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# On Super and Hereditarily Hopfian and co-Hopfian Abelian Groups

B. Goldsmith and K. Gong

**Abstract.** The notions of Hopfian and co-Hopfian groups have been of interest for some time. In this present work we characterize the more restricted classes of hereditarily Hopfian (co-Hopfian) and super Hopfian (co-Hopfian) groups in the case where the groups are Abelian.

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## 1. Introduction

The notions of Hopfian and co-Hopfian groups have been studied for a long time. The terminology "Hopfian" seems to have arisen from the fact that the topologist H. Hopf showed that the fundamental groups of certain closed two-dimensional manifolds have the defining property. The concept, and its dual, were studied by Baer [1], under the names  $Q$ -group and  $S$ -group. In modern terminology we say that a group  $G$  is *Hopfian* if every surjection  $: G \rightarrow G$  is an automorphism; it is said to be *co-Hopfian* if every injection  $: G \rightarrow G$  is an automorphism. Finite groups are, of course, the prototypes for both Hopfian and co-Hopfian groups. The existence of infinite co-Hopfian  $p$ -groups was first established by Crawley [3]. Abelian Hopfian and co-Hopfian groups have arisen recently in the study of algebraic entropy and its dual, adjoint entropy – see e.g. [4, 7, 9]. Despite the seeming simplicity of their definitions, Hopfian and co-Hopfian groups are notoriously difficult to handle and easily stated problems have remained open for a long time: if  $G$  is Hopfian, is the direct product  $G \times \mathbb{Z}$  Hopfian? The expository paper [11] gives a nice overview of this problem.

In this paper we consider two stronger versions of the concepts, the classes of so-called hereditarily Hopfian (co-Hopfian) groups and the super

Hopfian (co-Hopfian) groups. These are the classes obtained by requiring closure under subgroups, respectively homomorphic images. We obtain complete characterizations of these classes when the groups are Abelian. In the sequel, the word group shall mean an additively written Abelian group. The books [5] shall serve as a reference to ideas needed in Abelian group theory. We shall denote the set of rational primes by the symbol  $\mathbb{P}$ ; mappings are written on the right.

## 2. Preliminaries

In this section we record without proof some well-known facts about Hopfian and co-Hopfian groups; proofs may be found in e.g. [8].

It is easy to show that the Hopfian property for  $G$  is equivalent to  $G$  having no proper isomorphic factor group, while co-Hopfianity is equivalent to having no proper isomorphic subgroup. The groups  $\mathbb{Z}$  and  $\mathbb{Z}(p^\infty)$  show that the notions are independent of each other.

The following simple proposition records some well-known, and easily established, facts about Hopfianity and co-Hopfianity:

- Proposition 2.1.** (i) *A torsion-free group  $G$  is co-Hopfian if, and only if it is divisible of finite rank;*  
(ii) *A torsion-free group of finite rank is Hopfian;*  
(iii) *Finitely generated groups are Hopfian and finitely co-generated groups are co-Hopfian;*  
(iv) *A group  $G$  with  $\text{End}(G) \cong \mathbb{Z}$  is Hopfian; thus arbitrarily large Hopfian groups exist;*  
(v) *Reduced Hopfian (co-Hopfian)  $p$ -groups are semi-standard and so have cardinality at most  $2^{\aleph_0}$ ;*  
(vi) *A reduced countable Hopfian (co-Hopfian)  $p$ -group is finite.*

The classes of Hopfian and co-Hopfian groups exhibit some weak closure properties which are well known:

**Proposition 2.2.** *Let  $0 \rightarrow H \rightarrow G \rightarrow K \rightarrow 0$  be an exact sequence.*

- (i) *If  $H, K$  are both Hopfian and if  $H$  is left invariant by each surjection  $\phi : G \rightarrow G$ , then  $G$  is Hopfian. In particular, extensions of Hopfian torsion groups by torsion-free Hopfian groups are again Hopfian;*  
(ii) *If  $H, K$  are both co-Hopfian and if  $H$  is left invariant by each injection  $\psi : G \rightarrow G$ , then  $G$  is co-Hopfian. In particular, extensions of co-Hopfian torsion groups by torsion-free co-Hopfian groups are again co-Hopfian.*

