

TATE PROPERTIES, POLYNOMIAL-COUNT VARIETIES, AND MONODROMY OF HYPERPLANE ARRANGEMENTS

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Abstract. The order of the Milnor fiber monodromy operator of a central hyperplane arrangement is shown to be combinatorially determined. In particular, a necessary and sufficient condition for the triviality of this monodromy operator is given.

It is known that the complement of a complex hyperplane arrangement is cohomologically Tate and, if the arrangement is defined over \mathbb{Q} , has polynomial count. We show that these properties hold for the corresponding Milnor fibers if the monodromy is trivial.

We construct a hyperplane arrangement defined over \mathbb{Q} , whose Milnor fiber has a nontrivial monodromy operator, is cohomologically Tate, and has no polynomial count. Such examples are shown not to exist in low dimensions.

§1. Introduction

Let \mathcal{A} be a central arrangement of d hyperplanes in \mathbb{C}^{n+1} , with $d \geq 2$ and $n \geq 1$, given by a reduced equation $Q(x) = 0$. Consider the corresponding global Milnor fiber F defined by $Q(x) - 1 = 0$ in \mathbb{C}^{n+1} with monodromy action $h : F \rightarrow F$, $h(x) = \exp(2\pi i/d) \cdot x$.

A general investigation line is to check whether certain properties of the associated projective hyperplane arrangement complements $M(\mathcal{A})$ in \mathbb{P}^n extend to the Milnor fiber F . For instance, note the following.

(i) The cohomology ring $H^*(M(\mathcal{A}), \mathbb{Z})$ is determined by the combinatorics (see [20]), but the same question for the Betti numbers of the Milnor fiber F is widely open (see, e.g., [16]).

(ii) $H^*(M(\mathcal{A}), \mathbb{Z})$ is torsion-free (see [20]), and there is the open question about the torsion-freeness of $H^*(F, \mathbb{Z})$ (see [2]).

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(iii) The complement $M(\mathcal{A})$ is formal in the sense of Sullivan ([28], [4]), and it was recently shown that the Milnor fiber F may be not even 1-formal (see [30]).

We say that a complex variety Y is *cohomologically Tate* if for any cohomology group $H^m(Y, \mathbb{C})$, one has the following vanishing of mixed Hodge numbers: $h^{p,q}(H^m(F, \mathbb{C})) = 0$ for $p \neq q$. The fact that the hyperplane arrangement complements $M(\mathcal{A})$ are cohomologically Tate has been known for a long time: any cohomology group $H^m(M(\mathcal{A}), \mathbb{Q})$ is a pure Hodge structure of type (m, m) (see [14], [12], [25]).

When the monodromy action h^* is *trivial on all the cohomology groups* $H^*(F, \mathbb{C})$, it follows that we have an equality $H^m(F, \mathbb{Q}) = H^m(M(\mathcal{A}), \mathbb{Q})$ for any $0 \leq m \leq n$, and hence in this case F is cohomologically Tate. One may ask whether this is the only possibility for a hyperplane arrangement Milnor fiber F to be cohomologically Tate. The claim that F cohomologically Tate implies h^* trivial is shown to be true in the case $n = 1$ (obvious, using the mixed Hodge structure (MHS) on the Milnor fiber of an isolated homogeneous hypersurface singularity, given by Steenbrink [27] and recalled in [5, pp. 243–244]) and $n = 2$, that is, for plane arrangements, and negative in general. We do not know whether there is a similar result to Theorem 1.1 for $2 < n < 7$, and this explains why we go to dimension 7 to construct our example.

To state our results in this direction, we need some preliminaries.

In studying the cohomology $H^*(F, \mathbb{Q})$ of the Milnor fiber, the monodromy action $h^* : H^*(F, \mathbb{Q}) \rightarrow H^*(F, \mathbb{Q})$, or the number of points in $|F(\mathbb{F}_p)|$, we can, without any loss of generality, suppose that the arrangement \mathcal{A} is essential; that is, $\bigcap_{H \in \mathcal{A}} H = 0$. This is the same as supposing that the polynomials Q involve in an essential way all the variables x_0, \dots, x_n ; that is, one cannot choose the coordinates x on \mathbb{C}^{n+1} such that $Q(x_0, \dots, x_n) = R(x_0, \dots, x_u)$ for some $0 \leq u < n$ and a homogeneous polynomial $R \in \mathbb{C}[x_0, \dots, x_u]$.

The properties of the monodromy $h^* : H^*(F, \mathbb{Q}) \rightarrow H^*(F, \mathbb{Q})$ are rather mysterious, and many things that we know in general are related to the spectrum

$$(1.1) \quad \text{Sp}(\mathcal{A}) = \sum_{\alpha \in \mathbb{Q}} m_\alpha t^\alpha,$$

with $m_\alpha = \sum_j (-1)^{j-n} \dim Gr_F^p \tilde{H}^j(F, \mathbb{C})_\beta$, where $p = [n + 1 - \alpha]$ and $\beta = \exp(-2\pi i \alpha)$, which is combinatorially determined (see [1]). Surprisingly,

note that for most arrangements the situation is rather simple; namely, $h^m : H^m(F, \mathbb{Q}) \rightarrow H^m(F, \mathbb{Q})$ is trivial (i.e., the identity) for $0 \leq m < n$, and $\dim H^n(F, \mathbb{C})_\beta = |\chi(M(\mathcal{A}))|$, for any $\beta \in \mu_d = \{z \in \mathbb{C} \mid z^d = 1\}$ with $\beta \neq 1$ (see, e.g., [3], [15], [6, Propositions 2.5.4, 6.4.6, Example 6.4.14, Theorem 6.4.18]).

THEOREM 1.1. *Let \mathcal{A} be an essential central arrangement of d planes in \mathbb{C}^3 . The following conditions are equivalent.*

- (i) *The mixed Hodge numbers $h^{p,q}(H^2(F, \mathbb{C}))$ vanish for $p \neq q$.*
- (ii) *The arrangement \mathcal{A} is reducible.*
- (iii) *The monodromy action h^* is trivial on all the cohomology groups $H^*(F, \mathbb{C})$.*
- (iv) *The spectral numbers m_α in $\text{Sp}(\mathcal{A})$ vanish for all $\alpha \in (0, 1)$.*

Geometrically, property (ii) means the following: in the projective line arrangement \mathcal{A}' associated to \mathcal{A} , $(d-1)$ lines meet in one point, say, A , and the remaining line L_d does not contain A .

In terms of coordinates, this means that one may choose the coordinates $(x : y : z)$ on \mathbb{P}^2 such that $A = (0 : 0 : 1)$ and $L_d : z = 0$. With this choice, one has $Q(x, y, z) = Q_1(x, y)z$, where Q_1 is a degree $(d-1)$ reduced homogeneous polynomial in x, y . This property is exactly the definition of a reducible arrangement when $n = 2$.

To discuss the higher-dimensional case, we need the following precise characterization of arrangements with a trivial monodromy.

THEOREM 1.2. *For an essential central arrangement \mathcal{A} , the following conditions are equivalent.*

- (i) *The monodromy action h^* is trivial on all the cohomology groups $H^*(F, \mathbb{C})$.*
- (ii) *The arrangement \mathcal{A} is reducible and satisfies the following: if $\mathcal{A} = \mathcal{A}_1 \times \cdots \times \mathcal{A}_q$ is the decomposition of \mathcal{A} as a product of irreducible arrangements, and if $d_j = |\mathcal{A}_j|$ denotes the number of hyperplanes in \mathcal{A}_j , then $\text{GCD}(d_1, \dots, d_q) = 1$.*

Moreover, if \mathcal{A} is defined over \mathbb{Q} (i.e., each hyperplane in \mathcal{A} is defined over \mathbb{Q}), then all the irreducible arrangements \mathcal{A}_j are also defined over \mathbb{Q} .

