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THE CAUCHY-DAVENPORT THEOREM FOR SEMIGROUPS

SALVATORE TRINGALI

ABSTRACT. We generalize the Davenport transform to prove that, for $\mathfrak{A} = (A, +)$ a cancellative unital semigroup and X, Y subsets of \mathfrak{A} such that $\langle Y \rangle_{\mathfrak{A}}$ is commutative, one has

$$|X + Y| \geq \min(|X| + |Y| - 1, \sup_{y_0 \in Y \times} \min_{y \in Y \setminus \{y_0\}} \text{ord}_{\mathfrak{A}}(y - y_0))$$

if $2 \leq |X|, |Y| < \infty$. While extending the Cauchy-Davenport theorem to the broader and abstract setting of (possibly non-commutative) semigroups, this also strengthens a previous generalization by G. Károlyi relating to sum-sets in commutative groups, where each $\omega(X, Y)$ in the above estimate is replaced with the order of the smallest non-trivial subgroup of \mathfrak{A} , which is never greater than $\omega(X, Y)$, and indeed (much) smaller in some significant situations. Moreover, we show that the result includes, as a special case, I. Chowla's generalization of the Cauchy-Davenport theorem to arbitrary cyclic groups.

1. INTRODUCTION

The present paper is focused on semigroups, in continuation to the work initiated by the author in [27], which the reader is recommended to consult for (possibly non-standard) notation and terminology employed here without explanation. For the sake of generality, some definitions and results will, however, be phrased in the more abstract language of magmas, convinced as I am that theorems and theories are better understood (and possibly generalized) in absence of what may be referred to as “conceptual redundancies”. In this respect, let me remark from the outset, for any practical purposes, that all magmas (and hence semigroups, monoids and groups) considered in the sequel are always written in additive notation and not required to be commutative, unless differently specified, and that the axiom of choice (shortly, AC) is assumed.

That said, let $\mathfrak{A} = (A, +)$ be a magma. Given $a \in \mathfrak{A}$, $n \in \mathbb{N}^+$ and a parenthesization P of \mathfrak{A} of length n , we use $(na)_P$ for the n -fold sum $(a + a + \cdots + a)_P$, which is further simplified to na whenever \mathfrak{A} is associative (i.e., a semigroup), considering that, in this case, $(na)_P$ does not really depend on P . Moreover, for X, Y subsets of \mathfrak{A} we take

$$X + Y := \{x + y : x \in X, y \in Y\}, \quad X - Y := \{z \in A : z + y \in X \text{ for some } y \in Y\}.$$

Note that $X + Y := X - Y := \emptyset$ if one of X or Y is empty. In particular, we write $X + y$ in place of $X + Y$ and $X - y$ instead of $X - Y$ whenever $Y = \{y\}$. This will allow us to identify sums (and differences) of elements with sums (and differences) of sets, when it is appropriate or convenient to do so (see Remark 3). One refers to $X + Y$ and $X - Y$, respectively, as the sum-set and the difference-set of the pair (X, Y) , and then defines $-Y + X$ as the difference set of (X, Y) in the dual, $\mathfrak{A}^{\text{op}} := (A, +_{\text{op}})$, of \mathfrak{A} , where $+_{\text{op}}$ is the operation $A \times A \rightarrow A : (z_1, z_2) \mapsto z_2 + z_1$.

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We use \mathfrak{A}^\times for the set of units of \mathfrak{A} , with the convention that $\mathfrak{A}^\times := \emptyset$ if \mathfrak{A} is not unital (if \mathfrak{A} is unital with identity 0_A , a unit of \mathfrak{A} is an element $z \in \mathfrak{A}$ for which there exists $\tilde{z} \in \mathfrak{A}$, provably unique and called the *inverse of z in \mathfrak{A}* , such that $z + \tilde{z} = \tilde{z} + z = 0_A$). If $Z \subseteq \mathfrak{A}$, we then write: $\langle Z \rangle_{\mathfrak{A}}$ for the smallest submagma of \mathfrak{A} containing Z ; $C_{\mathfrak{A}}(Z)$ for the center of Z in \mathfrak{A} ; Z^\times for $Z \cap \mathfrak{A}^\times$; and $Z^{(1)}$ for the image of Z under the natural embedding of \mathfrak{A} , as a submagma, into its (canonical) unitization, herein denoted by $\mathfrak{A}^{(1)}$. Lastly, given $z \in \mathfrak{A}$ we use $\text{ord}_{\mathfrak{A}}(z)$ for the order of z in \mathfrak{A} , that is $\text{ord}_{\mathfrak{A}}(z) := |\langle z \rangle_{\mathfrak{A}}|$.

Sumsets in (mostly commutative) groups have been intensively investigated for several years (see [25] for a recent survey), and interesting results have been also obtained in the case of commutative monoids [11]. The present paper aims to be a further contribute to this popular (and very active) research area, in the direction of extending parts of the theory to the more general setting of semigroups (and magmas), motivated by the apparently reasonable expectation that, in the mean term, a further level of abstraction might provide huge benefits.

Historically, the first non-trivial achievement in the study of sum-sets is probably the Cauchy-Davenport theorem, originally established by A.L. Cauchy [2] in 1813, and independently rediscovered by H. Davenport [6, 7] more than a century later. Stated in the wording of group theory (rather than in terms of residue classes, as in the early formulations of Cauchy and Davenport), the theorem reads as follows:

Theorem 1 (The Cauchy-Davenport theorem). *Let $\mathfrak{A} = (A, +, -, 0_A)$ be a group of prime order p and X, Y non-empty subsets of \mathfrak{A} . Then, $|X + Y| \geq \min(p, |X| + |Y| - 1)$.*

The result has been the subject of many papers and much speculation, and has received a number of different proofs, favoring various points of view and eventually leading to significant progress on related questions, as in the remarkable case of the Alon-Tarsi's polynomial method (see [1] and references therein).

