138. An Analytical Proof of the Fundamental Theorem on Finite Abelian Groups

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The aim of this note is to give an analytical proof of the following fundamental theorem on finite abelian groups.

Theorem. For any finite abelian group $\mathfrak{G}$, there exists a basis $(t_\nu;\ 1\leqq\nu\leqq m)$ such that for any element t of $\mathfrak{G}$, we have one and only one representation $t=t_1^{r_1}t_2^{r_2}\cdots t_m^{r_m}$, where $1\leqq r_\nu\leqq n_\nu$ $(1\leqq\nu\leqq m)$, n_ν being the order of t_ν.

Proof. Let $\mathfrak{G}$ be a finite abelian group of order n and $\mathfrak{H}$ its group-ring over the complex number field C. The ring $\mathfrak{H}$ may constitute an (n-dimensional) Hilbert space with the inner product $(a, b)=\sum_{s\in\mathfrak{G}}\alpha(s)\overline{\beta(s)}$ ($\overline{\beta(s)}$=the complex conjugate number of $\beta(s)$), where $a=\sum_{s\in\mathfrak{G}}\alpha(s)s$ and $b=\sum_{s\in\mathfrak{G}}\beta(s)s$. Let U_t be a unitary operator defined by $U_t a=\sum_{s\in\mathfrak{G}}\alpha(t^{-1}s)s$ on $\mathfrak{H}$ and $\mathfrak{R}$ be the C^*-algebra generated by $(U_t;\ t\in\mathfrak{G})$. The algebra $\mathfrak{R}$ is homomorphic to $C(\Omega)$, the totality of the complex-valued continuous functions on Ω, where Ω is the character group of $\mathfrak{G}$, which consists of finite points $\{\lambda_\nu;\ 1\leqq\nu\leqq m\}$. In fact, for any element t of $\mathfrak{G}$, it follows from $t^n=1$ that a spectrum of U_t is an n-th root of 1. Hence, the number of characters of $\mathfrak{G}$ is at most n^n. Let $A\to\hat{A}$ be the canonical homomorphism from $\mathfrak{R}$ into $C(\Omega)$. Then, $t\to\hat{U}_t$ $(t\in\mathfrak{G})$ is an isomorphism. In fact, if $t\neq1$, then U_t has at least one spectrum ζ, where ζ is a primitive r-th root of 1 and r is the order of t. Hence, there exists a maximal ideal $\mathfrak{M}$ of $\mathfrak{R}$ containing $U_t-\zeta$, where $\mathfrak{R}/\mathfrak{M}$ is a cyclotomic field over C, that is $\mathfrak{R}/\mathfrak{M}=C$. Therefore, there exists a character λ of $\mathfrak{G}$ with $\lambda(t)\neq1$, where λ is the canonical homomorphism from $\mathfrak{R}$ onto $\mathfrak{R}/\mathfrak{M}$. Hence, we may assume without loss of generality that $t=\hat{U}_t(t\in\mathfrak{G})$. Let C_ν be $(t(\lambda_{\nu+1});\ t\in\mathfrak{G},\ t(\lambda_1)=1,\cdots,t(\lambda_\nu)=1)$, which is a finite cyclic group in C, because a subgroup of a cyclic group is again cyclic. Let $\mathfrak{G}_\nu$ be a subgroup of $\mathfrak{G}$, which consists of elements t's of $\mathfrak{G}$ with $t(\lambda_1)=\cdots=t(\lambda_\nu)=1$, and t_ν be an element of $\mathfrak{G}$, whose value at $\lambda_{\nu+1}$ is a generator η_ν of C_ν. In order to prove that, for any element t of $\mathfrak{G}$, there exists the representation stated in the theorem, we need only to prove that $t\in\mathfrak{G}_\nu$ implies $tt_{\nu+1}^{-r_{\nu+1}}\in\mathfrak{G}_{\nu+1}$ for one and only one natural number $r_{\nu+1}$ between 1 and $n_{\nu+1}$. And the number $r_{\nu+1}$ defined by $t(\lambda_{\nu+1})=\eta_{\nu+1}^{r_{\nu+1}}$ satisfies this condition.