^m \subset \mathbb{P}^{n+1}$ contained in a given projective variety $X \subset \mathbb{P}^{n+1}$. The main tool is Grothendieck’s Quot-scheme, which also allows one to gain information about the tangent space of the Fano variety at a point corresponding to $\mathbb{P}^m \subset X$.

1.1 Let $k$ be an arbitrary field and $X \subset \mathbb{P} := \mathbb{P}^{n+1}$ be an arbitrary subvariety and $0 \leq m \leq n + 1$. Then consider the \textit{Fano functor}

\begin{equation}
F(X, m): \text{(Sch}/k) \rightarrow \text{(Set)}
\end{equation}

that sends a $k$-scheme $T$ (of finite type) to the set of all $T$-flat closed subschemes $L \subset T \times X$ such that all fibres $L_t \subset X_{(t)} \subset \mathbb{P}_{(t)}$ are linear subspaces of dimension $m$. We shall mostly be interested in the case of lines, i.e. $m = 1$, and will write $F(X) := F(X, 1)$ in this case.

Remark 1.1. Here are a few examples and easy observations.

(i) For $X = \mathbb{P}$, one obtains the Grassmann functor
$$ F(\mathbb{P}, m) = \mathbb{G}(m, \mathbb{P}). $$

(ii) For $m = 0$, the functor $F(X, 0)$ is the functor of points $h_X$.

(iii) For closed subschemes $X \subset X' \subset \mathbb{P}$ there is a natural inclusion
$$ F(X, m) \subset F(X', m) \subset F(\mathbb{P}, m) = \mathbb{G}(m, \mathbb{P}). $$

(iv) Let $P_m(\ell) := \binom{m+1}{\ell}$ and $\text{Hilb}^{P_m}(X)$ be the Hilbert functor that sends a $k$-scheme $T$ to the set of all $T$-flat closed subschemes $Z \subset T \times X$ with fibrewise Hilbert polynomial $\chi(Z, O_Z(\ell)) = P_m(\ell)$. Then
$$ F(X, m) = \text{Hilb}^{P_m}(X). $$

Here, we leave it as an exercise to show that any closed subvariety $Z \subset \mathbb{P}$ with Hilbert polynomial $P_m$ is indeed a linear subspace $\mathbb{P}^m \subset \mathbb{P}$.

Theorem 1.2. The Fano functor $F(X, m)$ is represented by a projective $k$-scheme $F(X, m)$, the Fano variety of $m$-planes in $X \subset \mathbb{P}$.

There are various ways to argue, but in the end the proof always comes down to the representability of the Grassmann functor.

• Use (iv) in the above remark and the representability of $\text{Hilb}^P(X)$ (for arbitrary projective $X$ and $P$) by the Hilbert scheme $\text{Hilb}^P(X)$. This in turn is a special case of the representability of the Grothendieck Quot-functor $\text{Quot}^P_{V/E}$ of quotients $E \to F$ with Hilbert polynomial $P$. Indeed, $\text{Hilb}^P(X) \simeq \text{Quot}^P_{V/O_X}$.

• The inclusion $F(X, m) \subset \mathbb{G}(m, \mathbb{P})$ in (iii) above describes a closed sub-functor. As the Grassmann functor $\mathbb{G}(m, \mathbb{P})$ is representable by the Grassmann variety $\mathbb{G}(m, \mathbb{P})$, $F(X, m)$ is represented by a closed subscheme $F(X, m) \subset \mathbb{G}(m, \mathbb{P})$.

Let us spell out the second approach a bit further. But first recall that
$$ \mathbb{O}(m, \mathbb{P}^{n+1}) \simeq \text{Gr}(m + 1, n + 2), $$

where $\text{Gr}(m + 1, n + 2)$ is the Grassmann variety of linear subspaces of $k^{n+2}$ of dimension $m + 1$ or, in other words,
$$ \mathbb{O}(m, \mathbb{P}^{n+1}) \simeq \text{Gr}(m + 1, n + 2) \simeq \text{Quot}_{\text{Spec}(k)/V}^{P_m+1-m}, $$

where $V = k^{n+2}$ and so $\mathbb{P} = \mathbb{P}^{n+1} = \mathbb{P}(V)$. The isomorphism between the corresponding functors $\text{Gr}(m + 1, n + 2) \longrightarrow \mathbb{G}(m, \mathbb{P}^{n+1})$ is given by $[G \subset V \otimes O_T] \longrightarrow \mathbb{P}(G)$.
Chapter 3. Fano varieties of lines

Also recall that $\mathcal{G}(m, \mathbb{P})$ is an irreducible, smooth, projective variety of dimension
$$\dim(\mathcal{G}(m, \mathbb{P})) = (m + 1) \cdot (n + 1 - m).$$
It is naturally embedded into $\mathbb{P}(\wedge^{n+1} V)$ via the Plücker embedding
$$\mathcal{G}(m, \mathbb{P}) \hookrightarrow \mathbb{P}\left(\wedge^{m+1} V\right), \quad L = \mathbb{P}(W) \twoheadrightarrow [\det(W)].$$
Under this embedding, $O(1)|_G \simeq \wedge^{m+1}(S^*)$. Here, $S$ is the universal subbundle, which is part of the universal exact sequence
$$0 \rightarrow S \rightarrow V \otimes O_G \rightarrow Q \rightarrow 0.$$ (1.2)
The universal family of $m$-planes over $\mathcal{G}(m, \mathbb{P})$ is the $\mathbb{P}^m$-bundle associated with $S$:
$$p: L_G := \mathbb{P}(S) \rightarrow \mathcal{G}(m, \mathbb{P}).$$
The inclusion $S \subset V \otimes O_G$ corresponds to the natural embedding
$$L_G \subset \mathcal{G}(m, \mathbb{P}) \times \mathbb{P}^{n+1}.$$
The induced projection $L_G \rightarrow \mathbb{P}^{n+1}$ satisfies
$$q^* O_{\mathbb{P}}(1) \simeq O_p(1).$$
Assume now that $X \subset \mathbb{P}$ is a hypersurface defined by $F \in H^0(\mathbb{P}, O(d)) \simeq S^d(V^*)$. Dualizing (1.2) and taking symmetric powers yields a natural surjection
$$S^d(V^*) \otimes O_G \twoheadrightarrow S^d(S^*)$$
and hence a map $S^d(V^*) \twoheadrightarrow H^0(\mathcal{G}, S^d(S^*))$. Let $s_F \in H^0(\mathcal{G}, S^d(S^*))$ denote the image of $F \in S^d(V^*) = k[x_0, \ldots, x_{n+1}]_d$ under this map
$$S^d(V^*) \twoheadrightarrow H^0(\mathcal{G}, S^d(S^*)), \quad F \mapsto s_F.$$ Then the Fano variety of $m$-planes on $X$ is the closed subvariety of the Grassmann variety defined as the zero-locus of $s_F$:
$$F(X, m) = V(s_F) \subset \mathcal{G}(m, \mathbb{P}).$$
In particular, whenever $F(X, m)$ is non-empty, then
$$\dim(F(X, m)) \geq \dim(\mathcal{G}(m, \mathbb{P})) - \text{rk}(S^d(S^*))$$
$$= (m + 1) \cdot (n + 1 - m) - \binom{m + d}{d}. \quad (1.3)$$
Moreover, in case of equality the class of $F(X, m)$, in the Chow ring or just in cohomology, can be expressed as
$$[F(X, m)] = c_r(S^d(S^*)), \quad (1.4)$$
where \( r = \text{rk}(S^d(S^*)) = \binom{m+d}{d} \). We will come back to this later, see Section 3.2. For more general subvarieties \( X \subseteq \mathbb{P} \) the argument is similar: If \( X = \bigcap V(F_i) \), then \( \mathcal{F}(X, m) = \bigcap V(s_{F_i}) \), where \( s_{F_i} \in H^0(\mathcal{O}(S^d(S^*))) \), \( d_i = \deg(F_i) \).

We shall denote the universal family of \( m \)-planes over \( F(X, m) \) by

\[
\mathcal{L} \rightarrow F(X, m),
\]

which is nothing but the restriction \( \mathcal{L} = \mathcal{L}_G|_{F(X, m)} = \mathcal{P}(S|_{F(X, m)}) \) of \( \mathcal{L}_G \) to \( F(X, m) \subseteq \mathcal{O}(m, \mathbb{P}) \). The composition of this natural inclusion with the Plücker embedding \( \mathcal{G}(m, \mathbb{P}) \) yields the Plücker embedding of the Fano variety of \( X \)

\[
F(X, m) \hookrightarrow \mathcal{G}(m, \mathbb{P}) \hookrightarrow \mathbb{P}\left(\bigwedge^{m+1} V\right).
\]

The restriction of the hyperplane line bundle \( \mathcal{O}(1)|_{F(X, m)} \cong \bigwedge^{m+1}(S^*|_{F(X, m)}) \) is called the Plücker polarization and its first Chern class will be denoted

\[
g = c_1(S^*|_{F(X, m)}) \in \text{CH}^1(F(X, m)), \tag{1.5}
\]

often also considered as a class in \( H^2(F(X, m), \mathbb{Z})(1) \).

The following universal variant will be very useful. Consider the universal hypersurface \( \mathcal{X} \rightarrow |\mathcal{O}(d)| = \mathbb{P}^d \), cf. Section 1.3. Then consider

\[
F(\mathcal{X}, m): (\text{Sch} / |\mathcal{O}(d)|)^o \longrightarrow \text{Set} \tag{1.6}
\]

that sends \( T \rightarrow |\mathcal{O}(d)| \) to the set of all \( T \)-flat closed subschemes \( L \subseteq \mathcal{X}_T \subseteq T \times \mathbb{P} \) parametrizing \( m \)-planes \( \mathbb{P}^m \subseteq \mathbb{P} \) in the fibres of \( \mathcal{X} \rightarrow |\mathcal{O}(d)| \). Using the relative version of the Quot-scheme or of the Grassmannian, one finds that \( F(\mathcal{X}, m) \) as a scheme over \( |\mathcal{O}(d)| \) is represented by a projective morphism

\[
F(\mathcal{X}, m) \longrightarrow |\mathcal{O}(d)|.
\]

By functoriality the fibre over \( [X] \in |\mathcal{O}(d)| \) is \( F(X, m) \) and one should think of \( F(\mathcal{X}, m) \) as parametrizing pairs \( (L \subseteq X) \) of \( m \)-planes contained in hypersurfaces of degree \( d \).

As in the absolute case, \( F(\mathcal{X}, m) \) can be realized as a closed subscheme of the relative Grassmannian

\[
F(\mathcal{X}, m) = \mathcal{V}(s_G) \subseteq |\mathcal{O}(d)| \times \mathcal{G}(m, \mathbb{P}),
\]

where \( s_G \in H^0(|\mathcal{O}(d)| \times \mathcal{G}, \mathcal{O}(1) \boxtimes S^d(S^*)) \) is the image of the universal equation \( G \in H^0(|\mathcal{O}(d)|, \mathcal{O}_G) = H^0(|\mathcal{O}(d)|, \mathcal{O}(1)) \boxtimes S^d(V^*) \) under the map

\[
\mathcal{O}(1) \boxtimes (S^d(V^*) \boxtimes \mathcal{O}_G) \longrightarrow \mathcal{O}(1) \boxtimes S^d(S^*). \tag{1.7}
\]

Let us now look at the other projection \( \pi: F(\mathcal{X}, m) \longrightarrow |\mathcal{O}(d)| \). From the description of \( F(\mathcal{X}, m) \) as \( \mathcal{V}(s_G) \subseteq |\mathcal{O}(d)| \times \mathcal{G}(m, \mathbb{P}) \) one deduces the isomorphism

\[
F(\mathcal{X}, m) \cong \mathbb{P}(\mathcal{K}) \longrightarrow \mathcal{G}(m, \mathbb{P}).
\]
Here, $\mathcal{K} \coloneqq \text{Ker}(S^d(V^*) \otimes O_G \longrightarrow S^d(S^*)$. In more concrete terms, the fibre of $\mathcal{K}$ at the point $L \in \mathbb{G}(m, \mathbb{P})$ is the vector space $H^0(\mathbb{P}, I_L \otimes O(d))$.

**Remark 1.3.** Instead of introducing the two moduli functors (1.1) and (1.6) and arguing that they can be represented by projective schemes, one could alternatively just use this description of $F(X, m)$ as a projective bundle over $\mathbb{G}(m, \mathbb{P})$ and define $F(X, m)$ as its fibre over $X$ under the other projection $F(X, m) \longrightarrow |O(d)|$. However, as soon as one needs to understand the local structure of these Fano schemes a functorial approach is preferable.

The above description of the universal Fano scheme allows one to compute its dimension.

**Proposition 1.4.** The relative Fano variety $F(X, m)$ of $m$-planes in hypersurfaces of degree $d$ in $\mathbb{P}^{n+1}$ is an irreducible, smooth, projective variety of dimension

\[
\dim(F(X, m)) = (m + 1) \cdot (n + 1 - m) + \binom{n + d}{d} - \binom{m + d}{d} - 1. \tag*{\Box}
\]

For example, for $m = 1$ and $d = 3$ the formula reads

\[
\dim(F(X, m)) = (2n - 4) + \binom{n + 4}{3} - 1.
\]

The first part of the following immediate consequence confirms (1.3).

**Corollary 1.5.** If for an arbitrary hypersurface $X \subset \mathbb{P}^{n+1}$ of degree $d$ the Fano variety $F(X, m)$ is not empty, then

\[
\dim(F(X, m)) \geq \dim(F(X, m)) - \dim|O(d)| - \binom{m + d}{d}.
\]

Moreover, equality holds in (1.8) for generic $X \in |O(d)|$ unless $F(X)$ is empty. \tag*{\Box}

The case of interest to us is $d = 3$ and $m = 1$. In this case, (1.8) becomes

\[
\dim(F(X)) \geq 2n - 4
\]

for non-empty $F(X)$. Using deformation theory, we shall see that $F(X)$ really is non-empty of dimension $2n - 4$ for all smooth cubic hypersurfaces of dimension at least two. This shall be explained next.
Remark 1.6. Also relevant for us is the case $d = 3$ and $m = 2$. Then $\dim(F(X, 2)) \geq 3n - 13$ as soon as $F(X) \neq \emptyset$. The right hand side is non-negative for $n \geq 5$. For $n < 5$ one can conclude that $F(X, 2)$ is empty for generic $X \in |\mathcal{O}(3)|$. So, for example, the generic cubic threefold and the generic cubic fourfold do not contain planes.

1.2 Any further study of the Fano variety of $m$-planes needs at least some amount of deformation theory. Let us begin with a recollection of some classical facts and a reminder of the main arguments. Most of the following can be found in standard textbooks, e.g. [71],[91],[105],[115],[158]. As smoothness is preserved under base change, we may assume for simplicity that $k$ is algebraically closed.

As the Fano variety of $m$-planes is a special case of the Hilbert scheme which in turn is a special case of the Quot-scheme, let us start with the latter.

Let $\mathcal{F} := \mathcal{E} \rightarrow \mathcal{F}_0 \in \text{Quot}_{X/E}$ be a closed point in the Quot-scheme of quotients of a given coherent sheaf $\mathcal{E}$ on $X$. We denote the kernel by $K_0 := \ker (\mathcal{E} \rightarrow \mathcal{F}_0)$.

Then there exists a natural isomorphism [84, Exp. 221, Sec. 5]

$$T_q \text{Quot} \simeq \text{Hom}(K_0, \mathcal{F}_0).$$

Moreover, if $\text{Ext}^1(K_0, \mathcal{F}_0) = 0$, then Quot is smooth at $q$.

Let us quickly recall the main arguments for both statements. See [105, Ch. 2.2] or [71, Ch. 6.4] for technical details. By the functorial property of the Quot-scheme, the tangent space $T_q \text{Quot}$ parametrizes quotients $E_k \rightarrow \mathcal{F}$ of $E_k = E \otimes k[e]$ on $X_e := X \times \text{Spec}(k[e])$ which are flat over $k[e]$ and the restriction of which to $X \subset X_k[e]$ gives back $q$. It is convenient to study the following more general situation. Assume an extension $q_A := [E_A \rightarrow \mathcal{F}]$ of $q := [E \rightarrow \mathcal{F}_0]$ to $X_A = X \times \text{Spec}(A)$ has been found already. Here, $A$ is a local Artinian $k$-algebra with residue field $k$. Consider a small extension $A' \rightarrow A = A'/I$, i.e. a local Artinian $k$-algebra $A'$ with maximal ideal $m_{A'}$ such that $I \cdot m_{A'} = 0$. Any further extension of $q_A$ to $q_{A'} := [E_{A'} \rightarrow \mathcal{F}]' \rightarrow \mathcal{F}$ leads to a commutative diagram of vertical and horizontal short exact sequences of the form

Here, one uses that $\mathcal{F}' \otimes_{A'} I = \mathcal{F}_0 \otimes_k I$, etc. Next observe that

$$\mathcal{F}' \simeq \text{Coker} (\psi : K' \rightarrow E_{A'} / (K_0 \otimes_k I)).$$
where \( \psi \) is the obvious map. Furthermore, the composition of \( \psi \) with the projection \( \varphi: \mathcal{E}_A/(K_0 \otimes I) \to \mathcal{E}_A \) is the given inclusion \( \mathcal{K} \to \mathcal{E}_A \). Conversely, one can define an extension \( F' \) in this way if the short exact sequence of coherent sheaves on \( X_A \)

\[
0 \to F_0 \otimes I \to \varphi^{-1}(\mathcal{K}) \to \mathcal{K} \to 0
\]

is split. The class of (1.9) is an element

\[
\phi \in \text{Ext}^i_{X_A}(\mathcal{K}, F_0 \otimes I) = \text{Ext}^i(X_0, F_0) \otimes I,
\]

where we use flatness of \( \mathcal{K} \) for the isomorphism. If this class is zero and a split has been chosen, then all other extensions differ by elements in

\[
\text{Hom}_{X_0}(\mathcal{K}, F_0 \otimes I) = \text{Hom}_{X}(\mathcal{K}, F_0) \otimes I.
\]

Hence, Quot is (formally) smooth at \( q = [\mathcal{E} \to F_0] \) if \( \text{Ext}^1(K_0, F_0) = 0 \) and the possible extension of \( q \) to \( X \times \text{Spec}(k) \) are parametrized by \( \text{Hom}(K_0, F_0) \).

Applied to \( \text{Hilb}(X) \cong \text{Quot}_{X/V,L} \), one finds that the tangent space at \( [Z] \in \text{Hilb}(X) \) is given by

\[
T_{[Z]}\text{Hilb}(X) = \text{Hom}(\mathcal{I}_Z, \mathcal{O}_Z)
\]

and that \( \text{Hilb}(X) \) is smooth at \( [Z] \) if \( \text{Ext}^1(\mathcal{I}_Z, \mathcal{O}_Z) = 0 \). Now assume that \( Z \subset X \) is a regular embedding with normal bundle \( N_{Z/X} \). Then \( \text{Hom}(\mathcal{I}_Z, \mathcal{O}_Z) \cong H^0(Z, N_{Z/X}) \) and the local to global spectral sequence, cf. [101] Ch. 3,

\[
E^2_{p,q} = H^p(Z, \text{Ext}^q(\mathcal{I}_Z, \mathcal{O}_Z)) \Rightarrow \text{Ext}^{p+q}(\mathcal{I}_Z, \mathcal{O}_Z)
\]

provides us with an exact sequence

\[
H^1(Z, N_{Z/X}) \to \text{Ext}^1(\mathcal{I}_Z, \mathcal{O}_Z) \to H^0(Z, \text{Ext}^1(\mathcal{I}_Z, \mathcal{O}_Z)) \to H^2(Z, N_{Z/X}).
\]

Furthermore, the obstruction spaces \( \text{Ext}^1(\mathcal{I}_Z, \mathcal{O}_Z) \) are indeed isomorphic to \( H^1(Z, N_{Z/X}) \).

**Example 1.7.** Let us test this in the case of \( \mathcal{O}(m, \mathbb{P}) = \text{Hilb}^m(\mathbb{P}) \). We know that at \( [L = \mathbb{P}(W)] \in \mathcal{G} = \mathcal{G}(m, \mathbb{P}) \) the tangent space \( T_{[L]}/\mathcal{G} \) is isomorphic to \( \text{Hom}(W, V/W) \) or, more globally, that \( T_0 \cong \text{Hom}(\mathcal{S}, \mathcal{Q}) \) with \( \mathcal{S} \) and \( \mathcal{Q} \) as in (1.3). On the other hand, \( T_{[L]}\text{Hilb}(\mathbb{P}) = \text{Hom}(\mathcal{I}_L, \mathcal{O}_L) \). And indeed, there is a natural isomorphism

\[
\text{Hom}(W, V/W) \cong \text{Hom}(\mathcal{I}_L, \mathcal{O}_L)
\]

between the two descriptions obtained by applying \( \text{Hom}(, \mathcal{O}_L) \) to the Koszul complex

\[
\cdots \to \wedge^2(V/W)^* \otimes \mathcal{O}(-2) \to (V/W)^* \otimes \mathcal{O}(-1) \to \mathcal{I}_L \to 0,
\]

associated with the equations \( (V/W)^* \to V^* \) for \( L = \mathbb{P}(W) \), and by using the natural isomorphisms \( \text{Hom}(V/W)^* \otimes \mathcal{O}(-1), \mathcal{O}_L) \cong (V/W) \otimes H^0(L, \mathcal{O}_L(1)) \cong \text{Hom}(W, V/W) \).
Applied to the case \([L] \in F(X, m) = \text{Hilb}^F(X)\) for an \(m\)-plane \(L \subset X\) in a variety \(X \subset \mathbb{P}\) that is assumed to be smooth (along \(L\)), one obtains the following result.

**Proposition 1.8.** Let \(L \subset X\) be an \(m\)-plane contained in a variety \(X \subset \mathbb{P}^{m+1}\) which is smooth along \(L\). Then the tangent space \(T_{[L]}F(X, m)\) of the Fano variety \(F(X, m)\) at the point \([L] \in F(X, m)\) corresponding to \(L\) is naturally isomorphic to \(H^0(L, N_{L/X})\):

\[
T_{[L]}F(X, m) \cong H^0(L, N_{L/X}).
\]

If \(H^1(L, N_{L/X}) = 0\), then \(F(X, m)\) is smooth at \([L]\) of dimension \(h^0(L, N_{L/X})\). \(\square\)

**Remark 1.9.** There exists a relative version of the above. Assume \(X \longrightarrow S\) is a projective morphism over a locally Noetherian base \(S\) and \(E\) is a coherent sheaf on \(X\). Then the relative Quot-scheme \(\pi: \text{Quot}_{X/S; E} \longrightarrow S\) parametrizes \(T\)-flat quotients \(E_T \longrightarrow F_0\) on \(X \times_S T\) for all \(S\)-schemes \(T\). It is a locally projective \(S\)-scheme with fibres \(\pi^{-1}(s) = \text{Quot}_{X_s/E_s}\), where \(X = X_s\). In particular, the relative tangent space at a closed point \(q = [E|_X \longrightarrow F_0] \in \text{Quot}_{X/S; E} \subset \text{Quot}_{X/S; E} \longrightarrow S\) is the tangent space of the fibre \(\pi^{-1}(s) = \text{Quot}_{X_s/E_s}\), i.e.

\[
T_q \text{Quot}_{X/S; E} \cong \text{Hom}_X(K_0, F_0),
\]

where \(K_0 = \ker(E|_X \longrightarrow F_0)\). More interestingly, if locally in \(X\) no obstructions occur to deform \(E|_X \longrightarrow F_0\) and \(H^1(X, \text{Hom}(K_0, F_0)) = 0\), then \(\pi\) is smooth at \(q\).

This applies to our situation. Consider the universal family \(X \longrightarrow \mathbb{O}(d)\) of hypersurfaces of degree \(d\) and let \(F(X, m) \longrightarrow \mathbb{O}(d)\) be the associated family of Fano varieties of \(m\)-planes in the fibres. Then the morphism \(F(X, m) \longrightarrow \mathbb{O}(d)\) is smooth at a point \([L]\) corresponding to an \(m\)-plane \(L \subset X\) in a smooth (along \(L\)) fibre \(X = X_s\) if \(H^1(X, N_{L/X}) = 0\).

### 1.3 Construction and infinitesimal behaviour

To compute the normal bundle \(N_{L/X}\) of an \(m\)-plane \(\mathbb{P}^m \supset L \subset X\) we use the short exact sequence

\[
0 \longrightarrow N_{L/X} \longrightarrow N_{L/\mathbb{P}} \longrightarrow N_{X/\mathbb{P}^m} \longrightarrow 0 \tag{1.10}
\]

of locally free sheaves on \(L \cong \mathbb{P}^m\), where we again assume that \(X\) is smooth or at least smooth along \(L\).

The normal bundle \(N_{L/\mathbb{P}}\) can be readily computed by means of a comparison of the Euler sequences for \(L \cong \mathbb{P}^m\) and \(\mathbb{P} = \mathbb{P}^{m+1}\). One finds \(N_{L/\mathbb{P}} \cong \mathbb{O}(1)^{\mathbb{P}^{m+1}-m}\). More precisely, if \(L = \mathbb{P}(W) \subset \mathbb{P} = \mathbb{P}(V)\), then \(N_{L/\mathbb{P}} \cong \mathbb{O}_L(1) \otimes (V/W)\).

If now \(X \subset \mathbb{P}\) is a smooth (at least along \(L\)) hypersurface of degree \(d\), then the exact sequence (1.10) becomes

\[
0 \longrightarrow N_{L/X} \longrightarrow \mathbb{O}_L(1)^{\mathbb{P}^{m+1}-m} \longrightarrow \mathbb{O}_L(d) \longrightarrow 0. \tag{1.11}
\]

After the appropriate coordinate change, the surjection can be understood as given by
Lemma 1.10. Let \( L \) which equals the right hand side of (1.8). Then
\[
\begin{array}{c}
\bigoplus_{i=0}^{m} \mathcal{O}_L(1) \xrightarrow{\partial} \bigoplus_{i=0}^{n+1} \mathcal{O}_L(1) \xrightarrow{\partial} \bigoplus_{i=0}^{n+1} \mathcal{O}_L(1)
\end{array}
\] (1.12)

Observe that (1.11) has the following numerical consequences
\[
\det(N_{L/X}) = \mathcal{O}_L(n + 1 - m) - d), \quad \text{rk}(N_{L/X}) = n - m, \quad \text{and}
\]
\[
\chi(N_{L/X}) = \chi(\mathcal{O}_L(1)) \cdot (n + 1 - m) - \chi(\mathcal{O}_L(d)) = (m + 1) \cdot (n + 1 - m) - \left(\frac{m + d}{d}\right)
\]
which equals the right hand side of (1.8).

For the case \( m = 1 \) and \( d = 3 \) this allows one to classify all normal bundles.

**Lemma 1.10.** Let \( L \subset X \) be a line in a smooth (along \( L \)) cubic hypersurface \( X \subset \mathbb{P}^{n+1} \). Then \( N_{L/X} \cong \mathcal{O}_L(a_1) \oplus \cdots \oplus \mathcal{O}_L(a_{n-1}), a_1 \geq \cdots \geq a_{n-1}, \) with
\[
(a_1, \ldots, a_{n-1}) = \begin{cases} (1, \ldots, 1, 0, 0) & \text{or} \\ (1, \ldots, 1, 1, -1). \end{cases}
\]

**Proof** As \( L \cong \mathbb{P}^1 \), any locally free sheaf is isomorphic to a direct sum of invertible sheaves, so \( N_{L/X} \cong \bigoplus \mathcal{O}_L(a_i) \) with \( \sum a_i = n - 3 \). On the other hand, the inclusion \( N_{L/X} \subset \mathcal{O}_L(1)^n \) yields \( a_i \leq 1 \). This immediately proves the result. \( \square \)

**Definition 1.11.** Lines with \( (a_i) = (1, \ldots, 1, 0, 0) \) and \( (a_i) = (1, \ldots, 1, 1, -1) \) are called *lines of the first type* and *of the second type*, respectively.

**Exercise 1.12.** Show that for any line \( L \subset X \) in a smooth cubic hypersurface, normal bundle sequence splits and, therefore, \( \mathcal{T}_L | \mathcal{L} \cong \mathcal{O}(2) \oplus N_{L/X} \). Note that in particular, the property of being of the first or of the second type can also be read off from the shape of \( \mathcal{T}_L | \mathcal{L} \).

Lemma 1.10 also shows that for a line \( \mathbb{P}^1 \cong L \subset X \) contained in a smooth (along \( L \)) cubic hypersurface \( X \subset \mathbb{P}^{n+1} \) the Fano variety \( F(X) \) is smooth of dimension \( 2n - 4 \) at \( [L] \in F(X) \). Indeed, smoothness follows from Proposition 1.8 and \( H^i(\mathbb{P}^1, \mathcal{O}_{\mathbb{P}^1}(a)) = 0 \) for \( a = -1, 0, 1 \). For the dimension observe that \( h^0(L, \bigoplus \mathcal{O}(a_i)) = 2n - 4 \) in the two cases \( (a_i) = (1, \ldots, 1, 0, 0) \) and \( (a_i) = (1, \ldots, 1, 1, -1) \).
Proposition 1.13. Let \( X \subset \mathbb{P}^{n+1} \) be a smooth cubic hypersurface, \( n \geq 2 \). Then the Fano variety of lines \( F(X) \) is smooth, projective, and of dimension
\[
\dim(F(X)) = 2n - 4.
\]

Proof. The preceding discussion essentially proves the claim. It remains to show that \( F(X) \) is non-empty. For this consider the Fermat cubic \( X_0 = V(x_0^3 + \cdots + x_{n+1}^3) \) which is smooth for \( \text{char}(k) \neq 3 \). Then clearly the line \( L_0 := V(x_0 + x_1, x_2 + x_3, \ldots, x_{n+1}) \) is contained in \( X_0 \) and hence \( F(X_0) \neq \emptyset \). For \( \text{char}(k) = 3 \) with \( \xi = \sqrt{-1} \in k \) one may take \( X_0 := V(\sum_{i=0}^{n} x_i^3 x_{i+1}^3 + x_3^2) \), see Section 1.2.2 and the line \( L_0 := V(x_0 - \xi x_1, x_2, \ldots, x_{n+1}) \). Of course, for the assertion one may assume \( k = \bar{k} \).

According to Remark 1.9, the vanishing \( H^1(L_0, \mathcal{N}_{L_0/X}) = 0 \) not only proves that the fibre \( F(X_0) \) of \( F(X) \) over \( [X_0] \in |\mathcal{O}(3)| \) is smooth at \( [L_0] \) but that in fact the morphism is smooth at \( [L_0] \). In particular, the projective morphism \( F(X) \to |\mathcal{O}(d)| \) is surjective which proves \( F(X) \neq \emptyset \) for all cubics. Alternatively, one may combine Corollary 1.3 to conclude that the generic non-empty fibre is of dimension exactly \( 2n - 4 \). Hence, again by Corollary 1.5, \( F(X) \to |\mathcal{O}(3)| \) has to be surjective, i.e. \( F(X) \) is non-empty for all \( X \). Yet another, more direct argument will be given in Remark 2.6.

The existence of lines in cubic hypersurfaces has the following immediate consequence. The assumption on the field can be weakened. One only needs the existence of one line contained in \( X \).

Corollary 1.14. For any cubic hypersurface \( X \subset \mathbb{P}^{n+1} \) of dimension \( n > 1 \) defined over an algebraically closed field, there exists a rational dominant map of degree two
\[
\mathbb{P}^n \dashrightarrow X.
\]

In particular, cubic hypersurfaces are unirational, cf. Remark 1.5.3.

Proof. Pick a line \( L \subset X \) and consider the projectivization of the restricted tangent bundle \( \mathbb{P}(T_X|_L) \to L \). A point in \( \mathbb{P}(T_X|_L) \) is represented by a tangent vector \( 0 \neq v \in T_xX \), which then defines a unique line \( L_v \subset \mathbb{P} \) passing through \( x \) with \( T_xL_v \subset T_xX \) spanned by \( v \). Then, either the line \( L_v \) is contained in \( X \) or, and this is the generic case, it is not. In the latter case, \( L_v \) intersects \( X \) in a unique point \( y_v \in X \) with the property that the scheme theoretic intersection \( L_v \cap X = 2x + y_v \). Note that \( y_v = x \) can occur.

Unless \( X \) contains a hyperplane, one defines in this way a rational map
\[
\mathbb{P}(T_X|_L) \to X, \quad v \mapsto y_v, \quad (1.13)
\]
which is regular on a dense open subset intersecting each fibre \( \mathbb{P}(T_xX), x \in L \).

Now, pick a point \( y \in X \setminus L \) in the image and consider the cubic curve \( C_y := \gamma L \cap X \). If \( C_y = L \cup Q \) with the residual quadric \( Q \) not containing \( L \), then there exist at most two
lines $y \in L_i$, $i = 1, 2$, that intersect $L$ and are tangent to $X$ at their intersection points. They are given by the (at most) two points of the intersection $L \cap Q$. In other words, under the assumption on $C$, the non-empty fibre of $v \mapsto y_i$ over $y$ would consist of at most two points. Furthermore, for dimension reasons, $\mathbb{P}(T_{\mathcal{C}}_{Y}) \to \mathbb{P} X$ would be dominant. To show that $C_y = L \cup Q$ satisfies $L \not\subset Q$ for at least one $y$ (and then for the generic one), take any tangent vector $v \in T_{\mathcal{C}} X$, $x \in L$, not contained in $T_{\mathcal{C}} X$. Then the line $L_v$ will not be tangent to $X$ at $x$ and, therefore, $L \not\subset Q$ for the residual quadric of $L \subset \mathbb{P}_{\mathcal{C}} \setminus X$. But then for any point $y \in Q$ the cubic $C_y$ has the desired property. Hence, the rational map $\mathcal{C}$ is generically of degree two and dominant.

**Remark 1.15.** The restriction of the map $\mathcal{C}$ to the fibre over one point $x \in L$ yields a rational map

$$\mathbb{P}^{n-1} \cong \mathbb{P}(T_{\mathcal{C} X}) \to X. \quad (1.14)$$

The indeterminacies of this map are contained in the set of tangent directions $v$ for which the line $L_v$ is contained in $X$. As the line $L_v$ is determined by the two points $x, y_v$, as soon as $x \neq y_v$, the map is injective on the open subset of tangent directions with $L_v \cap X \neq 3x$. Note that this open set is not empty, e.g. take the tangent direction of any line $x \in L \subset \mathbb{P}(T_{\mathcal{C} X}) \subset \mathbb{P}$ going through a point $y$ in $X \cap \mathbb{P}^{n-1}$, where $\mathbb{P}^{n} \subset \mathbb{P}$ is a generic linear subspace not containing $x$, cf. Remark 2.6. Warning: The rational subvariety $\mathcal{C}$ is not linear.

In Section 5 we shall describe the indeterminacy locus of $\mathcal{C}$ explicitly for $n = 3$. See Remark 1.5.3 for an alternative argument proving unrationality of cubic hypersurfaces containing a linear subspace $\mathbb{P}^{n-2}$ and, in fact, rationally for $n \geq 7$.

**Remark 1.16.** There is a general expectation (conjecture of Debarre–de Jong) that for $d \leq n+1$ and $\text{char}(k) = 0$ or at least $\text{char}(k) \geq d$ the Fano variety of lines $F(X)$ is smooth of the expected dimension $2n - d - 1$. For $d \leq 6$ this has been proved in characteristic zero in [22] for which we also refer for further references. See also [69] Prop. 6.40, where the claim is reduced to the case $d = n+1$.

**Remark 1.17.** Note that for $m \geq 2$ and an $m$-plane $L \subset X$ contained in a smooth (along $L$) hypersurface $X$ of degree $d$ such that $\mathcal{N}_{L/X} = \bigoplus \mathcal{O}(a_i)$ the Fano variety $F(X, m)$ is smooth at $\mathcal{L}$ of dimension $\sum h^0(\mathbb{P}^{m}, \mathcal{O}(a_i))$. However, in contrast to locally free sheaves on $\mathbb{P}^3$, there is a priori no reason why $\mathcal{N}_{L/X}$ on $L \simeq \mathbb{P}^{m}$ should be a direct sum of invertible sheaves. Also the dimension of $F(X, m)$ is harder to control as other cohomology groups $H^i(L, \mathcal{N}_{L/X})$ enter the picture.

1.4 We now come back to the difference between lines of the first and of the second type. As a warm-up we propose the following.

**Exercise 1.18.** Prove that for a line $L \subset X$ in a smooth cubic hypersurface the following
conditions are equivalent: (i) $L$ is of the first type, (ii) $H^1(L, N_{L/X}(-1)) = 0$, and (iii) 
\[ \dim H^0(L, N_{L/X}(-1)) = n - 3. \]

Find similar descriptions in terms of the restriction of the tangent bundle $T_X|_L$, cf. Exercise 1.12.

Assume now that $L$ is contained in a smooth hyperplane section $Y = X \cap H$. Show that
if $L$ is of the first type as a line in $Y$ then it is so as a line in $X$. The converse does not hold in general.

**Remark 1.19.** From Exercise 1.18 and (1.12) we deduce that a line $L \subset X$ in a smooth
cubic hypersurface $X = V(F)$ is of the first type if and only if the partial derivatives
\[ \partial_i F|_L \in H^0(L, O_L(2)) \]
span the three-dimensional space $H^0(L, O_L(2))$. Hence, $L$ is of the
second type if and only if $\langle \partial_i F|_L \rangle \subset H^0(L, O_L(2))$ is of dimension two. Note that
dim $\langle \partial_i F|_L \rangle \geq 2$ for all lines, as otherwise the $\partial_i F$ would have a common zero in at
least one point of $L$, contradicting the smoothness of $X$. More abstractly, (1.12) yields
for $L = \mathbb{P}(W)$ a natural map $V/W \otimes O_L(1) \rightarrow O_L(3)$ which after twisting and taking
global sections leads to
\[ \psi_L: V/W \rightarrow H^0(L, O_L(2)) = S^2(W^*), \quad (1.15) \]
which is of rank at least two and of rank three if and only if $L$ is of the first type.

**Example 1.20.** Consider the Fermat cubic $X = V(\sum x_i^3) \subset \mathbb{P}^{n+1}$ over a field $k$
with char($k$) \neq 3. Then $L = V(x_0 + x_1, x_2 + x_3, x_4, \ldots, x_{n+1})$ is a line of the second type
contained in $X$, see proof of Proposition 1.13. Indeed, under $\mathbb{P}^1 \rightarrow L$, $[t : s] \mapsto [t : -t : s : -s : 0 : \cdots : 0]$ the partial derivatives $\partial_i F$, $i = 0, \ldots, n + 1$, pull-back to $3t^3, 3t^2, 3s^3, 3s^2, 0, 0, \ldots, 0$ and, therefore, span a subspace only of dimension two in $H^0(\mathbb{P}^1, O_{\mathbb{P}^1}(2))$. We leave it to the reader to work out an example in the case char($k$) = 3.

The algebraic characterization of lines of the first and of the second type can be turned into
a geometric one in terms of the **Gauss map**. Often, when the Gauss map is involved,
some assumptions on the characteristic char($k$) of the ground field $k$ have to be made.
As we will usually only consider hypersurfaces of degree three, it will suffice to assume
that char($k$) \neq 2, 3. Recall that the Gauss map for a hypersurface $X = V(F) \subset \mathbb{P} := \mathbb{P}^{n+1}$
is the map
\[ \gamma_X: \mathbb{P} \rightarrow \mathbb{P}^n, \quad x \mapsto [\partial_0 F(x) : \cdots : \partial_{n+1} F(x)], \]
which is regular for smooth $X$. For $d > 1$ the morphism is not constant and hence finite. Then,
also its restriction
\[ \gamma_X: X \rightarrow X^* \subset \mathbb{P} \]
onto the dual variety $X^*$ is finite. Geometrically, $\gamma_X$ maps $x \in X$ to the projective tangent
space $T_x X$. Moreover, $\gamma_X$ is generically injective as $\gamma_X \circ \gamma_X = \text{id}$, cf. [69] Ch. 12.

As an immediate consequence of Remark 1.19 one then finds the following.
Chapter 3. Fano varieties of lines

Exercise 1.21. Let $L \subset X$ be a line in a smooth cubic hypersurface $X$. Prove the following assertions:

(i) The line $L$ is of the first type if and only if $\gamma_X: L \hookrightarrow \gamma_X(L)$ is an isomorphism onto a smooth plane conic.

(ii) The line $L$ is of the second type if $\gamma_X: L \twoheadrightarrow \gamma_X(L)$ is a degree two covering of a line.

Note that Lemma 1.10 applied to the case $n = 2$ leaves only one possibility, namely $\mathcal{N}_{L/X} \cong \mathcal{O}_L(-1)$, which counts as a line of the first type. For $n > 2$ there are two cases and both can be geometrically realized on any smooth cubic hypersurface, see [69, Prop. 6.30]. Indeed, see Example 1.20 for lines of the second type and use the dimension formulae in Lemma 1.23 and Proposition 1.13 for lines of the first type.

Here, $(1, \ldots, 1, 0, 0)$ describes the generic case or, equivalently, the set of lines of the second type $F_2(X)$ is a proper closed subscheme.

Remark 1.22. The characterization of lines of the second type given in Remark 1.19 in terms of the map $\psi_L$ in (1.15) globalizes to the following description of $F_2(X)$: There exists a canonical sheaf homomorphism $\psi: \mathcal{O} \rightarrow S^2(\mathcal{S}^2_F)$ for which $F_2(X)$ is the degeneracy locus:

$$F_2(X) := \{ [L] \mid h^0(L, \mathcal{N}_{L/X}(-1)) \geq n - 2 \} \subset F(X).$$

This observation immediately yields a dimension formula for $F_2(X)$.

Lemma 1.23. If not empty, the locus $F_2(X) \subset F(X)$ of lines of the second type contained in a smooth cubic hypersurface $X$ of dimension $n$ is of dimension

$$\dim(F_2(X)) = n - 2 = (1/2) \dim(F(X)).$$

Consequently, the closed set of all $x \in X$ contained in a line of the second type is of dimension at most $n - 1$.

Proof The proof has two parts. First, the usual dimension formula for the dimension of degeneracy loci shows $\text{codim}(M_2(\psi)) \leq (\text{rk}(\mathcal{O})) - 2 \cdot (\text{rk}(S^2(\mathcal{S}^2_F)) - 2) = n - 2$, cf. [9] [69] [74]. Therefore, $\dim(F_2(X)) \geq n - 2$. The second part consists of proving that $n - 2$ is an upper bound for the dimension which was first observed in [42, Cor. 7.6].

As $\gamma_X: X \hookrightarrow X$ is generically injective, the image of $q: \mathbb{L}_2 := p^{-1}(F_2) \twoheadrightarrow X$ is a proper closed subscheme and, therefore, of dimension at most $n - 1$. Hence, as the first projection $p: \mathbb{L}_2 \twoheadrightarrow F_2$ is of relative dimension one, it suffices to show that the map $q_2 := q|_{\mathbb{L}_2}: \mathbb{L}_2 \twoheadrightarrow q(\mathbb{L}_2) \subset X$ is finite. For $x \in q_2(\mathbb{L}_2)$ consider the map
Section 1: Construction and infinitesimal behaviour

For a generic smooth cubic hypersurface $X$.

Proposition 1.24. For a generic smooth cubic hypersurface $X \subset \mathbb{P}^{n+1}$ of dimension $n > 2$ the locus $F_2(X) \subset F(X)$ of lines of the second type is smooth and of dimension $\dim(F_2(X)) = n - 2 = (1/2) \dim(F(X))$.

Proof. The dimension formula has been established for all smooth $X$ already by Lemma 1.23. So, we only have to prove non-emptiness and the smoothness for generic $X$. However, the following arguments, adapted from [6], also provide an alternative proof for the dimension formula.

Consider the universal Fano variety of lines of the second type

$$F_2(X) \subset F(X) \subset [\mathcal{O}_P(3)] \times \mathbb{G}(1, \mathbb{P}),$$

cf. Proposition 1.5. So the fibre of $F_2(X) \longrightarrow [\mathcal{O}_P(3)]$ over the point corresponding to a smooth cubic $X$ is $F_2(X)$. The fibres of the other projection $\pi : F_2(X) \longrightarrow \mathbb{G}(1, \mathbb{P})$ are all isomorphic to, say, the fibre over the line $L = V(x_0, \ldots, x_{n-1}) \subset \mathbb{P}$. It is a closed subscheme of the fibre of $F(X)$, which is the projective space $\mathbb{P}_L := [\mathcal{I}_L \otimes \mathcal{O}_P(3)]$.

Recall from Exercise 1.21 that $\pi^{-1}(L) \subset \mathbb{P}_L$ in points corresponding to smooth cubics is characterized by the property that $\partial_i F_L \in H^0(L, \mathcal{O}_L(2))$, $i = 0, \ldots, n - 1$, span a two-dimensional subspace. Thus, $\pi^{-1}(L)$ is the degeneracy locus $M_2(\phi) \subset \mathbb{P}_L$ of the map $\phi : (x_0, \ldots, x_{n-1}) \otimes \mathcal{O}_P \longrightarrow H^0(\mathcal{O}_L(2)) \otimes \mathcal{O}_P$ which at the point $[F] \in \mathbb{P}_L$ is $\phi_F(x_i) = \partial_i F|_L$. The coefficients of $\phi$ are $3n$ of the all linear coordinates of $[\mathcal{I}_L \otimes \mathcal{O}_P(3)]$.