The Cauchy-Davenport theorem applies especially to the additive group of the integers modulo p , with p being a natural prime. An extension to composite moduli have been very recently given by M.R. Murty and J.P. Whang [19, Theorem 5], based on work by T.C. Tao [26], using tools from Fourier analysis on commutative finite groups. More contributions in the same spirit were previously provided by I. Chowla [3, 4], J.G. van der Corput [5], S.S. Pillai [22], and J.M. Pollard [23]; a partial account of these early results can be found in [20, §2.3], along with an entire chapter dedicated to the celebrated Kneser's theorem [20, Chapter 4], which implies at once, among the other things, both Theorem 1 and the main result in [4].

Generalizations of a somewhat different flavor have been given, still in recent years, by several authors. More specifically, for a magma \mathfrak{A} let 0_A be the identity of $\mathfrak{A}^{(1)}$ and define $p(\mathfrak{A})$ to be the cardinality of the smallest submagma of $\mathfrak{A}^{(1)}$ generated by z as z ranges in $\mathfrak{A}^{(1)} \setminus \{0_A\}$, with the agreement that $p(\mathfrak{A}) := |\mathbb{N}|$ if $\mathfrak{A}^{(1)}$ is trivial. Equipped with this notation, G. Károlyi [15, Theorem 13] has then established the following:

Theorem 2 (G. Károlyi's theorem for commutative groups). *Let \mathfrak{A} be a commutative group and X, Y non-empty subsets of \mathfrak{A} . Then, $|X + Y| \geq \min(p(\mathfrak{A}), |X| + |Y| - 1)$.*

Károlyi's proof can be classified as a “transformation proof”, and is in spirit similar to other transformation proofs so far invented to deal with the Cauchy-Davenport theorem and related problems in the additive theory of groups; see [10] for details.

While Theorem 2 applies to both finite and infinite *commutative* groups, an analogous result is known to hold for all *finite* (commutative and noncommutative) groups:

Theorem 3 (G. Károlyi’s theorem for finite groups). *Let \mathfrak{A} be a finite group and X, Y non-empty subsets of \mathfrak{A} . Then, $|X + Y| \geq \min(p(\mathfrak{A}), |X| + |Y| - 1)$.*

This was first proved by Károlyi himself [16], based on the structure theory of group extensions, by reduction to the case of finite solvable groups in the light of the Feit-Thompson theorem. One consideration that immediately arises is that, given a finite commutative group \mathfrak{A} and non-empty subsets X, Y of \mathfrak{A} , the bound for the size of $|X + Y|$ provided by the above theorems is far too pessimistic in most situations, as is easily seen, for instance, in the limit case where $X = Y = \mathfrak{A}$ and $p(\mathfrak{A})$ is somewhat small with respect to the order of \mathfrak{A} .

The issue is basically that Theorems 2 and 3 involve a structural property of \mathfrak{A} , which is essentially extraneous to the pair (X, Y) . Thus, if one really wants to improve Károlyi’s results further, a good idea may be to replace $p(\mathfrak{A})$ with something more tightly related to X and Y , which has precisely been the main insight at the origin of this work.

Before stating the main results of the paper, we must however mention a few more generalizations of the Cauchy-Davenport theorem available in the literature. The first is due to J.H.B. Kemperman [17], and deals with torsion-free groups. The proof proceeds by cleverly iterating what is now sometimes referred to as the Kemperman transform; see, e.g., [10, §2]. As with the others above, we report it here for the sake of exposition:

Theorem 4 (J.H.B. Kemperman’s theorem for torsion-free groups). *Let \mathfrak{A} be a torsion-free group and X, Y non-empty subsets of \mathfrak{A} . Then, $|X + Y| \geq |X| + |Y| - 1$.*

Note that Kemperman’s bound boils down to an instance of Károlyi’s bounds in the special case of *commutative* torsion-free groups, and hence can be effectively regarded as a generalization of the Cauchy-Davenport theorem. On the other hand, Theorem 4 also represents a major generalization of the following folklore result in the additive theory of integers: Suppose X and Y are non-empty subsets of \mathbb{Z} (the ring of integers) of sizes k and ℓ , respectively, and let x_1, x_2, \dots, x_k be a one-to-one enumeration of X and y_1, y_2, \dots, y_ℓ a one-to-one enumeration of Y . Without loss of generality, we can assume $x_1 < x_2 < \dots < x_k$ and $y_1 < y_2 < \dots < y_\ell$. Then,

$$x_1 + y_1 < x_2 + y_1 < \dots < x_k + y_1 < x_k + y_2 < \dots < x_k + y_\ell,$$

with the result that $|X + Y| \geq k + \ell - 1$. Now, these simple considerations go through verbatim in the case of linearly (i.e., strictly and totally) orderable magmas, as recently observed by the author (see [27, Proposition 3.2]), and the following holds:

Proposition 1.1. *Suppose $\mathfrak{A} = (A, \cdot)$ is a linearly ordered magma, written multiplicatively. Pick an integer $n \geq 1$, and let X_1, X_2, \dots, X_n be non-empty subsets of \mathfrak{A} and $r_i := |X_i|$. Then, for any parenthesization P of \mathfrak{A} of length n , one has that*

$$(1) \quad |(X_1 X_2 \cdots X_n)_P| \geq 1 - n + \sum_{i=1}^n r_i.$$

Furthermore, (1) is sharp whenever \mathfrak{A} is a semigroup and the X_i ’s are finite, the lower bound being attained by taking, for instance, $X_i = \{x^j : j \in \mathbb{N}^+, j \leq r_i\}$ for each i , where x is a suitable element of \mathfrak{A} (not dependent on i).

