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WHICH ALTERNATING AND SYMMETRIC GROUPS ARE UNIT GROUPS?

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Abstract. We prove there is no ring with unit group isomorphic to $S_n$ for $n \geq 5$ and that there is no ring with unit group isomorphic to $A_n$ for $n \geq 5$, $n \neq 8$. To prove the non-existence of such a ring, we prove the non-existence of a certain ideal in the group algebra $\mathbb{F}_2[G]$, with $G$ an alternating or symmetric group as above. We also give examples of rings with unit groups isomorphic to $S_1, S_2, S_3, S_4, A_1, A_2, A_3, A_4,$ and $A_8$. Most of our existence results are well-known, and we recall them only briefly; however, we expect the construction of a ring with unit group isomorphic to $S_4$ to be new, and so we treat it in detail.

1. Introduction

Throughout this paper, our rings are assumed associative and to have identity element 1. We will consider a special case of the general question: For what finite groups $G$ is there a ring with unit group isomorphic to $G$? We shall see in the following example that this is a nontrivial condition.

Example 1.1. There does not exist a ring whose unit group is cyclic of order 5. The proof is by contradiction. A ring $R$ such that $R^\times \cong \mathbb{Z}_5$ would have no units of order 2, and hence $1 = -1$ in $R$. Thus $R$ is an $\mathbb{F}_2$-algebra. By considering the ring homomorphism

$$\mathbb{F}_2[x]/(x^5 - 1) \to R$$

which sends $x$ to a generator of $R^\times$, and by identifying $\mathbb{F}_2[x]/(x^5 - 1)$ with $\mathbb{F}_2 \times \mathbb{F}_{2^4}$, we find that $R$ must contain an isomorphic copy of $\mathbb{F}_{2^4}$. Hence $R$ has at least 15 units, and this is a contradiction.

Remark 1.2. The finite groups of odd order which occur as the unit group of a ring were determined in [2].

In the present paper, we determine which symmetric groups and alternating groups are unit groups. Our proofs are similar in several ways to the above proof. For example, although our groups do have elements of order 2 (except in trivial cases), we exploit the fact that our groups have no central elements of order 2 (except in trivial cases).

The main result proved in this paper is the following.

Theorem 1.3. The only finite symmetric groups and alternating groups which are unit groups of rings are the groups

$$S_1, S_2, S_3, S_4, A_1, A_2, A_3, A_4, A_8.$$
2. Unit groups with trivial center

In this section, we describe some general results which will be applied to the special cases of alternating groups and symmetric groups in the following sections. Our motivating question is the following.

**Question 2.1.** Let $G$ denote a group with trivial center. Does there exist a ring with unit group isomorphic to $G$?

We begin with an easy exercise.

**Proposition 2.2.** Let $G$ denote a finite group with trivial center, and let $R$ denote a ring with unit group $R^\times \cong G$. Then $R$ has characteristic 2.

**Proof.** The elements 1 and $-1$ are units in $R$ and are in the center of $R$, hence are in the center of $R^\times$. Hence $1 = -1$. \qed

The following reduces our Question 2.1 into a question about finite rings.

**Proposition 2.3.** Let $G$ denote a finite group with trivial center. If there exists a ring with unit group isomorphic to $G$, then there exists a two-sided ideal $I \subseteq F_2[G]$. 

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such that the quotient $\mathbb{F}_2[G]/I$ has unit group isomorphic to $G$, and furthermore such that the natural composition
\[ G \subseteq \mathbb{F}_2[G]^{\times} \to (\mathbb{F}_2[G]/I)^{\times} \cong G \]
is the identity map.

Proof. Let $R$ denote a ring with unit group isomorphic to $G$, and fix an isomorphism $R^{\times} \cong G$. There exists a unique homomorphism
\[ \varphi : \mathbb{Z}[G] \to R, \]
such that the induced map
\[ \varphi : G \to \mathbb{Z}[G]^{\times} \to R^{\times} \cong G \]
is the identity map. Because $G$ has trivial center, by Proposition 2.2, we know $R$ has characteristic 2. Hence our homomorphism $\varphi$ factors through a homomorphism
\[ \varphi : \mathbb{F}_2[G] \to R. \]

Let $R'$ denote the image of $\varphi$. Because $R'$ is a subring of $R$, we know that the unit group of $R'$ is a subgroup of $G$. On the other hand, we checked above that the image of $\varphi$ contains $G$. Hence the unit group of $R'$ is equal to $G$. Taking $I$ to be the kernel of $\varphi$ completes the proof. □

Our approach to Question 2.1 will be to consider the restrictions on an ideal $I \subseteq \mathbb{F}_2[G]$ as described in Proposition 2.3.

