3. Cubic forms

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3. Cubic forms

We shall assume henceforth that the ground ring R is an integral domain of characteristic not dividing 6. The field of fractions of R will be denoted by K as previously.

Let M be a projective R-module of rank 2, and let $M^* = \mathrm{Hom}_R(M, R)$ be its dual. Consider the symmetric algebra

$$\mathrm{Sym}_R(M^*) = \bigoplus_n \mathrm{Sym}_R^n(M^*).$$

In this paper, a binary n-form is a pair (M,F), where M is a projective R-module of rank 2, and $F \in \mathrm{Sym}_R^n(M^*)$. A morphism $(M,F) \to (M',F')$ is an R-linear map $\phi\colon M \to M'$ such that $F'\phi = F$.

DEFINITION 3.1. An element $F \in \mathrm{Sym}_R^n(M^*)$ will be called a *Gaussian n-form* if there is a symmetric n-linear form $T\colon M \times \cdots \times M \to R$ with $F(\mathbf{x}) = T(\mathbf{x}, \ldots, \mathbf{x})$.

The set of Gaussian n-forms is a submodule of $\mathrm{Sym}_R(M^*)$ and will be denoted by $S^n(M^*)$. The module $\mathrm{Sym}^n(M^*)$ is projective of rank $n+1$ over R. If no binomial symbol $\binom{n}{i}$ is zero in R for $0 < i < n$, then $S^n(M^*)$ is also a projective R-module of rank $n+1$. If each of these binomial symbols is invertible in R then $S^n(M^*) = \mathrm{Sym}_R^n(M^*)$. Note that for any R-homomorphism $M \to M'$, the induced map $\mathrm{Sym}_R^n(M'^*) \to \mathrm{Sym}_R^n(M^*)$ sends $S^n(M'^*)$ to $S^n(M^*)$.

In this section we shall concentrate on binary cubic forms ($n = 3$). Unless otherwise stated all the binary cubic forms we shall consider are assumed to be Gaussian forms.

Let $F \in S^3(M^*)$ and let T be the symmetric trilinear form such that $F(\mathbf{x}) = T(\mathbf{x},\mathbf{x},\mathbf{x})$. For fixed $\mathbf{x} \in M$ we consider the homomorphism

$$\begin{aligned} T_{\mathbf{x}}\colon M &\longrightarrow M^* \\ \mathbf{y} &\longmapsto [\mathbf{z} \to T(\mathbf{x},\mathbf{y},\mathbf{z})]. \end{aligned}$$

Applying the second alternating power functor $\wedge^2$ we get a homomorphism

$$\wedge^2 T_{\mathbf{x}}\colon \wedge^2 M \to \wedge^2 M^*,$$

thus an element of $\mathcal{D}(M) := \mathrm{Hom}_R(\wedge^2 M, \wedge^2 M^*)$. We define

$$q_F(\mathbf{x}) := \wedge^2 T_{\mathbf{x}}. \tag{14}$$

It is immediate from the definitions that

$$(M, q_F, \mathcal{D}(M)) \tag{15}$$

is a binary quadratic mapping in the sense of Section 2. It is also evident that if (M, F) is isomorphic to (M', F'), then $(M, q_F, \mathcal{D}(M))$ is isomorphic to $(M', q_{F'}, \mathcal{D}(M'))$.

DEFINITION 3.2. The quadratic mapping $(M, q_F, \mathcal{D}(M))$ is called the *determining mapping* of (M, F).

By abuse of language, we shall refer sometimes to q_F as the determining mapping of F, without referring explicitly to the underlying modules M and $\mathcal{D}(M)$.

