On the Proof of a Theorem of Pálfy

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Abstract

Pálfy proved that a group G is a CI-group if and only if $|G| = n$ where either $\gcd(n, \varphi(n)) = 1$ or $n = 4$, where φ is Euler's phi function. We simplify the proof of "if $\gcd(n, \varphi(n)) = 1$ and G is a group of order n, then G is a CI-group".

In 1987, Pálfy [6] proved perhaps the most well-known result pertaining to the Cayley isomorphism problem. Namely, that a group G of order n is a CI-group if and only if either $\gcd(n, \varphi(n)) = 1$ or $n = 4$, where φ is Euler's phi function. It is worth noting that every group of order n is cyclic if and only if $\gcd(n, \varphi(n)) = 1$. It is the purpose of this note to simplify some parts of Pálfy's original proof.

Definition 1 Let G be a group and define $g_L : G \to G$ by $g_L(x) = gx$. Let $G_L = \{g_L : g \in G\}$. Then G_L is the *left-regular representation of* G. (It is a subgroup of the symmetric group S_G of all permutations on G.) We define a *Cayley object of* G to be a combinatorial object X (e.g. digraph, graph, design, code) such that $G_L \leq \mathrm{Aut}(X)$, where $\mathrm{Aut}(X)$ is the *automorphism group of* X (note that this implies that the vertex set of X is in fact G). To say that G is a *CI-group* means that if X and Y are any Cayley objects of G such that X is isomorphic to Y, then some group automorphism of G is an isomorphism from X to Y.

CI-groups are characterized by the following result due to Babai [1].

Lemma 1 *For a group G, the following are equivalent:*

1. *G is a CI-group,*

2. *for every $\gamma \in S_G$, there exists $\delta \in \langle G_L, \gamma^{-1}G_L\gamma\rangle$ such that $\delta^{-1}\gamma^{-1}G_L\gamma\delta = G_L$.*

We will not simplify all of Pálfy's proof, so it will be worthwhile to discuss exactly which part of his proof we will simplify. First, we will not deal with groups G such that $|G| = 4$ at all. Second, we will only be concerned with showing that if $\gcd(n, \varphi(n)) = 1$, then $\mathbb{Z}_n$ is a CI-group. Third, Pálfy's original proof can be broken into two cases, with the first dealing with the case where $\langle(\mathbb{Z}_n)_L, \gamma^{-1}(\mathbb{Z}_n)_L\gamma\rangle$ is doubly-transitive and the second dealing with the case where $\langle(\mathbb{Z}_n)_L, \gamma^{-1}(\mathbb{Z}_n)_L\gamma\rangle$ is imprimitive (note that as $\mathbb{Z}_n$ is a Burnside group [3, Theorem 3.5A] for n composite, these are the only nontrivial cases). The doubly-transitive case was reduced by Pálfy to the imprimitive case using the fact that all doubly-transitive groups are known [2], which is a consequence of the Classification of the Finite Simple Groups. We shall do the same, using Pálfy's argument. Pálfy handled the imprimitive case by using a sequence of lemmas (Lemmas 1.1-1.4 in [6]) which, while not overly difficult, do involve some tedious calculations and do not seem to make transparent why the condition $\gcd(n, \varphi(n)) = 1$ is crucial. We shall show that Lemma's 1.2-1.4 of [6] can more or less be replaced by an application of Philip Hall's generalization of the Sylow Theorems for solvable groups.

Let π be a set of primes. A π-*group* is a group G such that every prime divisor of $|G|$ is contained in π. A Hall π-subgroup H of G is a subgroup of G such that H is a π-group, and no prime contained in π divides $|G|/|H|$. Hall π-subgroups need not exist, but we remind the reader that Hall's Theorem [4, Theorem 6.4.1] states that they do exist if G is solvable, and in that case any two Hall π-subgroups of G are conjugate in G.