We are not aware of other results that can be properly regarded as a “natural” generalization of Theorem 1, and indeed of no previous work concerned with an extension of the theorem to the setting of semigroups. Nonetheless, we point out for completeness that a graph-theoretic analogue has been recently proved by P. Hegarty [13], while S. Eliahou and M. Kervaire [9, Theorem 2.1], improving a result of S. Yuzvinsky linked to the Hurwitz problem in topology [30], have established a variant of the theorem for sum-sets in vector spaces over finite fields.

With this background in mind, we can finally state the main result of the paper, but first we need to introduce the notion of a Davenport class. But first we need the following:

Definition 1. Given a magma $\mathfrak{A} = (A, +)$ and a subset Z of \mathfrak{A} , we let

$$(2) \quad \omega_{\mathfrak{A}}(Z) := \sup_{z_0 \in Z} \min_{z \in Z \setminus \{z_0\}} \text{ord}_{\mathfrak{A}}(z - z_0),$$

which is denoted by $\omega(Z)$ if there is no danger of ambiguity. Then, given $X, Y \subseteq \mathfrak{A}$, we define $\Omega_{\mathfrak{A}}(X, Y) := 0$ if $X = \emptyset$ or $Y = \emptyset$; $\Omega_{\mathfrak{A}}(X, Y) := \max(|X|, |Y|)$ if one of X or Y is a singleton or infinite, and $\Omega_{\mathfrak{A}}(X, Y) := \min(\omega(Y), |X| + |Y| - 1)$ otherwise. We call $\Omega_{\mathfrak{A}}(X, Y)$ the Davenport constant of (X, Y) over \mathfrak{A} , and write it as $\Omega(X, Y)$ when \mathfrak{A} is understood from the context.

Every pair (X, Y) of subsets of a given magma \mathfrak{A} has a well-defined Davenport constant, which is notably zero (essentially by definition) if $Y^\times = \emptyset$ and $|Y| \geq 2$, provided that one assumes (as we do) that the supremum and maximum of \emptyset are 0 (regarding \emptyset as a set of cardinal numbers), while its infimum and minimum are ∞ . However, this is not the case, e.g., when \mathfrak{A} is a group, where $Y^\times = \emptyset$ if and only if $Y = \emptyset$. This serves as a motivation for the next:

Theorem 5. *Let \mathfrak{A} be a cancellative semigroup and X, Y subsets of \mathfrak{A} such that $\langle Y \rangle_{\mathfrak{A}}$ is commutative. Then $|X + Y| \geq \Omega(X^{(1)}, Y^{(1)})$.*

Theorem 5 represents the main contribution of the paper: Not only it extends Theorem 6 (and hence Theorem 1) to the more general and abstract setting of semigroups (see Section 5). It also provides a strengthening of Theorem 2, in that, given a cancellative unital semigroup $\mathfrak{A} = (A, +)$ and a subset Z of \mathfrak{A} with $|Z| \geq 2$ and $Z^\times \neq \emptyset$, it is found (see Lemma 5.1) that

$$\sup_{z_0 \in Z} \min_{z \in Z \setminus \{z_0\}} \text{ord}_{\mathfrak{A}}(z - z_0) \geq p(\mathfrak{A}),$$

with strict inequality in a number of significant cases (see Example 1). Theorem 5 is proved in Section 4. The argument is a delicate refinement of the transformation proof originally used by Davenport in [6]. This leads us to define what we call a generalized Davenport transform, which might perhaps be considered an interesting by-product in its own right.

Indeed, I am not aware of any previous use of essentially the same technique in a non-commutative setting, much less in relation to non-commutative semigroups. With few exceptions, remarkably including A.G. Vosper's original proof of his own famous theorem on critical pairs [28], the “Davenport transform” seems, in fact, to have been more or less forgotten, in favor of conceptually similar (but substantially different) “technology” such as the Dyson transform [20, p. 42] or the aforementioned Kemperman transform [17].

Remark 1. One thing seems worth mentioning before proceeding: While it is true that every commutative cancellative semigroup embeds as a subsemigroup into a group, this is false in the non-commutative case; see [18] for an explicit example. This serves as a fundamental motivation for the present paper, in that it shows that the study of sum-sets on cancellative semigroups cannot be systematically reduced, in the absence of commutativity, to the case of groups.

Many natural questions arise. In particular, one can ask if it is possible to generalize Theorem 5 in such a way to get rid of the assumption that one of $\langle Y \rangle_{\mathfrak{A}}$ is commutative. However, at present, I have no satisfactory answer in this respect, but the question looks interesting, in that an affirmative response would provide a comprehensive generalization of almost all the previous extensions of the Cauchy-Davenport theorem included in this introduction, and most remarkably of Theorems 3 and 4.

