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A Note on Hayden's Theorem

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The Case a finite Group G acts on Code.

1. Difinitions from Coding Theory

Yoshida [5] showed that there is a generalization of MacWilliams identity [3] to codes with group action. We use ideas from [1] to give an elementary proof to Yoshida's identity in a special case.

Let V be the vector space $\mathbf{F}_q^n$, where $\mathbf{F}_q$ is the field with q elements. From now on we assume that G is a finite permutation group on the coordinates of V and $|G|$ is prime to q. Then we can define a natural action of G on V as follows: If $\mathbf{v} = (v_1, \ldots, v_n)$ and $g \in G$, we let $\mathbf{v}g = (x_1, \ldots, x_n)$ where for $i = 1, \ldots, n, x_i = v_{ig^{-1}}$. In this way V becomes an FG-module. A G-code is an FG-submodule of V. As in [1], the operator θ is defined by

$$\theta = \frac{1}{|G|} \sum_{g \in G} g.$$

Here we note that $C_V(G) = V\theta$ and $\theta^T = \theta$ (see [1]).

Let $C_1, \ldots, C_t$ be the orbits of the coordinates of V under the action of G. Let m_i be the orbit length of C_i. Define $\overline{C}_i$ as the vector of V which has 1 as its entry for every point of C_i and 0 elsewhere. (This definition of the $\overline{C}_i$'s is slightly different from that in the proof of Theorem 4.3 in [1]). Then each of $\overline{C}_1, \ldots \overline{C}_t$ is in $U = V\theta$ and every element $\mathbf{u}$ of $U = V\theta$ is of the form

$$\mathbf{u} = \sum_{i=1}^{t} x_i \overline{C}_i.$$

This basis $\{\overline{C}_1, \ldots, \overline{C}_t\}$ of U is a key to our proof of Yoshida's result. Yoshida weight of a vector $\mathbf{u} = \sum_{i=1}^{t} x_i \overline{C}_i \in U$ denoted $wy(\mathbf{u})$ is defined as the number of non-zero x_i. So if G consists of the identity element, e, alone, then Yoshida weight $wy(\mathbf{u})$ of a vector $\mathbf{u}$ is the ordinary weight $|\mathbf{u}|$. If $\mathbf{a} = \sum_{i=1}^{t} a_i \overline{C}_i$ and $\mathbf{b} = \sum_{i=1}^{t} b_i \overline{C}_i$ are any two vectors in U, then inner product $(\mathbf{a}, \mathbf{b})_G$ of $\mathbf{a}$ and $\mathbf{b}$ is defined by

$$(\mathbf{a}, \mathbf{b})_G = a_1 b_1 + \cdots + a_t b_t. \tag{1}$$

Let D be a vector subspace of $U = V\theta$. $D_G^{\perp}$ is the dual of D in U with respect to the inner product (1). (Notice that if G consists of the identity element, e, alone, then $D_{\{e\}}^{\perp}$ is the ordinary dual $D^{\perp}$ of D in V.)

We describe a weight enumerator of a vector subspace D of $U = V\theta$. The weight enumerator $W_D(x,y)$ of D is defined by

$$W_D(x,y) = \sum_{\mathbf{u}\in D} x^{t-wy(\mathbf{u})} y^{wy(\mathbf{u})}.$$

Clearly if G is trivial, that is, $G = \{e\}$, then this weight enumerator becomes the ordinary weight enumerator. For notation and terminology, we will refer the following book and paper: [3] for coding theory; [5] for codes with group action.

2. G-Codes

We have the following theorem which is a special case of Yoshida's result [5] .

Theorem 1. *If C is a G-code, then*

$$W_{C^{\perp}\theta}(x,y) = \frac{1}{|C\theta|} W_{C\theta}(x+(q-1)y, x-y).$$

If G is trivial, that is, $G = \{e\}$, then our theorem is the ordinary MacWilliams theorem [3. pp 146]

In order to prove Theorem 1 we need the following proposition.