We show below (see Lemma 2.1) that in the (unique) decomposition $\mathcal{A} = \mathcal{A}_1 \times \cdots \times \mathcal{A}_q$ of \mathcal{A} as a product of irreducible arrangements \mathcal{A}_j , the integers q, d_1, \dots, d_q are determined by the combinatorics, that is, by the intersection lattice $L(\mathcal{A})$ (see [21]).

We recall that a central arrangement \mathcal{A} as above is *reducible* if one can choose the coordinates x on \mathbb{C}^{n+1} such that $Q(x_0, \dots, x_n) = R_1(x_0, \dots, x_u) \times R_2(x_{u+1}, \dots, x_n)$ for some $0 \leq u < n$ and homogeneous nonconstant polynomials R_1 and R_2 . We then write $\mathcal{A} = \mathcal{A}_1 \times \mathcal{A}_2$, with $\mathcal{A}_j : R_j = 0$.

It is known that an essential arrangement \mathcal{A} is reducible if and only if $\chi(M(\mathcal{A})) = 0$ (see [24]). On the other hand, a trivial monodromy action h^* implies that $\chi(M(\mathcal{A})) = 0$, as a simple consequence of the general formula

$$(1.2) \quad \sum_j (-1)^j \dim H^j(F, \mathbb{C})_\beta = \chi(M(\mathcal{A}))$$

for any $\beta \in \mu_d$ (see [6, Propositions 2.5.4, 6.4.6]; see also [1, (1.4.2)]).

REMARK 1.3. All compact Kähler manifolds are formal spaces (see [4]). When the monodromy h^* is trivial, the corresponding Milnor fiber is clearly a formal space in Sullivan's sense (see [28], [9]). Hence, Theorem 1.2 yields a wealth of new examples of formal spaces in the class of smooth affine varieties. Note also that there are examples of nonformal smooth affine surfaces, related either to Milnor fibers of central plane arrangements (see [30]), or to isolated weighted homogeneous singularities (see [10]).

Theorem 1.2 is an obvious consequence of the following *Thom-Sebastiani-type result*, where the sum of polynomials in disjoint sets of variables is replaced by their product. This result plays also a key role in the construction of our examples below.

THEOREM 1.4. *Let $\mathcal{A} = \mathcal{A}_1 \times \dots \times \mathcal{A}_q$ be the decomposition of the central essential arrangement \mathcal{A} as a product of irreducible arrangements, let $d_j = |\mathcal{A}_j|$ denote the number of hyperplanes in \mathcal{A}_j , and let $d_0 = \text{GCD}(d_1, \dots, d_q)$. Then the following hold.*

(i) *There is a natural identification of graded MHS defined over \mathbb{R} ,*

$$H^*(F, \mathbb{C}) = H^*(\mathbb{T}, \mathbb{C}) \otimes \left(\bigoplus_{\beta \in \mu_{d_0}} (H^*(F_1, \mathbb{C})_\beta \otimes \dots \otimes H^*(F_q, \mathbb{C})_\beta) \right).$$

More precisely, for any $\beta \in \mu_{d_0}$, there is an identification

$$H^*(F, \mathbb{C})_\beta = H^*(\mathbb{T}, \mathbb{C}) \otimes H^*(F_1, \mathbb{C})_\beta \otimes \dots \otimes H^*(F_q, \mathbb{C})_\beta.$$

(ii) *The monodromy operator $h^* : H^*(F, \mathbb{C}) \rightarrow H^*(F, \mathbb{C})$ has order d_0 , which is determined by the intersection lattice $L(\mathcal{A})$.*

Since each \mathcal{A}_j is irreducible, it follows from (1.2) that each $H^*(F_j)_\beta$ which occurs in Theorem 1.4 is nonzero.

REMARK 1.5. There are a number of papers dealing with Thom-Sebastiani-type results for the product of two polynomials f and g (or, more generally, for $h(f, g)$, with h a function of two variables) (see, e.g., [18], [23], [17], [29]). The decomposition in our Theorem 1.4(i) appears in Tapp [29]. However, in all of these papers there is no reference to the MHS involved, and the methods used, being purely topological, do not allow us in a direct way to derive such conclusions. Since these MHS play a central role in the remainder of our paper, we give below a proof of this decomposition rather different from that in [29], carefully handling the corresponding MHS.

We have noticed already that F is a cohomologically Tate variety when the monodromy action h^* is trivial. We give below an example showing that the converse claim is false in general (see Example 4.3). Example 4.3 is also interesting since it shows that the part $H^{<\text{top}}(F, \mathbb{C})_{\neq 1}$ of the Milnor fiber cohomology can be rather big, unlike all the previously known examples.

COROLLARY 1.6. *Consider the central rational hyperplane arrangement $\mathcal{A}_{u,v}$ in \mathbb{C}^{n+1} defined in Example 4.3, for any $u, v \in \mathbb{Z}_{>0}$. Then $n = 3u + 5v - 1$, the only eigenvalues of the monodromy operator h^* are ± 1 , and $\dim H^*(F_{u,v}, \mathbb{C})_{-1} = 2^{u+v-1}$. More precisely, the nontrivial (-1) -eigenspaces are exactly $H^{2u+4v+j}(F_{u,v}, \mathbb{C})_{-1}$ for $0 \leq j \leq u + v - 1$ and*

$$\dim H^{2u+4v+j}(F_{u,v}, \mathbb{C})_{-1} = \binom{u+v-1}{j}.$$

The smallest n for which our construction yields a counterexample is $n = 7$; the Milnor fiber of the corresponding hyperplane arrangement $\mathcal{A}_{1,1}$ is cohomologically Tate, but h^* is not trivial.

Recall that the (compactly supported) Hodge-Deligne polynomial (or E-polynomial) associated to a complex variety Y is given by

$$(1.3) \quad HD_X(x, y) = \sum_{u,v} \left(\sum_j (-1)^j h^{u,v}(H_c^j(Y, \mathbb{C})) \right) x^u y^v.$$

Assume that Y is in fact defined over \mathbb{Q} . We say that Y has *polynomial count with count polynomial* P_Y if there is a polynomial $P_Y \in \mathbb{Z}[t]$, such that for all but finitely many primes p , for any finite field \mathbb{F}_q with $q = p^s$ and $s \in \mathbb{N}^*$, the number of points of Y over \mathbb{F}_q is precisely $P_Y(q)$. As an

example, if the hyperplane arrangement \mathcal{A} is *defined over* \mathbb{Q} , then $M(\mathcal{A})$ has polynomial count (see, e.g., [7, Section (5.3)], [26, Theorem 5.15]). The above rationality assumption is essential; indeed, the line arrangement $\mathcal{A} : x^2 + y^2 = 0$ is defined over $\mathbb{Q}(i)$, and the corresponding complement $M(\mathcal{A})$ satisfies $|M(\mathcal{A})(\mathbb{F}_p)| = p - 1$ if $p \equiv 1 \pmod{4}$ and $|M(\mathcal{A})(\mathbb{F}_p)| = p + 1$ if $p \equiv 3 \pmod{4}$. Note that in this case $Q(x)$ has integer coefficients and \mathcal{A} is reducible, but the corresponding splitting $\mathcal{A} = \mathcal{A}_1 \times \mathcal{A}_2$ is not defined over \mathbb{Q} .