Thus, abstractly, the situation looks like $\phi = \begin{pmatrix} y_0 & \ldots & y_{n-1} \\ y_n & \ldots & y_{2n-1} \\ y_{2n} & \ldots & y_{3n-1} \end{pmatrix}$ on a projective space $\mathbb{P}^N$ with linear coordinates $y_0, \ldots, y_{3n-1}, y_0, \ldots, y_3$. Hence, $M_2(\phi)$ is the pre-image under the linear projection $\mathbb{P}^N \dashrightarrow \mathbb{P}(M(3, n))$ of the universal determinantal variety in $\mathbb{P}(M(3, n))$ (with the $3n$ coordinates $y_0, \ldots, y_{3n-1}$). Hence, the classical formulae apply, see [9][69], and show that $\text{codim}(M_2(\phi)) = (n - k) \cdot (3 - k)$. In particular, the fibre $\pi^{-1}(L)$ is of codimension $n - 2$ in $[\mathcal{I}_L \otimes \mathcal{O}_P(3)]$ and the singularities of the fibre over $L$ are contained in $M_1(\phi)$. This proves that $\dim(F_2(X)) = \dim([\mathcal{O}_P(3)] + n - 2$.

As the image of $F_2(X) \longrightarrow [\mathcal{O}_P(3)]$ meets the smooth locus, cf. Example 1.20 and
the fibre over any smooth \( X \in |\mathcal{O}_S(3)| \) is of dimension at most \( n - 2 \), cf. Lemma \[1.23]\n\( F_2(X) \) is indeed of dimension \( n - 2 \) for all smooth \( X \).

As \( \partial_i F_1 \in H^0(L, \mathcal{O}_L(2)) \) for a smooth cubic \( X = V(F) \) always span at least a two-dimensional space, the image of \( M_1(\phi) \) in \( |\mathcal{O}_S(3)| \) does not meet the open subset of smooth cubics. In other words, the open subset of \( F_2(X) \) lying over \( |\mathcal{O}_S(3)|_{\text{sm}} \subset |\mathcal{O}_S(3)| \) is smooth. Hence, \( F_2(X) \subset F(X) \) is smooth of dimension \( n - 2 \) for the generic smooth cubic hypersurface \( X \).

As an immediate consequence we show that the generic point \( x \in X \) is not contained in a line of the second type and that the generic point in the locus of points that are contained in a line of the second type is contained in only finitely many such.

**Corollary 1.25.** The image of \( \mathbb{L}_2 := p^{-1}(F_2(X)) \) under the projection \( q: \mathbb{L}_2 \to X \) is a divisor in \( X \).

**Proof** The \( \mathbb{P}^1 \)-bundle \( \mathbb{L}_2 \to F_2(X) \) was introduced already in the proof of Lemma \[1.23\] There, we showed that \( q: \mathbb{L}_2 \to X \) is finite on the dense open subset of points \( (\mathbb{L}, x) \in \mathbb{L}_2 \) for which the restriction of the Gauss map \( \gamma_{\mathbb{L}|\mathbb{L}} \) is not ramified in \( x \). This proves the assertion. \[\]

Later we will see that for specific \( n \) the locus \( F_2(X) \) often has a concrete geometric meaning, providing a different proof for \( \dim(F_2(X)) = n - 2 \). For example, for \( n = 3 \), so smooth cubic threefolds \( Y \subset \mathbb{P}^3 \), \( F_2(Y) \) is a ramification curve in the Fano surface \( F(Y) \) of a smooth cubic threefold \( Y \subset \mathbb{P}^4 \), see Section \[5.1.1\] Note however that \( F_2(Y) \) can be singular for specific smooth cubics and \( q: \mathbb{L}_2 \to X \) might have positive dimensional fibres, cf. Remark \[5.1.8\] Hence, the assumption that \( X \) is generic cannot be dropped, and

**Remark 1.26.** The description of \( F_2(X) \) as a degeneracy locus of the expected dimension allows one to compute its fundamental class \([F_2(X)] \in H^{n-2}(F(X), \mathbb{Z})\) in terms of Chern classes of \( S_F \) or, alternatively, of \( Q_F \) (Porteous’s formula). We will not do this in general, but see Section \[?? \] for the computation in the case of cubic fourfolds.

Lines of the first and of the second type can also be distinguished by the maximal dimension of linear subspaces that are tangent to it. In Section \[5.1.1\] especially Lemma \[5.2.1\], and Section \[6.3.2\], we will discuss the situation for cubic hypersurfaces of dimension three and four, but the general pictures as follows. First recall that a linear subspace containing a given line \( L = \mathbb{P}(W) \subset \mathbb{P}(U) \) is tangent to \( X \) along \( L \) if \( X \cap \mathbb{P}(U) \) is singular in all points of \( L \). More concretely, if \( L = V(x_2, \ldots, x_{n+1}) \subset \mathbb{P}(U) = V(x_{m+1}, \ldots, x_{n+1}) \) then \( \mathbb{P}(U) \) is tangent to \( X \) along \( L \) if and only if all derivatives \( \partial_i F, i = m+1, \ldots, n+1 \) vanish along \( L \), i.e. are contained in the kernel of the restriction map \( H^0(\mathbb{P}, \mathcal{O}_F(2)) \to H^0(L, \mathcal{O}_L(2)) \). Rewriting \[1.12\] shows that this is the case if and only if \( U \subset V \) maps to \( \mathcal{N}_{L/X}(-1) \subset \mathcal{N}_{L/\mathbb{P}}(-1) \) under the surjection \( V \otimes \mathcal{O} \to \mathcal{N}_{L/\mathbb{P}}(-1) \):
2 Global properties and a geometric Torelli theorem

Assume \( L \subset X \subset \mathbb{P}^{n+1} \) is a line contained in a smooth cubic.

(i) If \( L \) is of the first type, then there exists a unique linear \( L \subset \mathbb{P}(U_1) \approx \mathbb{P}^{n-2} \) that is tangent to \( X \) along \( L \).

(ii) If \( L \) is of the second type, then there exists a unique linear \( L \subset \mathbb{P}(U_2) \approx \mathbb{P}^{n-1} \) that is tangent to \( X \) along \( L \).

Proof In both cases, \( U \subset V \) is the pre-image under the map \( V \otimes \mathcal{O} \to \mathcal{N}_{X|P}(-1) \) of the maximal trivial subbundle \( \mathcal{O}_{L}^{\otimes k} \subset \mathcal{N}_{X|P}(-1) \subset \mathcal{N}_{L|P}(-1) \approx V/W \otimes \mathcal{O} \) with \( k = n-3 \) and \( k = n-2 \), respectively. \( \square \)

Note that for lines of the second type the linear \( L \subset \mathbb{P}(U_1) \approx \mathbb{P}^{n-2} \) as in (i) are the linear subspaces \( \mathbb{P}^{n-2} \subset \mathbb{P}(U_2) \) containing the line \( L \). They are naturally parametrized by a projective space \( \mathbb{P}^{n-3} \).

Remark 1.28. Consider the incidence variety \( \widetilde{F}(X) \) of all pairs \( (L, \mathbb{P}(U_1)) \in F(X) \times \mathbb{P}(n-2, \mathbb{P}) \) consisting of a line \( L \subset X \) and a linear subspace \( \mathbb{P}^{n-2} \approx \mathbb{P}(U_1) \subset \mathbb{P} \) such that \( L \) is contained in \( \mathbb{P}(U_1) \) and \( \mathbb{P}(U_1) \) is tangent to \( X \) along \( L \). Then

\[
\widetilde{F}(X) \to F(X), (L, \mathbb{P}(U_1)) \mapsto L
\]

is an isomorphism over \( F(X) \setminus F_2(X) \) and a \( \mathbb{P}^{n-3} \)-bundle over \( F_2(X) \subset F(X) \). So, at least over the open complement of the set \( F_2(X)_{\text{sing}} \subset F_2(X) \) of singular points of \( F_2(X) \), it looks like the blow-up \( \text{Bl}_{F_2(X)}(F(X)) \to F(X) \). Note that the other projection

\[
\widetilde{F}(X) \to \mathbb{P}(n-2, \mathbb{P}), (L, \mathbb{P}(U_1)) \mapsto \mathbb{P}(U_1)
\]

is a closed embedding if there is no linear subspace \( \mathbb{P}^{n-2} \subset X \).

2 Global properties and a geometric Torelli theorem

No information is lost when passing from a smooth cubic hypersurface to its Fano variety of lines. For cubic fourfolds the Plücker polarization of the Fano variety has to be
As the Fano variety is the zero set \( T \) and the adjunction formula yields
\[
\omega_F = O(4 - n)|_F.
\]

**Lemma 2.1.** For a smooth cubic hypersurface \( X \subset \mathbb{P}^{n+1} \) the canonical bundle \( \omega_F \) of the Fano variety of lines \( F = F(X) \subset \mathbb{C}(1, \mathbb{P}) \) is
\[
\omega_F = O(4 - n)|_F.
\]

**Proof** As the Fano variety is the zero set \( F = V(s_F) \subset \mathbb{C}(1, \mathbb{P}) \) of a regular section \( s_F \in H^0(\mathbb{C}, S^3(S^*)) \), the normal bundle sequence for \( F \subset \mathbb{C} \) takes the form
\[
0 \longrightarrow T_F \longrightarrow T_G|_F \longrightarrow S^3(S^*)_F \longrightarrow 0
\]
and the adjunction formula yields
\[
\omega_F = \det(T^*_F) = \left( \omega_G \otimes \det(S^3(S^*)) \right)|_F.
\]

As \( T_G \cong \text{Hom}(S, \mathbb{Q}) \), one has \( \omega_G = \det(S \otimes \mathbb{Q}) \cong \det(S^*)^{n-1} \otimes \det(Q^*)^3 \cong O(-n - 2)|_G \). Thus, it remains to prove that \( \det(S^3(S)) = \det(S)^6 \) which one deduces from a computation involving the splitting principle: Write formally \( S = L_0 \oplus L_1 \) and observe
\[
S^3(L_0 \oplus L_1) = L_0^3 \oplus (L_0^2 \oplus L_1) \oplus (L_0 \oplus L_1^2) \oplus L_1^3.
\]

Thus, for smooth cubic threefolds \( X \subset \mathbb{P}^4 \) the Fano variety of lines \( F(X) \) is a smooth projective surface with very ample canonical bundle, in particular \( F(X) \) is of general type. For smooth cubic fourfolds \( X \subset \mathbb{P}^5 \) the Fano variety \( F(X) \) has trivial canonical bundle \( \omega_F = O^* \) and we will later see that it is a four-dimensional hyperkähler manifold, see Theorem 6.2.7. Eventually, for \( n > 4 \) the Fano variety becomes a Fano variety in the sense that its anti-canonical bundle \( \omega_{F(X)}^* \) is ample. In short:
\[
\omega_{F(X)} = \begin{cases} 
\text{ample} & \text{if } n = 3, \\
\text{trivial} & \text{if } n = 4, \\
\text{anti-ample} & \text{if } n > 4.
\end{cases}
\]

**Exercise 2.2.** Use the arguments in the proof above to compute the Chern character \( \text{ch}(F) = \text{ch}(T_F) \). More precisely, if formally one writes \( c(S^*_F) = (1 + \ell_0) \cdot (1 + \ell_1) \), so that \( c_1(S^*_F) = \ell_0 + \ell_1 \) and \( c_2(S^*_F) = \ell_0 \cdot \ell_1 \), then for \( x_i := \exp(\ell_i) \)
\[
\text{ch}_2(F) = (x_0 + x_1) \cdot \left(n + 2 - (1/x_0) - (1/x_1) - x_0^2 - x_1^2\right).
\]
This gives back the above result \( c_1(F) = (n - 4) \cdot g \), where \( g = c_1(O(1)|_F) = -c_2(S_F) \), and
\[
\text{ch}_2(F) = (n/2 - 7) \cdot g^2 + (12 - n) \cdot c_2(S_F).
\]
which for \( n = 3 \) and \( n = 4 \) becomes \( c_2(F) = 6 \cdot g^2 - 9 \cdot c_2(S_F) \) and \( c_2(F) = 5 \cdot g^2 - 8 \cdot c_2(S_F) \).

We will later determine the (rational) cohomology of \( F(X) \) for any smooth cubic hypersurface \( X \subset \mathbb{P}^{n+1} \), cf. Section 3.5. At least in characteristic zero, the positivity property of the canonical bundle \( \omega_{F(X)} \) already implies certain vanishings, e.g. \( H^4(F(X), \mathcal{O}) = 0 \) for \( n > 4 \) and \( q > 0 \). See also Corollary 3.12 for an alternative approach. This allows one to prove the following result for \( n > 4 \).

**Corollary 2.3.** Let \( F = F(X) \) be the Fano variety of lines contained in the smooth cubic hypersurface \( X \subset \mathbb{P}^{n+1} \) over \( \mathbb{C} \). Then \( H^1(F, \mathbb{Z}) = 0 \) for \( n \geq 4 \) and, in particular, \( \text{Pic}^0(F) = 0 \). For \( n \geq 5 \) one has \( \text{Pic}(F) \cong H^2(F, \mathbb{Z})(1) \). \( \square \)

In fact, the vanishing of \( \text{Pic}^0(F) \) holds true in arbitrary characteristic, as Kodaira vanishing holds for liftable varieties [59].

Apart from the Fano variety of lines on a cubic surface, all others are connected, see [5 Thm. 1.16] and [12 Thm. 6]. This leads to the following strengthening of Proposition 1.13 [1].

**Proposition 2.4.** Let \( X \subset \mathbb{P}^{n+1} \) be a smooth cubic hypersurface of dimension \( n > 2 \). Then \( F(X) \) is an irreducible, smooth, projective variety of dimension \( 2n - 4 \).

**Proof.** More generally, Barth and Van den Ven [12] prove that the Fano variety of lines \( F(X) \) on any, not necessarily smooth, hypersurface \( X \subset \mathbb{P}^{n+1} \) of degree \( d \) is connected if \( d < 2(n - 1) \). They argue by bounding the dimension of the ramification locus (of the Stein factorization) of \( L \longrightarrow X \). Altman and Kleiman [5] use instead the Koszul complex

\[
\cdots \longrightarrow \wedge^2(S^3(S)) \longrightarrow S^3(S) \longrightarrow \mathcal{O}_X \longrightarrow \mathcal{O}_{F(X)} \longrightarrow 0. \tag{2.1}
\]

The induced spectral sequence

\[
E_1^{pq} = H^q(\mathcal{O}, \wedge^p(S^3(S))) \Rightarrow H^{p+q}(F(X), \mathcal{O}_{F(X)})
\]

combined with generalized Bott vanishing results for Grassmann varieties:

\[
H^p(\mathcal{O}, \wedge^p(S^3(S))) = 0 \text{ for all } p \neq 0
\]
yield \( H^p(\mathcal{O}, \mathcal{O}_X) \longrightarrow H^p(F(X), \mathcal{O}_{F(X)}) \). Hence, \( F(X) \) is connected.

For alternative arguments see Exercise 2.7 [2] for \( n \geq 4 \), and Example 3.16 [3]. \( \square \)

**Exercise 2.5.** Let \( X \subset \mathbb{P}^{n+1} \) be a cubic hypersurface and assume \( m \) is an integer with \( m^2 + 11m \leq 6n \). Show that there exists a linear subspace \( \mathbb{P}^m \subset X \subset \mathbb{P}^{n+1} \) of dimension \( m \) contained in \( X \).

---

1 One could think of applying the Fulton–Lazarsfeld connectivity [125 Thm. 7.2.1], to prove the connectivity of \( F(X, m) \) whenever \( \dim(F(X, m)) > 0 \). However, this would need the ampleness of \( S^d(S^*) \) which is just wrong.
Remark 2.6. For $n > 2$, the universal line $L = \mathbb{P}(S_{F/X}) \to F(X)$ maps onto $X$ or, equivalently, through every point $x \in X$ there exists at least one line $x \in L \subseteq X$, possibly defined only over a finite extension of the residue field of $x$.

To prove this claim we may assume that $k$ is algebraically closed. For a fixed point $x \in X$, let $\mathbb{P}^n \subseteq \mathbb{P}^{d+1}$ be a hyperplane not containing $x$. We may assume $x = [1 : 0 : \cdots : 0]$ and $\mathbb{P}^n = V(x_0)$. If $X = V(F)$, then the projective tangent space is the hyperplane $T_x X = V(\sum x_i \partial_i F(x)) \cong \mathbb{P}^n$ and any line $x \in L \subseteq T_x X$ has intersection multiplicity $\text{mult}_x (X, L) \geq 2$. For dimension reasons, there exists a point $y \in \mathbb{P}^n \cap T_x X \cap X \cap V(\partial_0 F)$. Then let $L = \overline{xy}$ be the line connecting the two points. We may choose coordinates such that $y = [0 : 1 : 0 : \cdots : 0]$ and then $F|_L$ is the polynomial $F(x_0, x_1, 0, \ldots, 0)$. By definition $\partial_0 F(y) = 0$ and by the Euler equation also $\partial_1 F(y) = 0$. Therefore, $\text{mult}_y (X, L) \geq 2$.

Alternatively, to prove surjectivity, one may first take hyperplane sections to reduce to the case of smooth cubic threefolds $Y \subseteq \mathbb{P}^4$. Then the result follows from [32] Cor. 8.2. Another more direct argument can be found in [43, Lem. 2.1]. The above proof is taken from [81].

Note that the argument also shows that the fibre of $L \to X$ over $x$ has the expected dimension $n - 3$ if and only if the intersection $\mathbb{P}^n \cap T_x X \cap X \cap V(\partial_0 F)$ is of this expected dimension $n - 3$.

Exercise 2.7. Assume $n \geq 4$ and observe that then $\mathbb{P}^n \cap T_x X \cap X \cap V(\partial_0 F)$ in Remark 2.6 is connected by Bertini’s theorem. Deduce from this that $F(X)$ is connected, thus proving Proposition 2.4 again for cubic hypersurfaces of dimension $n \geq 4$.

Remark 2.8. Consider the morphism $\sigma : L \to \mathbb{P}(T_X)$ that is induced by the inclusion $T_{L/F(X)} \hookrightarrow q^* T_X$. Concretely, $\sigma$ maps a point $([L], x) \in L$ to the tangent direction of $L$ at $x \in L$. On each fibre of the projection $p : L \to F(X)$ the morphism $\sigma$ is described by the natural embedding $L \cong \mathbb{P}(T_L) \hookrightarrow \mathbb{P}(T_X)$. It is injective, as the line $L$ is uniquely determined by the point $x$ and the tangent line $T_x L$. One checks that $\sigma$ also separates tangent directions and that, therefore, it is in fact a closed embedding. This yields the following picture

$$\begin{array}{ccc}
L & \xrightarrow{\sigma} & \mathbb{P}(T_X) \\
\downarrow p & & \downarrow q \\
F(X) & \xrightarrow{x} & X
\end{array}$$

Note that the various line bundles enjoy the following compatibilities:

$q^* \mathcal{O}_X(1) \simeq \mathcal{O}_p(1)$ and $\sigma^* \mathcal{O}_p(1) \simeq \mathcal{O}_p(-2) \otimes p^* \mathcal{O}_F(1)$. 

Chapter 3. Fano varieties of lines
For the second, combine \( \sigma^* \mathcal{O}_L(-1) \cong \mathcal{T}_{L/F(X)} \), which holds by definition of \( \sigma \), and the relative Euler sequence for \( p \).

Note that \( L \subset \mathbb{P}(T_X) \) is of codimension two. In particular, all fibres of \( q: L \to X \) satisfy
\[
\dim(q^{-1}(x)) \leq n - 1.
\]
Using Remark 2.6 one sees that the fibre \( q^{-1}(x) \subset \mathbb{P}(T_xX) \) is an intersection of a cubic and a quadric. So, if it is of the expected dimension \( n - 3 \), it is a \((2,3)\) complete intersection and, in particular, of degree six, cf. Lemma 4.6

**Exercise 2.9.** Show that the normal bundle of the natural embedding \( L \subset F(X) \times X \) is isomorphic to \( N_{L/F(X)\times X} \cong \sigma^*(\mathcal{T}_n \otimes \mathcal{O}_x(-1)) \cong \sigma^*\mathcal{T}_n \otimes \mathcal{O}_p(2) \otimes p^*\mathcal{O}_F(-1) \).

2.2 The following ‘geometric global Torelli theorem’ generalizes a well known result for \( n = 3 \) which we shall explain in Section 5.2.3. It turns out, that the general proof is less geometric but in the end much easier. We follow [39], where a more general version is proved allowing the cubic hypersurfaces to have isolated singularities.

**Proposition 2.10.** Assume \( X, X' \subset \mathbb{P}^{n+1} \) are smooth cubic hypersurfaces of dimension \( n > 2 \) and let \( F(X) \) and \( F(X') \) be their Fano varieties of lines endowed with the natural Plücker polarizations \( \mathcal{O}_F(1) \) and \( \mathcal{O}_{F'}(1) \), respectively.

Then \( X \cong X' \) if and only if \( (F(X), \mathcal{O}_F(1)) \cong (F(X'), \mathcal{O}_{F'}(1)) \) as polarized varieties. For \( n \neq 4 \) this is equivalent to \( F(X) \cong F(X') \) as unpolarized varieties.

**Proof** Any isomorphism \( X \cong X' \) is induced by an automorphism of the ambient projective space, cf. Corollary 13.6. Therefore, it naturally induces an isomorphism between the Fano varieties of lines, which in addition is automatically polarized.

For the converse assume that we have an isomorphism \( F(X) \cong F(X') \). As a first step one shows that for \( n \neq 4 \) the isomorphism be assumed to be polarized. Indeed, for \( n \neq 4 \), the canonical bundle \( \omega_F \cong \mathcal{O}_F(4-n) \) is a non-trivial, possibly negative, multiple of the Plücker polarization \( \mathcal{O}_F(1) \). Clearly, any isomorphism \( F(X) \cong F(X') \) respects the canonical bundle. Using that \( \text{Pic}(F(X)) \) is torsion free for \( n > 4 \), this implies that any isomorphism \( F(X) \cong F(X') \) is automatically polarized. To see that \( \text{Pic}(F(X)) \) is torsion free, observe that for a torsion line bundle \( L \) one has \( \chi(F(X), L) = \chi(F(X), \mathcal{O}) = 1 \), as \( F(X) \) is a Fano variety for \( n > 4 \), with \( H^i(F(X), L) = 0 \) for \( i > 0 \) by Kodaira vanishing (which holds also in positive characteristic zero, as \( F(X) \) is liftable to characteristic zero [59]), and, therefore, \( L \cong \mathcal{O} \). For \( n = 3 \), the fact that \( \omega_F \cong \mathcal{O}(1)|_F \) suffices to conclude.

Thus, from now on we can assume that we are given a polarized isomorphism between two Fano varieties \( (F(X), \mathcal{O}_F(1)) \cong (F(X'), \mathcal{O}_{F'(X)}(1)) \). The restriction under

---

2 Thanks to S. Stark for the argument. Alternatively, one can use [53]. As an aside, \( \text{Pic}(F(X)) \) is also torsion free for \( n = 4 \), as then \( F(X) \) is a hyperkähler manifold, see Chapter ?? ?? and, therefore, \( \text{Pic}(F(X) = \text{NS}(F(X)), \text{cf. Remark 3.14} \).
Chapter 3. Fano varieties of lines

$F(X) \subset \mathcal{G} \subset \mathbb{P}(\wedge^2 V)$ yields isomorphisms $H^0(\mathbb{P}(\wedge^2 V), \mathcal{O}(1)) \xrightarrow{\sim} H^0(\mathcal{G}, \mathcal{O}_\mathcal{G}(1)) \xrightarrow{\sim} H^0(F(X), \mathcal{O}_F(1))$ and similarly for $F(X')$. The first isomorphism is classical, Plücker coordinates form a complete linear system. For the second one, use the Koszul complex (2.1) twisted by $\mathcal{O}(1)$, the associated spectral sequence, and $H^i(\mathcal{G}, \wedge^i S^3(S)) = 0$ for all $i$, see [5, Thm. 5.1]. Thus, any given polarized isomorphism sits in a commutative diagram

\[
\begin{array}{ccc}
F(X) & \xrightarrow{\sim} & \mathcal{G} \\
& \downarrow & \downarrow \\
F(X') & \xrightarrow{\sim} & \mathcal{G}
\end{array}
\]

(2.3)

The next step consists of completing the diagram by an automorphism of $\mathcal{G}$. For this use again (2.1), now twisted by $\mathcal{O}(2)$. Again using [5 Thm. 5.1], one finds that restriction yields an injection $H^0(\mathcal{G}, \mathcal{O}_\mathcal{G}(2)) \xhookrightarrow{\sim} H^0(F(X), \mathcal{O}_F(2))$. In fact, it is also surjective except possibly for $n = 4$. On the other hand, it is known classically, see [77, Ex. 8.12], that $\mathcal{G} \subset \mathbb{P}(\wedge^2 V)$ is cut out by quadrics, i.e. by the kernel of the restriction map $H^0(\mathbb{P}(\wedge^2 V), \mathcal{O}(2)) \longrightarrow H^0(\mathcal{G}, \mathcal{O}_\mathcal{G}(2))$. As this kernel coincides with the kernel of the restriction map to $F(X)$, the automorphism of $\mathbb{P}(\wedge^2 V)$ in (2.3) restricts to an automorphism of $\mathcal{G}$.

However, automorphisms of $\mathcal{G}$ are classified. In our situation, they are all induced by automorphisms of $V$, see [41] or [88, Thm. 10.19]. This results in an automorphism of the whole correspondence $\mathcal{G} \xhookrightarrow{\sim} \mathbb{P}(S) \longrightarrow \mathbb{P}(V)$. The final result is the commutative diagram

\[
\begin{array}{ccc}
X & \xrightarrow{\sim} & \mathbb{P}(V) \\
& \downarrow & \downarrow \\
& \sim & \downarrow \\
& \sim & \downarrow \\
F(X) & \xrightarrow{\sim} & F(X')
\end{array}
\]

The surjectivity of $L \longrightarrow X$, i.e. the fact that there exists a line through every point, eventually shows that the automorphism of $\mathbb{P}(V)$ restricts to an isomorphism $X \cong X'$. □

The proof above shows more, namely that any (polarized) isomorphism $F(X) \cong F(X')$ is induced by an isomorphism $X \cong X'$. For $n = 3$ we will provide a different proof which relies on an isomorphism between the restriction of the tautological bundle $S_F$ and the tangent sheaf $T_F$, see Proposition [52.8]
Corollary 2.11. For a smooth cubic hypersurface $X \subset \mathbb{P}^{n+1}$ of dimension $n \neq 4$ the group of automorphisms $\text{Aut}(F(X))$ of its Fano variety of lines is finite and $H^0(X, \mathcal{T}_{F(X)}) = 0$. The vanishing holds as well for $n = 4$.

Proof By the arguments in the above proof, for $n \neq 4$ any automorphism $F(X) \cong F(X)$ is induced by an automorphism of $X$. As $\text{Aut}(X)$ is finite for all cubic hypersurfaces of dimension by Corollary 1.3.6 this proves the assertion. The tangent space of the group scheme $\text{Aut}(F(X))$ is $H^0(F(X), \mathcal{T}_{F(X)})$, which therefore has to vanish. For $n = 4$ one argues using polarized automorphisms. □

In the same vain, also the natural map

$$H^1(X, \mathcal{T}_X) \hookrightarrow H^1(F(X), \mathcal{T}_{F(X)})$$

(2.4)

that associates to a first order deformation of $X$ a first order deformation of $F(X)$ is injective for $n > 2$. We give a Hodge theoretic proof of this fact later, see Corollary 4.5.

3 Cohomology and motives

According to Proposition 2.10 the Fano variety $F(X)$ of lines contained in a smooth cubic hypersurface $X$ determines the hypersurface. Therefore, essentially all and, in particular, all cohomological and motivic information about $X$ should be encoded by $F(X)$. In this section we shall study the cohomology of $F(X)$ and we shall do this by first looking at the motive of $F(X)$.

3.1 As the Fano variety $F(X)$ itself, its motive is an interesting object to study. Now, the motive of $F(X)$ may mean various things. Here, we are interested in the class $[F(X)]$ of $F(X)$ in the Grothendieck ring of varieties $K_0(\text{Var}_k)$ and in its motive $h(F(X))$ in the category $\text{Mot}(k)$ of rational Chow motives.

We begin with the Grothendieck ring $K_0(\text{Var}_k)$ of varieties over a field $k$. Recall that by definition it is the abelian group generated by classes $[Y]$ of quasi-projective varieties modulo one relation $[Y] = [Z] + [U]$, the scissor relation, for any closed subset $Z \subset Y$ with open complement $U = Y \setminus Z$. The abelian group $K_0(\text{Var}_k)$ becomes a ring by defining multiplication by the formula $[Y] \cdot [Y'] = [Y \times Y']$.

The Lefschetz motive is the class $\ell := [A^1]$ of the affine line. An important consequence of the scissor relation is the fact that $[Y] = [F] \cdot [Z]$ for any Zariski locally trivial fibration $Y \rightarrow Z$ with fibre $F$. See for example [8] Ch. 13 or [38] Ch. 2 for more details.
Exercise 3.1. Note that for the last assertion it is not enough to assume that the fibration $Y \longrightarrow Z$ is étale locally trivial. Show that otherwise $\ell = 0$ in $K_0(\text{Var}_k)$.

In (75), the class $[F(X)] \in K_0(\text{Var}_k)$ is related to the class $[X^{(2)}] \in K_0(\text{Var}_k)$ of the Hilbert scheme $X^{(2)}$ of subschemes of $X$ of length two. The Hilbert scheme can be obtained as the blow-up of the symmetric product $X^{(2)} := (X \times X)/\mathbb{Z}_2$ along the diagonal $X \simeq \Delta \subset X^{(2)}$. Hence, in $K_0(\text{Var}_k)$ one has

$$[X^{(2)}] - [\mathbb{P}^{n-1}] \cdot [X] = [X^{(2)}] - [X]. \quad (3.1)$$

Proposition 3.2 (Galkin–Shinder). Let $X \subset \mathbb{P}^{n+1}$ be a smooth cubic hypersurface. Then in $K_0(\text{Var}_k)$

$$[X^{(2)}] = [\mathbb{P}^n] \cdot [X] + \ell^2 \cdot [F(X)]$$

and

$$[X^{(2)}] = (1 + \ell^3) \cdot [X] + \ell^2 \cdot [F(X)].$$

Proof. We follow closely the argument in (75), where one also finds a version for singular cubics.

Consider the universal family $F(X) \leftarrow \mathbb{L} \longrightarrow X$ of lines contained in $X$. As $\mathbb{L} \longrightarrow F(X)$ is the $\mathbb{P}^1$-bundle $\mathbb{P}(S|_{F(X)}) \longrightarrow F(X)$, its class in $K_0(\text{Var}_k)$ is given by

$$[\mathbb{L}] = [\mathbb{P}^1] \cdot [F(X)]. \quad (3.2)$$

Similarly, we let $\mathbb{G} = \mathbb{G}(1, \mathbb{P}) \longleftarrow \mathbb{L}_G \longrightarrow \mathbb{P}$ be the universal family of lines in $\mathbb{P} = \mathbb{P}^{n+1}$ and let $\mathbb{L}_G|_X$ be the pre-image of $X$ under the second projection. Then $\mathbb{L}_G|_X$ parametrizes pairs $(x, L)$ consisting of a line $L \subset \mathbb{P}$ and a point $x \in X \cap L$. It can also be described as the $\mathbb{P}^n$-bundle $\mathbb{P}(\mathbb{T}_x|_X) \longrightarrow X$, cf. the construction in the proof of Corollary (1.14). This shows that in $K_0(\text{Var}_k)$ one has

$$[\mathbb{L}_G|_X] = [\mathbb{P}^n] \cdot [X]. \quad (3.3)$$

Next, consider the morphism $\mathbb{L}_G|_X \backslash \mathbb{L} \longrightarrow X^{(2)}$ that sends $(x, L)$ to the residual intersection $[(L \cap X) \setminus \{x\}] \in X^{(2)}$. It is inverse to the morphism $X^{(2)} \setminus L^{(2)} \longrightarrow \mathbb{L}_G|_X$ that sends $[Z] \in X^{(2)}$ to $(x, L_Z)$, where $L_Z \subset \mathbb{P}$ is the unique line containing the length two-subscheme $Z \subset \mathbb{P}$ and $x$ is the residual point of the inclusion $Z \subset X \cap L_Z$.

Here, $L^{(2)}$ is the relative symmetric product of the universal line $p : \mathbb{L} \longrightarrow F(X)$, which equivalently can be described as the relative Hilbert scheme of subschemes of length two in the fibres of $p$ or, still equivalently, as $L^{(2)} = \mathbb{P}(S^2(S^*|_{F(X)})) \longrightarrow F(X)$. In particular,

$$[L^{(2)}] = [\mathbb{P}^2] \cdot [F(X)] \quad (3.4)$$

in $K_0(\text{Var}_k)$. The isomorphism

$$\mathbb{L}_G|_X \backslash \mathbb{L} \simeq X^{(2)} \setminus L^{(2)}$$
Cohomology and motives

3 Cohomology and motives

97
together with (3.2), (3.3), and (3.4) yields the first assertion. The second follows from
(3.1).
□

Remark 3.3. A closer inspection reveals, see [176, Prop. 2.9] for further details, that
the construction in the proof above leads to the following picture:

\[
\begin{align*}
\text{Bl}_L(L|_X) &= \text{Bl}_L(X^{[2]}) \\
\cup &
\end{align*}
\]

Here, \(E\) is the exceptional divisor of the two blow-up morphisms. In fact, \(\text{Bl}_L(L|_X) \cong \text{Bl}_L(X^{[2]})\) is an irreducible component of the incidence variety
\[
\{(x, L, Z) \mid x \in L \cap X, Z \subset L \cap X \} \subset X \times L|_X \times X^{[2]}
\]
and \(E \cong L \times F(X)\).

Let us apply the standard formulae for cohomology and motives of smooth blow-
ups and projective bundles to (3.5). For example, using \(\text{codim}(L \subset L|_X) = 3\) and
\(\text{codim}(L^{[2]} \subset X^{[2]}) = 2\), in the category of rational \(\text{Chow motives} \text{Mot}(k)\) one has
\[
\begin{align*}
\text{b}(&\text{Bl}_L(L|_X)) \oplus \text{b}(L)(-3) \cong \text{b}(L|_X) \oplus \text{b}(E)(-1)
\end{align*}
\]
and
\[
\begin{align*}
\text{b}(&\text{Bl}_L(X^{[2]})) \oplus \text{b}(L^{[2]})(-2) \cong \text{b}(X^{[2]}) \oplus \text{b}(E)(-1).
\end{align*}
\]
see [8][144]. Here, \(\text{b}(Y)(-i) := \text{b}(Y) \otimes (\mathbb{P}^1, [\mathbb{P}^1 \times X])^{\otimes i}\) is the twist with the \(i\)-th power of the Lefschetz motive. This can be combined with
\[
\begin{align*}
\text{b}(L) &= \text{b}(F(X)) \oplus \text{b}(F(X))(-1), \\
\text{b}(L|_X) &= \bigoplus_{i=0}^{n} \text{b}(X)(-i), \text{ and} \\
\text{b}(L^{[2]}) &= \text{b}(F(X)) \oplus \text{b}(F(X))(-1) \oplus \text{b}(F(X))(-2).
\end{align*}
\]
The isomorphism \(\text{Bl}_L(L|_X) \cong \text{Bl}_L(X^{[2]})\) then yields a formula which, if cancellation
holds in \(\text{Mot}(k)\), would look like this:
\[
\begin{align*}
\text{b}(F(X))(-2) \oplus \bigoplus_{i=0}^{n} \text{b}(X)(-i) \cong \text{b}(X^{[2]}).
\end{align*}
\]
That cancellation does hold in this case was proved in \cite{123}. The formula can be combined with the isomorphism
\[
h(X^{[2]}) \simeq S^2 h(X) \oplus \bigoplus_{i=1}^{n-1} h(X)(-i),
\]
which shows that finite-dimensionality of \( h(X) \) in the sense of Kimura implies finite-dimensionality of \( h(F(X)) \), cf. \cite{123, Thm. 4}.

One also expects the following isomorphism to hold:
\[
h(F(X))(-2) \oplus h(X) \oplus h(X)(-n) \simeq S^2 h(X),
\]
which would follow from the above if cancellation holds. Using the decomposition
\[
h(X) \simeq h^0(X)_{pr} \oplus \bigoplus_{i=0}^n Q(-i),
\]
and cancellation, this then becomes
\[
h(F(X))(-2) \oplus Q(-n) \simeq S^2 h^0(X)_{pr} \oplus \bigoplus_{i=1}^{n-1} h^0(X)_{pr}(-i) \oplus \bigoplus_{0 \leq i \leq n} Q(-i-j).
\]
Here, \( Q(1) \) is the Tate motive \( (\text{Spec}(k), \text{id}, 1) \), the dual of the Lefschetz motive.

**Remark 3.4.** Assigning the motive \( h(X) \) to a smooth projective variety \( X \) descends to a linear map
\[
K_0(\text{Var}_k) \longrightarrow K_0(\text{Mot}_k).
\]
The Grothendieck group on the right hand side is by definition the abelian group generated by all rational Chow motives \( h \) subject to the relation \([h] + [h'] = [h \oplus h']\). This allows one to deduce the above isomorphisms without assuming cancellation as equalities in \( K_0(\text{Var}_k) \).

### 3.2 Combining the information obtained from the description of \( F(X) \subset \mathbb{G}(1, \mathbb{P}) \) as the zero set \( V(s_F) \) and the description of its class \([F(X)] \in K_0(\text{Var}_k)\), one can deduce the following numerical information, see \cite[Prop. 1.6]{5} and \cite[Cor. 5.2]{75}. The case \( n = 3 \) goes back to \cite{28}.

**Proposition 3.5** (Altman–Kleiman, Galkin–Shinder). Let \( X \subset \mathbb{P}^{n+1} \) be a smooth cubic hypersurface and let \( F(X) \) be its Fano variety of lines considered with its Plücker embedding \( F(X) \hookrightarrow \mathbb{G}(1, \mathbb{P}) \hookrightarrow \mathbb{P}^{n+1} \). Then degree and Euler number of \( F(X) \) are given by the following formulae
\[
\deg(F(X)) = 27 \cdot \frac{(2n-4)!}{n! \cdot (n-1)!} \cdot (3n^2 - 7n + 4) \tag{3.10}
\]

\footnote{It is not known whether smooth cubic hypersurfaces of dimension \( 5 \neq n > 3 \) are Kimura finite-dimensional. For \( n = 3 \) the argument will be given in Section \cite[5]{5}. Finite-dimensionality is also known for \( n = 5 \) (with thanks to R. Laterveer for the explanation).}
and
\[ e(F(X)) = \frac{e(X) \cdot (e(X) - 3)}{2} = \frac{2^{n+4} + (-2)^n \cdot (6n + 1) + 3n \cdot (3n + 1) - 20}{18}. \tag{3.11} \]

**Proof**  As a special case of (1.4), we know that \([F(X)] = c_4(S^3(S^*))\) in the cohomology ring or in the Chow ring of \(\mathbb{G}\). Writing formally \(S^* = L_0 \oplus L_1\) and \(S^3(S^*) = L_0^3 \oplus (L_0^2 \oplus L_1) \oplus (L_0 \oplus L_1^2) \oplus L_1^3\) allows one to compute
\[
c_4(S^3(S^*)) = 9 \cdot (5 \ell_0^2 \ell_1^2 + 2 (\ell_0^3 \ell_1 + \ell_0 \ell_1^3)) = 9 \cdot (2 c_1(S^*)^2 + c_2(S^*)) \cdot c_2(S^*),
\]
where \(\ell_i = c_1(L_i)\). Hence,
\[
\deg(F(X)) = 9 \int \limits_{\mathbb{G}} c_1(S^*)^{2n-4} \cdot (2 c_1(S^*)^2 + c_2(S^*)) \cdot c_2(S^*).
\]
Using standard Schubert calculus (Pieri’s and Gambelli’s formulae), this is turned in [5] into a rather complicated formula which then can be simplified to the above.

In principle, the second assertion can also be deduced by Schubert calculus, as
\[
e(F(X)) = \int \limits_{F(X)} c_{2n-4} T_{F(X)} = \int \limits_{\mathbb{G}} \left( \frac{c(T_\mathbb{G})}{c(S^3(S^*))} \right)_{2n-4} \cdot c_4(S^3(S^*)).
\]
Here is a more illuminating way of doing this. Taking Euler numbers in the second equation in Proposition 3.2 yields
\[
e(X^{(2)}) = 2 \cdot e(X) + e(F(X)),
\]
where we use the additivity and the multiplicativity of the Euler number and \(e(l^n) = 1\), cf. [25]. As taking cohomology commutes with taking symmetric products, in other words \(H^*(X^{(n)}) = S^n H^*(X)\) (say with coefficients in a field of characteristic zero), cf. [83] Prop. 5.2.3 or [130], one has \(e(X^{(2)}) = (\frac{e(X) + 1}{2})^4\). This proves the first equality in (3.11) and the second follows from (1.16). \qed

---

4 The closed formula due to MacDonald says
\[
\sum_{n,o} e(X^{(n)}) z^n = (1 - z)^{-e(X)} = \exp \left( e(X) \cdot \sum_{r=1} \frac{z^r}{r!} \right),
\]
which is the geometric analogue of the well-known equality \(\sum_{n,o} |X^{(n)}(\mathbb{F}_q)| z^n = \exp \left( \sum \dim(F_q) \cdot z^r/r! \right)\) for the Zeta function of a variety over a finite field \(\mathbb{F}_q\) and which generalizes to an equality for the Poincaré polynomial
\[
\sum_{n,o} \left( \sum_{t=1} (-1)^t b_t(X^{(n)}) y^t \right) z^n = \frac{(1 - y^1 z^{b_1(X)}) \cdot (1 - y^2 z^{b_2(X)}) \cdots}{(1 - y z^\deg X) \cdot (1 - y^2 z^{\deg X}) \cdots}.
\]
Remark 3.6. Recall from Section 1.1.4 that the Euler numbers \( e(X_n) \) of smooth cubic hypersurfaces \( X_n \subset \mathbb{P}^{n+1} \) of arbitrary dimensions are encoded by the generating series
\[
\sum_{n=0}^{\infty} e(X_n) z^{n+1} = \frac{3z}{(1-z)^2(2z+1)}.
\]
A formal computation using Mathematica reveals
\[
\sum_{n=2}^{\infty} e(F(X_n)) z^{n+1} = \frac{27(1-2z)z^3}{(-1+z)^3(1+2z)^2(-1+4z)},
\]
but a conceptual understanding in the sense of Theorem 1.1.11 is not known.

<table>
<thead>
<tr>
<th>( n )</th>
<th>( \omega_{F(X)} )</th>
<th>( \dim(F(X)) )</th>
<th>( \deg(F(X)) )</th>
<th>( e(F(X)) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>( \mathcal{O} )</td>
<td>0</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td>3</td>
<td>( \mathcal{O}(1) )</td>
<td>2</td>
<td>45</td>
<td>27</td>
</tr>
<tr>
<td>4</td>
<td>( \mathcal{O} )</td>
<td>4</td>
<td>108</td>
<td>324</td>
</tr>
<tr>
<td>5</td>
<td>( \mathcal{O}(-1) )</td>
<td>6</td>
<td>297</td>
<td>702</td>
</tr>
</tbody>
</table>

3.3 The computation of the Euler number is only a shadow of the full cohomological information available. There are various ways to unpack the information encoded by the above motivic approach. We shall focus on the Hodge theoretic content and so assume from now on that \( k = \mathbb{C} \).

To start, let \( HS_{\mathbb{Z},n} \) be the additive category of polarizable, pure Hodge structures of weight \( n \), see [68] for more on this and the notation. Recall that the Tate twist defines an equivalence
\[
HS_{\mathbb{Z},n} \xrightarrow{\sim} HS_{\mathbb{Z},n-2}, \quad H \mapsto H(1) := H \otimes \mathbb{Z}(1),
\]
where \( \mathbb{Z}(1) = (2\pi i) \mathbb{Z} \) is the pure Hodge structure of weight \((-1,-1)\) geometrically realized by the dual of \( H^0(\mathbb{P}^1, \mathbb{Z}) \). We let \( HS_{\mathbb{Z}} = \bigoplus_{n} HS_{\mathbb{Z},n} \) be the additive category of graded pure, polarizable integral Hodge structures and denote its Grothendieck group by \( K_0(HS_{\mathbb{Z}}) \). By definition, this is the group generated by isomorphism classes of integral polarizable Hodge structures with the condition that \([H] + [H'] = [H \oplus H']\). In particular, two Hodge structures \( H \) and \( H' \) define the same class \([H] = [H']\) in \( K_0(HS_{\mathbb{Z}}) \) if and only if there exists a Hodge structure \( H_0 \) such that \( H \oplus H_0 \cong H' \oplus H_0 \). Note that the tensor product defines a natural ring structure on \( K_0(HS_{\mathbb{Z}}) \).

\[\text{\footnotesize 5} \quad \text{\footnotesize with thanks to P. Magni.}\]
\[\text{\footnotesize 6} \quad \text{\footnotesize Also, Mathematica did not come up with a generating series for } \deg(F(X_n)).\]
Recall that according to [24], $K_0(\text{Var}_\mathbb{C})$ can also be described as the quotient of the free abelian group generated by isomorphism classes of smooth projective varieties by the relation

$$[\text{Bl}_Z(Y)] + [Z] = [Y] + [E]$$

for every blow-up $\text{Bl}_Z(Y) \to Y$ of a smooth projective variety $Y$ along a smooth projective subvariety $Z \subset Y$ of codimension $r$ with exceptional divisor $E$. Using that for each such smooth blow-up there exists a graded isomorphism of polarizable integral Hodge structures, cf. [174, Ch. 7]:

$$H^r(\text{Bl}_Z(Y), Z) \oplus H^r(Z, Z)(-r) \cong H^r(Y, Z) \oplus H^r(E, Z)(-1),$$

one finds that there exists a ring homomorphism

$$K_0(\text{Var}_\mathbb{C}) \to K_0(\text{HS}_Z), [X] \mapsto [H^r(X, Z)].$$

(3.13)

Under this map, $\ell = [\mathbb{A}^1] = [\mathbb{P}^1] - [\text{pt}]$ is sent to $\mathbb{Z}(-1)$.