Proposition 1 (Hayden). *Let V be the vector space $\mathbf{F}_q^n$. Assume that G is a finite permutation group on the coordinates of V and $|G|$ is prime to q. If C is a G-code and*

$$\theta = \frac{1}{|G|}\sum_{g\in G} g,$$

then

$$(C\theta)^{\perp} = Ker\,\theta + C^{\perp}\theta.$$

Proof. See the proofs of Theorem 4.2 and Corollary 1 in [1]. ∎

We will prove Theorem 1. If $\mathbf{x} = \sum_i x_i\overline{C}_i \in C\theta$ and $\mathbf{y} = \sum_i y_i\overline{C}_i \in C^{\perp}\theta$, by Proposition 1 we have

$$0 = (\mathbf{x},\mathbf{y}) = \sum_i m_i x_i y_i = (\mathbf{x},\mathbf{y}')_G,$$

where $\mathbf{y}' = \sum_i m_i y_i \overline{C}_i$. From this it follows that

$$(C\theta)_G^{\perp} \supseteq (C^{\perp}\theta)M, \tag{2}$$

where

$$M = diag(a_1, \ldots, a_n) \quad i = 1, \ldots, n;$$
$$a_i = m_j \quad \text{if} \quad i \in C_j.$$

Next we will show that

$$(C\theta)_G^{\perp} \subseteq (C^{\perp}\theta)M. \tag{3}$$

If $\mathbf{x} = \sum_i x_i \overline{C}_i \in (C\theta)_G^{\perp}$, $\mathbf{x}' = \sum_i (x_i/m_i)\overline{C}_i$ and $\mathbf{y} = \sum_i y_i \overline{C}_i \in C\theta$, we have

$$(\mathbf{x}', \mathbf{y}) = \sum_i m_i (x_i/m_i) y_i = (\mathbf{x}, \mathbf{y})_G = 0.$$

This shows that

$$\mathbf{x}' \in (C\theta)^{\perp}. \tag{4}$$

Since $\mathbf{x}' \in U = V\theta$, (4) and Proposition 1 imply that $\mathbf{x}' \in C^{\perp}\theta$.
Hence, $\mathbf{x} = \mathbf{x}'M \in (C^{\perp}\theta)M$. Now we proved that

$$(C\theta)_G^{\perp} \subseteq (C^{\perp}\theta)M. \tag{5}$$

From (2) and (5) it follows that

$$(C\theta)_G^{\perp} = (C^{\perp}\theta)M. \tag{6}$$

Here notice that MacWilliams theorem [3. pp 146] for the ordinary weight enumerator of the code $C\theta$ in U $(= V\theta)$ holds in this case, too.

MacWilliams theorem.

$$W_{(C\theta)_G^{\perp}}(x, y) = \frac{1}{|C\theta|} W_{C\theta}(x + (q-1)y, x - y).$$

Now we will finish the proof of Theorem 1. By the above MacWilliams theorem and (6), we obtain the following.

$$W_{(C^{\perp}\theta)M}(x, y) = \frac{1}{|C\theta|} W_{C\theta}(x + (q-1)y, x - y). \tag{7}$$

Since $W_{(C^{\perp}\theta)M}(x, y) = W_{C^{\perp}\theta}(x, y)$, it follows from (7) that

$$W_{C^{\perp}\theta}(x, y) = \frac{1}{|C\theta|} W_{C\theta}(x + (q-1)y, x - y). \quad \blacksquare$$

Remark. Generalizing a result of Thompson, Hayden [1] has proved the following proposition.

Proposition 2. *Using the notation of Proposition 1, then with an appropriate orthonormal base for* U, *(extending* $\mathbf{F}_q$ *if necessary) we have where* $(C\theta)_U^{\perp}$ *is the dual in terms of this basis*

$$(C\theta)_U^{\perp} = C^{\perp}\theta.$$

So our result (6) is a generalization of Proposition 2 in a sense.

The Case a finite Group G acts on Lattice

3. Definitions from Lattice Theory

In [5] Yoshida raised the following problem.

Problem. What can we say about lattices with groups action ? Can we define the equivariant version of theta functions?

He showed in [5] that there is a generalization of MacWilliams identity [3] to codes with group action. In this paper we will prove that there is a lattice version of this result. In order to state our theorem we introduce notation and terminology in lattice theory. Let V be the real n-dimensional space $\mathbf{R}^n$. A lattice Λ [4] is a subgroup of V satisfying one of the following equivalent conditions:

i) Λ is discrete and V/Λ is compact;
ii) Λ is descrete and generates the $\mathbf{R}$-vector space V;
iii) There exists an $\mathbf{R}$-basis $(e_1, \ldots, e_n)$ of V which is a $\mathbf{Z}$-basis of Λ (i.e. $\Lambda = \mathbf{Z}e_1 \oplus \cdots \oplus \mathbf{Z}e_n$).

