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# On the Mathematical Work of Hans Reiter

By

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In [1]*) Reiter gave an elegant and simple proof of the theorem of Wiener—Lévy for locally compact abelian groups $G$; he also began to investigate the structure of the quotient $L^1(G)/I$ for a closed ideal $I$ of $L^1(G)$. For $f \in L^1(G)$ let $\hat{f}$ be the Fourier transform of $f$ and $(\hat{f})^{-1}(0)$ the set of all characters $\chi$ of $G$ ($\chi \in \hat{G}$) with $\hat{f}(\chi) = 0$. The cospectrum of $I$ (cosp $I$) is the set $\bigcap_{f \in I} (\hat{f})^{-1}(0)$. In [1] he proved that if the cospectrum of $I$ is a closed subgroup of the dual group $\hat{G}$, then $L^1(G)/I$ is isomorphic, as a Banach algebra, to $L^1(G/H)$ where $H$ is the closed subgroup of $G$ which consists of all $x$ in $G$ with $\chi(x) = 1$ for every $\chi \in \operatorname{cosp} I$.

In [2] he showed that if the cospectrum of $I$ is a countable independent subset $S$ of $\hat{G}$, then $L^1(G)/I$ is isomorphic to the Banach algebra $C_0(S)$ of all continuous functions vanishing at infinity on $S$. Curiously, this very interesting contribution is never attributed to him in the literature on the subject.

The investigation of $L^1(G)/I$ is a central theme in the work of Reiter. In [11] it is shown that, under appropriate conditions on the spectrum of $I$, $L^1(G)/I$ is isomorphic to $L^1(G/H, C_0(S))$. Incidentally, this is a very nice application of integration theory of Banach-valued functions in the sense of Bourbaki.

The articles [6] and [7] contain one of the most beautiful results of Reiter! Let $H$ be a closed subgroup of $G$, $F$ an arbitrary closed subset of $G/H$ and $\omega$ the canonical map of $G$ onto $G/H$. The set $F$ is of spectral synthesis in $G/H$ if and only if $\omega^{-1}(F)$ is of spectral synthesis in $G$. The proof is simple but very clever and represents one of the triumphs of the methods of Weil's book ⟨27⟩. Such an important result could not remain without further developments! We refer to Herz ⟨11⟩ (Lemma 5.6, Theorem 5.7, Theorem 5.8 and Theorem 6.1) and to de Leeuw and Herz ⟨15⟩. Mrs Lust—Piquard proved a similar result for sets of bounded spectral synthesis ⟨19⟩. Various extensions to non-

*) Items in square brackets [] refer to the list of publications of Reiter given at the end; those in angular brackets ⟨⟩ refer to other publications given in the references.

commutative groups were obtained by Lasser ⟨14⟩, by Hauenschild and Ludwig ⟨10⟩. Lohoué presented a deep and promising version of [6] and [7], involving convolution operators on non-commutative groups, in ⟨17⟩. ⟨4⟩ is in the same vein. In [8] Reiter proved, as a supplement to Schwartz's counterexample, that for $n \geqslant 3$, $S_{n-1} \cup E$ is not of spectral synthesis for any closed subset $E$ of $\mathbb{R}^n$ not containing $S_{n-1}$. He also observed that, for $n \geqslant 3$, single points are not sets of spectral synthesis, with respect to the Banach algebra of all radial functions in $L^1(\mathbb{R}^n)$.

The study of the quotient norm in $L^1(G)/I$ leads him [9] to an elegant formula for the distance (in $L^1(G)$) between 0 and the convex set generated by $\{f_h \mid h \in H\}$, where $f_h(x) = f(xh)$ and $H$ is an arbitrary abelian closed subgroup of $G$. See [19] (p. 174—177) and ⟨2⟩ for further improvements. This result is used in [14] to show that the image of a closed ideal under the canonical map of $L^1(G)$ onto $L^1(G/H)$ is closed. For a partial converse, see Rindler ⟨23⟩ and also Johnson ⟨13⟩ (p. 184—186).