A theorem of Katz in [11] says that if Y has polynomial count with count polynomial P_Y , then $HD_Y(x, y) = P_Y(xy)$ (see [11, Theorem 2.1.8, the remark at the bottom of p. 563, and Example 2.1.10] explaining that there can be allowed finitely many “bad characteristics” p). In particular, such a variety is not too far from being cohomologically Tate; that is, the not-Tate part of the cohomology should cancel out in $HD_Y(x, y)$.

One may ask what happens to the Milnor fibers of hyperplane arrangements. Again, we need a rationality assumption: the Milnor fiber $F : x^2 + y^2 = 1$ satisfies $|F(\mathbb{F}_p)| = p - 1$ if $p \equiv 1 \pmod{4}$ and $|F(\mathbb{F}_p)| = p + 1$ if $p \equiv 3 \pmod{4}$. Note that in this example the monodromy operator h^* is trivial and F is cohomologically Tate.

When \mathcal{A} is defined over \mathbb{Q} , we will always choose the defining equation $Q(x) = 0$ with integer coefficients. It turns out that the arithmetic properties of the corresponding Milnor fiber $F : Q(x) - 1 = 0$ do not depend on the choice of Q (see, e.g., Corollary 1.7).

So a first naive idea when trying to construct cohomologically Tate Milnor fibers of rational arrangements which have no polynomial count is to look for a hyperplane arrangement \mathcal{A} with a trivial monodromy h^* and such that the corresponding Milnor fiber F has no polynomial count. Such an attempt cannot succeed in view of the following result, implied by Theorem 1.2.

COROLLARY 1.7. *If the monodromy action h^* is trivial on all the cohomology groups $H^*(F, \mathbb{C})$ of the Milnor fiber F of an essential central arrangement \mathcal{A} defined over \mathbb{Q} , then F has a polynomial count, with the same count polynomial as the corresponding projective complement $M(\mathcal{A})$.*

In particular, this property of the Milnor fiber having a polynomial count, and the corresponding count polynomial, does not depend on the choice of defining equation Q in $\mathbb{Z}[x]$.

For $n = 2$ we have the following.

COROLLARY 1.8. *Consider the following conditions.*

- (i) Y has a polynomial count.
- (ii) Y is cohomologically Tate.

If Y is a smooth affine surface, then (i) \implies (ii). If, in addition, Y is the Milnor fiber of a central rational plane arrangement in \mathbb{C}^3 , then one also has (ii) \implies (i).

The hyperplane arrangement $\mathcal{A}_{1,1}$ introduced in Example 4.3 is defined over \mathbb{Q} , and the corresponding Milnor fiber is cohomologically Tate but has no polynomial count (see Theorem 5.2).

§2. Proof of Theorem 1.4 and of Corollary 1.7

Proof. We can, up to a linear coordinate change, write $Q(x) = Q_1(y_1) \cdots Q_q(y_q)$, where $x = (y_1, \dots, y_q) \in \mathbb{C}^{n+1}$, $y_j \in \mathbb{C}^{n_j}$ such that $n_1 + \cdots + n_q = n + 1$, $d_j = \deg Q_j > 0$, and $\mathcal{A}_j : Q_j = 0$ is an irreducible and essential arrangement in \mathbb{C}^{n_j} for $j = 1, \dots, q$.

Note that the existence of such a decomposition is equivalent to the following property: there is a partition of the hyperplanes in \mathcal{A} in q subsets A_1, \dots, A_q such that if we define $V_j = \bigcap_{H \notin A_j} H$, then there is a direct sum decomposition $\mathbb{C}^{n+1} = V_1 + V_2 + \cdots + V_q$, and this partition is the finest with this property. More precisely, we have the following result.

LEMMA 2.1. *Let $\mathcal{A} = \{H_i\}_{i \in I}$ be a central, essential hyperplane arrangement in $\mathbb{C}^{n+1} = V$. Consider the set P of partitions $I = I_1 \cup \cdots \cup I_m$ of I satisfying the following condition: $\sum_j \text{codim}(\bigcap_{i \in I_j} H_i) = \dim V$. Then the following hold.*

- (i) P is nonempty, since the trivial partition $I = I$ is in P .
- (ii) If $I = I_1 \cup \cdots \cup I_m$ and $I = I'_1 \cup \cdots \cup I'_{m'}$ are two partitions in P , then their intersection $I = \bigcup_{i,j} I_{i,j}$, where $I_{i,j} = I_i \cap I_j$ for $i = 1, m, j = 1, m'$ (the empty intersections $I_{i,j}$ are discarded), is again a partition in P .
- (iii) In the (unique) decomposition $\mathcal{A} = \mathcal{A}_1 \times \cdots \times \mathcal{A}_q$ of \mathcal{A} as a product of irreducible arrangements \mathcal{A}_j , the integers q, d_1, \dots, d_q are determined by the combinatorics, that is, by the intersection lattice $L(\mathcal{A})$.

Proof. Claim (i) is obvious.

Let E be the dual of V , and, for a given partition $I = I_1 \cup \cdots \cup I_m$ in P , let E_i be the vector subspace in E spanned by the equations of the hyperplanes in I_i . Since \mathcal{A} is essential, it follows that $\sum_j E_j = E$. Since $\dim E_j = \text{codim}(\bigcap_{i \in I_j} H_i)$, it follows that the above sum is in fact a direct sum.

When we have two partitions as above, we define $E_{i,j}$ to be the vector subspace in E spanned by the equations of the hyperplanes in $I_i \cap I'_j$. Then it follows immediately that the sum $\sum_j E_{i,j} = E_i$ is again direct sum for all i . Hence, the sum $\sum_{i,j} E_{i,j} = V$ is a direct sum, which proves claim (ii).

Since the set of partitions P is defined only in terms of the intersection lattice $L(\mathcal{A})$, it follows that the unique minimal element of P (with respect to the partial order given by refinement) is combinatorially determined. This minimal element is denoted above by $I = A_1 \cup \cdots \cup A_q$. The direct sum decomposition $\mathbb{C}^{n+1} = V_1 + V_2 + \cdots + V_q$ mentioned above is just the dual of the direct sum decomposition $\sum_j E_j = E$. Since $d_j = |A_j|$, they are also determined by the combinatorics. \square

REMARK 2.2. When \mathcal{A} is defined over \mathbb{Q} , it follows that all the vector subspaces V_j are defined over \mathbb{Q} . Then the arrangement \mathcal{A}_j , which is essentially given by the traces of $H \in A_j$ on V_j , is clearly defined over \mathbb{Q} . Moreover, the coordinate change from the coordinates x to the coordinates y is defined over \mathbb{Q} . This shows that when doing computations for almost all primes p , we may replace the equation $Q(x) = 0$ (resp., $Q(x) = 1$) by the corresponding equations $Q_1(y_1) \cdots Q_q(y_q) = 0$ (resp., $Q_1(y_1) \cdots Q_q(y_q) = 1$).

Proof of Theorem 1.4. Let $F_j : Q_j = 1$ and $h_j : F_j \rightarrow F_j$ be the corresponding Milnor fibers and monodromy homeomorphisms. Let us consider the corresponding least common multiple $m = \text{LCM}(d_1, \dots, d_q)$ and set $w_j = m/d_j$ for $j = 1, \dots, q$.