**Corollary 3.7.** Let $X \subset \mathbb{P}^{r+1}$ be a smooth cubic hypersurface. Then in $K_0(\text{HS}_Z)$ the following equality holds

$$[H^r(X^{[2]}, Z)(2)] = [H^r(\mathbb{P}^r, Z)(2)] \cdot [H^r(X, Z)] + [H^r(F(X), Z)].$$

(3.14)

**Proof** Apply (3.13) to Proposition 3.2 and twist by $\mathbb{Z}(2)$. □

As we shall see shortly, there is an isomorphism in $\text{HS}_Z$ behind (3.14), see Corollary 3.8.

Next consider the natural functor

$$\text{HS}_Z \to \text{HS}_Q, H \mapsto H \otimes_\mathbb{Z} \mathbb{Q},$$

to the category of graded pure, polarizable, rational Hodge structures. It induces a linear map

$$K_0(\text{Var}_\mathbb{C}) \to K_0(\text{HS}_Z) \to K_0(\text{HS}_Q).$$

(3.15)

As the category of graded pure, polarizable, rational Hodge structures $\text{HS}_Q$ is semi-simple (cf. [150, Cor. 2.12]), the natural map

$$\text{HS}_Q \to K_0(\text{HS}_Q)$$

is injective, i.e. two rational Hodge structures $H$ and $H'$ are isomorphic if and only if $[H] = [H']$ in $K_0(\text{HS}_Q)$ [7]. Thus, (3.14) becomes a graded isomorphism of rational Hodge structures.

---

[7] Injectivity does not hold for integral Hodge structures. Indeed, there exist elliptic curves $E$, $E'$, and $E_0$ such that $E$ and $E'$ are non-isomorphic but $E \times E_0 = E' \times E_0$, see [152]. In this case $H^1(E, \mathbb{Z}) = H^1(E', \mathbb{Z})$ in $K_0(\text{HS}_Z)$, but $H^1(E, \mathbb{Z})$ and $H^1(E', \mathbb{Z})$ are non-isomorphic Hodge structures. Thanks to B. Moonen for the reference.
structures

\[ H^*(X^{[2]}, \mathbb{Q})(2) \cong (H^*(\mathbb{P}^n, \mathbb{Q}) \otimes H^*(X, \mathbb{Q}))(2) \oplus H^*(F(X), \mathbb{Q}). \quad (3.16) \]

There is a shortcut to arrive at the isomorphism \((3.16)\) by just applying cohomology to \((3.6)\), i.e. using the commutativity of the diagram

\[
\begin{array}{c}
\text{(SmProj(C))} \\
\downarrow \\
K_0(\text{Var}_C) \\
\downarrow \\
K_0(\text{HS}_C) \\
\downarrow \\
K_0(\text{HS}_\mathbb{Q}).
\end{array}
\]

Similarly, either by applying cohomology to \((3.7)\) or by using \((3.15)\), one obtains an isomorphism of Hodge structures

\[ H^*(X^{[2]}, \mathbb{Q}) \cong S^2H^*(X, \mathbb{Q}) \oplus \bigoplus_{i=1}^{n-1} H^*(X, \mathbb{Q})(-i). \]

Altogether this leads to the isomorphism of Hodge structures

\[ S^2(H^*(X, \mathbb{Q}))(2) \cong H^*(X, \mathbb{Q})(2) \oplus H^*(X, \mathbb{Q})(2-n) \oplus H^*(F(X), \mathbb{Q}) \quad (3.17) \]

and, after decomposing into primitive parts, to

\[ H^*(F(X), \mathbb{Q}) \oplus \mathbb{Q}(2-n) \cong \bigoplus_{i=1}^{n-1} H^*(X, \mathbb{Q})_{pr}(2-i) \oplus \bigoplus_{0<i<j<n} \mathbb{Q}(2-i-j) \]

\[ \oplus \begin{cases} S^2(H^*(X, \mathbb{Q})_{pr})(2) & \text{for } n \equiv 0 \pmod{2}, \\ \wedge^2(H^*(X, \mathbb{Q})_{pr})(2) & \text{for } n \equiv 1 \pmod{2}, \end{cases} \quad (3.18) \]

cf. [75]. The latter can also be obtained by taking cohomology of \((3.9)\). In particular, for the middle cohomology of the Fano variety the formula yields

\[ H^{2n-2}(F(X), \mathbb{Q}) = \mathbb{Q}(2-n)^{\oplus n-2} \oplus \begin{cases} S^2(H^*(X, \mathbb{Q})_{pr})(2) & \text{for } n \equiv 0 \pmod{2}, \\ \wedge^2(H^*(X, \mathbb{Q})_{pr})(2) \oplus H^*(X, \mathbb{Q})_{pr}(1 - \frac{1}{2}) & \text{for } n \equiv 1 \pmod{2}. \end{cases} \]

### 3.4

Instead of using the abstract language of motives, it is possible to work entirely on the level of cohomology. In fact, working directly with cohomology makes some of the results more concrete and shows that the isomorphisms in \((3.18)\) are in fact algebraic.

Start with the diagram \((3.5)\) and apply the blow-up formula for cohomology, cf. [74], Ch. 7, to \(\sigma_1: B := \text{Bl}_E(L \mid L \mid \mathbb{X}) \to L \mid \mathbb{X} \). Note that its exceptional divisor \(\tau_1: E \to L\) is a \(\mathbb{P}^2\)-bundle. We obtain isomorphisms

\[
H^*(B, \mathbb{Z}) \cong H^*(L \mid L \mid \mathbb{X}, \mathbb{Z}) \oplus H^*(L \mid L \mid \mathbb{X}, \mathbb{Z})(-1) \oplus H^*(L \mid L \mid \mathbb{X}, \mathbb{Z})(-2)
\]

\[ \cong (H^*(\mathbb{P}^n, \mathbb{Z}) \oplus H^*(X, \mathbb{Z})) \oplus \begin{cases} H^*(F, \mathbb{Z})(-1) & \oplus \begin{cases} H^*(F, \mathbb{Z})(-2) & \oplus \begin{cases} H^*(F, \mathbb{Z})(-3) \end{cases} \end{cases} \end{cases} \quad (3.19) \]
The first isomorphism up to signs is given by \( \gamma \mapsto \sigma_1, \gamma \oplus \tau_1, (\gamma|_E \cdot [E]|_E) \oplus \tau_1, (\gamma|_E) \) with the inverse \((a, a_1, a_2) \mapsto \tau_1^* a + j, \tau_1^* a_1 + j, \tau_1^* a_2 \cdot [E] \), where \( j : E \hookrightarrow B \) is the inclusion. For the second isomorphism apply the Leray–Hirsch formula for the cohomology of a projective bundle to the \( \mathbb{P}^1 \)-bundle \( p : L \rightarrow F = F(X) \).

Next we use the blow-up formula for \( \sigma_2 : B \cong \text{Bl}_{L[j]}(X[2]) \rightarrow X[2] \). Note that this time the exceptional divisor \( \tau_2 : E \rightarrow L[2] \) is \( \mathbb{P}^1 \)-bundle. Using the cohomological description of the \( \mathbb{P}^2 \)-bundle \( \rho^{[2]} : L[2] \rightarrow F \), one finds

\[
H^*(B, \mathbb{Z}) \cong H^*(X[2], \mathbb{Z}) \oplus H^*(L[2], \mathbb{Z})(-1)
\]

\[
\cong H^*(X[2], \mathbb{Z}) \oplus \left\{ H^*(F, \mathbb{Z})(-1) \oplus H^*(F, \mathbb{Z})(-2) \oplus H^*(F, \mathbb{Z})(-3) \right\}.
\]

Combining the two descriptions of \( H^*(B, \mathbb{Z}) \) yields the following isomorphism of Hodge structures which gives back Corollary 3.7.

**Corollary 3.8.** Let \( X \subset \mathbb{P}^{n+1} \) be a smooth cubic hypersurface. Then there exists an isomorphism of integral Hodge structures

\[
H^*(X[2], \mathbb{Z}) \cong (H^*(\mathbb{P}^n, \mathbb{Z}) \oplus H^*(X, \mathbb{Z})) \oplus H^*(F, \mathbb{Z})(-2)
\]

\[
\oplus H^*(L[2], \mathbb{Z})(-1) \oplus H^*(L[2], \mathbb{Z})(-1).
\]

\[
(3.20)
\]

Note that apart from the obvious copy of \( H^*(F, \mathbb{Z})(-2) \) on the right hand side there are two other copies hidden in \( H^*(L[2], \mathbb{Z})(-1) \). They arise from the natural inclusions of direct summands

\[
H^*(F, \mathbb{Z})(-2) \hookrightarrow H^*(L, \mathbb{Z})(-1) \text{ and } H^*(F, \mathbb{Z})(-2) \hookrightarrow H^*(L, \mathbb{Z})(-2)
\]

in (3.19). Composing the inclusion \( H^*(X[2], \mathbb{Z}) \hookrightarrow H^*(B, \mathbb{Z}) \) with the projection

\[
H^*(B, \mathbb{Z}) \longrightarrow H^*(L, \mathbb{Z})(-1) \oplus H^*(L, \mathbb{Z})(-2) \longrightarrow H^*(F, \mathbb{Z})(-2) \oplus H^*(F, \mathbb{Z})(-2)
\]

yields a map

\[
(f_1, f_2) : H^*(X[2], \mathbb{Z}) \longrightarrow H^*(F, \mathbb{Z})(-2) \oplus H^*(F, \mathbb{Z})(-2).
\]

**Lemma 3.9.** With the above notation, \( f_1 = 0 \) and \( f_2(\alpha) = p_2^{[2]}(\alpha|_{L[2]}) \).

**Proof** The computation of \( f_2(\alpha) \) is a consequence of the commutativity of the diagram

\[
\begin{array}{cc}
H^*(X[2]) & \xrightarrow{\sigma_2^*} H^*(B) \\
\downarrow_{\rho_{L[j]}} & \downarrow_{\gamma_E} \\
H^*(L[2]) & \xrightarrow{\tau_2^*} H^*(E) \\
\downarrow_{\rho^{[2]}} & \downarrow_{\gamma_F} \\
H^{-4}(F) & \xrightarrow{\rho'} H^{-4}(L).
\end{array}
\]
Corollary 3.12. Let $X$ be a smooth cubic hypersurface of dimension $n$. The idea for the computation of $f_1$ is to write $[E]_{|E} = \tau_1^*e_1 + \tau_2^*e_2$, possibly up to classes on $F$ which will not affect the following. Here, $e_1$ and $e_2$ are the relative tautological classes of $p$ and $p[2]$. Then use $\tau_{1i}((\tau_1^*\delta_{1l}) \cdot [E]_{|E}) = \tau_{1i}((\tau_2^*\delta_{2l}) \cdot [E]_{|E})$ and $\delta_{2l} = p[2i]\delta_1 \oplus (p[2i]\delta_2 \cdot e_2)$, which yields $\tau_{1i}(\delta_{1l}) = \tau_1^*p^*\delta_1 \oplus (\tau_1^*p^*\delta_2 \cdot \tau_i^*\delta_2)$ for some classes $\delta_1 \in H^*(F)$ and $\delta_2 \in H^{*2}(F)$. Hence, $\tau_{1i}(\delta_{1l} \cdot [E]_{|E})$ is the sum of $\tau_{1i}(\tau_1^*p^*\delta_1 \cdot e_1 \cdot \tau_i^*\delta_2)$ and $\tau_{1i}(\tau_i^*p^*(\delta_2 \cdot e_1) \cdot \tau_i^*\delta_2) \oplus \tau_1^*p^*(\tau_1^*\delta_2 \cdot \tau_i^*\delta_2)$. The two parts of the first summand are trivial, because $\tau_{1i}\tau_1^* = 0$ and $\tau_{1i}\tau_2^*e_2 = 0$, for $\tau_1$ is a $\mathbb{P}^2$-bundle. Similarly, the first part of the second summand is trivial. Therefore, $\tau_{1i}(\delta_{1l} \cdot [E]_{|E}) = p^*\delta_2 \cdot \tau_{1i}\tau_2^*e_2^2$, the projection of which to $H^{2n-4}(F, \mathbb{Z}) \in H^{2n-2}(\mathbb{L}, \mathbb{Z})$ is trivial. □

Corollary 3.10. For the general smooth cubic hypersurface $X \subset \mathbb{P}^{n+1}$, the rational Hodge conjecture holds for $F(X)$ in the middle degree $2n - 4$. The space of Hodge classes satisfies $\dim H^{2n-2n+2}(F(X), \mathbb{Q}) = n - 1$.

Proof Consider the isomorphism (3.18) which by the preceding discussion is algebraic. On the right hand side, the direct sum $\mathbb{Q}(2 - n)^{2n-2}$ is spanned by Hodge classes which are all obviously algebraic. According to Remark 3.14 (ii), up to scalars the only Hodge class in the summand $S^2(H^*(X, \mathbb{Q})_{pr})$ for $n$ even and in $\bigwedge^2(H^*(X, \mathbb{Q})_{pr})$ for $n$ odd is the class that corresponds to the intersection form $q$ which is algebraic. □

3.5 Proposition 3.2 or, alternatively (3.18), allows one to compute all Betti and Hodge numbers of $F(X)$.

Corollary 3.11. The $\chi_s$-genus of the Fano variety of lines $F(X)$ of a smooth cubic hypersurface $X \subset \mathbb{P}^{n+1}$ is given by

$$
\chi_s(F(X)) = \frac{\chi_s(X) - 2\chi_2^s - 1}{2\chi_2^s} \cdot \chi_s(X).
$$

In principle, it should be possible to combine this with Hirzebruch’s formula for the generating series $\sum_{s=0}^{\infty} \chi_s(X_n) z^{s+1}$ of all $\chi_s$-genera of cubic hypersurfaces, see Theorem 11.11 to express $\sum_{s=0}^{\infty} \chi_s(F(X_n)) z^{s+1}$ as a rational function, cf. Remarks 3.6 and 3.17.

Before making some of the computations explicit in low-dimensional cases, we shall draw a few further consequences from (3.18).

Corollary 3.12. Let $X$ be a smooth cubic hypersurface of dimension $n$.

(i) If $n$ is even, then $H^*(X, \mathbb{Q}) = H^{2s}(X, \mathbb{Q})$ and $H^*(F(X), \mathbb{Q}) = H^{2s}(F(X), \mathbb{Q})$.

(ii) If $n$ is odd, then $H^*(X, \mathbb{Q}) = H^{2s}(X, \mathbb{Q}) \oplus H^s(X, \mathbb{Q})$ and

$$
H^*(F(X), \mathbb{Q}) = H^{2s}(F(X), \mathbb{Q}) \oplus \bigoplus_{i=1}^{n-1} H^s(F(X), \mathbb{Q})_{pr}(2 - i).
$$
The description of the first cohomology yields an alternative proof of Corollary 2.3.

**Corollary 3.13.** Assume \( n \geq 4 \). Then the Picard variety \( \text{Pic}^0(F(X)) \) of the Fano variety of lines \( F(X) \) on a smooth cubic hypersurface \( X \subset \mathbb{P}^{n+1} \) is trivial.

**Proof** Indeed, as \( H^{\text{odd}}(F(X), \mathbb{Q}) \) is trivial for even \( n \) and otherwise \( H^{\text{odd}}(F(X), \mathbb{Q}) \cong \bigoplus_{i=1}^{n-1} H^i(F(X), \mathbb{Q})_{\text{pr}}(2-i) \), one finds \( H^1(F(X), \mathbb{Q}) = 0 \) for \( n \geq 4 \). Hence, \( H^{0,1}(F(X)) = 0 \) which implies that \( \text{Pic}^0(F(X)) \) is trivial. \qed

**Remark 3.14.** In fact, \( F(X) \) is known to be simply connected for \( n \geq 4 \)\(^8\). For \( n = 4 \) it is due to [21], see Section 6.2.2 and for \( n > 4 \) the result follows from [163]. See [53] Prop. 1 & Ex. 3.3, where it is also shown that \( \text{Pic}(F(X)) \cong \mathbb{Z} \cdot \mathcal{O}_F(1) \) for \( n > 4 \).

Alternatively, one can use the fact that for \( n > 4 \) the Fano variety of lines \( F(X) \) is a Fano variety, i.e. has negative canonical bundle. Quite generally, due to results of Campana and Kollár rationally connected varieties \( Z \) are simply connected, cf. [52], [53].

Roughly, at least in characteristic zero, this follows from the observation that any finite étale cover \( \pi: \tilde{Z} \to Z \) would again be Fano and, therefore, \( 1 = \chi(\tilde{Z}, \mathcal{O}) = \chi(Z, \mathcal{O}) \cdot \deg(\pi) \).

The middle cohomology \( H^n(X, \mathbb{Q}) \) of the cubic hypersurface \( X \) carries the most information. As we will see again and again, for the Fano variety of lines it is the cohomology in degree \( n-2 \), which is below the middle for all \( n \geq 2 \). And indeed, the next result says that the two are intimately related. See Section 4 for an alternative argument.

**Corollary 3.15.** Let \( X \) be a smooth cubic hypersurface of dimension \( n \geq 2 \).

(i) If \( n \) is even, then there exists an isomorphism of Hodge structures

\[
H^{n-2}(F(X), \mathbb{Q}) \cong H^n(X, \mathbb{Q})_{\text{pr}}(1) \oplus \bigoplus \mathbb{Q}(2-i-j),
\]

where the direct sum is over all \( 0 < i \leq j < n \) such that \( 2(i+j) = n+2 \).

(ii) If \( n \) is odd, then \( H^{n-2}(F(X), \mathbb{Q}) = 0 \) and there exists an isomorphism of Hodge structures

\[
H^{n-2}(F(X), \mathbb{Q})_{\text{pr}} = H^{n-2}(F(X), \mathbb{Q}) = H^n(X, \mathbb{Q})(1) \cong H^n(X, \mathbb{Q})_{\text{pr}}(1). \]

**Example 3.16.** Let us start by computing \( H^0(F(X), \mathbb{Q}) \). For this, compare the proof of (3.18). We distinguish the two cases:

---

\(^8\) I am indebted to R. Laterveer and S. Stark for pointing this out to me and providing the references.
Chapter 3. Fano varieties of lines

(i) For \( n = 2 \), we obtain the isomorphism of vector spaces

\[
H^0(F(X), \mathbb{Q}) \oplus \mathbb{Q} \cong S^2(H^2(X, \mathbb{Q})_{pr}) \oplus H^2(X, \mathbb{Q})_{pr} \oplus \mathbb{Q}.
\]

Taking dimension while using \( b_2(X)_{pr} = 6 \), yields

\[
b_0(F(X)) + 1 = 21 + 6 + 1.
\]

Hence, \( b_0(F(X)) = 27 \), i.e. \( F(X) \) consists of 27 isolated points. We stress that using étale cohomology, the same conclusion can be drawn for smooth cubic surfaces over arbitrary algebraically closed fields.

(ii) For \( n > 2 \), one finds \( H^0(F(X), \mathbb{Q}) \cong \mathbb{Q} \), where the right hand side comes from \( \mathbb{Q}(2 - 1 - 1) \). This proves again that \( F(X) \) is connected, cf. Proposition 2.4 and Exercise 2.7.

We shall exploit (3.18) to compute the Hodge diamond of \( F(X) \) for smooth cubic hypersurfaces of dimensions \( n \leq 5 \), cf. [75]. For the computation of the Hodge diamonds for the corresponding cubic hypersurface see Section 1.1.4.

\( n = 3 \): Here, the formulae lead to the following isomorphisms of Hodge structures

\[
H^1(F(X), \mathbb{Q}) \cong H^3(X, \mathbb{Q})(1),
\]

where we use that \( H^3(X, \mathbb{Q}) \) is primitive, and

\[
H^2(F(X), \mathbb{Q}) \cong \bigwedge^2 H^3(X, \mathbb{Q})(2).
\]

Note that a priori the formulae involves a direct summand \( \mathbb{Q}(1) \) on both sides, which then cancels out. Combining the two isomorphisms yields an isomorphism \( \bigwedge^2 H^1(F(X), \mathbb{Q}) \cong H^2(F(X), \mathbb{Q}) \). A priori this isomorphism may not be the map given by exterior product in cohomology, but see Section 5.2.2 and Section 4.2. For the Hodge diamond this yields:

\[
\begin{array}{ccc}
b_0(F(X)) = 1 & 1 \\
b_1(F(X)) = 10 & 5 & 5 \\
b_2(F(X)) = 45 & 10 & 25 & 10
\end{array}
\]

\( n = 4 \): In this case, \( \dim(F(X)) = 4 \) and the cohomology of \( F(X) \) is concentrated in even degree.

\[
H^1(F(X), \mathbb{Q}) \cong H^4(X, \mathbb{Q})_{pr}(1) \oplus \mathbb{Q}(-1)
\]

and

\[
H^2(F(X), \mathbb{Q}) \cong S^2(H^4(X, \mathbb{Q})_{pr})(2) \oplus H^4(X, \mathbb{Q})_{pr} \oplus \mathbb{Q}(-2).
\]

There is an additional summand \( \mathbb{Q}(-2) \) on both sides which we have suppressed. For
the Betti and Hodge numbers this implies

\begin{align*}
\beta_0(\text{F}(X)) &= 1 \\
\beta_2(\text{F}(X)) &= 23 \\
\beta_4(\text{F}(X)) &= 276
\end{align*}

\(n = 5\): Here, \(\dim(\text{F}(X)) = 6\) and the rational cohomology of \(\text{F}(X)\) is described as follows

\[H^1(\text{F}(X), \mathbb{Q}) = 0, \quad H^2(\text{F}(X), \mathbb{Q}) \cong \mathbb{Q}(-1), \quad H^3(\text{F}(X), \mathbb{Q}) \cong \mathbb{Q}(\text{pr}(1)), \]

and

\[H^5(\text{F}(X), \mathbb{Q}) \cong \wedge^2(\text{H}^2(\text{F}(X), \mathbb{Q})_{\text{pr}})(2) \oplus \mathbb{Q}(-3).\]

Thus, the non-trivial part of the Hodge diamond below the middle looks like this:

\begin{align*}
\beta_0(\text{F}(X)) &= 1 \\
\beta_1(\text{F}(X)) &= 0 \\
\beta_2(\text{F}(X)) &= 1 \\
\beta_3(\text{F}(X)) &= 42 \\
\beta_4(\text{F}(X)) &= 2 \\
\beta_5(\text{F}(X)) &= 42 \\
\beta_6(\text{F}(X)) &= 862
\end{align*}

\[\text{Remark 3.17.}\] Instead of considering Hodge structures of hypersurfaces over \(\mathbb{C}\) and of their Fano varieties, one could look at hypersurfaces over finite fields. In \([75]\) one finds the following formula

\[|\text{F}(X)(\mathbb{F}_q)| = |\text{F}(X)|^2 - 2(1 + q^n) |\text{F}(X)| + |\text{F}(X)|^2,\]

which is a direct consequence of Proposition \([3,2]\) or its version \([3.7]\) in Mot(k) and similar to the arguments at the end of the proof of Proposition \([11,5]\) to compute \(e(F(X))\). One way to see this is by using that the Zeta function \(Z(X, z) = \exp\left(\sum_{p \geq 1} |X(\mathbb{F}_p)|^2 Z(\mathbb{F}_p)\right)\) can also be written as \(Z(X, z) = \sum z^{|X(\mathbb{F}_q)|\text{pr}}\) (with the sum running over all zero cycles) and so \(|X^{(2)}(\mathbb{F}_q)| = (1/2) (|X(\mathbb{F}_q)|^2 + |X(\mathbb{F}_q)|)\). In principle, this allows one to write \(Z(F(X), z)\) in terms of \(Z(X, z)\) (which according the Weil conjectures has a rather special form for cubic hypersurfaces, cf. Section \([11,6]\)). This has been spelled out in \([54]\).
4 The Fano correspondence

The way we related $H^n(X, \mathbb{Q})$ and $H^{n-2}(F(X), \mathbb{Q})$ was rather abstract and we shall now explain a more direct and canonical way. This makes use of the Fano correspondence \[(4.1)\] and the quadratic Fano correspondence \[(4.6)\].

4.1 The Fano correspondence is the diagram

\[
\begin{array}{ccc}
L & \xrightarrow{q} & X \\
\downarrow p & & \downarrow \\
F(X) & \xrightarrow{} & \end{array}
\] (4.1)

which yields homomorphisms of integral Hodge structures

\[
\varphi := p_* \circ q^* : H^m(X, \mathbb{Z}) \longrightarrow H^{m-2}(F(X), \mathbb{Z})(-1) \quad (4.2)
\]

for all $m$. Depending on the context, it may also be useful to consider the correspondence on the level of Chow groups

\[
\varphi : CH^i(X) \longrightarrow CH^{i-1}(F(X)) \quad (4.3)
\]

or to use other types of cohomology theories.

The key idea for the following computations is to use the decomposition of $H^*(L, \mathbb{Z})$ obtained from viewing $L \longrightarrow F(X)$ as the projective bundle $\mathbb{P}(S_F) \longrightarrow F := F(X)$:

\[
H^*(L, \mathbb{Z}) \cong p^*H^*(F(X), \mathbb{Z}) \oplus u \cdot p^*H^{m-2}(F(X), \mathbb{Z}).
\]

Here, $u := c_1(\mathcal{O}_F(1))$ and the pull-back map $p^* : H^*(F(X), \mathbb{Z}) \longrightarrow H^*(L, \mathbb{Z})$ is injective. Moreover, $u^2 + u \cdot p^*c_1(S_F) + p^*c_2(S_F) = 0$ and $p_*(p^*\gamma + u \cdot p^*\gamma') = \gamma'$. Similar formulæ hold for Chow groups.

**Lemma 4.1.** The correspondence $\varphi : H^4(X, \mathbb{Z}) \longrightarrow H^2(F(X), \mathbb{Z})(-1)$ maps the square of the hyperplane class $h^2$ to the Plücker polarization $g$, cf. \[(1.5)\]:

\[
\varphi(h^2) = g.
\]

Similarly, $h^2 \in CH^2(X)$ is mapped to $c_1(\mathcal{O}_F(1)) \in CH^1(F(X))$ under \[(4.3)\].

**Proof** Recall that $L \cong \mathbb{P}(S_F) \subset \mathbb{P}(V \otimes \mathcal{O}_F) \cong F \times \mathbb{P}(V)$ is induced by the natural inclusion $S_F \subset V \otimes \mathcal{O}_F$ and, thus, $\mathcal{O}_F(1) = q^*\mathcal{O}(1)$. Hence, $p_*\gamma h^2 = p_*(q^*c_1(\mathcal{O}(1))^2) = p_*(u^2) = -c_1(S_F) = g$. \[\square\]

**Exercise 4.2.** Show that more generally $\varphi(h^m) \in H^{2m-2}(F(X), \mathbb{Z})$ can be expressed as a polynomial in the two Chern classes $c_1(S_F)$ and $c_2(S_F)$ of the universal subbundle $S_F$. Concretely, for example, $\varphi(h^3) = c_1^2(S_F) - c_2(S_F)$.\[\]
The next proposition generalizes results from \[21,22\] in the case of \( n = 3, 4 \).

**Proposition 4.3.** The correspondence \( \varphi : H^n(X, \mathbb{Z}) \longrightarrow H^{n-2}(F(X), \mathbb{Z})(-1) \) is injective on \( H^n(X, \mathbb{Z})_{\text{pr}} \) and satisfies

\[
(\alpha, \beta) = -\frac{1}{6} \int_{F(X)} \varphi(\alpha) \cdot \varphi(\beta) \cdot g^{n-2}
\]

for all primitive classes \( \alpha, \beta \in H^n(X, \mathbb{Z})_{\text{pr}} \).

The pairing on the left hand side of (4.4) is the standard intersection pairing on the middle cohomology \( H^n(X, \mathbb{Z}) \). On the right hand side, the pairing is up to the scalar factor \(-1/6\) the Hodge–Riemann pairing associated with the Plücker polarization \( g \).

**Proof** The injectivity of the map \( \varphi : H^n(X, \mathbb{Z})_{\text{pr}} \hookrightarrow H^{n-2}(F(X), \mathbb{Z})(-1) \) follows from (4.4) which is proved by the following computation. The pull-back of \( \alpha \in H^n(X) \) can be written uniquely as

\[
q^* \alpha = p^* \varphi'(\alpha) + u \cdot p^* \varphi(\alpha).
\]

If \( \alpha \) is primitive, then \( h \cdot \alpha = 0 \) and hence \( u \cdot q^* \alpha = 0 \). Using \( u^2 = -p^* c_2(S_F) + u \cdot p^* g \), this becomes \( -p^*(\varphi(\alpha) \cdot c_2(S_F)) + u^2 \cdot p^* (\varphi'(\alpha) + g \cdot \varphi(\alpha)) = 0 \), which implies (i) \( \varphi'(\alpha) + g \cdot \varphi(\alpha) = 0 \) and \( \varphi(\alpha) \cdot c_2(S_F) = 0 \). The latter then implies (ii) \( u^2 \cdot p^* \varphi(\alpha) = u \cdot p^* (g \cdot \varphi(\alpha)) \).

Taking the product of (4.3) and the corresponding equation for another primitive class \( \beta \) yields

\[
q^*(\alpha \cdot \beta) = p^*(\varphi'(\alpha) \cdot \varphi'(\beta)) + u \cdot p^*(\varphi(\alpha) \cdot \varphi'(\beta) + \varphi'(\alpha) \cdot \varphi(\beta)) + u^2 \cdot p^*(\varphi(\alpha) \cdot \varphi(\beta)).
\]

Under \( p \), the first summand on the right hand side becomes trivial, while by means of (i) the direct image \( p_* \) of the second can be written as \(-2(g \cdot \varphi(\alpha) \cdot \varphi(\beta))\). Applying (ii) to the last summand shows that it equals \( u \cdot p^*(g \cdot \varphi(\alpha) \cdot \varphi(\beta)) \). Altogether, one obtains

\[
p_* q^*(\alpha \cdot \beta) = -g \cdot \varphi(\alpha) \cdot \varphi(\beta).
\]

The left hand side can also be written as \( (\alpha, \beta) \cdot p_* q^*[\text{pt}] \). Taking product with \( g^{n-3} \) and integrating proves

\[
(\alpha, \beta) \cdot \deg(p(q^{-1}(z))) = -\int_{F(X)} \varphi(\alpha) \cdot \varphi(\beta) \cdot g^{n-2}
\]

for generic \( z \in X \). The claim then follows from Lemma 4.6. \( \square \)

**Remark 4.4.** (i) Note that for \( n \) odd, \( H^{n-2}(F(X), \mathbb{Q}) = H^{n-2}(F(X), \mathbb{Q})_{\text{pr}} \), cf. Corollary 3.15 and so \( \varphi \) maps \( H^n(X, \mathbb{Q})_{\text{pr}} \) to \( H^{n-2}(F(X), \mathbb{Q})_{\text{pr}}(-1) \). This also holds true for \( n = 4 \) but the argument is more involved: One may assume that \( X \) is general, in which case \( H^n(X, \mathbb{Q})_{\text{pr}} \) is an irreducible Hodge structure, see Corollary 1.2.12. As the Fano correspondence \( \varphi \) sends \( H^{1,1}(X) \) to \( H^{2,0}(F(X)) \), the whole primitive cohomology \( H^2(X, \mathbb{Q})_{\text{pr}} \).
is mapped into the minimal sub-Hodge structure of \( H^2(F(X), \mathbb{Q}) \) containing the one-dimensional \( H^{p,q}(F(X)) \), hence into \( H^2(F(X), \mathbb{Q})_{\text{pr}} \), and, for dimension reasons, isomorphically onto it.

(ii) It seems feasible that the techniques used above also show the injectivity of \( \varphi \) on all of \( H^p(X, \mathbb{Z}) \). For \( n \) odd there is nothing to show. For \( n \) even it would suffice to verify that \( \varphi(h^{p/2}) \neq 0 \). Indeed, the injectivity of \( \varphi \) can be checked for general \( X \) and then \( H^p(X, \mathbb{Z})_{\text{pr}} \cong \varphi(H^4(X, \mathbb{Z})_{\text{pr}}) \) is an irreducible Hodge structure and, therefore, cannot contain the non-trivial Hodge class \( \varphi(h^{p/2}) \). Observe that according to Exercise 4.2, \( \varphi(h^{p/2}) \neq 0 \) translates into the non-vanishing of a certain polynomial in \( g = c_1(S_F) \) and \( c_2(S_F) \). Note that the injectivity does hold in full generality, see Section 4.3 and [163].

(iii) In [110, Thm. 4] it is claimed in full generality that the composition of \( \varphi \) with the projection onto the primitive cohomology yields an isomorphisms of integral Hodge structures. However, the projection does usually not map into integral cohomology and, therefore, one needs to at least invert some integers. For \( n \) odd or \( n = 4 \) one certainly obtains injections \( H^p(X, \mathbb{Z})_{\text{pr}} \hookrightarrow H^{p'-2}(F(X), \mathbb{Z})_{\text{pr}}(-1) \), which we shall see to be an isomorphism for \( n = 3 \) and \( n = 4 \), see Corollary 3.3 and Proposition 4.2.9.

Any deformation of a smooth cubic hypersurface \( X \subset \mathbb{P}^{n+1} \) induces a deformation of the associated Fano variety \( F(X) \). Using Hodge theory, the induced linear map between the spaces of deformations of first order, see (2.4), is shown to be injective.

**Corollary 4.5.** For \( n \geq 3 \) any non-trivial first order deformation of a smooth cubic hypersurface \( X \subset \mathbb{P}^{n+1} \) induces a non-trivial first order deformation of its Fano variety \( F(X) \), i.e.

\[
H^1(X, \mathcal{T}_X) \hookrightarrow H^1(F(X), \mathcal{T}_{F(X)}).
\]

**Proof.** According to the infinitesimal Torelli theorem, see Corollary 4.2.3, the map \( H^1(X, \mathcal{T}_X) \to \text{Hom}(H^p(X)_{\text{pr}}, H^p(X)_{\text{pr}}) \), measuring the first order variation of the Hodge structure \( H^p(X)_{\text{pr}} \), is injective.

Similarly, one can consider the map \( H^1(F, \mathcal{T}_F) \to \text{Hom}(H^{p-2}(F), H^{p-2}(F)) \) about which we do not know anything a priori. However, if a class \( v \in H^1(X, \mathcal{T}_X) \) is mapped to zero in \( H^1(F, \mathcal{T}_F) \) then the induced variation of the Hodge structure \( H^{p-2}(F) \) is trivial. However, due to Proposition 4.3, in this case also the variation of the Hodge structure \( H^p(X)_{\text{pr}} \) is trivial and hence \( v = 0 \).

**Lemma 4.6.** For \( n \geq 2 \) the generic fibre of the morphism \( q: \mathbb{P} \to X \) is of dimension \( n - 3 \) and degree six with respect to the Plücker polarization \( g \), i.e.

\[
\int_{q^{-1}(z)} g^{n-3} = 6.
\]

**Proof.** Pick a hyperplane \( \mathbb{F}^n \subset \mathbb{P}^{n+1} \) not containing a fixed point \( z \in X \). Then the linear
embedding
\[ \mathbb{P}^n \hookrightarrow \mathbb{O}(1, \mathbb{P}) \hookrightarrow \mathbb{P}(\wedge^2 V), \quad y \mapsto \overline{y}, \]
induces an isomorphism \( \{ y \in \mathbb{P}^n | \overline{y} \subset X \} \cong p(q^{-1}(z)) \). As in Remark 2.6, it yields
\[ \{ y \in \mathbb{P}^n | \overline{y} \subset X \} \cong \mathbb{P}^n \cap T_z X \cap X \cap P_z X. \]
Here, \( T_z X = V(\sum x_i \partial_i F(z)) \) is the projective tangent space of \( X = V(F) \) at \( z \in X \) and \( P_z X = V(\sum z_i \partial_i F) \) is its polar, cf. also Section 4.2.4. For generic choices of \( z \in X \) and \( \mathbb{P}^n \), this is a transversal intersection of the cubic \( X \), the quadric \( P_z X \), and the two hyperplanes \( \mathbb{P}^n \) and \( T_z X \) and, therefore, of degree six.

Example 4.7. For \( n = 3 \), i.e. smooth cubic threefolds, the result says that there are exactly six lines passing through every point in a Zariski open subset of \( Y \). We shall come back to this in Section 5.11.

Remark 4.8. In [12] it is shown that for \( n \geq 4 \) the fibres of \( q : L \to X \) are connected by proving that the codimension of the ramification locus is at least of codimension two, cf. the proof of Proposition 2.4. The description of the fibres as the intersection of two hypersurfaces of degree two and three in \( \mathbb{P}^{n-1} \) as in the proof above proves this more directly. Also observe that the connectedness of the fibres implies, once again, that \( F(X) \) is connected for \( n > 2 \), cf. Proposition 2.4, Exercise 2.7, and Example 3.16 (ii).

4.2 Let us now turn to the quadratic version of the Fano correspondence (4.1)
\[ L^{[2]} \xrightarrow{q^{[2]}} X^{[2]} \xrightarrow{p^{[2]}} F(X). \] (4.6)

Here, \( q^{[2]} : L^{[2]} \to X^{[2]} \) is the natural inclusion and \( p^{[2]} : L^{[2]} \to F(X) \) is the projection, see Remark 3.3. The quadratic Fano correspondence yields a homomorphism of integral Hodge structures
\[ q^{[2]} : p^{[2]*} \circ q^{[2]*} : H^m(X^{[2]}, \mathbb{Z}) \to H^{m-4}(F(X), \mathbb{Z})(-2). \] (4.7)

Lemma 4.9. Assume \( n \) is even. Then the homomorphism (4.7) for \( m = 2n \) composed with the natural map \( S^2 H^n(X, \mathbb{Z}) \to H^{2n}(X^{[2]}, \mathbb{Z}) \) equals the composition
\[ S^2 H^n(X, \mathbb{Z}) \xrightarrow{S^2 \omega} S^2 H^{n-2}(F, \mathbb{Z}) \xrightarrow{H^{2n-4}(F(X), \mathbb{Z}).} \] (4.8)
A similar statement holds for \( n \) odd with \( S^2 H^n \) replaced by \( \wedge^2 H^n \).
Chapter 3. Fano varieties of lines

**Proof** The assertion follows from the commutativity of the diagram

\[
\begin{array}{c}
H^n(X) \times H^n(X) \longrightarrow H^{2n}(X^{[2]}) \\
\downarrow \downarrow \\
H^n(L) \times H^n(L) \longrightarrow H^{2n}(L^{[2]}) \\
\downarrow \downarrow \\
H^{n-2}(F) \times H^{n-2}(F) \longrightarrow H^{2n-4}(F).
\end{array}
\]

The commutativity of the upper square is obvious and for the lower square it follows from the commutative diagram

\[
\begin{array}{c}
\mathbb{L} \times \mathbb{L} \longrightarrow \mathbb{L} \times F \longrightarrow \mathbb{L}^{[2]} \\
\downarrow \downarrow \\
F \times F \longrightarrow F,
\end{array}
\]

where the square is a fibre product. □

Recall from Lemma 3.9 that \((p_2[2] \circ q^{[2]r})(\alpha) = p_2[2](\alpha|_{L^{[2]}}) = f_2(\alpha)\), where

\[
f_2: H^n(X^{[2]}, \mathbb{Z}) \longrightarrow H^{n-4}(F(X), \mathbb{Z})
\]

was the projection to the second copy of \(H^{2n-4}(F(X), \mathbb{Z})\) on the right hand side of (3.19).

**Corollary 4.10.** Let \(n > 2\) be even. Then the square \(S^2(\varphi)\) of the Fano correspondence \(\varphi\) or, equivalently, the restriction of \(\varphi^{[2]}\) to \(S^nH^n(X, \mathbb{Z}) \subset H^{2n}(X^{[2]}, \mathbb{Z})\) is an injective homomorphism of integral Hodge structures

\[
S^2(\varphi): S^2H^n(X, \mathbb{Z})_{pr} \longrightarrow H^{2n-4}(F(X), \mathbb{Z})(-2). \tag{4.9}
\]

A similar statement holds for \(n\) odd with \(S^2H^n\) replaced by \(\wedge^2 H^n\).

**Proof** We restrict to the case that \(n\) is even, the odd case is similar. Also, as \(H^n(X, \mathbb{Z})\) is torsion free, the assertion is equivalent to the corresponding one for rational Hodge structures, so we may work with rational coefficients. Finally, as \(S^2(\varphi)\) does not change under deformations, we may assume that \(X\) is general.

Now split \(S^2H^n(X, \mathbb{Q})_{pr} \simeq \mathbb{Q} \cdot q_X \oplus q_X^\perp\), where \(q_X\) denotes the class corresponding to the intersection form. By Proposition 4.3, \(q_X \in S^2H^n(X, \mathbb{Q})_{pr}\) is mapped to a non-trivial Hodge class on \(F(X)\). According to Remark 12.13, the Hodge structure \(q_X^\perp\) is irreducible and, in particular, there are no non-trivial Hodge classes neither in \(q_X^\perp\) nor in its image under (4.9). Thus, it suffices to verify the injectivity of the restriction of (4.9) to \(q_X^\perp \subset S^2H^n(X, \mathbb{Q})_{pr}\), which, due to the irreducibility of \(q_X^\perp\), would follow from \(q_X^\perp \longrightarrow H^{2n-4}(F(X), \mathbb{Z})\) being not trivial.

Clearly, \(q_X^\perp\) maps injectively into the direct sum on the right hand side of (3.19). By Lemma 3.9, the component \(f_1\) to the first copy of \(H^{2n-4}(F(X), \mathbb{Z})\) is trivial and by
Lemma 4.9 the component \( f_2 \) to the second component is \( S^2(\varphi) \). Thus, it suffices to show that all other components vanish. However, the remaining part on the right hand side of (3.19) decomposes into Hodge structures of dimension \( < \dim q_X \). Thus, none of the projections into one of those can be injective on \( q_X \) and, therefore, they have all to be trivial. □

4.3 Let us study a few more formal aspects of the correspondence (4.1). On the level of cohomology we are interested in the two maps:

\[ \varphi := p \circ q^*: H^n(X, \mathbb{Z}) \rightarrow H^{n-2}(F(X), \mathbb{Z})(-1) \]

and

\[ \psi := q \circ p^*: H^{3n-6}(F(X), \mathbb{Z}) \rightarrow H^n(X, \mathbb{Z})(3 - n). \]

The degree shift for the map \( \psi \) is due to \( q: L \rightarrow X \) having generic fibre of dimension \( n - 3 \). Note that Poincaré duality for \( X \) and \( F(X) \) yields natural isomorphisms

\[ H^n(X, \mathbb{Z})^* \simeq H^n(X, \mathbb{Z}) \quad \text{and} \quad H^{n-2}(F(X), \mathbb{Z})^* \simeq H^{3n-6}(F(X), \mathbb{Z}), \]

the latter possibly up to torsion. The projection formula shows that \( \varphi \) and \( \psi \) are dual to each other, i.e.

\[ (\varphi(\alpha), \gamma)_F = (\alpha, \psi(\gamma))_X \]

for all \( \alpha \in H^n(X, \mathbb{Z}) \) and \( \gamma \in H^{3n-6}(F(X), \mathbb{Z}) \). Here, \((\, \cdot \,)_X \) and \((\, \cdot \,)_F \) denote the intersection pairings on \( X \) and \( F \). In [163] the correspondence \( \psi \) is considered as a map \( H_{n-3}(F(X), \mathbb{Z}) \rightarrow H_n(X, \mathbb{Z}) \). It is shown to be surjective, which yields an alternative proof of Proposition 4.3, and to be an isomorphism up to torsion for \( n \) odd, which follows from a comparison of Betti numbers.

The same formalism works on the level of Chow groups, but one has to distinguish between \( n \) even and odd.