Hypothesis 2.4. Throughout this section, let $G$ denote a finite group with trivial center and let $I$ denote an ideal as in Proposition 2.3. We also write $\varphi$ for the natural map $\mathbb{F}_2[G] \to \mathbb{F}_2[G]/I$.

Definition 2.5. The weight of an element $x \in \mathbb{F}_2[G]$ is the number of non-zero coefficients that appear in the expression
\[ x = \sum_{g \in G} a_g g \quad (a_g \in \mathbb{F}_2). \]

Lemma 2.6. The ideal $I$ contains no elements of weight 2.

Proof. We prove that if $g + h \in I$, then $g = h$; this implies that $I$ contains no weight 2 elements. If $g + h \in I$, then $\varphi(g) = -\varphi(h)$. Because our ring is characteristic 2, this implies $\varphi(g) = \varphi(h)$. Because we have assumed that the restriction of $\varphi$ to $G$ is injective, this can only happen if $g = h$. □

Lemma 2.7. Let $x \in \mathbb{F}_2[G]$ denote a unit. Then there exists $\sigma_x \in G$ such that $x + \sigma_x \in I$.

Proof. This follows from the following remarks:
- $\varphi(x)$ is a unit and so $\varphi(x) = \varphi(\sigma_x)$ for some $\sigma_x \in G$;
- $x \equiv \sigma_x$ mod $I$ for some $\sigma_x \in G$;
- $x + \sigma_x = x - \sigma_x$ because our ring is characteristic 2. □

Proposition 2.8. Let $\hat{T} \in \mathbb{F}_2[G]$ denote a unit, which we view as arising from a subset $T \subseteq G$. The element $\sigma_T$ described in Lemma 2.7 is in the centralizer of $N_G(T)$ in $G$, where $N_G(T)$ is the normalizer of $T$ in $G$.
Proof. Because $I$ is a two-sided ideal, for any $g \in G$ we have
$$g(\hat{T} + \sigma \hat{T}) \in I \quad (\hat{T} + \sigma \hat{T})g \in I.$$  
In particular, taking $g \in N_G(T)$ and adding these last two elements, we find
$$g\hat{T} + \hat{T}g + g\sigma \hat{T} + \sigma \hat{T}g \in I,$$
$$g\sigma \hat{T} + \sigma \hat{T}g \in I.$$  
By Lemma 2.6, the elements $g\sigma \hat{T}$ and $\sigma \hat{T}g$ cannot be distinct elements of $G$. Hence $g$ and $\sigma \hat{T}$ commute. Because $g \in N_G(T)$ was arbitrary, we deduce that $\sigma \hat{T}$ is in the centralizer of $N_G(T)$ in $G$, as required. $\square$

We are now ready to apply these general results to some specific groups.

3. An example: unit group $S_3$

There is a well-known ring with unit group isomorphic to $S_3$, namely, the matrix ring $M_{2 \times 2}(\mathbb{F}_2)$. In this section, we apply the general techniques of the previous section to the group $S_3$ as a way of illustrating our approach.

The symmetric group $S_3$ has trivial center, and so the results of Section 2 all apply in the case $G \cong S_3$. We consider the restrictions on an ideal $I \subseteq \mathbb{F}_2[S_3]$ such that
$$(\mathbb{F}_2[S_3]/I)^\times \cong S_3,$$
and such that furthermore the induced map
$$S_3 \to \mathbb{F}_2[S_3]^\times \to (\mathbb{F}_2[S_3]/I)^\times \cong S_3$$
is the identity map.

