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TERNARY CUBIC FORMS AND ÉTALE ALGEBRAS

by Mélanie RACZEK and Jean-Pierre TIGNOL*)

The configuration of inflection points on a nonsingular cubic curve in the complex projective plane has a well-known remarkable feature: a line through any two of the nine inflection points passes through a third inflection point. Therefore the inflection points and the 12 lines through them form a tactical configuration (94, 123), which is the configuration of points and lines of the affine plane over the field with 3 elements ([3, p. 295], [7, p. 242]). This property was used by Hesse to show that the inflection points of a ternary cubic over the rationals are defined over a solvable extension, see [11, §110]. As a result, any ternary cubic can be brought to a normal form $x_1^3 + x_2^3 + x_3^3 - 3\lambda x_1 x_2 x_3$ over a solvable extension of the base field¹). The purpose of this paper is to investigate this extension.

Throughout the paper, we denote by F an arbitrary field of characteristic different from 3, by F_s a separable closure of F and by $\Gamma = \operatorname{Gal}(F_s/F)$ its Galois group. Let V be a 3-dimensional F-vector space and let $f \in S^3(V^*)$ be a cubic form on V. Assume that f has no singular zero in the projective plane $\mathbf{P}_V(F_s)$. Then the set $\mathfrak{I}(f) \subseteq \mathbf{P}_V(F_s)$ of inflection points has 9 elements. There are 12 lines in $\mathbf{P}_V(F_s)$ that contain three points of $\mathfrak{I}(f)$; they are called inflectional lines. Their set $\mathfrak{L}(f)$ is partitioned into four 3-element subsets $\mathfrak{T}_0, \mathfrak{T}_1, \mathfrak{T}_2, \mathfrak{T}_3$ called inflectional triangles, which have the property that each inflection point is incident to exactly one line of each triangle. Let $\mathfrak{T}(f) = \{\mathfrak{T}_0, \mathfrak{T}_1, \mathfrak{T}_2, \mathfrak{T}_3\}$. There is a canonical map $\mathfrak{L}(f) \to \mathfrak{T}(f)$, which carries every inflectional line to the unique triangle that contains it. The Galois

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group Γ acts on $\mathfrak{I}(f)$, hence also on $\mathfrak{L}(f)$ and $\mathfrak{T}(f)$, and the canonical map $\mathfrak{L}(f) \to \mathfrak{T}(f)$ is a triple covering of Γ -sets, in the terminology of $[9, \S 2.2]$. Galois theory associates to the Γ -set $\mathfrak{L}(f)$ a 12-dimensional étale F-algebra L(f), which is a cubic étale extension of the 4-dimensional étale F-algebra T(f) associated to $\mathfrak{T}(f)$. We show in $\S 4$ that if one of the inflectional triangles, say \mathfrak{T}_0 , is defined over F, hence preserved under the Γ -action, then there are decompositions

$$T(f) \simeq F \times N$$
, $L(f) \simeq K \times M$,

where N and K are cubic étale F-algebras whose corresponding Γ -sets are $\mathfrak{X}(N) = \{\mathfrak{T}_1, \mathfrak{T}_2, \mathfrak{T}_3\}$ and $\mathfrak{X}(K) = \mathfrak{T}_0$ respectively, and M is a 9-dimensional étale F-algebra containing N, associated to K and a unit $a \in K^{\times}$. One can then identify the vector space V with K in such a way that

(0.1)
$$f(X) = \mathsf{T}_K(a^{-1}X^3) - 3\lambda \, \mathsf{N}_K(X) \quad \text{for some } \lambda \in F,$$

where T_K and N_K are the trace and the norm of the F-algebra K. Conversely, if f can be reduced to the form (0.1), then one of the inflectional triangles is defined over F, and $\mathfrak{X}(K)$ is isomorphic to the set of lines of the triangle. Note that the (generalized) Hesse normal form

$$a_1 x_1^3 + a_2 x_2^3 + a_3 x_3^3 - 3\lambda x_1 x_2 x_3$$

is the particular case of (0.1) where $K = F \times F \times F$ (i.e., the Γ -action on $\mathfrak{X}(K)$ is trivial) and $a = (a_1^{-1}, a_2^{-1}, a_3^{-1})$. As an application, we show that the form $T_K(X^3)$ can be reduced over F to a generalized Hesse normal form if and only if K has the form $F[\sqrt[3]{d}]$ for some $d \in F^{\times}$, see Example 4.4.

The 9-dimensional étale F-algebra M associated to a cubic étale F-algebra K and a unit $a \in K^{\times}$ was first defined by Markus Rost in relation with Morley's theorem. We are grateful to Markus for allowing us to quote from his private notes [10] in § 2.

For background information on cubic curves, we refer to [3], Chapter 11 of [7], or [2].

1. ÉTALE ALGEBRAS OVER A FIELD

An étale F-algebra is a finite-dimensional commutative F-algebra A such that $A \otimes_F F_s \simeq F_s \times \cdots \times F_s$; see [1, Ch. 5, §6] or [8, §18] for various other characterizations of étale F-algebras. For any étale F-algebra A, we denote by $\mathfrak{X}(A)$ the set of F-algebra homomorphisms $A \to F_s$. This is a finite set with

cardinality $|\mathfrak{X}(A)| = \dim_F A$. Composition with automorphisms of F_s endows $\mathfrak{X}(A)$ with a Γ -set structure, and \mathfrak{X} is a contravariant functor that defines an anti-equivalence of categories between the category Et_F of étale F-algebras and the category Set_Γ of finite Γ -sets, see [1, Ch. 5, §10] or [8, (18.4)].

Let G be a finite group of automorphisms of an étale F-algebra A. The group G acts faithfully on the Γ -set $\mathfrak{X}(A)$.

PROPOSITION 1.1. If G acts freely (i.e., without fixed points) on $\mathfrak{X}(A)$, then

$$H^1(G,A^{\times})=1$$
.

Proof. The G-action on $\mathfrak{X}(A)$ maps each Γ -orbit on a Γ -orbit, since the actions of G and Γ commute. We may thus decompose $\mathfrak{X}(A)$ into a disjoint union

$$\mathfrak{X}(A) = \mathfrak{X}_1 \coprod \ldots \coprod \mathfrak{X}_n$$

where each \mathfrak{X}_i is a union of Γ -orbits permuted by G. Using the antiequivalence between Et_F and $\operatorname{Set}_\Gamma$, we obtain a corresponding decomposition of A into a direct product of étale F-algebras

$$A = A_1 \times \cdots \times A_n$$
.

