Further Pathologies in Algebraic Geometry

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FURTHER PATHOLOGIES IN ALGEBRAIC GEOMETRY.* ¹

By DAVID MUMFORD.

The following note is not strictly a continuation of our previous note [1]. However, we wish to present two more examples of algebro-geometric phenomena which seem to us rather startling. The first relates to characteristic $p$ behaviour, and the second relates to the hypothesis of the completeness of the characteristic linear system of a maximal algebraic family. We will use the same notations as in [1].

I.

The first example is an illustration of a general principle that might be said to be indicated by many of the pathologies of characteristic $p$:

A non-singular characteristic $p$ variety is analogous to a general non-Kähler complex manifold; in particular, a projective embedding of such a variety is not as "strong" as a Kähler metric on a complex manifold; and the Hodge-Lefschetz-Dolbeault theorems on sheaf cohomology break down in every possible way.

In this case we wish to look at the two dimensional cohomology of an algebraic surface $F$, non-singular, and of any characteristic but 0. The surface we shall choose will (a) be specialization of a characteristic 0 surface $F'$, and (b) will satisfy $q = \text{h}^{0,1} = \text{h}^{1,0}$. Consequently the second Betti number $B_2$ is the same, whether defined (i) as that of $F'$ in the topological sense, (ii) as $\text{h}^{2,0} + \text{h}^{1,1} + \text{h}^{0,2}$, or (iii) following Igusa [2], as $\text{Deg}(\text{c}_2) + 4q - 2$. Let $\rho$ be the base number of $F$. Igusa showed that, in fact, $B_2 \geq \rho$. However, in characteristic 0, one has the stronger result, $B_2 = \text{h}^{2,0} + \text{h}^{1,1} + \text{h}^{0,2} \geq 2\rho + \rho$ (where $\rho = \text{h}^{2,0} + \text{h}^{0,2}$ is the geometric genus of $F$) as a result of the Hodge-Dolbeault theorems. Therefore the question arises whether this stronger inequality is valid in characteristic $p$. The answer is no.

A rather complicated example was discovered in 1961 by J. Tate and A. Ogus. Here is a very simple example: let $E$ be a super-singular elliptic

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¹ This work was supported by the Army Research Office (Durham).
curve of characteristic \( p \) (i.e. such that the rank of \( \text{End}(E) \) is 4). Let \( F = E \times E \). In this case, in fact:

\[
\rho = B_2 = 6; \quad p_q = 1.
\]

Here \( p_q = 1 \) since the sheaf \( \Omega_f^2 \cong \mathcal{O}_f \); and \( B_2 = 6 \) by Igusa’s definition, for example, since \( \text{Deg}(c_2) = 0 \), and \( q = 2 \). Finally \( \rho = 6 \) since in general, for any two elliptic curves \( E_1 \) and \( E_2 \), one knows that the base number \( \rho \) for \( E_1 \times E_2 \) equals 2 plus the rank of \( \text{Hom}(E_1, E_2) \).

There remains one outstanding conjecture still neither proven nor disproven in characteristic \( p \), which according to the general principle mentioned above ought to be false. This is the Regularity of the Adjoint, which may be stated as follows: if \( V \) is a non-singular projective surface and if \( H \) is a non-singular hyperplane section, then

\[
H^1(\mathcal{O}_V) \rightarrow H^1(\mathcal{O}_H)
\]

is injective.

II.

The second example concerns space curves in characteristic 0. Let \( A \) be any family of non-singular space curves, and let \( a \in A \) represent the curve \( \gamma \subset P_3 \). Let \( T_a \) denote the Zariski tangent space to \( A \) at \( a \), and let \( N \) denote the sheaf of sections of the normal bundle to \( \gamma \) in \( P_3 \). Then it is well-known [3] that there is a “characteristic” map:

\[
T_a \rightarrow H^0(N).
\]

The problem of completeness consists in asking when, for given \( \gamma \), there is a family \( A \) containing \( \gamma \) such that the characteristic map is surjective. Kodaira [3] has shown that such a family exists if \( H^1(N) = (0) \). Our example shows that if \( H^1(N) \neq (0) \), then there need not be such a family.