Our first aim is to obtain a description of the (total) Milnor fiber F in terms of the collection of Milnor fibers F_1, \dots, F_q . For this we consider the affine torus

$$(2.1) \quad \mathbb{T} = \{t = (t_1, \dots, t_q) \in (\mathbb{C}^*)^q \mid t_1 t_2 \cdots t_q = 1\}.$$

Consider the mapping

$$(2.2) \quad f : \mathbb{T} \times F_1 \times \cdots \times F_q \rightarrow F$$

given by

$$(2.3) \quad (t, y_1, \dots, y_q) \mapsto (t_1^{w_1} y_1, \dots, t_q^{w_q} y_q).$$

It is easy to check that this mapping f is surjective and that one has

$$f(t, y_1, \dots, y_q) = f(t', y'_1, \dots, y'_q)$$

if and only if the points (t, y_1, \dots, y_q) and (t', y'_1, \dots, y'_q) are in the same G -orbit, where the group

$$(2.4) \quad G = \{g = (g_1, \dots, g_q) \in \mu_m^q \mid g_1 g_2 \cdots g_q = 1\}$$

acts on $X = \mathbb{T} \times F_1 \times \cdots \times F_q$ via

$$(2.5) \quad g \cdot ((t_1, \dots, t_q), y_1, \dots, y_q) = ((g_1^{-1} t_1, \dots, g_q^{-1} t_q), g_1^{w_1} y_1, \dots, g_q^{w_q} y_q).$$

It follows that $F = X/G$ and, in particular, that $H^*(F, \mathbb{Q}) = H^*(X, \mathbb{Q})^G$, the G -fixed part of the cohomology of X under the induced G -action. This is an isomorphism of MHS, since the G -action is algebraic. Note that

$$(2.6) \quad H^*(X, \mathbb{C}) = H^*(\mathbb{T}, \mathbb{C}) \otimes H^*(F_1, \mathbb{C}) \otimes \cdots \otimes H^*(F_q, \mathbb{C}).$$

Moreover, the group G acts trivially on the factor $H^*(\mathbb{T}, \mathbb{C})$, since \mathbb{T} is a connected algebraic group and $G \subset \mathbb{T}$. If we set

$$H^* = H^*(F_1, \mathbb{R}) \otimes \cdots \otimes H^*(F_q, \mathbb{R}),$$

then it follows that

$$H^*(F, \mathbb{R}) = H^*(\mathbb{T}, \mathbb{R}) \otimes (H^*)^G.$$

The G -action on $H_{\mathbb{C}}^*$, the complexification of H^* , is given by the following: if $\eta = \eta_1 \otimes \cdots \otimes \eta_q$, then

$$(2.7) \quad g\eta = (h_1)^{k_1}(\eta_1) \otimes \cdots \otimes (h_q)^{k_q}(\eta_q).$$

Here $g = (\lambda^{k_1}, \dots, \lambda^{k_q})$ with $\lambda = \exp(2\pi i/m)$ and $k_1 + \cdots + k_q$ is divisible by m , the k_j being otherwise arbitrary integers.

Let $\eta_j \in H^*(F_j, \mathbb{C})$ be now chosen such that for any $j = 1, \dots, q$ there is a $\beta_j \in \mu_{d_j} \subset \mu_m$ with $h_j^* \eta_j = \beta_j \eta_j$, and look at $\eta = \eta_1 \otimes \cdots \otimes \eta_q$. Such elements form a \mathbb{C} -basis of $H_{\mathbb{C}}^*$, and hence to determine $(H_{\mathbb{C}}^*)^G$ is the same as finding all η of this form which are fixed under the G -action. By choosing $k_q = m - k_1 - \cdots - k_{q-1}$, we get from (2.7) the following:

$$g\eta = \left(\frac{\beta_1}{\beta_q}\right)^{k_1} \cdots \left(\frac{\beta_{q-1}}{\beta_q}\right)^{k_{q-1}} \eta,$$

where now there is no condition on the integers k_1, \dots, k_{q-1} . By taking one of them equal to 1 and the rest zero, we see that $\eta \in (H_{\mathbb{C}}^*)^G$ implies that $\beta_1 = \cdots = \beta_q$. Call this common value λ_0 , and note that $\lambda_0 \in \mu_{d_0} = \bigcap_{j=1, q} \mu_{d_j}$.

Conversely, for any $\lambda_0 \in \mu_{d_0}$ and any $\eta \in H^*(F_1, \mathbb{C})_{\lambda_0} \otimes \cdots \otimes H^*(F_q, \mathbb{C})_{\lambda_0}$, we see by using (2.7) that $\eta \in (H_{\mathbb{C}}^*)^G$.

Moreover, set $E_{\lambda_0} = H^*(F_1, \mathbb{C})_{\lambda_0} \otimes \cdots \otimes H^*(F_q, \mathbb{C})_{\lambda_0}$, and note that $\overline{E}_{\lambda_0} = E_{\overline{\lambda_0}}$.

It follows that if we set $M_{\lambda_0} = E_{\lambda_0}$ when $\lambda_0 \in \mathbb{R}$ and $M_{\lambda_0} = E_{\lambda_0} + E_{\overline{\lambda_0}}$ when $\lambda_0 \notin \mathbb{R}$, then M_{λ_0} is endowed with a natural \mathbb{R} -MHS (see also (4.1)).

To prove the second part of Theorem 1.4(i), we construct a nice G -equivariant lifting $\tilde{h} : X \rightarrow X$ of the monodromy morphism $h : F \rightarrow F$. We set

$$(2.8) \quad \tilde{h}(t_1, \dots, t_q, y_1, \dots, y_q) = (\gamma_1 t_1, \dots, \gamma_q t_q, \beta_1 y_1, y_2, \dots, y_q),$$

where $\beta_1 = \exp(2\pi i/d_1)$ and $\gamma_j = \exp(2\pi i a_j)$ with $w_1 a_1 = 1/d - 1/d_1$ and $w_j a_j = 1/d$ for $j > 1$. Then $\sum_j a_j = 0$; that is, $(\gamma_1 t_1, \dots, \gamma_q t_q) \in \mathbb{T}$, and $f \circ \tilde{h} = h \circ f$. Then \tilde{h}^* acts as identity on all the factors in the tensor product (2.6), except on $H^*(F_1, \mathbb{C})$, where it acts via h_1^* . We get the second part of claim (i) by using the description of the cohomology $H^*(F, \mathbb{C})$ given in the first part of claim (i).

To prove claim (ii), note that the affine torus \mathbb{T} acts on the Milnor fiber F by

$$(2.9) \quad t(y_1, \dots, y_q) = (t_1^{w_1} y_1, \dots, t_q^{w_q} y_q).$$

Hence, to show that $(h^*)^{d_0}$ is trivial, it is enough to show the existence of an element $t = (t_1, \dots, t_q) \in \mathbb{T}$ such that $t_j^{w_j} = \exp(2\pi i d_0/d)$ for $j = 1, \dots, q$. Since $\text{GCD}(d_1, \dots, d_q) = d_0$, there are integers k_j such that

$$(2.10) \quad k_1 d_1 + \cdots + k_q d_q = (m - 1)d_0.$$

For $j = 1, \dots, q$, we set

$$(2.11) \quad t_j = \exp\left[2\pi i \left(\frac{d_0}{d w_j} + \frac{k_j}{w_j}\right)\right].$$

The relations $t_j^{w_j} = \exp(2\pi i d_0/d)$ are clearly satisfied. Moreover,

$$t_1 t_2 \cdots t_q = \exp\left[2\pi i \left(\sum_j \left(\frac{d_0 d_j}{d m} + \frac{k_j d_j}{m}\right)\right)\right] = \exp\left[2\pi i d_0 \left(\frac{1}{m} + \frac{m-1}{m}\right)\right] = 1.$$

Hence, $t \in \mathbb{T}$, so it follows that $(h^*)^{d_0}$ is trivial. We conclude using the following fact: since each \mathcal{A}_j is irreducible, it follows from (1.2) that each $H^*(F_j)_\beta$ which occurs in Theorem 1.4 is nonzero. Hence, each $H^*(F)_\beta$ is nonzero; that is, the order of h^* is indeed d_0 . \square

REMARK 2.3. Consider the central essential hyperplane arrangement \mathcal{A} in \mathbb{C}^{n+1} and its decomposition $\mathcal{A} = \mathcal{A}_1 \times \cdots \times \mathcal{A}_q$ as a product of irreducible arrangements \mathcal{A}_j for $j = 1, \dots, q$. Then it is easy to show that

$$M(\mathcal{A}) = \mathbb{T} \times M(\mathcal{A}_1) \times \cdots \times M(\mathcal{A}_q).$$

This implies the following for the cohomology of the corresponding projective complements:

$$H^*(M(\mathcal{A})) = H^*(\mathbb{C}^*)^{\otimes(q-1)} \otimes H^*(M(\mathcal{A}_1)) \otimes \cdots \otimes H^*(M(\mathcal{A}_q)),$$

that is, the case $\beta = 1$ in Theorem 1.4(iii) (see also [29]).