The classes of Hopfian and co-Hopfian groups are not, however, closed under taking subgroups or forming homomorphic images: for example, if  $G$  is an unbounded  $p$ -group which is both Hopfian and co-Hopfian (such groups exist, the first example being due to Pierce [12, Theorem 16.4]), then any basic subgroup  $B$  of  $G$  is an unbounded direct sum of cyclic groups and

hence is neither Hopfian nor co-Hopfian; it is, however, both a subgroup and a homomorphic image of  $G$ , the latter following from the well-known theorem of Szele [5, Theorem 36.1].

### 3. Strengthening the concepts

It is clear from our earlier discussions that the classification of both Hopfian and co-Hopfian groups looks extremely difficult. In this section we strengthen both concepts in two natural ways.

- Definition 3.1.** (i) A group  $G$  is said to be *super Hopfian* (*super co-Hopfian*) if every homomorphic image of  $G$  is Hopfian (co-Hopfian);
- (ii) A group  $G$  is said to be *hereditarily Hopfian* (*hereditarily co-Hopfian*) if every subgroup of  $G$  is Hopfian (co-Hopfian).

The terminology “super Hopfian” seems to have originated in the paper [10] of Hirshon and we continue to use it here. Clearly, super and hereditarily Hopfian (co-Hopfian) groups are Hopfian (co-Hopfian); indeed the super class is easily seen to be closed under homomorphic images, while the hereditary class is closed under subgroups.

The classification of reduced hereditarily co-Hopfian groups is easily obtained: suppose that  $G$  is such a group and observe that if  $G$  is not torsion, then it has a subgroup isomorphic to  $\mathbb{Z}$ . Since  $\mathbb{Z}$  is not co-Hopfian, we conclude that  $G$  must be torsion so that there is a primary decomposition  $G = \bigoplus_{p \in \mathbb{P}} G_p$ . Since  $G$  is hereditarily co-Hopfian, each  $G_p$  is also hereditarily co-Hopfian and hence a basic subgroup  $B_p$  of  $G_p$  is both a direct sum of cyclic groups and co-Hopfian. It is therefore finite and it follows easily that  $G_p$  is finite for all  $p \in \mathbb{P}$ . Since any subgroup of a group of the form  $H = \bigoplus_{p \in \mathbb{P}} H_p$ , where each  $H_p$  is finite, is again of this form, we deduce:

**Theorem 3.2.** *A group  $G$  is hereditarily co-Hopfian if, and only if, it is of the form  $G = \bigoplus_{p \in \mathbb{P}} (\bigoplus_{r_p} \mathbb{Z}(p^\infty) \oplus G_p)$ , where each  $r_p (p \in \mathbb{P})$  is finite and each  $G_p$  is a finite  $p$ -group.*

*Proof.* We have already established the form of the reduced part of  $G$ , so it suffices to consider divisible hereditarily co-Hopfian groups. As we have seen above, such groups must be torsion and so they have the form  $G = \bigoplus_{p \in \mathbb{P}} (\bigoplus_{r_p} \mathbb{Z}(p^\infty))$ , where each  $r_p (p \in \mathbb{P})$  is finite. Since any subgroup of such a group is a direct sum of fully invariant finitely cogenerated groups, it is easily seen to be co-Hopfian.  $\square$

We now consider the problem of determining the super co-Hopfian groups; firstly, we shall suppose that  $D$  is such a group and that  $D$  is divisible. Since any homomorphic image of a divisible group is divisible, it is an easy exercise to see that a divisible super co-Hopfian group must have the form  $D = \bigoplus_{r_0} \mathbb{Q} \oplus \bigoplus_{p \in \mathbb{P}} (\bigoplus_{r_p} \mathbb{Z}(p^\infty))$ , where  $r_0$  and all  $r_p (p \in \mathbb{P})$  are finite. Conversely every such group is easily seen to be super co-Hopfian. We record this as