In fact, in our example, this incompleteness holds for every curve in an open set of the corresponding Chow variety. Consequently, it is also an example where the Hilbert scheme [4] has a multiple component, i.e. is not reduced at one of its generic points. Another corollary of this example is obtained by blowing up such a space curve \( \gamma \subset P_3 \) to a surface \( E \) in a new three-dimensional variety \( V_3 \). Then Kodaira [5] has shown essentially that the local moduli scheme of the variety \( V_3 \) is isomorphic to the germ of the
Hilbert scheme of $P_3$ at the point corresponding to $\gamma$. Therefore we have constructed a non-singular projective three-dimensional variety whose local moduli scheme is nowhere reduced; in other words, any small deformation of $V_3$ is a variety the number of whose moduli is less than the dimension of $H^1(\Theta)$ (where $\Theta$ is the sheaf of vector fields).

The curves $\gamma$ that we have in mind have degree 14 and genus 24. In the following, $h$ will stand for the divisor class on $\gamma$ induced by plane sections, and $K_\gamma$ will stand for the canonical divisor on $\gamma$; also $F$ will stand for a cubic or quartic surface in $P_3$, and $H$ will stand for the (Cartier) divisor class on $F$ induced by plane sections. The first step is partial classification of all space curves of this degree and genus, which confirms the results of M. Noether's well-known table [6].

(A) Any non-singular space curve $\gamma$ of degree 14 and genus 24 is contained in a pencil $P$ of quartic surfaces.

Proof. Since $\text{Deg}(4h) = 56$, and $\text{Deg}(K_\gamma) = 46$, the linear system $|4h|_\gamma$ is non-special, and has dimension $56 - 24 = 32$. Since there is a 34-dimensional family of quartics in $P_3$, (A) follows.

There are 2 cases: (a) the pencil has no fixed components, and (b) the pencil has fixed components. In case (a), note first that if $F'$ and $F''$ span $P$, then $F' \cdot F'' = \gamma + c$, where $c$ is a conic. Now $c$ has at most double points, hence $\gamma + c$ has at most triple points. Therefore no point $x$ is a double point for both $F'$ and $F''$. Noting that both $F'$ and $F''$ are non-singular and transversal along $\gamma - c$, hence at all but a finite number of points of $\gamma$, it follows that almost every $F \in P$ is non-singular everywhere along $\gamma$.

(B) Every algebraic family of space curves of type (a) has dimension less than or equal 56.

Proof. It is enough to show that every family of pairs $(\gamma, F)$ consisting of such curves $\gamma$, and quartics $F \supseteq \gamma$, $F$ being non-singular along $\gamma$, has dimension at most 57. Now since all such quartics contains conics, they are not generic [7], and there is at most a $34 - 1 - 33$ dimensional family of quartics $F$ involved in such a family of pairs. Moreover, the dimension of the set of all $\gamma$ on one such $F$ can be computed from the Riemann-Roch theorem on $F$:

---

$^2$ Here and below, $|D|_V$ always means the linear system on $V$ in which the Cartier divisor $D$ varies. Also, $(D^2)_V$ always denotes the self-intersection of $D$, as a divisor class on $D$ (assuming $D$ effective).
\[ \dim | \gamma |_F = \frac{\text{Deg}(\gamma^2)_F}{2} + 1 + \{ \dim H^1(\mathcal{O}_F(\gamma)) - \dim H^2(\mathcal{O}_F(\gamma)) \}. \]

But \((\gamma^2)_F = K_F\) on \(\gamma\), hence \(\text{Deg}(\gamma^2)_F = 46\). Moreover, \(H^i(\mathcal{O}_F(\gamma))\) is dual to \(H^{2-i}(\mathcal{O}_F(-\gamma))\) by Serre duality. This cohomology group can be computed from the exact sequence:

\[ 0 \to \mathcal{O}_F(-\gamma) \to \mathcal{O}_F \to \mathcal{O}_\gamma \to 0. \]

It follows that both are zero, hence \(\dim | \gamma |_F = 24\). Therefore, indeed, the set of pairs \((\gamma, F)\) has dimension at most \(33 + 24 = 57\). ^3

Now consider case (b). Such a \(\gamma\) must be contained in a reducible quartic, hence in a plane, a quadric, or a cubic surface. The first two possibilities are readily checked and it happens that they contain no curves of the required degree and genus. Moreover, such a curve is contained in a unique cubic surface \(F\), because \(\text{Deg}(\gamma) = 14 > 9 = \text{Deg}(F' \cdot F'')\), for two distinct cubic surfaces \(F'\) and \(F''\). We will say that \(\gamma\) is of type \((b_0)\) if the cubic \(F\) is nonsingular; otherwise, we will say that \(\gamma\) is of type \((b_1)\).