Now we pass to the proof of Corollary 1.7. Since the monodromy h^* is trivial, we know by Theorem 1.2 that $\text{GCD}(d_1, \dots, d_q) = 1$. Hence, there exist integers m_j such that $m_1 d_1 + \cdots + m_q d_q = 1$.

Let \mathbb{F} be a finite field, and consider the mapping $Q: \mathbb{F}^{n+1} \rightarrow \mathbb{F}$ induced by the polynomial Q .

For $a \in \mathbb{F}$, denote by $F(a)$ the fiber $Q^{-1}(a)$. Denote also $M(\mathcal{A}, \mathbb{F})$ the corresponding (projective) hyperplane arrangement complement over \mathbb{F} . It is clear that

$$(2.12) \quad |\mathbb{F}^{n+1} \setminus F(0)| = (|\mathbb{F}| - 1) \cdot |M(\mathcal{A}, \mathbb{F})|.$$

Consider the following \mathbb{F}^* -action on \mathbb{F}^{n+1} :

$$(2.13) \quad t \cdot x = t \cdot (y_1, y_2, \dots, y_q) = (t^{m_1} y_1, t^{m_2} y_2, \dots, t^{m_q} y_q).$$

The relation $Q(t \cdot x) = tQ(x)$ shows that all the fibers $F(a)$ for $a \in \mathbb{F}^*$ have the same cardinal. Since their disjoint union is exactly $\mathbb{F}^{n+1} \setminus F(0)$, (2.12) yields

$$(2.14) \quad |F(1)| = |M(\mathcal{A}, \mathbb{F})|.$$

This equality completes the proof of Corollary 1.7.

§3. Proof of Theorem 1.1 and of Corollary 1.8

Proof. It follows from the discussion just after Theorem 1.1 that, assuming Theorem 1.1(ii), the Milnor fiber F is isomorphic to the complement of the central line arrangement given by $Q_1 = 0$ in \mathbb{C}^2 . (Indeed, the only

partitions of 3 are $1 + 2 = 2 + 1 = 1 + 1 + 1 = 3$.) Hence, the implication (ii) \Rightarrow (i) is obviously true.

Note that for $n = 2$ and $\alpha \in (0, 1)$, the corresponding spectral number is by definition

$$(3.1) \quad m_\alpha = h^{2,0}(H^2(F, \mathbb{C})_\beta) + h^{2,1}(H^2(F, \mathbb{C})_\beta)$$

with $\beta = \exp(-2\pi i\alpha)$. Indeed, $h^{2,2}(H^2(F, \mathbb{C})_\beta) = 0$, as follows from [8, Theorem 1.3].

Since $H^2(F, \mathbb{C})_1$ is known to be of type $(2, 2)$, the equivalence of Theorem 1.1(i), (iv) follows. Moreover, the equivalence of claims (ii) and (iii) follows from Theorem 1.2, using again the partitions of 3.

So from now on we assume that Theorem 1.1(iv) holds, and we prove (ii). The fact that the arrangement is essential implies that $d \geq 3$ and that the lines in \mathcal{A}' do not pass all through the same point; that is, there is no point s of multiplicity $m_s = d$. To prove (ii) we have to show the existence of a point of multiplicity $d - 1$.

For $d = 3$ there are only two types of arrangements, described better in terms of their associated projective line arrangements \mathcal{A}' :

- (a) three lines forming a triangle, in which case one may take $Q = xyz$ and $F = \mathbb{C}^* \times \mathbb{C}^*$, and
- (b) three lines meeting at one point.

The claim (i) \Rightarrow (ii) is clear by the previous remark.

We assume from now on that $d \geq 4$.

Next we recall the following key formula from [1, Theorem 3] (rewritten slightly for our needs). If $0 < \alpha = j/d < 1$, then

$$(3.2) \quad m_\alpha = \binom{j-1}{2} - \sum_{s; m_s \geq 3} \binom{[jm_s/d] - 1}{2},$$

where the sum is over all multiple points s in \mathcal{A}' with multiplicity $m_s \geq 3$. By convention, $\binom{a}{b} = 0$ if $a < b$.

If we use the above formula for $j = 3$, we get that the corresponding vanishing $m_\alpha = 0$ is equivalent to the existence of a unique point s of multiplicity $m_s > 2d/3$ in \mathcal{A}' . For $d = 4$ (resp., $d = 5$), this means a point of multiplicity $m_s \geq 3$ (resp., $m_s \geq 4$). As above (case $d = 3$, (b)), the case $m_s = 4$ (resp., $m_s = 5$) is discarded since \mathcal{A}' is essential. Hence, $m_s = 3$ (resp., $m_s = 4$), which gives exactly an arrangement \mathcal{A}' as claimed in (ii).

From now on we assume that $d > 5$. We apply (3.2) for $j = d - 1$. Since one clearly has

$$m - 1 < \frac{(d-1)m}{d} < m,$$

it follows that $\lceil (d-1)m/d \rceil = m$, and hence the vanishing $m_\alpha = 0$ in this case is equivalent to the equality

$$(3.3) \quad \binom{d-2}{2} = \sum_{s; m_s \geq 3} \binom{m_s - 1}{2}.$$

Similarly, for $j = d - 2$ we get from $m_\alpha = 0$ the equality

$$(3.4) \quad \binom{d-3}{2} = \sum_{s; 3 \leq m_s < d/2} \binom{m_s - 1}{2} + \sum_{s; m_s \geq d/2} \binom{m_s - 2}{2}.$$

By taking the difference of (3.3) and (3.4), we get the equality

$$(3.5) \quad d - 3 = \sum_{s; m_s \geq d/2} (m_s - 2).$$

It follows that, if the set $S = \{s; m_s \geq d/2\}$ contains exactly one element, then the corresponding multiple point s satisfies $m_s = d - 1$, and we are done.

Suppose now that the set S contains at least two elements. Since one of them has to be the point s with multiplicity $m_s > 2d/3$ obtained above for $j = 3$, we get in this case

$$(3.6) \quad d - 3 > (2d/3 - 2) + (d/2 - 2).$$

This is equivalent to $d < 6$, a contradiction with our hypothesis $d > 5$. \square

The proof of Corollary 1.8 is very easy now. If Corollary 1.8(i) holds, then it follows from Katz's theorem that the Hodge-Deligne polynomial of Y contains only the monomials $1, xy, (xy)^2$. The possible nonzero mixed Hodge numbers in this situation are

$$\begin{aligned} & h^{2,2}(H_c^4(Y, \mathbb{C})), h^{1,2}(H_c^3(Y, \mathbb{C})), h^{2,1}(H_c^3(Y, \mathbb{C})), \\ & h^{1,1}(H_c^3(Y, \mathbb{C})), h^{2,0}(H_c^2(Y, \mathbb{C})), \\ & h^{1,1}(H_c^2(Y, \mathbb{C})), h^{0,2}(H_c^2(Y, \mathbb{C})), h^{0,1}(H_c^2(Y, \mathbb{C})), \end{aligned}$$

$$h^{1,0}(H_c^2(Y, \mathbb{C})), h^{0,0}(H_c^2(Y, \mathbb{C})).$$

It follows that the only cancellations in the Hodge polynomial can occur in the coefficient of xy . Hence, all the mixed Hodge numbers $h^{u,v}(H_c^m(Y, \mathbb{C}))$ vanish for $u \neq v$; that is, Y is cohomologically Tate.