Consider the element
$$H_1 := \sum_{\sigma \in S_3} \sigma \in \mathbb{F}_2[S_3]$$

corresponding to the full subgroup $S_3$. It is easy to check that $H_1^2 = 0$ and that $(H_1 + \iota)^2 = \iota$. Hence $H_1 + \iota$ is a unit in $\mathbb{F}_2[S_3]$. If we write $T = S_3 \setminus \{\iota\}$, then we can abbreviate this unit by $\hat{T}$. By Lemma 2.7 there must exist an element $\sigma \hat{T} \in S_3$ such that $\hat{T} + \sigma \hat{T} \in I$. Because the normalizer of $T = S_3 \setminus \{\iota\}$ in $S_3$ is the full group $S_3$, by Proposition 2.8 we must have $\sigma \hat{T} = \iota$, and hence $\hat{T} + \iota \in I$, and hence $H_1 \in I$. The reader may check that the 32-element ring $\mathbb{F}_2[S_3]/(H_1)$ has unit group isomorphic to $S_3$.

Let $\tau \in S_3$ denote a 3-cycle, and let $H_2 := \iota + \tau + \tau^2$. Then $(H_2) = (H_1, H_2)$, and the reader may check that the 16-element ring $\mathbb{F}_2[S_3]/(H_2)$ is another example of a ring with unit group isomorphic to $S_3$.

4. Unit group $S_n$

Having analyzed the case of $S_3$ in the previous section, we postpone the case of $S_4$ and turn our attention to $S_n$ for $n \geq 5$. These groups have trivial center, so again the results of Section 2 apply. Our goal is to prove the following theorem.

**Theorem 4.1.** There does not exist a ring with unit group isomorphic to $S_n$ for any $n \geq 5$. 
Theorem. Our goal is to produce an element of weight 2 in the ideal isomorphic to \( S \).

By way of contradiction, we suppose that we have a ring with unit group isomorphic to \( S \).

Proof. Let \( \tau = (12345) \) and consider the element \( T := \iota + \tau^2 + \tau^3 \in F_2[S_n] \). The fact that \( T \) is a unit of order 3 and with inverse \( 1 + \tau + \tau^4 \) is readily verified. By Lemma 2.7 there exists some \( \sigma \in S_n \) such that \( \iota + \tau^2 + \tau^3 + \sigma \in I \). By Proposition 2.8 the element \( \sigma \) must be in the centralizer of the normalizer of \( \{\iota, \tau^2, \tau^3\} \) in \( S_n \). One may check that the normalizer of \( \{\iota, \tau^2, \tau^3\} \) in \( S_n \) is \( D_5 \times S_{n-5} \) and that the centralizer of \( D_5 \times S_{n-5} \) is \( Z(S_{n-5}) \).

Thus \( \sigma \in Z(S_{n-5}) \). If \( \sigma = \iota \), then \( \iota + \tau^2 + \tau^3 + \iota = \tau^2 + \tau^3 \in I \) is a weight 2 element in \( I \), which is not allowed. The only remaining case is \( n = 7 \) and \( \sigma = (67) \). Let \( T = \iota + \tau^2 + \tau^3 + \sigma \in I \). Raising both sides to the 16-th power, we find that

\[
T^{16} = \iota^{16} + (\tau^2)^{16} + (\tau^3)^{16} + \sigma^{16} \in I.
\]

(We used here that \( \tau \) and \( \sigma \) commute, and that our base ring has characteristic 2.) Because \( \tau \) has order five and \( \sigma \) has order two, we find

\[
T^{16} = \iota + \tau^2 + \tau^3 + \iota = \tau^2 + \tau^3 \in I,
\]

which is a contradiction. This completes the proof that there are no rings with unit group isomorphic to \( S_n \), for \( n \geq 5 \).

5. Unit group \( A_n \)

The methods of the previous section carry over directly to the case of the alternating groups \( A_n \). The only substantive difference is that our proof breaks down in the case \( A_8 \), essentially because \( A_{8-5} = A_3 \) is abelian. This is to be expected, though, because as we will see in Theorem 7.6 the ring \( M_{4 \times 4}(F_2) \) has unit group isomorphic to \( A_8 \).

Theorem 5.1. There does not exist a ring with unit group isomorphic to \( A_n \) for any \( n \geq 5 \), \( n \neq 8 \).