Assume \( n \equiv 0 \ (2) \) and write \( n = 2m \). Then (4.1) induces maps

\[ \text{CH}^{2m-3}(F(X)) \xrightarrow{\phi} \text{CH}^{2m}(X) \xrightarrow{\varphi} \text{CH}^{2m-1}(F(X)). \]

Using the compatibility with the cycle class maps, one obtains commutative diagrams

\[ \begin{array}{ccc}
\text{CH}^{2m-3}(F(X)) & \xrightarrow{\phi} & \text{CH}^{2m}(X) \\
\downarrow & & \downarrow \\
H^{2m-6}(F(X), \mathbb{Z})(3m - 3) & \xrightarrow{\phi} & H^{2m}(X, \mathbb{Z})(m) \\
\downarrow & & \downarrow \\
H^{2m-2}(F(X), \mathbb{Z})(m - 1) & \xrightarrow{\phi} & H^{2m-2}(F(X), \mathbb{Z})(m - 1).
\end{array} \]

To avoid potential confusion, let us stress that the diagram is not supposed to suggest that the rows are exact or even that the compositions are zero.
For $n \equiv 1 \pmod{2}$ write $n = 2m - 1$ and consider as above

$$\text{CH}^{3m-4}(F(X)) \xrightarrow{\psi} \text{CH}^m(X) \xrightarrow{\psi} \text{CH}^{m-1}(F(X)).$$

However, in this case the cycle map does not relate this to the middle cohomology of $X$. Instead, one has to restrict to the homologically trivial parts and use the Abel–Jacobi maps to intermediate Jacobians, which for a smooth projective variety $Z$ of dimension $N$ are the complex tori

$$J^{2k-1}(Z) := \frac{H^{2k-1}(Z, \mathbb{C})}{F^k H^{2k-1}(Z) + H^{2k-1}(Z, \mathbb{Z})} \cong \frac{F^{N-k+1} H^{2N-2k+1}(Z)^*}{H^{2N-2k+1}(Z, \mathbb{Z})}.$$  

Both description are used in the following commutative diagram

$$\begin{array}{ccc}
\text{CH}^{3m-4}(F(X))_{\text{hom}} & \xrightarrow{\psi} & \text{CH}^m(X)_{\text{hom}} & \xrightarrow{\psi} & \text{CH}^{m-1}(F(X))_{\text{hom}} \\
\xrightarrow{\text{AJ}_F} & & \xrightarrow{\text{AJ}_F} & & \xrightarrow{\text{AJ}_F} \\
J^{3n-6}(F(X)) & \xrightarrow{\psi} & J^n(X) & \xrightarrow{\psi} & J^{n-2}(F(X)) \\
\cong \frac{F^{n-1/2} H^{n-2}(F(X), \mathbb{C})}{H^{n-2}(F(X), \mathbb{Z})} & \cong \frac{F^{n-1/2} H^n(X)^*}{H^n(X, \mathbb{C})} & \cong \frac{H^{3n-6}(F(X), \mathbb{C})}{F^{3n-6} H^{3n-6}(F(X), \mathbb{C})} & \cong \frac{H^{3n-6}(F(X), \mathbb{C})}{F^{3n-6} H^{3n-6}(F(X), \mathbb{C})}
\end{array}$$

Note that the intermediate Jacobian $J^n(X)$ is selfdual and the two maps in the bottom row are naturally dual to each other.
Cubic surfaces

The general theory presented in previous chapters applied to the case of smooth cubic surfaces $S \subset \mathbb{P}^3$ provides us with some crucial information.

On the purely numerical side, we have seen that the Hodge diamond is only non-trivial in bidegree $(p, p)$, i.e.
\[ H^1(S, \mathcal{O}_S) = H^0(S, \Omega^6_S) = 0 \quad \text{and} \quad H^2(S, \mathcal{O}_S) = H^0(S, \Omega_S^2) = 0. \]
Moreover, \[ H^{1,1}(S) = H^1(S, \Omega_S^2) = k^7, \text{ see Sections 1.2 and 1.3.} \]

The linear system of all cubic surfaces $|\mathcal{O}(3)| = \mathbb{P}^{19}$ comes with a natural $\text{PGL}(4)$-action and its GIT quotient, the moduli space of semi-stable cubic surface, is four-dimensional, see Sections 1.2.1 and 1.1.3.

We have also seen that the Fano variety $F(S)$ of lines contained in $S$ is non-empty, smooth, and zero-dimensional of degree 27, see Proposition 3.3.5 and Example 3.3.16.

Hence, over an algebraically closed field $k$ the Fano variety $F(S)$ consists of 27 isolated $k$-rational points or, in other words, any smooth cubic surface $S \subset \mathbb{P}^3$ defined over an algebraically closed field contains exactly 27 lines. In this chapter we denote them by $\ell_1, \ldots, \ell_{27}$ or, viewing $S$ as a blow-up of $\mathbb{P}^2$, as $E_1, \ldots, E_6, L_1, \ldots, L_6, L_{12}, \ldots, L_{56}$, see below. There are more classical arguments to deduce this result and we will touch upon some of the techniques in this chapter. However, we will have to resist the temptation to dive into the classical theory too much and instead refer to the rich literature on the subject, see for example [18, 63, 90, 95, 116, 131, 171].

1 Picard group

Let $S \subset \mathbb{P}^3$ be a smooth cubic surface over an arbitrary field $k$. Its Picard group $\text{Pic}(S)$ coincides with the Néron–Severi group $\text{NS}(S) = \text{Pic}(S)/\text{Pic}^0(S)$, as $H^1(S, \mathcal{O}_S) = 0$. It is endowed with the intersection product $(\mathcal{L}, \mathcal{L}')$, which satisfies the Hodge index theorem and in particular the inequality $(\mathcal{L}, \mathcal{L}')^2 \geq (\mathcal{L})^2 \cdot (\mathcal{L}')^2$ for all line bundles $\mathcal{L}, \mathcal{L}'$ such that $(\mathcal{L})^2 \geq 0$.
The only line bundles that come for free on any smooth cubic surface are \( O_S(1) \) and its powers \( O_S(n) \). For example, the canonical bundle is determined by the adjunction formula, see Lemma 1.1.

\[
\omega_S \cong O_S(-1),
\]

with a very ample dual \( \omega_S^* \cong O_S(1) \). For an arbitrary line bundle \( L \) on \( S \) the Hirzebruch–Riemann–Roch formula takes the form

\[
\chi(S, L) = \frac{(\mathcal{L})^2 + (\mathcal{L}, \mathcal{O}_S(1))}{2} + 1,
\]

where we use \( \chi \), Lemma 1.1.

Any numerically trivial line bundle \( \mathcal{L} \) on \( S \) is trivial. In particular, \( \text{Pic}(S) \) is torsion free of finite rank and \( \text{Pic}^0(S) = 0 \).

**Proof** Indeed, if a numerically trivial line bundle \( \mathcal{L} \) is not trivial, then \( (\mathcal{L}, \mathcal{O}_S(1)) = 0 \) implies \( H^0(S, \mathcal{L}) = 0 \) and \( H^2(S, \mathcal{L}) = H^0(S, \mathcal{L}^* \otimes \omega_S)^* = 0 \). Hence, \( \chi(S, \mathcal{L}) \leq 0 \), which contradicts (1.1) showing \( \chi(S, \mathcal{L}) = 1 \).

**Corollary 1.2.** For a smooth cubic surface \( S \subset \mathbb{P}^3 \) over an arbitrary field \( k \) one has

\[
\text{Pic}(S) \cong \text{NS}(S) = \text{Num}(S) \cong \mathbb{Z}^{\rho(S)}
\]

with \( 1 \leq \rho(S) \leq 7 \). For a field extension \( k \subset k' \) the base change map

\[
\text{Pic}(S) \hookrightarrow \text{Pic}(S_{k'})
\]

is injective. Moreover, if \( k \) is algebraically closed, then \( \rho(S) = 7 \) and any further base change (1.2) is an isomorphism.

**Proof** Use that an invertible sheaf \( \mathcal{L} \) on \( S \) is trivial if and only if \( H^0(S, \mathcal{L}) \neq 0 \) and \( H^0(S, \mathcal{L}^* \otimes \omega_S) \neq 0 \). As \( H^0(S_{k'}, \mathcal{L}_{k'}) \cong H^0(S, \mathcal{L}) \otimes_k k' \), this shows the injectivity of (1.2).

Assume \( k \) is algebraically closed. The Kummer sequence

\[
\begin{array}{cccccc}
0 & \rightarrow & \mu_n & \rightarrow & \mathbb{G}_m & \rightarrow & \mathbb{G}_m \\
& & \phi \downarrow & & \downarrow & \\
& & \mathbb{G}_m & \rightarrow & \mathbb{G}_m & \rightarrow & 0
\end{array}
\]

with \( n = \ell^m \) prime to char(\( k \)), yields injections \( \text{Pic}(S) \otimes \mathbb{Z}/\ell^m \mathbb{Z} \hookrightarrow H^2_{et}(S, \mathbb{G}_m) \) with a cokernel contained in \( H^2(S, \mathbb{G}_m) \). Taking limits, one obtains

\[
\text{Pic}(S) \otimes \mathbb{Z}/\ell^m \mathbb{Z} \hookrightarrow H^2_{et}(S, \mathbb{Z}/\ell^m \mathbb{Z}) \cong \mathbb{Z}/\ell^m \mathbb{Z} (1)^{\otimes 7},
\]

as \( b_2(S) = 7 \), cf. Section 1.1.6. Together with (1.2), this proves \( \rho(S) \leq 7 \) for arbitrary base field \( k \).

For \( k \) algebraically closed, the Brauer group is trivial, i.e. \( \text{Br}(S) = H^2(S, \mathbb{G}_m) = 0 \). This is analogous to \( H^2(S, O_S^*) = H^2(S, O_S)/H^2(S, \mathbb{Z}) = 0 \) for \( k = \mathbb{C} \). Hence, (1.3) is an isomorphism and, therefore, \( \rho(S) = 7 \). The last assertion follows from a standard
spreading out argument and the fact that for \( k = \bar{k} \) the Picard variety \( \text{Pic}_S \) consists of isolated, reduced, \( k \)-rational points, cf. [103, Lem. 17.2.2].

**Example 1.3.** Examples of smooth cubics with \( \rho(S) < 7 \) can be easily produced. For example, if \( S \twoheadrightarrow |\mathcal{O}(3)| \) is the universal cubic surface, then the scheme-theoretic generic fibre \( S_\eta \) satisfies \( \text{Pic}(S_\eta) \cong \mathbb{Z} \cdot \mathcal{O}(1)|_{S_\eta} \). Here, \( S_\eta \) is a smooth cubic surface over the (non algebraically closed) function field \( k(\eta) \cong k(t_1, \ldots, t_{19}) \).

Similarly, if \( S_{\mathbb{P}^1} \twoheadrightarrow \mathbb{P}^3 \) is a Lefschetz pencil, then the other projection \( \tau : S_{\mathbb{P}^1} \twoheadrightarrow \mathbb{P}^3 \) is the blow-up of \( \mathbb{P}^3 \) in the smooth intersection \( S_1 \cap S_2 \subset \mathbb{P}^3 \) of two smooth cubics. Hence, \( \text{Pic}(S_{\mathbb{P}^1}) \cong \mathbb{Z} \cdot \mathcal{O}(1)|_{S_{\mathbb{P}^1}} \oplus \mathbb{Z} \cdot \mathcal{O}(E) \) by the blow-up formula, where \( E = \mathbb{P}(N_{S_1 \cap S_2}/\mathbb{P}^3) \) is the exceptional divisor of \( \tau \). Therefore, the fibre \( S_\eta \) over the generic point \( \eta \in \mathbb{P}^1 \), with residue field \( k(\eta) \cong k(t) \), satisfies \( \text{Pic}(S_\eta) \cong \mathbb{Z} \).

It should be possible to construct in a similar manner examples of smooth cubic surfaces with arbitrary prescribed Picard number \( 1 \leq \rho \leq 7 \).

It is an entirely different matter to produce cubic surfaces with prescribed Picard number over special types of fields, like number fields or finite fields. See below for examples and comments.

The Picard group \( \text{Pic}(S) \cong \text{NS}(S) \cong \mathbb{Z}^{\rho(S)} \) together with its non-degenerate intersection pairing defines a lattice of signature \((1, \rho(S) - 1)\). It is an odd lattice, because \( (\mathcal{O}_S(1))^2 = 3 \). The orthogonal complement \( \mathcal{O}_S(1)^\perp \subset \text{Pic}(S) \) is negative definite of rank \( \leq 6 \).

For \( k = \mathbb{C} \) the exponential sequence yields an isomorphism of lattices

\[
\text{Pic}(S) \cong H^2(S, \mathbb{Z}).
\]

As \( H^2(S, \mathbb{Z}) \) is unimodular and odd, it is isomorphic to \( I_{1,6} \) and \( \mathcal{O}_S(1)^\perp \cong H^2(S, \mathbb{Z})_{\text{pr}} \cong E_6(-1) \), cf. Corollary [11.13] and Proposition [11.14]. The same conclusions hold over an arbitrary algebraically closed field, as we will show next.

**Corollary 1.4.** Let \( S \subset \mathbb{P}^3 \) be a smooth cubic surface over an algebraically closed field \( k \). Then

\[
\text{Pic}(S) \cong I_{1,6} \text{ and } \mathcal{O}_S(1)^\perp \cong E_6(-1).
\]

For an explicit basis of both lattices in terms of lines see Section [3.4].

**Proof** Completely geometric arguments for this description exist. For example, one can use that \( S \) is a blow-up of \( \mathbb{P}^2 \) in six points, which we, however, will deduce from the description of the Picard group, or that \( S \) admits a conic fibration \( S \twoheadrightarrow \mathbb{P}^1 \) with five singular fibres, see Section [2.3] and [161], IV.2.5. We shall here derive the claim from the description of the intersection pairing \( H^2(S, \mathbb{Z}) \) of a smooth cubic surface over \( \mathbb{C} \).

In characteristic zero, the assertion follows from the complex case and the standard
Lefschetz principle. The general case can be reduced to it by means of the specialization map
\[\text{Pic}(S_{\overline{\eta}}) \hookrightarrow \text{Pic}(S_t).\]

Here, \(S \rightarrow \text{Spec}(R)\) is a smooth family of cubic surfaces over a DVR and \(t\) and \(\eta\) are the closed and generic points with residue fields \(k(t)\) and \(k(\eta)\) of positive and zero characteristic, respectively. Specialization is injective, because it is compatible with the intersection product. But \(\text{Pic}(S_{\overline{\eta}}) \cong \mathbb{I}_{1,6}\) is a unimodular lattice and any isometric embedding of finite index of a unimodular lattice is an isomorphism. Once \(\text{Pic}(S)\) is determined, its primitive part is described as in the proof of Proposition 11.1.14. \(\square\)

Remark 1.5. The Galois group \(\text{Gal}(\overline{k}/k)\) naturally acts on \(\text{Pic}(S_{\overline{k}})\) and its sublattice \(\mathcal{O}_S(1)^\perp \cong E_6(-1)\). It therefore defines a subgroup \(G \subset O(E_6)\), cf. Section 1.2.5. Alternatively, the Galois group acts on the configuration of lines \(L(S)\), see Section 3.6, whose automorphism group is \(W(E_6)\). Which subgroups can be realized in this way? It is a classical fact that the scheme theoretic generic cubic surface, which lives over the function field of \(|O(3)|\), leads to \(G = W(E_6)\), see Corollary 1.12.

1.2 We next aim at a purely numerical characterization of lines contained in smooth cubic surfaces.

Remark 1.6. (i) Observe that any \(\mathbb{P}^1 \cong L \subset S\) with \((L)^2 = -1\) is in fact a line, i.e. the degree of \(L\) as a subvariety of the ambient \(\mathbb{P}^3\) is \(\text{deg}(L) = 1\) or, still equivalently, \((\mathcal{O}_S(1), \mathcal{O}(L)) = \text{deg}(\mathcal{O}_S(1)|_L) = 1\). Indeed, by adjunction \(\mathcal{O}(-2) \cong \omega_L = (\omega_S \otimes \mathcal{O}(L))|_L = \mathcal{O}_S(-1)|_L \otimes \mathcal{O}(-1)\).

(ii) For a geometrically integral curve \(C \subset S\), one obtains from (1.1)
\[1 \geq 1 - h^1(C, \mathcal{O}_C) = \chi(C, \mathcal{O}_C) = \chi(S, \mathcal{O}_S) - \chi(S, \mathcal{O}_S(-C)) = \frac{-(C)^2 - \text{deg}(C)}{2}\]
and, therefore,
\[(C)^2 \geq \text{deg}(C) - 2 \geq -1.\]

If, in addition, \((C)^2 = -1\), then automatically \(\text{deg}(C) = 1\) and \(h^1(C) = 0\). Hence, again, \(L := C \cong \mathbb{P}^1\) is a line.

So, combining (i) and (ii), we find that a \((-1)\)-curve, i.e. a geometrically integral curve with \((C)^2 = -1\), on a smooth cubic surface is the same thing as a line.

(iii) Similarly, if \(L \in \text{Pic}(S)\) with \((L, \mathcal{O}_S(1)) = 1\) and \((L)^2 = -1\), then \(\chi(S, L) = 1\) by (1.1) and, therefore, \(H^0(S, L) \neq 0\). Hence, \(L \cong \mathcal{O}_S(L)\) for some curve \(L \subset S\). But \(\text{deg}(L) = (L, \mathcal{O}_S(1)) = 1\) then implies that \(L\) is geometrically integral and hence a line.

Note that these arguments only use the numerical properties of \((S, \mathcal{O}_S(1))\) and the
Thus, if \( \text{Pic}(S) \cong I_{1,6} \) and \( \alpha \in I_{1,6} \) is a characteristic vector of square \( (\alpha)^2 = 3 \) (cf. proof of Proposition 1.1.14), then there are natural bijections

\[
\{ \mathbb{P}^1 \cong L \subset S \mid \text{line} \} \\
\cong \{ C \subset S \mid \text{integral, } (C)^2 = -1 \} \\
\cong \{ \beta \in I_{1,6} \mid (\beta)^2 = -1, (\alpha, \beta) = 1 \},
\]

see also the proof below.

We draw two immediate but crucial consequences from this. The first one is usually deduced from a concrete geometric reasoning, which is avoided in the present approach.

**Corollary 1.7.** Assume \( S \subset \mathbb{P}^3 \) is a smooth cubic surface over an algebraically closed field. Then \( S \) contains six pairwise disjoint lines \( \ell_1, \ldots, \ell_6 \subset S \).

**Proof** By Corollary 1.4, the Picard lattice is \( \text{Pic}(S) \cong I_{1,6} \) and this is all that is needed in the following. As argued in the proof of Proposition 1.1.14 the class \( \alpha = (3, -1, \ldots, -1) \in I_{1,6} \) (with the harmless but convenient sign change), written in the standard basis \( v_0, \ldots, v_6 \), and the hyperplane section \( h_S \) are both characteristic classes of the same square \( (\alpha)^2 = (h_S)^2 = 3 \). Hence, after applying an appropriate orthogonal transformation, they coincide. But then the classes \( v_i, i = 1, \ldots, 6 \) correspond to line bundles \( L_i \) with \( (L_i)^2 = -1 \) and \( (L_i, O_S(1)) = 1 \). According to the above remark, \( L_i = O(\ell_i) \), where the curves \( \ell_i \subset S \) are lines. As \( (L_i, L_j) = (v_i, v_j) = 0 \) for \( i \neq j \), they are pairwise disjoint. \( \square \)

Note that the existence of two disjoint lines already implies that \( S \) is rational, see Corollary 1.5.4.

**Remark 1.8.** It is curious to observe that one can reverse the flow of information and deduce from the geometry of a cubic surface information about the lattice \( I_{1,6} \) or \( E_6 \). For example, the fact that the Fano variety \( F(S) \) of lines on a smooth cubic surface over an algebraically closed field consists of 27 isolated, smooth \( k \)-rational points translates into the fact that in the lattice \( I_{1,6} \) there exist exactly 27 classes \( \ell \) with \( (\ell, (3, 1, \ldots, 1)) = 1 \) and \( (\ell)^2 = -1 \).

**Corollary 1.9.** On a smooth cubic surface \( S \subset \mathbb{P}^3 \) over an arbitrary field \( k \) an invertible sheaf \( L \) is ample if and only if \( (L)^2 > 0 \) and \( (L, L) > 0 \) for every line \( L \subset S \).

**Proof** Only the ‘if-direction’ requires a proof. Recall the Nakai-Moishezon criterion for smooth projective surfaces over arbitrary fields, cf. [10]: An invertible sheaf \( L \) is ample if and only if \( (L)^2 > 0 \) and \( (L, C) > 0 \) for every curve \( C \subset S \). It is of course enough to test integral curves \( C \), but we may not necessarily be able to reduce to geometrically integral ones. For this reason, one has to take all lines in the base change \( S \bar{k} \) into account.
As $\mathcal{L}$ is ample if and only if its base change to $S_k$ is ample, one can thus reduce to the case $k = k$. Then any integral curve $C$ is geometrically integral and either $(C)^2 = -1$, in which case $\mathbb{P}^1 \cong C$ is a line, or $(C)^2 \geq 0$. To prove $(L,C) > 0$ in the latter case we shall apply the Hodge index theorem. First note that there exists a hyperplane $\mathbb{P}^2 \subset \mathbb{P}^3$ such that the intersection $S \cap \mathbb{P}^2$ consists of three lines $\ell_1 \cup \ell_2 \cup \ell_3$, cf. Sections 2.5 or 3.3.

As $(L,\ell_i) > 0$, also $(\mathcal{L},\mathcal{O}_S(1)) > 0$. Hence, $\mathcal{L}$ and $\mathcal{O}_S(1)$ are contained in the same connected component $C^0$ of the positive cone $\mathcal{C} \coloneqq \{ x \in \text{NS}(S) \otimes \mathbb{R} \mid (x)^2 > 0 \} = C^0 \cup (-C^0)$. Similarly, $(\mathcal{O}_S(1),C) > 0$ implies $[C] \in C^0$ and, therefore, also $(\mathcal{L},C) > 0$.

The same remark as at the end of Remark 1.6 applies: Only the numerical properties of $(S,\mathcal{O}_S(1))$ and the facts that $\omega_S \cong \mathcal{O}_S(-1)$ and $(\mathcal{L},\mathcal{O}_S(1)) > 0$ have been used in the proof. 

We summarize the situation by a description of the ample cone and the effective cone. By definition, the effective cone is the cone of all finite, non-negative real linear combinations of curves

$$\text{NE}(S) \coloneqq \left\{ \sum a_i [C_i] \mid a_i \in \mathbb{R}_{\geq 0} \right\},$$

where $C_i \subset S$ are arbitrary irreducible (or integral) curves. Its dual is the nef cone which can also be described as the closure of the (open) ample cone

$$\text{Amp}(S) \coloneqq \left\{ \sum a_i \mathcal{L}_i \mid a_i \in \mathbb{R}_{\geq 0}, \mathcal{L}_i \text{ ample} \right\}.$$  

**Proposition 1.10.** Let $S$ be a smooth cubic surface over an algebraically closed field. Then the effective cone is

$$\text{NE}(S) = \left\{ \sum_{i=1}^{27} a_i [\ell_i] \mid a_i \in \mathbb{R}_{\geq 0} \right\},$$

the closed rational polyhedron spanned by the 27 lines $\ell_1, \ldots, \ell_{27} \subset S$. The ample cone is the interior of its dual $\text{NE}(S)^*$, which is again rationally polyhedral:

$$\text{Amp}(S) = \text{Int}(\text{NE}(S)^*).$$

**Proof** As above, $C^0$ denotes the connected component of the positive cone that contains $\mathcal{O}_S(1)$. By (1.1) all integral classes in $C^0$ are contained in $\text{NE}(S)$. Furthermore, any integral curve $C$ with $[C]$ not contained in the closure of $C^0$ is a line, see Remark 1.6. Hence, the closure of $\text{NE}(S)$ is spanned by the closure of $C^0$ and $K \coloneqq \sum_{i=1}^{27} \mathbb{R} [\ell_i]$. Now, $K \cap C^0 \neq \emptyset$. Indeed, as used before the class $\mathcal{O}_S(1)$ can be written as the sum of three lines. In order to show that $C^0 \subset K$, it therefore suffices to argue that no class in $C^0$ can be written as $a \ell_i + b \ell_j$ with $a,b \geq 0$. As two distinct lines are either disjoint or intersect transversally in exactly one point, $(\ell_i,\ell_j) = 0$ or $= 1$. Hence, $(a \ell_i + b \ell_j)^2 = -(a^2 + b^2)$ or $= -(a^2 + b^2 - 2ab)$, which are both non-positive. 

□
This result in particular shows that the ample cones of smooth cubic surfaces over algebraically closed fields all look the same. This is in stark contrast to other types of surfaces, for example K3 surfaces, cf. [103, Ch. 8].

For non algebraically closed fields these cones can be described via the inclusion $\text{Pic}(S) \hookrightarrow \text{Pic}(\bar{S})$ as $\text{Amp}(S) = \text{Amp}(\bar{S}) \cap \text{Pic}(S)$ and, dually, $\text{NE}(S) = \text{NE}(\bar{S}) \cap \text{Pic}(S)$. Hence, rephrasing Corollary 1.9, $L$ is ample if and only if $(L.C) > 0$ for all curves $C$ which after base change to the algebraic closure are unions (with multiplicities) of lines.

**Remark 1.11.** It is not difficult to prove that an ample invertible sheaf on a cubic surface is automatically very ample, see [90, V. Thm. 4.11].

**1.3** Consider the family of all smooth cubic surfaces $S \rightarrow U := |\mathcal{O}(3)|_{\text{sm}}$. In Section 1.2.5 we discussed the monodromy group of this family, i.e. the image of the natural representation

$$
\pi_1(U) \rightarrow \text{O}(H^2(S, \mathbb{Z})),
$$

where $S = S_0$ is a distinguished smooth fibre. According to Theorem 1.2.9 this is the group $\tilde{O}^+(H^2(S, \mathbb{Z}))$ of all orthogonal transformations of the lattice $H^2(S, \mathbb{Z})$ with trivial spinor norm that fix the hyperplane class. In fact, what has been argued in the discussion there is that the monodromy group, as a subgroup of the orthogonal group of the lattice $H^2(S, \mathbb{Z})_{\text{pr}} \cong E_6(-1)$, is the Weyl group $W(E_6)$. Recall that its order is

$$|W(E_6)| = 51,840 = 2^7 \cdot 3^4 \cdot 5$$

and that it is a subgroup of index two of $\text{O}(E_6)$, only the orthogonal transformation given by a global sign change is missing, cf. [48, Sec. 15]. We shall rephrase this in terms of the family of 27 lines. Recall from Section 1.2.5 that the relative Fano variety of lines of $S \rightarrow U$ is an étale morphism

$$F := F(S/U) \rightarrow U$$

of degree 27. The image of the naturally induced map $\rho: \pi_1(U) \rightarrow \mathcal{S}_{27}$ also called the monodromy group of the family. The image is isomorphic to the Galois group of the covering, cf. [67, Sec. 1].

**Corollary 1.12.** The Galois group or, equivalently, the monodromy group $\text{Im}(\rho) \subset \mathcal{S}_{27}$ of the universal family $F \rightarrow U$ of the 27 lines in smooth cubic surfaces $S \subset \mathbb{P}^3$ is isomorphic to the Weyl group $W(E_6)$.

**Proof**
Chapter 4. Cubic surfaces

2 Representing cubic surfaces

Cubic surfaces can be viewed from different angles and can be described geometrically in various ways. Each representation highlights particular features. We will briefly describe the most common ones.

2.1 To start, let us try to realize cubic surfaces as blow-ups of simpler surfaces.

Let $S \subset \mathbb{P}^3$ be a smooth cubic over an arbitrary field $k$ and let $E \subset S$ be a smooth, integral, rational curve. Assume $E$ is a $(-1)$-curve, i.e. $(E)^2 = -1$ or, equivalently, that $E$ is a line, cf. Remark 1.6 (i). Then $S$ is the blow-up

$$\tau : S \longrightarrow \tilde{S}$$

of a smooth projective surface $\tilde{S}$ in a point $x \in \tilde{S}$ with exceptional line $E$. This is a special case of Castelnuovo’s theorem [10, 18, 90]. Alternatively, one could study the linear system $|O_S(1) \otimes O(E)|$, which can be checked to be base point free.

More generally, one proves the following.

Lemma 2.1. Assume $E_1, \ldots, E_m \subset S$ are $m$ pairwise disjoint $(-1)$-curves. Then $S$ is isomorphic to the blow-up $\tau : S \cong \text{Bl}_{x_i}(\tilde{S}) \longrightarrow \tilde{S}$ of a smooth, projective surface $\tilde{S}$ with $E_i = \tau^{-1}(x_i)$ as exceptional lines. Furthermore, the following assertions hold.

(i) The Picard number satisfies $m \leq \rho(S) - 1 \leq 6$.

(ii) If $m = 6$, then $\tilde{S} \cong \mathbb{P}^2$.

(iii) If $m = 5$, then $\tilde{S} \cong \text{Bl}_x(\mathbb{P}^2)$ or $\tilde{S} \cong \mathbb{P}^1 \times \mathbb{P}^1$.

Proof Indeed, the blow-up of a smooth surface in one point increases the Picard number by one. As $S$ is projective, $\rho(S) \geq 1$. This proves the lower bound in (i). For the upper bound see Corollary 1.2.

If $m = 6$, then $\tilde{S}$ is minimal and its canonical bundle $\omega_S$ satisfies $\omega_S \cong \tau^* \omega_{\tilde{S}} \otimes O(\sum E_i)$, where $E_i, i = 1, \ldots, 6$, are the exceptional lines. Thus, $(\omega_S)^2 = 9$. Hence, classification theory of minimal surfaces of Kodaira dimension $-\infty$ yields $\tilde{S} \cong \mathbb{P}^2$. Note that ruled surfaces over curves of positive genus can be excluded by using $H^1(S, O_S) = 0$.

If $m = 5$, then, similarly, $(\omega_S)^2 = 8$. Now, if $\tilde{S}$ is not minimal, then it can be blown down once more and the resulting surfaces will then have to be $\mathbb{P}^2$. If $\tilde{S}$ is minimal, then by classification theory $\tilde{S}$ is a Hirzebruch surface, i.e. $\tilde{S} \cong \mathbb{F}_n := \mathbb{P}(O \oplus O(n))$ over $\mathbb{P}^1$ with $0 \leq n \neq 1$. We need to exclude all the cases $0 < n$. However, $C_n = \mathbb{P}(O(n)) \subset \mathbb{F}_n$ is a smooth rational curve with $(C_n)^2 = -n$. Its strict transform in $S$ is thus a smooth rational curve $\tilde{C}_n$ with self-intersection $(\tilde{C}_n)^2 \leq -n$. Hence, according to Remark 1.6 (ii), $n = 0$ or $n = 1$.

Remark 2.2. Consider the two cases $\tau : S \longrightarrow \mathbb{P}^2$ and $\tau : S \longrightarrow \mathbb{P}^1 \times \mathbb{P}^1$ as above. They
are given by the linear systems $\mathcal{O}_3(1) \otimes \mathcal{O}(\sum_{i=1}^{m} E_i)$ with $m = 6$ and $m = 5$, respectively. Hence, for degree reasons,

$$\mathcal{O}_3(1) \cong \tau^*\mathcal{O}_{\mathbb{P}^2}(3) \otimes \mathcal{O}(-\sum_{i=1}^{6} E_i)$$

and

$$\mathcal{O}_3(1) \cong \tau^*\mathcal{O}(2, 2) \otimes \mathcal{O}(-\sum_{i=1}^{5} E_i),$$

respectively. Here, $\mathcal{O}(2, 2) := \mathcal{O}_{\mathbb{P}^2}(2) \otimes \mathcal{O}_{\mathbb{P}^2}(2)$ on $\mathbb{P}^1 \times \mathbb{P}^1$. Numerically, in the second case $\mathcal{O}_3(1)$ could a priori also be, for example, $\tau^*\mathcal{O}(4, 1) \otimes \mathcal{O}(-\sum_{i=1}^{5} E_i)$. However, in this case the first ruling would lead to a family of lines on $S$, which we know not to exist.

2.2 Assume a smooth cubic $S \subset \mathbb{P}^3$ contains six pairwise disjoint lines $E_1, \ldots, E_6 \subset S$. The induced classes $[E_i] \in \text{Pic}(S) \cong \mathbb{I}_{6,6}$ generate a sublattice $\mathbb{I}_{1,6} \subset \mathbb{I}_{6,6}$. In fact, together with $\tau^*\mathcal{O}_{\mathbb{P}^2}(1) \in \text{Pic}(S)$ they form a standard basis of $\mathbb{I}_{1,6}$ and so in particular $\text{Pic}(S) \longrightarrow \text{Pic}(S') = \mathbb{I}_{1,6}$. Note that $\mathcal{O}_3(1)$ and the classes of $E_1, \ldots, E_6$ span a proper sublattice of $\text{Pic}(S)$ of index three.

Thus, as a consequence of Corollary 1.7 we obtain the following classical description of cubic surfaces as blow-ups of $\mathbb{P}^2$. The assumption of $k$ being algebraically closed can be weakened to $\text{Pic}(S)$ being a unimodular lattice of rank seven or, equivalently, $\text{Pic}(S) \cong \mathbb{I}_{1,6}$.

**Proposition 2.3.** Let $S \subset \mathbb{P}^3$ be a smooth cubic surface over an algebraically closed field $k$. Then $S$ is isomorphic to the blow-up $\text{Bl}_{x_i}(\mathbb{P}^2)$ of $\mathbb{P}^2$ in six distinct points $x_i \in \mathbb{P}^2$, $i = 1, \ldots, 6$. □

**Remark 2.4.** Assume $S$ can be presented as $\text{Bl}_{x_i}(\mathbb{P}^2)$ as in the proposition. Then there are three sets of curves readily visible that will turn out to be lines:

(i) The exceptional lines $E_1, \ldots, E_6$.
(ii) The strict transform $L_{ij}, i \neq j$, of the line $L_{ij} \subset \mathbb{P}^2$ passing through $x_i \neq x_j \in \mathbb{P}^2$.
(iii) The strict transform $L_i$ of a smooth conic $C_i \subset \mathbb{P}^2$ passing through the five points $x_j \in \mathbb{P}^2, j \neq i$.

Let us count them. There are six of type (i). There are 15 of type (ii) under the assumption that no three points are collinear, i.e. that no $x_k \in \hat{L}_{ij}$ for any $k$ distinct from $i$ and $j$. To count the curves of type (iii), observe that $|\mathcal{O}_{\mathbb{P}^2}(2)|$ is of dimension five. Hence, for arbitrary five points, there exists a conic $C$ containing them all. As the conic $C$ is either smooth or the union of two distinct lines or a double line, under the assumption that no three of the points $x_1, \ldots, x_6$ are collinear, there exists indeed a unique $L_i$ for every $i$. This yields another six curves exactly when the six points are not all contained in one conic.

As it turns out, these conditions are automatically satisfied, see Remark 2.6. Moreover, under these conditions the $L_{ij}$ and the $L_i$ are indeed lines, i.e. $(L_{ij})^2 = (L_i)^2 = -1$.
Chapter 4. Cubic surfaces

cf. Remark 1.6 (i). Hence, starting with a smooth cubic surface $S$, the lines of type (i), (ii), and (iii) account for 27, and hence all, lines.

Let us now address the converse and consider the blow-up $\tau : S \xrightarrow{\text{Bl}} \mathbb{P}^2$ in six distinct points $x_1, \ldots, x_6 \in \mathbb{P}^2$. Is $S$ then automatically a cubic surface? It turns out that the same conditions on the points $\{x_i\}$ as above have to be imposed.

**Proposition 2.5.** Assume $x_1, \ldots, x_6 \in \mathbb{P}^2$ are general in the sense that no three of them are collinear and that they are not all contained in one conic. Then the blow-up $\text{Bl}_{\{x_i\}}(\mathbb{P}^2)$ is isomorphic to a cubic surface $S \subset \mathbb{P}^3$.

**Proof** More precisely, one shows that the invertible sheaf $\mathcal{L} := \tau^* \mathcal{O}(3) \otimes \mathcal{O}(-\sum E_i)$ is very ample and that the image of the induced closed embedding $\text{Bl}_{\{x_i\}}(\mathbb{P}^2) \xrightarrow{\sim} S \subset \mathbb{P}^3$ is a cubic surface. Here, $E_1, \ldots, E_6$ denote the exceptional divisors.

Classically, the assertion is proved by showing that $\mathcal{L}$ separates points and tangent directions, cf. [13][90]. We shall instead give an argument that uses the general Nakai–Moishezon criterion and some of our earlier considerations.

First note that numerically $\text{(Bl}_{\{x_i\}}(\mathbb{P}^2), \mathcal{L})$ indeed behaves like a cubic surface. By the blow-up formula, its Néron–Severi lattice is isomorphic to $\mathbb{Z}^6$ with $\mathcal{L}$ corresponding to the characteristic vector $(3, -1, \ldots, -1)$ and, in particular, $(\mathcal{L})^2 = 3$. Hence, Corollary 1.9 is valid, see the comment at the end of its proof. In fact, only $(\mathcal{L})^2 = 3$, $\omega_S \simeq \mathcal{L}^*$, and $\mathcal{L}$ effective are needed.

Therefore, $\mathcal{L}$ is ample if and only if $(\mathcal{L}, L) > 0$ for every $L \subset \text{Bl}_{\{x_i\}}(\mathbb{P}^2)$ with $(L)^2 = -1$. If $L$ is one of the exceptional lines, then clearly, $(\mathcal{L}, L) = -(\mathcal{L}, E_i) = 1$. If not, let $D := \tau(L)$ be its image. Then $D \in |\mathcal{O}_{\mathbb{P}^2}(d)|$ for some $d$. Denote by $m_i := \text{mult}_x(D)$ the multiplicity of $D$ at the point $x_i$. Thus, $m_i = 0$ if $x_i \notin D$ and $m_i = 1$ if $x_i$ is a smooth point of $D$. Moreover, $L$ is the strict transform of $D$ and $\tau^* D = L + \sum m_i E_i$. The latter
shows $d^2 = (D)^2 = (\tau^*D)^2 = -1 + 2 \sum m_i - \sum m_i^2 = 5 - \sum (m_i - 1)^2$ from which we deduce that $d = 1$ or $d = 2$, i.e. $D$ is a line or a conic. Now, $\langle L, L \rangle \leq 0$ is equivalent to $3d \leq \sum m_i$, which for $d = 1, 2$ reads $3 \leq \sum m_i$ and $6 \leq \sum m_i$, respectively. Hence, for $d = 1$, the line $D$ passes through at least three of the points $x_1, \ldots, x_6$. If $d = 2$ and $D$ is a smooth conic, then $D$ contains all $x_1, \ldots, x_6$. If $d = 2$ and $D$ is singular, i.e. consists of two lines, then one of the two contains at least three of the points. However, for general points $x_1, \ldots, x_6$ these two situations are excluded. Hence, $L$ is indeed ample.

In order to prove that $L$ is very ample, one first shows that there exists a smooth curve $C \in |L|$, which then is an elliptic curve. As $H^0(\text{Bl}_{x_6}(\mathbb{P}^2), L) \cong H^0(\mathbb{P}^2, L_1^6) \otimes \mathcal{O}_{\mathbb{P}^2}(3))$ the existence of $C$ follows from Bertini’s theorem with base points, cf. [90, III. Rem. 10.9.2]. In other words, there exists a smooth elliptic curve in $\mathbb{P}^2$ passing through $x_1, \ldots, x_6$. Its strict transform is $C$, still a smooth elliptic curve. Next observe that the restriction map

$$H^0(\text{Bl}_{x_6}(\mathbb{P}^2), L) \longrightarrow H^0(C, L|_C)$$

is surjective due to $H^1(\text{Bl}_{x_6}(\mathbb{P}^2), \mathcal{O}) = H^1(\mathbb{P}^2, \mathcal{O}) = 0$. As $\deg(L|_C) = 3$ and any line bundle of degree three on a smooth elliptic curve is very ample, one deduces that $L$ is base point free. As $(L)^2 = 3$, the induced morphism $\varphi_C : \text{Bl}_{x_6}(\mathbb{P}^2) \longrightarrow \mathbb{P}^3$ is either of degree one or three. However, the latter would imply that $S := \text{Im}(\varphi_C)$ is a plane contradicting $h^0(L) = 4$. Hence, $\varphi_C$ is generically injective. It does not contract any curve, as $L$ is ample, and is therefore the normalization of its image $S$, a possibly singular cubic surface. However, the natural injection $H^0(S, \mathcal{O}_S(m)) \longrightarrow H^0(\text{Bl}_{x_6}(\mathbb{P}^2), L^m)$ is a bijection, as both spaces are of the same dimension. Using that $L^m$, $m \gg 0$, is very ample, this suffices to conclude that $\text{Bl}_{x_6}(\mathbb{P}^2) \longrightarrow S$. □

**Remark 2.6.** The proof also reveals that whenever a smooth cubic surface $S$ is viewed as a blow-up $S = \text{Bl}_{x_6}(\mathbb{P}^2) \longrightarrow \mathbb{P}^2$, then the points $x_1, \ldots, x_6 \in \mathbb{P}^2$ have to be in general position.

**Dimension check:** The choice of six generic points in $\mathbb{P}^2$ modulo the action of $\text{PGL}(3)$ accounts for a parameter space of dimension $4 = \dim |\mathcal{O}_{\mathbb{P}^2}(3)| - \dim \text{PGL}(4)$, the dimension of the moduli space of smooth cubic surfaces, cf. Section 1.2.1

### 2.3 A similar analysis can be done for blow-ups $\tau : S \longrightarrow \mathbb{P}^1 \times \mathbb{P}^1$ in five points. If the five points $x_1, \ldots, x_5 \in \mathbb{P}^1 \times \mathbb{P}^1$ are completely arbitrary, then $L := \tau^*\mathcal{O}(2, 2) \otimes \mathcal{O}(-\sum E_i)$ may not be ample. For example, if two points $x_1, x_2$ are contained in the same fibre $F$ of one of the two projections, then $\langle L, F \rangle = 0$ for the strict transform $F$ of that fibre. Similarly, not four of them can lie on the diagonal.

**Exercise 2.7.** Work out the exact conditions for the five points in $\mathbb{P}^1 \times \mathbb{P}^1$ that ensure that the blow-up is a cubic surface.
2.4 Let now \( u \in S \) be a point not contained in any line. Consider the projection of \( S \) from the point \( u \) to a generic plane \( \mathbb{P}^2 \subset \mathbb{P}^3 \). This yields morphisms

\[
S \dashrightarrow \tilde{S} := \text{Bl}_u(S) \dashrightarrow \mathbb{P}^2,
\]
determined by the linear system \([\mathcal{I}_u \otimes \mathcal{O}_S(1)]\) on \( S \) or, alternatively, by the complete, base point free linear system \([\mathcal{L} \otimes \mathcal{O}_S(1)]\) on \( \tilde{S} \), where \( \mathcal{L} := \sigma^{-1}(u) \). The fibre \( \varphi^{-1}(y) \) over \( y \in \mathbb{P}^2 \) consists of the intersection of the line \( \overline{uy} \) through \( u \) and \( y \) with \( S \) or, more precisely, the residual intersection \( \overline{uy} \setminus u \).

Thus, as we may assume that \( u \) is not contained in any line, \( \varphi: \tilde{S} \rightarrow \mathbb{P}^2 \) is a finite morphism of degree two ramified along the intersection of \( S \) with the polar quadric \( P_uS := V(\sum_i x_i \partial_i F) \). To see the last assertion, choose coordinates such that \( u = [1 : 0 : 0 : 0] \), \( \mathbb{P}^2 = V(x_0) \), and \( y = [0 : 1 : 0 : 0] \). Then \( P_uS = V(\partial_0 F) \). On the other hand, the intersection of \( S \) with the line \( V(x_2, x_3) \) through \( u \) and \( y \) is singular at \( z = [z_0 : z_1 : 0 : 0] \), i.e. \( z \) is a branch point of the projection, if and only if \( \partial_0 F(z) = 0 \).

Note that \( C := S \cap P_uS \) is singular at \( u \). Indeed, the tangent plane of \( P_uS \) at \( u \in P_uS \) is given by \( \sum_i x_i \sum_j u_j (\partial_i \partial_j F)(u) = \sum_i x_i \sum_j u_j (\partial_i \partial_j F)(u) = 2 \sum_i x_i (\partial_i F)(u) \), which is also the equation for the tangent plane of \( S \) at \( u \). Similarly, one checks that \( S \cap P_uS \) is smooth in every other point. The strict transform \( \tilde{C} \subset \tilde{S} \) of \( C \) is the branch curve of \( \varphi \). Observe that this implies that \( \tilde{C} \) is contained in the linear system of \( \varphi^*\mathcal{O}_{\mathbb{P}^2}(3) \otimes \sigma^*\mathcal{O}_S(-1) \otimes \mathcal{O}(E) = \varphi^*\mathcal{O}_{\mathbb{P}^2}(2) \otimes \sigma^*\mathcal{O}_S(2) \otimes \mathcal{O}(2E) \), which confirms \( \tilde{C} \in \mathcal{O}_S(2) \). Also note that the smoothness of \( S \) implies that \( \tilde{C} \) is smooth, i.e. \( C \) is smooth away from \( u \) and has multiplicity two at \( u \). Moreover, \( D := \varphi(\tilde{C}) \subset \mathbb{P}^2 \) is a smooth quartic.

Summarizing, the blow-up of a smooth cubic surface in a point not contained in any line is a double cover of \( \mathbb{P}^2 \) ramified over a smooth quartic curve. The converse of the construction holds as well:

**Proposition 2.8.** Assume \( k = \mathbb{C} \) and let \( \varphi: \tilde{S} \rightarrow \mathbb{P}^2 \) be a double cover ramified along a smooth quartic curve \( D \subset \mathbb{P}^2 \). Then there exists a \((-1)\)-curve in \( \tilde{S} \) the contraction \( \tilde{S} \rightarrow S \) of which is isomorphic to a smooth cubic surface \( S \).

**Proof.** First note that \( \omega_\tilde{S} = \varphi^*(\omega_{\mathbb{P}^2} \otimes \mathcal{O}_{\mathbb{P}^2}(2)) = \varphi^*\mathcal{O}_{\mathbb{P}^2}(-1) \). Next, let \( E \subset \tilde{S} \) be the irreducible component of the pre-image of one of the 28 bitangents \( \ell \) of \( D \) that is a \((-1)\)-curve, cf. Section [5.7]. We show that its contraction yields a cubic surface.