Now for Milnor fibers of a central plane arrangement, we have seen that Theorem 1.1(ii) implies that Y is isomorphic to a line arrangement complement in \mathbb{C}^2 , and hence it has polynomial count.

§4. A purity result and the key example

Let \mathcal{A} be a central arrangement of d hyperplanes in \mathbb{C}^{n+1} , with $n \geq 1$, given by a reduced equation $Q(x) = 0$. Then clearly $H^n(F, \mathbb{Q})_1$ and $H^n(F, \mathbb{C})_{-1}$ are mixed Hodge substructures in $H^n(F, \mathbb{Q})$. Moreover, for $\beta \in \mu_d$, $\beta \neq \pm 1$, the same is true for the subspace

$$(4.1) \quad H^n(F, \mathbb{C})_{\beta, \bar{\beta}} = H^n(F, \mathbb{C})_{\beta} \oplus H^n(F, \mathbb{C})_{\bar{\beta}} = \ker[(h^n)^2 - 2\operatorname{Re}(\beta)h^n + Id],$$

which is in fact defined over \mathbb{R} (as the last equality shows). For $\beta = -1$, we set $H^n(F, \mathbb{C})_{\beta, \bar{\beta}} = H^n(F, \mathbb{C})_{-1}$ for uniformity of notation.

Let

$$D = Q^{-1}(0) = \bigcup_{H \in \mathcal{A}} H.$$

For a point $x \in D$, $x \neq 0$, let $L_x = \bigcap_{H \in \mathcal{A}, x \in H} H$, and denote by \mathcal{A}_x the central hyperplane arrangement induced by \mathcal{A} on a linear subspace T_x , passing through x and transversal to L_x . We may choose $\dim T_x = \operatorname{codim} L_x$ and identify x with the origin in the linear space T_x . Let $h_x^* : H^*(F_x, \mathbb{C}) \rightarrow H^*(F_x, \mathbb{C})$ be the corresponding monodromy operator at x .

With this notation, we have the following result.

PROPOSITION 4.1. *Let $\beta \in \mu_d$, $\beta \neq 1$ be a root of unity which is not an eigenvalue for any monodromy operator h_x^* for $x \in D$, $x \neq 0$. Then the corresponding eigenspace $H^n(F, \mathbb{C})_{\beta, \bar{\beta}}$ is a pure Hodge structure of weight n .*

In particular, if $\beta = \exp(-2\pi i\alpha)$ for some $\alpha \in \mathbb{Q}$, then the coefficients in the corresponding spectrum $\operatorname{Sp}(\mathcal{A})$ have the following symmetry property:

$$(4.2) \quad m_{\alpha} = m_{n+1-\alpha}.$$

Proof. This result is a direct consequence of [22, Lemma 3.6]. Indeed, our hypothesis on β implies that the nearby cycle sheaf $\psi_{Q, \beta} \mathbb{C}$ is supported at

the origin, and hence it is identified to $H^n(F, \mathbb{C})_\beta$. This identification in turn implies that the logarithm of the unipotent part of the monodromy N is trivial on $\psi_{Q, \beta} \mathbb{C}$ (as this holds for $H^n(F, \mathbb{C})_\beta$, the monodromy h^* being semisimple).

The last claim about the symmetry property in (4.2) is proved in the usual way. In view of the purity result, we have $h^{p,q}(H^n(F, \mathbb{C})_\beta) = 0$ for $p + q \neq n$.

For example, assume that $\alpha = j/d$ with $0 < j < d$. It follows from the definition of the spectrum (1.1) that $m_\alpha = \dim h^{n,0}(H^n(F, \mathbb{C})_\beta)$, $m_{n+1-\alpha} = \dim h^{0,n}(H^n(F, \mathbb{C})_{\bar{\beta}})$. The claimed equality follows by considering the action of the complex conjugation on the pure Hodge structure $H^n(F, \mathbb{C})_{\beta, \bar{\beta}}$. \square

COROLLARY 4.2. *Assume that \mathcal{A} is a generic central hyperplane arrangement; that is, the associated projective divisor in \mathbb{P}^n is a divisor with normal crossing. Then*

$$H^n(F, \mathbb{C})_{\neq 1} = \bigoplus_{\beta \neq 1} H^n(F, \mathbb{C})_\beta$$

is a pure Hodge structure of weight n , and for any rational number $\alpha \in \mathbb{Q} \setminus \mathbb{Z}$ one has $m_\alpha = m_{n+1-\alpha}$.

This symmetry of the coefficients of the spectrum $\text{Sp}(\mathcal{A})$ of a generic central arrangement is alluded to in [22] (see the remarks just after Corollary 1 in the introduction). The result above follows from Proposition 4.1 using the simple fact that in this case all the monodromy operators h_x^* are the identity. For more on the monodromy of generic arrangements, see [21, pp. 209–210], [1, (3.2)], and [3, Section 3].

Now we pass to our example.

EXAMPLE 4.3. For $n \geq 2$, let \mathcal{G}_n be the central arrangement in \mathbb{C}^{n+1} given by the equation

$$Q_n(x) = Q_n(x_0, \dots, x_n) = x_0 \cdot x_1 \cdots x_n \cdot (x_0 + x_1 + \cdots + x_n).$$

Hence, the degree d_n of Q_n is $n + 2$, and clearly \mathcal{G}_n is a generic, irreducible arrangement. Assume that $n = 2k$ is even, and use [3, Theorem 3.2] (or refer to the original paper [19]) to get that

$$(4.3) \quad H^m(F, \mathbb{C}) = H^m(F, \mathbb{C})_1$$

for $0 \leq m < n$ and $\dim H^n(F, \mathbb{C})_{-1} = 1$.

It follows that all the spectral coefficients in $\mathrm{Sp}(\mathcal{G}_n)$ corresponding to the monodromy eigenvalue -1 vanish except for $m_{k+(1/2)} = 1$ (which is the only autodual element in the sum with respect to the symmetry given by Corollary 4.2). It follows that the eigenspace $H^n(F, \mathbb{C})_{-1}$ is spanned by a cohomology class ω_n of Hodge type (k, k) .

Let us return now to the setting of the proof of Theorem 1.2 in Section 2. Let $\mathcal{A}_{u,v}$ be the central hyperplane arrangement obtained by taking the product of $u > 0$ copies of the arrangement \mathcal{G}_2 and $v > 0$ copies of \mathcal{G}_4 . It follows that $n = 3u + 5v - 1$, $d = 4u + 6v$, $q = u + v$, and $d_0 = \mathrm{GCD}(d_1, \dots, d_q) = 2$.