(C) Every maximal algebraic family of curves \(\gamma\) of type \((b_0)\) has dimension 56.

**Proof.** Let \(\gamma\) be a curve of type \((b_0)\), and let \(F\) be the corresponding cubic surface. Since \(K_F = -H\), by the Riemann-Roch theorem on \(F\):

\[ \dim | \gamma |_F = \frac{\text{Deg}(\gamma \cdot \gamma + H)_F}{2} + \{ \dim H^1(\mathcal{O}_F(\gamma)) - \dim H^2(\mathcal{O}_F(\gamma)) \}. \]

But \(K_F = \gamma \cdot (\gamma + K_F)\), hence \(46 = \text{Deg}(\gamma^2)_F - \text{Deg}(\gamma \cdot H)_F = \text{Deg}(\gamma^2)_F - 14\), hence \(\text{Deg}(\gamma^2)_F = 60\). Also, \(H^i(\mathcal{O}_F(\gamma))\) is dual to \(H^{2-i}(\mathcal{O}_F(-H - \gamma))\), and this group can be computed from the exact sequence:

\[ 0 \to \mathcal{O}_F(-H - \gamma) \to \mathcal{O}_F \to \mathcal{O}_H(\gamma) \to 0. \]

Since \(H + \gamma\) is a reduced and connected curve, \(H^0(\mathcal{O}_H(\gamma)) = k\) (constants), and this implies \(H^i(\mathcal{O}_F(-H - \gamma)) = (0)\) for \(i = 1\) and 2. Putting all this together, we see that \(\dim | \gamma |_F = 37\). Since there is a 19-dimensional family

---

^3 It may be objected that we have used the Riemann-Roch theorem, and Serre duality as though \(F\) were non-singular. But since \(F\) is non-singular along \(\gamma\), the former can be proved by means of the exact sequence:

\[ 0 \to \mathcal{O}_F \to \mathcal{O}_F(\gamma) \to \mathcal{O}_H((\gamma^2)_F) \to 0. \]

And the latter can be proven either (a) directly by resolving the singularities of \(F\) and comparing the cohomology on \(F\) and on its resolution, or (b) as a consequence of Grothendieck's general theory [8]. In the second case, one merely has to note that \(F\) is always a Cohen-Macaulay variety; and since it is a quartic surface the canonical sheaf is simply \(\mathcal{O}_F\) itself.
of cubic surfaces, (C) follows if we show that a generic $\gamma$ in a maximal algebraic family is contained in a generic cubic surface. But let $\gamma \subset F$ be any curve of the family. Then recalling that the divisor class group of any non-singular cubic surface is the same as that of any other, it follows that if the set of all non-singular cubic surfaces are suitably parametrized the invertible sheaf $\mathcal{O}_F(\gamma)$ will be a specialization of an invertible sheaf $L$ defined on the generic cubic surface $F^*$. And since $H^i(\mathcal{O}_F(\gamma)) \equiv (0)$ for $i = 1$ and 2, by the upper semi-continuity of cohomology [9], we conclude that $H^i(L) \equiv (0)$ for $i = 1$ and 2, and that all sections of $\mathcal{O}_F(\gamma)$ are specializations of sections of $L$. Therefore $\dim H^0(L) = 38$; and since almost all sections of $\mathcal{O}_F(\gamma)$ are non-singular, so are almost sections of $L$. Hence there is a non-singular $\gamma^* \subset F^*$ specializing to $\gamma \subset F$. QED.

Now suppose $C$ is the Chow variety of non-singular curves of degree 14, and genus 24. Let $C_b \subset C$ be the locus of curves of type $(b)$, and let $C_{b_1} \subset C_b$ be the locus of curves of type $(b_1)$. Then it is clear that $C_b$ and $C_{b_1}$ are closed (possibly reducible) subvarieties of $C$. By (B) and (C), every component of $C - C_b$ has dimension $\leq 56$, and every component of $C_b - C_{b_1}$ has dimension $= 56$. Therefore if $C_o$ equals $C$ minus $C_{b_1}$ and minus the closure of $C - C_b$, $C_o$ is an open set in the Chow variety, of dimension 56, and parametrizing almost all curves of type $(b_o)$.