Definition 2 Let G be a transitive permutation group of degree mk that admits a complete block system $\mathcal{B}$ of m blocks of size k. If $g \in G$, then g permutes the m blocks of $\mathcal{B}$ and hence induces a permutation in the symmetric group S_m, which we denote by $g/\mathcal{B}$. We define $G/\mathcal{B} = \{g/\mathcal{B} : g \in G\}$. Let $\mathrm{fix}_G(\mathcal{B}) = \{g \in G : g(B) = B \text{ for every } B \in \mathcal{B}\}$, and for $B \in \mathcal{B}$, let $\mathrm{Stab}_G(B) = \{g \in G : g(B) = B\}$.

We shall use Pálfy's notation, repeated here for convenience. Let x be the n-cycle $(0\ 1\ \ldots\ n-1)$ (so that $\langle x\rangle = (\mathbb{Z}_n)_L$) and y any conjugate of x in S_n such that $\langle x, y\rangle$ admits a complete block system of m blocks of size k. Let $x^m = z_0z_1\cdots z_{m-1}$ where each z_i is a k-cycle that permutes i. Finally, let $P = \langle z_i : i \in \mathbb{Z}_m\rangle$. The following result combines Lemmas 1.2, 1.3, and 1.4 of [6].

Lemma 2 *If $\langle x, y\rangle$ admits a complete block system $\mathcal{B}$ with m blocks of size k such that $y^m \in P$, $\mathbb{Z}_m$ is a CI-group, and* $\gcd(m, k\cdot\varphi(k)) = 1$, *then $\langle y\rangle$ is conjugate to $\langle x\rangle$ in $\langle x, y\rangle$.*

Proof. As $\langle x\rangle$ and $\langle y\rangle$ are abelian, and a transitive abelian subgroup is regular [3, Theorem 4.2A (v)], we have that $\mathrm{fix}_{\langle x\rangle}(\mathcal{B})$ and $\mathrm{fix}_{\langle y\rangle}(\mathcal{B})$ have order k and $\langle x\rangle/\mathcal{B}$, $\langle y\rangle/\mathcal{B}$ are cyclic of order m. As $\mathbb{Z}_m$ is a CI-group, by Lemma 1, there exists $\delta_1 \in \langle x, y\rangle/\mathcal{B}$ such that $\delta_1^{-1}\langle y\rangle\delta_1/\mathcal{B} = \langle x\rangle/\mathcal{B}$. We thus assume without loss of generality that $\langle y\rangle/\mathcal{B} = \langle x\rangle/\mathcal{B}$.

For $i \in \mathbb{Z}_m$, we have that $x^{-1}z_ix = z_{\sigma(i)}$ for some $\sigma \in S_m$ and, as $y^m \in P$ and $\langle y\rangle$ is abelian, we also have that $y^{-1}z_iy = z_{\delta(i)}^{a_i}$ for some $\delta \in S_m$ and $a_i \in \mathbb{Z}_k^*$. We conclude that both x and y normalize P, so that x and y normalize $P' = P \cap \langle x, y\rangle$. Thus $P' \triangleleft \langle x, y\rangle$. Hence $P' \triangleleft \mathrm{Stab}_{\langle x,y\rangle}(B)$, $B \in \mathcal{B}$, so that $\mathrm{Stab}_{\langle x,y\rangle}(\mathcal{B})|_B$ is a transitive group of degree k and contains a normal regular abelian subgroup of degree k. By [3, Corollary 4.2B], we have that $\mathrm{Stab}_{\langle x,y\rangle}(B)|_B$ is isomorphic to the semidirect product $\mathrm{Aut}(\mathbb{Z}_k)\ltimes\mathbb{Z}_k = N(k)$. It is well known that $\mathrm{Aut}(\mathbb{Z}_k)$ is solvable of order $\varphi(k)$, so that $N(k)$ is solvable of order $\varphi(k)\cdot k$. By the Embedding Theorem [5, Theorem 2.6], $\langle x,y\rangle$ is permutation group isomorphic to a subgroup of the wreath product $(\langle x,y\rangle/\mathcal{B})\wr N(k)$ so that $\langle x,y\rangle$ is permutation group isomorphic to a subgroup of $\mathbb{Z}_m\wr N(k)$. Hence $\langle x,y\rangle$ is solvable. Let π be the set of primes dividing m. As $|\mathbb{Z}_m\wr N(k)| = m\cdot[\varphi(k)\cdot k]^m$ and $\gcd(m,\varphi(k)) = 1$, we have that $\gcd(m,[\varphi(k)\cdot k]^m) = 1$. Thus $\langle x^k\rangle$ and $\langle y^k\rangle$ are Hall π-subgroups of $\langle x,y\rangle$ and by Hall's Theorem are conjugate in $\langle x,y\rangle$. We may thus assume without loss of generality that $\langle x^k\rangle = \langle y^k\rangle$.