Let the coordinates of the basis vectors be

$$\begin{aligned} e_1 &= (e_{11}, \ldots, e_{1n}), \\ e_2 &= (e_{12}, \ldots, e_{2n}), \\ &\vdots \\ e_n &= (e_{1n}, \ldots, e_{nn}). \end{aligned}$$

The $n \times n$ matrix M with (i, j)-entry equal to e_{ij} is called a generator matrix for Λ. The determinant of Λ is defined to be $\det \Lambda = |\det M|$. Given two vectors $\mathbf{u} = (u_1, \ldots, u_n)$,

$\mathbf{v} = (v_1, \ldots, v_n)$ of V, their inner product will be denoted by $\mathbf{u} \cdot \mathbf{u}$ or $(\mathbf{u}, \mathbf{u})$. The dual lattice is defined by

$$\Lambda^{\perp} = \{\mathbf{u} \in \mathbf{R}^n \mid \mathbf{u} \cdot \mathbf{v} = u_1 v_1 + \cdots + u_n v_n \in \mathbf{Z} \text{ for } all\ \mathbf{v} \in \Lambda\}.$$

The theta series $\Theta_\Lambda(z)$ of a lattice Λ is given by

$$\Theta_\Lambda(z) = \sum_{\mathbf{u} \in \Lambda} q^{\mathbf{u} \cdot \mathbf{u}},$$

where $q = e^{\pi i z}$. Jacobi's formula for the theta series of the dual lattice:

$$\Theta_{\Lambda^\perp}(z) = (\det \Lambda)(i/z)^{n/2} \Theta_\Lambda(-1/z). \tag{8}$$

The main purpose of this paper is to generalize equation (8) when a finite group G acts on Λ. From now on we assume that G is a finite permutation group on the coordinates of V. Then we can define a natural action of G on V as follows: If $\mathbf{v} = (v_1, \ldots, v_n) \in V$ and $g \in G$, we let $\mathbf{v}g = (x_1, \ldots, x_n)$ where for $i = 1, \ldots, n$, $x_i = v_{ig^{-1}}$. In this way V becomes an $\mathbf{R}G$-module. A G-lattice is a lattice which is also an $\mathbf{Z}G$-submodule of V. As in [1], the operator θ is defined by

$$\theta = \frac{1}{|G|} \sum_{g \in G} g.$$

Here we note that $V\theta = \{\mathbf{v} \in V \mid \mathbf{v}g = \mathbf{v} \text{ for } all\ g \in G\}$ and $\theta^T = \theta$ (see [1]).

Let $C_1, \ldots, C_t$ be the orbits of the coordinates of V under the action of G. Let m_i be the orbit length of C_i. Define $\overline{C}_i$ as the vector of V which has $1/\sqrt{m_i}$ as its entry for every point of C_i and 0 elsewhere. (This definition of the $\overline{C}_i$'s is similar to that in the proof of Theorem 4.3 in [1]). Then each of $\overline{C}_1, \ldots \overline{C}_t$ is in $V\theta$ and every element $\mathbf{u}$ of $V\theta$ is of the form

$$\mathbf{u} = \sum_{i=1}^{t} x_i \overline{C}_i.$$

If $\mathbf{a} = \sum_{i=1}^t a_i \overline{C}_i$ and $\mathbf{b} = \sum_{i=1}^t b_i \overline{C}_i$ are any two vectors in $V\theta$, then inner product $\mathbf{a} \circ \mathbf{b}$ of $\mathbf{a}$ and $\mathbf{b}$ is defined by

$$\mathbf{a} \circ \mathbf{b} = a_1 b_1 + \cdots + a_t b_t. \tag{9}$$

Let D be a lattice in $V\theta$. $D_G^\perp$ is the dual of D in $V\theta$ with respect to the inner product (9). The norm of $\mathbf{u} \in D$ is $\mathbf{u} \circ \mathbf{u}$.

We describe the theta series $\Theta_D(z)$ of a sublattice D as follows:

$$\Theta_D(z) = \sum_{\mathbf{u} \in D} q^{\mathbf{u} \circ \mathbf{u}},$$

where $q = e^{\pi i z}$.

For notation and terminology, we will refer the following book and paper: [4] for lattice theory; [5] for lattices with group action.

4. G-Lattices

We have the following:

Theorem 2. *If Λ is a G-lattice and $\Lambda_0 = \{\mathbf{r} \in \Lambda \mid \mathbf{r}\theta \in \Lambda\}$, then*

$$\Theta_{\Lambda_0^\perp\theta}(z) = (\det \Lambda_0\theta)(i/z)^{n/2}\Theta_{\Lambda_0\theta}(-1/z).$$

Note that $\Lambda_0\theta = \Lambda \cap \Lambda\theta = \{\mathbf{v} \in \Lambda \mid \mathbf{v}g = \mathbf{v} \text{ for } all\ g \in G\}$.