1.1. Organization. The plan of the paper is as follows. In Section 2 we establish basic identities and estimates concerning sum-sets in semigroups and magmas. In Section 3 we introduce the generalized Davenport transform and prove some of its fundamental properties. In Section 4 we prove the main theorem and some immediate corollaries. Lastly, in Section 5 we provide some corollaries, including a proof of Theorem 2 and I. Chowla's theorem for composite moduli [3].

2. PRELIMINARIES

This section collects a few properties of sum-sets in semigroups and magmas that will be used later to introduce the generalized Davenport transform and prove Theorem 5. The proofs are direct and standard, but we have no explicit references to anything similar in the context of semigroups (and magmas), and hence we include them here for completeness. We start with a series of lemmas, providing trivial identities or estimates on sum-sets (cf. [26, Lemma 2.1]).

Lemma 2.1. *Let X, Y, X_1, X_2, Y_1, Y_2 be subsets of a magma $\mathfrak{A} = (A, +)$. Then*

- (i) $X + Y = Y +_{\text{op}} X$, and hence $|X + Y| = |Y +_{\text{op}} X|$.
- (ii) $X_1 + Y \subseteq X_2 + Y$ and $X + Y_1 \subseteq X + Y_2$, so $|X_1 + Y| \leq |X_2 + Y|$ and $|X + Y_1| \leq |X + Y_2|$.

Proof. (i) This is true essentially by definition, since $x + y = y +_{\text{op}} x$ for every $(x, y) \in X \times Y$.
(ii) If $x \in X_1$ and $y \in Y$ then $x + y \in X_2 + Y$ as $X_1 \subseteq X_2$, to the effect that $X_1 + Y \subseteq X_2 + Y$. Using that $Y_1 \subseteq Y_2$, it follows by duality that $X + Y_1 = Y_1 +_{\text{op}} X \subseteq Y_2 +_{\text{op}} X = X + Y_2$. ■

In spite of being so basic, Lemma 2.1 is useful in many situations, for instance to prove that a certain property holds for semigroups that are left or right cancellative by just proving that it holds in one of the two cases, as with the next lemma. In particular, to express that something is true by point (i) of Lemma 2.1, we will simply say that it is true “by duality”.

Lemma 2.2. *For a left cancellative magma $\mathfrak{A} = (A, +)$ the following holds:*

- (i) $|X| = |z + X|$ for every $z \in \mathfrak{A}$ and $X \subseteq \mathfrak{A}$.
- (ii) If X, Y are subsets of \mathfrak{A} and $X \neq \emptyset$, then $|Y| \leq |X + Y|$.
- (iii) Given an integer $n \geq 1$, let X_1, X_2, \dots, X_n be non-empty subsets of \mathfrak{A} and P a parenthesization of \mathfrak{A} of length n . One then has that $|X_n| \leq |(X_1 + X_2 + \dots + X_n)_P|$.

Proof. (i) Take $z \in \mathfrak{A}$ and let $X \subseteq \mathfrak{A}$. The claim is obvious if $X = \emptyset$. Otherwise, as \mathfrak{A} is left cancellative, the map $\phi : X \rightarrow z + X : x \mapsto z + x$ is bijective, with the result that $|X| = |z + X|$.

(ii) Pick $x \in X$ (using that X is non-empty) and observe that on the one hand $x + Y \subseteq X + Y$, to the effect that $|Y| = |x + Y| \leq |X + Y|$ by point (ii) of Lemma 2.1 and point (i) above.

(iii) Set $X := (X_1 + X_2 + \dots + X_n)_P$. The claim is obvious for $n = 1$, while for $n = 2$ it reduces to point (ii) above. As a consequence, let $n \geq 3$ and suppose the statement holds true for every $k = 1, 2, \dots, n - 1$. There exists a parenthesization Q of \mathfrak{A} of length $n - 1$ such that $X = (X_1 + \dots + X_{n-1})_Q + X_n$ or $X = X_1 + (X_2 + \dots + X_n)_Q$. Since the X_i 's are non-empty, point (ii) above and the inductive hypothesis then give that $|X_n| \leq |X|$ in the first case, and $|X_n| \leq |(X_2 + \dots + X_n)_Q| \leq |X|$ in the second. Thus, the conclusion follows (by induction). ■

For the subsequent lemma we assume that $0 \cdot \kappa := \kappa \cdot 0 := 0$ for every cardinal number κ .

Lemma 2.3. *Let $\mathfrak{A} = (A, +)$ be an arbitrary magma. One has the following:*

- (i) If X, Y are subsets of \mathfrak{A} , then $|X + Y| \leq |X| \cdot |Y|$.
- (ii) Given an integer $n \geq 1$, let X_1, X_2, \dots, X_n be subsets of \mathfrak{A} and P a parenthesization of \mathfrak{A} of length n . Then $|(X_1 + X_2 + \dots + X_n)_P| \leq \prod_{k=1}^n |X_k|$.

Proof. (i) $X + Y := \{x + y : (x, y) \in X \times Y\}$, whence $|X + Y| \leq |X \times Y| = |X| \cdot |Y|$.

