SOME NEW CANONICAL FORMS FOR POLYNOMIALS

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Abstract. We give some new canonical representations for forms over $\mathbb{C}$. For example, a general binary quartic form can be written as the square of a quadratic form plus the fourth power of a linear form. A general cubic form in $(x_1,\dots,x_n)$ can be written uniquely as a sum of the cubes of linear forms $\ell_{ij}(x_i,\dots,x_j)$, $1 \le i \le j \le n$. A general ternary quartic form is the sum of the square of a quadratic form and three fourth powers of linear forms. The methods are classical and elementary.

1. Introduction

Let $H_d(\mathbb{C}^n)$ denote the $N(n,d) = \binom{n+d-1}{d}$-dimensional vector space of complex forms of degree d in n variables, or *n-ary d-ic forms*. One of the major accomplishments of 19th century algebra was the discovery of canonical forms for certain classes of n-ary d-ics, especially as the sum of d-th power of linear forms. By a *canonical form* we mean a polynomial expression $F(t;x)$, $t \in \mathbb{C}^{N(n,d)}$ so that, for general $p \in H_d(\mathbb{C}^n)$, there exists t for which $p(x) = F(t;x)$. In this paper, we present some new canonical forms, whose main novelty is that they involve intermediate powers of forms of higher degree, or forms with a restricted set of monomials. (These variations are suggested by the study of Hilbert's 17th problem, as well as by a theorem of B. Reichstein.) They are less susceptible to apolarity arguments than the traditional canonical forms, and lead naturally to (mostly open) enumeration questions.

To take a simple, yet familiar example,

$$F(t_1,t_2,t_3;x,y) = (t_1x + t_2y)^2 + (t_3y)^2 \tag{1.1}$$

is a canonical form for binary quadratic forms. By the usual completion of squares, $p(x,y) = ax^2 + 2bxy + cy^2 = a(x + \frac{b}{a}y)^2 + (c - \frac{b^2}{a})y^2$, as long as $a \neq 0$. Many of the examples in this paper can be viewed as attempts to generalize (1.1).

In 1851, Sylvester [38, 39] presented canonical expressions for binary forms.

Theorem 1.1 (Sylvester's Theorem)**.**
(i) A general binary form p of odd degree $2s-1$ can be written as

$$p(x,y) = \sum_{j=1}^{s} (\alpha_j x + \beta_j y)^{2s-1}. \tag{1.2}$$

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(ii) A general binary form p of even degree $2s$ can be written as

$$p(x,y) = \lambda x^{2s} + \sum_{j=1}^{s} (\alpha_j x + \beta_j y)^{2s}. \tag{1.3}$$

for some $\lambda \in \mathbb{C}$.

The somewhat unsatisfactory nature of the asymmetric summand in (1.3) has been the inspiration for other canonical forms for binary forms of even degree.

Another familiar canonical form is the generalization of (1.1) into the upper-triangular expression for quadratic forms, found by repeated completion of the square:

Theorem 1.2. *A general quadratic form $p \in H_2(\mathbb{C}^n)$ can be written as:*

$$p(x_1,\dots,x_n) = \sum_{k=1}^{n} (t_{k,k}x_k + t_{k,k+1}x_{k+1} + \cdots + t_{k,n}x_n)^2, \quad t_{k,\ell} \in \mathbb{C}. \tag{1.4}$$

There are two ways to verify that a candidate expression $F(t;x)$ is, in fact, a canonical form. One is the classical non-constructive method based on the existence of a point at which the Jacobian matrix has full rank. (See Corollary 2.3, and see Theorem 3.2 for the apolar version.) Lasker [23] attributes the underlying idea to Kronecker and Lüroth – see [45, p.208].

Ideally, however, a canonical form can be derived constructively, and the number of different representations can thereby be determined. The convention in this paper will be that two representations are the same if they are equal, up to a permutation of like summands and with the identification of f^k and $(\zeta f)^k$ when $\zeta^k = 1$. The representation in (1.2) is unique in this sense, even though there are $s! \cdot (2s-1)^s$ different $2s$-tuples $(\alpha_1, \beta_1, \dots, \alpha_s, \beta_s)$ for which (1.2) is valid.

In addition to Theorem 1.1, another motivational example for this paper is a remarkable canonical form for cubic forms found by Reichstein [30] in 1987, which can be thought of as a "completion of the cube".

Theorem 1.3 (Reichstein)**.** *A general cubic $p \in H_3(\mathbb{C}^N)$ can be written uniquely as*

$$p(x_1,\dots,x_n) = \sum_{k=1}^{n} \ell_k^3(x_1,\dots,x_n) + q(x_3,\dots,x_n), \tag{1.5}$$

where $\ell_k \in H_1(\mathbb{C}^n)$ and $q \in H_3(\mathbb{C}^{n-2})$.

This is a canonical form, provided q is viewed as a t-linear combination of the monomials in $(x_3,\dots,x_n)$; since $N(n,3) = n^2 + N(n-2,3)$, the constant count is right. Iteration (see (6.1)) gives p as a sum of roughly $n^2/4$ cubes. The minimum from constant-counting, which is justified by the Alexander-Hirschowitz Theorem [1], is roughly $n^2/6$. We give Reichstein's constructive proof of Theorem 1.3 in section six.

Here are some representative examples of the new canonical forms in this paper.

Theorem 1.4. *A general cubic form $p \in H_3(\mathbb{C}^n)$ has a unique representation*

$$p(x_1, \dots, x_n) = \sum_{1 \le i \le j \le n} (t_{\{i,j\},i} x_i + \cdots + t_{\{i,j\},j} x_j)^3, \tag{1.6}$$

where $t_{\{i,j\},k} \in \mathbb{C}$.

Theorem 1.5. *A general binary sextic $p \in H_6(\mathbb{C}^2)$ can be written as $p(x, y) = f^2(x, y) + g^3(x, y)$, where $f \in H_3(\mathbb{C}^2)$ is a cubic form and $g \in H_2(\mathbb{C}^2)$ is a quadratic form.*

Theorem 1.4 has a constructive proof. Theorem 1.5 is in fact, a very special case of much deeper recent results of Várilly-Alvarado. (See [42], especially Theorem 1.2 and Remark 4.5, and section 1.2 of [43].) We include it because our proof, in the next section, is very short.

Theorems 1.1 and 1.5 are both special cases of a more general class of canonical forms for $H_d(\mathbb{C}^n)$, which is a corollary of [8, Thm. 4.4] (see Theorem 3.4), but not worked out explicitly there.

Theorem 1.6. *Suppose $d \ge 1$, $\{\ell_j : 1 \le j \le m\}$ is a fixed set of pairwise non-proportional linear forms, and suppose $e_k \mid d$, $d > e_1 \ge \cdots \ge e_r$, $1 \le k \le r$, and*

$$m + \sum_{k=1}^{r} (e_k + 1) = d + 1. \tag{1.7}$$

Then a general binary d-ic form $p \in H_d(\mathbb{C}^2)$ can be written as

$$p(x, y) = \sum_{j=1}^{m} t_j \ell_j^d(x, y) + \sum_{k=1}^{r} f_k^{d/e_k}(x, y), \tag{1.8}$$

where $t_j \in \mathbb{C}$ and $f_k \in H_{e_k}(\mathbb{C}^2)$.

The condition $e_k < d$ excludes the vacuous case $m = 0, r = 1, e_1 = d$. If each $e_k = 1$ and $r = \lfloor \frac{d+1}{2} \rfloor$, then $m = d+1-2\lfloor \frac{d+1}{2} \rfloor \in \{0, 1\}$ and Theorem 1.6 becomes Theorem 1.1; Theorem 1.5 is Theorem 1.6 in the special case $d = 6, m = 0, r = 2, e_1 = 3, e_2 = 2$. As an example of a canonical form which is unlikely to find a constructive proof: for a general $p \in H_{84}(\mathbb{C}^2)$, there exist $f \in H_{42}(\mathbb{C}^2), g \in H_{28}(\mathbb{C}^2)$ and $h \in H_{12}(\mathbb{C}^2)$ so that $p = f^2 + g^3 + h^7$.

By taking $d = 2s$, $e_1 = 2$, $e_2 = \cdots = e_{s-1} = 1$ and $m = 0$, in Theorem 1.6, we obtain an alternative to the dangling term " λx^{2s}" in (1.3).

Corollary 1.7. *A general binary form p of even degree $2s$ can be written as*

$$p(x, y) = (\alpha_0 x^2 + \beta_0 xy + \gamma_0 y^2)^s + \sum_{j=1}^{s-1} (\alpha_j x + \beta_j y)^{2s}. \tag{1.9}$$

Cayley proved that, after an invertible linear change of variables $(x, y) \mapsto (X, Y)$, a general binary quartic can be written as $X^4 + 6\lambda X^2Y^2 + Y^4$. There are two natural ways to generalize this to higher even degree, and almost 100 years ago, Wakeford [44, 45] did both.

Theorem 1.8 (Wakeford's Theorem)**.** *After an invertible linear change of variables, a general $p \in H_d(\mathbb{C}^n)$ can be written so that the coefficient of each x_i^d is 1 and the coefficient of each $x_i^{d-1}x_j$ is zero.*

There are $N(n, d) - n^2$ unmentioned monomials above, and when combined with the n^2 coefficients in the change of variables, the constant count is correct for a canonical form. Wakeford was also interested in knowing *which* sets of $n(n-1)$ monomials can be eliminated by a change of variables, and we are able to settle this for binary forms in Theorem 2.4. (Theorem 1.8 was independently discovered by Guazzone [14] in 1975, as an attempt to generalize the canonical form $X^3 + Y^3 + Z^3 + 6\lambda XYZ$ for $H_3(\mathbb{C}^3)$. Babbage [2] subsequently observed that this can be proved by the Lasker-Wakeford Theorem, without noting that Wakeford had already done so in [45].)

The second generalization of $X^4 + 6\lambda X^2Y^2 + Y^4$ will not be pursued here; see [8, Cor. 4.11]. A canonical form for binary forms of even degree $2s$ is given by

$$\sum_{k=1}^{s} \ell_k^{2s}(x, y) + \lambda \prod_{k=1}^{s} \ell_k^2(x, y), \quad \ell_k(x, y) = \alpha_k x + \beta_k y. \tag{1.10}$$

This construction is due to Sylvester [39] for $2s = 4, 8$. His methods failed for $2s = 6$, but Wakeford was able to prove it in [44]. The full version of (1.10) is proved in [45, p.408], where Wakeford notes that "the number of ways this reduction can be performed is interesting", citing "3,8,5" for $2s = 4, 6, 8$.

The non-trivial study of canonical forms was initiated by Clebsch's 1861 discovery ([5], see e.g. [12, pp.50-51] and [31, pp.59-60]) that, despite the fact that $N(3, 4) = 5 \times N(3, 1)$, a general ternary quartic cannot be written as a sum of five fourth powers of linear forms. This was early evidence that constant-counting can fail. But $N(3, 4)$ is also equal to $1 \times N(3, 2) + 3 \times N(3, 1)$, and ternary quartics *do* satisfy an alternative canonical form as a mixed sum of powers.

Theorem 1.9. *A general ternary quartic $p \in H_4(\mathbb{C}^3)$ can be written as*

$$p(x_1, x_2, x_3) = q^2(x_1, x_2, x_3) + \sum_{k=1}^{3} \ell_k^4(x_1, x_2, x_3), \tag{1.11}$$

where $q \in H_2(\mathbb{C}^3)$ and $\ell_k \in H_1(\mathbb{C}^3)$.

One might also consider polynomial maps $F : S \mapsto H_d(\mathbb{C}^n)$, where S is an N-dimensional subspace of some $\mathbb{C}^M$. In the simplest case, for binary quadratic forms, observe that the coefficient of x^2 in

$$(t_1x + t_2y)^2 + (it_1x + t_3y)^2, \tag{1.12}$$

is 0, so (1.12) is not canonical. This is essentially the only kind of exception.