The G-action preserves each A_i , hence

$$H^1(G,A^{\times}) = H^1(G,A_1^{\times}) \times \cdots \times H^1(G,A_n^{\times}).$$

It therefore suffices to prove that $H^1(G,A^{\times})=1$ when G acts transitively on the Γ -orbits in $\mathfrak{X}(A)$. These Γ -orbits are in one-to-one correspondence with the primitive idempotents of A. Let e be one of these idempotents and let $H\subseteq G$ be the subgroup of automorphisms that leave e fixed. Let also B=eA. The map $g\otimes b\mapsto g(b)$ for $g\in G$ and $b\in B$ induces isomorphisms of G-modules

$$A = \mathbf{Z}[G] \otimes_{\mathbf{Z}[H]} B$$
, $A^{\times} = \mathbf{Z}[G] \otimes_{\mathbf{Z}[H]} B^{\times}$,

hence the Eckmann-Faddeev-Shapiro lemma (see for instance [4, Prop. (6.2), p. 73]) yields an isomorphism

$$H^1(G, A^{\times}) \simeq H^1(H, B^{\times})$$
.

Now, B is a field and each element $h \in H$ restricts to an automorphism of B. Let $\xi \in \mathfrak{X}(A)$ be such that $\xi(e) = 1$, hence $\xi(x) = \xi(ex)$ for all $x \in A$. If $h \in H$ restricts to the identity on B then

$$e h(x) = h(ex) = ex$$
 for all $x \in A$,

and hence

$$\xi(h(x)) = \xi(x)$$
 for all $x \in A$.

It follows that h leaves ξ fixed, hence h = 1 since G acts freely on $\mathfrak{X}(A)$. Therefore H embeds injectively in the group of automorphisms of B. Hilbert's Theorem 90 then yields $H^1(H, B^{\times}) = 1$, see [8, (29.2)].

2. Morley algebras

Let K be an étale F-algebra of dimension 3. To every unit $a \in K^{\times}$ we associate an étale F-algebra M(K,a) of dimension 9 by a construction due to Markus Rost [10], which will be crucial for the description of the Γ -action on inflectional lines of a nonsingular cubic, see Theorem 3.2.

DEFINITION 2.1. Let D be the discriminant algebra of K (see [8, p. 291]); this is a 2-dimensional étale F-algebra such that $K \otimes_F D$ is the S_3 -Galois closure of K, see [8, §18.C]. We thus have F-algebra automorphisms σ , ρ of $K \otimes_F D$ such that

$$\sigma|_D = \operatorname{Id}_D$$
, $\rho|_K = \operatorname{Id}_K$, $\sigma^3 = \rho^2 = \operatorname{Id}_{K \otimes D}$, and $\rho \sigma = \sigma^2 \rho$.

We identify each element $x \in K$ with its image $x \otimes 1$ in $K \otimes_F D$ and denote its norm by $N_K(x)$.

Now, fix an element $a \in K^{\times}$. Let s, t be indeterminates and consider the quotient F-algebra

$$A = K \otimes_F D[s, t] / (s^3 - \sigma^2(a) \sigma(a)^{-1}, t^3 - N_K(a)).$$

Since the characteristic is different from 3, every F-algebra homomorphism $K \otimes_F D \to F_s$ extends in 9 different ways to A, so A is an étale F-algebra. Abusing notation, we also denote by s and t the images in A of the indeterminates. Straightforward computations show that σ and ρ extend to automorphisms of A by letting

$$\sigma(s) = st\sigma^{2}(a)^{-1}, \quad \sigma(t) = t, \quad \rho(s) = s^{-1}, \quad \rho(t) = t,$$

and that the extended σ , ρ satisfy $\sigma^3 = \rho^2 = \operatorname{Id}_A$ and $\rho\sigma = \sigma^2\rho$, so they generate a group G of automorphisms of A isomorphic to the symmetric group S_3 . The subalgebra of A fixed under G is called the *Morley F-algebra* associated with K and G. It is denoted by M(K, a).

Since G acts freely on $\mathfrak{X}(K \otimes_F D)$, it also acts freely on $\mathfrak{X}(A)$, hence

$$\dim_F M(K, a) = 9$$
.

It readily follows from the definition that M(K, a) contains the 3-dimensional étale F-algebra

$$N(K, a) = F[t],$$
 with $t^3 = N_K(a)$.

Clearly, if $a' = \lambda k^3 a$ for some $\lambda \in F^{\times}$ and $k \in K^{\times}$, then there is an isomorphism $M(K, a') \simeq M(K, a)$ induced by $s' \mapsto s\sigma^2(k) \sigma(k)^{-1}$, $t' \mapsto t\lambda \, N_K(k)$.

EXAMPLE 2.2. Let $K = F \times F \times F$ and $a = (a_1, a_2, a_3) \in K^{\times}$. Then $D \simeq F \times F$, so $K \otimes_F D \simeq F^6$. We index the primitive idempotents of $K \otimes D$ by the elements in G, so that the G-action on the primitive idempotents $(e_{\tau})_{\tau \in G}$ is given by

$$\theta(e_{\tau}) = e_{\theta\tau}$$
 for $\theta, \tau \in G$.

We identify K with a subalgebra of $K \otimes D$ by

$$(x_1, x_2, x_3) = x_1(e_{Id} + e_{\rho}) + x_2(e_{\sigma} + e_{\rho\sigma}) + x_3(e_{\sigma^2} + e_{\rho\sigma^2})$$

for $x_1, x_2, x_3 \in F$. Then $A \simeq F^6[s, t]$ where

$$s^{3} = \frac{\sigma^{2}(a)}{\sigma(a)} = \frac{a_{2}}{a_{3}}e_{\mathrm{Id}} + \frac{a_{3}}{a_{1}}e_{\sigma} + \frac{a_{1}}{a_{2}}e_{\sigma^{2}} + \frac{a_{3}}{a_{2}}e_{\rho} + \frac{a_{2}}{a_{1}}e_{\sigma\rho} + \frac{a_{1}}{a_{3}}e_{\sigma^{2}\rho}$$

and

$$t^3 = a_1 a_2 a_3$$
.

Let $r = \sum_{\tau \in G} \tau(s) e_{\tau} \in M(K, a)$. Then $r^3 = \frac{a_2}{a_3}$ and M(K, a) = F[r, t]. Note that $\left(\frac{r^2 t}{a_2}\right)^3 = \frac{a_1}{a_3}$, so

$$M(K,a) \simeq F\left[\sqrt[3]{\frac{a_1}{a_3}}, \sqrt[3]{\frac{a_2}{a_3}}\right]$$
 and $N(K,a) \simeq F\left[\sqrt[3]{a_1 a_2 a_3}\right]$.