In order to prove Theorem 2 we need the following proposition.

Proposition 3. *Let V be the vector space $\mathbf{R}^n$. Assume that G is a finite permutation group on the coordinates of V. If Λ is a G-lattice and $\Lambda_0 = \{\mathbf{r} \in \Lambda \mid \mathbf{r}\theta \in \Lambda\}$, then*

$$(\Lambda_0\theta)^\perp = Ker\,\theta \oplus \Lambda_0^\perp\theta.$$

Proof. Our proof is similar to the proof of Theorem 4.2 in [1]. We note that Λ_0 is a G-sublattice of G-lattice Λ. If $\mathbf{r} \in \Lambda_0$, $\hat{\mathbf{r}} \in \Lambda_0^\perp$ and $\mathbf{y} \in Ker\,\theta^T (= \theta)$, we have

$$(\hat{\mathbf{r}}\theta^T, \mathbf{r}\theta) = (\hat{\mathbf{r}}, \mathbf{r}\theta^2) = (\hat{\mathbf{r}}, \mathbf{r}\theta) \in Z,$$

since $\mathbf{r}\theta \in \Lambda \cap \Lambda\theta \subseteq \Lambda_0$ and

$$(\mathbf{y}, \mathbf{r}\theta) = (\mathbf{y}\theta^T, \mathbf{r}) = 0 \in Z.$$

This shows that

$$Ker\,\theta + \Lambda_0^\perp\theta \subseteq (\Lambda_0\theta)^\perp. \tag{10}$$

If $\mathbf{r} \in \Lambda_0$, $\mathbf{y} \in (\Lambda_0\theta)^\perp$, we have

$$(\mathbf{y}\theta^T, \mathbf{r}) = (\mathbf{y}, \mathbf{r}\theta) \in Z.$$

So

$$\mathbf{y}\theta^T = \mathbf{y}\theta \in \Lambda_0^\perp.$$

Hence

$$\mathbf{y} = \mathbf{y} - \mathbf{y}\theta + (\mathbf{y}\theta)\theta \in Ker\,\theta + \Lambda_0^\perp\theta.$$

This implies that

$$(\Lambda_0\theta)^{\perp} \subseteq Ker\,\theta + \Lambda_0^{\perp}\theta. \tag{11}$$

(10) and (11) complete the proof of Proposition 3. ∎

We will prove Theorem 2. If $\mathbf{x} = \sum_i x_i\overline{C}_i \in \Lambda_0\theta$ and $\mathbf{y} = \sum_i y_i\overline{C}_i \in \Lambda_0^{\perp}\theta$, by Proposition 3 we have

$$\mathbf{x} \circ \mathbf{y} = (\mathbf{x}, \mathbf{y}) \in Z.$$

So

$$\Lambda_0^{\perp}\theta \subseteq (\Lambda_0\theta)_G^{\perp}. \tag{12}$$

Now take $\mathbf{x} = \sum_i x_i\overline{C}_i \in (\Lambda_0\theta)_G^{\perp}$, $\mathbf{y} = \sum_i y_i\overline{C}_i \in \Lambda_0\theta$. and observe

$$(\mathbf{x}, \mathbf{y}) = \mathbf{x} \circ \mathbf{y} \in Z.$$

This shows that

$$\mathbf{x} \in (\Lambda_0\theta)^{\perp}. \tag{7}$$

Since $\mathbf{x} \in V\theta$, (13) and Proposition 3 imply that $\mathbf{x} \in \Lambda_0^{\perp}\theta$.
Now we proved that

$$(\Lambda_0\theta)_G^{\perp} \subseteq \Lambda_0^{\perp}\theta. \tag{14}$$

From (12) and (14) it follows that

$$(\Lambda_0\theta)_G^{\perp} = \Lambda_0^{\perp}\theta.$$

Now we will finish the proof of Theorem 2. Jacobi's formula for the theta series of the dual lattice $(\Lambda_0\theta)_G^{\perp}$ in $V\theta$:

$$\Theta_{(\Lambda_0\theta)_G^{\perp}}(z) = (\det \Lambda_0\theta)(i/z)^{n/2}\Theta_{\Lambda_0\theta}(-1/z).$$

Hence $(\Lambda_0\theta)_G^{\perp} = \Lambda_0^{\perp}\theta$ establishes our theorem. ∎

Remark. It is easy to prove that

$$\Lambda/\Lambda_0 \cong \Lambda\theta/\Lambda \cap \Lambda\theta,$$
$$\Lambda_0 = (\Lambda \cap Ker\,\theta) \oplus (\Lambda \cap \Lambda\theta).$$

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