Theorem 1.10. *Suppose $(c_1, c_2, c_3, c_4) \in \mathbb{C}^4$, and it is not true that $c_3 = \epsilon c_1$ and $c_4 = \epsilon c_2$ for $\epsilon \in \{\pm i\}$. Then for general $p \in H_2(\mathbb{C}^2)$, there exists $(t_1, t_2, t_3, t_4) \in \mathbb{C}^4$ satisfying $\sum_{j=1}^4 c_j t_j = 0$ and such that*

$$p(x, y) = (t_1 x + t_2 y)^2 + (t_3 x + t_4 y)^2. \tag{1.13}$$

In the exceptional case, there exists (x_0, y_0) so that for all feasible choices of t_j, $p(x_0, y_0) = 0$.

Another alternative version of (1.3) is the following conjecture, which can be verified up to degree 8.

Conjecture 1.11. *A general binary form p of even degree $2s$ can be written as*

$$p(x, y) = \sum_{j=1}^{s+1} (\alpha_j x + \beta_j y)^{2s}, \quad \textit{where } \sum_{j=1}^{s+1} (\alpha_j + \beta_j) = 0. \tag{1.14}$$

Here is an outline of the paper. In section two, we introduce notation and definitions. The definition of canonical form is the classical one and roughly parallels that in Ehrenborg-Rota [8], an important updating of this subject about 20 years ago. Our point of view is considerably more elementary in many respects than [8], but uses the traditional criterion: A polynomial map $F : \mathbb{C}^N \mapsto H_d(\mathbb{C}^n)$ is a *canonical form* if a general $p \in H_d(\mathbb{C}^n)$ is in the range; this occurs if and only if there is at least one point $u \in \mathbb{C}^N$ so that $\{\frac{\partial F}{\partial t_j}(u)\}$ spans $H_d(\mathbb{C}^n)$. (See Corollary 2.3.) This leads to immediate non-constructive proofs of Theorems 1.2, 1.5, 1.8 and 1.9, and a somewhat more complicated proof of Theorem 2.4, which answers Wakeford's question about missing monomials for binary forms.

In section three, we discuss classical apolarity and its implications for canonical forms. (Apolarity methods become more complicated when a component of a canonical form comes from a restricted set of monomials.) A generalization of the classical Fundamental Theorem of Apolarity from [33] allows us to identify a class of bases for $H_d(\mathbb{C}^n)$ which give a non-constructive proof of Theorem 1.6, and hence Theorem 1.1. We also present Sylvester's Algorithm, Theorem 3.8, allowing for a constructive proof of Theorem 1.1. We conclude with a brief summary of connections with the theorems of Alexander-Hirschowitz and recent work on the rank of forms.

In section four we discuss some special cases of Theorem 1.6. Sylvester's Algorithm is used in constructive proof of Theorem 1.6 when $e_k \equiv 1$, in which case the representation is unique. We give some other constructive proofs for $d \le 4$, and present numerical evidence regarding the number of representations in Corollary 1.7 and a few other cases. Using elementary number theory, we show that, for each r, there are only finitely many canonical forms (1.8) with $m = 0$, and, up to degree N, there are $N + \mathcal{O}(N^{1/2})$ such canonical forms in which the e_k's are equal.

Section five discusses some familiar results on sums of two squares of binary forms and canonical representations of quadratic forms as a sum of squares of linear forms.

This includes a constructive proof of Theorem 1.2, which provides the groundwork for the proof of Theorem 1.4. Constant-counting has long been recognized as not fully applicable to sums of squares. We also give a short proof of a canonical form which illustrates the classical result that a general ternary quartic is the sum of three squares of quadratic forms.

In section six, we turn to forms in more than two variables and low degree, give constructive proofs of Theorems 1.3 and 1.4, as well as the non-canonical Theorem 6.2, which shows that *every* cubic in $H_3(\mathbb{C}^n)$ is a sum of at most $\frac{n(n+1)}{2}$ cubes of linear forms. Theorem 1.3 can be "lifted" to an ungainly canonical form for quartics as a sum of fourth powers (see Corollary 6.3), but not further to quintics. Number theoretic considerations rule out a Reichstein-type canonical form for quartics in 12 variables; see Theorem 6.4 for other instances of this phenomenon.

In section seven, we offer a preliminary discussion of canonical forms in which the domain of a polynomial map $F : \mathbb{C}^M \mapsto H_d(\mathbb{C}^n)$ is restricted to an N-dimensional subspace of $\mathbb{C}^M$, of which Theorem 1.10 and Conjecture 1.11 are examples.

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2. Canonical forms

Let $\mathcal{I}(n,d)$ denote the index set of monomials in $H_d(\mathbb{C}^n)$:

$$\mathcal{I}(n,d) = \Big\{(i_1,\dots,i_n) : 0 \le i_k \in \mathbb{Z}, \quad \sum_k i_k = d\Big\}. \tag{2.1}$$

Let $x^i = x_1^{i_1}\cdots x_n^{i_n}$ and $c(i) = \frac{d!}{\prod i_k!}$ denote the multinomial coefficient. If $p \in H_d(\mathbb{C}^n)$, then we write

$$p(x_1,\dots,x_n) = \sum_{i\in\mathcal{I}(n,d)} c(i)a(p;i)x^i, \quad a(p;i) \in \mathbb{C}. \tag{2.2}$$

We say that two forms are *distinct* if they are non-proportional, and a set of forms is *honest* if the forms are pairwise distinct. For later reference, recall Biermann's Theorem; see [31, p.31].

Theorem 2.1 (Biermann's Theorem)**.** *If $p \in H_d(\mathbb{C}^n)$ and $p \neq 0$, then there exists $i \in \mathcal{I}(n,d)$ so that $p(i) \neq 0$.*

The easy verification of whether a formula is a canonical form for $H_d(\mathbb{C}^n)$ relies on a crucial alternative. A self-contained accessible proof is in [8, Thm. 2.4], for which Ehrenborg and Rota thank M. Artin and A. Mattuck. For further discussion of the underlying algebraic geometry, see Section 9.5 in Cox, Little and O'Shea [7].

Theorem 2.2. *Suppose $M \geq N$ and $F : \mathbb{C}^M \to \mathbb{C}^N$ is a polynomial map; that is,*

$$F(t_1, \dots, t_M) = (f_1(t_1, \dots, t_M), \dots, f_N(t_1, \dots, t_M))$$

where each $f_j \in \mathbb{C}[t_1, \dots, t_M]$. Then either (i) or (ii) holds:

(i) The N polynomials $\{f_j : 1 \leq j \leq N\}$ are algebraically dependent and $F(\mathbb{C}^M)$ lies in some non-trivial variety $\{P = 0\}$ in $\mathbb{C}^N$.

(ii) The N polynomials $\{f_j : 1 \leq j \leq N\}$ are algebraically independent and $F(\mathbb{C}^M)$ is dense in $\mathbb{C}^N$.

The second case occurs if and only there is a point $u \in \mathbb{C}^M$ at which the Jacobian matrix $\left[\frac{\partial f_i}{\partial t_j}(u)\right]$ has full rank.

When $M = N = N(n,d)$, we may interpret such an F as a map from $\mathbb{C}^N$ to $H_d(\mathbb{C}^n)$ by indexing $\mathcal{I}(n,d)$ as $\{i_k : 1 \leq k \leq N\}$ and making the interpretation in an abuse of notation that

$$F(t;x) = \sum_{k=1}^{N} c(i_k) f_k(t_1 \dots, t_N) x^{i_k}. \tag{2.3}$$

Definition. A *canonical form for $H_d(\mathbb{C}^n)$* is any polynomial map $F : \mathbb{C}^N \mapsto H_d(\mathbb{C}^n)$ in which F satisfies Theorem 2.2(ii).

That is, F is a canonical form if and only if, for a general $p \in H_d(\mathbb{C}^n)$, there exists $t \in \mathbb{C}^N$ so that $p(x) = F(t;x)$. In the rare cases where F is surjective, we say that the canonical form is *universal.* By translating the definitions and using (2.1) and (2.3), we obtain an immediate corollary of Theorem 2.2:

Corollary 2.3. *The polynomial map $F : \mathbb{C}^N \mapsto H_d(\mathbb{C}^n)$ is a canonical form if and only if there exists $u \in \mathbb{C}^n$ so that $\{\frac{\partial F}{\partial t_j}(u)\}$ spans $H_d(\mathbb{C}^n)$.*

We shall let $J := J(F;u)$ denote the span of the forms $\{\frac{\partial F}{\partial t_j}(u)\}$. In any particular case, the determination of whether $J = H_d(\mathbb{C}^n)$ amounts to the computation of the determinant of an $N(n,d) \times N(n,d)$ matrix. As much as possible in this paper, we give proofs which can be checked by hand, by making a judicious choice of u and ordering of the monomials in $H_d(\mathbb{C}^n)$, showing sequentially that they all lie in J.

Classically, the use of the term "canonical form" has been limited to cases in which $F(t;x)$ has a natural interpretation as a combination of forms in $H_d(\mathbb{C}^n)$, such as a sum of powers of linear forms, or as a result of a linear change of variables. It seems odd that canonical forms are perceived as rare, since a "general" polynomial map from $\mathbb{C}^N \mapsto H_d(\mathbb{C}^n)$ is a canonical form. (This is an observation which goes back at least to [37].) For example, if $\{f_j(x)\}$ is a basis for $H_d(\mathbb{C}^n)$, then

$$F(t;x) = \sum_{j=1}^{N} t_j f_j(x) \tag{2.4}$$

should be (but usually isn't) considered a canonical form. In particular, (2.2) with $f_j(x) = c(i_j)x^{i_j}$ is itself a canonical form.

The following computation will occur repeatedly. If $es = d$, then

$$g = \sum_{i_j \in \mathcal{I}(n,e)} t_j x^{i_j} \implies \frac{\partial g^s}{\partial t_j} = s x^{i_j} g^{s-1}. \tag{2.5}$$

If g is specialized to be a monomial, then all these partials will also be monomials.

Non-constructive proof of Theorem 1.2. Given (1.4), let

$$\ell_k(x) = \sum_{m=k}^{n} t_{k,m} x_m, \quad F(x) = \sum_{k=1}^{n} \ell_k^2(x).$$

Then $\frac{\partial F}{\partial t_{k,m}} = 2x_m \ell_k$. Set $t_{k,m} = \delta_{k,m}$, so that $\ell_k = x_k$ and $\frac{\partial F}{\partial t_{k,m}} = 2x_k x_m$. Since $1 \le k \le m \le n$, all monomials from $H_2(\mathbb{C}^n)$ appear in J. □

Non-constructive proof of Theorem 1.5. Suppose

$$\begin{gathered} p(x,y) = f^2(x,y) + g^3(x,y) : \\ f(x,y) = t_1x^3 + t_2x^2y + t_3xy^2 + t_4y^3, \quad g(x,y) = t_5x^2 + t_6xy + t_7y^2. \end{gathered} \tag{2.6}$$

Then by (2.5), the partials with respect to the t_j's are:

$$2x^3f,\ 2x^2yf,\ 2xy^2f,\ 2y^3f; \quad 3x^2g^2,\ 3xyg^2,\ 3y^2g^2.$$

Upon specializing at $f = x^3, g = y^2$, these become:

$$2x^6,\ 2x^5y,\ 2x^4y^2,\ 2x^3y^3; \quad 3x^2y^4,\ 3xy^5\ , 3y^6.$$

It is then evident that $J = H_6(\mathbb{C}^2)$. □

Non-constructive proof of Theorem 1.8. Let $\mathcal{L} \subset \mathcal{I}(n,d)$ consist of all n-tuples except the permutations of $(d,0,\dots,0)$ and $(d-1,1,\dots,0)$ and let $X_i = \sum_{j=1}^n \alpha_{ij}x_j$. The assertion is that, with the $(N(n,d) - n - \binom{n}{2}) + n^2 = N(n,d)$ parameters t_ℓ and α_{ij},

$$\sum_{i=1}^{n} X_i^d + \sum_{\ell \in \mathcal{L}} t_\ell X^\ell \tag{2.7}$$

is a canonical form. Evaluate the partials at the point where $X_i = x_i$ and $t_\ell = 0$: they are $dx_jx_i^{d-1}$ (for α_{ij}) and x^ℓ (for t_ℓ). Taking $1 \le i,j \le n$ and $\ell \in \mathcal{L}$, we see that J contains all monomials in $H_d(\mathbb{C}^n)$. □

As a special case (used later in Theorem 4.6), we obtain the familiar result that after appropriate linear changes of variable, a general binary quartic may be written as $x^4 + 6\lambda x^2y^2 + y^4$. It is classically known (see [9, §211]) that for a given general quartic, there are six different values of λ: $\pm\lambda, \pm\frac{1-\lambda}{1+3\lambda}, \pm\frac{1+\lambda}{1-3\lambda}$. We do not know any other quantitative results about the number of different values for the t_k's which appear in (2.7).