**Proposition 3.3.** *A divisible group  $D$  is super co-Hopfian if, and only if,  $D$  has the form  $D = \bigoplus_{r_0} \mathbb{Q} \oplus \bigoplus_{p \in \mathbb{P}} (\bigoplus_{r_p} \mathbb{Z}(p^\infty))$ , where  $r_0$  and all  $r_p (p \in \mathbb{P})$  are finite.*

So we now consider reduced super co-Hopfian groups. Clearly, if  $G$  is such a group and  $G$  is torsion-free, then it must be the trivial group: super co-Hopfian groups are, in particular, co-Hopfian and the only co-Hopfian torsion-free groups are divisible. If  $G$  is torsion, then it has the form  $G = \bigoplus_{p \in \mathbb{P}} G_p$  where each  $G_p$  is a reduced  $p$ -group. If  $B_p$  is a basic subgroup of  $G_p$ , then it is a homomorphic image of  $G_p$  and hence of  $G$ . As we have seen before, this forces  $B_p$  and  $G_p$  to be finite. Conversely every image of such a group is again of that form and hence is super co-Hopfian. Thus the classification of super co-Hopfian groups reduces to the classification of the reduced mixed super co-Hopfian groups.

We shall also have need of the following result of A.L.S. Corner [2] - the result was not published by Corner (see [6]) but the main ideas are outlined in [7, Section 4] - which is an extension of the well-known Szele Theorem on basic subgroups as endomorphic images.

**Theorem 3.4.** *(Corner) Let  $G$  be an extension of a torsion group  $T$  by a countable torsion-free group, and let  $B_p$  be a basic subgroup of the  $p$ -component of  $T$ . Then  $B_p$  is an endomorphic image of  $G$ .*

**Theorem 3.5.** *A group  $G$  is super co-Hopfian group if and only if its torsion-free quotient,  $G/t(G)$ , is divisible of finite rank and its torsion group  $t(G)$  has the form  $t(G) = \bigoplus_{p \in \mathbb{P}} (\bigoplus_{r_p} \mathbb{Z}(p^\infty) \oplus G_p)$ , where each  $r_p$  is finite and each  $G_p$  is a finite  $p$ -group.*

*Proof.* Suppose that  $G$  has the form that  $t(G) = \bigoplus_{p \in \mathbb{P}} (\bigoplus_{r_p} \mathbb{Z}(p^\infty) \oplus G_p)$ , where each  $r_p$  is finite and each  $G_p$  is a finite  $p$ -group and its torsion-free quotient,  $G/t(G)$ , is divisible of finite rank, we show that  $G$  is super co-Hopfian. Assume that  $X$  is an arbitrary homomorphic image of  $G$ . Since the divisible part of  $G$  is of finite torsion-free rank and finite  $p$ -rank for each prime  $p \in \mathbb{P}$ , the divisible hull of  $G$  is of the form  $\bigoplus_{p \in \mathbb{P}} (\bigoplus_{r_p} \mathbb{Z}(p^\infty)) \oplus \bigoplus_{r_0} \mathbb{Q}$ , where  $r_0$  and all  $r_p$  are finite. Now the divisible subgroup of  $X$  is an epimorphic image of the divisible hull of  $G$  and hence is of similar form to the divisible hull; in particular, it is co-Hopfian. To establish that  $X$  is co-Hopfian there is no loss in generality in assuming that  $X$  is reduced.

Let  $\phi : G \twoheadrightarrow X$  be the epimorphism, so that  $G/Y \cong X/t(X)$ , where  $Y = \phi^{-1}(t(X)) \geq t(G)$ . However,  $G/Y$  is a homomorphic image of  $G/t(G)$  and hence, since  $G/t(G)$  is divisible of finite rank as we assumed, so is  $G/Y$ . Thus  $X/t(X)$  is torsion-free divisible of finite rank; in particular it is co-Hopfian.