(ii) Set $X := (X_1 + X_2 + \cdots + X_n)_P$. For $n = 1$ the assertion is obvious, while for $n = 2$ it reduces to point (i) above. As a consequence, assume $n \geq 3$ and let the statement hold true for every $k = 1, 2, \dots, n - 1$. There exists a parenthesization Q of \mathfrak{A} of length $n - 1$ such that $X = (X_1 + \cdots + X_{n-1})_Q + X_n$ or $X = X_1 + (X_2 + \cdots + X_n)_Q$. It follows from point (i) that $|X| \leq |(X_1 + \cdots + X_{n-1})_Q| \cdot |X_n|$ in the first occurrence and $|X| \leq |X_1| \cdot |(X_2 + \cdots + X_n)_Q|$ in the second. Whatever the case may be, the inductive hypothesis then gives that $|X| \leq \prod_{k=1}^n |X_k|$, which implies the claim (by induction). ■

Remark 2. No matter if the ambient semigroup is cancellative, nothing similar to Lemmas 2.2 and 2.3 applies, in general, to difference-sets of type $X - Y$, to the extent that $X - Y$ can be empty even if X and Y are infinite. On another hand, it follows, by duality, from point (i) of the Lemma 2.2 that, in presence of cancellativity, the cardinality of sum-sets of type $X + Y$ is preserved under translation, which is a point in common with the case of groups, save the fact that one cannot take advantage of this here, to “normalize” either of X or Y in such a way as to contain some distinguished element of \mathfrak{A} .

The next lemma is central to the use of Davenport transforms in our proof of Theorem 5.

Lemma 2.4. *Let \mathfrak{A} be a semigroup and X, Y subsets of \mathfrak{A} . Then, the following are equivalent:*

- (i) $X + 2Y \subseteq X + Y$.
- (ii) $X + nY \subseteq X + Y$ for all $n \in \mathbb{N}^+$.
- (iii) $X + \langle Y \rangle_{\mathfrak{A}} \subseteq X + Y$.

Proof. (ii) and (iii) are clearly equivalent, as $X + \langle Y \rangle_{\mathfrak{A}} = \bigcup_{n=1}^{\infty} (X + nY)$, and (i) is obviously implied by (ii). Thus, we are left to prove that (ii) follows from (i), which is immediate, by a routine induction, using the fact that if $X + nY \subseteq X + Y$ for some $n \in \mathbb{N}^+$ then $X + (n+1)Y = (X + nY) + Y \subseteq (X + Y) + Y = X + 2Y \subseteq X + Y$. ■

On another hand, the following lemma shows that, in reference to Theorem 5, there is no loss of generality in assuming that the ambient semigroup is unital.

Lemma 2.5. *Suppose that $\mathfrak{A}_1 = (A_1, +_1)$ and $\mathfrak{A}_2 = (A_2, +_2)$ are magmas, and let $\phi : \mathfrak{A}_1 \rightarrow \mathfrak{A}_2$ be a (magma) monomorphism and X, Y subsets of \mathfrak{A}_1 . Then $|X +_1 Y| = |\phi(X) +_2 \phi(Y)|$.*

Proof. The proof is straightforward. Because ϕ is one-to-one, one has $|X +_1 Y| = |\phi(X +_1 Y)|$, which is enough to conclude when considering that $\phi(X +_1 Y) = \phi(X) +_2 \phi(Y)$. ■

We conclude with some simple but remarkable properties of units:

Lemma 2.6. *Let $\mathfrak{A} = (A, +)$ be a unital semigroup with identity 0_A , X a subset of \mathfrak{A} , and z a unit of \mathfrak{A} with inverse \tilde{z} . Then the following holds:*

- (i) $X - z = X + \tilde{z}$ and $-z + X = \tilde{z} + X$.
- (ii) If \mathfrak{A} is cancellative, then $|-z + X| = |X - z| = |X|$.
- (iii) If $z \in C_{\mathfrak{A}}(X)$ and \mathfrak{A} is cancellative, then $\tilde{z} \in C_{\mathfrak{A}}(X)$, and in addition $\langle X - z \rangle_{\mathfrak{A}}$ and $\langle -z + X \rangle_{\mathfrak{A}}$ are commutative if $\langle X \rangle_{\mathfrak{A}}$ is commutative.

Proof. (i) By duality, it suffices to prove that $X - z = X + \tilde{z}$. And this is trivial from the fact that $w \in X - z$ if and only if there exists $x \in X$ such that $w + z = x$, which in turn is clearly equivalent to saying that $x + \tilde{z} = w + z + \tilde{z} = w$, viz $w \in X + \tilde{z}$.

(ii) It is straightforward by duality, point (i) of Lemma 2.2 and point (i) above.

(iii) Suppose $z \in C_{\mathfrak{A}}(X)$ and pick $x \in X$. By cancellativity, one has that $x + \tilde{z} = \tilde{z} + x$ if and only if $x = \tilde{z} + x + z$, and this condition is certainly verified as $\tilde{z} + x + z = \tilde{z} + z + x = x$ by the hypothesis that z is in the center of \mathfrak{A} . It follows that $\tilde{z} \in C_{\mathfrak{A}}(X)$. With this in hand, assume that $\langle X \rangle_{\mathfrak{A}}$ is commutative and let $w_1, w_2 \in \langle X - z \rangle_{\mathfrak{A}}$. By point (i) above, there must exist $x_1, x_2 \in X$ such that $w_i = x_i + \tilde{z}$, which easily implies that

$$w_1 + w_2 = x_1 + \tilde{z} + x_2 + \tilde{z} = x_1 + x_2 + 2\tilde{z} = x_2 + x_1 + 2\tilde{z} = x_2 + \tilde{z} + x_1 + \tilde{z} = w_2 + w_1,$$

using that $\tilde{z} \in C_{\mathfrak{A}}(X)$, as we have just proved, and $\langle X \rangle_{\mathfrak{A}}$ is commutative. This ultimately shows that $\langle X - z \rangle_{\mathfrak{A}}$ is commutative too, which completes the proof by duality. \blacksquare

Remark 3. There is a notational subtlety here that it may be worth to underline before proceeding. Suppose that \mathfrak{A} is a unital semiring and $x, y \in \mathfrak{A}$. In principle, $x - y$ and $-y + x$ are not elements of \mathfrak{A} : In fact, they are (difference) sets, and no other meaningful interpretation is (a priori) possible. However, if $y \in \mathfrak{A}^\times$ and y' is the inverse of y in \mathfrak{A} , then $x - y = \{x + y'\}$ and $-y + x = \{y' + x\}$ by point (i) of Lemma 2.6, and we are allowed to identify $x - y$ with $x + y'$ and $-y + x$ with $y' + x$, which will turn to be very useful later on.