EXAMPLE 2.3. Let K be an arbitrary cubic étale F-algebra and let a=1. Let $F[\omega]$ be the quadratic étale F-algebra with $\omega^2 + \omega + 1 = 0$. By the Chinese Remainder Theorem we have

$$N(K,1) = F[t]/(t^3 - 1) \simeq F \times F[\omega].$$

The corresponding orthogonal idempotents in N(K, 1) are

$$e_1 = \frac{1}{3}(1+t+t^2)$$
 and $e_2 = \frac{1}{3}(2-t-t^2)$.

Let $A_1 = e_1A$ and $A_2 = e_2A$, so $A = A_1 \oplus A_2$ and the G-action preserves A_1 and A_2 . Let

$$\begin{split} e_{11} &= \tfrac{1}{3}(1+s+s^2)\,e_1 \in A_1\,, \qquad e_{12} &= \tfrac{1}{3}(2-s-s^2)\,e_1 \in A_1\,, \\ \varepsilon_1 &= \tfrac{1}{3}(1+s+s^2)\,e_2 \in A_2\,, \qquad \varepsilon_2 &= \tfrac{1}{3}(1+st+s^2t^2)\,e_2 \in A_2\,, \\ \varepsilon_3 &= \tfrac{1}{3}(1+st^2+s^2t)\,e_2 \in A_2\,. \end{split}$$

These elements are pairwise orthogonal idempotents, and we have

$$e_1 = e_{11} + e_{12}$$
, $e_2 = \varepsilon_1 + \varepsilon_2 + \varepsilon_3$.

The G-action fixes e_{11} and e_{12} , while

$$\sigma(\varepsilon_1) = \varepsilon_2 , \qquad \sigma(\varepsilon_2) = \varepsilon_3 , \qquad \sigma(\varepsilon_3) = \varepsilon_1 ,$$
 $\rho(\varepsilon_1) = \varepsilon_1 , \qquad \rho(\varepsilon_2) = \varepsilon_3 , \qquad \rho(\varepsilon_3) = \varepsilon_2 .$

We have $e_1t = e_1$ and $e_{11}s = e_{11}$, hence $e_{11}A \simeq K \otimes D$ and $e_{11}M(K, 1) \simeq F$. On the other hand, $e_{12}s$ is a primitive cube root of unity in $e_{12}M(K, 1)$. It is fixed under σ and $\rho(e_{12}s) = e_{12}s^{-1}$. Therefore we have

$$e_{12}A \simeq K \otimes D \otimes F[\omega]$$
 and $e_{12}M(K,1) \simeq (D \otimes F[\omega])^{\rho}$,

where ρ acts non-trivially on D and $F[\omega]$. The quadratic étale algebra $(D \otimes F[\omega])^{\rho}$ is the *composite* of D and $F[\omega]$ in the group of quadratic étale F-algebras, see [9, Prop. 3.11]. It is denoted by $D * F[\omega]$. Finally, we have an isomorphism $K \otimes F[\omega] \simeq e_2 M(K,1)$ by mapping $x \in K$ to $x\varepsilon_1 + \sigma(x)\varepsilon_2 + \sigma^2(x)\varepsilon_3$ and ω to $e_2 t$, so

$$M(K, 1) \simeq F \times (D * F[\omega]) \times (K \otimes F[\omega])$$
.

Under this isomorphism, the inclusion $N(K,1) \hookrightarrow M(K,1)$ is the map

$$F \times F[\omega] \to F \times (D * F[\omega]) \times (K \otimes F[\omega]), \qquad (x, y) \mapsto (x, x, y).$$

In particular, if F contains a cube root of unity, then $F[\omega] \simeq F \times F$ and

$$M(K, 1) \simeq F \times D \times K \times K$$
.

The inclusion $N(K,1) \hookrightarrow M(K,1)$ is then given by

$$F \times F \times F \to F \times D \times K \times K$$
, $(x, y, z) \mapsto (x, x, y, z)$.

Details are left to the reader.

In the rest of this section, we show how the Γ -set $\mathfrak{X}(M(K,a))$ can be characterized as the fibre of a certain (ramified) covering of the projective plane.

Viewing K as an F-vector space, we may consider the projective plane \mathbf{P}_K , whose points over the separable closure F_s are

$$\mathbf{P}_K(F_s) = \{x \cdot F_s^{\times} \mid x \in K \otimes_F F_s, \ x \neq 0\}.$$

Let

(2.1)
$$\pi: \mathbf{P}_K(F_s) \to \mathbf{P}_K(F_s), \quad x \cdot F_s^{\times} \mapsto x^3 \cdot F_s^{\times} \quad \text{for } x \in K \otimes F_s, \ x \neq 0.$$

We show in Theorem 2.6 below that there is an isomorphism of Γ -sets

$$\mathfrak{X}(M(K,a)) \simeq \pi^{-1}(a \cdot F_s^{\times})$$
 for $a \in K^{\times}$.

In view of the anti-equivalence between Et_F and Set_Γ , this result characterizes the Morley algebra M(K,a) up to isomorphism.

Until the end of this section, we fix $a \in K^{\times}$ and denote M(K, a) simply by M. We identify $K \otimes M$ with the subalgebra of A fixed under ρ .

LEMMA 2.4. There exists $u \in (K \otimes M)^{\times}$ such that $s = \sigma^{2}(u) \sigma(u)^{-1}$.

Proof. Define a map $c: G \to A^{\times}$ by

$$c(\mathrm{Id}) = c(\sigma^2 \rho) = 1$$
, $c(\sigma) = c(\rho) = s$, $c(\sigma^2) = c(\sigma \rho) = \sigma^2(s)^{-1}$.

Computation shows that $s\sigma(s)\sigma^2(s)=1$, and it follows that c is a 1-cocycle. Proposition 1.1 yields an element $v \in A^{\times}$ such that $c(\tau)=v\tau(v)^{-1}$ for all $\tau \in G$; in particular, we have

$$s = v\sigma(v)^{-1} = v\rho(v)^{-1}$$
.

Let $u = \sigma^2(v)^{-1}$. The equations above yield

$$s = \sigma^2(u) \sigma(u)^{-1}$$
 and $\rho(u) = u$.

Therefore $u \in K \otimes M$, and this element satisfies the condition.

LEMMA 2.5. The set $\pi^{-1}(a \cdot F_s^{\times})$ has 9 elements if it is non-empty.