Over any open subset of $\operatorname{Spec} R$ where M is free, the choice of a local basis $\mathbf{m} = \{\mathbf{m}_1, \ \mathbf{m}_2\}$ of M allows us to write

$$F(\mathbf{x}) = a_0 x_1^3 + 3a_1 x_1^2 x_2 + 3a_2 x_1 x_2^2 + a_3 x_2^3, \tag{16}$$

where $\mathbf{x} = x_1\mathbf{m}_1 + x_2\mathbf{m}_2$. Let $\mathbf{m}^* = \{\mathbf{m}_1^*, \ \mathbf{m}_2^*\}$ be the dual basis of M^*. An easy computation gives

$$T_{\mathbf{x}}(\mathbf{m}_1) = (a_0x_1 + a_1x_2)\,\mathbf{m}_1^* + (a_1x_1 + a_2x_2)\,\mathbf{m}_2^*,$$
$$T_{\mathbf{x}}(\mathbf{m}_2) = (a_1x_1 + a_2x_2)\,\mathbf{m}_1^* + (a_2x_1 + a_3x_2)\,\mathbf{m}_2^*.$$

In the bases $\mathbf{m}_1 \wedge \mathbf{m}_2$ for $\wedge^2 M$ and $-\mathbf{m}_1^* \wedge \mathbf{m}_2^*$ for $\wedge^2 M^*$ (note the sign change), the determining form q_F is given by

$$\begin{aligned} q_F(\mathbf{x}) &= -\begin{vmatrix} a_0x_1 + a_1x_2 & a_1x_1 + a_2x_2 \\ a_1x_1 + a_2x_2 & a_2x_1 + a_3x_2 \end{vmatrix} \\ &= (a_1^2 - a_0a_2)x_1^2 + (a_1a_2 - a_0a_3)x_1x_2 + (a_2^2 - a_1a_3)x_2^2, \end{aligned} \tag{17}$$

which shows that (15) coincides locally with Eisenstein's determining form (2).

Now let C be a quadratic R-algebra as in Section 2 and let M be a projective C-module of rank one.

DEFINITION 3.3. Let $F \in S^3(M^*)$ and let T be the symmetric trilinear form associated to F. We will say that F is a *C-form* if $T(c\mathbf{x}, \mathbf{y}, \mathbf{z})$ is symmetric in $\mathbf{x}, \mathbf{y}, \mathbf{z}$ for any $c \in C$.

REMARK 3.4. The above definition makes sense for forms in $S^n(M^*)$ for any n. In particular, one has the notion of a quadratic C-form. This should not be confused with the concept of a quadratic form *of type* C. Indeed, it is easy to see that a quadratic form q is of type C if and only if the symmetric bilinear form b attached attached to q satisfies $b(c\mathbf{x},\mathbf{y}) = b(\mathbf{x},\bar{c}\mathbf{y})$; whereas the condition for a C-form reads $b(c\mathbf{x},\mathbf{y}) = b(\mathbf{x},c\mathbf{y})$.

We will use throughout the notation

$$M_C^{\otimes 3} = M \otimes_C M \otimes_C M, \quad M_R^{\otimes 3} = M \otimes_R M \otimes_R M .$$

Note that there is a natural epimorphism of R-modules $p\colon M_R^{\otimes 3} \to M_C^{\otimes 3}$. We have the following characterization of C-forms:

LEMMA 3.5. *Let $F \in S^3(M^*)$ and let T be the associated symmetric R-trilinear form, viewed as a linear form on $M_R^{\otimes 3}$. Then F is a C-form if and only if there exists a linear map $\lambda\colon M_C^{\otimes 3} \to R$ such that $T = \lambda \circ p$. Furthermore, the map λ is unique.*

Proof. It is enough to prove the lemma locally, so we assume that M is free over C.

Let $\lambda\colon M_C^{\otimes 3} \to R$ be an R-homomorphism. Write $M = C\mathbf{m}$ for some $\mathbf{m} \in M$ and let $\mathbf{x} = c_1\mathbf{m}$, $\mathbf{y} = c_2\mathbf{m}$, $\mathbf{z} = c_3\mathbf{m}$ with $c_i \in C$.