In this case, the cohomology of the corresponding total Milnor fiber $F_{u,v}$ can be described via Theorem 1.4 as the direct sum $H^*(F_{u,v}, \mathbb{C}) = H^*(F_{u,v}, \mathbb{C})_1 \oplus H^*(F_{u,v}, \mathbb{C})_{-1}$, where

$$(4.4) \quad H^*(F_{u,v}, \mathbb{C})_1 = H^*(\mathbb{T}, \mathbb{C}) \otimes H^*(M(\mathcal{G}_2), \mathbb{C})^{\otimes u} \otimes H^*(M(\mathcal{G}_4), \mathbb{C})^{\otimes v}$$

and

$$(4.5) \quad H^*(F_{u,v}, \mathbb{C})_{-1} = H^*(\mathbb{T}, \mathbb{C}) \otimes (\mathbb{C}\omega_2)^{\otimes u} \otimes (\mathbb{C}\omega_4)^{\otimes v}.$$

It follows that $F_{u,v}$ is a cohomologically Tate variety of dimension $n = 3u + 5v - 1$, but the corresponding monodromy action h^* is not trivial. By choosing various values for u, v , we can get $n = 7$ as a minimal value as well as any integer $n \geq 15$.

REMARK 4.4. If one is interested only in irreducible arrangements, then such examples with large cohomology $H^{<\mathrm{top}}(F, \mathbb{C})$ can be obtained by taking a generic hyperplane section of the arrangement $\mathcal{A}_{u,v}$.

§5. Finite field computations

In this section we use the following notation. Let $F = F_{1,1}$ be the variety defined over \mathbb{Z} by $Q(x) = 1$, where

$$Q(x) = x_1 \cdot x_2 \cdot x_3 \cdot (x_1 + x_2 + x_3) \cdot x_4 \cdot x_5 \cdot x_6 \cdot x_7 \cdot x_8 \cdot (x_4 + x_5 + x_6 + x_7 + x_8).$$

For any prime p , we denote by $A(p)$ the number of points of F over $\mathbb{F}_p = \mathbb{Z}/p\mathbb{Z}$; that is, the number of solutions of the equation $Q(x) = 1$ in \mathbb{F}_p^8 . For $a \in \mathbb{F}_p^*$, consider the varieties

$$F_1(a) = \{(x_1, x_2, x_3) \in \mathbb{F}_p^3 \mid x_1 \cdot x_2 \cdot x_3 \cdot (x_1 + x_2 + x_3) = a\}$$

and

$$F_2(a) = \left\{ (x_4, x_5, x_6, x_7, x_8) \in \mathbb{F}_p^5 \mid a \cdot x_4 \cdot x_5 \cdot x_6 \cdot x_7 \cdot x_8 \cdot (x_4 + x_5 + x_6 + x_7 + x_8) = 1 \right\}.$$

Let $n_1(a) = |F_1(a)|$, let $n_2(a) = |F_2(a)|$, and note that obviously one has

$$(5.1) \quad A(p) = \sum_{a \in \mathbb{F}_p^*} n_1(a)n_2(a).$$

From now on we assume that p is a prime number in the arithmetic progression $12b + 11$, where $b \in \mathbb{N}$.

LEMMA 5.1. *Consider the group morphism $p(k) : \mathbb{F}_p^* \rightarrow \mathbb{F}_p^*$ given by $t \mapsto t^k$. Then the following hold.*

(i) *There is an index 2 subgroup $H \subset \mathbb{F}_p^*$ such that $p(4)(\mathbb{F}_p^*) = p(6)(\mathbb{F}_p^*) = H$.*

(ii) *If a and a' have the same class in \mathbb{F}_p^*/H , then $n_1(a) = n_1(a')$ and $n_2(a) = n_2(a')$.*

Proof. Since the multiplicative group \mathbb{F}_p^* is cyclic, of order $p - 1 = 12b + 10$, it follows that to prove (i) it is enough to show that $p(4)(\mathbb{F}_p^*)$ and $p(6)(\mathbb{F}_p^*)$ have both cardinal $(p - 1)/2$. This is the same as proving that the corresponding kernels have order 2. Note that the equation $t^4 = 1$ (resp., $t^6 = 1$) is equivalent to $t^2 = 1$ (look at the order of t , which must be a divisor of $12b + 10$). Hence, $\ker p(4) = \ker p(6) = \{\pm 1\}$ and hence have order 2.

To prove (ii), consider the action of \mathbb{F}_p^* on \mathbb{F}_p^3 (resp., \mathbb{F}_p^5) given by the usual multiplication of a vector by a scalar. This multiplication by $t \in \mathbb{F}_p^*$ induces a bijection $F_1(a) = F_1(t^4a)$ (resp., $F_2(a) = F_2(t^6a)$). This completes the proof. \square

We denote $n'_1 = n_1(1)$, $n'_2 = n_2(1)$, $n''_1 = n_1(a)$, and $n''_2 = n_2(a)$, for $a \in (\mathbb{F}_p^* \setminus H)$. We also write $p = 12b + 11 = 4k + 3$; that is, we set $k = 3b + 2$. With this notation, (5.1) may be rewritten as

$$(5.2) \quad A(p) = |H|(n'_1n'_2 + n''_1n''_2) = (2k + 1)(n'_1n'_2 + n''_1n''_2).$$

The (affine or projective) hyperplane arrangement complements have polynomial count (see, e.g., [7, Section (5.3)], [26, Theorem 5.15]). So we apply this fact to the *projective* hyperplane arrangement complements \mathcal{A}'_1

in \mathbb{P}^2 (resp., \mathcal{A}'_2 in \mathbb{P}^4) corresponding to $x_1x_2x_3(x_1 + x_2 + x_3) = 0$ (resp., $x_4x_5x_6x_7x_8(x_4 + x_5 + x_6 + x_7 + x_8) = 0$). Using the formulas for the Betti numbers in [3], the fact that each cohomology group H^m is pure of type (m, m) , and the duality between H^m and H_c^{2d-m} (where d is the corresponding (complex) dimension), it follows that

$$(5.3) \quad HD_{M(\mathcal{A}'_1)}(x, y) = (xy)^2 - 3(xy) + 3$$

and

$$(5.4) \quad HD_{M(\mathcal{A}'_2)}(x, y) = (xy)^4 - 5(xy)^3 + 10(xy)^2 - 10(xy) + 5.$$

It follows that the corresponding counting polynomials are

$$(5.5) \quad P_{M(\mathcal{A}'_1)}(t) = t^2 - 3t + 3$$

and

$$(5.6) \quad P_{M(\mathcal{A}'_2)}(t) = t^4 - 5t^3 + 10t^2 - 10t + 5.$$

Using these two polynomials, it follows that, for almost all $p = 4k + 3$, one has

$$(5.7) \quad N'_1(p) = |M(\mathcal{A}'_1)(\mathbb{F}_p)| = p^2 - 3p + 3 \equiv 4k + 3 \pmod{8}$$

and

$$(5.8) \quad N'_2(p) = |M(\mathcal{A}'_2)(\mathbb{F}_p)| = p^4 - 5p^3 + 10p^2 - 10p + 5 \equiv 4k + 3 \pmod{8}.$$

Let \mathcal{A}_1 (resp., \mathcal{A}_2) denote the corresponding central hyperplane arrangements in \mathbb{C}^3 (resp., \mathbb{C}^5) and $M(\mathcal{A}_1)$ (resp., $M(\mathcal{A}_2)$) the associated *affine* complements. Then, using (5.7) and (5.8), we get

$$(5.9) \quad N_1(p) = |M(\mathcal{A}_1)(\mathbb{F}_p)| = (p-1)(p^2 - 3p + 3) \equiv 4k + 6 \pmod{8}$$

and

$$N_2(p) = |M(\mathcal{A}_2)(\mathbb{F}_p)| = (p-1)(p^4 - 5p^3 + 10p^2 - 10p + 5) \equiv 4k + 6 \pmod{8}.$$

(5.10)

Now, note that $M(\mathcal{A}_1)$ (resp., $M(\mathcal{A}_2)$) is the disjoint union of all the hyper-surfaces $F_1(a)$ (resp., $F_2(a)$) for $a \in \mathbb{F}_p^*$. Lemma 5.1, (5.9), and (5.10) yield

$$(5.11) \quad n'_1 + n''_1 = 2(p^2 - 3p + 3) \equiv 6 \pmod{8}$$

and

$$(5.12) \quad n'_2 + n''_2 = 2(p^4 - 5p^3 + 10p^2 - 10p + 5) \equiv 6 \pmod{8}.$$

It follows that $n''_1 \equiv 6 - n'_1 \pmod{8}$ and $n''_2 \equiv 6 - n'_2 \pmod{8}$. Using (5.2), we get

$$(5.13) \quad A(p) = (2k+1)(n'_1 n'_2 + n''_1 n''_2) \equiv 2(2k+1)(2 + n'_1 n'_2 - 3n'_1 - 3n'_2) \pmod{8}.$$

Now we can state and prove our main result of this section.