Proof. Suppose $x_0 \in K \otimes F_s$ is such that $x_0^3 \cdot F_s^\times = a \cdot F_s^\times$. Then the map $y \cdot F_s^\times \mapsto x_0 y \cdot F_s^\times$ defines a bijection between $\pi^{-1}(1 \cdot F_s^\times)$ and $\pi^{-1}(a \cdot F_s^\times)$, so it suffices to show that $|\pi^{-1}(1 \cdot F_s^\times)| = 9$. Identify $K \otimes F_s = F_s \times F_s \times F_s$, and let $\omega \in F_s^\times$ be a primitive cube root of unity. To simplify notation, write

 $(z_1: z_2: z_3) = (z_1, z_2, z_3) \cdot F_s^{\times}$ for $z_1, z_2, z_3 \in F_s$. It is easy to check that $\pi^{-1}(1 \cdot F_s^{\times})$ consists of the following elements:

$$\begin{array}{lll} (1:1:1)\,, & (1:\omega:\omega^2)\,, & (1:\omega^2:\omega)\,, \\ (1:1:\omega)\,, & (1:\omega:1)\,, & (\omega:1:1)\,, \\ (1:1:\omega^2)\,, & (1:\omega^2:1)\,, & (\omega^2:1:1)\,. \end{array}$$

Each $\xi \in \mathfrak{X}(M)$ extends uniquely to a K-algebra homomorphism

$$\widehat{\xi}\colon K\otimes_F M\to K\otimes_F F_s$$
.

THEOREM 2.6 (Rost). Let $u \in (K \otimes M)^{\times}$ be such that $\sigma^2(u) \sigma(u)^{-1} = s$. The map $\xi \mapsto \widehat{\xi}(u) \cdot F_s^{\times}$ defines an isomorphism of Γ -sets

$$\Phi \colon \mathfrak{X}(M) \xrightarrow{\sim} \pi^{-1}(a \cdot F_s^{\times}).$$

Proof. If $u \in (K \otimes M)^{\times}$ satisfies $\sigma^{2}(u) \sigma(u)^{-1} = s$, then

$$\sigma^2(u^3) \, \sigma(u^3)^{-1} = s^3 = \sigma^2(a) \, \sigma(a)^{-1}$$

so $a^{-1}u^3$ is fixed under σ , hence $a^{-1}u^3 \in M^{\times}$. Therefore $a^{-1}\widehat{\xi}(u)^3 \in F_s^{\times}$, hence $\widehat{\xi}(u) \cdot F_s^{\times}$ lies in $\pi^{-1}(a \cdot F_s^{\times})$.

Note that the map Φ does not depend on the choice of u: indeed, u is determined uniquely up to a factor in M^{\times} , and for $m \in M^{\times}$ we have $\widehat{\xi}(um) = \widehat{\xi}(u) \, \xi(m)$, so $\widehat{\xi}(um) \cdot F_s^{\times} = \widehat{\xi}(u) \cdot F_s^{\times}$.

It is clear from the definition that the map Φ is Γ -equivariant. Since $|\mathfrak{X}(M)| = |\pi^{-1}(a \cdot F_s^{\times})| = 9$, it suffices to show that Φ is injective to complete the proof. Extending scalars, we may assume that $K \simeq F \times F \times F$, and use the notation of Example 2.2. Then, up to a factor in M^{\times} , we have

$$u = \sigma^2 \rho(s) e_{\mathrm{Id}} + \sigma(s) e_{\sigma} + e_{\sigma^2} + \sigma(s) e_{\rho} + e_{\sigma\rho} + \sigma^2 \rho(s) e_{\sigma^2 \rho}$$

$$= \frac{r^2 t}{a_2} (e_{\mathrm{Id}} + e_{\rho}) + r(e_{\sigma} + e_{\sigma^2 \rho}) + (e_{\sigma^2} + e_{\sigma\rho})$$

$$= \left(\frac{r^2 t}{a_2}, r, 1\right) \in K \otimes M = M \times M \times M.$$

If ξ , $\eta \in \mathfrak{X}(M)$ satisfy $\widehat{\xi}(u) \cdot F_s^{\times} = \widehat{\eta}(u) \cdot F_s^{\times}$, then $\xi(\frac{r^2t}{a_2}) = \eta(\frac{r^2t}{a_2})$ and $\xi(r) = \eta(r)$. Since M is generated by r and t, it follows that $\xi = \eta$.

REMARK 2.7. As pointed out by Rost [10], the map π factors through

$$W(F_s) = \{(\lambda, x) \cdot F_s^{\times} \mid \lambda^3 = N_K(x)\} \subset \mathbf{P}_{F \times K}(F_s)$$
:

we have $\pi = \pi_1 \circ \pi_2$, where

$$\pi_2 \colon \mathbf{P}_K(F_s) \to W(F_s), \qquad x \cdot F_s^{\times} \mapsto (\mathsf{N}_K(x), x^3) \cdot F_s^{\times}$$

and

$$\pi_1 \colon W(F_s) \to \mathbf{P}_K(F_s) \,, \qquad (\lambda, x) \cdot F_s^{\times} \mapsto x \cdot F_s^{\times} \,.$$

There is a commutative diagram

$$\mathfrak{X}(M(K,a)) \xrightarrow{\Phi} \mathbf{P}_{K}(F_{s})$$

$$\mathfrak{X}(i) \downarrow \qquad \qquad \downarrow \pi_{2}$$

$$\mathfrak{X}(N(K,a)) \xrightarrow{\Phi'} W(F_{s})$$

$$\downarrow \qquad \qquad \downarrow \pi_{1}$$

$$\mathfrak{X}(F) \xrightarrow{\Phi''} \mathbf{P}_{K}(F_{s})$$

where $\mathfrak{X}(i)$ is the map functorially associated to the inclusion

$$i: N(K,a) \hookrightarrow M(K,a)$$

and Φ'' maps the unique element of $\mathfrak{X}(F)$ to $a \cdot F_s^{\times}$. The induced map Φ' is an isomorphism of Γ -sets

$$\Phi' : \mathfrak{X}(N(K,a)) \xrightarrow{\sim} \pi_1^{-1}(a \cdot F_s^{\times}).$$

3. Inflection point configurations

Let V be a 3-dimensional vector space over F. Let $S^3(V^*)$ be the third symmetric power of the dual space V^* , i.e., the space of cubic forms on V. A cubic form $f \in S^3(V^*)$ is called *triangular* if its zero set in the projective plane $\mathbf{P}_V(F_s)$ defines a triangle or, equivalently, if there exist linearly independent linear forms $\varphi_1, \varphi_2, \varphi_3 \in V^* \otimes_F F_s$ such that $f = \varphi_1 \varphi_2 \varphi_3$ in $S^3(V^* \otimes F_s)$. The *sides of the triangle* are the zero sets of φ_1, φ_2 , and φ_3 ; they form a 3-element Γ -set $\mathfrak{S}(f)$.