3. THE DAVENPORT TRANSFORM REVISED

As mentioned in the introduction, Davenport's proof [6, Statement A] of Theorem 1 is a transformation proof. Loosely speaking, the idea is to map a pair (X, Y) of non-empty subsets of a commutative group $\mathfrak{A} = (A, +, -, 0_A)$ to a new pair (X, Y') , which is smaller than (X, Y) in an appropriate sense, and specifically such that

$$|Y'| < |Y|, \quad |X + Y'| + |Y| \leq |X + Y| + |Y'|.$$

One then refers to (X, Y') as a Davenport transform of (X, Y) ; cf., e.g., [24, §3]. The construction assumes that $X + Y \subsetneq \mathfrak{A}$ and $0_A \in Y$, to the effect that $|Y| \geq 2$.

As broadly expected, many difficulties arise when attempting to adapt the same approach to semigroups, and that all the more if these are non-commutative. Even the possibility of embedding a semigroup into a monoid does not resolve anything at all, since the fundamental problem is that, contrary to the case of groups, cardinality is not preserved “under difference”. To wit, if $\mathfrak{A} = (A, +)$ is a unital semigroup (and hence a monoid) with identity 0_A , X is a subset of \mathfrak{A} , and a is an element of \mathfrak{A} , then the cardinalities of X , $X - a$ and $-a + X$ can be greatly different from each other, even supposing that \mathfrak{A} is cancellative. Thus, unless \mathfrak{A} is a group in disguise or, more generally, embeds as a submonoid into a group, one is not allowed to assume, for instance, that $0_A \in Y$ (see Remark 2).

In fact, the primary goal of this section is to show that, in spite of such issues, Davenport's original ideas can be successfully extended to the more general setting of (cancellative) semigroups, and used to give a proof of Theorem 5.

To start with, suppose that $\mathfrak{A} = (A, +)$ is a unital semigroup with identity 0_A and let X, Y be subsets of \mathfrak{A} and $mX + 2Y \not\subseteq X + Y$ for some $m \in \mathbb{N}^+$. For brevity, define

$$Z := (mX + 2Y) \setminus (X + Y).$$

Our assumptions give $Z \neq \emptyset$. Thus, fix $z \in Z$, and take $x_z \in (m - 1)X$ and $y_z \in Y$ such that $z \in x_z + X + Y + y_z$, where $0X := \{0_A\}$. Finally, set

$$(3) \quad \tilde{Y}_z := \{y \in Y : z \in x_z + X + Y + y\}, \quad Y_z := Y \setminus \tilde{Y}_z.$$

We refer to (X, Y_z) as a *generalized Davenport z -transform of (X, Y) (associated with z)* and, based on this notation, proceed on with the next proposition, intentionally organized in a list

of properties deduced starting from various hypotheses (rather than general assumptions), to remark differences with the “classical” Davenport transform and highlight which is used for which purpose.

Proposition 3.1. *If $Y_z \neq \emptyset$, then the triple (X, Y_z, \tilde{Y}_z) satisfies the following properties:*

- (i) Y_z and \tilde{Y}_z are non-empty disjoint proper subsets of Y , and $\tilde{Y}_z = Y \setminus Y_z$.
- (ii) If \mathfrak{A} is right cancellative, then $(x_z + X + Y_z) \cup (z - \tilde{Y}_z) \subseteq x_z + X + Y$.
- (iii) If $\langle Y \rangle_{\mathfrak{A}}$ is commutative, then $(x_z + X + Y_z) \cap (z - \tilde{Y}_z) = \emptyset$.
- (iv) If \mathfrak{A} is left cancellative, then $|z - \tilde{Y}_z| \geq |\tilde{Y}_z|$.
- (v) If \mathfrak{A} is cancellative and $\langle Y \rangle_{\mathfrak{A}}$ commutative, then $|X + Y| + |Y_z| \geq |X + Y_z| + |Y|$.

Proof. (i) By construction, $\tilde{y}_z \in Y_z$, that is Y_z and \tilde{Y}_z are both non-empty. Also, (3) gives that $Y_z, \tilde{Y}_z \subseteq Y$ and $Y_z \cap \tilde{Y}_z = \emptyset$, to the effect that $Y \setminus Y_z = Y \setminus (Y \setminus \tilde{Y}_z) = \tilde{Y}_z$ and $Y_z, \tilde{Y}_z \subsetneq Y$.

(ii) Since $Y_z \subseteq Y$ by point (i) above, $x_z + X + Y_z \subseteq x_z + X + Y$ by Lemma 2.2. On the other hand, if $w \in z - \tilde{Y}_z$ then there exists $y \in \tilde{Y}_z$ such that $z = w + y$. But $y \in \tilde{Y}_z$ implies by (3) that $z = \tilde{w} + y$ for some $\tilde{w} \in x_z + X + Y$, whence $w = \tilde{w}$ by right cancellativity, i.e. $w \in x_z + X + Y$.