Wakeford asserts that Theorem 1.8 is also true with $x_i^{d-1}x_j$ replaced by $x_i^{d-r}x_j^r$ (evidently when $r \neq \frac{d}{2}$), but his proof seems sketchy. He also gives necessary conditions for sets of $n(n-1)$ monomials which may be omitted, and these are hard to follow as well. Below, we answer his question in the binary case: in the only two excluded cases below, (2.8) has a square factor, and so cannot be canonical.

Theorem 2.4. *Let $\mathcal{B} = (m_1, m_2, n_1, n_2)$ be four distinct integers in $\{0, \dots, d\}$ so that $\{m_1, m_2\} \neq \{0, 1\}, \{d-1, d\}$. Then, after an invertible linear change of variable, a general binary form p of degree d can be written as*

$$p(x, y) = x^{d-n_1}y^{n_1} + x^{d-n_2}y^{n_2} + \sum_{k \notin \mathcal{B}} t_k x^{d-k}y^k \tag{2.8}$$

for some $\{t_k\} \subset \mathbb{C}$.

Proof. Writing $(x, y) \mapsto (\alpha_1 x + \alpha_2 y, \alpha_3 x + \alpha_4 y) := (X, Y)$, we have

$$F = X^{d-n_1}Y^{n_1} + X^{d-n_2}Y^{n_2} + \sum_{k \notin \mathcal{B}} t_k X^{d-k}Y^k. \tag{2.9}$$

Evaluate the partials of (2.9) at $(\alpha_1, \alpha_2, \alpha_3, \alpha_4) = (1, 0, 0, 1)$ (so $X = x, Y = y$) and $t_k = 1$ (note the difference with the previous proof, in which $t_k = 0$). The $d-3$ partials with respect to the t_k's are simply $x^{d-k}y^k$, $k \notin \mathcal{B}$, so these are in J. Further,

$$\frac{\partial F}{\partial \alpha_1} = \sum_{j \neq m_1, m_2} (d-j)x^{d-j}y^j, \quad \frac{\partial F}{\partial \alpha_4} = \sum_{j \neq m_1, m_2} j x^{d-j}y^j. \tag{2.10}$$

Since most monomials used in (2.10) are already in J, it follows that J also contains

$$(d-n_1)x^{d-n_1}y^{n_1} + (d-n_2)x^{d-n_2}y^{n_2}, \quad n_1 x^{d-n_1}y^{n_1} + n_2 x^{d-n_2}y^{n_2}, \tag{2.11}$$

and since $(d-n_1)n_2 \neq (d-n_2)n_1$, (2.11) implies that $x^{d-n_j}y^{n_j} \in J$ for $j = 1, 2$. To this point, we have shown that J contains all monomials from $H_d(\mathbb{C}^2)$ except for $x^{d-m_j}y^{m_j}$, where $m_1 < m_2$. The two remaining partial derivatives are

$$\frac{\partial F}{\partial \alpha_2} = \sum_{j \neq m_1, m_2} (d-j)x^{d-j-1}y^{j+1}, \quad \frac{\partial F}{\partial \alpha_3} = \sum_{j \neq m_1, m_2} j x^{d-j+1}y^{j-1}, \tag{2.12}$$

and so J contains as well the forms in (2.12) of the shape $c_1 x^{d-m_1}y^{m_1} + c_2 x^{d-m_2}y^{m_2}$. We need to distinguish a number of cases. If $m_1 = 0, m_2 = d$, then these forms are y^d, x^d. If $m_1 = 0$ and $2 \le m_2 \le d-1$, then these forms are $(d-m_2)x^{d-m_2}y^{m_2}$ and $x^d + (m_2+1)x^{d-m_2}y^{m_2}$, and similarly when $1 \le m_1 \le d-2$ and $m_2 = d$. In the remaining cases, $1 \le m_1 < m_2 \le d-1$. If $m_2 = m_1 + 1$, then these forms are

$(d-(m_1-1))x^{d-m_1}y^{m_1}$ and $(m_2+1)x^{d-m_2}y^{m_2}$. Finally, if $m_2 > m_1+1$, then all four terms appear, and the forms are

$$\begin{aligned}(d-m_1+1)x^{d-m_1}y^{m_1} + (d-m_2+1)x^{d-m_2}y^{m_2},\\ (m_1+1)x^{d-m_1}y^{m_1} + (m_2+1)x^{d-m_2}y^{m_2}.\end{aligned} \tag{2.13}$$

In each of the cases, linear combinations of the forms produce the missing monomials, so $J = H_d(\mathbb{C}^2)$. □

Remark. By writing $p(x,y) = \prod_k (x+\alpha_k y)$, it follows from Theorem 1.8 that, for a general set of d complex numbers α_k, there exists a Möbius transformation T so that

$$\sum_{k=1}^d T(\alpha_k) = 0, \quad \sum_{k=1}^d T(\tfrac{1}{\alpha_k}) = 0, \quad \prod_{k=1}^d T(\alpha_k) = 1. \tag{2.14}$$

Non-constructive proof of Theorem 1.9. Write (1.11) as $F(x;t)$, where

$$\begin{aligned}q(x_1,x_2,x_3) &= t_1x_1^2 + t_2x_2^2 + t_3x_3^2 + t_4x_1x_2 + t_5x_1x_3 + t_6x_2x_3,\\ \ell_k(x_1,x_2,x_3) &= t_{k1}x_1 + t_{k2}x_2 + t_{k3}x_3.\end{aligned}$$

Evaluate the partials at: $q = x_1x_2 + x_1x_3 + x_2x_3$ and $(\ell_1,\ell_2,\ell_3) = (x_1,x_2,x_3)$. Then $\frac{\partial F}{\partial t_{k\ell}} = 4x_\ell x_k^3$, so $x_i^4, x_i^3x_j \in J$; since $\frac{\partial F}{\partial t_1} = 2x_1^2 q = 2x_1^2(x_1x_2+x_1x_3+x_2x_3)$, it follows that $x_1^2x_2x_3 \in J$, similarly, by considering $\frac{\partial F}{\partial t_2}$ and $\frac{\partial F}{\partial t_3}$, it follows that $x_1x_2^2x_3, x_1x_2x_3^2$ are in J. Finally, $\frac{\partial F}{\partial t_4} = 2x_1x_2q = 2x_1x_2(x_1x_2+x_1x_3+x_2x_3)$, and so now $x_1^2x_2^2 \in J$. Similarly, by considering $\frac{\partial F}{\partial t_5}$ and $\frac{\partial F}{\partial t_6}$, it follows that $x_1^2x_3^2, x_2^2x_3^2$ are also in J, and this accounts for all monomials in $H_4(\mathbb{C}^3)$. □

Other applications of Corollary 2.3 to canonical forms can be found in [8], [37] and [41, pp.265-269].

3. Apolarity

Using the notation of (2.1) and (2.2), for $p,q \in H_d(\mathbb{C}^n)$, define the following bilinear form:

$$[p,q] = \sum_{i\in\mathcal{I}(n,d)} c(i)a(p;i)a(q;i). \tag{3.1}$$

Recall two basic notations. For $\alpha \in \mathbb{C}^n$, define $(\alpha\cdot)^d \in H_d(\mathbb{C}^n)$ by

$$(\alpha\cdot)^d(x) = (\alpha\cdot x)^d = \left(\sum_{j=1}^n \alpha_j x_j\right)^d = \sum_{i\in\mathcal{I}(n,d)} c(i)\alpha^i x^i. \tag{3.2}$$

Define the differential operator $f(D)$ for $f \in H_e(\mathbb{C}^n)$ in the usual way by

$$f(D) = \sum_{i\in\mathcal{I}(n,e)} c(i)a(f;i)\left(\frac{\partial}{\partial x_1}\right)^{i_1}\cdots\left(\frac{\partial}{\partial x_n}\right)^{i_n}. \tag{3.3}$$

It follows immediately that for $\alpha \in \mathbb{C}^n$,

$$[p, (\alpha\cdot)^d] = \sum_{i \in \mathcal{I}(n,d)} c(i) a(p;i) \alpha^i = p(\alpha), \tag{3.4}$$

If $i \neq j \in \mathcal{I}(n,d)$, then $i_k > j_k$ for some k, so $D^i x^j = 0$; otherwise $D^i x^i = \prod_k (i_k)! = d!/c(i)$. Suppose $p, q \in H_d(\mathbb{C}^n)$. Bilinearity and (3.3) imply the classical result that

$$p(D)q = \sum_{i \in \mathcal{I}(n,d)} c(i) a(p;i) D^i \left(\sum_{j \in \mathcal{I}(n,d)} c(j) a(q;j) x^j \right) =$$

$$\sum_{i \in \mathcal{I}(n,d)} \sum_{j \in \mathcal{I}(n,d)} c(i) c(j) a(p;i) a(q;j) D^i x^j = \sum_{i \in \mathcal{I}(n,d)} c(i) c(i) a(p;i) a(q;i) D^i x^i \tag{3.5}$$

$$= \sum_{i \in \mathcal{I}(n,d)} c(i)^2 a(p;i) a(q;i) \frac{d!}{c(i)} = d![p,q] = d![q,p] = q(D)p.$$

Definition. If $p \in H_d(\mathbb{C}^n)$ and $q \in H_e(\mathbb{C}^n)$, then p and q are *apolar* if $p(D)q = q(D)p = 0$.

Note that if $d = e$, then p and q are apolar if and only if $[p,q] = 0$ and if $d > e$, say, then the equation $p(D)q = 0$ is automatic, so only $q(D)p = 0$ need be checked. By (3.4), p is apolar to $(\alpha\cdot)^d$ if and only if $p(\alpha) = 0$.

The following lemma is both essential and trivial.

Lemma 3.1. *Suppose $X = span(\{h_j\}) \subseteq H_d(\mathbb{C}^n)$. Then $X = H_d(\mathbb{C}^n)$ if and only if there is no $0 \neq p \in H_d(\mathbb{C}^n)$ which is apolar to each of the h_j's.*

From this point of view, Theorem 3.2 is a direct consequence of Corollary 2.3:

Theorem 3.2 (Lasker-Wakeford)**.** *If $F : \mathbb{C}^N \to H_d(\mathbb{C}^n)$, then F is a canonical form if and only if there is a point u so that there is no non-zero form $q \in H_d(\mathbb{C}^n)$ which is apolar to all N forms $\{\frac{\partial F}{\partial t_k}(u)\}$.*

The attribution "Lasker-Wakeford" (for [23, 45]) is taken from [41]: H. W. Turnbull (1885-1961) was one of the last practicing invariant theorists who had been trained in the pre-Hilbert approach, see [10, pp.231-232]. (His text [41] is a Rosetta Stone for understanding the 19th century approach to algebra in more modern terminology.) Turnbull referred to Theorem 3.2 as "paradoxical and very curious". E. Lasker (1868-1941) received his Ph.D. under M. Noether at Göttingen in 1902. He is probably better known for being the world chess champion for 27 years (1894-1921), spanning the life of E. K. Wakeford (1894-1916). J. H. Grace, Wakeford's professor at Oxford, edited the second half of his thesis into the article [45] and also wrote a memorial article [13] for him in 1918:

> "He [EKW] was slightly wounded early in 1916, and soon after coming home was busy again with Canonical Forms.... [H]e discovered a paper of Hilbert's which contained the very theorem he had long been in

> want of – first vaguely, and later quite definitely. This was in March; April found him, full of the most joyous and reverential admiration for the great German master, working away in fearful haste to finish the dissertation ... He returned to the front in June and was killed in July.... He only needed a chance, and he never got it."

The following properties are easily established; see, e.g., [31, 33] for proofs.