PROPOSITION 3.1. Let $f \in S^3(V^*)$ be a triangular cubic form and let K be the cubic étale F-algebra such that $\mathfrak{X}(K) \simeq \mathfrak{S}(f)$. Then we may identify the F-vector spaces V and K so as to identify f with a multiple of the norm form of K,

$$f = \lambda \, \mathsf{N}_K$$
 for some $\lambda \in F^{\times}$.

In particular, the Γ -action on $\mathfrak{S}(f)$ is trivial if and only if f factors into a product of three independent linear forms in V^* .

Proof. Let $f = \varphi_1 \varphi_2 \varphi_3$ for some linearly independent linear forms $\varphi_1, \varphi_2, \varphi_3 \in V^* \otimes F_s$. Since ${}^{\gamma}\varphi_1{}^{\gamma}\varphi_2{}^{\gamma}\varphi_3 = \varphi_1\varphi_2\varphi_3$ for $\gamma \in \Gamma$, it follows by unique factorization in $S^3(V^*)$ that there exist a permutation π_{γ} of $\{1,2,3\}$ and scalars $\lambda_{\pi_{\gamma}(i),\gamma} \in F_s^{\times}$ such that

$$^{\gamma}\varphi_i = \lambda_{\pi_{\gamma}(i),\gamma}\varphi_{\pi_{\gamma}(i)}$$
 for $i = 1, 2, 3$.

Since $\gamma \delta \varphi_i = \gamma(\delta \varphi_i)$ for $\gamma, \delta \in \Gamma$, we have

$$\lambda_{\pi_{\gamma\delta}(i),\gamma\delta}\,\varphi_{\pi_{\gamma\delta}(i)} = \gamma(\lambda_{\pi_{\delta}(i),\delta})\,\lambda_{\pi_{\gamma}\pi_{\delta}(i),\gamma}\,\varphi_{\pi_{\gamma}\pi_{\delta}(i)}\,,$$

hence $\pi_{\gamma\delta} = \pi_{\gamma}\pi_{\delta}$ and

(3.1)
$$\lambda_{\pi_{\gamma\delta}(i),\gamma\delta} = \gamma(\lambda_{\pi_{\delta}(i),\delta}) \lambda_{\pi_{\gamma}\pi_{\delta}(i),\gamma}.$$

The Γ -set $\mathfrak{S}(f)$ is $\{1,2,3\}$ with the Γ -action $\gamma \mapsto \pi_{\gamma}$; therefore we may identify K with the F-algebra of Γ -equivariant maps

$$K = \text{Map}(\{1, 2, 3\}, F_s)^{\Gamma}$$
.

For $\gamma \in \Gamma$, define $a_{\gamma} \in \operatorname{Map}(\{1,2,3\}, F_s^{\times}) = (K \otimes F_s)^{\times}$ by

$$a_{\gamma}(i) = \lambda_{i,\gamma}$$
.

Clearly, $a_{\gamma}=1$ if γ fixes φ_1 , φ_2 , and φ_3 ; moreover, by (3.1) we have $a_{\gamma}{}^{\gamma}a_{\delta}=a_{\gamma\delta}$ for $\gamma,\delta\in\Gamma$, hence $(a_{\gamma})_{\gamma\in\Gamma}$ is a continuous 1-cocycle. By Hilbert's Theorem 90 [8, (29.2)], we have $H^1(\Gamma,(K\otimes F_s)^{\times})=1$, hence there exists $b\in \operatorname{Map}(\{1,2,3\},F_s^{\times})$ such that $a_{\gamma}=b^{\gamma}b^{-1}$ for all $\gamma\in\Gamma$. For i=1,2,3, let $\psi_i=b(i)\,\varphi_i\in V^*\otimes F_s$. Let also

$$\lambda = (b(1)b(2)b(3))^{-1}.$$

Computation shows that ${}^{\gamma}\psi_i = \psi_{\pi_{\gamma}(i)}$ for $\gamma \in \Gamma$ and i = 1, 2, 3, and $f = \lambda \psi_1 \psi_2 \psi_3$ in $S^3(V^* \otimes F_s)$, hence $\lambda \in F^{\times}$. Define

$$\Theta$$
: $V \otimes F_s \to \operatorname{Map}(\{1,2,3\},F_s) = K \otimes F_s$

by

$$\Theta(x): i \mapsto \psi_i(x)$$
 for $i = 1, 2, 3$ and $x \in V \otimes F_s$.

Since ψ_1 , ψ_2 , ψ_3 are linearly independent, Θ is an F_s -vector space isomorphism. It restricts to an isomorphism of F-vector spaces $V \xrightarrow{\sim} K$ under which f is identified with λN_K .

Now, let $\mathfrak{I} \subseteq \mathbf{P}_V(F_s)$ be a 9-point set that has the characteristic property of the set of inflection points of a nonsingular cubic curve: the line through any two distinct points of \mathfrak{I} passes through exactly one third point of \mathfrak{I} . Let \mathfrak{L} be the set of lines in $\mathbf{P}_V(F_s)$ that are incident to three points of \mathfrak{I} . This set has 12 elements, and \mathfrak{I} , \mathfrak{L} form an incidence geometry that is isomorphic to the affine plane over the field with three elements, see [7, §11.1]. In particular, there is a partition of \mathfrak{L} into four subsets $\mathfrak{T}_0, \ldots, \mathfrak{T}_3$ of three lines, which we call *triangles*, with the property that each point of \mathfrak{I} is incident to one and only one line of each triangle.

Assume \mathfrak{I} is stable under the action of Γ , and Γ preserves the triangle \mathfrak{T}_0 . Let K be the cubic étale F-algebra whose Γ -set $\mathfrak{X}(K)$ is isomorphic to \mathfrak{T}_0 . By Proposition 3.1, we may identify V with K in such a way that the union of the lines in \mathfrak{T}_0 is the zero set of the norm N_K .