Then $T(\mathbf{x}\otimes\mathbf{y}\otimes\mathbf{z}) = \lambda(c_1c_2c_3(\mathbf{m}\otimes\mathbf{m}\otimes\mathbf{m}))$ is visibly symmetric and satisfies the condition of Definition 3.3.

Conversely, if $T(c\mathbf{x},\mathbf{y},\mathbf{z})$ is symmetric then in particular T itself is symmetric ($c = 1$), and hence

$$T(c\,\mathbf{x},\mathbf{y},\mathbf{z}) = T(\mathbf{x},c\mathbf{y},\mathbf{z}) = T(\mathbf{x},\mathbf{y},c\,\mathbf{z}),$$

showing the existence of λ. Uniqueness follows from the fact that p is onto. $\square$

Let $S_C^3(M^*) \subset S^3(M^*)$ be the submodule of cubic C-forms on M. Note that the lemma above can be summarized by saying that the map

$$\begin{aligned} \mathrm{Hom}_R(M_C^{\otimes 3}, R) &\longrightarrow S_C^3(M^*) \\ \lambda &\longmapsto [\mathbf{x} \mapsto \lambda(\mathbf{x}\otimes\mathbf{x}\otimes\mathbf{x})] \end{aligned} \tag{18}$$

is an isomorphism of R-modules.

On the other hand, we also have

LEMMA 3.6. *Let L be any projective C-module of finite rank. Then the map*

$$\begin{aligned} \mathrm{Hom}_C(L, C^*) &\longrightarrow \mathrm{Hom}_R(L, R) \\ f &\longmapsto (\mathbf{x} \mapsto f(\mathbf{x})(1)) \end{aligned} \tag{19}$$

is an isomorphism of C-modules (the dual $P^* = \mathrm{Hom}_R(P, R)$ is made into a C-module by setting $(c\lambda)(x) = \lambda(cx)$ for $\lambda \in P^*$).

Proof. By localization, it is sufficient to prove the lemma when $L = C$, in which case the map is the identity. □

Combining the isomorphisms (18) and (19) with $L = M_C^{\otimes 3}$, we obtain

PROPOSITION 3.7. *The map*

$$\begin{aligned} \mathrm{Hom}_C(M_C^{\otimes 3}, C^*) &\longrightarrow S_C^3(M^*) \\ \phi &\longmapsto [F_\phi \colon \mathbf{x} \mapsto \phi(\mathbf{x} \otimes \mathbf{x} \otimes \mathbf{x})(1)] \end{aligned} \tag{20}$$

is an isomorphism of R-modules.

Using the isomorphism (20) we give $S_C^3(M^*)$ the C-module structure so that this bijection becomes a C-module isomorphism. Note that

$$T_\phi(\mathbf{x}, \mathbf{y}, \mathbf{z}) := \phi(\mathbf{x} \otimes \mathbf{y} \otimes \mathbf{z})(1)$$

is the symmetric trilinear form attached to F_ϕ. Hence the C-module structure on $S_C^3(M^*)$ is given explicitly by

$$(cF)(\mathbf{x}) = T(c\mathbf{x}, \mathbf{x}, \mathbf{x})\,. \tag{21}$$

LEMMA 3.8. *C^* is an invertible C-module.*

Proof. Locally over $\mathrm{Spec}\, R$, we have $C = R[\omega] = R[x]/(x^2+bx+c)$. Then the R-module C^* is freely generated by λ_1, λ_2, where $\lambda_1(1) = 1$, $\lambda_1(\omega) = 0$, $\lambda_2(1) = 0$, $\lambda_2(\omega) = 1$. One sees that $\omega\lambda_2 = \lambda_1 - b\lambda_2$, so that λ_2 is a local C-module basis of C^*. □

By virtue of (20) and this lemma, $S_C^3(M^*)$ is an invertible C-module.

In the next section we will give alternate characterizations of the cubic C-forms on M, related to their determining mapping.