Compute the normal bundle \( \mathcal{N}_{E/S} \) as the kernel of \( \varphi^*\mathcal{N}_{E/\mathbb{P}^2} \rightarrow \mathcal{O}_{\text{red} \times \text{red}} \) to see that indeed \( (E)^2 = -1 \). Let \( \sigma: \tilde{S} \rightarrow S \) be the contraction of \( E \). If we let \( \mathcal{O}_S(1) \) be the dual of \( \omega_S \), then \( \sigma^*\mathcal{O}_S(1) \otimes \mathcal{O}(-E) = \omega_{\tilde{S}} \). To conclude, one argues as in the proof of
Proposition 2.5. First, twisting the structure sequence for \( E \subset \tilde{S} \) with \( \varphi^*\mathcal{O}_{\mathbb{P}^2}(1) \otimes \mathcal{O}(E) \) shows that \( h^0(S, \mathcal{O}_S(1)) = 4 \). Therefore, the associated linear system defines a map to \( S \to \mathbb{P}^3 \), which is readily seen to be regular. Using ampleness of \( \varphi^*\mathcal{O}_{\mathbb{P}^2}(1) \), one shows that it is in fact an embedding. Eventually, observe that \((\mathcal{O}_S(1))^2 = (\varphi^*\mathcal{O}_{\mathbb{P}^2}(1) \otimes \mathcal{O}(E))^2 = 2 (\mathcal{O}_{\mathbb{P}^2}(1))^2 + 2 (\varphi^*\mathcal{O}_{\mathbb{P}^2}(1).E) + (E)^2 = 3. \)

\[ \square \]

**Dimension check:** The moduli space \( \mathcal{M}_g \) of smooth curves of genus \( g = 3 \) is of dimension \( 3g - 3 = 6 \). The canonical embedding of the non-hyperelliptic ones yield smooth plane curves \( D \subset \mathbb{P}^2 \) of degree four. Cubic surfaces together with the choice of the additional point \( u \in S \) needed for the passage to plane quartic curves also make up for a six-dimensional family.

2.5 We apply the general construction of Section 1.5.1. So, pick a line \( L \subset S \) in a smooth cubic surface and consider the linear projection

\[ \varphi: S \to \mathbb{P}^1 \]

from \( L \) to a generic line \( \mathbb{P}^1 \subset \mathbb{P}^3 \). Usually, the linear projection is only rational, but as \( L \) is of codimension one it is regular in this case or, equivalently, \( \text{Bl}_L(S) \to S \) is an isomorphism. The fibres \( \varphi^{-1}(y) \) are the residual conics of the intersection \( L \subset S \cap \tilde{y} \).

In particular, \((\varphi^{-1}(y).L) = 2 \) and, therefore, \( \varphi: L \to \mathbb{P}^1 \) is of degree two.

According to Proposition 1.5.1 there are exactly five singular fibres. For degree reasons, none of the fibres is multiple. Hence, the singular fibres \( \varphi^{-1}(s_i), i = 1, \ldots, 5 \) consist of two lines intersecting each other and both intersecting \( L \).
3 Lines on cubic surfaces

Once the 27 lines have been found and described geometrically, one can study the configurations from various angles. We collect a few observations concerning their positions, which have been studied classically, just by looking at the three types of lines (i)-(iii) as introduced in Remark 2.4. In the following, we let $S$ be a smooth cubic surface with fixed six pairwise disjoint lines $E_1, \ldots, E_6$ viewed as the exceptional lines of a contraction $\tau: S \to \mathbb{P}^2$.

The 27 lines on a cubic surface are among the most studied geometric objects in classical mathematics. That there are only finitely many was proved by Cayley in 1849 and then Salamon immediately observed that there are exactly 27 of them. Both papers, with the same title, appeared in the same volume of the Cambridge and Dublin Math. Journal [37, 157]. We recommend the introduction to [95] and the essay [49] for more on the history and a discussion of the various notations.

3.1 Any line $L \subset S$ can be realized as an exceptional line $E'_i$ of some blow-down $S \to \mathbb{P}^2$. In other words, for any line $L \subset S$ there exist five lines $E'_2, \ldots, E'_6$ such that $E'_i \subset L$, $E'_i \cap E'_j = \emptyset$ for $i \neq j$. This is clear if $L$ is of type (i), i.e. if $L$ is already one of the exceptional lines $E_i$.

For those of type (ii) and (iii) just observe that $L_{12}, L_{13}, L_{14}, L_{15}, E_6, L_6$ is a collection of pairwise disjoint lines involving at least one line of each type. That the first five are pairwise disjoint is easy and also that $E_6$ and $L_6$ are disjoint. To see that $L_6 \cap L_{1j} = \emptyset$ for $j \neq 6$, observe that the intersections of their images, a conic and a line in $\mathbb{P}^2$, satisfies $L_6 \cap L_{1j} = \{x_1, x_j\}$. Therefore, the intersection is transversal at both points and, hence, the intersection of the strict transforms is empty.
Remark 3.1. Note that \( L_i \cap L_{ij} \neq \emptyset \neq L_j \cap L_{ij} \). Indeed, either \( \bar{L}_i \cap \bar{L}_{ij} \) consists of \( x_j \) and another point \( x \notin \{x_k\} \) or of \( x_j \) with multiplicity two. In the first case, \( L_i \) and \( L_{ij} \) intersect in \( x \) (or rather in the unique point lying above \( x \)), while in the second case they meet in the point in \( E_j \) corresponding to the common tangent direction of \( \bar{L}_i \) and \( \bar{L}_{ij} \) at \( x_j \).

3.2 Any two disjoint lines are alike, i.e. any two disjoint lines \( L, L' \) can be complemented to \( E' = L, E'_1 = L', E'_2, \ldots, E'_6 \) of six pairwise disjoint lines, which then can be viewed as the exceptional lines of a blow-down of \( S \) to \( \mathbb{P}^2 \).

Indeed, we only have to consider the following three cases: (i) \( L = E_1 \) and \( L' = E_2 \), (ii) \( L = E_1 \) and \( L' = E_{23} \), and (iii) \( L = E_1 \) and \( L' = L_4 \). Of course, (i) can be completed by \( E_3, \ldots, E_6 \) and for (ii) and (iii) use a configuration of the type considered above already: \( E_1, L_1, L_{23}, L_{24}, L_{25}, L_{26} \).

3.3 For every line \( L \subset S \) there exist exactly 10 lines intersecting \( L \). Moreover, these 10 lines come in pairs \( \{\ell_1, \ell'_1, \ldots, \ell_5, \ell'_5\} \) such that every two pairs say, \( \{\ell_1, \ell'_1\} \) and \( \{\ell_2, \ell'_2\} \), are disjoint, i.e. \( (\ell_1 \cup \ell'_1) \cap (\ell_2 \cup \ell'_2) = \emptyset \). Furthermore, all triangles \( L, \ell, \ell' \) are coplanar, i.e. there exists a plane \( \mathbb{P}^3 \subset \mathbb{P}^3 \) with \( S \cap \mathbb{P}^2 = L \cup \ell \cup \ell' \).

According to Section 3.1 we may assume \( L = E_6 \). Going through the list, one finds that indeed \( E_6 \) intersects only \( L_{16}, L_{26}, L_{36}, L_{46}, L_{56} \) and \( L_1, L_2, L_3, L_4, L_5 \). We let \( \ell_i := L_{6i} \) and \( \ell'_i := L_i, i = 1, \ldots, 5 \).

Then check that for \( i, j \in \{1, \ldots, 5\} \), for example \( i = 1, j = 2 \), one has \( L_{6i} \cap L_{6j} = \emptyset \), \( L_{6i} \cap L_i = \emptyset \) (see the arguments in Section 3.1), and \( L_i \cap L_j = \emptyset \). For the last one use that, for example \( L_1 \cap L_2 \) consists of the four points \( x_3, \ldots, x_6 \). Hence, the intersection is transversal and, therefore, the intersection \( L_1 \cap L_2 \) of their strict transforms is empty.

It remains to verify that \( L, \ell_i, \ell'_i \) are coplanar. For this assume \( i = 1 \) and observe that

\[
\begin{align*}
\mathcal{O}(E_6) \otimes \mathcal{O}(L_{16}) \otimes \mathcal{O}(L_1) & \cong \mathcal{O}(E_6) \otimes (\tau^* \mathcal{O}(1) \otimes \mathcal{O}(-E_1 - E_6)) \otimes (\tau^* \mathcal{O}(2) \otimes \mathcal{O}(-\sum E_i)) \\
& \cong \tau^* \mathcal{O}(3) \otimes \mathcal{O}(\sum E_i) \cong \mathcal{O}(\mathbb{P}^1)^{10}.
\end{align*}
\]

Note that the plane containing \( L, \ell_i, \ell'_i \) is tangent at the point of intersection of each pair of these three lines.

Remark 3.2. Each of the coplanar unions \( L \cup \ell_i \cup \ell'_i \) is either a triangle, i.e. it has three singular points, or consists of three lines all going through one point. This corresponds to the two possibilities that the line \( L_{6i} \) and the conic \( \bar{L}_i \) intersect transversally in \( x_6 \) or with multiplicity two, so \( L_{6i} \) tangent to \( \bar{L}_i \) at \( x_6 \).

From the above count, one deduces that every smooth cubic surface admits exactly 45 tritangent planes, i.e. planes that intersect the cubic in the union of three pairwise distinct planes.

It is possible to show that there are nine of the tritangent plane which cut out all the 27
To prove the existence of the five pairs of lines intersecting \( L \subset S \) one could alternatively use the linear projection \( \varphi : S \to \mathbb{P}^4 \) from \( L \), see Section 2.5. They occur as the five singular fibres \( \varphi^{-1}(y_i) = \ell_i \cup \ell_i' \) of \( \varphi \).

3.4 The above discussion of the geometry of lines is useful when it comes to writing down explicit bases of \( \text{Pic}(S) \cong I_{1,6} \) and \( \mathcal{O}_S(1)^\perp \cong \mathcal{E}_6(-1) \) in terms of lines.

If \( f_0, \ldots, f_6 \) denotes the standard basis of \( I_{1,6} \), set \( f_i = -[E_i], i = 1, \ldots, 6 \). Then consider a tritangent plane, for example \( 3f_0 + f_1 + \cdots + f_6 \). So, \( E_1, \ldots, E_6 \) together with \( [E_6] + [L_1] + [L_{16}] \) already generate a sublattice of \( I_{1,6} \) of index three. To generate all of \( I_{1,6} \) by lines, observe that \( (L_1, E_i) = 1, i = 2, \ldots, 6, (L_1, E_1) = 0 \) and, therefore \( L_1 = 2f_0 + 0f_1 + f_2 + \cdots + f_6 \).

Spelling out the comments in the proof of Proposition 1.14 a basis of \( \mathcal{O}_S(1)^\perp \cong \mathcal{E}_6(-1) \) is then given by \( e_1 = E_1 - E_2, e_2 = E_2 - E_3, e_3 = E_3 - E_4, e_4 = E_4 - E_5, e_5 = E_5 - E_6, e_6 = E_6 + 2E_6 + L_{16} \).

3.5 For any pair of disjoint lines \( L, L' \) there exist exactly five lines \( \ell_1, \ldots, \ell_5 \) meeting both. Moreover, those five lines are pairwise disjoint.

According to Section 3.2 we may assume \( L = E_1 \) and \( L' = E_2 \). The lines meeting \( E_1 \) are

\[ L_{12}, L_{13}, L_{14}, L_{15}, L_{16}, L_2, L_3, L_4, L_5, L_6 \]

and those meeting \( E_2 \) are

\[ L_{42}, L_{23}, L_{24}, L_{25}, L_{26}, L_1, L_3, L_4, L_5, L_6 \]

Hence, the ones meeting both lines, \( E_1 \) and \( E_2 \), are \( L_{12}, L_3, L_4, L_5, L_6 \), which we have seen to be pairwise disjoint already.

This collection of five pairwise disjoint lines is special and not at all like, for example, the lines \( E_1, \ldots, E_5 \). Namely, there is no further line disjoint to all of the lines \( L_{12}, L_3, L_4, L_5, L_6 \). Indeed, the lines \( E_i \) all intersect at least one of them. The lines \( L_{1j}, j = 3, \ldots, 6 \), intersect \( L_j \), cf. Remark 3.1. The lines \( L_{ij}, 2 < i < j, \) intersect \( L_{12} \), and, again by Remark 3.1, \( L_1, L_2 \) also both intersect \( L_{12} \). As a consequence of Lemma 2.1 one finds

**Corollary 3.3.** Any pair of disjoint lines \( L, L' \subset S \) gives rise to a blow-down

\[ S \to L \times L' \cong \mathbb{P}^1 \times \mathbb{P}^1 \]

contracting exactly the five lines intersecting both lines \( L, L' \). □
There is a very geometric way of describing this blow-down, cf. [18]. Namely, for any point $x \in S \setminus (L \cup L')$ the plane $xL'$ spanned by $L'$ and $x$ intersects $L$ in exactly one point $u_x$. Similarly, $xL$ intersects $L'$ in a unique point $u'_x$. This defines $S \setminus (L \cup L') \rightarrow L \times L', \ x \mapsto (u_x, u'_x)$, which can be extended to all of $S$ by replacing $xL'$ for $x \in L'$ by the tangent plane $T_xS$ (which contains $L'$). Also, in this description one sees that exactly the lines $\ell_1, \ldots, \ell_5$ are contracted. Their images are the points $(u_i, u'_i)$, where $\ell_i \cap L = \{u_i\}$ and $\ell_i \cap L' = \{u'_i\}$.

3.6 Consider the configuration

$$\mathcal{L} := \mathcal{L}(S) := \{ \ell_1, \ldots, \ell_{27} \}$$

of all lines contained in a cubic surface $S$. By definition, it not only encodes the set of all lines, but also their intersection numbers (but not, for examples, the intersection points and, in particular, not whether there are triple intersection points), and is independent of the actual surface $S$. Alternatively, view $\mathcal{L}$ as the graph with vertices $\ell_i$ and with two vertices $\ell_i, \ell_j$ connected if the two lines intersect. Its complement, i.e. the graph with the same set of vertices but with vertices connected by an edge if and only if they are not connected in $\mathcal{L}$, is the so-called Schlafli graph.

Note that naming the first six lines as $\ell_1 = E_1, \ldots, \ell_6 = E_6$ as the exceptional lines of a blow-up $S \rightarrow \mathbb{P}^2$ determines uniquely the remaining 21 lines. For example, $L_{12}$ is the unique line that intersects $\ell_1$ and $\ell_2$ but no $\ell_3, \ldots, \ell_6$ and $L_3$ is the unique line that intersects $\ell_3, \ldots, \ell_6$ but not $\ell_1$. Moreover, according to Lemma 2.1 any subset $\{\ell_1, \ldots, \ell_6\}$ of six pairwise disjoint lines can be realized as the exceptional lines of a blow-up $S \rightarrow \mathbb{P}^2$. In other words, for any two choices $\ell_1, \ldots, \ell_6$ and $\ell'_1, \ldots, \ell'_6$ of six pairwise disjoint lines, there exists an automorphism $g: \mathcal{L} \rightarrow \mathcal{L}$ of the configuration with $g(\ell_i) = \ell'_i$. Thus, choosing six pairwise disjoint lines $\ell_1, \ldots, \ell_6$ is equivalent to giving an element in $\text{Aut}(\mathcal{L})$. This allows one to compute the order

$$|\text{Aut}(\mathcal{L})| = 27 \cdot 16 \cdot 10 \cdot 6 \cdot 2 = 2^7 \cdot 3^4 \cdot 5 = 51,849.$$ 

Indeed, there are 27 choices for $E_1$, then 16 choices for $E_2$, etc. Of course, it is no coincidence that the order is the order of the Weyl group $W(E_6)$.

The configuration of lines presented by the entries of the matrix

$$\begin{pmatrix} E_1 & E_2 & E_3 & E_4 & E_5 & E_6 \\ L_1 & L_2 & L_3 & L_4 & L_5 & L_6 \end{pmatrix}$$

is what is called a Schlafli double six. It has the property that each line intersects exactly those lines in the matrix that are neither contained in the same row nor in the same column. As $L_i, L_j, i \neq j$, are disjoint, there are exactly 30 intersection points.

Example 3.4. Show that there exist 36 double sixes in each smooth cubic surface.
Chapter 4. Cubic surfaces

It is a classical fact that any double six of actual lines in \( \mathbb{P}^3 \) contained in a cubic surface \( S \) determines the surface uniquely. In fact, given five skew lines in \( \mathbb{P}^3 \) and one that intersects them all (think of \( E_1, \ldots, E_5 \) and \( L_6 \)), there exists a unique cubic surface containing the six lines as part of a double six.

In Section 12.5 we have seen that the monodromy group of the family of all smooth cubics is the Weyl group \( W(E_6) \). As the discriminant divisor has degree 26, see Theorem 12.2, the Weyl group is generated by 26 reflections. In [47] it has been shown that \( W(E_6) \) can also be generated by six reflections and one transformation that is given by interchanging the two rows of a double six.

3.7 Let us now make use of the description of a cubic surface \( S \) as a double cover of \( \mathbb{P}^2 \), cf. Section 2.4. So, fix a point \( u \in S \) not contained in any of the lines, consider the blow-up \( \sigma: \tilde{S} = \text{Bl}_u(S) \rightarrow S \), and let \( \varphi: \tilde{S} = \text{Bl}_u(S) \rightarrow \mathbb{P}^2 \) be the projection onto a generic plane. We denote the exceptional line of the blow-up by \( E \) and the ramification curve by \( D = \varphi(C) \subset \mathbb{P}^2 \), a smooth quartic curve. Then there exists a natural bijection between the 28 bitangent lines of \( D \) and the 27 lines in \( S \) together with \( E \):

\[
\{ \ell \subset \mathbb{P}^2 \mid \text{bitangents to } D \} \leftrightarrow \{ \ell_1, \ldots, \ell_{27} \subset S \mid \text{lines} \} \cup \{ E \}.
\]

First, observe that each line \( \ell \subset S \), simultaneously considered as a curve in \( \tilde{S} \), satisfies \( 1 = (\ell_i, O_3(1)) = (\ell_i, \varphi^* O_{\mathbb{P}^2}(1)) \). Hence, \( \varphi(\ell_i) \subset \mathbb{P}^2 \) is a line and \( \ell_i \rightarrow \tilde{\ell}_i \) := \( \varphi(\ell_i) \) is an isomorphism. Similarly, \( (E, \varphi^* O_{\mathbb{P}^2}(1)) = 1 \) and, therefore, \( E \rightarrow E := \varphi(E) \subset \mathbb{P}^2 \) is also a line. However, lines in \( \mathbb{P}^2 \) whose pre-image under \( \varphi \) split off a copy of the line cannot intersect \( D \) transversally at any point. Hence, it has to be a bitangent of \( D \).

**Lemma 3.5.** Let \( D \subset \mathbb{P}^2 \) be a smooth quartic curve over an algebraically closed field \( k \) with \( \text{char}(k) \neq 2 \). Then \( D \) admits exactly 28 bitangent lines.

**Proof** As a first step one observes that \( \omega_D = O_{\mathbb{P}^2}(1)|_D \). Therefore, a bitangent through \( x, y \in D \) (or a hyperflex through \( x = y \in D \)) corresponds to an invertible sheaf \( N \in \text{Pic}^2(D) \) with \( H^0(D, N) \neq 0 \) and \( N^2 = \omega_D \). The number of square roots of \( \omega_D \), called theta-characteristics, is of course \( 2^{2g(D)} = 64 \). However, only 28 of them are effective. For this one has to compute the degree of the map \( S^2(D) \rightarrow \text{Pic}^2(D) \rightarrow \text{Pic}^1(D) \).

Alternatively, one could use the Plücker formula for smooth curves \( C \subset \mathbb{P}^2 \) with only bitangents and simple flexes. It turns out that there exist 24 flexes and 28 bitangents, see [87] Sec. II.

As \( \varphi^{-1}(\tilde{\ell}_i) \rightarrow \tilde{\ell}_i \) is of degree two, \( \varphi^{-1}(\tilde{\ell}_i) = \ell_i \cup \ell_i' \) with \( \ell_i' \rightarrow \varphi(\ell_i') = \tilde{\ell}_i \). The two curves \( \ell_i \) and \( \ell_i' \) intersect in the pre-image of the points of contact \( \tilde{\ell}_i \cap D \). Note that

---

1 By definition, a bitangent of \( D \) is a line in \( \mathbb{P}^2 \) that intersects \( D \) in two points \( x, y \) with multiplicity (at least) two. The case \( x = y \) is allowed, in which the bitangent has multiplicity four at this point. This is sometimes also called a hyperflex. The locus of smooth quartic curves with a hyperflex is a divisor in the moduli space of curves of genus three, cf. [50/89].
\(\ell'_i\) does not correspond to a line in \(S\), as two lines in \(S\) intersect at most in one point and there transversally. Instead, \((\sigma(\ell'_i).O_3(1)) = 2\) and \((\ell'_i,E) = 1\), i.e. \(u\) is a smooth point of the curve \(\sigma(\ell'_i)\). Indeed, \(\ell_i \cup \ell'_i = \phi^{-1}(\ell_i)\) is a curve in the linear system of \(\phi^*O_3(1) = \phi^*O_3(1) \otimes \mathcal{O}(-E)\). Hence, \(2 = (\ell_i \cup \ell'_i, \phi^*O_3(1)) = 1+(\ell'_i, \phi^*O_3(1) \otimes \mathcal{O}(-E)).\) As \(\ell'_i\) is not a line and, hence, \((\ell'_i, E) > 1\), one has \((\ell'_i, E) \geq 1\) and in fact \((\ell'_i, E) = 1\), because the two lines \(\phi(\ell'_i) = \ell_i\) and \(\phi(E)\) intersect in one point only.

For example, for the line \(\bar{L}_{12}\) there exists a unique conic \(Q\) through \(x_3, x_4, x_5, x_6\) and \(\varphi(u)\) intersecting \(L_{12}\) in two points distinct from \(x_1, x_2\). The strict transform \(\bar{Q} \subset \bar{S}\) of \(Q\) is contained in the linear system of \(\sigma^*(\tau^*\mathcal{O}(2) \otimes \mathcal{O}(-\sum_{i=1,2} E_i)) \otimes \mathcal{O}(-E)\). This line bundle is indeed isomorphic to \(\varphi^*O_3(1) \otimes \mathcal{O}(-L_{12})\), and, hence, \(L_{12} \cup \bar{Q} = \varphi^{-1}(\varphi(L_{12}))\).

Note that \(\bar{Q}\) is a \((-1)\)-curve in \(\bar{S}\), but not its image in \(S\).

**Remark 3.6.** For the universal family \(\mathcal{D} \longrightarrow U \coloneqq |O_{\mathbb{P}^3}(4)|_{\text{sm}}\) of smooth quartic curves in \(\mathbb{P}^3\), the relative family of bitangents \(B(\mathcal{D}/U) \longrightarrow U\) is an étale map of degree 28. Its Galois group or, equivalently, its monodromy group \(\text{Im}(\pi_1(U) \longrightarrow \pi_2)\) is isomorphic to \(\text{Sp}_6(\mathbb{Z}/2\mathbb{Z})\), which is of order \(288 \cdot 7! = 2^8 \cdot 3^4 \cdot 5 \cdot 7\). See [67, Sec. II:4] and compare this to Corollary [1.12] and the discussion Section [1.25]. For example, to compute the monodromy group of the 27 lines on the universal family of smooth cubic surfaces one has to consider the stabilizer of one of the 28 bitangents, which amounts to fixing the exceptional curve blown-down to the point \(u \in S\). Hence, the order is \(288 \cdot 7! / 28 = 2^7 \cdot 3^4 \cdot 5\) which confirms Corollary [1.12]. For a short historic account of the interplay between lines on cubic surfaces and bitangents to quartic curves we also recommend [171] Ch. 7.

### 3.8 A point \(x \in S\) in a smooth cubic surface \(S\) is called an **Eckardt point** if the tangent plane at \(x \in S\) intersects \(S\) in three lines through \(x\). How many Eckardt points can a smooth cubic surface have?

In Remark [2.8] we have seen examples of this, namely three lines consisting of an exceptional line \(E_6\), the strict transform \(L_i, i \neq 6\), of the conic \(\bar{L}_i\) (which contains \(x_6\)), and the strict transform \(L_{\bar{6}}\) of the line \(\bar{L}_6\) tangent to \(\bar{L}_i\) (at \(x_6\)). As for each \(i\) there exist only two lines through \(x_i\) tangent to \(\bar{L}_i\) at some point, each conic \(\bar{L}_i\) will give rise to at most two Eckardt points. So altogether, there exist at most 12 Eckardt points of this type.

However, Eckardt points may arise in a different way namely as the triple intersection \(\bar{L}_{i_1} \cap \bar{L}_{i_2} \cap \bar{L}_{i_3}\) with \([i_1, \ldots, i_6] = \{1, \ldots, 6\}\). Generically, this triple intersection would consist of three points, but star shaped configuration are of course possible.\(^2\)

For generic choices of points \(x_1, \ldots, x_6 \in \mathbb{P}^3\) one does not expect any of these two

\(^2\) I would guess that some combinatorial argument shows that at most six points can occur in this way. However, the next result may be valid without it. A priori it could happen that whenever there are more stars in the line configuration associated with the six points, then fewer conics \(\bar{L}_i\) are tangent to those lines.
possibilities to occur. Namely, neither will any of the conics $L_i$ be tangent to any line $L_{ij}$ nor will the line configuration show stars.

**Proposition 3.7.** The number of Eckardt points on a cubic surface $S$ is one of the following numbers: 0, 1, 2, 3, 4, 6, 9, 10, or 18.

**Remark 3.8.** The article [170] (see also the author’s thesis) studies the loci $H_k \subset |\mathcal{O}_{\mathbb{P}^3}(3)|_{sm}$ of smooth cubic surfaces with at least $k$ Eckardt points. They are invariant under the action of $\text{PGL}(4)$ and, thus, determine closed subschemes

$$\tilde{H}_k := H_k/\text{PGL}(4) \subset M_3 = M_{3,3}$$

of the four-dimensional moduli space of smooth cubic surfaces. For example, it turns out that $\tilde{H}_1 \subset M_3$ is an irreducible divisor, i.e. of dimension three, and that $\tilde{H}_k$ is zero-dimensional for $k \geq 10$.

This is of course compatible with the above proposition. As soon as the surface $S$ contains more than 10 Eckardt points, it contains 18 Eckardt points.

Moreover, $\tilde{H}_{10}$ consists of exactly two points, corresponding to the Clebsch surface and the Fermat cubic. The latter admits 18 Eckardt points and is the only point in $\tilde{H}_{11} = \cdots = \tilde{H}_{18}$. We refer to [63] for more details.

**4 Moduli space**

**4.1**
This chapter is devoted to cubic hypersurfaces $Y \subset \mathbb{F}(V) \cong \mathbb{P}^4$ of dimension three. We will be mostly interested in smooth ones, but (mildly) singular ones will also occur. Cubic threefolds and their Fano surfaces of lines have a long and distinguished history in algebraic geometry, going back to the Italian school, and Gino Fano [70] in particular, and the landmark article of Clemens and Griffiths [42], proving irrationality of all smooth cubic threefolds and introducing the intermediate Jacobian as a key tool. Cubic threefolds have also served as a testing ground for the Weil conjectures already in [28] and their geometry has been investigated further in the series of papers of Tyurin [168,169,167], Murre [141,142], Beauville [13,14], and many others.

Before getting started, let us collect the basic facts on cubic threefolds that follow from the general theory as presented in Chapter 1. For simplicity we usually work over $\mathbb{C}$, see Section ?? for some comments on cubic threefolds over other fields.

0.1 The canonical bundle of a smooth cubic threefold $Y \subset \mathbb{P}^4 = \mathbb{F}(V)$ is $\omega_Y \cong \mathcal{O}_Y(-2)$, which is the square of the dual of the ample generator of $\text{Pic}(Y) \cong \mathbb{Z} \cdot \mathcal{O}_Y(1)$. The non-trivial Betti numbers of $Y$ are as follows:

\[
b_0(Y) = b_2(Y) = b_4(Y) = b_6(Y) = 1 \quad \text{and} \quad b_3(Y) = 10
\]

and, therefore, its Euler number $e(Y) = -6$, see Section [11]. The linear system of all cubic threefolds is $|\mathcal{O}_{\mathbb{P}^4}(3)| \cong \mathbb{P}^{34}$ and the moduli space of smooth cubic threefolds is of dimension ten, see Section [12].

0.2 As for cubic surfaces, the geometry of lines on cubic threefolds is particularly rich and interesting. In dimension three however, every point is contained in a line and a generic point is contained in exactly six lines, cf. Example [3]. As for a smooth cubic threefold $\text{Pic}(Y) \cong \mathbb{Z} \cdot \mathcal{O}_Y(1)$, there are no planes contained in $Y$, see also Remark [3].

Chapter 5. Cubic threefolds

The general theory of Fano varieties of lines as outlined in Section 3.1 provides us with very useful information:

(i) The Fano variety of lines $F := F(Y)$ of a smooth cubic threefold $Y$ is a smooth, irreducible, projective surface, the Fano surface of $Y$.

(ii) The canonical bundle $\omega_F$ of $F$ is ample and

$$\omega_F \simeq O_F(1).$$

Here, $O_F(1)$ is the Plücker polarization induced by $F \hookrightarrow O(1, P^4) \hookrightarrow P(\wedge^2 V)$, see Lemma 3.2.1.

(iii) Its degree with respect to the Plücker polarization $g = c_1(O_F(1))$ is, cf. Section 3.3.2:

$$\deg(F) = \int_F g^2 = 45.$$

(iv) The Euler number of the Fano surface is $e(F) = 27$, see Proposition 3.3.5 and Section 2.1.

(v) The Hodge diamond (half of it) of $F$ is, cf. Section 3.3.5:

$$\begin{array}{ccc}
    b_0(F(Y)) = 1 & 1 \\
    b_1(F(Y)) = 10 & 5 & 5 \\
    b_2(F(Y)) = 45 & 10 & 25 & 10.
\end{array}$$

(vi) For the universal family of lines on $Y$

$$F(Y) \xrightarrow{p} \mathbb{L} \xrightarrow{q} Y$$

the morphism $q: \mathbb{L} \rightarrow Y$ is generically finite of degree six cf. Lemma 3.4.6.

(vii) The Fano correspondence $\varphi = p^* \circ q^*: H^1(Y, \mathbb{Q}) \rightarrow H^1(F, \mathbb{Q})(-1)$ is an isomorphism of rational Hodge structures. According to Proposition 3.4.3 it satisfies

$$(\alpha, \beta) = -\frac{1}{6} \int_F \varphi(\alpha) \cdot \varphi(\beta) \cdot g,$$

(viii) There exist isomorphisms of Hodge structures, cf. Section 3.3.5

$$H^1(Y, \mathbb{Q})(1) \simeq H^1(F(Y), \mathbb{Q}) \quad (0.1)$$

and

$$\wedge^2 H^3(Y, \mathbb{Q})(2) \simeq \wedge^2 H^3(F(Y), \mathbb{Q}) \simeq H^2(F(Y), \mathbb{Q}). \quad (0.2)$$

The isomorphism in (0.1) has been obtained via the Fano correspondence, see Proposition 3.3.5 or, alternatively, via the motivic approach in Section 3.3.5. The first isomorphism in (0.2) is deduced by taking exterior products of (0.1) and for the second see Lemma 2.3 below.

For a very general $Y$ cubic threefold, the only rational Hodge classes in $\wedge^2 H^3(Y, \mathbb{Q})$
are multiples of the one given by the intersection product on $Y$, see Remark 12.13. Then the existence of the second isomorphism already shows that for the very general cubic threefold $Y \subset \mathbb{P}^4$ the Picard number of its Fano surface is

$$\rho(F(Y)) = \text{rk} \text{NS}(F(Y)) = 1.$$ 

1 Lines on the cubic and curves on its Fano surface

The Fano surface $F(Y)$ of a cubic threefold $Y$ parametrizes all lines $L \subset \mathbb{P}^4$ contained in $Y$. They can be of the first or of the second type, i.e. $N_{L/Y} \simeq \mathcal{O}_L \oplus \mathcal{O}_L$, or $N_{L/Y} \simeq \mathcal{O}_L(1) \oplus \mathcal{O}_L(-1)$.

We consider natural curves in $F(Y)$ of a smooth cubic threefold $Y \subset \mathbb{P}^4$ over an arbitrary algebraically closed field. Firstly, there is the curve of lines of the second type $R \subset F(Y)$. Hence, $\det(\mathcal{T}_L) \simeq q^* \mathcal{T}_Y$, which we consider as a section of $\omega_L \otimes q^* \omega_Y$. Now, $q^* \omega_Y \simeq q^* \mathcal{O}_Y(2) \simeq \mathcal{O}_p(2)$, see Lemma 34.1. Furthermore, the relative Euler sequence $0 \to \mathcal{O}_L \to p^* \mathcal{S}_F \otimes \mathcal{O}_p(1) \to \mathcal{T}_p \to 0$ for the projective bundle $p: \mathcal{L} \simeq \mathbb{P}(\mathcal{S}_F) \to F$ shows that $\omega_L$ is isomorphic to $\omega_p \otimes p^* \omega_F \simeq p^* \det(\mathcal{S}_F^*) \otimes \mathcal{O}_p(-2) \otimes p^* \mathcal{O}_F(1)$. Hence, $\det(dq) \in H^0(\mathcal{L}, p^* \mathcal{O}_F(2)) \simeq H^0(F, \mathcal{O}_F(2))$. □

Remark 1.2. The proposition goes back to Fano. In [42, Sec. 10] the argument uses the observation that for the generic hyperplane section $S := Y \cap \mathbb{P}^3$ the pre-image $q^{-1}(S)$ is the blow-up $p: q^{-1}(S) \to F(Y)$ in the 27 points $[\ell_i] \in F(Y)$ corresponding to the 27 lines $\ell_i \subset S$ contained in the cubic surface $S$.

The kernel of the tangent map $\mathcal{T}_{[L]} \to T_Y$ at a point $(L, x) \in \mathcal{L} \subset F \times Y$ is
the space of first order deformations of $L \subset Y$ through $x \in L$. This space is naturally isomorphic to the subspace $H^0(L, N_{L/Y} \otimes \mathcal{I}_x) \subset H^0(L, N_{L/Y})$, cf. [115, Thm. II.1.7]. As the ideal sheaf $\mathcal{I}_x$ of $x \in L \cong \mathbb{P}^1$ is isomorphic to $\mathcal{O}_L(-1)$, this space is non-zero if and only if $L \subset Y$ is a line of the second type, i.e. $N_{L/Y} \cong \mathcal{O}_L(1) \oplus \mathcal{O}_L(-1)$, cf. Lemma 31.10.

**Corollary 1.3.** The morphism $q: \mathbb{L} \rightarrow Y$ is smooth at $(L, x) \in \mathbb{L}$ if and only if $L \subset Y$ is a line of the first type. □

**Exercise 1.4.** Show that every point $x \in Y$ that is not contained in any line of the second type is contained in exactly six lines.

**Exercise 1.5.** Show that every Eckardt point $x \in Y$ is contained in infinitely many lines of the second type. In fact, according to [141, Lem. 1.18] every point contained in a line of the first type is only contained in finitely many lines and, therefore, all lines containing an Eckardt point are of the second type.

**Exercise 1.6.** It turns out that the ramification of $q: \mathbb{L} \rightarrow Y$ along $R$ is generically simple, see [42, Lem. 10.18]. Consider the projection $q: (q) \rightarrow \mathbb{R} := q(R(q)) \subset Y$ and denotes its degree by $d$. Show that $\mathbb{R} \in |\mathcal{O}_Y(30/d)|$. See also Remark 1.17.

Note that the non-vanishing of $H^0(L, N_{L/Y} \otimes \mathcal{I}_x)$ only depends on $L \subset Y$ and not on the point $x \in L$. In particular, $q: \mathbb{L} \rightarrow Y$ is ramified along all of $L = p^{-1}([L]) \subset \mathbb{L}$ or not at all. This confirms that $R(f) = p^{-1}R$ for a curve $R \subset F(Y)$.

**Corollary 1.7.** The ramification divisor $R(q) \subset \mathbb{L}$ is the pull-back of the curve $R \subset F(Y)$ that parametrizes all lines $L \subset Y$ of the second type. □

The set $R$ of all lines of the second type $[L] \in F$ is viewed with this scheme structure, i.e. as a curve in the linear system $|\mathcal{O}_F(2)|$. Note that $R(q)$, and hence $R$, cannot be empty. Indeed, otherwise $L \rightarrow Y$ would be an étale covering of degree six of the simply connected threefold $Y$. As $\mathbb{L}$ is connected, this is absurd. It is maybe also worth pointing out that a priori it is not even clear that lines of the second type do not define isolated points in $F(Y)$ or that not every line is of the second type. A stronger version of the latter is proved in Corollary 1.10.

**Remark 1.8.** According to Proposition 31.124 for generic $Y$ the curve $R = F_3(Y)$ is smooth. It seems that in [141, Cor. 1.9] a local computation is used to show that $R$ is always actually smooth. However, for special smooth cubics the morphism $q: \mathbb{L} \rightarrow Y$ may contract curves $E_x \subset \mathbb{L}$ to so-called Eckardt points $x \in Y$, i.e. points lying on infinitely many lines. A cubic $Y \subset \mathbb{P}^4$ can admit at most finitely many Eckardt points [42 Lem. 8.1] and, according to [154], in fact at most 30. In these cases, $R$ will contain

\[^1\] I would expect $d = 1$, but do not know how to prove it.
The double line between these two cases: contained in a unique plane. Similarly, for infinitesimal deformations one distinguishes at all or in exactly one point (and there transversally). In the second case, they are Lemma 1.9. Let \( L \) be of the first type if and only if there exists a (unique) plane \( \mathbb{P}^2 \) such that \( \dim(\mathbb{P}^2) = \dim(R) = 1 \), and \( R = \{ L \in F \mid \det(\psi_L) = 0 \} \in |\mathcal{O}_F(2)| \), for \( \det(Q) \) and \( \det(S^2(S^2)) = \mathcal{O}_F(2) \). Note that the scheme structures of \( R = F_2(Y) = M_2(\psi) \) all coincide.

Clearly, two distinct lines \( L_1, L_2 \subset \mathbb{P}^4 \), contained in the cubic \( Y \) or not, do not intersect at all or in exactly one point (and there transversally). In the second case, they are contained in a unique plane. Similarly, for infinitesimal deformations one distinguishes between these two cases:

(i) Let \( L \subset Y \) be a line of the first type. Then the lines \( L_t \subset Y \) corresponding to \( t \in F(Y) \) close to \( \{ L \in F(Y) \} \) are disjoint to \( L \). Indeed, a first order deformation keeping the intersection non-empty, would correspond to a global section of \( \mathcal{N}_{L_t} \otimes \mathcal{I}_t \cong \mathcal{O}_L(-1) \oplus \mathcal{O}_L(-1) \) for some point \( x \in L \).

(ii) On the other hand, if \( L \subset Y \) is of the second type, then for each point \( x \in L \), the subspace \( H^0(L, \mathcal{N}_{L_t} \otimes \mathcal{I}_t) \subset H^0(L, \mathcal{N}_{L_t} \otimes \mathcal{I}_t) = T_{[L]}F(Y) \) is one-dimensional and corresponds to a deformation \( \text{Spec} k[x] \times \{ x \} \subset \text{Spec} k[x] \times Y \). Its image under the second projection is contained in the intersection of a plane \( \mathbb{P}^2 \cong \mathbb{P}_x^2 \) with \( Y \), i.e. \( \mathbb{P}_x^2 \cap Y \) is the double line \( 2L \) in the plane \( P_L \). Note that the subspace \( H^0(L, \mathcal{N}_{L_t} \otimes \mathcal{I}_t) \subset H^0(L, \mathcal{N}_{L_t}) \) is independent of \( x \) and so is \( P_L \). So, we have proved:

**Lemma 1.9.** Let \( L \subset Y \) be a line in a smooth cubic threefold. Then \( L \) is of the second type if and only if there exists a (unique) plane \( \mathbb{P}^2 \cong P_L \subset \mathbb{P}^4 \), that is tangent to \( Y \) at every point of \( L \), i.e. \( 2L \subset P_L \cap Y \).

It may happen that for a line \( L \subset Y \) of the second type \( 3L = P_L \cap Y \). However, this happens for at most finitely many \( [L] \in R \), see [42, Lem. 10.15].

**Corollary 1.10.** The generic line \( L \subset Y \) is of the first type. In fact, for a dense open subset of lines \( [L] \in F(Y) \) any plane \( \mathbb{P}^2 \subset \mathbb{P}^4 \) containing \( L \) intersects \( Y \) in two further distinct lines, i.e. such that \( \mathbb{P}^2 \cap Y \) is reduced.

**Proof** Lines of the second type are parametrized by the curve \( R \). So, any line \( [L_1] \in F(Y) \setminus R \) is of the first type. Furthermore, for any line of the second type \( L_2 \subset Y \) there exists a unique plane \( \mathbb{P}^2 \cong P_{L_2} \subset \mathbb{P}^4 \) which intersects \( Y \) along \( L_2 \) with multiplicity at least two. The points \( [L] \in F \) corresponding to residual curves \( L \subset Y \) of \( L_2 \subset P_{L_2} \cap Y \) while \( [L_2] \) moves in \( R \) sweep out a curve \( R^* \subset F(Y) \). Then any line corresponding to a point in \( F(Y) \setminus (R \cup R^*) \) has the required property. □
1.2 We move to the next class of curves in $F(Y)$. For a fixed line $[L] \in F$ we define the curve

$$C_L \subset F(Y)$$

as the closure of the curve of all lines $L' \subset Y$ different from $L$ but with non-empty intersection $L \cap L'$. To make this rigorous, one may use the formalism of Section 3 and consider

$$\varphi = p_* \circ q^*: \CH^2(Y) \longrightarrow \CH^1(F(Y)) \simeq \Pic(F(Y)).$$

By definition, $p_*$ is trivial on components of $q^{-1}(L)$ with positive fibre dimension over $F(Y)$, e.g. the class of the component $p^{-1}([L]) \subset q^{-1}(L)$ is mapped to zero under $p_*$. The image of the class of the line $L \subset Y$ under $\varphi$ is a line bundle $\mathcal{O}(C_L)$ that comes with a natural section (up to scaling) vanishing along $L$. Indeed, as explained above, if $[L] \in C_L$, then $H^0(L, N_{L/Y}(-1)) \neq 0$, i.e. $L$ is of the second type. For the converse, consider all planes $P \subset \mathbb{P}^4$ containing $L$ and write $P \cap Y = L \cup L_1 \cup L_2$. Then $[L_1], [L_2] \in C_L$ and, when $P$ approaches $P_L$ (use the connectivity of the discriminant curve $D_L$, see below), one of the two lines specializes to $L$ and hence $[L] \in C_L$.

Assume now that $L$ is of the first type, i.e. $[L] \in F(Y) \setminus C_L$. In this case, $q^{-1}(L)$ is the disjoint union of $p^{-1}([L]) \cong L$ and a curve mapping isomorphically onto $C_L$:

$$q^{-1}(L) = p^{-1}([L]) \sqcup C_L.$$  \hfill (1.1)

Indeed, for $[L'] \in C_L$, the line $L' = q(p^{-1}([L']))$ intersects $L$ transversally in exactly one point. Hence, $p^{-1}([L'])$ and $q^{-1}(L)$ intersect with multiplicity one.

**Remark 1.12.** Any curve in $F(Y)$ intersects the ample curve $R \subset F(Y)$ of all lines of the second type. Applied to $C_L$, this shows that any line $L \subset Y$ intersects some line $L' \subset Y$ of the second type.

**Remark 1.13.** It is not difficult to show that distinct lines $L$ yield distinct curves $C_L$:

$$L \neq L' \Rightarrow C_L \neq C_{L'}.$$  

For example, if $L$ and $L'$ intersect in a point $x \in Y$, in other words $\overline{LL'} = \mathbb{P}^2$, then the intersection $C_L \cap C_{L'}$ parametrizes all lines passing through $x$ and the uniquely determined residual line of $L \cup L' \subset \overline{LL'} \cap Y$. This is just a finite set unless $x$ is an Eckardt point. In the latter case, $C_L = C_{L'}$ would imply that all lines intersecting $L$ at all, would intersect it in the Eckardt point $x$, which is absurd.
1 Lines on the cubic and curves on its Fano surface

The argument is more involved in the case of disjoint lines $L \cap L' = \emptyset$. Then $\Pi \Pi' \simeq \mathbb{P}^3$ and the intersection with $Y$ yields a cubic surface $S \subset Y$. If $S$ is smooth, then it contains only finitely many lines and hence the intersection $C_L \cap C_{L'}$ is finite. If $S$ is normal and not a cone, then $S$ has only rational double points as singularities and still contains only finitely many lines [62, Ch. 9.2.2]. If $S$ is a cone over a cubic curve, then we may assume that $L$ is a line through the vertex and $L'$ is a component of the cubic curve. In particular one finds a line intersecting $L$ but not $L'$. Finally, if $S$ is neither normal nor a cone, then $S$ is reducible or projectively equivalent to one of two specific surfaces [62 Thm. 9.2.1]. One has to argue separately in the two cases.

**Lemma 1.14.** For any two lines $L_1, L_2 \subset Y$ the curves $C_{L_1}, C_{L_2} \subset F(Y)$ are algebraically equivalent. Moreover, $\mathcal{O}(C_{L_1})^{\otimes 3}$ is algebraically equivalent to $\mathcal{O}_F(1) \simeq \omega_F$.

**Proof.** As $[C_{L_1}]$ is the image of $[L] \in \text{CH}^2(Y)$ under $\varphi: \text{CH}^2(Y) \longrightarrow \text{CH}^1(F(Y))$ and all lines, which are parametrized by the connected Fano surface $F(Y)$, are algebraically equivalent to each other, the algebraic equivalence class of $C_L$ is independent of $L$.

For the second statement use Lemma 3.41. As $h^2 \in \text{CH}^2(Y)$ is represented by the intersection with an arbitrary plane $\mathbb{P}^2 \subset \mathbb{P}^4$, it can be written as a sum of three lines $h^2 = [L_1] + [L_2] + [L_3]$. For example, for $\mathbb{P}^2 = P_L$ for $L$ of the second type, $h^2 = 2[L] + [L']$ with $L'$ the residual line of $2L \subset P_L \cap Y$.