THEOREM 3.2. There exists $a \in K^{\times}$ such that the Γ -set of vertices of the triangles $\mathfrak{T}_1, \mathfrak{T}_2, \mathfrak{T}_3$ is $\pi^{-1}(a \cdot F_s^{\times})$, where $\pi \colon \mathbf{P}_K(F_s) \to \mathbf{P}_K(F_s)$ is defined in (2.1). The set \mathfrak{I} is the set of inflection points of the cubics in the pencil spanned by the forms $\mathsf{T}_K(a^{-1}X^3)$ and $\mathsf{N}_K(X)$, and we have isomorphisms of Γ -sets

$$\mathfrak{L} \simeq \mathfrak{X}(K) \coprod \mathfrak{X}(M(K,a)), \qquad \{\mathfrak{T}_1,\mathfrak{T}_2,\mathfrak{T}_3\} \simeq \mathfrak{X}(N(K,a)).$$

Proof. Fix an isomorphism $K \otimes F_s \simeq F_s \times F_s \times F_s$, and write simply $(x_1 : x_2 : x_3)$ for $(x_1, x_2, x_3) \cdot F_s^{\times}$. The sides of \mathfrak{T}_0 are then the lines with equation $x_1 = 0$, $x_2 = 0$, and $x_3 = 0$. Let $\mathfrak{I} = \{p_1, \ldots, p_9\}$. We label the points so that the incidence relations can be read from the representation of the affine plane over F_3 in Figure 1.

Say the line through p_1 , p_2 , p_3 is $x_1 = 0$, and the line through p_4 , p_5 , p_6 is $x_2 = 0$. We can then find u_1 , u_2 , u_3 , $v \in F_s^{\times}$ such that

$$p_i = (0: u_i: 1)$$
 for $i = 1, 2, 3$, and $p_4 = (1: 0: v)$.

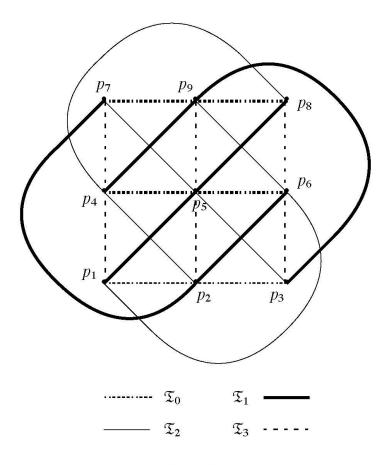


FIGURE 1 Incidence relations on \Im

Since p_7 lies at the intersection of $x_3 = 0$ with the line through p_1 and p_4 , we have

$$p_7 = (1: -u_1v: 0).$$

Similarly,

$$p_8 = (1: -u_2v: 0)$$
 and $p_9 = (1: -u_3v: 0)$.

Finally, since p_5 (resp. p_6) lies at the intersection of $x_2 = 0$ with the line through p_1 and p_8 (resp. p_9), we have

$$p_5 = (u_1 : 0 : u_2 v)$$
 and $p_6 = (u_1 : 0 : u_3 v)$.

Collinearity of the points p_2 , p_6 , p_7 (resp. p_2 , p_5 , p_9 ; resp. p_3 , p_6 , p_8) yields

$$u_1^2 = u_2 u_3$$
, (resp. $u_2^2 = u_1 u_3$; resp. $u_3^2 = u_1 u_2$).

Therefore

$$u_1^3 = u_2^3 = u_3^3 = u_1 u_2 u_3$$
.

Since u_1 , u_2 , u_3 are pairwise distinct, it follows that there is a primitive cube root of unity $\omega \in F_s$ such that

$$u_2 = \omega u_1$$
 and $u_3 = \omega^2 u_1$.

Straightforward computations yield the vertices of the triangles \mathfrak{T}_1 , \mathfrak{T}_2 , \mathfrak{T}_3 :

$$\mathfrak{T}_1: q_1 = (1:\omega^2 u_1 v: -v), \quad q_1' = (1:u_1 v: -\omega^2 v), \quad q_1'' = (\omega^2: u_1 v: -v),$$

$$\mathfrak{T}_2: q_2 = (\omega: u_1v: -v), \qquad q_2' = (1: u_1v: -\omega v), \quad q_2'' = (1: \omega u_1v: -v),$$

$$\mathfrak{T}_3: q_3 = (1:\omega u_1 v: -\omega^2 v), \quad q_3' = (\omega^2:\omega u_1 v: -v), \quad q_3'' = (1:u_1 v: -v).$$

Let $a_0 = (1, u_1^3 v^3, -v^3) \in (K \otimes F_s)^{\times}$. It is readily verified that

$$\{q_1, q_1', q_1'', q_2, q_2', q_2'', q_3, q_3', q_3''\} = \pi^{-1}(a_0 \cdot F_s^{\times}).$$

Since \Im is stable under the action of Γ , the point $a_0 \cdot F_s^{\times}$ is fixed under Γ , hence for $\gamma \in \Gamma$ there exists $\lambda_{\gamma} \in F_s^{\times}$ such that

$$\gamma(a_0) = a_0 \lambda_{\gamma}$$
 in $K \otimes F_s$.

Then $(\lambda_{\gamma})_{\gamma \in \Gamma}$ is a continuous 1-cocycle of Γ in F_s^{\times} . Hilbert's Theorem 90 yields an element $\mu \in F_s^{\times}$ such that $\lambda_{\gamma} = \mu \gamma(\mu)^{-1}$ for all $\gamma \in \Gamma$. Then for $a = a_0 \mu$ we have $a_0 \cdot F_s^{\times} = a \cdot F_s^{\times}$ and $\gamma(a) = a$ for all $\gamma \in \Gamma$, hence $a \in K^{\times}$.

The inflection points of the cubics in the pencil spanned by $T_K(a^{-1}X^3)$ and $N_K(X)$ are the points $(x_1 : x_2 : x_3)$ such that

$$\begin{cases} x_1^3 + (u_1 v)^{-3} x_2^3 - v^{-3} x_3^3 = 0, \\ x_1 x_2 x_3 = 0. \end{cases}$$

The solutions of this system are exactly the points p_1, \ldots, p_9 .