To establish our claim it is sufficient to show that  $t(X)$  is co-Hopfian. Let  $t(X) = X_p \oplus \bigoplus_{q \neq p} X_q$  be the primary decomposition of  $t(X)$  and set  $X'_p = \bigoplus_{q \neq p} X_q$ . Then  $X/X'_p \cong G/\phi^{-1}(X'_p)$  and note that  $\phi^{-1}(X'_p) \geq G'_p = \bigoplus_{q \neq p} G_q$ . Thus  $G/\phi^{-1}(X'_p)$  is a homomorphic image of  $G/G'_p$  and this

latter satisfies  $G/G'_p/t(G)/G'_p \cong G/t(G)$ . Hence  $G/G'_p$  is an extension of the finite  $p$ -group  $t(G)/G'_p$  by  $\mathbb{Q}^{(n)}$  for some finite  $n$ . However, such an extension necessarily splits and so  $X_p \cong X/X'_p \cong G/\phi^{-1}(X'_p)$  is a homomorphic image of a group of the form  $F \oplus \mathbb{Q}^{(n)}$ . It follows from Lemma 3.7 below that  $X_p$  is again of the form  $F_1 \oplus D_1$ , where  $F_1$  is finite and  $D_1$  is divisible. Since we assumed that  $X$  was reduced, we have that  $X_p$  is finite and hence co-Hopfian. It follows immediately that  $t(X)$  is also co-Hopfian, as required.

Now suppose that  $G$  is a super co-Hopfian group and let  $G = D_t \oplus G_0$ , where  $D_t$  is the maximal divisible subgroup of  $T(G)$ ; note that  $G_0$  is then a group with a reduced torsion subgroup. Now the divisible part,  $D_t$ , of  $t(G)$  is super co-Hopfian; thus, by Proposition 3.3  $D_t$  is of the form  $D = \bigoplus_{p \in \mathbb{P}} (\bigoplus_{r_p} \mathbb{Z}(p^\infty))$ , where each  $r_p$  is finite. On the other hand,  $G/t(G) \cong G_0/t(G_0)$ , as an epimorphic image of  $G$ , is super co-Hopfian; thus,  $G_0/t(G_0)$  is divisible of finite rank. Hence  $G_0$  is a countable torsion-free extension of the reduced torsion group  $t(G_0)$  and so by Corner's Theorem 3.4, any basic subgroup  $B_p$  of the  $p$ -component  $G_p$  of  $t(G_0)$ , is an endomorphic image of  $G_0$  and consequently must be a co-Hopfian group; since it is also a direct sum of cyclic groups, it is finite. This in turn implies that  $G_p$  is finite and hence  $t(G_0) = \bigoplus_{p \in \mathbb{P}} G_p$  is a direct sum of finite groups, as required.  $\square$

Some specific cases are recorded as:

**Corollary 3.6.** *Let  $G$  be a super co-Hopfian group then*

- (i) *if  $G$  is torsion-free, it has the form  $G = \bigoplus_{r_0} \mathbb{Q}$ , where  $r_0$  is finite;*
- (ii) *if  $G$  is torsion, it has the form  $G = \bigoplus_{p \in \mathbb{P}} (\bigoplus_{r_p} \mathbb{Z}(p^\infty) \oplus G_p)$ , where each  $r_p$  is finite and each  $G_p$  is a finite  $p$ -group;*
- (iii) *if  $G$  is splitting mixed, it has the form  $G = \bigoplus_{r_0} \mathbb{Q} \oplus \bigoplus_{p \in \mathbb{P}} (\bigoplus_{r_p} \mathbb{Z}(p^\infty) \oplus G_p)$ , where  $r_0$  and each  $r_p$  are finite and each  $G_p$  is a finite  $p$ -group;*

*Conversely, every group of the form (i) - (iii) is super co-Hopfian.*

**Lemma 3.7.** *Every homomorphic image of a group of the form  $F \oplus D$ , where  $F$  is finite and  $D$  is divisible of finite rank, is again of the form  $F_1 \oplus D_1$ , where  $F_1$  is finite and  $D_1$  is divisible of finite rank.*