Hence, $c_1(\mathcal{O}_F(1)) = \varphi(h^2) = [C_{L_1}] + [C_{L_2}] + [C_{L_3}]$, which is algebraically equivalent to $3[C_{L_3}]$. \hfill \Box

**Exercise 1.15.** To make the above more explicit, represent a plane $\mathbb{P}^2 \subset \mathbb{P}^4$ as the intersection $V(s_1) \cap V(s_2)$, where $s_1, s_2 \in \mathbb{V}^*$, $H^0(\mathbb{P}^4, \mathcal{O}(1)) \simeq H^0(F,F')$ are two linearly independent sections. Then the zero set of the image of $s_1 \wedge s_2$ under the natural map $\wedge^2 \mathbb{V}^* \longrightarrow H^0(F(Y), \wedge^2 S_F^*) \simeq H^0(F(Y), \mathcal{O}_F(1))$ is the set of all lines $L = \mathbb{P}(W)$ with $(s_1 \wedge s_2)|_W = 0$. The latter is equivalent to $L \cap \mathbb{P}^2 \neq \emptyset$ or, equivalently, to $L \cap (L_1 \cup L_2 \cup L_3) \neq \emptyset$, i.e., $[L] \in C_{L_1} \cup C_{L_2} \cup C_{L_3}$. Here, $\mathbb{P}^2 \cap Y = L_1 \cup L_2 \cup L_3$.

**Exercise 1.16.** The self-intersection and the (arithmetic) genus of $C_L$ are given by

$$(C_L)^2 = 5 \quad \text{and} \quad g(C_L) = 11.$$ 

**Remark 1.17.** Let $L_0 \subset Y$ be a fixed line of the first type.

(i) As $q: L \longrightarrow Y$ is of degree six, the map that sends $[L] \in C_{L_0} \subset F$ to the point of intersection of $L_0$ and $L$ defines a morphism $\pi: C_{L_0} \longrightarrow L_0$, $[L] \longmapsto L_0 \cap L$ of degree five. Due to (1.1), the two morphisms $\pi$ and $q$ coincide. The ramification points of $C_{L_0} \longrightarrow L_0$, i.e. the points in the intersection $R(q) \cap C_{L_0}$, correspond to lines of the second type intersecting $L_0$. The Hurwitz formula applied to $\pi: C_{L_0} \longrightarrow L_0$ yields $d \cdot (R.L_0) = (R(q).C_{L_0}) = 30$, which confirms $R \in |\mathcal{O}_Y(30/d)|$, see Exercise 1.6
In the proof of Corollary 1.25 we will see that \( h^0(\pi^*\mathcal{O}_{L_0}(1)) = 2 \).

(ii) For \([L] \in C_{i_0}\) one finds
\[
\pi^*\mathcal{O}_{L_0}(1) \cong \mathcal{O}(C_L)|_{C_{i_0}} \otimes \mathcal{O}_{C_{i_0}}([L] - [L']) \tag{1.2}
\]

Here, \( L' \) is the residual line of \( L_0 \cup L \subset \overline{\Delta L} \cap Y \) which could be \( L \). Indeed, if \([x] = L_0 \cap L\), then \( \pi^{-1}(x) \) parametrizes the five lines (with multiplicities) \( L_1 := L, L_2, \ldots, L_5 \) distinct from \( L_0 \) containing \( x \). Hence, \( \pi^*\mathcal{O}(1) \cong \mathcal{O}_{C_{i_0}}(\sum[L_i]) \). On the other hand, \( C_{i_0} \cap C_L = \{ [L'], [L_2], \ldots, [L_5] \} \) and, therefore, \( \pi^*\mathcal{O}_{L_0}(1) \cong \mathcal{O}(C_L)|_{C_{i_0}} \otimes \mathcal{O}_{C_{i_0}}([L] - [L']) \).

**Corollary 1.18.** The Plücker class \( g = c_1(\mathcal{O}_F(1)) \in H^2(F(Y), \mathbb{Z}) \) is divisible by three and so is the Hodge–Riemann pairing \( \int_F \gamma_1 \cdot \gamma_2 \cdot g \) on \( H^1(F(Y), \mathbb{Z}) \), cf. Proposition 1.4.3. \( \square \)

**Remark 1.19.** For general \( Y \subset \mathbb{P}^4 \), the line bundle \( \mathcal{O}(C_L) \) generates the Néron–Severi group
\[
\text{NS}(F(Y)) \cong \mathbb{Z} \cdot \mathcal{O}(C_L).
\]

Indeed, we have remarked that \( \text{NS}(F(Y)) \) is of rank one for general \( Y \) and due to \( (C_L)^2 = 5 \), the line bundle \( \mathcal{O}(C_L) \) defines a primitive class in \( \text{NS}(F(Y)) \).

### 1.3 We study the linear projection from a line \( L \subset Y \) as a special case of the construction in Section 1.5.1

Let \( L = \mathbb{P}(W) \subset \mathbb{P}^4 = \mathbb{P}(V) \) be a line contained in the smooth cubic hypersurface \( Y \subset \mathbb{P}^4 \). Assume \( \mathbb{P}^2 \subset \mathbb{P}^4 \) is a plane disjoint to \( L \), of which we think as \( \mathbb{P}(V/W) \). The linear projection \( Y \cap L \rightarrow \mathbb{P}^2 \) is the rational map associated with the linear system \( |\mathcal{O}_Y(1) \otimes \mathcal{O}_L| \subset |\mathcal{O}_Y(1)| \). It is resolved by a simple blow-up \( \tau : \text{Bl}_L(Y) \rightarrow Y \). The induced morphism \( \varphi : \text{Bl}_L(Y) \rightarrow \mathbb{P}^2 \) is then associated with the complete linear system \( |\pi^*\mathcal{O}_Y(1) \otimes \mathcal{O}(-E)| \).

The fibre over a point \( y \in \mathbb{P}^2 \) is the residual conic of \( L \subset Y \cap \overline{\mathbb{P}^2} \subset \overline{\mathbb{P}^2} \). The conic is smooth or a union of two lines \( L_1, L_2 \), possibly non-reduced or with \( L_i = L \). Note that in the case that \( L_i = L \), the plane \( \overline{\mathbb{P}^2} \) intersects \( Y \) with higher multiplicity along \( L \) and hence \( L \) would be of the second type. Therefore, if \( L \) was chosen to be of the first type, then the fibres of \( \varphi : \text{Bl}_L(Y) \rightarrow \mathbb{P}^2 \) are either smooth conics or possibly non-reduced unions of two lines both different from \( L \).

**Corollary 1.20.** Let \( L \subset Y \) be a line of the first type.

(i) Then the linear projection from \( L \) defines a morphism
\[
\varphi : \text{Bl}_L(Y) \rightarrow \mathbb{P}^2,
\]
with a discriminant curve \( D_L \subset \mathbb{P}^2 \) of degree five and arithmetic genus six.
(ii) The fibre over a point \( y \in D_L \) is the possibly non-reduced union of two lines \( \varphi^{-1}(y) = L_1 \cup L_2 \) with \( L, L_1, L_2 \) coplanar.

(iii) With the notation of (ii), \( L_1 = L_2 \) if and only if \( y \) is a singular point of \( D_L \), which then is an ordinary double point.

(iv) For \( L \subset Y \) generic in the sense of Corollary 1.10, i.e. \([L] \in F(Y) \setminus (R \cup R')\), then \( \varphi^{-1}(y) = L_1 \cup L_2 \) with \( L_1 \neq L_2 \) for all \( y \in D_L \).

Proof Most of this has been verified already. For (iii) see [13, Prop. 1.2] or [28, Lem. 2].

The last assertion is a consequence of Proposition 15.1. The fibre over \( y \in D_L \) cannot be a double line \( L_1 = L_2 \), as then \( \mathbb{P}^2 \cap Y = L_1 \cup 2L_1 \), and so \( L_1 \) would be of the second type, which is excluded for \( L \) generic. \( \square \)

Remark 1.21. The abstract approach matches nicely with the intuitive picture. Here are two comments in this direction.

(i) That \( D_L \) is of degree five, i.e. \( D_L \in |\mathcal{O}(5)| \), can be linked to the fact that a line in a smooth cubic surface \( S \subset \mathbb{P}^3 \) is intersected by five mutually disjoint pairs of lines, see Section 4.3.3. Indeed, if \( L \subset Y \subset \mathbb{P}^4 \) is intersected with a generic hyperplane \( \mathbb{P}^3 \subset \mathbb{P}^4 \) containing \( L \), then \( D_L \subset \mathbb{P}^2 \) is intersected with a generic line \( \mathbb{P}^1 \subset \mathbb{P}^3 \). The fibres over the intersection points \( y \in D_L \cap \mathbb{P}^1 \) are the pairs of lines in \( Y \) contained in the cubic surface \( S := Y \cap \mathbb{P}^3 \) intersecting \( L \), of which there are exactly five.

(ii) For a line of the first kind the exceptional divisor \( \mathbb{P}^1 \times \mathbb{P}^1 \cong \mathbb{P}(N_L(Y)) \subset \text{Bl}_L(Y) \) has normal bundle \( \mathcal{O}(0, -1) \). Hence, the restriction of \( \varphi^*\mathcal{O}(1) \cong \mathcal{O}(1) \otimes \mathcal{O}(-E) \) to \( \mathbb{P}^1 \times \mathbb{P}^1 \) is \( \mathcal{O}(1, 1) \). In particular, the composition \( \mathbb{P}^1 \times \mathbb{P}^1 \cong \mathbb{P}(N_L(Y)) \subset \text{Bl}_L(Y) \longrightarrow \mathbb{P}^2 \) is a morphism of degree two, which confirms the geometric description: \( \tau(\varphi^{-1}(y)) \cap L \) is the intersection of the residual conic of \( L \subset \overline{yL} \) with \( L \).

Consider the restriction \( \varphi^{-1}(D_L) \longrightarrow D_L \) of the linear projection to the discriminant curve. We assume that \( L \) is generic in the sense of Corollary 1.10 so that all fibres are reduced singular conics, i.e. unions of two distinct lines. The curve parametrizing lines in the fibres is thus an étale cover

\[
\overline{D_L} \longrightarrow D_L
\]

of degree two. The morphism is indeed unramified which can be shown by abstract deformation theory or simply by arguing that any map between two curves with exactly two disting points in each fibre is étale. As \( D_L \) parametrizes lines in \( Y \), it comes with a classifying morphism \( D_L \longrightarrow F(Y) \) which is easily seen to be a closed immersion.

Alternatively, \( \overline{D_L} \) can be obtained as the Stein factorization of the composition of the normalization of \( \varphi^{-1}(D_L) \) with \( \varphi \). The morphism to \( F(Y) \) can then be viewed as follows: The natural rational map \( \varphi^{-1}(D_L) \longrightarrow \overline{D_L} \) is regular on the complement of
the section of \( \varphi^{-1}(D_L) \rightarrow D_L \) given by the intersection point of the two lines in each fibre. Composing with \( p : L \rightarrow F(Y) \) yields \( \tilde{D}_L \hookrightarrow F(Y) \).

**Lemma 1.22.** For a generic line \( L \subset Y \) the curves \( \tilde{D}_L, C_L \subset F(Y) \) coincide. Furthermore, \( \tilde{D}_L = C_L \) is a smooth curve of genus 11.

**Proof** Indeed, \( \tilde{D}_L \) and \( C_L \) both parametrize all lines \( L \neq L' \subset Y \) intersecting \( L \). We know that the (arithmetic) genus of \( C_L \) is \( g(C_L) = 11 \) and the same is true for \( \tilde{D}_L \) by Hurwitz’s formula. This is enough to conclude equality. Smoothness of \( \tilde{D}_L \) follows from the smoothness of \( D_L \). \( \square \)

**Corollary 1.23.** For a generic line \( L \subset Y \), i.e. \([L] \in F(Y) \setminus (R \cup R')\), the curve \( \tilde{D}_L = C_L \) is connected or, equivalently, irreducible.

**Proof** For a general cubic \( Y \), one has \( \rho(F(Y)) = 1 \) and hence \( \tilde{D}_L = C_L \) would be numerically equivalent to a multiple of each of its irreducible components. However, then the existence of more than one irreducible curve would contradict \( (C_L)^2 = 5 \). As under deformations of \( L \subset Y \) with \( L \in F(Y) \setminus (R \cup R') \) the topology of the situation does not change, this proves the assertion in general.

Alternatively, one may use the general fact that effective ample divisors are connected, cf. [90, III. Cor. 7.9]. \( \square \)

**Remark 1.24.** See also [78] for yet another proof that does not reduce to the case \( \rho(F(Y)) = 1 \) or uses the ampleness of \( C_L \). The idea there is that sending a line \([L'] \in C_L \) to its intersection with \( L \) defines a map \( C_L \rightarrow L \) of degree five, cf. Remark [1.17]. If \( C_L \) is not irreducible, then one of the irreducible components is rational, which would contradict the injectivity of the Albanese map in Corollary [2.6] or hyperelliptic. However, \( F(Y) \) is not covered by hyperelliptic curves, cf. [78, Sec. 3].

If \( L \) is not generic but \([L] \in R \subset F(Y) \) is still a generic point of \( R \), then the curve \( C_L \) is still irreducible, its genus is eleven, and it comes with a morphism \( C_L \rightarrow \mathbb{P}^1 \) of degree four, see [78, Lem. 3.3].

A Riemann–Roch computation reveals that \( \chi(F(Y), \mathcal{O}(C_L)) = 1 \). Although there is a priori no reason for the higher cohomology groups of \( \mathcal{O}(C_L) \) to vanish, the following result was proved in [169, Lem. 1.8].

**Corollary 1.25.** For every line \( L \subset Y \) the induced curve \( C_L \subset F(Y) \) is unique in its linear system, i.e. \( h^0(F(Y), \mathcal{O}(C_L)) = 1 \). As a consequence, one obtains an injection \( F(Y) \hookrightarrow \text{Pic}(F(Y)), \ [L] \mapsto \mathcal{O}(C_L) \).

**Proof** Assume \( C_L \) contains a generic line \( L_0 \). From the exact sequence

\[
0 \longrightarrow \mathcal{O}(C_L - C_{L_0}) \longrightarrow \mathcal{O}(C_L) \longrightarrow \mathcal{O}(C_L)_{|L_0} \longrightarrow 0
\]
and Remark 1.13 we deduce that it suffices to prove \( h^0(C_{L_0}, O(C_{L})|_{C_{L_0}}) = 1 \). Note that according to (1.2), we have \( O(C_{L})|_{C_{L_0}} = \pi^* O_{L_0}(1) \otimes O_{C_{L_0}}([L'] - [L]) \). So, it may happen that the residual line \( L' \) of \( L_0 \cup L \subset T_0 L \cap Y \) coincides with \( L \) and then \( h^0(C_{L_0}, O(C_{L})|_{C_{L_0}}) \geq 2 \), but by choosing an \( L_0 \) nearby this can be avoided.

Suppose now \( h^0(O(C_{L})|_{C_{L_0}}) \geq 2 \). Then, using the inclusion \( O(C_{L})|_{C_{L_0}} \hookrightarrow \pi^* O_{L_0}(1) \otimes O_{C_{L_0}}([L']) \) and the fact that \( [L] \neq [L'] \), we find \( h^0(\pi^* O_{L_0}(1) \otimes O_{C_{L_0}}([L'])) \geq 3 \). As \( \pi^* O_{L_0}(1) \) is base point free, the only possible base point of \( [\pi^* O_{L_0}(1) \otimes O_{C_{L_0}}([L'])] \) is \( [L'] \), but then \( h^0(\pi^* O_{L_0}(1)) \geq 3 \). For a generic two-dimensional linear system in \( \pi^* O_{L_0}(1) \) the image of the induced morphism \( \xi : C_{L_0} \to \mathbb{P}^2 \) cannot be a line and, therefore, \( \deg(\xi) = 1 \). But then \( \Im(\xi) \subset \mathbb{P}^2 \) is a curve of degree five and, hence, of arithmetic genus six, which contradicts \( g(C_{L_0}) = 11 \). Thus, \( [\pi^* O_{L_0}(1) \otimes O_{C_{L_0}}([L'])] \) is base point free. We choose a generic (hence base point free) two-dimensional linear subsystem of it and consider the induced morphism \( \xi : C_{L_0} \to \mathbb{P}^2 \). Note that \( \deg(\xi) = 1 \), because otherwise \( \xi^{-1}(\xi([L'])) = [L'] + [L_1] + \cdots \) (with multiplicities) and, therefore, \( \pi^* O_{L_0}(1) \) would have \( [L_1] \) as a base point, which is absurd. But \( \deg(\xi) = 1 \) implies that \( \xi(C_{L_0}) \subset \mathbb{P}^2 \) is of degree at most six and, therefore, of arithmetic genus at most ten. The latter again contradicts \( g(C_{L_0}) = 11 \).

If \( C_L \) does not contain a generic \( L_0 \), then the arguments have to be modified. For example, if \( L_0 \) is not generic but of the first type, then \( C_{L_0} \) is not smooth any longer and in the discussion above it has to be replaced by its normalization. If all \( [L_0] \) are of the second type, then one has to work with the morphism \( \pi : C_{L_0} \to L_0 \) strictly smaller degree than five and the description of \( O(C_{L})|_{C_{L_0}} \) has to be adapted.

For the second assertion use again Remark 1.13. \[ \square \]

2 Albanese of the Fano surface

Fix a point \( t_0 = [L_0] \in F = F(Y) \) and consider the Albanese morphism

\[
a : F \to A \coloneqq \text{Alb}(F) = H^1(F/F^*/H_1(F, \mathbb{Z}) = \left( \alpha \mapsto \int_{t_0}^t \alpha \right)
\]

According to the numerical results, \( A \) is an abelian variety of dimension five.

The goal of this section is to compare the following two pictures

\[
\begin{align*}
L = \mathbb{P}(S_F) & \xrightarrow{\phi} Y \subset \mathbb{P}(V) = \mathbb{P}^4 \\
P & \downarrow F \\
F \xrightarrow{a} A
\end{align*}
\]

\[
\begin{align*}
\mathbb{P}(T_F) & \xrightarrow{\phi} \mathbb{P}(T_A) \hookrightarrow \mathbb{P}(T_0A) \cong \mathbb{P}^4 \\
\downarrow & \\
F & \xrightarrow{a} A
\end{align*}
\]

(2.1)
We will show that they describe the same geometric situation.

2.1 Let us begin with some preliminary comments:

(i) The natural inclusion $S_F \subset V \otimes \mathcal{O}_F$ yields an embedding $L \cong \mathbb{P}(S_F) \subset F \times \mathbb{P}(V)$, which is in fact nothing but the composition of the two inclusions $L \subset F \times Y$ and $F \times Y \subset F \times \mathbb{P}(V)$. Thus, the relative tautological line bundle is described by $\mathcal{O}_F(1) \cong q^* \mathcal{O}(1)$, cf. Lemma [3.1] and the pull-back yields a homomorphism

$$H^0(\mathbb{P}^4, \mathcal{O}(1)) \longrightarrow H^0(Y, \mathcal{O}_Y(1)) \longrightarrow H^0(L, \mathcal{O}_L(1)) \cong H^0(F, S_F^3).$$

(2.2)

It is injective, because $Y = q(L) \subset \mathbb{P}(V)$ is not contained in any hyperplane. However, at this point it is not clear that the map is also surjective or, equivalently, that the morphism $q: L \longrightarrow \mathbb{P}(V)$ is the morphism associated with the complete linear system $|\mathcal{O}_F(1)|$.

(ii) The differential of the Albanese morphism $a: F \longrightarrow A = \text{Alb}(F)$ induces a homomorphism $da: T_F \longrightarrow a^* T_A$ between the tangent sheaves. It is a priori not clear that this induces a morphism $\mathbb{P}(T_F) \longrightarrow \mathbb{P}(a^* T_A) \longrightarrow \mathbb{P}(T_A)$. For this we will have to argue that $da: T_t F \longrightarrow T_{a(t)} A$ is injective for all $t \in F$. Note that the tangent bundle $T_A$ is trivial, which yields a natural projection $\mathbb{P}(T_A) \cong A \times \mathbb{P}(T_{0A}) \longrightarrow \mathbb{P}(T_{0A})$.

(iii) Finally note that there is indeed an isomorphism $V \cong T_{0A}$. Namely, compose $T_{0A} \cong H^{1,0}(F)^* \cong H^{2,1}(Y)^*$ with the dual of $H^{2,1}(Y) \cong R_1 \cong V^*$ provided by Theorem [1.4.20]. Here, $R = \bigoplus R_i \cong \mathbb{C}[V^*/(\partial_i F)$ is the Jacobian ring of $Y \cong V(F)$, cf. [42], Sec. 12]. However, in the discussion below, the isomorphism between the two spaces will be obtained in a different manner.

The first step is to show that $T_F$ and $S_F$ are naturally isomorphic. Evidence for the existence of such an isomorphism comes from the observations

$$\det(T_F) \cong \omega_F \cong \mathcal{O}_F(-1) \cong \det(S_F) \text{ and } c_2(T_F) = c_2(F) = 27 = c_2(S_F).$$

The latter is shown by the following argument, which a posteriori explains geometrically the curious observation that $c_2(F) = 27$ is the number of lines on a cubic surface. Consider a generic hyperplane section $S := Y \cap V(s), s \in H^0(\mathbb{P}^4, \mathcal{O}(1))$, which is a cubic surface $S \subset V(s) \cong \mathbb{P}^3$. Let $s_F$ be the image of $s$ under $H^0(\mathbb{P}(V), \mathcal{O}(1)) \longrightarrow H^0(F, S_F^3)$. Its zero set $V(s_F) \subset F$ is the set of lines $[L] \in F$ with $s|_L = 0$, i.e. the set of all lines contained in the cubic surface $S$.

Alternatively, one can use $c_2(F) = 6 \cdot g^2 - 9 \cdot c_2(S)$ (which actually holds in the Chow ring and not only in cohomology where for degree reasons it would only be an equality of numbers), see Exercise 3.2.2 and $\int_F g^2 = 45$.

**Proposition 2.1.** Let $Y \subset \mathbb{P}^4$ be a smooth cubic threefold and $F = F(Y)$ its Fano variety...
The key to describing the nested inclusion of two tangent bundles: \[ \bigwedge^2 T \]

On the other hand, applying the more algebraic approach in [5].

Proof  The result was originally proved in [42, 168] by very clever geometric arguments. We follow the natural isomorphism \[ T_F \cong S_F \]

between the tangent bundle \( T_F \) of \( F \) and the restriction \( S_F \) of the universal subbundle \( S \subset V \otimes \mathcal{O}_Y \) under the natural embedding \( F \subset \mathbb{G}(1, \mathbb{P}^4) \).

Deformation theory, see Section 3[1.2] provides us with descriptions of the fibres of the two tangent bundles:

\[ T_{[1]}F \cong H^0(L, N_{L/Y}) \text{ and } T_{[1]}\mathbb{G} \cong H^0(L, N_{L/Y}). \]

Moreover, fibrewise (2.3) is described as the cohomology sequence of the exact sequence \[ 0 \rightarrow N_{L/Y} \rightarrow N_{L/Y} \rightarrow \mathcal{O}(3) \rightarrow 0 \] of normal bundles for the nested inclusion \( L \subset Y \subset \mathbb{P}^4 \). The global version of the latter is the exact sequence of normal bundles of the nested inclusion \( L \subset Y \subset F \times F \): \[ 0 \rightarrow N_{L/F, Y} \rightarrow N_{L/F, Y} \rightarrow N_{F, Y/F, \mathbb{G}} \rightarrow 0. \]

The key to describing \( T_F \) is to view it as the direct image of the sheaf \( \mathcal{N} := N_{L/F, Y} \). Taking determinants of (2.4) shows \[ \bigwedge^2 \mathcal{N} \cong \text{det}(\mathcal{N}) \cong \text{det}\left(p^* \mathcal{Q}_F \otimes \mathcal{O}_p(1)\right) \otimes \mathcal{O}_p(-3) \cong p^* \text{det}(\mathcal{Q}_F). \]

On the other hand, applying \( \bigwedge^2 \) and \( \otimes \mathcal{O}_p(-3) \) to (2.4) yields the exact sequence \[ 0 \rightarrow \bigwedge^2 \mathcal{N} \otimes \mathcal{O}_p(-3) \rightarrow p^* \bigwedge^2 \mathcal{Q}_F \otimes \mathcal{O}_p(-1) \rightarrow \mathcal{N} \rightarrow 0. \]
Corollary 2.2. The natural map in (2.2) is an isomorphism

$$\Lambda^2 V^* \longrightarrow H^0(F, S_F^0).$$

Hence, $q: \mathbb{L} \longrightarrow Y \subset \mathbb{P}(V)$ is the morphism associated with the complete linear system $|O_p(1)|$.

**Proof** Use $\dim H^0(F, S_F^0) = \dim H^0(F, T_F^0) = \dim H^1(F, O_F) = 5$.

2.2 So far, we have shown that there exists an isomorphism $L \cong \mathbb{P}(S_F) \cong \mathbb{P}(T_F)$, but not that the two morphisms in (2.1) are related. In fact, we have not yet even properly defined the morphism $\mathbb{P}(T_F) \longrightarrow \mathbb{P}(T_0 A)$. This will be done next.

The first step towards it will be to show that exterior product yields an isomorphism

$$\Lambda^2 H^1(F, Q) \cong H^2(F, Q)$$

of Hodge structures. Due to Section 3.3 we in fact know already that the two Hodge structures are isomorphic

$$\Lambda^2 H^1(F, Q) \cong \Lambda^2 H^1(Y, Q)(2) \cong H^2(F, Q),$$

but not that this isomorphism is given by exterior product.

**Lemma 2.3.** The exterior product defines isomorphisms

$$\Lambda^2 H^{1,0}(F) \cong H^{0,2}(F) \quad \text{and} \quad \Lambda^2 H^1(F, Q) \cong H^2(F, Q). \quad (2.6)$$

**Proof** The lemma can be viewed as a special case of Corollary 3.4.10. Let us nevertheless outline the traditional argument for the first part using the isomorphism $S_F \cong T_F$.

The Hodge theoretic assertion is thus turned into the geometric assertion that the natural map $\Lambda^2 H^0(F, S_F^0) \longrightarrow H^0(F, \Lambda^2 S_F^0)$ is an isomorphism. Using the commutative diagram

$$\Lambda^2 V^* \longrightarrow \Lambda^2 H^0(F, S_F^0) \quad \xrightarrow{\sim} \quad H^0(\mathbb{P}(\Lambda^2 V), O(1)) \longrightarrow H^0(F, \Lambda^2 S_F^0) \cong H^0(F, O_F(1))$$
The proof of Corollary 2.4.10 in this particular case boils down to the following argument: As the map \( H^2(F, \mathbb{Q}) \hookrightarrow H^2(F, \mathbb{Q}) \) is topologically defined, its injectivity is independent of the smooth cubic threefold. It is thus enough to check it for one \( F = F(Y) \). However, for the very general cubic \( \wedge^2 H^1(Y, \mathbb{Q})(2) \cong \wedge^2 H^1(F, \mathbb{Q}) \) is the direct sum \( \mathbb{Q}(-1) \oplus H \) of two irreducible Hodge structures of weight two. The first summand is pure and spanned by the intersection product \( q_f \) on \( H^3(Y, \mathbb{Q}) \), which by Proposition 2.4.13 is mapped onto a non-trivial Hodge class. The irreducibility of \( H = q_f \) follows from the fact that \( \text{Sp}(H^1(Y)) \) acts irreducibly on it, see Remark 2.13. Due to the irreducibility of the Hodge structure \( H \), the map \( H \hookrightarrow H^2(F, \mathbb{Q}) \) is injective if and only if \( \wedge^2 H^1(F) \hookrightarrow H^2(F) \) is non-trivial, which we have shown already. Moreover, \( H^2(F) \) is contained in \( H^2(F, \mathbb{C}) \) and, therefore, \( H \hookrightarrow H^2(F, \mathbb{Q}) \). Altogether, this proves the injectivity of \( \wedge^2 H^1(F, \mathbb{Q}) \hookrightarrow H^2(F, \mathbb{Q}) \) and, due to dimension reasons, its bijectivity.

Geometrically, the first injectivity \((2.6)\) is equivalent to saying that the image of the Albanese morphism \( a : F \rightarrow A \) is a surface.

**Corollary 2.4.** The Albanese morphism \( a : F \rightarrow A \) is unramified, i.e. for all \( t \in F \) the tangent map \( da_t : T_tF \rightarrow T_{at(t)}A \) is injective. In particular, the Albanese map defines the morphism \( \tilde{q} \) in \((2.7)\)

\[
\tilde{q} : \mathbb{P}(T_F) \rightarrow \mathbb{P}(T_A) \rightarrow \mathbb{P}(T_0A).
\]

**Proof** Assume \( da_t \) is not injective for some \( t \in F \). Then the induced map

\[
\wedge^2 T_tF \rightarrow \wedge^2 T_{at(t)}A
\]

is trivial. However, this map is dual to the map

\[
\wedge^2 T_{at(t)}A \cong \wedge^2 H^{1,0}(A) \cong \wedge^2 H^{1,0}(F) \twoheadrightarrow H^{2,0}(F) = H^0(F, \omega_F) \rightarrow \omega_F \otimes k(t),
\]

which then is also trivial. As \( \omega_F \) is very ample and, in particular, globally generated, this is absurd.

**Lemma 2.5.** The morphism \( \tilde{q} : \mathbb{P}(T_F) \rightarrow \mathbb{P}(T_0A) \) is the morphism associated with the complete linear system \( [\mathcal{O}_p(1)] \)

**Proof** First, \( \tilde{q}^* \mathcal{O}(1) \cong \mathcal{O}_p(1) \), as \( \mathcal{P}(T_F) \subset \mathcal{P}(a^*T_0) \cong \mathcal{P}(T_0A) \times A \) is induced by the inclusion \( T_F \hookrightarrow T_A \cong T_0A \otimes \mathcal{O}_F \). It remains to show that the linear system is complete, i.e. that the pull-back map \( H^0(\mathcal{P}(T_0A), \mathcal{O}(1)) \rightarrow H^0(\mathcal{P}(T_F), \mathcal{O}_p(1)) \) is a bijection. Both
Chapter 5. Cubic threefolds

sides are of dimension five, so it suffices to prove the injectivity. If the map were not injective, then all tangent spaces \( T_tF \hookrightarrow T_0A \) would be contained in a hyperplane. But this would contradict the bijectivity of the dual map \( H^0(A, \Omega_A) \longrightarrow H^0(F, \Omega_F) \), which is the pull-back of one-forms under the Albanese map \( a: F \longrightarrow A \).

This proves the main result of this section:

**Proposition 2.6.** There exist isomorphisms \( S_F \cong T_F \) and \( V \cong T_0A \) inducing a commutative diagram

\[
\begin{array}{ccc}
P(S_F) & \longrightarrow & P(V) \\
\downarrow & & \downarrow \\
P(T_F) & \longrightarrow & P(T_0A)
\end{array}
\]

\( \square \)

**Corollary 2.7.** The Albanese morphism \( a: F \longrightarrow A \) is unramified and generically injective.

**Proof** The first assertion is Corollary 2.4. To prove the injectivity generically, we choose the above isomorphism \( V \cong T_0A \) such that the two inclusions

\[
T_tF \subseteq a^*T_A \cong T_0A \otimes O_F
\]
and

\[
S_F \subseteq V \otimes O_F
\]

coincide. Hence, the morphism \( F \longrightarrow \mathbb{G}(1, P(T_0A)), t \mapsto \{T_tF \subset T_0(A)\} \) is identified with the natural embedding \( F \longrightarrow \mathbb{G}(1, P(V)) \). However, if for all points \( s \in a(F) \) and distinct points \( t_1 \neq t_2 \in a^{-1}(s) \) the tangent spaces \( T_{t_1}F \subset T_0A \) and \( T_{t_2}F \subset T_0A \) are different, then the generic fibre can only consist of just one point. \( \square \)

In fact, it has been shown by Beauville that \( a \) is injective and hence a closed immersion \([15, \text{Thm. } 4]\), see Corollary 3.4. We will see that in the end this assertion is equivalent to saying that the invertible sheaves \( O(C_{L_1}) \) and \( O(C_{L_2}) \) associated with two distinct lines \( L_1 \neq L_2 \subset Y \) are never isomorphic, which we proved as Corollary 1.25 already.

2.3 The following is a special case of the ‘geometric global Torelli theorem’, see Proposition 3.2.10. The result in dimension three \([42]\) predates the general result and the proof is different.

**Proposition 2.8.** Two smooth cubic threefolds \( Y, Y' \subset \mathbb{P}^4 \) are isomorphic if and only if their Fano surfaces \( F(Y) \) and \( F(Y') \) are isomorphic:

\[ Y \cong Y' \Leftrightarrow F(Y) \cong F(Y'). \]

**Proof** For any smooth cubic threefold \( Y \subset \mathbb{P}^4 \), the Picard group \( \text{Pic}(Y) \) is generated by \( O_Y(1) \). Hence, any isomorphism \( Y \cong Y' \) is induced by an automorphism of
the ambient $\mathbb{P}^4$ and, therefore, induces an isomorphism $F(Y) \cong F(Y')$ between their Fano surfaces. Conversely, any isomorphism $F(Y) \cong F(Y')$ induces an isomorphism $Y \cong Y'$ between the images of the natural morphisms $\mathbb{P}(T_{F(Y)}) \rightarrow \mathbb{P}(T_0\text{Alb}(F(Y)))$ and $\mathbb{P}(T_{F(Y')}) \rightarrow \mathbb{P}(T_0\text{Alb}(F(Y')))$, given by the differentials of the Albanese maps. $\Box$

**Exercise 2.9.** The same techniques show that for any smooth cubic threefold $Y \subset \mathbb{P}^4$ there exists a natural isomorphism of finite groups, cf. Corollary 1.3.6

$$\text{Aut}(Y) \cong \text{Aut}(F(Y)).$$

Quotients of $F(Y)$ by subgroups of $\text{Aut}(F(Y))$ have been studied in [155].

We complement this result by the following infinitesimal statement.

**Proposition 2.10.** Let $Y \subset \mathbb{P}^4$ be a smooth cubic threefold and let $F = F(Y)$ be its Fano surface. Then the natural map

$$H^1(Y, T_Y) \rightarrow H^1(F, T_F)$$

is an isomorphism.

**Proof.** The injectivity of the map holds for all smooth cubics of dimension at least three, see Corollary 3.4.5.

To prove the surjectivity one only needs to check that $h^1(F(Y), T_{F(Y)}) = 10$. Note that the Hirzebruch–Riemann–Roch formula shows $\chi(F(Y), T_{F(Y)}) = 30$. Hence, by applying $H^0(F(Y), T_{F(Y)}) = 0$, see Corollary 3.2.1, one obtains $h^1(T_{F(Y)}) = h^2(T_{F(Y)}) = 30$. $\Box$

The result can be rephrased as saying that the Fano surface $F(Y)$ stays a Fano surface after small deformation, which is false for example for the Fano variety of lines on a smooth cubic fourfold, see Section 3.3.3.

### 3 Albanese, Picard, and Prym

The general theory set up in Section 3.4.3 provides us with a commutative diagram

$$\begin{array}{ccc}
\text{CH}^2(F)_{\text{alg}} & \rightarrow & \text{CH}^2(Y)_{\text{alg}} \\
\downarrow & & \downarrow \\
\text{A}(F) & \rightarrow & J(Y) \\
\downarrow & & \downarrow \\
& \rightarrow & \text{Pic}^0(F),
\end{array}$$

Note that $\text{CH}^2(F)_{\text{alg}}$ is known to be big (over $\mathbb{C}$), while $\text{CH}^1(F) = \text{Pic}(F)$.

The intermediate Jacobian $J(Y) \cong J^3(Y)$ of $Y$ is self-dual and the two maps on the bottom are dual to each other, cf. Section 3.4.3. Indeed, they are induced by the Fano
correspondence \( \varphi : H^1(Y, \mathbb{Z}) \to H^1(F, \mathbb{Z})(-1) \) and its dual \( \psi : H^1(F, \mathbb{Z}) \to H^1(Y, \mathbb{Z}) \) (up to torsion, see Remark 3.9). Moreover, as the two maps induce isomorphisms between the cohomology groups with rational coefficients, they are isogenies of abelian varieties of dimension five.

The aim of this section is to show that all three abelian varieties are isomorphic and, moreover, can be identified with the Prym variety of the morphism \( C_L \approx \tilde{D}_L \to D_L \) in Section 1.3.

### 3.1

In order to understand the composition \( A = A(F) \to J(Y) \to \text{Pic}^0(F) \), we compose it with the Albanese map \( a : F \to A \), which depends on the additional choice of a point \( t_0 = [L_0] \in F \) and factorizes via \( F \to \text{CH}^2(F)_{\text{alg}}, t \to [t]-[t_0] \) and the Abel–Jacobi map \( \text{CH}^2(F)_{\text{alg}} \to \text{CH}^2(F)_{\text{hom}} \to A(F) \). Note that eventually Corollary 3.10 will imply that

\[
\text{CH}^2(Y)_{\text{alg}} \to \text{CH}^2(Y)_{\text{hom}} \text{ and Pic}^0(F) \cong \text{CH}^1(F)_{\text{alg}} \cong \text{CH}^1(F)_{\text{hom}}.
\]

The latter is equivalent to \( \text{Pic}(F)/\text{Pic}^0(F) \) being torsion free or, still equivalently, to \( H^2(F, \mathbb{Z}) \) being torsion free.

**Lemma 3.1.** The composition \( F \to A(F) \to J(Y) \to \text{Pic}^0(F) \) sends a point \([L] \in F\) to the invertible sheaf \( \mathcal{O}(C_L - C_{t_0}) \).

**Proof** Clearly, the class of the point \( t = [L] \in F \) under \( \varphi : \text{CH}^2(F) \to \text{CH}^2(Y) \) is mapped to the class \([L] \in \text{CH}^2(Y)\) of the line \( L \subset Y \). The image of the latter under the correspondence \( \psi : \text{CH}^2(Y) \to \text{CH}^1(F) \) is by construction \( \mathcal{O}(C_L) \).

The result can be extended to provide for every (smooth) curve \( C \subset F \) a description of the composition

\[
C \to A(C) \to A(F) \to J(Y) \to \text{Pic}^0(F) \to \text{Pic}^0(C),
\]

as \([C] \to \mathcal{O}(C_L - C_{t_0})_C\). This is particularly useful when \( C \) is ample, e.g. \( C = C_L \). In this case, one finds

\[
A(C) \to A(F) \quad \text{and} \quad \text{Pic}^0(F) \to \text{Pic}^0(C).
\]

The first follows directly from the Kodaira vanishing theorem showing \( H^1(F, \mathcal{O}_F(-C)) = 0 \) and hence \( H^1(F, \mathcal{O}_F) \to H^1(C, \mathcal{O}_C) \) is injective. For the second use that for a line bundle \( L \) of degree zero on \( F \), the line bundle \( L^*(C) \) is still ample. Hence, \( H^1(F, L(-C)) = 0 \) and, therefore, \( H^0(F, L) \to H^0(C, L_{|C}) \). The latter shows that with \( L_{|C} \) trivial also \( L \) is.

Let \([L] \in F\) be generic and consider \( C_L \) as the étale cover

\[
\pi : C_L \approx \tilde{D}_L \to D_L
\]

of degree two, see Section 1.3.
Corollary 3.2. The composition

$$\Pic^0(D_L) \longrightarrow \Pic^0(C_L) = A(C_L) \longrightarrow A(F) \longrightarrow J(Y) \longrightarrow \Pic^0(F)$$

is trivial. Dually, the image of the restriction map $H^1(F, \mathbb{Z}) \longrightarrow H^1(C_L, \mathbb{Z})$ is contained in the kernel of $\pi_* : H^1(C_L, \mathbb{Z}) \longrightarrow H^1(D_L, \mathbb{Z})$.

Proof. Observe that under the natural map

$$D_L \longrightarrow \Pic(D_L) \longrightarrow \Pic(C_L) \longrightarrow \Pic^2(F) \longrightarrow \Pic^2(Y)$$

a point $y \in D_L$ is mapped to $[L_1] + [L_2] \in \Pic^2(Y)$, where $L_1$ and $L_2$ correspond to the two points of the fibre $\pi^{-1}(y)$.

Clearly, for the plane $\mathbb{P}^2 = yL$, one has $[L_1] + [L_2] = [L_1] + [L_2] + [L] = [\mathbb{P}^2_y] - [L]$. As $[yL] \in \Pic^2(\mathbb{P}^4) = \mathbb{Z}$ is independent of $y \in D_L$, the class $[L_1] + [L_2] \in \Pic^2(Y)$ is independent of $y$ and, therefore, $D_L \longrightarrow \Pic^2(Y) \longrightarrow \Pic^2(F)$ is constant. \hfill $\Box$

By a purely topological description of étale coverings of degree two, one computes that the intersection pairing on $H^1(C_L, \mathbb{Z})$ restricted to the submodule

$$H^1(C_L, \mathbb{Z})^\perp := \text{Ker}(\pi_* : H^1(C_L, \mathbb{Z}) \longrightarrow H^1(D_L, \mathbb{Z}))$$

is divisible by two, cf. Section 3.2. Hence, the Hodge–Riemann pairing $(\cdot, \cdot)_F$ on $H^1(F, \mathbb{Z})$ with respect to the Plücker polarization is of the form

$$(\gamma, \gamma')_F = \int_F \gamma \cdot \gamma' \cdot g = 3 \int_{C_L} \gamma|_{C_L} \cdot \gamma'|_{C_L} \in 6\mathbb{Z},$$

where we use $3[C_L] = g \in H^2(F, \mathbb{Z})$, cf. Lemma 1.14. Then, according to Proposition 3.4.3, the Fano correspondence yields an injection of integral(!) symplectic lattices

$$\varphi : (H^1(Y, \mathbb{Z}), (\cdot, \cdot)_Y) \longrightarrow (H^1(F, \mathbb{Z}), (-1/6)(\cdot, \cdot)_F)$$

of finite index. As the left hand side is unimodular, it has to be an isomorphism. We thus have proved the following result.

Corollary 3.3. The Fano correspondence induces an isomorphism of Hodge structures

$$\varphi : H^1(Y, \mathbb{Z}) \longrightarrow H^1(F, \mathbb{Z})(-1)$$

and the induced morphisms between the associated abelian varieties are isomorphisms

$$A(F) \sim A J(Y) \sim \Pic^0(F).$$

The next result improves Corollary 2.7, cf. [15, Thm. 4].
Corollary 3.4. The Albanese morphism

\[ a : F \hookrightarrow A(F) \]

is a closed immersion. Equivalently, the natural morphism \( F \hookrightarrow \text{Pic}(F), [L] \mapsto \mathcal{O}(C_L) \) is a closed immersion.

Proof Indeed, due to Corollary 2.7, the morphism \( F \to A(F) \) is unramified and its composition with \( A(F) \to J(Y) \to \text{Pic}(F) \), which is an isomorphism by Corollary 3.3, is the injective map \( [L] \to \mathcal{O}(C_L) \), cf. Corollary 1.25.

3.2 The next aim is to relate the intermediate Jacobian \( J(Y) \) to the Prym variety of the étale cover \( C_L \to D_L \) for any generic line \( L \subset Y \). Let us begin with a reminder on Prym varieties. See [13, 122, 138] for a detailed discussion and [72] for a historical account.

We consider an étale cover \( \pi : C \to D \) of degree two between smooth projective curves. Its corresponding two-torsion line bundle \( L_x = \pi_*\mathcal{O}_C/\mathcal{O}_D \in \text{Pic}^0(D) \) satisfies \( \pi^*L_x \simeq \mathcal{O}_C \). We shall denote the covering involution by \( \iota \) and its natural action on the Picard variety by \( \iota^* : \text{Pic}(C) \to \text{Pic}(C) \).

Lemma 3.5. The pull-back \( \pi^* : \text{Pic}(D) \to \text{Pic}(C) \) yields an isomorphism

\[ \text{Pic}(D)/\langle L_x \rangle \simeq \text{Ker}(\text{Pic}(C) \xrightarrow{1-\iota^*} \text{Pic}(C)). \]

Proof The morphism \( 1 - \iota^* \) maps a line bundle \( \mathcal{L} \) to \( \mathcal{L} \otimes \iota^*\mathcal{L} \). Clearly, if \( \mathcal{L} \simeq \pi^*\mathcal{M} \), then \( (1 - \iota^*)(\mathcal{L}) \simeq \mathcal{O}_C \). For the other inclusion use that any \( \iota^* \)-invariant invertible sheaf descends to an invertible sheaf on \( D \).

Following [13], the descent can be shown explicitly as follows: Suppose \( \mathcal{L} = \mathcal{O}(E) \) satisfies \( \iota^*\mathcal{L} \simeq \mathcal{L} \). Write \( E = \iota^*E \) as the principal divisor \( f \) for some \( f \in K(C) \) and observe that then \( f \cdot \iota^*f \) has neither zeros nor poles, so we may assume \( f \cdot \iota^*f = 1 \) (we need \( k \) to admit square roots for this). Pick an element \( g \in K(C) \) with \( \iota^*g = -g \) and set \( f_0 := g \cdot (f - 1) \). Then, \( f = f_0 \cdot (\iota^*f_0)^{-1} \) and, therefore, \( E_0 := E - (f_0) \) is the pull-back of a divisor on \( D \). We leave it to the reader to verify that \( \mathcal{O}_D \) and \( L_x \) are the only line bundles with trivial pull-back to \( C \).