Theorem 3.3.
(i) If $f \in H_e(\mathbb{C}^n)$, $g \in H_{d-e}(\mathbb{C}^n)$ and $p \in H_d(\mathbb{C}^n)$, then

$$d![fg, p] = (fg)(D)p = f(D)g(D)p = e![f, g(D)p]. \tag{3.6}$$

Thus, p is apolar to every multiple of g in $H_d(\mathbb{C}^n)$ if and only if p and g are apolar.
(ii) If $p \in H_d(\mathbb{C}^n)$, then $\frac{1}{d}\frac{\partial p}{\partial x_j}(\alpha) = [p, x_j(\alpha\cdot)^{d-1}]$. Thus, p is apolar to $(\alpha\cdot)^{d-1}$ if and only if p is singular at α. More generally, p is apolar to $(\alpha\cdot)^{d-e}$ if and only if p vanishes to e-th order at α.
(iii) If $e \le d$ and $g \in H_{d-e}(\mathbb{C}^n)$, then $g(D)(\alpha\cdot)^d = \frac{d!}{e!}g(\alpha)(\alpha\cdot)^e$.

By (2.5), if $h(x) = \sum_{\ell \in \mathcal{I}(n,e)} t_\ell x^\ell$ and $F(t;x)$ contains h^s as a summand, then $\frac{\partial F}{\partial t_\ell} = s x^\ell h^{s-1}$, and if p is apolar to each $\frac{\partial F}{\partial t_\ell}$, then it is apolar to h^{s-1}. It is critical to note that this observation fails in case h is defined as a sum from a restricted set of monomials.

We are now able to give a short proof of the "Second main theorem on apolarity" from [8], which was not concerned with preserving the constant-count.

Theorem 3.4. *Suppose $j_\ell = (j_{\ell,1}, \dots, j_{\ell,m})$, $1 \le \ell \le r$, are m-tuples of non-negative integers, and suppose positive integers d_k, $1 \le k \le m$, and d are chosen so that*

$$u_\ell := d - \sum_{k=1}^{m} j_{\ell,k} d_k \ge 0. \tag{3.7}$$

Fix forms $q_\ell \in H_{u_\ell}(\mathbb{C}^n)$ and for $f_k \in H_{d_k}(\mathbb{C}^n)$, define

$$F(f_1, \dots, f_m) = \sum_{\ell=1}^{r} q_\ell(x) f_1^{j_{\ell,1}} \cdots f_m^{j_{\ell,m}}. \tag{3.8}$$

Let $F_j := \frac{\partial F}{\partial f_j}$. Then a general $p \in H_d(\mathbb{C}^n)$ can be written as (3.8) if and only if there exists a specific $\bar{f} = (\bar{f}_k)$ so that no non-zero $p \in H_d(\mathbb{C}^n)$ is apolar to each $F_j(\bar{f})$, $1 \le j \le m$. If, in addition,

$$\sum_{k=1}^{m} N(n, d_k) = N(n, d), \tag{3.9}$$

then (3.8) is a canonical form.

Proof. Let

$$f_j(x) = \sum_{i_v \in \mathcal{I}(n,d_j)} t_{j,v} x^{i_v}. \tag{3.10}$$

By Theorem 2.2, (3.7) and Lemma 3.1, (3.8) represents general $p \in H_d(\mathbb{C}^n)$ if and only if there is some $\bar{f}$ so that there is no non-zero form in $p \in H_d(\mathbb{C}^n)$ which is apolar to each $\frac{\partial F}{\partial t_{j,v}}(\bar{f}) = d_k x^{i_v} F_j(\bar{f})$, or by Theorem 3.3(i), to each $F_j(\bar{f})$. The constant count is checked by (3.9). □

By Theorem 3.3(ii) and Theorem 3.4, $F = \sum_{k=1}^r (\alpha_k \cdot)^d$ is a canonical form if and only if there exist r points $\bar{\alpha}_k \in \mathbb{C}^n$ at which no non-zero form $p \in H_d(\mathbb{C}^n)$ is singular. This result is classical. A particularly deep result of Alexander and Hirschowitz [1] from the early 1990s states that a general form in $H_d(\mathbb{C}^n)$, $d \geq 3$, may be written as a sum of $\lceil \frac{1}{n} N(n,d) \rceil$ d-th powers of linear forms, except when $(n,d) = (5,3),(3,4),(4,4),(5,4)$, when an extra summand is needed. (For much more on this, see [12, Lecture 7], [16, Cor.1.62], [21, Ch.15] and [29, Thm.0.2]; for a brief exposition of the proof, see [21, Ch.15].) These references also discuss the exceptional examples, which were all known in the 19th century. The expression of forms as a sum of powers of forms is currently a very active area of interest; see the references above as well as [3], [11] and [22].

The Fundamental Theorem of Apolarity (see [33] for a history) states that if f is irreducible and $p \in H_d(\mathbb{C}^n)$, then f and p are apolar if and only if p can be written as a sum of terms of the form $(\alpha \cdot)^d$, where $f(\alpha_j) = 0$. This was generalized in [33].

Theorem 3.5. [33, Thm. 4.1] *Suppose $q \in H_e(\mathbb{C}^n)$ factors as $\prod_{j=1}^r q_j^{m_j}$ into a product of distinct irreducible factors and suppose $p \in H_d(\mathbb{C}^n)$. Then $q(D)p = 0$ if and only if there exist $\alpha_{jk} \subset \{q_j(\alpha) = 0\}$, and $\phi_{jk} \in H_{m_j-1}(\mathbb{C}^n)$ such that*

$$p(x) = \sum_{j=1}^r \left(\sum_{k=1}^{n_j} \phi_{jk}(x)(\alpha_{jk} \cdot x)^{d-(m_j-1)} \right).$$

The application of apolarity to binary forms is particularly simple, because zeros correspond to factors. If $e = d+1$, then $q(D)p = 0$ for every $p \in H_d(\mathbb{C}^n)$, and we obtain the following result, also found in [8, Thm.4.5].

Corollary 3.6. *Suppose $\{\alpha_j x + \beta_j y : 1 \leq j \leq r\}$ is honest and suppose $\sum_{j=1}^r m_j = d+1$. Then the following set is a basis for $H_d(\mathbb{C}^2)$:*

$$\mathcal{S} = \left\{ x^k y^{m_j-1-k} (\beta_j x - \alpha_j y)^{d-m_j+1} : 0 \leq k \leq m_j - 1, \quad 1 \leq m_j \leq r \right\}. \tag{3.11}$$

Proof. If p is apolar to each term in (3.11), then $(\alpha_j x + \beta_j y)^{m_j} \mid p$ by Theorem 3.3(ii). Thus $p = 0$ by degree considerations, and $\mathcal{S}$ has $d+1$ elements, so it is a basis. □

If each $m_j = 1$, then Corollary 3.6 states that an honest set $\mathcal{S} = \{(\alpha_j x + \beta_j y)^d\}$ of $d+1$ forms is a basis for $H_d(\mathbb{C}^2)$. This is easily proved directly, since the representation of $\mathcal{S}$ with respect to the basis $\{\binom{d}{j}x^{d-j}y^j\}$, $[\alpha_j^{d-k}\beta_j^k]$, has Vandermonde determinant

$$\prod_{1\le i<j\le n}(\alpha_i\beta_j-\alpha_j\beta_i). \tag{3.12}$$

Each product in (3.12) is non-zero because $\{(\alpha_j x+\beta_j y)^d\}$ is honest. One implication of this independence is found in [35, Cor.4.3].

Lemma 3.7. *If $p(x,y)\in H_d(\mathbb{C}^2)$ has two honest representations*

$$p(x,y)=\sum_{i=1}^{m}(\alpha_i x+\beta_i y)^d=\sum_{j=1}^{n}(\gamma_j x+\delta_j y)^d \tag{3.13}$$

and $m+n\le d+1$, then the representations are permutations of each other.

Proof. If (3.13) holds, then $\{(\alpha_i x+\beta_i y)^d,(\gamma_j x+\delta_j y)^d\}$ is linearly dependent, which is impossible unless the dependence is trivial. □

It follows immediately from Lemma 3.7 that the representations (1.2) and (1.3), if they exist for p, are unique. When $n\ge 3$, the linear dependence of a set $\{(\alpha_j\cdot)^d\}$ depends on the geometry of the points as well as the number (see the discussion of Serret's Theorem in [31, p.29].) Even for powers of binary forms of degree $e\ge 2$, there are singular cases. It is not hard to show that a *general* set of $(2k+1)$ k-th powers of quadratic forms is linearly independent; however, for example, $(x^2-y^2)^2+(2xy)^2=(x^2+y^2)^2$. For much more on this, see [36].

Non-constructive proof of Theorem 1.6. For $1\le k\le r$, write

$$f_k(x,y)=\sum_{\ell=0}^{e_k}t_{k,\ell}x^{e_k-\ell}y^\ell.$$

By Corollary 2.3 and (2.5), (1.8) is a canonical form in the variables $\{t_j,t_{k,\ell}\}$ provided there is a point at which the partials

$$\{\ell_j^d,\ 1\le j\le m\}\cup\ \{x^{e_k-\ell}y^\ell f_k^{d/e_k-1},\ 1\le \ell\le e_k,\quad 1\le k\le r\}$$

span $H_d(\mathbb{C}^2)$. Let $f_k=\tilde{\ell}_k^{e_k}$, where $\{\ell_1,\dots,\ell_m,\tilde{\ell}_1,\dots,\tilde{\ell}_r\}$ is chosen to be honest. Then by (1.7), the desired assertion follows immediately from Corollary 3.6. □

We present now Sylvester's Algorithm. For modern discussions of this, along with Gundelfinger's generalization [15], which is not included here, see [20, §5], [17],[18], [19], [33] and [35].

Theorem 3.8 (Sylvester's Algorithm)**.** *Let*

$$p(x,y)=\sum_{j=0}^{d}\binom{d}{j}a_j x^{d-j}y^j$$

be a given binary form and suppose $\{\alpha_j x + \beta_j y\}$ *is an honest set. Let*

$$h(x,y) = \sum_{t=0}^{r} c_t x^{r-t} y^t = \prod_{j=1}^{r} (\beta_j x - \alpha_j y).$$

Then there exist $\lambda_k \in \mathbb{C}$ *so that*

$$p(x,y) = \sum_{k=1}^{r} \lambda_k (\alpha_k x + \beta_k y)^d$$

if and only if

$$\begin{pmatrix} a_0 & a_1 & \cdots & a_r \\ a_1 & a_2 & \cdots & a_{r+1} \\ \vdots & \vdots & \ddots & \vdots \\ a_{d-r} & a_{d-r+1} & \cdots & a_d \end{pmatrix} \cdot \begin{pmatrix} c_0 \\ c_1 \\ \vdots \\ c_r \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{pmatrix}. \tag{3.14}$$

Theorem 3.8 can be put in the context of our previous discussion. Let $A_r(p)$ denote the $(d-r+1) \times (r+1)$ Hankel matrix on the left-hand side of (3.14). If $h(D) = \prod_{j=1}^{r} (\beta_j \frac{\partial}{\partial x} - \alpha_j \frac{\partial}{\partial y})$, then a direct computation shows that

$$h(D)p = \sum_{m=0}^{d-r} \frac{d!}{(d-r-m)!m!} \left(\sum_{i=0}^{d-r} a_{i+m} c_i \right) x^{d-r-m} y^m. \tag{3.15}$$

It follows from (3.15) that the coefficients of $h(D)p$ are thus, up to multiple, the rows of the matrix product, so (3.14) is equivalent to $h(D)p = 0$. In this way, Theorem 3.8 follows from Theorem 3.5. Sylvester's algorithm can also be visualized as seeking constant-coefficient linear recurrences satisfied by $\{a_k\}$ and looking for the shortest one whose characteristic equation has distinct roots; this is the proof given in [35]. In this case, Gundelfinger's results handle the case when the roots are not distinct.

Constructive proof of Theorem 1.1. Suppose $d = 2s-1$ is odd. The matrix $A_s(p)$ is $s \times (s+1)$ and has a non-trivial null-vector. The corresponding h (which can be given in terms of the coefficients of p) has distinct factors unless its discriminant vanishes. Thus for general $p \in H_{2s-1}(\mathbb{C}^2)$, Theorem 3.8 gives p as a sum of s $(2s-1)$-st powers of linear forms.