Proof. The proof is very similar to the proof of Theorem 4.1, so we focus only on the main steps. Let \( I \subseteq F_2[A_n] \) denote an ideal satisfying the hypotheses of Proposition 2.3. Because the 5-cycle \( \tau = (12345) \) is in \( A_n \) for any \( n \geq 5 \), we again have a unit \( \iota + \tau^2 + \tau^3 \), and we again wish to consider possible values of \( \sigma \in A_n \) such that \( \iota + \tau^2 + \tau^3 + \sigma \in I \). One may check that the normalizer of \( \{\iota, \tau^2, \tau^3\} \) in \( A_n \) is \( D_5 \times A_{n-5} \). If \( n \geq 5 \), \( n \neq 8 \), then the centralizer of this subgroup in \( A_n \) is trivial, and hence \( \sigma = \iota \), and we are finished as before.

Remark 5.2. If \( n = 8 \), then the element \( \sigma \) described in the previous proof should be in the centralizer of \( D_5 \times A_3 \); this centralizer is a cyclic group of order 3. In the proof of Theorem 4.7, we at one point considered \( \sigma^{16} \). In the \( S_n \) case, we were able to prove that \( \sigma^{16} \) was always trivial. In the \( A_8 \) case, \( \sigma \) may have order 3, and so the proof breaks down, as it should because \( (M_{4 \times 4}(F_2))^\times \cong A_8 \); see Theorem 7.6 below.

\(^1\)The existence of such an order 3 unit \( T \) is explained as follows. By the Chinese Remainder Theorem, \( F_2[\tau] \cong F_2 \times F_{2^4} \). The unit group of \( F_{2^4} \) is cyclic of order 15 and hence \( F_2[\tau]^\times \) has a cyclic subgroup of order 3.
6. Unit group $S_4$

The only remaining nonabelian symmetric group to consider is $S_4$. We describe rings with unit group isomorphic to $S_4$ in this section. We first need some results similar to the results in Section 2.

**Lemma 6.1.** Let $H \subseteq S_n$ denote a subgroup of even order. Then $\hat{H}^2 = 0 \in F_2[S_n]$ and $\hat{H} + \iota$ is a unit in $F_2[S_n]$. (Recall our convention that we write $\hat{H}$ for the element $\sum_{h \in H} h \in F_2[S_n]$.)

**Proof.** For the first assertion, we have $\hat{H}^2 = |H| \cdot \hat{H} = 0$, because $|H|$ is even. For the second assertion, one checks that $(\hat{H} + \iota)^2 = \iota$. □

**Proposition 6.2.** Let $R$ denote a ring with unit group isomorphic to $S_4$, and let $I \subseteq F_2[S_4]$ denote an ideal as in Proposition 2.3.

1. The ideal $I$ contains $\hat{H}$, for $H$ an isomorphic copy of $S_3$ (and hence for $H$ any isomorphic copy of $S_3$) inside of $S_4$.

2. The ideal $I$ contains either

   $\iota + (24) + (12)(34) + (1234)$

   or

   $\iota + (24) + (12)(34) + (1432)$.

**Proof.** To prove (1), let $H$ denote an isomorphic copy of $S_3$ contained inside of $S_4$, and view $\hat{H}$ as an element of $F_2[S_4]$ as usual. Then by Lemma 6.1 $\hat{H} + \iota$ is a unit in $F_2[S_4]$. Then by Proposition 2.8 we find that

   $\hat{H} + \iota + \sigma \in I$

for some $\sigma$ in the centralizer of $H$ in $S_4$. The only possibility is $\sigma = \iota$, which completes the proof of (1).

To prove (2), we again find a unit $T \in F_2[S_4]$ and consider the possible values of $\sigma$ such that $T + \sigma \in I$. Let $T = \iota + (24) + (12)(34)$. The fact that $T$ is a unit of order 4 with inverse

   $\iota + (1234) + (1432) + (14)(23) + (13)$

is readily verified. Using Magma, it was verified that $\sigma = (1234)$ and $\sigma = (1432)$ were the only choices for which the two-sided ideal generated by $T + \sigma$ did not contain an element of weight 2. □

**Theorem 6.3.** Let $J_1$ (respectively, $J_2$) denote the two-sided ideal in $F_2[S_4]$ generated by the two elements

$\iota + (24) + (12)(34) + (1234)$

(respectively, $\iota + (24) + (12)(34) + (1432)$)

and

$\iota + (12) + (23) + (13) + (123) + (132)$.