Definition 3.6. The Prym variety of an étale cover \( \pi : C \to D \) of degree two is defined as

\[ \text{Prym}(C/D) := \text{Im}(\text{Pic}^0(C) \xrightarrow{1-\iota^*} \text{Pic}(C)). \]

Hence, there exists a natural exact sequence [28, Thm. 2], [13, Sec. 2.6], [132, Sec. 10.9]

\[ 0 \to \langle L_x \rangle \to \text{Pic}^0(D) \to \text{Pic}^0(C) \to \text{Prym}(C/D) \to 0. \tag{3.1} \]

One could think that the absence of fixed points is important here. It is not, although for the descent of invariant invertible sheaves on surfaces, fixed points do cause problems.
Alternatively, the Prym variety can be viewed as a connected component of the kernel of the norm map. Recall that the norm map \( N: \text{Pic}(C) \rightarrow \text{Pic}(D) \) is the push-forward map \( \pi_*: \text{CH}^1(C) \rightarrow \text{CH}^1(D) \) or, on the identity component and using \( \text{Pic}^0 \approx \text{Alb} \) for curves, the natural map \( \text{Alb}(C) \rightarrow \text{Alb}(D) \). It can also be described as \( N(\mathcal{L}) \approx \text{det} \pi_* \mathcal{L} \otimes (\text{det} \pi_* \mathcal{O}_C)^* \). For example, for the line bundle \( \mathcal{L} = \mathcal{O}(x), x \in C \), the exact sequence \( 0 \rightarrow \mathcal{O}_C \rightarrow \mathcal{L} \rightarrow k(x) \rightarrow 0 \) indeed yields \( \mathcal{O}(\pi(x)) \approx \text{det} \pi_* k(x) \approx \text{det} \pi_* \mathcal{L} \otimes (\text{det} \pi_* \mathcal{O}_C)^* \). Clearly, \( N \) as defined by \( \pi_* \) is a group homomorphism, which is not quite so apparent in the latter description. Then we claim that

\[
\text{Prym}(C/D) = \text{Im}(1 - \iota') \cong \text{Ker}(N)'
\]

is the connected component of the kernel containing \( \mathcal{O}_C \). In fact, \( \text{Ker}(N) \) has exactly two connected components \( \text{Ker}(N) = \text{Prym} \sqcup \text{Prym}' \), which are non-canonically isomorphic to each other. For one inclusion use \( \pi_* \iota' = \pi_* \) and compute \( N(\mathcal{L} \otimes \iota' \mathcal{L}') \approx \text{det} \pi_* (\mathcal{L} \otimes \iota' \mathcal{L}') \approx \mathcal{O}_D \). For the other, observe that \( N: \text{Pic}^0(C) \rightarrow \text{Pic}^0(D) \) is surjective and hence \( \text{Prym}(C/D) \subset \text{Ker}(N)'' \) is an inclusion of abelian varieties of the same dimension.

To summarize, in addition to the exact sequence \((3.1)\) there is an exact sequence

\[
0 \longrightarrow \text{Prym} \sqcup \text{Prym}' \longrightarrow \text{Pic}^0(C) \xrightarrow{N} \text{Pic}^0(D) \longrightarrow 0. \tag{3.2}
\]

\( \cong \text{A}(C) \quad \cong \text{A}(D) \)

It may be helpful to describe both points of view in terms of integral Hodge structures. Recall that

\[
\text{Pic}^0(C) \approx \frac{H^1(C, \mathcal{O}_C)}{H^1(C, \mathbb{Z})} \approx \frac{H^0(C, \omega_C)^*}{H_1(C, \mathbb{Z})}
\]

and similarly for \( \text{Pic}^0(D) \). As explained in [122, Ch. 12.4], \( H^1(C, \mathbb{Z}) \) admits a symplectic basis of the form \( \lambda_0, \mu_0, \lambda_1^+, \mu_1^+, \ldots, \lambda_g(D) - 1, \mu_g(D) - 1 \) with \( \lambda_0, \mu_0 \) fixed by the action of \( \iota' \) on \( H^1(C, \mathbb{Z}) \) and \( \iota' \iota(\lambda_i^+) = \lambda_i^+, \iota'(\mu_i^+) = \mu_i^+ \). This allows one to describe the eigenspaces \( H^1(C, \mathbb{Z})^\pm \subset H^1(C, \mathbb{Z}) \) of the involution \( \iota' \) as

\[
H^1(C, \mathbb{Z})^+ = \langle \lambda_0 + \mu_0, \lambda_i^+ + \lambda_i^-, \mu_i^+ + \mu_i^- \rangle \quad \text{and} \quad H^1(C, \mathbb{Z})^- = \langle \lambda_i^+, \lambda_i^-, \mu_i^+, \mu_i^- \rangle.
\]

The latter implies the fact alluded to before that the intersection pairing on \( H^1(C, \mathbb{Z})^- \) is divisible by 2, which was used in the proof of Corollary [3.3]. Moreover, the image of the pull-back map

\[
\pi^*: H^1(D, \mathbb{Z}) = \langle \lambda_i, \mu_i \rangle_{i=0, \ldots, g(D)-1} \hookrightarrow H^1(C, \mathbb{Z})^*,
\]

which is given by \( \lambda_0 \mapsto \lambda_0, \mu_0 \mapsto 2\mu_0, \lambda_i \mapsto \lambda_i^+ + \lambda_i^-, \) and \( \mu_i \mapsto \mu_i^+ + \mu_i^- \), for \( i = 1, \ldots, g(D) - 1 \), yields a sublattice of index two. With this notation, topologically the
étale covering \( C \to D \) can be constructed by cutting \( D \) along the standard loop representing \( \mu_0 \) and glueing two copies of \( D \) along \( \mu_0 \). This explains why in particular the pull-back of \( \mu_0 \) yields \( 2 \mu_0 \).

Also observe that the image of
\[
H^1(C, \mathbb{Z}) \to H^1(C, \mathbb{Z})^*, \quad \alpha \mapsto \alpha + \epsilon \alpha
\]
is contained in \( \pi^*H^1(D, \mathbb{Z}) \subset H^1(C, \mathbb{Z})^* \) with index two. On the other hand,
\[
H^1(C, \mathbb{Z}) \to H^1(C, \mathbb{Z})^*, \quad \alpha \mapsto \alpha - \epsilon \alpha
\]
is surjective. The sequence (3.1) is induced by the exact sequence
\[
0 \to H^1(C, \mathbb{Z})^* \to H^1(C, \mathbb{Z}) \to H^1(C, \mathbb{Z})^{-} \to 0,
\]
which allows one to describe the Prym variety as
\[
\text{Prym}(C/D) \cong \frac{H^1(C, \mathcal{O}_C)^*}{H^1(D, \mathbb{Z})}.\]

**Remark 3.7.** The Prym variety is commonly viewed as a principally polarized abelian variety: Indeed, the last isomorphism together with the description of \( H^1(C, \mathbb{Z})^{-} \) as \( \langle \lambda^+_1 - \lambda^-_1, \mu^+_1 - \mu^-_1 \rangle \) allows one to define a principal polarization on \( \text{Prym}(C/D) \) explicitly as given by the intersection pairing on \( H^1(C, \mathbb{Z})^{-} \) up to the factor \( (1/2) \).

The kernel of \( \text{Pic}^0(C) \to \text{Prym}(C/D) \) can be written as the degree two quotient
\[
\text{Pic}^0(D) \cong \frac{H^1(C, \mathcal{O}_C)^*}{H^1(D, \mathbb{Z})}.\]

On the other hand, the sequence (3.2) corresponds to
\[
0 \to H^1(C, \mathbb{Z})^{-} \to H^1(C, \mathbb{Z}) \to (1 + \epsilon)H^1(C, \mathbb{Z}) \to 0,
\]
using the degree two quotient
\[
\frac{H^1(C, \mathcal{O}_C)^+}{(1 + \epsilon)H^1(C, \mathbb{Z})} \cong \text{Pic}^0(D).
\]

Let us now apply this to the cover \( C_L \to D_L \) associated with any generic line \( L \subset Y \).

**Proposition 3.8 (Mumford).** For a generic line \( L \subset Y \), the inclusion \( i: C_L \to F(Y) \) induces an isomorphism
\[
\text{Prym}(C_L/D_L) \cong A(F) = J(Y) \cong \text{Pic}^0(F).
\]

**Proof** The assertion follows from a comparison of (3.3) with the exact sequence
\[
0 \to \text{Ker}(\xi) \to H^1(C_L, \mathbb{Z}) \to H^1(Y, \mathbb{Z}) \to 0.
\]
3 Albanese, Picard, and Prym

Here, $\xi$ is the composition of the push-forward map $i_* : H^1(C_L, \mathbb{Z}) \to H^1(Y, \mathbb{Z})$ induced by $i : C_L \hookrightarrow F(Y)$ and of the dual $\psi : H^3(Y, \mathbb{Z}) \to H^1(Y, \mathbb{Z})$ of the Fano correspondence. The surjectivity of $i_*$ is a consequence of the ampleness of $C_L$ and the Lefschetz hyperplane theorem: $H^1(C_L, \mathbb{Z}) \cong H_1(C_L, \mathbb{Z}) \to H_1(F(Y), \mathbb{Z}) \cong H^1(Y, \mathbb{Z})$. As $\psi$ is (up to torsion) dual to $\psi : H^3(Y, \mathbb{Z}) \to H^1(Y, \mathbb{Z})$, which is an isomorphism according to Corollary 3.3, $\psi$ is surjective, too.

Due to Corollaries 3.2 and 3.3 we know that $H^3(D_L, \mathbb{Z}) \to H^1(Y, \mathbb{Z})$ is trivial and, hence, $H^3(D_L, \mathbb{Z}) \subset \text{Ker}(\xi)$. Both are free $\mathbb{Z}$-modules of the same rank and $\text{Ker}(\xi)$ is saturated, as its cokernel is the torsion free $H^3(Y, \mathbb{Z})$. On the other hand, $H^3(D_L, \mathbb{Z})$ is also contained with finite index in $H^1(C_L, \mathbb{Z})^*$, which is a saturated submodule of $H^1(C_L, \mathbb{Z})$ (its cokernel is the torsion free $H^1(C_L, \mathbb{Z})^*$). Hence, $\text{Ker}(\xi)$ and $H^3(D_L, \mathbb{Z})$ both realize the saturation of $H^3(D_L, \mathbb{Z}) \subset H^1(C_L, \mathbb{Z})$ and, therefore, coincide. But then there is an isomorphism of Hodge structures (up to Tate twist) $H^3(Y, \mathbb{Z}) \cong H^1(C_L, \mathbb{Z})^*$ and, hence, $\text{Prym}(C_L/D_L) \cong J(Y)$.

**Remark 3.9.** There is a subtlety that has been avoided in the above discussion: Is $\psi : H^3(F(Y), \mathbb{Z}) \to H^1(Y, \mathbb{Z})$ an isomorphism? This is true up to torsion in $H^3(F(Y), \mathbb{Z})$, which in any case does not effect the isomorphism $J(Y) \cong A(F)$. Nevertheless, it would be interesting to decide whether there is non-trivial torsion in $H^3(F(Y), \mathbb{Z})$ or, similarly, in $H^3(Y, \mathbb{Z})$. The torsion freeness of the latter would in particular prove that numerical equals algebraic equivalence for line bundles on $F(Y)$, see below.

As a consequence, one obtains a description of the algebraically trivial part of the Chow group of curves on $Y$.

**Corollary 3.10.** For a generic line $L \subset Y$ (in the sense of Corollary 1.10) the Abel–Jacobi map yields an isomorphism of groups

$$\text{CH}^3(Y)_{\text{alg}} \cong J(Y) \cong \text{Prym}(C_L/D_L).$$

**Proof** The result can be seen as an application of a result of Bloch and Srinivas [26, Thm. 1]: If $Y$ is a smooth complex projective variety with $\text{CH}_0(Y) \cong \mathbb{Z}$, then the Abel–Jacobi map induces isomorphisms of groups

$$\text{CH}^3(Y)_{\text{alg}} \cong \text{CH}^3(Y)_{\text{hom}} \cong J(Y).$$

Clearly, as on a cubic threefold any two points can be connected by a chain of lines, cubic threefolds satisfy the assumption.

However, in our case of a smooth cubic threefold more direct arguments for the isomorphism $\text{CH}^3(Y)_{\text{alg}} \cong J(Y)$ exist, see [141, 142, 143] or [13, Thm. 3.1].

**Remark 3.11.** The arguments in the above discussion heavily rely on the ground field being $\mathbb{C}$. In fact, already the definition of the intermediate Jacobian $J(Y)$ over other fields is problematic. However, $\text{CH}^3(Y)$ and $\text{Prym}(C_L/D_L)$ make perfect sense over arbitrary
Chapter 5. Cubic threefolds

fields. And, indeed, Murre [141] describes an algebraic approach that yields the isomorphism $\mathrm{CH}^2(Y)_{\text{alg}} \simeq \text{Prym}(C_L/D_L)$ over arbitrary algebraically closed fields. In fact, the isomorphism was originally stated up to elements of order two, but the divisibility of $\mathrm{CH}^2(Y)_{\text{alg}}$ (pointed out by Bloch, see the review of [141]), yields the full statement.

Remark 3.12. In [42 App. A] one finds a geometric argument that shows a weaker version of the first isomorphism in (3.4), namely that the difference between $\mathrm{CH}^2(Y)_{\text{hom}}$ and $\mathrm{CH}^2(Y)_{\text{alg}}$ is annihilated by 6. More precisely, it is shown that $6 \cdot \mathrm{CH}^2(Y)_{\text{hom}} = \mathrm{CH}^2(Y)_{\text{alg}}$. The idea is the following: Let $C \subset Y$ be any curve. Then a surface $C \subset S \subset Y$ is constructed such that $6C$ on $S$ is rationally equivalent to the sum of $nH|S$ and a sum of lines $\sum a_iL_i$. As $\text{Pic}(Y) \simeq \mathbb{Z}$, this proves the assertion. The surface $S$ is obtained as the image $q(S)$ of the surface $S := p^{-1}(p(q^{-1}(C)))$ parametrizing pairs $(L, x)$ consisting of a point $x$ contained in the line $L$ that intersects $C$. Clearly, $S$ is a $\mathbb{P}^1$-bundle over $p(q^{-1}(C))$, which comes with a natural section $q^{-1}(C) \subset S$. Its image under $q_*$ yields $6C$.

4 Global Torelli theorem and irrationality
Cubic fourfolds

In this chapter we turn to cubic hypersurfaces $X \subset F(V) \cong \mathbb{P}^5$ of dimension four. The key new feature is the unexpected appearance of K3 surfaces and hyperkähler manifolds. K3 surfaces come in via their Hodge structure, which turns out to be close to the one of cubic fourfolds. The reason for the occurrence of hyperkähler manifolds is more geometric: As shown by Beauville and Donagi [21], the Fano variety $F(X)$ of lines contained in a smooth cubic fourfold $X \subset \mathbb{P}^5$ is a hyperkähler manifold. More precisely, $F(X)$ is a hyperkähler manifold that is deformation equivalent to the four-dimensional Hilbert scheme $S^{(2)}$ of subschemes of length-two of a K3 surface $S$.

We begin again by collecting immediate consequences of the results discussed in earlier chapters. We will restrict to the case of $k = \mathbb{C}$, but see Section ?? for comments on arbitrary fields $k$.

0.1 The canonical bundle of a smooth cubic fourfold $X \subset \mathbb{P}^5$ is given by $\omega_X \cong \mathcal{O}_X(-3)$. For the Picard group one has $\text{Pic}(X) \cong \mathbb{Z} \cdot \mathcal{O}_X(1)$ and the non-trivial Betti numbers of $X$ are given by

$$b_0(X) = b_2(X) = b_6(X) = b_8(X) = 1 \text{ and } b_4(X) = 23,$$

see Section [11]. In particular, for the Euler number one has $\varepsilon(X) = 27$. The lattice $H^4(X, \mathbb{Z})$ with its Hodge structure is of central importance and will be discussed in detail below. The linear system of all cubic hypersurfaces in $\mathbb{P}^5$ is $|\mathcal{O}_{\mathbb{P}^5}(3)| \cong \mathbb{P}^{55}$ and the moduli space of all smooth cubic fourfolds is of dimension 20, cf. Section [12].

0.2 A smooth cubic fourfold $X \subset \mathbb{P}^5$ never contains any linear $\mathbb{P}^3 \subset \mathbb{P}^5$ and a generic one does not contain any linear $\mathbb{P}^2 \subset \mathbb{P}^5$, see Remark [31.6]. However, some smooth cubic fourfolds do contain planes $\mathbb{P}^2 \subset \mathbb{P}^5$ and, as we will see, those containing a plane are parametrized by a divisor in the moduli space. But the most interesting Fano variety

Version Jan 22, 2020. This is all still in very rough form. Feedback will be most welcome.
associated with a cubic fourfold is again the Fano variety of lines \( \mathbb{P}^1 \subset X \). Here are some facts that can be deduced from the general discussion in Chapter 3.

(i) The Fano variety \( F(X) \) of lines contained in a smooth cubic fourfold \( X \subset \mathbb{P}^5 \) is an irreducible, smooth projective variety of dimension four with trivial canonical bundle \( \omega_{F(X)} = \mathcal{O}_{F(X)} \), see Proposition 3.1.13 and Lemma 3.2.1. 

(ii) The degree of the Plücker embedding \( F(X) \overset{\varphi}{\longrightarrow} \mathbb{O}(1, \mathbb{P}^5) \overset{\varphi}{\longrightarrow} \mathbb{F}(\wedge^2 V) \), i.e. with respect to \( g = c_1(\mathcal{O}_{F(X)}(1)) \), is
\[
\deg(F(X)) = \int_{F(X)} g^4 = 108,
\]
cf. Section 3.3.2. Later, we will show that \( F(X) \) is a hyperkähler manifold, cf. Theorem 2.6, and its degree will be given in terms of the Beauville–Bogomolov square as \( q_{F(X)}(g) = ? \), see Section 2.1.

(iii) The Euler number of \( F(X) \) is \( e(F(X)) = 324 \) and its Hodge diamond up to the middle looks like, cf. Section 3.3.5
\[
\begin{array}{cccc}
\ b_0(F(X)) & = 1 & & \\
\ b_2(F(X)) & = 23 & 1 & 21 & 1 \\
\ b_4(F(X)) & = 276 & 1 & 21 & 232 & 21 & 1 \\
\end{array}
\]
The Betti numbers suggest that the map \( S^2 H^2(F(X), \mathbb{Q}) \to H^4(F(X), \mathbb{Q}) \) may be an isomorphism. This is indeed true and can be proved by using the analogous result for the Hilbert scheme \( S^{[2]} \) of a K3 surface \( S \), cf. Corollary 1.7. However, it also essentially follows from the discussion in Section 3.3.2 purely in the context of Fano varieties of lines where the injectivity \( S^2 H^2(F(X), \mathbb{Q})_{pr} \to H^4(F(X), \mathbb{Q}) \) was observed already. We leave it to the reader to extend the argument there to prove the full statement.

(iv) The projection \( q: L \to X \) from the universal family \( p: L \to F(X) \) of lines contained in \( X \) is surjective and its generic fibre \( q^{-1}(x) \) is isomorphic to a smooth complete intersection curve of type \( (2,3) \) in \( \mathbb{P}^5 \) and, therefore, of genus \( g(q^{-1}(x)) = 4 \), see Remark 3.2.6 and Lemma 3.4.6.

(v) The Fano correspondence \( \varphi = p_\ast \circ q^\ast \) induces an injective morphism of integral Hodge structures, see Proposition 3.4.3
\[
H^4(X, \mathbb{Z}) \hookrightarrow H^2(F(X), \mathbb{Z})(-1).
\] (0.1)

As both sides are of rank 23, the injection is of finite index. Moreover, \( \varphi \) maps \( H^4(X, \mathbb{Z})_{pr} \) to \( H^2(F(X), \mathbb{Z})_{pr} \), see Remark 3.4.4, and for \( \alpha, \beta \in H^4(X, \mathbb{Z})_{pr} \) we have
\[
(\alpha, \beta) = -\frac{1}{6} \int_{F(X)} \varphi(\alpha) \cdot \varphi(\beta) \cdot g^2.
\]
Strictly speaking Proposition 3.4.3 only proves the injectivity of \( \varphi \) on \( H^4(X, \mathbb{Z})_{pr} \). However, as \( \varphi(h^2) = g \) the arguments in Remark 3.4.4 also yield the injectivity on all of \( H^4(X, \mathbb{Z}) \).
By Deligne’s invariant cycle theorem or by the stronger Corollary 12.12, we know that $H^2(X, \mathbb{Z})_{pr} = 0$ for the very general smooth cubic fourfold $X \subset \mathbb{P}^5$, which for its Fano variety of lines implies

$$\rho(F(X)) = \text{rk} \text{NS}(F(X)) = 1.$$  

**(vi)** The dual of the Fano correspondence $\varphi := p \circ q^*: H^4(X, \mathbb{Z}) \longrightarrow H^2(F(X), \mathbb{Z})$ is given by $\psi := q_* \circ p^*: H^6(F(X), \mathbb{Z}) \longrightarrow H^2(F(X), \mathbb{Q})$, see Section 3.4.3. Tensoring with $\mathbb{Q}$ and using (0.1) yields a surjection of Hodge structures $H^6(F(X), \mathbb{Q}) \longrightarrow H^4(X, \mathbb{Q})_{pr}$ and, in particular, a surjection $H^{1,3}(F(X), \mathbb{Q}) \longrightarrow H^{2,2}(X, \mathbb{Q})_{pr}$, which by definition of $\psi$ maps algebraic classes to algebraic classes. The Lefschetz (1, 1)-theorem shows that all classes in $H^{1,1}(F(X), \mathbb{Q})$ are algebraic. Hence, by applying the Lefschetz operator, we also know that all classes in $H^{1,3}(F(X), \mathbb{Q})$ are algebraic. This proves the Hodge conjecture for $H^{2,2}(X, \mathbb{Q})$, see Section ?? for the integral version.

## 1 Geometry of special cubic fourfolds

### 1.1 Planes

Ever since the work of Beauville and Donagi [21], Pfaffian cubic fourfolds occupy a special place in the theory of cubic hypersurfaces. Pfaffian cubics are parametrized by a divisor in the moduli space of all cubic fourfolds and for them the link to K3 surfaces is particularly close and well understood.

We start with a vector space $W$ of dimension six and consider $P(\wedge^2 W) \simeq \mathbb{P}^{14}$, which via the Plücker embedding contains the Grassmannian of planes in $W$:

$$G := G(1, P(W)) = G(2, W) \hookrightarrow P(\wedge^2 W).$$

We can also think of $G$ as the subvariety of two-forms $\omega \in \wedge^2 W$, up to scaling, of rank two, i.e. such that the associated alternating linear map $\omega: W^* \longrightarrow W$ has an image of dimension two. Recall that $\dim(G(1, P(W))) = 8$.

But $P(\wedge^2 W)$ contains another natural subvariety, the *Pfaffian hypersurface* $\text{Pf}(W) \subset P(\wedge^2 W)$ of all non-trivial two-forms $\omega$ that are degenerate, i.e. for which the associated linear map $\omega: W^* \longrightarrow W$ is not bijective or, equivalently, for which $\text{Ker}(\omega)$ is either of dimension two or four. This hypersurface is of degree three, which can be seen either by describing it as

$$\text{Pf}(W) = \{ \omega \in P(\wedge^2 W) \mid \omega \wedge \omega = 0 \text{ in } \wedge^4 W \} \subset P(\wedge^2 W)$$

or, alternatively, by recalling that the determinant $\text{det}(\omega)$ of an alternating matrix has
a canonical square root, the Pfaffian Pf(ω). The two subvarieties are contained in each other
\[ G = G(1, \mathbb{P}(W)) \subset \text{Pf}(W) \subset \mathbb{P}(\bigwedge^2 W) \]
and \( G \) is the singular locus of \( \text{Pf}(W) \). The last assertion can be proved by using
the theory of degeneracy loci, see e.g. [9]. The smoothness of \( \text{Pf}(W) \setminus G \), which is all we
need, simply follows from the observation that it is homogenous under the action of \( \text{PGL}(W) \). Of course, the same picture
\[ G^* := G(1, \mathbb{P}(W^*)) \subset \text{Pf}(W^*) \subset \mathbb{P}(\bigwedge^2 W^*) \]
events for the dual space \( W^* \) and the two sides are linked by natural correspondences.

The first that comes to mind is \( B \subset \mathbb{P}(W) \times \text{Pf}(W^*) \):
\[ B := \{ (W_0, \omega) \mid W_0 \subset \text{Ker}(\omega) \} \xrightarrow{q} \text{Pf}(W^*) \quad (1.1) \]
\[ p \]
\[ \mathbb{P}(W). \]

The projection \( p \) is a fibre bundle with fibre \( \mathbb{P}((\bigwedge^2 W)/W_0) \) over the point in \( \mathbb{P}(W) \) corresponding to a line \( W_0 \subset W \). The projection \( q \) is a \( \mathbb{P}^1 \)-bundle over the smooth locus \( \text{Pf}(W^*) \setminus G^* \) of \( \text{Pf}(W^*) \).

Another natural correspondence is given by \( \Sigma \subset G(1, \mathbb{P}(W^*)) \times \text{Pf}(W^*) \):
\[ \Sigma := \{ (P, \omega) \mid P \cap \text{Ker}(\omega) \neq 0 \} \longrightarrow \text{Pf}(W^*) \quad (1.2) \]
\[ \mathbb{G}(1, \mathbb{P}(W)). \]

Here, \( \omega|_P \) for a two-form \( \omega \in \bigwedge^2 W^* \) on \( W \) denotes the restriction to \( P \), i.e. its image under the natural \( \bigwedge^2 W^* \longrightarrow \bigwedge^2 P \). Observe the in general strict implications:
\[ P \subset \text{Ker}(\omega) \Rightarrow P \cap \text{Ker}(\omega) \neq 0 \Rightarrow \omega|_P = 0 \]
for planes \( P \subset W \). In particular, \( \Sigma \subset C \) and the map \( \omega \longrightarrow \text{Ker}(\omega) \) defines a section of the projection \( \Sigma \longrightarrow \text{Pf}(W^*) \) over the smooth locus \( \text{Pf}(W^*) \setminus G^* \).

**Remark 1.1.** We collect some easy facts used frequently below.

(i) Assume \( P \neq Q \subset W \) are two distinct planes. Then the projective line \( PQ \) in \( \mathbb{P}((\bigwedge^2 W) \) through the two points \( P, Q \in G = G(1, \mathbb{P}(W)) \subset \mathbb{P}(\bigwedge^2 W) \) is contained in \( G \) if and only if \( \dim(P + Q) = 3 \), which in turn is equivalent to \( \dim(P \cap Q) = 1 \) and, still equivalent, to \( P \cap Q \neq 0 \). In this case, \( G(2, \mathbb{P}(P + Q)) \subset G(2, \mathbb{P}(W)) \) is the linear subspace \( \mathbb{P}((\bigwedge^2(P + Q)) \cong \mathbb{P}^2 \).

(ii) The Grassmannian \( F(G) \) of lines in \( \mathbb{P}(\bigwedge^2 W) \) that are contained in \( G \) is related to
the Grassmannian $G(2, \mathbb{P}(W))$ by the open variety \((P, Q) \mid \dim (P + Q) = 3\) and the two projections \((P, Q) \mapsto \mathbb{P}(Q) \in F(\mathbb{G})\) and \((P, Q) \mapsto (P + Q) \in G(2, \mathbb{P}(W))\). As the fibres of the two projections are of dimension two and three, one finds \(\dim (F(\mathbb{G})) = 10\).

In order to make contact to cubic fourfolds, the Pfaffian $\text{Pf}(W^*)$ has to be intersected with a related linear space yields a K3 surface. The starting point is the following observation [21].

Lemma 1.2. Consider generic linear subspaces

\[ \mathbb{P}^5 \cong \mathbb{P}(V) \subset \mathbb{P}(\wedge^2 W^*) \quad \text{and} \quad \mathbb{P}^8 \cong \mathbb{P}(U) \subset \mathbb{P}(\wedge^2 W) \]

and let

\[ X_V := \text{Pf}(W^*) \cap \mathbb{P}(V) \quad \text{and} \quad S_U := \mathbb{G}(1, \mathbb{P}(W)) \cap \mathbb{P}(U). \]

(i) Then $X_V \subset \mathbb{P}(V)$ is a smooth cubic hypersurface

(ii) $S_U$ is a K3 surface which is of degree 14 with respect to the polarization $\mathcal{O}(1)|_{S_U}$.

Moreover, $X_V$ does not contain any plane $\mathbb{P}^2 \subset \mathbb{P}(V)$ and $S_U$ does not contain any line $\mathbb{P}^1 \subset \mathbb{P}(U)$.

Proof. The first assertion follows from the classical Bertini theorem and the observation that the singular locus $\mathbb{G}(1, \mathbb{P}(W^*)) \subset \text{Pf}(W^*)$ is of codimension five and, therefore, is not intersected by the generic linear subspace $\mathbb{P}(V)$ of codimension nine.

For (ii) use that $\omega_{G} \cong \text{det}(\mathcal{S} \otimes Q^*) \cong \mathcal{O}(-6)|_{G}$, cf. Lemma [21], and $\omega_{S_U} \cong \omega_G|_{S_U} \otimes \text{det}(\mathcal{N}_{S_U/G}) \cong \mathcal{O}_{S_U}$, because $\mathcal{N}_{S_U/G} \cong \mathcal{O}(1)^{66}$. The vanishing $H^1(G, \mathcal{O}_G) = 0$ follows from $H^1(G, \mathcal{O}_G) = 0$ and the standard Lefschetz theorem. Hence, $S_U$ is indeed a K3 surface. To compute its degree with respect to the Plücker polarization observe that $\text{deg}(S_U) = \text{deg}(G)$ and use $\text{deg}(\mathbb{G}(1, \mathbb{P}^m)) = \frac{2m-21}{m-17}$, cf. [69, Prop. 4.12].

Consider the correspondence $T_1 := \{ (L, \mathbb{P}(U)) \mid L \subset \mathbb{P}(U) \subset F(\mathbb{G}) \times \mathbb{G}(8, \mathbb{P}(\wedge^2 W)) \}$ and recall that $\dim (F(\mathbb{G})) = 10$, see Remark [1.1]. As the fibre of the first projection $T_1 \mapsto F(\mathbb{G})$ over a line $L = \mathbb{P}(K) \in F(\mathbb{G})$ is the Grassmannian $\mathbb{G}(6, \mathbb{P}(\wedge^2 W)/K)$, which is of dimension 42, one has $\dim (T_1) = 52$. Now use $\dim (\mathbb{G}(8, \mathbb{P}(\wedge^2 W))) = 54$ to conclude that the image of the second projection cannot be surjective. In other words, for the generic $\mathbb{P}^8 \cong \mathbb{P}(U) \subset \mathbb{P}(\wedge^2 W)$ there are no lines in $G \cap \mathbb{P}(U) = S_U$.

The idea for the proof of the remaining assertion is similar. Consider the correspondence $T_2 := \{ (\mathbb{P}^2, \mathbb{P}(V)) \mid \mathbb{P}^2 \subset \mathbb{P}(V) \subset F(\text{Pf}(W^*), 2) \times \mathbb{G}(5, \mathbb{P}(\wedge^2 W^*)) \}$. Here, $F := F(\text{Pf}(W^*), 2)$ is the Fano variety of planes $\mathbb{P}^2 \subset \mathbb{P}(\wedge^2 W^*)$ contained in the smooth locus $\text{Pf}(W^*)_{\text{sm}} = \text{Pf}(W^*) \setminus G(1, \mathbb{P}(W^*))$ of the cubic hypersurface $\text{Pf}(W^*) \subset \mathbb{P}(\wedge^2 W^*) \cong \mathbb{P}^{14}$. According to Corollary [1.5] the Fano variety of planes $\mathbb{P}^2 \subset \mathbb{P}^{14}$ contained in the generic cubic hypersurface in $\mathbb{P}^{14}$ is of dimension 26, but a priori there is no reason that the Pfaffian cubic has this property. However, it was shown in [132].
Chapter 6. Cubic fourfolds

Cor. 5] that indeed \( F(\text{Pf}(W^*)) \) consists of four smooth connected components of dimension 26. The fibre of the projection \( T_2 \to F \) over the point corresponding to a plane \( \mathbb{P}^2 = \mathbb{P}(N) \subset \text{Pf}(W^*) \) is the Grassmannian \( \mathbb{G}(2, \mathbb{P}((\Lambda^2 W^*)/N)) \), which has dimension 27. Hence, \( \dim(T_2) = 53 \) and, as \( \dim(\mathbb{G}(5, \mathbb{P}((\Lambda^2 W^*))) = 54 \), this allows one to conclude that the second projection \( T_2 \to \mathbb{G}(5, \mathbb{P}((\Lambda^2 W^*) \) cannot be surjective.

In Remark ?? we will give another argument for the last part relying on Hodge theory instead of the explicit description of \( F(\text{Pf}(W^*, 2)) \) provided by [132]. □

Definition 1.3. A smooth cubic fourfold \( X \subset \mathbb{P}^5 \) is a Pfaffian cubic fourfold if it is isomorphic to a cubic fourfold of the form \( \mathbb{P}^5 \).

Remark 1.4. Unlike the case of cubics of dimension two and three, not every cubic fourfold is Pfaffian. In fact, a naive dimension count reveals that the space of Pfaffian cubics up to isomorphisms is of dimension \( \dim(\mathbb{G}(5, \mathbb{P}((\Lambda^2 W^*) \) \) = 53, whereas the moduli space of all smooth cubic fourfolds is of dimension 20, see Section 12.1. Similarly, the space of K3 surfaces constructed as \( S_U \) up to isomorphisms is of dimension \( \dim(\mathbb{G}(8, \mathbb{P}((\Lambda^2 W^*))) = 54 \), and are ultimately induced by \( W \) and \( W^* \), cf. [88, Thm. 10.19].

In the following we will consider \( X_V \) and \( S_U \) for \( U := V^\perp = \text{Ker}(\Lambda^2 W^* \to V^*) \). In this case, we shall also write \( S_V \) for the latter, which is then explicitly described as \( S_V = \{ P \in \mathbb{G} | \omega_{SP} = 0 \text{ for all } \omega \in V \} \).

The next results provides closed embeddings into appropriate Grassmannians for all three four-dimensional varieties in the picture: The Pfaffian cubic \( X_V \), the Hilbert scheme \( S_{[2]} \) of length-two subschemes of the K3 surface \( S_V \), and the Fano variety \( F(X_V) \) of lines in \( X_V \).

Corollary 1.5. Let \( \mathbb{P}^5 = \mathbb{P}(V) \subset \mathbb{P}((\Lambda^2 W^*) \) be a generic linear subspace. Then the maps

\[
\begin{align*}
i_{[2]} & : S_{[2]} \to \mathbb{G}(3, \mathbb{P}(W)), \quad \{ P, Q \} \mapsto P + Q, \\
i_X & : X_V \to \mathbb{G}(1, \mathbb{P}(W)), \quad \omega \mapsto P_{\omega} := \text{Ker}(\omega), \\
i_F & : F(X_V) \to \mathbb{G}(3, \mathbb{P}(W)), \quad L = \omega_1 \omega_2 \mapsto W_L := P_{\omega_1} + P_{\omega_2}
\end{align*}
\]

define closed embeddings.

Proof We shall explain that the natural maps are well defined and prove that they are injective. We will leave to the reader the verification that the maps are regular, and in fact closed immersions.
1 Geometry of special cubic fourfolds

By virtue of Remark 1.1 and Lemma 1.2 we know that for any two \( P \neq Q \in S_V \) the sum \( P + Q \) is of dimension four. Hence, \( i_{S_V} \) is certainly well defined on the open subset in \( S_V^{[2]} \) parametrizing reduced length-two subschemes of \( S_V \). A non-reduced subscheme of length two in \( S_V \) is gained by a point \( P \in S_V \) and a tangent direction \( v \in T_P S_V \subset T_P \mathbb{G}(1, \mathbb{P}(W)) \cong \text{Hom}(P, W/P) \). Sharpening the argument in Remark 1.1 one proves that the pre-image \( \pi^{-1}(v(P)) \) of \( v(P) \subset W/P \) under the projection \( \pi : W \longrightarrow W/P \) is again a four-dimensional space. Setting \( i_{S_V}(P, v) := \pi^{-1}(v(P)) \subset \mathbb{G}(3, \mathbb{P}(W)) \) extends \( (P, Q) \longrightarrow P + Q \) to a map \( i_{S_V} : S_V^{[2]} \longrightarrow \mathbb{G}(3, \mathbb{P}(W)) \). For the injectivity of \( i_{S_V} \) use the arguments of Exercise 1.8 below.

As any \( \omega \in X_V \) has rank four, \( P_\omega \subset W \) is indeed a plane and, therefore, \( i_X \) is well defined. The fibre of \( i_X \) through \( \omega \) is the linear space \( \mathbb{P}(\mathbb{P}(L \cap \mathbb{P}(W))) \), i.e., \( i_X \) is well defined. Using similar arguments, also with the roles of \( \omega_1, \omega_2 \) reversed, shows \( \omega_1, \omega_2 \in V_L := \{ \omega \in V \mid \omega |_{W_j} = 0 \}. \) Clearly, \( \mathbb{P}(V_L) \subset X_V \) and, as \( X_V \) does not contain any planes, \( \dim(V_L) = 2 \). In other words, \( L = \mathbb{P}(V_L) \) and, therefore, the line \( L \) is uniquely determined by its image \( W_L = i_F(L) \subset \mathbb{P}(3, \mathbb{P}(W)), \) i.e., \( i_F \) is injective. \( \square \)

**Remark 1.6.** Here is a slightly less ad hoc way of introducing \( i_X \). The universal section \( O \longrightarrow \wedge^2 W^* \otimes O \) over \( \mathbb{P}(\wedge^2 W) \) can equivalently be given as a universal map \( W \otimes O \longrightarrow \wedge^2 W^* \otimes O(1) \). Restricted to \( \mathbb{P}(V) \cong \mathbb{P}^5 \) it yields a short exact sequence

\[
0 \longrightarrow W \otimes O(1) \longrightarrow \wedge^2 W^* \otimes O(1) \longrightarrow \mathcal{E} \longrightarrow 0,
\]

where \( \mathcal{E} \) is a rank two bundle over \( X_V \subset \mathbb{P}(V) \). The restriction of \( (1.3) \) to \( X_V \) leads to an exact sequence

\[
0 \longrightarrow \mathcal{E} \otimes O_{X_V}(1) \longrightarrow W \otimes O_{X_V} \longrightarrow \wedge^2 W^* \otimes O_{X_V}(1) \longrightarrow \mathcal{E} \longrightarrow 0,
\]

which at the point \( \omega \in X_V \) is nothing but \( \text{Ker}(\omega) \subset W \longrightarrow W^* \longrightarrow \text{Ker}(\omega)^* \). The morphism \( i_X \) is the classifying morphism for the inclusion \( \mathcal{E}^* \otimes O_{X_V}(1) \subset W \otimes O_{X_V} \).

Although, both \( S_V \) and \( X_V \cong i_X(X_V) \) are closed subvarieties of \( \mathbb{G} = \mathbb{G}(1, \mathbb{P}(W)) \), the link between the two in this setting becomes clear only after passing to the associated four-dimensional varieties \( S_V^{[2]} \).
Corollary 1.7 (Beauville–Donagi). Let $\mathbb{P}^5 \cong \mathbb{P}(V) \subset \mathbb{P}(\wedge^2 W^*)$ be a generic linear subspace. Then the images of $i_S$ and $i_P$ in $\mathcal{O}(3, \mathbb{P}(W))$ coincide and, therefore,

$$S^{[2]}_V \cong F(X_V). \quad (1.4)$$

Proof As $S^{[2]}_V$ and $F(X_V)$ are both smooth subvarieties of $\mathcal{O}(3, \mathbb{P}(W))$ of dimension four, it suffices to show that for any $\{P \neq Q\} \in S^{[2]}_V$ the four-space $P + Q$ is of the form $W_L$ for some line $L \subset X_V$. To this end, consider the linear subspace $\{\omega \in V \mid \omega|_{P \cap Q} = 0\} \subset V$. Its projectivization defines a linear subspace of $\mathbb{P}(V)$ contained in $X_V$ and, therefore, is of dimension at most two. To see that it is of dimension two and thus defines a line $L \subset X_V$, pick a basis such that $P = \langle x_1, x_2 \rangle$ and $Q = \langle x_3, x_4 \rangle$. As $P, Q \in S_V$, we know that $\omega|_P = \omega|_Q = 0$ for all $\omega \in V$. Hence, for $\omega = \sum a_i x^i$, the condition $\omega|_{P \cap Q} = 0$ translates into the four equations $a_{13} = a_{14} = a_{23} = a_{24} = 0$. They define a subspace of codimension at most four.

Exercise 1.8. Show that an inverse map $F(X_V) \rightarrow S^{[2]}_V$ can be described as follows. For $L \in F(X_V)$ the intersection of the two linear spaces $\mathbb{P}^5 \cong \mathbb{P}(\wedge^2 W_L), \mathbb{P}^8 \cong \mathbb{P}(V^*) \subset \mathbb{P}(\wedge^2 W) = \mathbb{P}^{14}$ is a line (use that the plane corresponding to the line $L$ is contained in the kernel of the projection $V \subset \wedge^2 W^* \rightarrow \wedge^2 W_L^*$), which intersects the quadric $\mathbb{Q}(1, \mathbb{P}(W_L)) \subset \mathbb{P}(\wedge^2 W_L)$ in two points (corresponding to planes $P, Q \subset W_L$). They are both automatically contained in $S_V$ and, therefore, define a point $\{P, Q\} \in S^{[2]}_V$. See [21] for more details.

Remark 1.9. If $V$ is not chosen generically in the sense of Lemma [1.2] but still $X_V$ and $S_V$ are smooth, there is still a birational isomorphism

$$S^{[2]}_V \cong F(X_V). \quad (1.5)$$

Indeed, the isomorphism in Corollary [1.7] specializes to a correspondence between $F(X_V)$ and $S^{[2]}_V$ and, using that both varieties have trivial canonical bundle, this proves that there is a unique irreducible component of the correspondence that yields (1.5).

Let us now study the restriction of [1.2]

$$\Sigma_V := \Sigma \cap (S_V \times X_V) \subset S_V \times X_V,$$

which eventually links the cubic $X_V$ and its associated K3 surface $S_V$ more directly.

Lemma 1.10. Let $\mathbb{P}^5 \cong \mathbb{P}(V) \subset \mathbb{P}(\wedge^2 W^*)$ be a generic linear subspace.

(i) For $P \in S_V$ and a line $W_0 \subset P$, the set $\{\omega \in \mathbb{P}(V) \mid W_0 \subset \ker(\omega)\}$ is a line in $X_V$.

(ii) Conversely, if $(P, \omega) \in \Sigma_V$, then $P \cap \ker(\omega) \subset P$ is a line.

Proof The quickest way to prove (i) is by introducing a basis: $x_1, \ldots, x_6 \in W$ with $W_0 = \langle x_1 \rangle \subset P = \langle x_1, x_2 \rangle$. For $\omega = \sum_{i<j} a_{ij} x^i \wedge x^j \in \wedge^2 W^*$ the condition $W_0 \subset \ker(\omega)$ is equivalent to the five equations $a_{12} = \cdots = a_{16} = 0$. As $P \in S_V$, the vanishing
\[a_{12} = 0\] is automatic for all \(\omega \in V \subset \wedge^2 W^*\). Therefore, the remaining four equations \(a_{13} = \cdots = a_{16} = 0\) define a subspace of dimension at least two and in fact of dimension exactly two, as for generic \(V\) we may assume that \(X_V\) does not contain any projective plane, cf. Lemma 1.2.

It is worth pointing out that the set defined in (i) only depends on \(W_0\). The proof just uses that there exists a \(P \in S_V\) in the background.

For (ii) it suffices to exclude that \(P = \text{Ker}(\omega)\) for any \((P, \omega) \in S_V \times X_V\) for generic choice of \(V\). To this end, consider the correspondence \(T \subset \mathcal{O}(1, \mathbb{P}(W)) \times \mathbb{P}(W^*) \times \mathcal{G}(5, \mathbb{P}(\wedge^2 W^*))\) of all \((P, \omega, V)\) with \(P \subset \text{Ker}(\omega), \omega \in X_V, \text{and } P \in S_V\). Once \(P\) is fixed, \(\omega\) varies in the six-dimensional subspace \(V_P\) of all forms containing \(P\) in the kernel. If \(P\) and \(\omega \in V_P\) are fixed, then \(V\) varies in a 40-dimensional Grassmannian.

Indeed, after picking appropriate coordinates, we may write \(P = \langle x_1, x_2 \rangle\) and \(\omega = x^3 \wedge x^4 + x^5 \wedge x^6\). Then \(V/\langle \omega \rangle\) varies in the Grassmannian of five-dimensional subspaces of \(\langle x^i \wedge x^j | (i, j) \neq (1, 2) \rangle / \langle \omega \rangle\). Counting dimensions yields \(\dim(T) = 8 + 5 + 40 = 53 < 54 = \dim(\mathcal{G}(5, \mathbb{P}(\wedge^2 W^*)))\). Therefore, the projection \(T \rightarrow \mathcal{G}(5, \mathbb{P}(\wedge^2 W^*))\) is not surjective.

To a fixed \(\mathbb{P}(V) \subset \mathbb{P}(\wedge^2 W^*)\) as above, one associates the restriction of the correspondence \((1, 1)\), where we keep the notation for the projections:

\[
\begin{array}{c}
B_V \xrightarrow{q^{-1}(X_V)} X_V \\
p \downarrow \\
\mathbb{P}(W).
\end{array}
\]

Note that \(q: B_V \rightarrow X_V\) is a \(\mathbb{P}^1\)-bundle, so that \(B_V\) is smooth and of dimension five. The fibre of \(p\) over the point in \(\mathbb{P}(W)\) corresponding to a line \(W_0 \subset W\) is the linear subspace of all \(\omega \in \mathbb{P}(V)\) with \(W_0 \subset \text{Ker}(\omega)\). The situation is more precisely described as follows.