If $d = 2s$, the matrix $A_s(p)$ is square, and if p is a sum of s $2s$-th powers, then $\det A_s(p) = 0$. Conversely, if $\det A_s(p) = 0$ and the corresponding h has distinct factors (which is generally true), then p is a sum of s $2s$-th powers. If M_1 and M_2 are two square matrices and $\operatorname{rank}(M_2) = k$, then $\det(M_1 + \lambda M_2)$ is a polynomial in λ of degree k. In particular, if $q = (\alpha x + \beta y)^{2s}$, then $\operatorname{rank}(H_s(q)) = 1$. Thus, in general, there is a unique value of λ and some matrix M so that $0 = \det A_s(p - \lambda(\alpha x + \beta y)^{2s}) = \det A_s(p) - \lambda \det M$. (When $\alpha x + \beta y = x$, M is the (1,1)-cofactor of $A_s(p)$.) In the special case $\alpha x + \beta y = x$, this proves Theorem 1.1(ii). The same argument shows that for general $q \in H_{2s}(\mathbb{C}^2)$, there exist $s+1$ values of λ so that $p - \lambda q$ is a sum of s $2s$-th powers. $\square$

In 1869, Sylvester [40] recalled his discovery of this algorithm and its consequences.

> "I discovered and developed the whole theory of canonical binary forms for odd degrees, and, as far as yet made out, for even degrees too, at one evening sitting, with a decanter of port wine to sustain nature's flagging energies, in a back office in Lincoln's Inn Fields. The work was done, and well done, but at the usual cost of racking thought — a brain on fire, and feet feeling, or feelingless, as if plunged in an ice-pail. *That night we slept no more.*"

Example 3.1. This example of Sylvester's algorithm will be used in Example 4.1. Let $p(x,y) = 2x^3+3x^2y-21xy^2-41y^3 = \binom{3}{0}\cdot 2\,x^3+\binom{3}{1}\cdot 1\,x^2y+\binom{3}{2}\cdot(-7)\,xy^2+\binom{3}{3}\cdot(-41)\,y^3$ Since

$$\begin{pmatrix} 2 & 1 & -7 \\ 1 & -7 & -41 \end{pmatrix} \cdot \begin{pmatrix} 6 \\ -5 \\ 1 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix},$$

we have $h(x,y) = 6x^2 - 5xy + y^2 = (2x-y)(3x-y)$. It now follows that $p(x,y) = \lambda_1(x+2y)^3 + \lambda_2(x+3y)^3$, and a simple computation shows that $\lambda_1 = 5, \lambda_2 = -3$.

Lemma 3.1, when applied to Theorem 2.1, yields the following corollary.

Corollary 3.9. *A basis for $H_d(\mathbb{C}^n)$ is given by $\{(i\cdot)^d : i \in \mathcal{I}(n,d)\}$.*

This in turn gives a weak version of the Alexander-Hirschowitz Theorem,

Corollary 3.10. *A general form in $H_d(\mathbb{C}^n)$ is a sum of $N(n,d-1) = \frac{nd}{n+d-1}\cdot\frac{1}{n}N(n,d)$ d-th powers of linear forms.*

Proof. Consider the sum

$$\sum_{\ell=1}^{N(n,d-1)} (t_{\ell,1}x_1 + \cdots + t_{\ell,n}x_n)^d,$$

and apply Corollary 2.3 with t_ℓ specialized to $i_\ell \in \mathcal{I}(n,d-1)$. Then J contains $x_k(i_\ell\cdot)^{d-1}$ for each k,ℓ and hence $x_kH_{d-1}(\mathbb{C}^n) \subseteq J$ for each k, so $J = H_d(\mathbb{C}^n)$. $\square$

4. Some new binary canonical forms

This section is devoted to special cases of Theorem 1.6. First, if $e_k = 1$, we give a constructive proof showing uniqueness, which gives a kind of interpolation between Sylvester's Theorem and the representations of $H_d(\mathbb{C}^2)$ by (2.4) with a fixed basis consisting of d-th powers, as in Corollary 3.6.

Corollary 4.1. *Suppose $d \ge 1$, and $\{\ell_j(x,y) = \alpha_jx + \beta_jy\}$ is a fixed honest set of $m = d+1-2r$ linear forms. Then a general binary d-ic form $p \in H_d(\mathbb{C}^2)$ can be written uniquely as*

$$p(x,y) = \sum_{j=1}^{m} t_j(\alpha_jx+\beta_jy)^d + \sum_{k=1}^{r}(t_{k1}x+t_{k2}y)^d. \tag{4.1}$$

for some $t_k \in \mathbb{C}$.

Proof. Let

$$f(x,y) = \prod_{j=1}^{m} (\beta_j x - \alpha_j y).$$

Then $f(D)p$ has degree $d - m = 2r - 1$ and by Theorem 3.8 generally has a unique representation as a sum of r $2r-1$-st powers of linear forms, say

$$f(D)p = \sum_{k=1}^{r} (u_{k1}x + u_{k2}y)^{2r-1}. \tag{4.2}$$

Further, it is generally true that $f(u_{k1}, u_{k2}) \neq 0$. Let

$$q(x,y) = \frac{(2r-1)!}{d!} \sum_{k=1}^{r} \frac{(u_{k1}x + u_{k2}y)^d}{f(u_{k1}, u_{k2})}. \tag{4.3}$$

It follows from Theorem 3.3(iii), (4.2) and (4.3) that $f(D)p = f(D)q$. Since f has distinct factors, it then follows from Theorem 3.8 that there exist $t_j \in \mathbb{C}$ so that

$$p(x,y) - q(x,y) = \sum_{j=1}^{m} t_j (\alpha_j x + \beta_j y)^d.$$

Conversely, suppose p has two different representations:

$$\sum_{j=1}^{m} t_j \ell_j^d(x,y) + \sum_{k=1}^{r} (t_{k1}x + t_{k2}y)^d = \sum_{j=1}^{m} \tilde{t}_j \ell_j^d(x,y) + \sum_{k=1}^{r} (\tilde{t}_{k1}x + \tilde{t}_{k2}y)^d. \tag{4.4}$$

By combining the first sum on each side, (4.4) becomes a linear dependence with $m + 2r = d + 1$ summands, which by Lemma 3.7 must be trivial; thus, the representations in (4.4) are essentially the same. $\square$

Example 4.1. Let $\ell_1(x,y) = x + y$ and $\ell_2(x,y) = -x + 3y$ and let

$$p(x,y) = -x^5 + 15x^4y - 170x^3y^2 + 390x^2y^3 - 505x^2y^3 + 483y^5.$$

In an application of the last proof, $f(x,y) = (x-y)(3x+y) = 3x^2 - 2xy - y^2$, and

$$3\frac{\partial^2 p}{\partial x^2} - 2\frac{\partial^2 p}{\partial x \partial y} - \frac{\partial^2 p}{\partial y^2} = 160x^3 + 240x^2y - 1680xy^2 - 3280y^3.$$

Example 3.1 implies that this expression equals $400(x+2y)^3 - 240(x+3y)^3$. Since $f(1,2) = -5$ and $f(1,3) = -12$, it follows that

$$p(x,y) =$$
$$\frac{3! \cdot 400}{5! \cdot (-5)}(x+2y)^5 + \frac{3! \cdot (-240)}{5! \cdot (-12)}(x+3y)^5 + t_1(x+y)^5 + t_2(-x+3y)^5 =$$
$$-4(x+2y)^5 + (x+3y)^5 + t_1(x+y)^5 + t_2(-x+3y)^5$$

and it can be readily be computed that $t_1 = \frac{7}{2}$ and $t_2 = \frac{3}{2}$.

If each $e_k = 2$ in Theorem 1.6 and m is as small as possible, then we obtain an analogue of Sylvester's Theorem for forms of even degree.

Corollary 4.2.
(i) A general binary form of degree $d = 6s$ can be written as

$$\lambda x^{6s} + \sum_{j=1}^{2s} (\alpha_j x^2 + \beta_j xy + \gamma_j y^2)^{3s} \tag{4.5}$$

for some $\lambda \in \mathbb{C}$.
(ii) A general binary form of degree $d = 6s+2$ can be written as

$$\sum_{j=1}^{2s+1} (\alpha_j x^2 + \beta_j xy + \gamma_j y^2)^{3s+1}. \tag{4.6}$$

(iii) A general binary form of degree $d = 6s+4$ can be written as

$$\lambda_1 x^{6s+4} + \lambda_2 y^{6s+4} + \sum_{j=1}^{2s+1} (\alpha_j x^2 + \beta_j xy + \gamma_j y^2)^{3s+2} \tag{4.7}$$

for some $\lambda_i \in \mathbb{C}$.

We have not been able to find an analogue to Sylvester's Algorithm for determining the representations (4.5), (4.6), (4.7) in Corollary 4.2. In the linear case, $(\alpha x + \beta y)^d$ is killed by $\beta \frac{\partial}{\partial x} - \alpha \frac{\partial}{\partial y}$, and two operators of this shape commute. Although each $(\alpha x^2 + 2\beta xy + \gamma y^2)^d$ is killed by the non-constant-coefficient $(\beta x + \gamma y)\frac{\partial}{\partial x} - (\alpha x + \beta y)\frac{\partial}{\partial y}$, two operators of this kind do not usually commute. The smallest constant-coefficient differential operator which kills $(\alpha x^2 + 2\beta xy + \gamma y^2)^d$ has degree $d+1$; the product of any two of these would kill every form of degree $2d$ and so provide no information.

Let us say that (1.8) is a *neat* canonical form if $m = 0$, and of *Sylvester-type* if it is neat and if $e_k = e$ for $1 \le k \le r$. Counting the numbers of neat and Sylvester-type canonical forms leads to some number theory. The first lemma is standard.

Lemma 4.3. *Given $0 < \frac{p}{q} \in \mathbb{Q}$ and $0 < n \in \mathbb{N}$, there exist only finitely many choices of $m_j \in \mathbb{Z}$, $0 < m_1 \le m_2 \cdots \le m_n$, such that $\frac{p}{q} = \sum_{j=1}^{n} \frac{1}{m_j}$.*

Proof. If $n = 2$, then $\frac{p}{q} > \frac{1}{m_1} \ge \frac{p}{2q}$ implies that there are finitely many integral choices for m_1, each of which determines $m_2 = (\frac{p}{q} - \frac{1}{m_1})^{-1}$. Supposing the lemma valid for $n-1$, we have $\frac{p}{q} > \frac{1}{m_1} \ge \frac{p}{nq}$, and each choice of m_1 implies the equation $\frac{p}{q} - \frac{1}{m_1} = \sum_{j=2}^{n} \frac{1}{m_j}$. This has finitely many solutions by the induction hypothesis. $\square$

Theorem 4.4. *For fixed value of r, there are only finitely many neat canonical forms* (1.8) *with r summands.*

Proof. Suppose $m = 0$ in Theorem 1.6. Write $d = e_k m_k$, then by (1.7),

$$d + 1 = \sum_{k=1}^{r} \left(\frac{d}{m_k} + 1 \right) \implies 1 = \sum_{k=1}^{r} \frac{1}{m_k} + \frac{r-1}{d} = \sum_{k=1}^{r} \frac{1}{m_k} + \sum_{\ell=1}^{r-1} \frac{1}{d}. \tag{4.8}$$

Now apply Lemma 4.3 with $\frac{p}{q} = 1$ and $n = 2r - 1$: there are only finitely many expressions of 1 as a sum of $2r - 1$ unit fractions, of which only a subset satisfy the additional restrictions of (4.8). $\square$

It is not hard to work out that for $r = 2$, there are three neat canonical forms: $(d, e_1, e_2) = (3, 1, 1)$, $(4, 2, 1)$ and $(6, 3, 2)$. The first is Theorem 1.1(i) with $d = 3$, the second is Corollary 1.7 with $d = 4$ (see Theorem 4.6 below), and the third is Theorem 1.5. When $r = 3$, there are twenty-two neat canonical forms.

Let $s(d)$ denote the number of neat Sylvester-type canonical forms of degree d. Suppose $e_k = e$ for all k in one of these. Then $e \mid d$ and, by (1.7), $r(e+1) = d+1$, so $(e+1) \mid (d+1)$. Since $d \equiv 0 \pmod{e}$ and $d \equiv -1 \pmod{(e+1)}$, it follows from the Chinese Remainder Theorem that $d \equiv e \pmod{e(e+1)}$; that is, $d = e + ue(e+1)$, $u \geq 1$, so that $e < \sqrt{d}$.