Finally, the Γ -set of sides of the triangle \mathfrak{T}_0 is isomorphic to $\mathfrak{X}(K)$ by hypothesis, and the map that associates to each side of a triangle its opposite vertex defines an isomorphism between the set of sides of \mathfrak{T}_1 , \mathfrak{T}_2 , \mathfrak{T}_3 and the set $\{q_1,\ldots,q_3''\}=\pi^{-1}(a\cdot F_s^\times)$. By Theorem 2.6, we have $\pi^{-1}(a\cdot F_s^\times)\simeq\mathfrak{X}(M(K,a))$, hence

$$\mathfrak{L} \simeq \mathfrak{X}(K) \coprod \mathfrak{X}(M(K,a)).$$

This isomorphism induces an isomorphism

$$\{\mathfrak{T}_1,\mathfrak{T}_2,\mathfrak{T}_3\}\simeq \mathfrak{X}(N(K,a)),$$

which can be made explicit by the following observation: the triangular cubic forms in the pencil spanned by $T_K(a^{-1}X^3)$ and $N_K(X)$ are the scalar multiples of $N_K(X)$ (whose zero set is the triangle \mathfrak{T}_0) and of $T_K(a^{-1}X^3) - 3z N_K(X)$, where $z \in F_s^{\times}$ is such that $z^3 = N_K(a^{-1})$. The zero set of the latter form is \mathfrak{T}_1 , \mathfrak{T}_2 or \mathfrak{T}_3 depending on the choice of z, and the three values of z are in one-to-one correspondence with the elements in the fibre of the map π_1 in Remark 2.7.

4. Normal forms of ternary cubics

Let V be a 3-dimensional vector space over F and let $f \in S^3(V^*)$ be a nonsingular cubic form. Recall from the introduction the notation $\mathfrak{I}(f)$ (resp. $\mathfrak{L}(f)$, resp. $\mathfrak{T}(f)$) for the set of inflection points (resp. inflectional lines, resp. inflectional triangles) of f. The following result is a direct application of Theorem 3.2:

COROLLARY 4.1. Let K be a cubic étale F-algebra. The following conditions are equivalent:

- (i) f is isometric to a cubic form $T_K(a^{-1}X^3) 3\lambda N_K(X)$ for some unit $a \in K^{\times}$ and some scalar $\lambda \in F$;
- (ii) Γ has a fixed point $\mathfrak{T}_0 \in \mathfrak{T}(f)$ with $\mathfrak{T}_0 \simeq \mathfrak{X}(K)$ (as Γ -sets of 3 elements). When these conditions hold, we have

$$\mathfrak{L}(f) \simeq \mathfrak{X}(K) \coprod \mathfrak{X}(M(K,a))$$
 and $\mathfrak{T}(f) \simeq \{\mathfrak{T}_0\} \coprod \mathfrak{X}(N(K,a))$.

Proof. If $f(X) = \mathsf{T}_K(a^{-1}X^3) - 3\lambda \, \mathsf{N}_K(X)$, then computation shows that the zero set of N_K is an inflectional triangle of f. This triangle is clearly preserved under the Γ-action. Conversely, if $\mathfrak{T}_0 \in \mathfrak{T}(f)$ is preserved under the Γ-action and K is the cubic étale F-algebra such that $\mathfrak{X}(K) \simeq \mathfrak{T}_0$, Theorem 3.2 yields an element $a \in K^\times$ such that the forms $\mathsf{T}_K(a^{-1}X^3)$ and $\mathsf{N}_K(X)$ span the pencil of cubics whose set of inflection points is $\mathfrak{I}(f)$.

Applying Corollary 4.1 in the case where F is a finite field yields a direct proof of the following result from [7, p. 276]:

COROLLARY 4.2. Suppose F is a finite field with q elements. For any nonsingular cubic form f, the number of inflectional triangles of f defined over F is 0, 1, or 4 if $q \equiv 1 \mod 3$; it is 0 or 2 if $q \equiv -1 \mod 3$.

Proof. Since F is finite, the action of Γ on $\mathfrak{T}(f)$ factors through a cyclic group. If there is at least one fixed triangle \mathfrak{T}_0 , then Corollary 4.1 yields a decomposition

$$\mathfrak{T}(f) \simeq {\mathfrak{T}_0} \coprod \mathfrak{X}(N(K,a)),$$

where N(K,a) = F[t] with $t^3 = N_K(a)$. If N(K,a) is a field, then it must be a cyclic extension of F, hence F contains a primitive cube root of unity and therefore $q \equiv 1 \mod 3$. Similarly, if $N(K,a) \simeq F \times F \times F$, then F contains a primitive cube root of unity. Thus, if $q \equiv -1 \mod 3$, the Γ -action on $\mathfrak{T}(f)$ has either 0 or 2 fixed points. If $q \equiv 1 \mod 3$ then F contains a primitive cube root of unity and either the polynomial $x^3 - N_K(a)$ is irreducible or it splits into linear factors. Therefore the Γ -action on $\mathfrak{T}(f)$ has either 0, 1 or 4 fixed points.

We next spell out the special case of Corollary 4.1 where the cubic étale F-algebra K is the split algebra $F \times F \times F$:

COROLLARY 4.3. There is a basis of V in which f takes the generalized Hesse normal form $a_1x_1^3 + a_2x_2^3 + a_3x_3^3 - 3\lambda x_1x_2x_3$ for some $a_1, a_2, a_3 \in F^{\times}$ and $\lambda \in F$ if and only if Γ has a fixed point $\mathfrak{T}_0 \in \mathfrak{T}(f)$ and acts trivially on \mathfrak{T}_0 (viewed as a 3-element subset of $\mathfrak{L}(f)$).

EXAMPLE 4.4. Let K be a cubic étale F-algebra and let $f(X) = \mathsf{T}_K(X^3)$. By Corollary 4.1 we have

$$\mathfrak{L}(f) \simeq \mathfrak{X}(K) \coprod \mathfrak{X}(M(K,1))$$
 and $\mathfrak{T}(f) \simeq {\mathfrak{T}_0} \coprod \mathfrak{X}(N(K,1))$.

The Γ -sets $\mathfrak{X}(M(K,1))$ and $\mathfrak{X}(N(K,1))$ are determined in Example 2.3:

$$\mathfrak{X}(M(K,1)) \simeq \mathfrak{X}(F) \ [\] \ \mathfrak{X}(D * F[\omega]) \ [\] \ \mathfrak{X}(K \otimes F[\omega])$$

and

$$\mathfrak{X}(N(K,1)) \simeq \mathfrak{X}(F) \ [\ \mathfrak{X}(F[\omega]) \ .$$

The map $\mathfrak{X}(i)$: $\mathfrak{X}(M(K,1)) \to \mathfrak{X}(N(K,1))$ functorially associated to the inclusion $i: N(K,1) \hookrightarrow M(K,1)$ maps $\mathfrak{X}(F) \coprod \mathfrak{X}(D * F[\omega])$ to $\mathfrak{X}(F)$ and $\mathfrak{X}(K \otimes F[\omega])$ to $\mathfrak{X}(F[\omega])$.