Let $R_1 := F_2[S_4]/J_1$ and let $R_2 := F_2[S_4]/J_2$.

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2The unit $T$ was found using [4, Theorem 1.2], which shows that $(24) + (12)(34)$ is nilpotent, because it is an even weight element consisting of elements in a copy of the 2-group $D_4 \subset S_4$.  


The rings $R_1$ and $R_2$ are nonisomorphic rings with 128 elements and with unit group isomorphic to $S_4$. Every ring with unit group isomorphic to $S_4$ contains a subring isomorphic to either $R_1$ or $R_2$.

Proof. It can be verified in Magma that $R_1$ is a ring with 128 elements and with exactly 24 distinct units corresponding to the cosets $\sigma + J_1$, for $\sigma \in S_4$. (Sample Magma code which verifies this claim is given in Appendix A.) The same can be done for $R_2$, or it can be checked that $R_2 \cong R_1^{op}$, from which the claim that $R_2^x \cong R_1^x$ follows.

We next check that $R_1$ and $R_2$ are not isomorphic. An isomorphism $\psi : R_1 \to R_2$ would induce an isomorphism $\psi : R_1^x \to R_2^x$. Because the only automorphisms of $S_4$ are inner automorphisms, the restriction of $\psi$ to $S_4$ would have to correspond to conjugation by some element $\tau \in S_4$. Consider the image of an arbitrary element $x := \sigma_1 + \cdots + \sigma_n \in J_1$ under the composition

$$F_2[S_4] \to F_2[S_4]/J_1 \xrightarrow{\psi} F_2[S_4]/J_2.$$

On one hand, $x$ must map to the coset $J_2$. On the other hand, $x$ must map to $\tau \sigma_1 \tau^{-1} + \cdots + \tau \sigma_n \tau^{-1} + J_2$.

Thus we have shown that if there is an isomorphism $\psi : R_1 \to R_2$, then there exists an element $\tau \in S_4$ such that $\tau J_1 \tau^{-1} \subseteq J_2$ and thus $J_1 \subseteq \tau^{-1} J_2 \tau$. Because $J_2$ is a two-sided ideal, this would imply

$$J_1 \subseteq \tau^{-1} J_2 \tau \subseteq J_2.$$

However, $J_1 \subseteq J_2$ implies that both the elements

$$\iota + (24) + (12)(34) + (1234) \quad \text{and} \quad \iota + (24) + (12)(34) + (1432)$$

are in $J_2$, and hence so is their sum $(1234) + (1432)$. This contradicts the fact that the cosets $(1234) + J_2$ and $(1432) + J_2$ are distinct.

We now prove the final assertion, that any ring $R$ with unit group isomorphic to $S_4$ contains a subring isomorphic to $R_1$ or $R_2$. We know that such a ring $R$ contains a subring $F_2[S_4]/I$, where $I$ is an ideal as in Proposition 2.3. So it suffices to show that if $I$ is an ideal as in Proposition 2.3 then $I = J_1$ or $J_2$. It was proven in Proposition 6.2 that $I$ must contain either $J_1$ or $J_2$. So it remains only to show that the ideal $I$ cannot be strictly larger than $J_1$ or $J_2$. It was verified in Magma that for each nonzero principal ideal $(x)$ in $R_1$, the ring $R_1/(x)$ has at most 6 units, and hence cannot have unit group isomorphic to $S_4$. \hfill $\square$

7. The remaining cases

7.1. The abelian cases. These cases are trivial, but we include them for the sake of completeness.

Proposition 7.1. For each group $G$ in the list

$$S_1, S_2, A_1, A_2, A_3,$$

there exists a ring with unit group isomorphic to $G$.

Proof. The groups $S_1, S_2, A_1, A_2, A_3$ are cyclic groups of order $1, 2, 1, 1, 3$, respectively. Hence, they are isomorphic to the unit groups of the fields $F_2, F_3, F_2, F_2, F_4$, respectively. \hfill $\square$
7.2. Unit group $A_4$. In this section we give two different rings with unit group isomorphic to $A_4$. We describe the first ring as an explicit quotient of $F_2[A_4]$. We describe the second ring as a quotient of the ring of Hurwitz quaternions.