Theorem 4.5. *Let $S(N) := \sum_{d=1}^{N} s(d)$. Then $S(N) = N + \mathcal{O}(N^{1/2})$ and $\sup_d s(d) = \infty$.*

Proof. The generating function for the sequence $(s(d))$ is

$$\sum_{n=1}^{\infty} s(d)x^d = \sum_{e=1}^{\infty} \sum_{u=1}^{\infty} x^{e+ue(e+1)} = \sum_{e=1}^{\infty} \frac{x^{e^2+2e}}{1 - x^{e^2+e}}. \tag{4.9}$$

Let $T = \lfloor N^{1/2} \rfloor$. It follows from (4.9) that

$$S(N) = \sum_{n=1}^{N} s_n = \sum_{e=1}^{\infty} \left\lfloor \frac{N-e}{e^2+e} \right\rfloor = \sum_{e=1}^{T} \left\lfloor \frac{N-e}{e^2+e} \right\rfloor. \tag{4.10}$$

Thus, using the telescoping sum for $\sum \frac{1}{e(e+1)}$, (4.10) implies that

$$\begin{aligned} S(N) &\leq \sum_{e=1}^{T} \frac{N-e}{e^2+e} = N \sum_{e=1}^{T} \frac{1}{e^2+e} - \sum_{e=1}^{T} \frac{1}{e+1} \\ &\leq N(1 - \tfrac{1}{T+1}) - \log T + \mathcal{O}(1) = N - N^{1/2} + \mathcal{O}(\log N). \end{aligned} \tag{4.11}$$

The lower bound is the same, minus T, so (4.11) implies that $S(N) = N + \mathcal{O}(N^{1/2})$.

Now, $s(d)$ counts the number of $e < d$ so that e divides d and $e+1$ divides $d+1$. If $d = 2^r - 1$, then $e + 1 \mid 2^r$ implies that $e + 1 = 2^t$ for some $t < r$. But $2^t - 1 \mid 2^r - 1$ if and only if $t \mid r$, hence $s(2^r - 1) = d(r) - 1$, where $d(n)$ denotes the divisor function. In particular, $s(2^{2^t} - 1) = t$, so the sequence $(s(d))$ is unbounded. More generally, if $e \mid d$ and $e + 1 \mid d + 1$, then $e \mid d^2 + 2d$ and $e + 1 \mid d^2 + 2d + 1$, and since $e = d$ contributes to the count in $s(d^2 + 2d)$ but not in $s(d)$, $s(d^2 + 2d) \geq s(d) + 1$. $\square$

Half of the neat Sylvester forms come from Theorem 1.1(i), another sixth come from Corollary 4.2(ii), etc. The smallest d for which $s(d) = 2$ is $d = 15$: $(e, r) = (1, 8), (3, 4)$, so a general binary form of degree 15 is a sum of eight linear forms to the 15th power, or four cubics to the 5th power. The smallest d for which $s(d) = 3$ is $d = 99$: $(e, r) = (1, 50), (3, 25), (9, 10)$. For $d < 10^7$, the largest value of $s(d)$ is $s(7316000) = 12$. Note that $2^{2^{13}} - 1 = 2^{4096} - 1 \approx 1.04 \times 10^{1233}$, so the examples given in the proof are not likely to describe the fastest growth. We conjecture as well that $\{s(d)\}$ has an underlying distribution.

If the degree d is prime, then Theorem 4.1 accounts for all canonical forms in Theorem 1.6. The smallest d which is not covered by Theorem 4.1 is then $d = 4$, and there are two such cases, one of which is neat: $e_1 = 2, e_2 = 1, m = 0$ and $e_1 = 2, m = 2$. Both can be discussed constructively.

Theorem 4.6. *A general binary quartic $p \in H_4(\mathbb{C}^2)$ can be written as*

$$p(x, y) = (t_1x^2 + t_2xy + t_3y^2)^2 + (t_4x + t_5y)^4 \tag{4.12}$$

in six different ways. Further, the set $\{\frac{t_5}{t_4}\}$ is the image of the set $\{0, \infty, 1, -1, i, -i\}$ under a Möbius transformation.

Proof. By Theorem 2.4, if p is a general binary quartic, then there exist c_i, λ so that $p(c_1x + c_2y, c_3x + c_4y) = p_\lambda(x, y) := x^4 + 6\lambda x^2y^2 + y^4$. If (4.12) holds for p_λ, then

$$\begin{gathered} 1 = t_1^2 + t_4^4, \quad 0 = 2t_1t_2 + 4t_4^3t_5, \quad 6\lambda = 2t_1t_3 + t_2^2 + 6t_4^2t_5^2, \\ 0 = 2t_2t_3 + 4t_4t_5^3, \quad 1 = t_3^2 + t_5^4. \end{gathered} \tag{4.13}$$

First suppose that $t_4 = 0$. Then (4.13) implies that $1 = t_1^2$ and $0 = 2t_1t_2$, so $t_1 = 1$ (without loss of generality) and $t_2 = 0$. The remaining equations imply that $t_3 = 3\lambda$ and $t_5^4 = 1 - 9\lambda^2$. A similar argument works if $t_5 = 0$, giving two representations:

$$p_\lambda(x, y) = (x^2 + 3\lambda y^2)^2 + (1 - 9\lambda^2)y^4 = (3\lambda x^2 + y^2)^2 + (1 - 9\lambda^2)x^4. \tag{4.14}$$

Now suppose $t_4t_5 \neq 0$, so $t_1t_2t_3 \neq 0$ and so

$$\frac{t_3}{t_1} = \frac{-2t_2t_3}{-2t_1t_2} = \frac{4t_4t_5^3}{4t_4^3t_5} = \frac{t_5^2}{t_4^2} \implies \frac{1 - t_3^2}{1 - t_1^2} = \frac{t_5^4}{t_4^4} = \frac{t_3^2}{t_1^2} \implies t_1^2 = t_3^2.$$

It follows that $t_5 = i^kt_4$ and $t_3 = (-1)^kt_1$, and (4.13) can be completely solved:

$$t_4^4 = 1 - t_1^2, \quad t_2 = 2i^k(t_1 - t_1^{-1}), \quad 2 + 6(-1)^k\lambda = 4t_1^{-2}.$$

After some massaging of the algebra, this gives four representations:

$$\begin{aligned} p_\lambda(x, y) = {} & \left(\frac{(-1)^k 2}{3\lambda + (-1)^k}\right) \left(x^2 - i^{3k}(3\lambda - (-1)^k)xy + (-1)^ky^2\right)^2 \\ & + \left(\frac{3\lambda - (-1)^k}{3\lambda + (-1)^k}\right) \left(x + i^ky\right)^4, \quad k = 0, 1, 2, 3. \end{aligned} \tag{4.15}$$

In order to find the six representations of p as (4.12), we start with the six representations of p_λ given in (4.14) and (4.15), in which $t_4x + t_5y$ is a multiple of

d	$e_1,\dots,e_r$	m	$F(d;e)$	Source
d	$1^{\lfloor \frac{d+1}{2} \rfloor}$	0 or 1	1	Theorem 1.1
d	1^r	$d+1-2r$	1	Theorem 4.1
4	2,1	0	6	Theorem 4.6
4	2	2	2	Theorem 4.7
6	3,2	0	40	[42, 43]
6	$2,1^2$	0	22	Experiment
6	3,1	1	14	Experiment
6	2^2	1	9	Experiment
6	2,1	2	12	Experiment
6	3	3	5	Experiment
6	2	4	5	Experiment
8	$2,1^3$	0	62	Experiment
10	$2,1^4$	0	147	Experiment
12	$2,1^5$	0	308	Experiment
$2s$	$2,1^{s-1}$	0	$2\binom{s+3}{5}-\binom{s+2}{3}$	Conjecture

TABLE 1. Values of $F(d;e)$

one of the six linear forms $x, y, x+i^k y$. Apply the the inverse of the map $(x,y)\mapsto(c_1x+c_2y, c_3x+c_4y)$, which takes t_4x+t_5y to a multiple of $t_4(c_4x-c_2y)+t_5(-c_3x+c_1y)$: $\frac{t_5}{t_4}\mapsto G(\frac{t_5}{t_4})$, where $G(z)=\frac{c_1z-c_2}{c_4-c_3z}$. □

Theorem 4.7. *Given two fixed distinct binary linear forms ℓ_1,ℓ_2, a general binary quartic in $H_4(\mathbb{C}^2)$ has two representations as*

$$p(x,y)=(t_1x^2+t_2xy+t_3y^2)^2+t_4\ell_1^4+t_5\ell_2^4. \tag{4.16}$$

Proof. Given p,ℓ_1,ℓ_2, make an invertible linear change of variable taking $(\ell_1,\ell_2)\mapsto(x,y)$, and suppose $p(x,y)\mapsto q(x,y)=\sum_i a_ix^{4-i}y^i$. Then q has the shape (4.16) if and only if the coefficients of x^3y, x^2y^2, xy^3 in $(t_1x^2+t_2xy+t_3y^2)^2$ and q agree. Thus, we seek to solve the system

$$a_1=2t_1t_2,\quad a_2=2t_1t_3+t_2^2,\quad a_3=2t_2t_3. \tag{4.17}$$

But (4.17) implies $a_1t_2^2-2a_2t_1t_2+2a_3t_1^2=0$, hence in general, there are exactly two values of β so that $t_2=\beta t_1$; in each case, $t_1^2=\frac{a_1}{2\beta}$. The two choices of sign for t_1 lead to the same square, and $t_3=\frac{a_1}{a_3}t_1$, so (4.17) has these two solutions. □

In the case of Theorem 1.6 let $F(d;e_1,\dots,e_r)$ denote the number of different representations that a general $p\in H_d(\mathbb{C}^2)$ has, by our convention. We present in Table 1 a complete list of proved or conjectural values when $d\le 6$, reflecting numerical experiments on Mathematica. (Recall that if d is prime, then Theorem 4.1 presents all possible canonical forms of this type.) The conjectural value of $F(2s;2,1^{s-1})$ is suggested by the given data for $2 \le s \le 6$ and OEIS[24, A081282].

Várilly-Alvarado, in [42, 43], constructs explicitly all 240 representations of x^6+y^6 as f^2+g^3; he considers forms multiplied by roots of unity as different, which explains the appearance of $\frac{240}{2\cdot 3}$ in the table above. This is also proved to be the number of representations for a general sextic.

To describe the experiments for $F(2s;2,1^{s-1})$ more precisely, we generate a form

$$p(x,y) = \sum_{k=0}^{2s} \binom{2s}{k} a_k x^{2s-k} y^k,$$

where $a_k = t + iu$ for random integers t, u in $[-100, 100]$. In case $m \le 2$, we assume a change of variables so that the fixed linear forms are x^d or y^d; for $m > 2$ we choose additional linear forms with random coefficients. Let $h(x,y) = Ux^2 + Vxy + Wy^2$ for variables (U,V,W) and let $q(x,y) = p(x,y) - h^s(x,y)$, and apply Sylvester's Algorithm to q. That is, we construct the $(s+2)\times s$ matrix $A_{s-1}(q)$, with polynomial entries in (U,V,W) of degree s and require that it have rank $< s$. This is done by counting the number of (U,V,W) which are common zeros of all $s \times s$ minors. This number is divided by s to account for $h^s = (\zeta_s^k h)^s$. As a back of the envelope calculation, one might take the first $s-1$ rows of A_{s-1} and use the cofactors to compute a non-trivial null-vector. Ignoring possible cancellation, the components would be polynomials of degree $s(s-1)$ in (U,V,W). Taking the dot product with the last three rows of A_{s-1} gives three polynomials of degree s^2. Ignoring cancellations and multiplicity, there should be $(s^2)^3$ common zeros, and dividing by s gives an upper bound for $F(2s;2,1^{s-1})$ of s^6. The conjectural value is asymptotically $\frac{1}{60}s^5$, which at least has the same order of growth.