If $K \simeq F \times F \times F$, then $f(x_1, x_2, x_3) = x_1^3 + x_2^3 + x_3^3$ so f has a Hesse normal form. If $K \not\simeq F \times F \times F$, then the Γ -action on $\mathfrak{X}(K)$, hence also on $\mathfrak{X}(K \otimes F[\omega])$, is nontrivial. Therefore it follows from Corollary 4.3 that f has a generalized Hesse normal form over F if and only if the Γ -action on $\mathfrak{X}(D * F[\omega])$ is trivial. This happens if and only if $D \simeq F[\omega]$, which is

equivalent to $K \simeq F[\sqrt[3]{d}]$ for some $d \in F^{\times}$, by [8, (18.32)]. Indeed, for $X = x_1 + x_2\sqrt[3]{d} + x_3\sqrt[3]{d^2}$, computation yields

$$f(X) = 3(x_1^3 + dx_2^3 + d^2x_3^3 + 6dx_1x_2x_3).$$

Corollary 4.3 applies in particular when F is the field \mathbf{R} of real numbers:

Corollary 4.5. Every nonsingular cubic form over \mathbf{R} can be reduced to a generalized Hesse normal form.

Proof. It is clear from the Weierstrass normal form that every nonsingular cubic over \mathbf{R} has three real collinear inflection points, see [3, Prop. 14, p. 305]. The inflectional line through these points is fixed under Γ , hence the Γ -action on $\mathfrak{T}(f)$ has at least one fixed point. The same argument as in Corollary 4.2 then shows that Γ has exactly two fixed points in $\mathfrak{T}(f)$. Let \mathfrak{T}_0 , $\mathfrak{T}_1 \in \mathfrak{T}(f)$ be the fixed inflectional triangles. Assume the Γ -action on \mathfrak{T}_0 (viewed as a 3-element set) is not trivial, hence $K \simeq \mathbf{R} \times \mathbf{C}$ in the notation of Corollary 4.1; we shall prove that the Γ -action on \mathfrak{T}_1 is trivial. By Corollary 4.1, there is a unit $a = (a_1, a_2) \in \mathbf{R} \times \mathbf{C}$ such that

$$\mathfrak{L}(f) \simeq \mathfrak{X}(\mathbf{R} \times \mathbf{C}) \coprod \mathfrak{X}(M(\mathbf{R} \times \mathbf{C}, a))$$
.

By Theorem 2.6, we have an isomorphism of Γ -sets

$$\Phi \colon \mathfrak{X} \big(M(\mathbf{R} \times \mathbf{C}, a) \big) \stackrel{\sim}{\longrightarrow} \pi^{-1}(a \cdot \mathbf{C}^{\times}) \subset \mathbf{P}_{\mathbf{R} \times \mathbf{C}}(\mathbf{C}) \,.$$

We identify $(\mathbf{R} \times \mathbf{C}) \otimes_{\mathbf{R}} \mathbf{C}$ with $\mathbf{C} \times \mathbf{C} \times \mathbf{C}$ by mapping $(r, x) \otimes y$ to $(ry, xy, \overline{x}y)$ for $r \in \mathbf{R}$ and $x, y \in \mathbf{C}$. Then the Γ -action on $\mathbf{P}_{\mathbf{R} \times \mathbf{C}} = \mathbf{P}_{\mathbf{C}}^3$ is such that the complex conjugation — acts by

$$(x_1:x_2:x_3)\mapsto (\overline{x_1}:\overline{x_3}:\overline{x_2}).$$

If $\xi \in \mathbf{R}$ and $\eta \in \mathbf{C}$ satisfy $\xi^3 = a_1$ and $\eta^3 = a_2$, and if $\omega \in \mathbf{C}$ is a primitive cube root of unity, then the proof of Lemma 2.5 shows that $\pi^{-1}(a \cdot \mathbf{C}^{\times})$ consists of the following elements:

$$\begin{array}{lll} (\xi:\eta:\overline{\eta})\,, & (\xi:\omega\eta:\overline{\omega\eta})\,, & (\xi:\overline{\omega}\eta:\omega\overline{\eta})\,, \\ (\xi:\eta:\omega\overline{\eta})\,, & (\xi:\omega\eta:\overline{\eta})\,, & (\omega\xi:\eta:\overline{\eta})\,, \\ (\xi:\eta:\overline{\omega\eta})\,, & (\xi:\overline{\omega}\eta:\overline{\eta})\,, & (\overline{\omega}\xi:\eta:\overline{\eta})\,. \end{array}$$

The three points in the first row of this table are fixed under the Γ -action, whereas the Γ -action interchanges the second and third row. Therefore the first row corresponds to \mathfrak{T}_1 under Φ , and the proof is complete.

When the conditions in Corollary 4.1 do not hold, we may still consider the 4-dimensional étale F-algebra T(f) such that $\mathfrak{X}\big(T(f)\big)=\mathfrak{T}(f)$, and the 12-dimensional étale F-algebra L(f) such that $\mathfrak{X}\big(L(f)\big)=\mathfrak{L}(f)$, which is a cubic étale extension of T(f). The separability idempotent $e \in T(f) \otimes_F T(f)$ satisfies $e \cdot \big(T(f) \otimes T(f)\big) \simeq T(f)$, and hence yields a decomposition

$$T(f) \otimes_F T(f) \simeq T(f) \times T(f)_0$$

for some cubic algebra $T(f)_0$ over T(f). Likewise, multiplication in L(f) yields an isomorphism

$$e \cdot (L(f) \otimes T(f)) \simeq L(f);$$

hence

$$L(f) \otimes_F T(f) \simeq L(f) \times L(f)_0$$

for some cubic algebra $L(f)_0$ over $T(f)_0$. By functoriality of the construction of L and T, the cubic form $f_{T(f)}$ over $V \otimes_F T(f)$ obtained from f by scalar extension to T(f) satisfies

$$L(f_{T(f)}) \simeq L(f) \otimes_F T(f)$$
 and $T(f_{T(f)}) \simeq T(f) \otimes_F T(f)$.

Corollary 4.1 applied to $f_{T(f)}$ shows that $f_{T(f)}$ is isometric to

$$\mathsf{T}_{L(f)}(a^{-1}X^3) - 3\lambda \, \mathsf{N}_{L(f)}(X)$$

for some $\lambda \in T(f)^{\times}$ and some $a \in L(f)^{\times}$ such that $L(f)_0$ is a Morley T(f)-algebra $L(f)_0 \simeq M(L(f), a)$.

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