(iii) Assume the contrary and let $w \in (x_z + X + Y_z) \cap (z - \tilde{Y}_z)$. There then exist $x \in X$, $y_1 \in Y_z$ and $y_2 \in \tilde{Y}_z$ such that $w = x_z + x + y_1$ and $z = w + y_2$. Using that $\langle Y \rangle_{\mathfrak{A}}$ is commutative thus gives that $z = x_z + x + y_1 + y_2 = x_z + x + y_2 + y_1$, which implies that $y_1 \in \tilde{Y}_z$ by (3) since $Y_z, \tilde{Y}_z \subseteq Y$ by point (i). This is however absurd as Y_z and \tilde{Y}_z are disjoint, again by point (i).

(iv) We have from (3) that for each $y \in \tilde{Y}_z$ there exists $w \in x_z + X + Y$ such that $z = w + y$, which yields that $w \in z - \tilde{Y}_z$. On the other hand, since \mathfrak{A} is left cancellative, it cannot happen that $w + y_1 = w + y_2$ for some $w \in \mathfrak{A}$ and distinct $y_1, y_2 \in \tilde{Y}_z$. Thus, \tilde{Y}_z embeds as a set into $z - \tilde{Y}_z$, with the result that $|\tilde{Y}_z| \leq |z - \tilde{Y}_z|$.

(v) Since \mathfrak{A} is cancellative and $X \neq \emptyset$ (otherwise $Z = \emptyset$), one has $|X + Y| \geq \max(|X|, |Y|)$ by point (ii) of Lemma 2.1 and point (ii) of Lemma 2.2. This implies the claim if Y is infinite, since then either $|X + Y| > |Y|$, and hence $|X + Y| + |Y_z| = |X| = |X + Y_z| + |Y|$, or $|X + Y| = |Y|$, and accordingly $|X + Y_z| + |Y_z| = |Y| = |X + Y_z| + |Y|$ (note that we are using here the AC). Thus, we are left with the case where Y is finite, for which the inclusion-exclusion principle, points (ii)-(iv) above, the same point (ii) Lemma 2.1 and point (i) of Lemma 2.2 entail that

$$|X + Y| = |x_z + X + Y| \geq |x_z + X + Y_z| + |z - \tilde{Y}_z| = |X + Y_z| + |z - \tilde{Y}_z| \geq |X + Y_z| + |\tilde{Y}_z|.$$

But $\tilde{Y}_z = Y \setminus Y_z$ and $Y_z \subseteq Y$ by point (i), to the effect that $|X + Y| \geq |X + Y_z| + |Y| - |Y_z|$. ■

Remark 4. To apply the generalized Davenport transform to the proof of Theorem 5, it will be enough to consider the case where $m = 1$, for which it is easily seen that $0_A \in Y_z$ if $0_A \in Y$ (we continue with the notation from above), as in the contrary case we would have $z \in X + Y$, contradicting the fact that $z \in (X + 2Y) \setminus (X + Y)$. However, it seems intriguing that the same machinery can be used, at least in principle, even if $m \geq 2$ in so far as one has a way to prove that $Y_z \neq \emptyset$, which is the reason why we decided to approach this topic as we have done.

4. THE MAIN RESULT AND SOME COROLLARIES

Lemma 3.1 accounts for some elementary properties of generalized Davenport transforms. We use it here to establish the main result of the paper. For all practical intents, we remark that some results from Section 2, as basic as they are, will be used in the proof without explicit mention. This is especially the case of point (ii) of Lemma 2.1 and point (i) of Lemma 2.2.

Proof of Theorem 5. Since every semigroup embeds as a subsemigroup into its (canonical) unitization and the unitization of a cancellative semigroup is cancellative in its own right, there is no loss of generality in assuming (as we do in the sequel), in the light of Lemma 2.5 and Definition 1, that \mathfrak{A} is unital, to the effect that $X = X^{(1)}$ and $Y = Y^{(1)}$.

Thus, suppose by contradiction that the theorem is false. Then, there must exist at least one pair (X, Y) of subsets of \mathfrak{A} for which $|X + Y| < \Omega(X, Y)$, whence

$$(4) \quad 2 \leq |X|, |Y| < \infty.$$

In fact, if one of X or Y is empty then $|X + Y| = 0$, while if both X and Y are non-empty but one of them is a singleton or infinite then $|X + Y| = \max(|X|, |Y|)$. In both cases, Definition 1 gives that $|X + Y| = \Omega(X, Y)$, contradicting our assumptions. It follows from (2) and (4) that

$$(5) \quad |X + Y| < \sup_{y_0 \in Y} \min_{y \in Y \setminus \{y_0\}} \text{ord}_{\mathfrak{A}}(y - \tilde{y}_0), \quad |X + Y| \leq |X| + |Y| - 2.$$

Additionally, we can assume (as we do) that (X, Y) is such that $|X| + |Y|$ is minimal among the pairs for which (4) and (5) are presumed to hold. Now, since $|X + Y|$ is finite by (4) and point (i) of Lemma 2.3, one gets by (5) that $Y^\times \neq \emptyset$ and there exists $\tilde{y}_0 \in Y^\times$ such that

$$(6) \quad |X + Y| < \min_{y \in Y \setminus \{\tilde{y}_0\}} \text{ord}_{\mathfrak{A}}(y - \tilde{y}_0).$$