5. Quadratic forms and sums of squares

We begin this section with a constructive proof of Theorem 1.2 which will serve as a template for constructive proofs involving cubic forms.

Constructive Proof of Theorem 1.2. Suppose $p \in H_2(\mathbb{C}^n)$, and specifically,

$$p(x_1,\dots,x_n) = \sum_{i=1}^{n} a_{ii}x_i^2 + 2\sum_{1\le i<j\le n} a_{ij}x_ix_j.$$

Then $\frac{\partial p}{\partial x_1} = 2\sum_{j=1}^n a_{1j}x_j$, Since $a_{11} \ne 0$ in general, we can define $q(x_1,\dots,x_n) = p(x_1,\dots,x_n) - \frac{1}{a_{11}}(\sum_{j=1}^n a_{1j}x_j)^2$; observe that $\frac{\partial q}{\partial x_1} = 0$, so $q = q(x_2,\dots,x_n)$. Iterating this argument gives the construction. There is only one linear form $\pm\ell$ so that $\frac{\partial p}{\partial x_1} = 2\ell\frac{\partial \ell}{\partial x_1}$, so the representation is unique. $\square$

As we saw in the proof of Theorem 5.2, constant-counting for sums of squares is complicated by the action of the orthogonal group on a sum of t squares. If

$M \in Mat_t(\mathbb{C})$ and $MM^t = I$, then

$$\sum_{i=1}^{t} f_i^2 = \sum_{i=1}^{t} \left(\sum_{j=1}^{t} m_{ij} f_j \right)^2 .$$

When $t = 2$, choose $\theta \in \mathbb{C}$ and let $e^{i\theta} = \cos\theta + i \sin\theta := (u, v)$, so that

$$f^2 + g^2 = (uf - vg)^2 + (vf + ug)^2. \tag{5.1}$$

This means that we may safely remove one monomial from one of the summands.

Theorem 5.1. *A general binary form $p \in H_{2s}(\mathbb{C}^2)$ can be written as*

$$\left(\sum_{k=0}^{s} t_k x^{s-k} y^k \right)^2 + \left(\sum_{k=1}^{s} t_{s+k} x^{s-k} y^k \right)^2 . \tag{5.2}$$

in $\binom{2s-1}{s}$ different ways.

Proof. The non-constructive proof is a simple application of Corollary 2.3. Writing (5.2) as $f^2 + g^2$ gives the partials with respect to the t_j's as

$$\left\{ 2x^{s-k} y^k f,\ 0 \le k \le s \right\} \cup \left\{ 2x^{s-k} y^k g,\ 1 \le k \le s \right\};$$

specializing to $f = x^s$ and $g = y^s$ above gives all monomials in $H_{2s}(\mathbb{C}^2)$.

The more obvious expression

$$p(x, y) = f^2(x, y) + g^2(x, y), \qquad g, h \in H_s(\mathbb{C}^2) \tag{5.3}$$

is not a canonical form, because $2(s+1) > 2s+1$. However, every sum of two squares can be formally factored, and these behave nicely with respect to (5.1).

$$f^2 + g^2 = (f + ig)(f - ig) \iff$$
$$(uf + vg)^2 + (vf - ug)^2 = \left(e^{i\theta}(f + ig) \right) \left(e^{-i\theta}(f - ig) \right).$$

Suppose $p(1, 0) = a_0 \ne 0$ (true for general p) and (5.3) holds, where $f(1, 0) = \rho$ and $g(1, 0) = \tau$. Then $\rho^2 + \tau^2 = a_0$, so that $\frac{\tau}{\rho} \ne \pm i$ and the coefficient of x^s in $vf + ug$ will be $v\rho + u\tau = \sin\theta\rho + \cos\theta\tau$, which is zero exactly when $\tan\theta = -\frac{\tau}{\rho}$. Thus for precisely one value of $\tan\theta$, the right-hand side of (5.1) will be in the form (5.2). This determines a pair $(\pm u, \pm v)$; however, the squares in (5.2) will be the same.

In other words, each distinct factorization of p (up to multiple) as a product of two s-ic forms, when combined with the orthogonal action of (5.1), yields exactly one representation as (5.2). A general $p \in H_{2s}(\mathbb{C}^2)$ is a product of $2s$ distinct linear factors; these can be organized into an unordered pair of products of s distinct linear factors in $\frac{1}{2}\binom{2s}{s} = \binom{2s-1}{s}$ ways. □

The "lost" degree of freedom in a sum of squares never arises in Theorem 1.6 because $2(\frac{d}{2} + 1) > d + 1$. The missing monomial x^s in the second summand of (5.2) may be replaced by any specified $x^{s-k_0} y^{k_0}$ by a similar argument.

Another classical result is that a general ternary quartic is a sum of three squares of quadratic forms, generally in 63 different ways up to the action of the orthogonal group (see [28].) Hilbert proved that every (not just a general) positive semidefinite real $p \in H_4(\mathbb{R}^3)$ is a sum of three squares from $H_2(\mathbb{R}^3)$. A constructive discussion has recently been given in papers by Powers and the author [27], Powers, Scheider, Sottile and the author [28], Pfister and Scheiderer [25] and Plaumann, Sturmfels and Vinzant [26]. A non-constructive proof (without the count) can easily be given.

Theorem 5.2. *A general ternary quartic $p \in H_4(\mathbb{C}^3)$ can be written as $p = q_1^2 + q_2^2 + q_3^2$, where $q_j \in H_2(\mathbb{C}^3)$.*

Proof. We take q_i's so that the monomial x^2 only appears in q_1 and the monomial y^2 only appears in q_1 and q_2, and so the number of coefficients in the q_j's is $6 + 5 + 4 = 15$. Taking the partials where $(q_1, q_2, q_3) = (x^2, y^2, z^2)$ shows that J contains $2x^2\{x^2, y^2, z^2, xy, xz, yz\}$, $2y^2\{y^2, z^2, xy, xz, yz\}$ and $2z^2\{z^2, xy, xz, yz\}$, and so is equal to $H_4(\mathbb{C}^3)$. $\square$

Since $3\binom{m+2}{2} - 3 < \binom{2m+1}{2}$ for $m \ge 3$, this result does not generalize to ternary forms of higher even degree.

The situation is somewhat simpler over $\mathbb{R}$. A real version of Theorem 5.1 appears in [34]. If p is real and positive definite and $p = f^2 + g^2$, where f and g are also real, then the factors of p consist of s conjugate pairs. In the factorization $p = (f + ig)(f - ig)$, the pairs must be split between the conjugate factors, and if p has distinct factors, this can be done in 2^{s-1} different ways. A real generalization of Theorem 5.2 appears in [4, Cor.2.12]. Suppose a real psd form $p \in H_{2s}(\mathbb{R}^n)$ is a sum of t squares and $x^{\beta_i} \in H_s(\mathbb{R}^n), 1 \le i \le t$, is given. Then there is a representation $p = \sum_{j=1}^t g_j^2$, in which x^{β_i} does not occur in g_j for $j > i$. This argument can also be applied to a *general* sum of t squares over $\mathbb{C}$, but it is not universal, and depends on the psd condition: if $xy = (ax + by)^2 + (cx + dy)^2$, then $abcd \ne 0$.

6. Cubic forms

In this section, we present three representations for forms in $H_3(\mathbb{C}^n)$ as a sum of cubes of linear forms. The first two are canonical; the third isn't, but it *is* universal.

We begin with Theorem 1.3, which first appeared [30] in a 1987 paper of Boris Reichstein. At the time of this writing, [30] has had no citations in MathSciNet. (It was discussed in [32] and, from there, in [6]. The former was never submitted for publication and the latter appeared in an unindexed journal.) The original presentation and proof in [30] were given for trilinear forms (see §2); the theorem is applied to cubic forms there mainly in the examples.

By iterating (1.5), we obtain a canonical form for $p \in H_3(\mathbb{C}^n)$, see [30, p.98].

Corollary 6.1. *A general n-ary cubic $p \in H_3(\mathbb{C}^n)$ can be written uniquely as*

$$p(x_1, \dots, x_n) = \sum_{m=0}^{\lfloor (n-1)/2 \rfloor} \sum_{k=1}^{n-2m} (t_{m,1+2m}^{\{k\}} x_{1+2m} + \cdots + t_{m,n}^{\{k\}} x_n)^3 \tag{6.1}$$

for some $t_{m,j}^{\{k\}} \in \mathbb{C}$.

This gives p as a sum of $n+(n-2)+\cdots = \lfloor \frac{(n+1)^2}{4} \rfloor$ cubes. Recall that by Alexander-Hirschowitz, for $n \neq 5$, a general cubic form in n variables can be written as a sum of $\lceil \frac{(n+1)(n+2)}{6} \rceil$ cubes. Thus (6.1) represents a general cubic as a sum of about 50% more cubes than the true minimum; this is due to the large number of linear forms with restricted sets of variables.

Reichstein's proof of Theorem 1.3 requires the well-known "generalized eigenvalue problem" for pairs of symmetric matrices, as interpreted for quadratic forms: if a general pair of quadratic forms $f, g \in H_2(\mathbb{C}^n)$ is given, then there exist n linearly independent forms $L_i(x) = \sum_{j=1}^n \alpha_{ij} x_j$ and $c_i \in \mathbb{C}$ so that

$$f = \sum_{i=1}^n L_i^2, \qquad g = \sum_{i=1}^n c_i L_i^2. \tag{6.2}$$

We may also assume that the coefficients α_{ij} are generally non-zero; c.f. Corollary 6.3.

Proof of Theorem 1.3. For general $p \in H_3(\mathbb{C}^n)$, we simultaneously diagonalize $f = \frac{\partial p}{\partial x_1}$ and $g = \frac{\partial p}{\partial x_2}$ as in (6.2). Since mixed partials are equal,

$$\frac{\partial f}{\partial x_2} = \frac{\partial g}{\partial x_1} = \sum_{i=1}^n 2\alpha_{i2} L_i = \sum_{i=1}^n 2c_i \alpha_{i1} L_i, \tag{6.3}$$

and since the L_i's are linearly independent, (6.3) implies that $\alpha_{i2} = c_i \alpha_{i1}$.

It is generally true that $\alpha_{i1} \neq 0$. Let

$$q(x_1, \dots, x_n) = p(x_1, \dots, x_n) - \sum_{i=1}^n \tfrac{1}{3\alpha_{i1}} L_i^3.$$

It follows that

$$\frac{\partial q}{\partial x_1} = \frac{\partial p}{\partial x_1} - \sum_{i=1}^n \frac{3\alpha_{i1}}{3\alpha_{i1}} L_i^2 = \frac{\partial p}{\partial x_1} - \sum_{i=1}^n L_i^2 = 0,$$

$$\frac{\partial q}{\partial x_2} = \frac{\partial p}{\partial x_2} - \sum_{i=1}^n \frac{3\alpha_{i2}}{3\alpha_{i1}} L_i^2 = \frac{\partial p}{\partial x_2} - \sum_{i=1}^n c_i L_i^2 = 0.$$

Since $\frac{\partial q}{\partial x_1} = \frac{\partial q}{\partial x_2} = 0$, we have $q = q(x_3, \dots, x_n)$. □

We now give a constructive proof of Theorem 1.4, which gives a different canonical form for $H_3(\mathbb{C}^n)$ requiring even more cubes.

Proof of Theorem 1.4. The constant-counting makes this a potential canonical form: the variables are $t_{\{i,j\},k}$ with $1 \le i \le j \le k \le n$, and there are $\binom{n+2}{3} = N(n,3)$ such triples (i,j,k). Given $p \in H_3(\mathbb{C}^n)$, $\frac{\partial p}{\partial x_n}$ is a quadratic form, so we can generally complete the square by Theorem 1.2:

$$\frac{\partial p}{\partial x_n} = \sum_{j=1}^{n} (t_{jj}x_j + \cdots + t_{jn}x_n)^2.$$

Then $t_{jn} \ne 0$ for general p and if we let

$$q(x_1,\dots,x_n) = p(x_1,\dots,x_n) - \sum_{j=1}^{n} \tfrac{1}{3t_{jn}}(t_{jj}x_j + \cdots + t_{jn}x_n)^3,$$

then $\frac{\partial q}{\partial x_n} = 0$, so $q = q(x_1,\dots,x_{n-1})$. Iterate this construction to get (1.6). $\square$

It is not hard to give nonconstructive proofs of Theorems 1.3 and 1.4 using Corollary 2.3. These are left for the reader.