As P' is abelian, y^m commutes with x^m. As $\langle y^k\rangle = \langle x^k\rangle$ and y^m commutes with y^k, we have that y^m also commutes with x^k. As $\langle x^m, x^k\rangle = \langle x\rangle$ is a transitive abelian group, and a transitive abelian group is self-centralizing [3, Theorem 4.2A (v)], we have that $y^m\in\langle x\rangle$. As $\langle y^k\rangle\le\langle x\rangle$, we have that $\langle y\rangle\le\langle x\rangle$ so that $\langle y\rangle = \langle x\rangle$. □

For completeness, we include the following proof. Note that it is essentially Pálfy's original proof, with Lemma 2 replacing Lemmas 1.2, 1.3, and 1.4 of [6].

Theorem 3 (Pálfy) *If n is a positive integer and $\gcd(n,\varphi(n)) = 1$, then $\mathbb{Z}_n$ is a CI-group.*

PROOF. Let $n = p_1\cdots p_r$ be the prime factorization of n. (Note that $p_1,\ldots,p_r$ are distinct, because n is relatively prime to $\varphi(n)$.) We proceed by induction on r.

If $r = 1$, then any two regular cyclic subgroups of S_n are Sylow n-subgroups of S_n, and thus are conjugate. The result then follows by Lemma 1.

Assume that the result holds for all n with $\gcd(n,\varphi(n)) = 1$ such that n has $r-1$ distinct prime factors. Let n have $r\ge 2$ distinct prime factors, and x be as above. Let $y\in S_n$ be any n-cycle (so that $\langle y\rangle$ is conjugate to $\langle x\rangle$ in S_n). As $\mathbb{Z}_n$ is a Burnside group, by [3, Theorem 3.5A], we have that $\langle x,y\rangle$ is either doubly-transitive or imprimitive.

If $\langle x,y\rangle$ is imprimitive, admitting a complete block system $\mathcal{B}$ of m blocks of size k, then by [6, Lemma 1.1], there exists $y'\in S_n$ such that y' is conjugate of y in $\langle x,y\rangle$ and $(y')^m\in P$. By Lemma 2, we then have that $\langle y'\rangle$ is conjugate to $\langle x\rangle$ in $\langle x,y'\rangle$, so that $\langle x\rangle$ is conjugate to $\langle y\rangle$ in $\langle x,y\rangle$. By Lemma 1, $\mathbb{Z}_n$ is a CI-group and the result follows by induction.

If $\langle x,y\rangle = S_n$, then clearly $\langle y\rangle$ is conjugate to $\langle x\rangle$ in $\langle x,y\rangle$. If $\langle x,y\rangle = A_n$, then by [6, Lemma 3.1] we have that $\langle y\rangle$ and $\langle x\rangle$ are conjugate in A_n. Thus if $\langle x,y\rangle = A_n$ or S_n, then the result follows by Lemma 1. Otherwise, by [6, Lemma 2.1], there exists a prime divisor p of n such that the Sylow p-subgroups of $\langle x,y\rangle$ have order p. Then $\langle x^{n/p}\rangle$ and $\langle y^{n/p}\rangle$ are Sylow p-subgroups of $\langle x,y\rangle$ and are thus conjugate. Hence there exists $y'\in S_n$ such that $\langle y'\rangle$ is conjugate to $\langle y\rangle$ in $\langle x,y\rangle$ and $(y')^{n/p} = x^{n/p}$. Then $\langle x^{n/p}\rangle\triangleleft\langle x,y'\rangle$, and so $\langle x,y'\rangle$ admits a complete block system $\mathcal{B}$ consisting of n/p blocks of size p, reducing this case to the imprimitive case above. The result then follows by induction. □

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