THEOREM 5.2. *The variety F satisfies the following.*

- (i) F is a cohomologically Tate variety.
- (ii) F has no polynomial count.

Proof. The proof of the first claim was given already in Example 4.3. Moreover, it follows from the description of the cohomology given there that the corresponding Hodge-Deligne polynomial is

$$(5.14) \quad \begin{aligned} HD_F(x, y) &= (xy)^7 - 9(xy)^6 + 36(xy)^5 - 82(xy)^4 \\ &\quad + 119(xy)^3 - 110(xy)^2 + 60(xy) - 15. \end{aligned}$$

Assume that (ii) fails, that is, that F has polynomial count with polynomial P_F . Then according to Katz's theorem (see [11]), we must have

$$(5.15) \quad P_F(t) = t^7 - 9t^6 + 36t^5 - 82t^4 + 119t^3 - 110t^2 + 60t - 15.$$

We will reach a contradiction by showing that $P_F(p) \neq A(p)$ for infinitely many primes, namely, for all the primes p in the progression $12b+11$ (Dirichlet prime number theorem). Let p be such a prime, and write $p = 4k+3$ as above. Then a simple computation (e.g., using Maple) shows that

$$(5.16) \quad \begin{aligned} P_F(4k+3) &= 8(2k+1)(1024k^6 + 2560k^5 + 2752k^4 \\ &\quad + 1632k^3 + 584k^2 + 129k + 15). \end{aligned}$$

Hence, to complete the proof, it is enough to show that $A(p) \not\equiv 0 \pmod{8}$ for any prime p as above. Using (5.13), this is equivalent to showing that

$$(5.17) \quad 2 + n'_1 n'_2 - 3n'_1 - 3n'_2 \not\equiv 0 \pmod{4}.$$

This in turn follows from the following.

LEMMA 5.3. *Let p be a prime number of the form $4k + 3$. Then both n'_1 and n'_2 are divisible by 4.*

Proof. Consider the group $G = \{\pm 1\} \times \{1, \tau\}$ acting on the (finite) Milnor fiber $F_1(1)$ by

$$\begin{aligned} -1 \cdot (x_1, x_2, x_3) &= (-x_1, -x_2, -x_3), \\ \tau \cdot (x_1, x_2, x_3) &= (x_2, x_1, x_3), \end{aligned}$$

and

$$-\tau \cdot (x_1, x_2, x_3) = (-x_2, -x_1, -x_3).$$

There are two types of G -orbits. First, we have the orbits Gx , corresponding to points x such that $x_1 \neq x_2$. Then the isotropy group G_x is trivial, and the orbit Gx consists of four points. Since we are interested in a computation modulo 4, we can forget about such orbits.

The second type of orbit corresponds to points x such that $x_1 = x_2 = t$. Then $x \in F_1(1)$ is equivalent to

$$(5.18) \quad (x_3 + t)^2 = \Delta(t),$$

where $\Delta(t) = t^2 + t^{-2}$. There are two possibilities.

(a) $\Delta(t) \notin H$; that is, $\Delta(t)$ is not a square in \mathbb{F}_p^* . Then (5.18) is impossible, and we do not get a point in $F_1(1)$.

(b) $\Delta(t)$ is a square in \mathbb{F}_p^* . Then (5.18) has two solutions, namely, $x_3 = -t + y$ and $x_3 = -t - y$, with y satisfying $y^2 = \Delta(t)$. In this way we get two points in $F_1(1)$. Note that $\Delta(t) = \Delta(-t)$; hence, for the point $(-t)$ we are exactly in the same situation as for the point t . It follows that for each pair $\{t, -t\}$ (i.e., orbit of the obvious $\{\pm 1\}$ -action on \mathbb{F}_p^*), we get either 0 points in the (finite) Milnor fiber $F_1(1)$, or we get four points. This proves the claim for n'_1 .

Consider next the group $G = \{\pm 1\} \times \{1, \tau\} \times \{1, \sigma\}$ acting on the (finite) Milnor fiber $F_2(1)$ by

$$\begin{aligned} -1 \cdot (x_4, x_5, x_6, x_7, x_8) &= (-x_4, -x_5, -x_6, -x_7, -x_8), \\ \tau \cdot (x_4, x_5, x_6, x_7, x_8) &= (x_5, x_4, x_6, x_7, x_8), \end{aligned}$$

and

$$\sigma \cdot (x_4, x_5, x_6, x_7, x_8) = (x_4, x_5, x_7, x_6, x_8)$$

(and their obvious consequences). Since we are interested in a computation modulo 4, we can forget about all orbits corresponding to points having an isotropy group of order at most 2. Now let x be a point such that $G_x = \{1, \tau\} \times \{1, \sigma\}$. Then $x = (s, s, t, t, x_8)$ and $x \in F_2(1)$ is equivalent to

$$(5.19) \quad (x_8 + s + t)^2 = \Delta(s, t),$$

where $\Delta(t) = (s+t)^2 + (st)^{-2}$. Note that $\Delta(s, t) = \Delta(-s, -t)$; hence, for the point $(-s, -t)$ we are exactly in the same situation as for the point (s, t) . It follows that for each orbit of the obvious $\{\pm 1\}$ -action on $(\mathbb{F}_p^*)^2$, we get either zero points in the (finite) Milnor fiber $F_2(1)$, or we get four points. This proves the claim for n'_2 . \square

REMARK 5.4. Surprisingly, it seems that $P_F(p) = A(p)$ for many primes of the form $p = 4k + 1$. Indeed, by a computer-aided computation, we have obtained the equality $P_F(p) = A(p)$ for the first 18 prime numbers of the form $p = 4k + 1$.

REMARK 5.5. Kisin and Lehrer [13] have considered a notion of *mixed Tate variety* (imposing conditions on the eigenvalues of Frobenius action on p -adic étale cohomology) (see [13, Definition (2.6)]) and shown that if a variety Y is mixed Tate, then Y is cohomologically Tate (see [13, Theorem (2.2)(2)]). Then in [13, Remark 2.4, p. 213], they discuss *the conjectural equivalence* between cohomologically Tate and mixed Tate conditions. Any hyperplane arrangement complement is mixed Tate (see [13, Proposition 3.1.1]).

We say that Y has *weak polynomial count with count polynomial* P_Y if there is a polynomial $P_Y \in \mathbb{Z}[t]$ such that for all but finitely many primes p , there is an integer $k_p > 0$ satisfying the following: if we set $q = p^{k_p}$, then for any finite field \mathbb{F}_{q^s} with $s \in \mathbb{N}^*$, the number of points of Y over \mathbb{F}_{q^s} is precisely $P_Y(q^s)$.

Kisin and Lehrer have shown that if a variety Y is mixed Tate, then Y has weak polynomial count (see [13, Proposition 3.4]).

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