*Proof.* Suppose that  $G$  is of the desired form and  $\phi : G \rightarrow X$  is an epimorphism. Then  $D\phi$  is a divisible subgroup of  $X$  and so  $X = D\phi \oplus X_1$ . But then  $X_1 \cong X/D\phi = G\phi/D\phi \cong G/(D + \text{Ker}\phi)$  and, since  $G/(D + \text{Ker}\phi)$  is a homomorphic image of  $G/D$ , it is finite. Thus  $X = D_1 \oplus F_1$  where  $F_1 \cong X_1$  is finite and  $D_1 \cong D\phi$  is divisible of finite rank.  $\square$

We now turn our attention to hereditarily Hopfian groups.

**Theorem 3.8.** *A group  $G$  is hereditarily Hopfian if and only if it is an extension of  $\bigoplus_{p \in \mathbb{P}} G_p$  by a torsion-free finite rank group, where each  $G_p$  is a finite  $p$ -group; in other words,  $G$  is hereditarily Hopfian if and only if, the torsion subgroup,  $t(G)$ , has the form  $\bigoplus_{p \in \mathbb{P}} G_p$ , and the torsion-free quotient  $G/t(G)$  is of finite rank.*

*Proof.* Suppose that  $G$  is a hereditarily Hopfian group, then its divisible part  $D$ , is also hereditarily Hopfian; then  $D$  must have the form  $D = \bigoplus_{p \in \mathbb{P}} (\bigoplus_{r_p} \mathbb{Z}(p^\infty))$ . However, as the groups  $\mathbb{Z}(p^\infty)$  are never Hopfian, so we deduce that the torsion subgroup  $t(G)$  is reduced. Moreover, a basic subgroup  $B_p$  of  $G_p$  - the  $p$ -component of  $t(G)$  - is also Hopfian, so it must be finite, then so is  $G_p$ . Therefore,  $t(G)$ , has the form  $\bigoplus_{p \in \mathbb{P}} G_p$ , where each  $G_p$  is a finite  $p$ -group.

Choose an independent system  $L$  which contains only torsion-free elements and which is maximal with respect to this property; so the subgroup  $\langle L \rangle$  generated by  $L$  is a free group of rank the cardinality of  $L$ . Since  $G$  is hereditarily Hopfian, so is  $\langle L \rangle$ ; which implies  $\langle L \rangle$  is of finite rank. Hence the torsion-free rank of  $G$ , which is equal to the cardinality of  $L$ , is finite. Thus the torsion-free quotient,  $G/t(G)$  is of finite rank.

Conversely, if  $G$  has the conditions stated in the theorem, we show that it is a hereditarily Hopfian group. For an arbitrary subgroup  $H$ , we show that it is Hopfian. As the torsion subgroup  $t(H)$  of  $H$  is exactly  $t(G) \cap H$ , so  $t(H)$  has the form  $\bigoplus_{p \in \mathbb{P}} H_p$  where each  $H_p$  is a finite  $p$ -group; in particular, it is a Hopfian group. Furthermore,  $H/t(H) = H/(t(G) \cap H) \cong (t(G) + H)/t(G)$  which is a subgroup of  $G/t(G)$  and so we see that  $H/t(H)$  is torsion-free of finite rank, in particular, it is Hopfian. By (i) in Proposition 2.2,  $H$  is a Hopfian group.  $\square$

We can obtain more specific information in some cases:

**Corollary 3.9.** *Let  $G$  be a hereditarily Hopfian group. Then*

- (i) *if  $G$  is torsion-free, then  $G$  is of finite rank;*
- (ii) *if  $G$  is torsion, then  $G \cong \bigoplus_{p \in \mathbb{P}} G_p$ , where each  $G_p$  is a finite  $p$ -group;*
- (iii) *if  $G$  is splitting mixed, then  $G \cong F \oplus \bigoplus_{p \in \mathbb{P}} G_p$ , where  $F$  is torsion-free of finite rank and each  $G_p$  is a finite  $p$ -group;*

*Conversely, every group of the form (i) – (iii) is hereditarily Hopfian.*

We now consider super Hopfian groups. Our first observation is elementary:

**Proposition 3.10.** *A super Hopfian group has no non-trivial divisible epimorphic image; in particular, it is reduced and if it is torsion-free, then it is of finite rank.*

*Proof.* Since an epimorphic image of a super Hopfian group is super Hopfian, it suffices for the first part to show a super Hopfian group is reduced. So suppose that  $G$  is super Hopfian and that the divisible part of  $G$  is non-trivial. Since a super Hopfian group is necessarily Hopfian, it follows that the divisible part of  $G$  must be torsion-free. However, since  $\mathbb{Q}$  has the quasi-cyclic groups  $\mathbb{Z}(p^\infty)$  as homomorphic images, this would imply that each  $\mathbb{Z}(p^\infty)$  is Hopfian - contradiction. Thus a super Hopfian group must be reduced.

The final remark follows from Reid's work [13]: a torsion-free group which has no non-zero divisible epimorphic image is necessarily of finite rank.  $\square$

A super Hopfian  $p$ -group  $G$  is easily seen to be finite: a basic subgroup of  $G$  is, by Szele's theorem, an epimorphic image of  $G$  and hence must be simultaneously Hopfian and a direct sum of cyclic groups, and as we have seen, this forces  $G$  to be finite. It follows immediately that a torsion super Hopfian group is a direct sum of finite  $p$ -groups ( $p \in \mathbb{P}$ ).

We are now in a position to establish the classification of super Hopfian groups.

**Theorem 3.11.** *A group  $G$  is super Hopfian if and only if it is an extension of a free group of finite rank by a torsion group which is a direct sum of finite primary components; in other words,  $G$  is super Hopfian if and only if there exists a finite rank free subgroup  $F$  of  $G$  such that the quotient group  $G/F$  is torsion and has a primary decomposition with finite primary components.*

*Proof.* For the necessity, suppose that  $G$  is super Hopfian. Then its torsion-free quotient,  $G/t(G)$ , is also super Hopfian and by Proposition 3.10 must be of finite rank. Therefore, there is a free subgroup  $F$  of  $G$  having finite rank such that  $G/F$  is torsion. Again,  $G/F$  is super Hopfian, thus it is a direct sum of finite primary components as observed above.

For the sufficiency, suppose that there exists a finite rank free subgroup  $F$  of  $G$  such that the quotient group  $G/F$  is a direct sum of finite primary components. First we note that the torsion subgroup,  $t(G)$ , of  $G$ , is also a direct sum of finite primary components since we have the isomorphism  $(t(G) + F)/F \cong t(G)$ . The torsion-free quotient,  $G/t(G)$  is of finite rank, since it is an extension of the free group  $(F \oplus t(G))/t(G)$  by a torsion group.

Suppose that  $X = G\phi$  is a homomorphic image of  $G$  for a given homomorphism  $\phi$ . Now  $X/t(X)$  is a homomorphic image of  $G/t(G)$  and so  $X/t(X)$  is a group of finite rank. We need to show that  $X$  is a Hopfian group. It suffices, by Proposition 2.2 (i), to show that  $t(X)$  is Hopfian. We show that for any  $p \in \mathbb{P}$ , the  $p$ -component,  $X_p$  of  $t(X)$ , is finite. So in this case,  $t(X)$  is a direct sum of finite primary components and so is Hopfian.

The group  $X/F\phi$  is an epimorphic image of  $G/F$  and hence is a torsion group with finite primary components. Moreover, as  $F$  is free of finite rank, the group  $t(X) \cap F\phi$  is both torsion and finitely generated, whence it is finite. Also we have that  $X_p/(X_p \cap F\phi)$  is a finite  $p$ -group since it is isomorphic to a subgroup of  $X/F\phi$ . Since  $(X_p \cap F\phi) \leq (t(X) \cap F\phi)$ , it is also finite and so  $X_p$  is finite, as required.  $\square$

Finally observe that, unlike Hopfian groups which may have arbitrarily large cardinality, super Hopfian groups are necessarily countable.

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