We first presented this next construction in [32]; an outline of the proof can be found in [6]. This is not a canonical form, but is included here because it gives an absolute upper bound for the length of cubic forms.

Theorem 6.2. *If $p \in H_3(\mathbb{C}^n)$, then there exists an invertible linear change of variables $y_j = \sum \lambda_{jk}x_k$ and n linear forms ℓ_j so that*

$$p(x_1,\dots,x_n) = \sum_{j=1}^{n} \ell_j^3(x_1,\dots,x_n) + q(y_2,\dots,y_n). \tag{6.4}$$

Thus every cubic in n variables is a sum of at most $\binom{n+1}{2}$ cubes of linear forms.

Proof. Define linear forms $\ell_{j,m}(y)$ for $1 \le j \le m+1$ by

$$\begin{aligned} \ell_{j,m}(y_1,\dots,y_n) &= y_j + \alpha \sum_{j=1}^{m} y_j, \qquad 1 \le j \le m, \\ \ell_{m+1,m}(y_1,\dots,y_n) &= -(1+m\alpha)\sum_{j=1}^{m} y_j, \qquad \alpha = \frac{-(m+1)+\sqrt{m+1}}{m(m+1)}. \end{aligned} \tag{6.5}$$

Then it can be easily checked that

$$\sum_{j=1}^{m+1} \ell_{j,m}(y) = 0 \quad \text{and} \quad \sum_{j=1}^{m+1} \ell_{j,m}^2(y) = \sum_{k=1}^{m} y_k^2. \tag{6.6}$$

Suppose $0 \ne p \in H_3(\mathbb{C}^n)$. Use Biermann's Theorem to find a point u where $p(u) \ne 0$, and after an invertible linear change of variables, taking $\{x_j\} \mapsto \{u_j\}$, we may assume that $p(1,0,\dots,0) = 1$ and so

$$p = u_1^3 + 3h_1(u_2,\dots,u_n)u_1^2 + 3h_2(u_2,\dots,u_n)u_1 + h_3(u_2,\dots,u_n), \tag{6.7}$$

where $deg\ h_j = j$. Now let $u_1 = y_1 - h_1(u_2, \dots, u_n)$ to clear the quadratic term, so

$$p = y_1^3 + 3y_1\tilde{h}_2(u_2, \dots, u_n) + \tilde{h}_3(u_2, \dots, u_n), \tag{6.8}$$

where again $deg\ \tilde{h}_j = j$. Diagonalize $\tilde{h}_2(u_2, \dots, u_n)$ as a quadratic form into $y_2^2 + \cdots + y_r^2$, where $r \le n$, and make the accompanying change of variables. We now have

$$p = y_1^3 + 3y_1(y_2^2 + \cdots + y_r^2) + k_3(y_2, \dots, y_n); \quad r \le n, \tag{6.9}$$

where $deg\ k_3 = 3$. Finally, using (6.5) and (6.6), we construct g, a sum of $r \le n$ cubes:

$$\begin{aligned} g(y_1, \dots, y_n) &:= \frac{1}{r}\sum_{j=1}^{r} \left(y_1 + \sqrt{r}\cdot \ell_{j,r-1}(y_2, \dots, y_r)\right)^3 \\ &= \frac{1}{r}\sum_{j=1}^{r} y_1^3 + \frac{3}{\sqrt{r}}\sum_{j=1}^{r} y_1^2\ell_{j,r-1} + 3\sum_{j=1}^{r} y_1\ell_{j,r-1}^2 + \sqrt{r}\sum_{j=1}^{r}\ell_{j,r-1}^3 \\ &= y_1^3 + 3y_1(y_2^2 + \cdots + y_r^2) + \sqrt{r}\sum_{j=1}^{r}\ell_{j,r-1}^3(y_2, \dots, y_r). \end{aligned} \tag{6.10}$$

Then $q := p - g$ is a cubic form in $(y_2, \dots, y_n)$ as in (6.4). Iteration of this argument shows that any cubic $p \in H_3(\mathbb{C}^n)$ is a sum of at most $\frac{n(n+1)}{2}$ cubes. $\square$

Theorem 1.5 can be extended to a canonical form for quartics as a sum of fourth powers of linear forms. Note that x_n appears in each summand of (6.1), with, generally, a non-zero coefficient.

Corollary 6.3. *For general $p \in H_4(\mathbb{C}^n)$, there exist $\ell_k \in H_1(\mathbb{C}^n)$ and $q \in H_4(\mathbb{C}^{n-1})$ so that, with $a(n) = \lfloor\frac{(n+1)^2}{4}\rfloor$,*

$$p(x_1, \dots, x_n) = \sum_{k=1}^{a(n)} \ell_k(x_1, \dots, x_n)^4 + q(x_1, \dots, x_{n-1}).$$

As a consequence, a general $p \in H_4(\mathbb{C}^n)$ can be written as

$$p(x_1, \dots, x_n) = \sum_{m=0}^{\lfloor(n-1)/2\rfloor}\ \sum_{r=1+2m}^{n}\ \sum_{k=1}^{r-2m} (t_{m,r,1+2m}^{\{k\}}x_{1+2m} + \cdots + t_{m,r,r}^{\{k\}}x_r)^4.$$

Proof. By Corollary 1.3 and (6.1), for general $p \in H_4(\mathbb{C}^n)$, we can write

$$\begin{aligned} \frac{\partial p}{\partial x_n} &= \sum_{m=0}^{\lfloor(n-1)/2\rfloor}\ \sum_{k=1}^{n-2m} (t_{m,1+2m}^{\{k\}}x_{1+2m} + \cdots + t_{m,n}^{\{k\}}x_n)^3 \\ &:= \sum_{m=0}^{\lfloor(n-1)/2\rfloor}\ \sum_{k=1}^{n-2m} (\ell_m^{\{k\}}(x))^2. \end{aligned} \tag{6.11}$$

As before, if $q = p - \sum_{k,m} \frac{1}{4t^{\{k\}}_{m,n}} \ell^4_{k,m}$, then $\frac{\partial q}{\partial x_n} = 0$, so $q = q(x_1, \dots, x_{n-1})$. Repeat as before. There are $N(n,3)$ coefficients in (6.11), and since $N(n,3) + N(n-1,4) = N(n,4)$, the count is correct for a canonical form. $\square$

Note that there is no variable which appears in each linear form in (6.11), so the argument can't be extended to quintics. For the same reason, Theorem 1.4 does not extend to quartics. By combining Theorems 1.3 and 6.3, we obtain canonical forms as a sum of powers of linear forms in the four exceptional cases of Alexander-Hirschowitz, of course at the expense of the number of summands. With regards to ternary quartics, and Theorem 1.9, Corollary 6.3 becomes the following canonical form for $H_4(\mathbb{C}^3)$ as a sum of seven fourth powers.

$$\sum_{k=1}^{3}(t_{k1}x_1 + t_{k2}x_2 + t_{k3}x_3)^4 + t_{10}x_3^4 + \sum_{\ell=1}^{2}(u_{\ell 1}x_1 + u_{\ell 2}x_2)^4 + u_5 x_1^5.$$

There is an arithmetic obstruction to a "Reichstein-type" canonical form for quartics; that is, one in which each linear form is allowed to involve each variable. If

$$p(x_1, \dots, x_n) = \sum_{k=1}^{r}(\alpha_{k1}x_1 + \cdots + \alpha_{kn}x_n)^4 + q(x_1, \dots, x_m). \tag{6.12}$$

were a canonical form for some n, then we would have $N(n,4) = rn + N(m,4)$. However, for $n = 12$, there does not exist $m < 12$ so that $12 \mid \binom{15}{4} - \binom{m+3}{4}$, so no such canonical form can exist. More generally, let

$$A_d = \left\{ n : 0 \le m < n \implies n \not\mid \tbinom{n+d-1}{d} - \tbinom{m+d-1}{d} \right\} \tag{6.13}$$

denote the set of n for which this argument rules out Reichstein-type canonical forms. We present without proof a number of results about A_d. Note that there is no obstacle for (6.12) in prime degree, such as $d = 2, 3$.

Theorem 6.4.
(i) If $3 \not\mid k$, then $n = 2^{2k} \cdot 3 \in A_4$.
(ii) If $p \equiv 1 \pmod{144}$ is prime, then $12p \in A_4$.
(iii) If p is prime, then $p \mid \binom{n+p-1}{p} - \binom{n}{p}$, hence $A_p = \emptyset$ for prime p .
(iv) The smallest elements of $A_6, A_8, A_{10}, A_{12}, A_{14}$ and A_{15} are 10, 1792, 6, 242, 338 and 273 respectively. If A_9 or A_{16} are non-empty, then their smallest elements are at least 10^5.

7. Subspace canonical forms

One natural generalization of the definition of canonical forms is to consider maps $F : X \mapsto H_d(\mathbb{C}^n)$ where $X \subset \mathbb{C}^M$ is an $N(n,d)$-dimensional subspace of $\mathbb{C}^M$. These can be analyzed completely in the simplest non-trivial case: $M = 4, N(2,2) = 3$.

Proof of Theorem 1.10. Assume that some $c_j \neq 0$. Without loss of generality, we may assume that $c_4 \neq 0$ and divide through by c_4 so that the equation is $t_4 = a_1t_1 + a_2t_2 + a_3t_3$, where $a_i = -c_i/c_4$ for $i = 1, 2, 3$. Then (1.13) can be parameterized as a map from $\mathbb{C}^3 \mapsto H_2(\mathbb{C}^2)$ as:

$$F(t; x) = (t_1x + t_2y)^2 + (t_3x + (a_1t_1 + a_2t_2 + a_3t_3)y)^2. \tag{7.1}$$

The partials with respect to the t_j's are:

$$\begin{gathered} 2x(t_1x + t_2y) + 2a_1y(t_3x + (a_1t_1 + a_2t_2 + a_3t_3)y), \\ 2y(t_1x + t_2y) + 2a_2y(t_3x + (a_1t_1 + a_2t_2 + a_3t_3)y), \\ 2(x + a_3y)(t_3x + (a_1t_1 + a_2t_2 + a_3t_3)y). \end{gathered} \tag{7.2}$$

Now, (7.1) is a canonical form if and only if there exists a choice of t_i so that the three quadratics in (7.2) span $H_2(\mathbb{C}^2)$. A computation shows that the determinant of the forms in (7.2) with respect to the basis $\{x^2, xy, y^2\}$ is the cubic

$$-8((a_1a_2 - a_3)t_1 + (1 + a_2^2)t_2 + (a_2a_3 + a_1)t_3)(a_1t_1^2 + a_2t_1t_2 + a_3t_1t_3 - t_2t_3). \tag{7.3}$$

The second factor in (7.3) always has the term $-t_2t_3$ and so never vanishes, hence this determinant is not identically zero (and (7.1) is a canonical form), unless

$$a_1a_2 - a_3 = 1 + a_2^2 = a_2a_3 + a_1 = 0. \tag{7.4}$$

In the exceptional case where (7.4) holds, then $a_2 = \epsilon$, where $\epsilon = \pm i$, and $a_3 = \epsilon a_1$. Evaluating (7.1) at $(x, y) = (a_1, \epsilon)$ yields

$$\begin{gathered} (a_1t_1 + \epsilon t_2)^2 + (a_1t_3 + \epsilon a_1t_1 + \epsilon^2t_2 + \epsilon^2a_1t_3)^2 \\ = (a_1t_1 + \epsilon t_2)^2 + ((1 + \epsilon^2)a_1t_3 + \epsilon a_1t_1 + \epsilon^2t_2)^2 = (a_1t_1 + \epsilon t_2)^2 + \epsilon^2(a_1t_1 + \epsilon t_2)^2 = 0, \end{gathered}$$

as claimed. $\square$

It would be interesting to know how this generalizes in higher degrees.

Conjecture 1.11 is true for degree 2 by Theorem 1.10. We have verified it for even degrees up to eight by Corollary 2.3 applied to random choices for α_j, β_j in (1.14). We hold some hope that generalizations such as Corollary 1.11 will have applications in more than two variables as well.

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