Dieudonné showed in ⟨5⟩ (p. 288) that for a nilpotent connected Lie group $G$ and for every $1 \leqslant p < \infty$ the following property (called property $P_p$) is satisfied, given any compact subset $K$ of $G$ and given $\varepsilon > 0$ there is an $s \in L^p(G)$ with $s \geqslant 0$ $\|s\|_p = 1$ and $\int_G |s(kx) - s(x)|^p \, dx < \varepsilon^p$ for all $k \in K$. He recalls that Reiter had already obtained $P_1$ for abelian locally compact groups in [1] (p. 405—406). Dieudonné proved that $P_1$ implies $P_p$ for every $1 < p < \infty$. By a very clever computation he proved in ⟨6⟩ that a finitely generated non-abelian free group does not have $P_1$. Answering questions raised by Dieudonné in ⟨5⟩ (p. 289), Reiter proved that every solvable locally compact group has $P_1$ [12], whereas $SL(n, \mathbb{R})$, $SL(n, \mathbb{C})$ do not [13]. In fact, although this result is not explicitely stated there, he already obtained in [1] (p. 418) that every $G$ having $P_1$ is necessarily amenable. In [15] and [17] he proved the equivalence of the following properties:

1) $G$ has $P_1$;
2) $G$ has $P_2$;
3) the function 1 can be approximated uniformly on compact subsets of $G$ by functions of the form $f * \tilde{f}$ where $f$ is continuous with compact support and $\tilde{f}(x) = \overline{f(x^{-1})}$;
4) $G$ is amenable.

Already in ⟨27⟩, Weil had proved that $\int_G \phi(x) \, dx \geqslant 0$ for every positive-definite function $\phi$ which is in $L^1(G)$ if $G$ is compact (p. 60) and if $G$ is abelian (p. 120).Later, Godement in ⟨9⟩ observed that the preceding property is equivalent to 3).

The equivalence of 1) with 4) gives to $P_1$ a particular importance. Amenability has a "metaphysical character": it is in fact impossible to exhibit (or to construct) an invariant mean on $\ell^\infty(\mathbb{Z})$ or on the space of all continuous bounded functions on $\mathbb{R}$. On the other hand, given $\varepsilon > 0$ and $K$ compact subset of $\mathbb{Z}$ or of $\mathbb{R}$, it is easy to define explicitely a function which realizes $P_1$. In other words, $P_1$ is some sort of "analytical" version of amenability.

Stegeman ⟨26⟩ proved that if $P_{p_0}$ is verified for a certain $1 < p_0 < \infty$, then $P_p$ holds for every $1 \leqslant p < \infty$. In [18] Reiter proved that every closed subgroup of an amenable group is amenable. In fact, this result had also been obtained independently by Hulanicki ⟨12⟩ by a different method. The case of discrete subgroups is already in [13].

In 1968, he published his well-known book [19] "*Classical Harmonic Analysis and Locally Compact Groups*". The general philosophy of the book follows a principle enunciated by A. Weil in his masterpiece "*L'intégration dans les groupes topologiques et ses applications*" [27] (p. 111): "Les groupes abéliens, localement compacts, forment le domaine naturel de l'analyse harmonique". Reiter's book is extremely pleasant to read, the proofs are always clear, complete and totally convincing. The approach choosen by Reiter to describe the different topics is always the most transparent. The book is not encyclopedic. The author only considers the parts of the subject that attracted him. The exposition of Wiener—Lévy's and Wiener's Theorem (p. 5—11) in less than six pages is an example of the author's clarity of exposition. The book contains most of the subjects treated in his articles [1] to [18]. Particularly useful for a beginner is a selection of those parts of Bourbaki's integration theory which suffice for studying harmonic analysis on groups (p. 45—67). Of particular interest are the exposition of Schwartz's counterexample to spectral synthesis and the marvellous proof of C. Herz of the fact that $S_1$ is of spectral synthesis in $\mathbb{R}^2$. One of the most pleasant features of this book is the stress on a few general principles, which are important for the development of the subject. For example on p. 107 he very clearly formulates what he called the "principle of relativization". This principle covers Poisson's formula and leads to very interesting developments in both the commutative and the non-commutative case. Chapter 8 gives, I think, the best exposition on quasi-invariant measures on quotients (p. 157—168) and one of the most lucid introduction to locally compact amenable groups. And, all this in 32 pages! Particularly elegant and original is the proof of the non-amenability of all non-compact connected semi-simple Lie groups with finite center (not the one which consists in picking out in $SL(2, \mathbb{R})$ a free non-abelian discrete subgroup). In short: this book is a gem!