**Theorem 7.2.** Let $J \subseteq F_2[A_4]$ denote the two-sided ideal generated by the elements
\[ \iota + (12)(34) + (13)(24) + (14)(23) \]
and
\[ \iota + (132) + (12)(34) + (143). \]
Then the quotient $F_2[A_4]/J$ is a ring with 32 elements and with unit group isomorphic to $A_4$.

**Proof.** By adapting the Magma code in Appendix A, this assertion is readily verified. □

We next use quaternions to give a second example of a ring with unit group isomorphic to $A_4$. First we set some notation.

**Definition 7.3.** Let $B$ denote the division algebra $\mathbb{Q} + \mathbb{Q}i + \mathbb{Q}j + \mathbb{Q}k$, where $i, j, k$ are defined as in the Hamilton quaternions. Let $\omega = \frac{1+i+j+k}{2}$ and let $O \subseteq B$ denote $\mathbb{Z} \oplus \mathbb{Z}i \oplus \mathbb{Z}j \oplus \mathbb{Z}\omega \subseteq B$; then $O$ is a subring of $B$ known as the Hurwitz quaternions.

The authors thank Noam Elkies for the following example.

**Theorem 7.4.** Let $O$ denote the ring of Hurwitz quaternions, as in Definition 7.3. The quotient ring $O/2O$ is a ring with 16 elements and with unit group isomorphic to $A_4$.

**Proof.** By [3, Proposition 3], the unit group $O^\times$ is isomorphic to the binary tetrahedral group; in particular, there is a short exact sequence
\[ 1 \to \{\pm 1\} \to O^\times \to A_4 \to 1. \]
The kernel of the induced map
\[ O^\times \to (O/2O)^\times \]
is exactly $O^\times \cap (1 + 2O) = \{\pm 1\}$. Hence $(O/2O)^\times$ contains a subgroup isomorphic to $A_4$. On the other hand, $O/2O$ is a ring with 16 elements. Hence its unit group must be precisely $A_4$. □

**Remark 7.5.** The ring $O/2O$ from Theorem 7.4 is isomorphic to $F_2[A_4]/J$, where $J$ is the ideal generated by $\iota + (123) + (132)$.

7.3. Unit group $A_8$. The only remaining case is $A_8$, which we recall in the following theorem.

**Theorem 7.6.** The unit group of $M_{4\times 4}(F_2)$ is isomorphic to $A_8$.

**Proof.** We have
\[ M_{4\times 4}(F_2)^\times = GL_4(F_2) = PSL_4(F_2) \cong A_8. \]
For this last isomorphism, see [7, Section 3.12.1]. □
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Appendix A. Sample Magma code

To find a ring with unit group isomorphic to $S_4$, we explicitly computed the unit group of a certain quotient of $F_2[S_4]$. The computation was done in Magma, and we next provide sample code which performs this computation.

Example A.1. The following was used at the beginning of the proof of Theorem 6.3. It first creates the ring $R_1$ and counts its total number of elements as well as its number of units. It then ensures that no elements $\sigma_1 \neq \sigma_2$ become equal in $R_1 \cong F_2[S_4]/I$.

G:=SymmetricGroup(4);
F2G:=GroupAlgebra(GF(2), G);
x1:= F2G!G!1+F2G!G!(2,4)+F2G!G!(1,2)(3,4)+F2G!G!(1,2,3,4);
x2:=F2G!0;
H1:=sub<G|(1,2),(1,2,3)>;
for h in H1 do
   x2:=x2+F2G!h;
end for;
I:=ideal<F2G|x1, x2>;
R1:= F2G/I;
numunits:=0;
for x in R1 do
   if IsUnit(x) then
      numunits:=numunits+1;
   end if;
end for;

#(F2G/I);
numunits;

for y1 in G do
   for y2 in G do
      if F2G!y1 + F2G!y2 in I then
         if y1 ne y2 then
            y1;
y2;
         end if;
      end if;
   end for;
end for;
end for;
end for;

References


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