We shall now single out a set of components of $C_o$ such that, if $N$ is the normal sheaf to a $\gamma$ in one of these components, then $\dim H^0(N) = 57$. In fact, we say that $\gamma \subset F$ is of type $(b'_o)$ if there is a line $E$ on $F$ such that $\gamma = 4H + 2E$ on $F$. Then the corresponding $C'_o \subset C_o$ which is the locus of such curves is clearly closed in $C_o$. But it is also open: if $\gamma^* \subset F^*$ specializes to $\gamma \subset F$, and if $\gamma = 4H + 2E$ on $F$, then first of all, there is a line $E^* \subset F^*$ (possibly only rationally defined after a suitable base extension) which specializes to $E$; and secondly, since the divisor class group is discrete and constant for all non-singular cubics,

$$\gamma - 4H - 2E \equiv 0$$

implies $\gamma^* - 4H^* - 2E^* \equiv 0$.

Therefore $\gamma^*$ is of type $(b'_o)$.

(D) If $\gamma \subset F$ is of type $(b'_o)$, then $\dim H^0(N) = 57$.

Proof. Let $N_F$ be the sheaf of normal vector fields to $\gamma$ and in $F$, and let $N_P$ be the sheaf of normal vector fields to $F$, and in $P_s$, which are defined along $\gamma$. Then we have the sequence:

$$0 \rightarrow N_F \rightarrow N \rightarrow N_P \rightarrow 0.$$
But if $D$ is a non-singular divisor on a non-singular variety $V$, then its normal sheaf is isomorphic to $\mathcal{O}_D((D^2)_\nu)$. Therefore $N_F \cong \mathcal{O}_\gamma((\gamma^2)_F)$ and $N_F \cong \mathcal{O}_\gamma(3h)$. But since $K_F \equiv (\gamma^2)_F + \gamma \cdot K_F \equiv (\gamma^2)_F + h$, it follows that $(\gamma^2)_F$ is a non-special divisor, of degree 60 in fact. Therefore $H^1(N_F) = 0$ and $\dim H^0(N_F) = 60 - (24 - 1) = 37$. On the other hand, by the Riemann-Roch theorem for curves,

$$
\dim H^0(\mathcal{O}_\gamma(3h)) = 42 - (24 - 1) + \dim H^0(\mathcal{O}_\gamma(K_F - 3h)) \\
= 19 + \dim H^0(\mathcal{O}_\gamma((\gamma^2)_F - 4h)) \\
= 19 + \dim H^0(\mathcal{O}_\gamma(2\gamma \cdot E))
$$

(using the hypothesis $\gamma \equiv 4H + 2E$). But now, use the exact sequence:

$$0 \to \mathcal{O}_F(-4H) \to \mathcal{O}_F(2E) \to \mathcal{O}_\gamma(2\gamma \cdot E) \to 0.$$

It is readily seen that $H^i(\mathcal{O}_F(-4H)) = (0)$ for $i = 0$ and 1, and that $\dim H^0(\mathcal{O}_F(2E)) = 1$. Putting all this information together we conclude:

$$\dim H^0(N) = 3\gamma + 19 + 1 = 57. \quad \text{QED.}$$

It remains only to note:

(E) If $F$ is any non-singular cubic surface, and $E \subset F$ is any line, there exist non-singular curves $\gamma \in |4H + 2E|$, and they have degree 14 and genus 24.

**Proof.** The degree and genus of such a $\gamma$ are computed by the usual formulae, recalling that $\text{Deg}(E^2)_F = -1$. To see that such a $\gamma$ exists, it suffices, by the characteristic 0 Bertini theorem, to prove that $|4H + 2E|$ has no base points. But the only possible base points are the points of $E$, and we use the exact sequence:

$$0 \to \mathcal{O}_F(4H + E) \to \mathcal{O}_F(4H + 2E) \to \mathcal{O}_E(2) \to 0.$$

Since the sections of $\mathcal{O}_E(2)$ have no base points, it suffices to prove $H^1(\mathcal{O}_F(4H + E)) = (0)$. But this follows from the sequence:

$$0 \to \mathcal{O}_F(4H) \to \mathcal{O}_F(4H + E) \to \mathcal{O}_E(3) \to 0,$$

since $H^1(\mathcal{O}_F(4H)) = (0)$, and $H^1(\mathcal{O}_E(3)) = (0)$. QED.

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