Reiter's book was very well received (see Rajagopalan ⟨21⟩) and it was sold out within a few months. It opened new directions of research, particularly in the context of non-commutative groups. For example, an analogue of the property $P_1$ for quotients was studied by Eymard ⟨7⟩. Several problems raised in [19] have now been solved. Among them, the relation between the closed ideals of $L^1(H)$ and $L^1(G)$ ($H$ being a closed subgroup of $G$) (p. 148) was completely elucidated by Hauenschild and Ludwig (⟨10⟩ Theorem 2.3 p. 170). A direct proof of the fact that if $G$ has $P_1$, then so has every closed subgroup of $G$ (see [19], p. 173) is given in ⟨3⟩.

In [20] Reiter proved that the amenability of $G$ (or equivalently property $P_1$) is equivalent to the fact that the ideal of $L^1(G)$ which consists of all functions $f$ with $\int_G f(x)\,dx = 0$ has bounded approximate units. This was a further motivation for studying the closed ideals of $L^1(G)$ which have the above mentioned property. For work directly related to [20], see Johnson ⟨13⟩, Rindler ⟨22⟩, ⟨3⟩, Liu van Rooij and Wang ⟨16⟩ and also Willis ⟨30⟩.

[21] is a systematic study of certain dense subalgebras of $L^1(G)$ (called *Segal algebras*) which are themselves Banach algebras under a suitable norm, as, for example, $L^1(\mathbb{R}) \cap C_0(\mathbb{R})$ with the norm $\|f\|_1 + \|f\|_\infty$. Particularly interesting is § 17 which gives, as a complement to [19], a complete description of the closed ideals of $L^1(G)$ having bounded approximate units, for an abelian or a compact group $G$. The subject, for $G$ non-abelian, is far from being exhausted.

In [23], using only methods of commutative harmonic analysis and avoiding any Lie-techniques he was able to describe, for an important class of non-commutative group including the Heisenberg group, all maximal closed two-sided ideals $I$ of $L^1(G)$. For such an $I$ he also described the quotient algebra $L^1(G)/I$. This applies for example to the case of the discrete Heisenberg group: $\mathbb{Z}^3$ with the product $(x_1, x_2, x_3)(y_1, y_2, y_3) = (x_1 + y_1, x_2 + y_2, x_3 + y_3 + x_1 y_2)$.

In 1976, he began to study two papers of A. Weil: ⟨28⟩ and ⟨29⟩. In fact, all his remaining work (with the exception of [32]) is the fruit of this investigation. For a locally compact abelian group $G$, Weil introduced in ⟨28⟩ the notion of character of second degree. Here, $G$ is supposed to be isomorphic to its dual group $\hat{G}$ (examples: $\mathbb{R}^n$, a finite dimensional vector space over a local field, etc). A character of second degree is a continuous function $\psi$ on $G$ with $|\psi(x)| = 1$ and $\psi(x+y) = \psi(x)\,\psi(y)[\varrho(y)](x)$ for $x, y \in G$, where $\varrho$ is an isomorphism of $G$ onto $\hat{G}$. Examples of characters of second degree are: for $G = \mathbb{R}$ $\psi(x) = e^{i\pi\lambda x^2}$, $\lambda \neq 0$; for $G = \mathbb{R}^n$ $\psi(x) = e^{i\pi\, {}^t x A x}$ where $A$ is a symmetric real matrix. Weil proved (⟨28⟩ p. 161, Théorème 2) that there exists a unique constant $\gamma(\psi)$ such that for every nice $f$ on $G$ the following relation is satisfied

$$(1) \qquad \int_G \psi(x)\hat{f}(\varrho(x))\,dx = \frac{\gamma(\psi)}{\sqrt{\Delta(\varrho)}} \int_G \overline{\psi(-x)}\,f(x)\,dx$$

$\Delta(\varrho)$ being the module of the morphism $\varrho$.