**Lemma 1.11.** For a generic linear subspace \(\mathbb{P}^5 \cong \mathbb{P}(V) \subset \mathbb{P}(\wedge^2 W^*)\) the first projection \(p: B_V \rightarrow \mathbb{P}(W) \cong \mathbb{P}^5\) is the blow-up in the smooth and irreducible subvariety \(Z_V := \{[W_0] | \dim(p^{-1}[W_0]) > 0 \} \subset \mathbb{P}(W)\) with \(\dim(Z_V) = 3\) and \(\deg(Z_V) = 9\).

**Proof** The morphism \(p: B_V \rightarrow \mathbb{P}(W)\) is surjective and its fibres are linear subspaces of \(X_V\) of dimension zero or one. More precisely, over the point in \(\mathbb{P}(W)\) corresponding to a line \(W_0 \subset W\) the fibre is \(\mathbb{P}((\wedge^2 U_0^*) \cap V)\), where \(U_0 := W/W_0\).

The degree of \(Z\) can be computed using Porteous’s formula, see [69, Ch. 12]. Taking the second exterior power of the Euler sequence on \(P = \mathbb{P}(W)\) yields the short exact sequence

\[
0 \rightarrow \Omega_P^2 \rightarrow \wedge^2 W^* \otimes \mathcal{O}(-2) \rightarrow \Omega_P \rightarrow 0.
\]

The surjection composed with the inclusion \(V \subset \wedge^2 W^*\) defines then a generically surjective morphism \(\eta: V \otimes \mathcal{O}
}
Chapter 6. Cubic fourfolds

\( \mathcal{O}(-2) \to \Omega_{\mathbb{P}} \). The fibre of \( \eta \) at the point \([W_0]\) has kernel \((\wedge^2 U'_0) \cap V\). Hence, \( Z \) is the degeneracy locus \( M_4(\eta) = \{[W_0] \mid \text{rk } \eta_{|W_0} \leq 4\} \subset \mathbb{P}(W) \). As it has the expected codimension two, its class is given by \((c_1^2 - c_2)(\Omega_{\mathbb{P}}(2)) = 9 \cdot h^2\), and therefore, \( \text{deg}(Z) = 9 \).

Note that the fact that the fibres of \( \rho : B_V \to \mathbb{P}(W) \) are of dimension at most one, translates into the fact that the rank of \( \eta \) is at least four at each point and, therefore, \( M_4(\eta) \) is smooth.

Below we will describe \( Z_V \) explicitly as a \( \mathbb{P}^1 \)-bundle over the K3 surface \( S_V \), which in particular proves its irreducibility. Alternatively, one can use that \( \Omega_{\mathbb{P}}(2) \) is ample and the general connectivity criterion for degeneracy loci \([74]\). \( \square \)

**Lemma 1.10.** can be rephrased as saying that the natural projection from \( \Sigma_V \) onto \( S_V \) can be written as the composition of two \( \mathbb{P}^1 \)-bundles

\[ \Sigma_V \to \mathbb{P}(S_{S_V}) \to S_V, \quad (P, \omega) \mapsto (P, P \cap \text{Ker}(\omega)) \to P \]

Here, \( S_{S_V} \), the restriction of the universal subbundle to \( S_V \subset \mathbb{G}(1, \mathbb{P}(W)) \). Moreover, the natural inclusion \( \mathbb{P}(S_{S_V}) \subset S_V \times \mathbb{P}(W) \) yields a projection

\[ \tau_V : \mathbb{P}(S_{S_V}) \to \mathbb{P}(W). \]

Restricted to the fibre of \( \mathbb{P}(S_{S_V}) \to S_V \) over the point in \( S_V \) corresponding to a plane \( P \subset W \) it is the embedding of the line \( \mathbb{P}^1 \simeq \mathbb{P}(P) \subset \mathbb{P}(W) \).

**Corollary 1.12.** For a generic linear subspace \( \mathbb{P}^5 \simeq \mathbb{P}(V) \subset \mathbb{P}(\wedge^2 W^*) \) the morphism \( \tau_V \) is a closed embedding with image \( Z_V \):

\[ \tau_V : \mathbb{P}(S_{S_V}) \hookrightarrow Z_V \subset \mathbb{P}(W). \]

**Proof.** Combining Lemma [1.10 (i) and Lemma 1.11] shows that \([W_0] \in Z_V\) for any \( W_0 \subset P \subset S_V \). Similarly, one checks that for any \([W_0] \in Z_V\) there in fact exists a \( P \in S_V \) with \( W_0 \subset P \). This also follows from the fact that \( Z_V \) is irreducible and that \( \tau_V \) is injective. To verify the latter, observe that for \( P \neq Q \in S_V \) the two lines \( \mathbb{P}(P), \mathbb{P}(Q) \subset \mathbb{P}(W) \) intersect if and only if the line \( \overline{PQ} \subset \mathbb{P}(\wedge^2 W^*) \) is contained in \( G \) or, equivalently, in \( S_V \), see Remark [1.4]. However, by virtue of Lemma 1.12 for generic choice of \( V \) the K3 surface \( S_V \) does not contain any lines. \( \square \)

This leads to the following picture, where \( E \) denotes the exceptional divisor:

\[ \begin{array}{c c c c c c}
\Sigma_V & \to & E & \cap & B_V & \xrightarrow{p^!} & X_V \\
p^! & \downarrow & & \downarrow & & \\
\mathbb{P}(S_{S_V}) & \to & Z_V & \cap & \mathbb{P}(W) & \\
p^! & \downarrow & & \downarrow & & \\
S_V & & & & & \\
\end{array} \] (1.6)
Remark 1.13. In particular, to any \((W_0, \omega) \in E \subset B_V\) one naturally associates two planes \(P_{W_0}, P_\omega \in \mathcal{O}(1, \mathbb{P}(W))\), cf. Corollary \[1.5\]. Here, \(P_{W_0}\) is the unique plane defining a point in \(S_V\) with \(W_0 \subset P_{W_0}\). Clearly, the compositions \(E \subset B_V \to X_V \to \mathcal{O}(1, \mathbb{P}(W))\) and \(E \to Z_V \to S_V \subset \mathcal{O}(1, \mathbb{P}(W))\) do not commute.

Note that if \(P_{W_0} \neq P_\omega\) for \((W_0, \omega) \in E\), then \(P_\omega \in X_V \setminus S_V \subset \mathcal{O}(1, \mathbb{P}(W))\). Indeed, as otherwise, according to Remark \[1.1\], this would produce a line in \(S_V\), the existence of which is excluded for generic \(V\) by Lemma \[1.2\].

Remark 1.14. The \(\mathbb{P}^1\)-bundle \(E \to Z_V\) together with the projection \(E \subset B_V \to X_V\) can be viewed as a family of lines in \(X_V\) parametrized by \(Z_V\). The classifying morphism \(Z_V \to F(X_V)\) is a closed immersion and describes a uniruled divisor in the fourfold \(F(X_V)\). For the injectivity of \(Z_V \to F(X_V)\) use the explicit description in the proof of Lemma \[1.10\] which shows that the linear subspace \(\{\omega \in \mathbb{P}(V) \mid W_0 \subset \ker(\omega)\}\) determines \(W_0\). The base of the ruling is the K3 surface \(S_V\).

As \(Z_V \to F(X_V)\) is injective, the family of lines is dominant, i.e. \(\Sigma_V \cong E \to X_V\) is surjective and, for dimension reasons, generically injective. The degree of the projection is four, see Lemma \[1.16\].

The above commutative diagram yields a motivic relation between the cubic fourfold \(X_V\) and the K3 surface \(S_V\), see Section \[3.1\] for the notation.

Proposition 1.15. Let \(\mathbb{P}^5 \cong \mathbb{P}(V) \subset \mathbb{P}(\Lambda^2 W^*)\) be a generic linear subspace. Then

\[
\mathcal{O}^1 \cdot [X_V] = [\mathbb{P}^5] + [S_V] \cdot (\ell + 1) \quad \text{(1.7)}
\]

in \(K_0(\text{Var}_k)\) and

\[
\mathcal{O}(1) \cdot \mathcal{O}(X_V) \oplus \mathcal{O}(Z_V)(-2) \cong \mathcal{O}(\mathbb{P}^5) \oplus \mathcal{O}(S_V)(-1) \oplus \mathcal{O}(Z_V)(-2) \quad \text{(1.8)}
\]

in \(\text{Mot}(k)\).

The part \(S_V \to \Sigma_V \to X_V\) of the above correspondence is of particular importance, for the geometry of the situation as well as for its derived aspects, see Section \[2.2\]. For each \(P \in S_V\) one obtains a surface \(\Sigma_P\) which is described by the next result, see \[92\].

Lemma 1.16. Assume \(\mathbb{P}^5 \cong \mathbb{P}(V) \subset \mathbb{P}(\Lambda^2 W^*)\) is a generic linear subspace.

(i) The fibre \(\Sigma_P\) of \(\Sigma_V \to S_V\) over a point \(P \in S_V\) describes a quartic rational normal scroll contained in \(X_V\).

(ii) The self-intersection number of the surface \(\Sigma_P \subset X_V\) satisfies \((\Sigma_P \cdot \Sigma_V) = 10\).

(iii) The projection \(\Sigma_V \to X_V\) is a generically finite morphism of degree four.

Scrolls are classical objects in algebraic geometry. A two-dimensional scroll is by definition a ruled surface \(\pi: T \cong \mathbb{P}(\mathcal{E}) \to C\) over some curve \(C\) together with an embedding \(T \hookrightarrow \mathbb{P}^N\) such that all fibres of \(\pi\) are lines in \(\mathbb{P}^N\). The scroll is a rational scroll.
if $T$ as a surface is rational, i.e. birational to $\mathbb{P}^2$, which is equivalent to $C \cong \mathbb{P}^1$. It is a rational normal scroll if in addition the embedding is projectively normal, i.e. if the maps $H^0(\mathbb{P}^N, \mathcal{O}(n)) \to H^0(T, \mathcal{O}_T(n))$ are surjective.

A classical result in algebraic geometry says that any smooth projective surface of degree $d$ in $\mathbb{P}^{d+1}$ not contained in any hyperplane is either a rational normal scroll, a linear $\mathbb{P}^2$ with $d = 1$, or the image of $\mathbb{P}^2$ under the Veronese embedding into $\mathbb{P}^5$. Furthermore, for $d = 4$, which is the case of interest to us, the surface is either isomorphic to $T(\mathcal{O}_P \oplus \mathcal{O}_P(-2))$ or to the Hirzebruch surface $\mathbb{F}_2 = \mathbb{P}(\mathcal{O}_P \oplus \mathcal{O}_P(-2))$, the latter being obtained by specialization of the former. See [20, Ch. V.2] for more information and references.

**Proof**  To compute the degree of $\Sigma_P$ we intersect it with a generic $\mathbb{P}^3 \cong \mathbb{P}(V_0) \subset \mathbb{P}(V)$. The quickest way to compute $\Sigma_P \cap \mathbb{P}(V_0)$ is maybe by picking coordinates. So, let us assume $P = \langle x_1, x_2 \rangle \subset W = \langle x_1, \ldots, x_9 \rangle$. For $\omega = \sum a_{ij} x^i x^j \in V_0$ we consider the composition $\omega' : P \subset W \xrightarrow{\omega} W'$. Then $\Sigma_P \cap \mathbb{P}(V_0)$ is described by the additional linear condition $a_{12} = 0$, which holds for $P \in S_V$, and $\bigwedge^2 \omega' = 0$, which amounts to the quadratic equations $a_{1k} a_{2k} = a_{1l} a_{2l}$. For dimensions reasons, two of the quadratic equations are enough which proves $\deg(\Sigma_P) = |\Sigma \cap \mathbb{P}(V_0)| = 4$.

To compute the self-intersection number we assume for simplicity that $\Sigma_P \cong \mathbb{P}^1 \times \mathbb{P}^1$ the case of the Hirzebruch surface $\mathbb{F}_2$ is similar, with the first factor corresponding to $\mathbb{P}(P)$, and $h_{\Sigma_P} = 2h_1 + h_2$, where $h_1$ and $h_2$ are the hyperplane classes on the two factors. Then $(\Sigma_P, \Sigma_P) = c_2(N_{\Sigma_P/X_V})$ can be computed by using the Euler sequence and the normal bundle sequences for $\Sigma_P \subset X_V$ and $X_V \subset \mathbb{P}$. Altogether one finds $(1 + 2h_1 + h_2)^6 = c(O_{\Sigma_P}(1))^6 = c(T_{\Sigma_P}) = c(T_{\Sigma_P} \cdot c(O_{\Sigma_P}(3))) = c(T_{\Sigma_P} \cdot c(N_{\Sigma_P/X_V}) \cdot c(O_{\Sigma_P}(3))) = (1 + 2h_1)(1 + 2h_2)(1 + c_1 + c_2)(1 + 3(2h_1 + h_2))$, which allows one to compute the Chern classes $c_1$ and $c_2$ of the normal bundle $N_{\Sigma_P/X_V}$ as $c_1 = 4h_1 + h_2$ and $c_2 = 10$.

The following argument for the computation of the degree is taken from [5, Lem. 4]. As observed earlier, the projection $\Sigma_V = E \longrightarrow X_V$ is surjective and hence generically finite. The fibre over $\omega \in X_V$ is the intersection of the Schubert cycle $\{P \mid P \cap \text{Ker}(\omega) \neq 0\} \subset \mathbb{G}(1, \mathbb{P}(W))$ with $S_V$. In other words, the fibre is this Schubert cycle intersected with the linear subspace $\mathbb{P}(V^*) \cong \mathbb{P}^5$ of codimension five. As the degree of the Schubert cycle is indeed four, this proves the last assertion.

**Corollary 1.17.** The two cycles $h_2^3$ and $\Sigma_P$ on $X_V$, both of codimension two, span a rank two lattice with intersection from

$$\begin{pmatrix} 3 & 4 \\ 4 & 10 \end{pmatrix}.$$ 

\[ \square \]

Usually we will work over $\mathbb{C}$ and then the lattice will be viewed as $\langle h_2^3, [\Sigma_P] \rangle \subset H^2(X, \mathbb{Z})(2)$, but, of course, it makes sense in any other cohomology theory or in the Chow group.
Exercise 1.18. Study the induced rational map $X_V \rightarrow S^{[4]}$ and show that it defines a Lagrangian subvariety of the hyperkähler manifold $S^{[4]}$, cf. Section 2.1.

Exercise 1.19. Show that $\Sigma \subset X_V$ can also be described as the degeneracy locus $M_1(\eta) := \{ \omega \in X_V \mid \text{rk} \eta_\omega \leq 1 \}$ of the composition $\eta: P \otimes O_{X_V} \hookrightarrow W \otimes O_{X_V} \rightarrow W^* \otimes O_{X_V}(1)$, where the last map is the universal alternating form over $X_V$. See Remark 1.6.

The next step consists of cutting with a hyperplane section. So let $H = \mathbb{P}(W') \subset \mathbb{P}(W)$ be a generic hyperplane section, $Z_{V,H} := Z_V \cap H$, and $B_{V,H} := B_V \cap (H \times X_V)$. Then

$$B_{V,H} \xrightarrow{q_{\eta}} X_V \xrightarrow{p_{\eta}} H$$

(1.9)

describes a birational correspondence between $H \cong \mathbb{P}^4$ and $X_V$. The picture immediately yields the rationality of $X_V$ via the map

$$X_V \dashrightarrow H \subset \mathbb{P}(W), \ \omega \mapsto \text{Ker}(\omega) \cap W'. \quad (1.10)$$

The result goes back to [21] and an independent and more direct argument can be found in [27]. The situation is described more precisely as follows.

**Corollary 1.20.** Any Pfaffian cubic fourfold $X_V$ is rational.

(i) The indeterminacy loci of the birational map $\mathbb{P}^4 \dashrightarrow X_V$ described above is the blow-up of $S_V$ in five points in $\mathbb{P}^4$.

(ii) The indeterminacy locus of the inverse rational map $X_V \dashrightarrow \mathbb{P}^4$ is the surface $Y_H := X_V \cap \mathbb{G}(1,H)$, where $X_V \subset \mathbb{G}(1,\mathbb{P}(W))$ is as in Remark 1.13.

**Proof** In the above arguments we have often chosen $\mathbb{P}(V)$ generic not only to ensure smoothness of $X_V$ but also to exclude planes in $X_V$. For the rational map (1.10), constructed above to be generically injective, planes in $X_V$ or lines in $S_V$ do not alter the argument.

The birational correspondence between $X_V$ and $\mathbb{P}^4$ is provided by (1.9). Clearly, $B_{V,H} \rightarrow H$ is the blow-up of $H$ in the surface $Z_{V,H} \subset H$, which via $Z_{V,H} \subset Z_V \cong \mathbb{P}(S_V) \rightarrow S_V$ projects onto $S_V$. More precisely, $Z_{V,H} \rightarrow S_V$ is the blow-up of $S_V$ in exactly those points that correspond to lines $\mathbb{P}(P) \subset \mathbb{P}(W)$ contained in $H$, i.e. in the intersection $S_V \cap \mathbb{G}(1,H)$. As $\text{deg}(\mathbb{G}(1,H)) = 5$, this proves (i). Alternatively, the number of points that are blown up can be deduced from $\text{deg}(S_V) - \text{deg}(Z_{V,H}) = 5$.

To verify (ii), simply observe that the fibre of $B_{V,H} \rightarrow X_V$ over $\omega$ is either a reduced point or the line $\mathbb{P}^1 \cong \mathbb{P}(\text{Ker}(\omega))$. The latter occurs exactly when $\mathbb{P}(\text{Ker}(\omega)) \subset H$, i.e. when $\omega \in Y_H$. \qed
Chapter 6. Cubic fourfolds

For more on the surface $Y_H$ see [94, Sec. 1.2].

Remark 1.21. According to [117], which in turn was triggered by [145], rationality is preserved under specialization. Thus, in the above proof one could have chosen $\mathbb{P}(V)$ as generic as needed and would still get rationality for all Pfaffian cubic fourfolds.

Remark 1.22. In [93] one finds an argument showing that any smooth cubic $X \subset \mathbb{P}^5$ that contains a rational normal scroll of degree four is rational.

Exercise 1.23. Show that the above construction yields a rational and generically injective map $\mathbb{P}^3 \approx \mathbb{P}(W) \subset \mathbb{P}^5$. Its closure is a rational Lagrangian subvariety of the ten-dimensional hyperkähler manifold $S^5_V$, cf. Section 2.1.

Corollary 1.24. Using the above notation one finds the following equations

$$[X_V] = [\mathbb{P}^1] + [S_V] \cdot \ell + S \cdot (\ell - 1) - [Y_H] \cdot \ell \quad (1.11)$$

in $K_0(\text{Var}_k)$. \hfill \Box

Note that (1.11) describes the class of $[X_V]$, while (1.7) is only about $[\mathbb{P}^1] \cdot [X_V]$.

Exercise 1.25. Assume we are in the situation described by Corollary 1.20.

(i) Combine (1.7) and (1.11) to relate the two surface classes $[S_V], [Y_H] \in K_0(\text{Var}_k)$.

(ii) Apply the blow-up formula in $\text{Mot}(k)$ to relate $h(X_V)$ and $h(S_V)$ similar to (1.8).

Let us from now on assume that the ground field is $\mathbb{C}$. Then the above constructions can be exploited to relate $H^4(X_V, \mathbb{Z})$ to $H^4(S_V, \mathbb{Z})$. Let us start with (1.9), where $p_H : B := B_{\psi_H} \longrightarrow H$ is the blow-up in the surface $S := Z_{\psi_H}$, which itself is the blow-up of the K3 surface $S_V$ in five points, and $q_H : B \longrightarrow X_V$ is the blow-up in the surface $Y_H \subset X_V$. This yields isomorphisms of Hodge structures

$$H^4(B, \mathbb{Z}) \simeq H^4(X_V, \mathbb{Z}) \oplus H^2(Y_H, \mathbb{Z})(-1) \quad (1.12)$$

$$H^4(B, \mathbb{Z}) \simeq H^4(H, \mathbb{Z}) \oplus H^2(S, \mathbb{Z})(-1) \simeq H^4(H, \mathbb{Z}) \oplus H^2(S_V, \mathbb{Z})(-1) \oplus \mathbb{Z}(-2)^{15}. \quad (1.13)$$

The inclusion $H^4(X_V, \mathbb{Z}) \longrightarrow H^4(B, \mathbb{Z})$ in (1.12), which respects the intersection pairing, followed by the projection $H^4(B, \mathbb{Z}) \longrightarrow H^2(S_V, \mathbb{Z})(-1)$ in (1.13) yields

$$\xi : H^4(X_V, \mathbb{Z}) \longrightarrow H^2(S_V, \mathbb{Z})(-1).$$

This map is the composition of the pull-back $H^4(X_V, \mathbb{Z}) \longrightarrow H^4(B, \mathbb{Z}) \longrightarrow H^4(S_V, \mathbb{Z})$ followed by the push-forward $H^4(S_V, \mathbb{Z}) \longrightarrow H^2(Z_V, \mathbb{Z})(-1)$ and $H^2(Z_V, \mathbb{Z}) \longrightarrow H^2(S, \mathbb{Z})$, induced by the restriction.
which restricts to a Hodge isometry

Proposition 1.26 (Hassett). The map \( \xi \) is a map of Hodge structures of weight four which restricts to a Hodge isometry

\[
(h^2_X, [\Sigma_p])^+ \longrightarrow H^2(S_V, \mathbb{Z})_{\text{pr}}(1) \subset H^2(S_V, \mathbb{Z})(1).
\]

On the right hand side, the primitive cohomology is with respect to the Plücker polarization of degree 14, see Lemma 1.2, and the intersection pairing is altered by a sign.

Proof By construction, \( \xi \) is a morphism of Hodge structure. To prove the second assertion, we may pick \( V \) generic and even general, because all the correspondences constructed before come in families. The parameter count in Remark ?? shows that for general \( V \) the K3 surface \( S_V \) has Picard rank one or, in other words, \( H^2(S_V, \mathbb{Z})_{\text{pr}} \) is an irreducible Hodge structure. It is the smallest saturated sub-Hodge structure of \( H^2(B, \mathbb{Z}) \) in (1.13) that does not consists of Hodge classes only, i.e. such that it contains \( H^{3,1}(B) = H^{2,0}(S_V) \). Similarly, in (1.12) we have \( H^{3,1}(B) = H^{3,1}(X_V) \subset (h^2_X, [\Sigma_p])^+ \) and comparing ranks one deduces that \( (h^2_X, [\Sigma_p])^+ \subset H^4(B, \mathbb{Z}) \) is the smallest saturated sub-Hodge structure containing \( H^{3,1}(B) \). Hence, \( \xi \) indeed induces \( (h^2_X, [\Sigma_p])^+ \cong H^2(S_V, \mathbb{Z})_{\text{pr}}(1) \) an isomorphism of Hodge structures.

To see that it is also an isometry (with the sign changed on the right hand side), recall that \( H^2(S_V, \mathbb{Z})(-1) \hookrightarrow H^2(B, \mathbb{Z}) \) is induced by \( \alpha \mapsto i_\star \alpha \), where we denote by \( \pi : D \coloneqq \Sigma_{CH} \longrightarrow \mathcal{S} = Z_{CH} \) the projection from the exceptional divisor and \( i : D \hookrightarrow B \) is the inclusion, cf. the discussion in Section 13.4. Then one computes for \( \alpha, \beta \in H^2(S_V, \mathbb{Z}) \) that

\[
i_\star \pi^\star x \cdot \pi^\star y \beta = \int_D x_\alpha \cdot \pi^\star \beta = \int_D [D]_D \cdot \pi^\star \alpha \beta = \int_{\mathcal{S}} \pi_\star ([D]_D \cdot \alpha \beta) = -(\alpha \beta)_\mathcal{S}, \quad \text{for } \pi_\star([D]_D) = [-\mathcal{S}].
\]

Remark 1.27. We have seen that for each Pfaffian cubic fourfold \( X_V \) there is naturally associated a K3 surface \( S_V \). The geometry of \( X_V \) and \( S_V \) are related in various ways:

(i) The blow-up of \( S_V \) in five points is the locus of indeterminacies for a birational correspondence \( \mathbb{P}^2 - \longrightarrow X_V \), see Corollary 1.20.
Chapter 6. Cubic fourfolds

(ii) The K3 surface $S_V$ is the base of a family of quartic rational normal scrolls $\Sigma_P \subset X_V$, see Lemma 1.16.

(iii) There exists a birational correspondence $F(X_V) \sim S_V^{[2]}$, see Corollary 1.7 and Remark 1.9.

Remark 1.28. In the course of the preceding discussion the linear subspace $\mathbb{P}(V) \subset \mathbb{P}(\wedge^2 W^*)$ had to be chosen generically. More precisely, this was necessary to ensure the following properties:

(i) $X_V$ is a smooth cubic of dimension four not containing any plane, see Lemma 1.2.
(ii) $S_V$ is a smooth surface not containing any line, see Lemma 1.2.
(iii) $P \cap \text{Ker}(\omega) \neq P$ for all $(P, \omega) \in \Sigma_P$, see Lemma 1.10 (ii).
(iv) $Z_V$ is a smooth threefold or, more technically, $\mathbb{V} \mathcal{O} \subset \wedge^2 W^* \mathcal{O} \longrightarrow \Omega_{P(W)} \mathcal{O}(2)$ is generically surjective, see Lemma 1.11.

Each of these conditions describes a dense open subset inside $\mathcal{O}(5, \mathbb{P}(\wedge^2 W^*))$ and, therefore, hold all together for $V$ in a dense open subset. Note that for example the open subset for which $X_V$ is smooth is strictly larger that the set for which in addition there are no planes contained in $X_V$.

1.3 The Fano variety as a hyperkähler fourfold

In this section we will briefly recall the main notions concerning hyperkähler manifolds and prove that the Fano variety of lines contained in a smooth cubic fourfold is a hyperkähler fourfold deformation equivalent to the Hilbert square of a K3 surface. Furthermore, following Charles [39], we will show how to use Verbitsky’s global Torelli theorem for hyperkähler manifolds to deduce Voisin’s global Torelli theorem for cubic fourfolds. The section also contains a discussion of various special subvarieties of the Fano variety from the hyperkähler point of view.

2.1 The Fano variety $F(X)$ of lines contained in a smooth cubic fourfold $X \subset \mathbb{P}^5$ is, as $X$ itself, smooth, projective, and of dimension four. However, unlike $X$, it has a trivial canonical bundle $\omega_{F(X)} = O_{F(X)}$. As such, $F(X)$ belongs to a distinguished class of varieties. There are three classes of smooth, projective varieties with trivial canonical bundle, which form the building blocks for all of them: abelian varieties, hyperkähler (or irreducible holomorphic symplectic) manifolds, and Calabi–Yau manifolds. For the precise meaning of this statement we refer to [16]. As it turns out, the Fano variety $F(X)$ belongs to the class of hyperkähler manifolds and we will focus on those exclusively.
Definition 2.1. A smooth, complex projective variety $Z$ is called hyperkähler (or irreducible holomorphic symplectic) if $Z$ is simply connected and $H^0(Z, \Omega^2_Z)$ is spanned by an everywhere non-degenerate form.

Note that a hyperkähler manifold is always of even dimension $\text{dim}(Z) = 2m$.

Remark 2.2. (i) If $0 \neq \sigma \in H^0(Z, \Omega^2_Z)$ for a hyperkähler manifold $Z$, then the naturally induced map $T_Z \rightarrow \Omega_Z$ is an alternating isomorphism and its Pfaffian $\text{Pf}(\omega)$ yields a trivialization of $\omega_Z$ and so $\omega_Z \simeq \mathcal{O}_Z$.

(ii) For a hyperkähler manifold the space $H^0(Z, \Omega^k_Z)$ is one-dimensional for $k$ even, i.e. $H^0(Z, \Omega^k_Z) \simeq \mathbb{P}^n$, $\mathbb{C}$. Conversely, if a smooth, projective variety $Z$ has this property and the generator of $H^0(Z, \Omega^2_Z)$ is symplectic, then $Z$ is also simply connected and hence hyperkähler, see [106, Prop. A.1].

Example 2.3. By definition, two-dimensional hyperkähler manifolds are nothing but K3 surfaces. In higher dimensions, examples are provided by Hilbert schemes of K3 surfaces. More precisely, if $S$ is a projective K3 surface, then the Hilbert scheme $S^{[n]}$ of all subschemes of $S$ of length $n$ is a hyperkähler manifold of dimension $2n$, cf. the original [16] or [105, Thm. 6.2.4].

Definition 2.4.

Example 2.5. The Beauville–Bogomolov form on the Hilbert scheme $S^{[2]}$ of a K3 surface $S$ yields the lattice, cf. [16]:

$$(H^2(S^{[2]}, \mathbb{Z}), q) \simeq H^2(S, \mathbb{Z}) \oplus \mathbb{Z} \cdot \delta.$$  

Here, $H^2(S, \mathbb{Z})$ is endowed with the intersection form of the K3 surface $S$, the class $\delta$ is orthogonal to it, and $(\delta)^2 = -2$. Geometrically, $2\delta$ is the class of the exceptional divisor of the Hilbert–Chow morphism $S^{[2]} \rightarrow S^{(2)}$.

The Hodge structure of weight two provided by $H^2(Z, \mathbb{Z})$ together with the Beauville–Bogomolov form determines much of the the geometry of the hyperkähler manifold $Z$. The classical global Torelli theorem for K3 surfaces, due to Pjatecki-Šapiro and Šafarevič in the algebraic context and to Burns and Rapoport in the non-algebraic, is the most striking example, see [103] for the statement and references. A weaker version, due to Verbitsky, holds in higher dimensions as well [172], see also [102].

Theorem 2.6 (Verbitsky). Assume $\eta: (H^2(Z, \mathbb{Z}), q_Z) \rightarrow (H^2(Z', \mathbb{Z}), q_{Z'})$ is a Hodge isometry between two hyperkähler manifolds $Z$ and $Z'$ that can be realized by parallel transport along a proper, smooth, connected family $Z \rightarrow C$ with fibres $Z = Z_i$ and

1 The first step in the proof of [106 Prop. A.1], which excludes the abelian factor in any finite étale cover $\pi: \tilde{Z} \rightarrow Z$, is incorrect. Instead, use that, on the one hand, $\chi(O_{\tilde{Z}}) = \deg(\pi) \cdot \chi(O_Z) = \deg(\pi) \cdot (1 + \text{dim}(Z)/2) \neq 0$ and, on the other hand, $\chi(O_Z) = 0$ if $Z = Y \times \mathbb{C}^*/\Gamma$. 

For the last isomorphism use that the normal bundle is established by the following result, which was originally proved by using the isomorphism $S^{[2]} \cong F(X)$ for generic Pfaffian cubic fourfolds, see Corollary 1.7.

**Theorem 2.7** (Beauville–Donagi). The Fano variety $F(X)$ of lines contained in a smooth cubic fourfold $X \subset \mathbb{P}^5$ is a hyperkähler manifold of dimension four.

**Proof** We know that $H^{2,0}(F(X))$ is one-dimensional, see Section 3.3. Pick any $0 \neq \sigma \in H^{2,0}(F(X))$. We claim that $\sigma \wedge \sigma \in H^{2,0}(F(X)) = H^0(F(X), \Omega^2_X)$ is non-zero. Indeed, this follows immediately from Corollary 3.4.10 see also the analogous statement for threefolds stated as Corollary 5.2.3 Then, as $\Omega^3_X \cong \omega_X \cong \mathcal{O}_X$, the form $\sigma \wedge \sigma$ defines a trivializing section of $\omega$. Therefore, $\sigma : T_X \longrightarrow \Omega_X$ is an isomorphism, i.e. $\sigma$ is a holomorphic symplectic form.

In order to conclude that $F(X)$ is a hyperkähler manifold, it suffices to show that it is simply connected. As we know the Hodge numbers of $F(X)$, see Section 3.3, this follows from Remark 2.2 (ii). 

**Remark 2.8.** In [51] Sec. 5 one finds the following modular description of a non-degenerate two form $\sigma \in H^0(F(X), \Omega^2_{F(X)}) \cong H^{2,0}(F(X))$. For a line $L \subset X$ the normal bundle of the nested inclusions $L \subset X \subset \mathbb{P} = \mathbb{P}^5$ sit in the natural short exact sequence

$$0 \longrightarrow N_{L/X} \longrightarrow N_{L/P} \longrightarrow N_{X/P|L} \longrightarrow 0$$

with $N_{X/P} \cong \mathcal{O}(3)$. Taking exterior products and twisting with $\mathcal{O}_L(-3)$ produces the short exact sequence

$$0 \longrightarrow \wedge^3 N_{L/X} \otimes \mathcal{O}(-3) \longrightarrow \wedge^3 N_{L/P} \otimes \mathcal{O}(-3) \longrightarrow \wedge^2 N_{L/X} \longrightarrow 0,$$

the boundary map of which is used to construct the map

$$\wedge^2 H^0(L, \wedge^2 N_{L/X}) \longrightarrow H^0(L, \wedge^2 N_{L/X}) \longrightarrow H^1(L, \wedge^3 N_{L/X} \otimes \mathcal{O}(-3)) \cong k. \quad (2.2)$$

For the last isomorphism use that the normal bundle is $N_{L/X} \cong \mathcal{O}_L(1) \oplus \mathcal{O}_L \oplus \mathcal{O}_L$ or $N_{L/X} \cong \mathcal{O}_L(1) \oplus \mathcal{O}_L(1) \oplus \mathcal{O}_L(-1)$, see Lemma 3.1.10 and, therefore, in both cases, $\wedge^3 N_{L/X} \otimes \mathcal{O}(-3) \cong \mathcal{O}_L(-2)$. Note that the boundary map $\delta$ is always surjective and that for $L$ of the first type the natural map $\wedge^2 H^0(N_{L/X}) \longrightarrow H^0(\wedge^2 N_{L/X})$ is, too. Composing (2.2) with the canonical isomorphism $T_{\{L\}} F(X) \cong H^0(L, N_{L/X})$, see Proposition 3.1.8 yields a two-form at the point $[L] \in F(X)$:

$$\sigma_{\{L\}} : \wedge^2 T_{\{L\}} F(X) \longrightarrow k.$$
Note that for lines of the first type \( \sigma_{(L)} \) is by construction non-zero.

The construction globalizes as follows: First, replace (2.1) by

\[
0 \longrightarrow N_{L/F(X)\mathbb{X}} \longrightarrow N_{L/F(X)\mathbb{P}} \longrightarrow q^*\mathcal{O}_X(3) \longrightarrow 0.
\]

Then use the global description of the tangent bundle \( T_F \approx p_* N_{L/F(X)\mathbb{X}} \) and, applying Exercise 3.2.9, deduce \( \wedge^3 N_{L/F(X)\mathbb{X}} \otimes q^*\mathcal{O}_X(-3) \approx \wedge^3 \mathcal{O}_F \otimes \mathcal{O}_X(-1) \otimes q^*\mathcal{O}_X(-3) \approx \mathcal{O}_X(1) \otimes \mathcal{O}_F(-2) \times p^*\mathcal{O}_{F(X)}(1) \). Finally, applying relative Serre duality to \( p : L \longrightarrow F = F(X) \), one obtains a two-form \( \sigma \in H^0(F(X), \Omega^2_{F(X)}) \):

\[
\wedge^2 T_F \approx \wedge^2 p_* N_{L/F(X)\mathbb{X}} \longrightarrow p_* \wedge^2 N_{L/F(X)\mathbb{X}} \longrightarrow R^1 p_* \mathcal{O}_F(-2) \otimes \mathcal{O}_F(1) \approx \mathcal{O}_F.
\]

At each point \([L] \in F(X)\) the construction gives back \( \sigma_{(L)} \) and, because \( \sigma_{(L)} \neq 0 \) for every line \( L \) of the first type and those do exist by Lemma 3.1.23, \( \sigma \) is really not trivial. As \( F(X) \) is holomorphic symplectic and \( H^0(F(X), \Omega^2_{F(X)}) \) is one-dimensional, \( \sigma \) defines a holomorphic symplectic structure on \( F(X) \).

Beware that the above construction does not yield a canonical symplectic form \( \sigma \in H^0(F(X), \Omega^2_{F(X)}) \) on \( F(X) \). Indeed, implicitly in the above construction we have used an isomorphism \( \det(T_X) \otimes N_{X/F}^\vee \approx \mathcal{O}_X \), which does depend on the choice of an equation \( F \in H^0(\mathbb{F}_4, \mathbb{O}(3)) \) defining \( X \). Recall that from the Fano correspondence one obtains a canonical isomorphism \( H^{3,1}(X) \approx H^{2,0}(F(X)) \), but that the isomorphism \( H^{3,1}(X) \approx R_{0,3} \approx \mathbb{C} \) in Theorem 1.4.20 depends on the choice of a defining equation for \( X \).

Later we will describe a more categorical approach to the construction of the symplectic form on \( F(X) \), see Section 3.4.4.

2.3 The following result is due to Beauville–Donagi [21]. It can be proved via the isomorphism in Corollary 1.7 for generic Pfaffian cubic fourfolds or, closer to our discussions in Section 3.4.4 and 5.2, directly for arbitrary smooth cubic fourfolds.

**Proposition 2.9.** The Fano correspondence, cf. Section 3.4, induces an isomorphism of integral Hodge structures

\[
\varphi : H^4(X, \mathbb{Z}) \xrightarrow{\sim} H^2(F(X), \mathbb{Z})(-1),
\]

which induces a Hodge isometry(!)

\[
\varphi : H^4(X, \mathbb{Z})_{pt} \xrightarrow{\sim} H^2(F(X), \mathbb{Z})_{pt}(-1)
\]

between their primitive parts. Here, \( H^2(F(X), \mathbb{Z})_{pt} \) is endowed with the quadratic form \( \langle \varphi, \varphi' \rangle_F := (-1/6) \int_F \varphi \cdot \varphi' \cdot q^2 \).

**Proof.** We know already that \( \varphi \) induces an injective homomorphism of integral Hodge structures \( H^4(X, \mathbb{Z}) \xrightarrow{\sim} H^2(F(X), \mathbb{Z})(-1) \) of finite index, see (0.1). Moreover, \( h^2 \in \)
$H^4(X,\mathbb{Z})$ is mapped to the Plücker polarization $g \in H^2(F(X),\mathbb{Z})$ and $\varphi(H^4(X,\mathbb{Z})_{pr} \subset H^2(F(X),\mathbb{Z})_{pr}(-1)$, see Remark 3.4.4.

As $(\alpha,\beta) = (\varphi(\alpha),\varphi(\beta))_F$ by Proposition 4.3, it suffices to show the following assertions:

(i) $(\cdot)_F$ is integral on $H^2(F,\mathbb{Z})_{pr}$ and

(ii) $H^2(F,\mathbb{Z})_{pr} \oplus \mathbb{Z} \cdot g \subset H^2(F(X),\mathbb{Z})$ is of index at most three.

Indeed, then the embedding of lattices $\varphi: H^4(X,\mathbb{Z})_{pr} \hookrightarrow (H^2(F(X),\mathbb{Z})_{pr},(\cdot)_F)$ would have to be an isomorphism, because $\text{disc}(H^4(X,\mathbb{Z})_{pr}) = 3$. Compare this to the discussion in Section 4.3. Furthermore, from the commutative diagram

$$
\begin{array}{ccc}
H^4(X,\mathbb{Z})_{pr} \oplus \mathbb{Z} \cdot h^2 & \xrightarrow{\sim} & H^2(F(X),\mathbb{Z})_{pr} \oplus \mathbb{Z} \cdot g \\
\downarrow & & \downarrow \\
H^4(X,\mathbb{Z}) \xrightarrow{\sim} & H^2(F(X),\mathbb{Z}),
\end{array}
$$

in which the upper horizontal map is an isomorphism of Hodge structures (which is, however, an isometry only on the first summand) and the two vertical maps are both inclusions of index three, one deduces that also the lower horizontal map is an isomorphism of Hodge structures (but not an isometry).

To verify (i) and (ii) TBC.... □

2.4 The global Torelli theorem is a cornerstone result in the theory of smooth cubic fourfolds. It was originally proved by Voisin in [173, 175]. The proof we present here follows the approach by Charles [39], which makes use of the global Torelli theorem for hyperkähler manifolds, Theorem 2.6, and the geometric global Torelli theorem for cubic hypersurfaces, Proposition 3.2.10.

**Theorem 2.10** (Voisin). Assume $\zeta: H^4(X,\mathbb{Z}) \xrightarrow{\sim} H^4(X',\mathbb{Z})$ is a Hodge isometry between two smooth cubic fourfolds with $\zeta(h^2_X) = h^2_{X'}$. Then there exists a unique isomorphism $f: X \xrightarrow{\sim} X'$ with $f_* = \zeta$.

**Proof** First, use $\zeta$ and the Fano correspondences $\varphi: H^4(X,\mathbb{Z})_{pr} \xrightarrow{\sim} H^2(F(X),\mathbb{Z})_{pr}(-1)$ and $\varphi': H^4(X',\mathbb{Z})_{pr} \xrightarrow{\sim} H^2(F(X'),\mathbb{Z})_{pr}(-1)$ to define the Hodge isometry

$$
\eta := \varphi' \circ \zeta \circ \varphi^{-1}: H^2(F(X),\mathbb{Z})_{pr} \xrightarrow{\sim} H^2(F(X'),\mathbb{Z})_{pr}
$$

between the hyperkähler manifolds $F(X)$ and $F(X')$.

From Section 12.1.4 we know that any isometry $H^4(X,\mathbb{Z}) \cong H^4(X',\mathbb{Z})$ with $h^2_X \xrightarrow{\sim} h^2_{X'}$ can be realized by parallel transport. In other words, there exists a smooth and proper family $X \xrightarrow{\sim} C$ over a connected base with fibres $X = X_1$ and $X' = X_2$ such that parallel transport from $X_1$ to $X_2$ yields $\zeta$. Parallel transport along the induced relative family of Fano varieties $F(X'/C) \xrightarrow{\sim} C$ with special fibres $F(X) = F(X/C)_1$ and
\(F(X') = F(X'/\mathbb{C})\) yields a map \(\tilde{\eta} : H^2(F(X), \mathbb{Z}) \sim H^2(F(X'), \mathbb{Z})\). As the Fano correspondence is purely topological and exists in families, the restriction of \(\tilde{\eta}\) to the primitive cohomology yields \(\eta\).

The Plücker polarizations \(g\) and \(g'\) on \(F(X)\) and \(F(X')\) satisfy \(\varphi(h^2_1) = g\) and \(\varphi'(h^2_2) = g'\), see Lemma [11]. Parallel transport along \(X \rightarrow C\) preserves the hyperplane section and, therefore, the Hodge isometry \(\tilde{\eta}\) maps \(g\) to \(g'\). Hence, by Theorem [2.6], \(\eta\) is induced by an isomorphism \(f : F(X) \sim F(X')\) with \(f_\ast = \eta\).

To conclude the existence of an isomorphism \(X \equiv X'\) inducing the given \(\zeta\), apply the geometric global Torelli theorem, Proposition [3.2.10] see also the comments after its proof.

Eventually, to prove that \(f\) is unique \(\square\).

### 2.5 Surfaces in \(F(X)\):

(i) For \(Y = X \cap \mathbb{P}^4\) smooth hyperplane section \(F(Y) \subset F(X)\) is a Lagrangian surface (of general type). Compute cohomology class of \(F(Y)\) (in what terms). Note \([F(Y)]^2 = 27\). For this pick two generic \(Y_1, Y_2\). Then \(F(Y_1) \cap F(Y_2) = F(Y_1 \cap Y_2)\) which is the Fano variety of the cubic surface \(Y_1 \cap Y_2\) and, therefore, consists of 27 points.

(ii) Lines of first type \(\mathcal{N} = \mathcal{O}(1) \oplus \mathcal{O} \oplus \mathcal{O}\) and of the second type \(\mathcal{N}' = \mathcal{O}(1) \oplus \mathcal{O}(1) \oplus \mathcal{O}(-1)\). By Lemma 1.12 \(\dim(F_2(X)) \leq 2\). This is a non Lagrangian surface.

### 2.6 Endo of \(F(X)\) of degree 14, see Amerik, Voisin.

### 2.7 The surface \(F_2(X) \subset F(X)\), \([F_2(X)] = 5g^2 - 5c_2(\mathcal{S})\).

What is known about \(F_2(X)\)? Hodge numbers, connected? Constant cycle?

Four natural classes in \(H^4(F(X))\): \(c_2(\mathcal{S}), c_2(F(X)), g^2, [F(Y)] = c_2(\mathcal{S})\) and \([F_2(X)]\).

Have seen already that \(c_2(F) = 5g^2 - 8c_2(\mathcal{S})\). So only get rank at most two subspace. Is this all generically?

### 2.8 Cut with hyperplane section \(F(Y) \subset F(X)\). Then short exact sequence

\[
0 \rightarrow \mathcal{S}_{|F(Y)} \rightarrow T_{F(X)|F(Y)} \rightarrow \mathcal{S}_{|F(Y)} \rightarrow 0.
\]

Also \(27 = \int_{F(X)} c_2(\mathcal{S})^2\) as \(F(\mathcal{S}) = V(s_1, s_2)\) for generic \(s_i \in H^0(F(X), \mathcal{S}^*)\).
References


Chapter 6. References


References


Chapter 6. References

[69] David Eisenbud and Joe Harris. 3264 and all that—a second course in algebraic geometry. Cambridge University Press, Cambridge, 2016. (Cited on pages 74, 84, 85, 86, 87, 105 and 107)


References


Chapter 6. References


References

Chapter 6. References


[166] Sho Tanimoto and Anthony Várilly-Alvarado.