Suppose $\psi$ is equal to 1 on a closed subgroup $H$ of $G$ and let $H^\varrho$ be the set of all $x \in G$ with $\varrho(x)\,(h) = 1$ for every $h \in H$. Let $\psi'$ be the lifting of $\psi$ on $H^\varrho/H$. Cartier proved in ⟨1⟩ (Satz 3) that $\psi'$ is a character of second degree on $H^\varrho/H$ with $\gamma(\psi') = \gamma(\psi)$. The special case of $H^\varrho = H$ is already in ⟨28⟩ (p. 169, Théorème 5). For $G = \mathbb{R}$, $k$ a positive even integer, $\psi(x) = e^{i\pi k x^2}$, $H = \mathbb{Z}$, one gets $H^\varrho = \frac{1}{k}\mathbb{Z}$ and the relation $\sum_{j=1}^{k} e^{\frac{i\pi j^2}{k}} = \sqrt{\frac{k}{2}}(1+i)$. For $G = \mathbb{R}^n$, $A$, $B$ regular matrices with coefficients in $\mathbb{Z}$ and such that ${}^t AB$ is symmetric, $\psi(x) = e^{i\pi\, {}^t x\, {}^t A B x}$, $H = A^{-1}\mathbb{Z}^n$ one obtains*) as shown by Reiter in [26], a formula due to Krazer ⟨25⟩ (p. 337, Satz 2). [26] also gives an approach to the result of Cartier in the spirit of ⟨28⟩. Define on $L^2(G)$ the following operators $A_G(\psi)f = \psi f$, $W_G(\varrho)f = \sqrt{\Delta(\varrho)}\hat{f} \circ \varrho$ and $[U_G(t)f](x) = tf(x)$ for $t \in \mathbb{T}$. The relation (1) is equivalent to $[A_G(\psi) \circ W_G(\varrho)^{-1}]^3 = U_G(\gamma(\psi))$. Now let $M_\psi(G)$ be the group generated by $A_G(\psi)$, $W_G(\varrho)$ and $U_G(t)$ $t \in \mathbb{T}$. Then Cartier's result is a consequence of the fact that the group $M_{\psi'}(H^\varrho/H)$ is, in a natural way, the homomorphic image of $M_\psi(G)$. [31] is an attempt to understand the proof and the nature of Théorème 6 of ⟨28⟩. In fact he established it for a larger class of functions, introduced by Feichtinger ⟨8⟩. In (II) (unpublished manuscript) he began to treat in a similar way Théorème 5 of ⟨29⟩.

Before closing this very brief description let me mention that the

*) without any induction on $n$!

interested reader can find useful information on the work of Reiter and its developments in the excellent book of Pier ⟨20⟩. For more recentand very promising results related to property $P_1$, we refer to Losert and Rindler ⟨18⟩ and to Sarnak ⟨24⟩ (chapter 2).

Reiter was extremely precise and careful in his way of writing mathematics. He also was very anxious to give to a theorem the "right" proof. With property $P_1$ he gave a very concrete analytical interpretation of amenability. He also showed that a large part of harmonic analysis does not depend on commutativity but rather on amenability. This opened new directions of research which are far from being all explored. Such developments also shed a new light on classical results; at this point I prefer to quote Reiter himself ([21], p. 94): *"It often occurs that the proof of a result in classical harmonic analysis may be divided into two parts: one that admits an extension to non-abelian groups and another, strictly abelian one. A clear recognition of these two components is of considerable interest: it leads not only to more general results, but also to greater simplicity in the proofs."*

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## Unpublished manuscripts

[I] (without title) Complement to [23] (5.9. Lemma).
[II] On the Siegel—Weil Formula.
[III] Classical Harmonic Analysis and Locally Compact Groups, Old and New (It is a report on (II). It also contains a list of corrections to [31]).

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