So letting 0_A denote the identity of \mathfrak{A} and taking $W_0 := Y - \tilde{y}_0$ imply by (5) and (6) that

$$(7) \quad |X + W_0| < \min_{w \in W_0 \setminus \{0_A\}} \text{ord}_{\mathfrak{A}}(w), \quad |X + W_0| \leq |X| + |W_0| - 2,$$

as on the one hand $|Y - \tilde{y}_0| = |Y|$ and $|X + Y - \tilde{y}_0| = |X + Y|$ by point (ii) of Lemma 2.6, and on the other hand $y \in Y \setminus \{\tilde{y}_0\}$ only if $y - \tilde{y}_0 \in (Y - \tilde{y}_0) \setminus \{0_A\}$ and $w \in (Y - \tilde{y}_0) \setminus \{0_A\}$ only if $w + \tilde{y}_0 \in Y \setminus \{\tilde{y}_0\}$ (see also Remark 3). We claim that

$$(8) \quad Z := (X + 2W_0) \setminus (X + W_0) \neq \emptyset.$$

For suppose the contrary. Then, $X + W_0 = X + \langle W_0 \rangle_{\mathfrak{A}}$ by Lemma 2.4, with the result that

$$|X + W_0| = |X + \langle W_0 \rangle_{\mathfrak{A}}| \geq |\langle W_0 \rangle_{\mathfrak{A}}| \geq \max_{w \in W_0} \text{ord}_{\mathfrak{A}}(w) \geq \min_{w \in W_0 \setminus \{0_A\}} \text{ord}_{\mathfrak{A}}(w),$$

where we use, in particular, point (ii) of Lemma 2.2 for the first inequality and the fact that $|W_0| \geq 2$ for the last one. This is however absurd in that it contradicts (7). Hence, (8) is proved.

Pick $z \in Z$ and let (X, W'_0) be a generalized Davenport transform of (X, W_0) associated with z . As Y generates a commutative subsemigroup of \mathfrak{A} (by hypothesis), the same holds true with W_0 , by point (iii) of Lemma 2.6. Moreover, $0_A \in W_0$ (essentially by construction), and hence

$$(9) \quad 0_A \in W'_0 \neq \emptyset, \quad W'_0 \subsetneq W_0,$$

when taking into account Remark 4 and point (i) of Proposition 3.1. As a consequence, point (v) of the same Proposition 3.1 yields, together with (7), that

$$|X + W'_0| + |W_0| \leq |X + W_0| + |W'_0| \leq |X| + |W_0| - 2 + |W'_0|,$$

which ultimately means, since $|W_0| = |Y| < \infty$ by (4), that

$$(10) \quad |X + W'_0| \leq |X| + |W'_0| - 2.$$

It follows from (9) that $1 \leq |W'_0| < |W_0|$, and indeed $|W'_0| \geq 2$, as otherwise (10) would give that $|X| = |X + W'_0| \leq |X| - 1$, which is absurd since $|X| < \infty$ by (4). To summarize, one has

$$(11) \quad 2 \leq |W'_0| < |W_0| < \infty.$$

Furthermore, (7) and (9) entail that

$$(12) \quad |X + W'_0| \leq |X + W_0| < \min_{w \in W'_0 \setminus \{0_A\}} \text{ord}_{\mathfrak{A}}(w),$$

where we use the elementary property that $\min(C_1) \leq \min(C_2)$ if C_1 and C_2 are sets of cardinal numbers with $C_2 \subseteq C_1$. Now, since $0_A \in W_0'^\times$, then (12) implies that

$$(13) \quad |X + W_0'| < \sup_{w_0 \in W_0'^\times} \min_{w \in W_0' \setminus \{w_0\}} \text{ord}_{\mathfrak{A}}(w),$$

which gives, together with (4), (10) and (11), that $|X + W_0'| < \Omega(X, W_0')$, contradicting the minimality of $|X| + |Y|$ in that $|W_0'| < |W_0| = |Y|$, and hence $|X| + |W_0'| < |X| + |Y|$. ■

5. COROLLARIES

Now we prove a series of corollaries, the first of which will confirm that Theorem 5 is indeed at the same time a generalization of Theorem 1 and a strengthening of Theorem 2, as already mentioned by the end of the introduction. First, we give two simple lemmas.

Lemma 5.1. *Let \mathfrak{A} be a cancellative unital semigroup and Y a subset of \mathfrak{A} such that $|Y| \geq 2$ and $Y^\times \neq \emptyset$. Then $\sup_{y_0 \in Y^\times} \min_{y \in Y \setminus \{y_0\}} \text{ord}_{\mathfrak{A}}(y - y_0) \geq p(\mathfrak{A})$.*

Proof. Pick $y_0 \in Y^\times$ and $y \in Y \setminus \{y_0\}$, using that $Y^\times \neq \emptyset$ and $|Y| \geq 2$. Thus, $\text{ord}_{\mathfrak{A}}(y - y_0) \geq p(\mathfrak{A})$, which is clearly enough to complete the proof. ■

In the case of groups, Lemma 5.1 obviously applies to *any* subset with two or more elements.

Lemma 5.2. *Let \mathfrak{A} be a cancellative semigroup and X, Y non-empty subsets of \mathfrak{A} such that $Y^\times \neq \emptyset$. Then $\Omega(X^{(1)}, Y^{(1)}) \geq \min(p(\mathfrak{A}), |X| + |Y| - 1)$.*

Proof. If (at least) one of X or Y is a singleton or infinite, the assertion is trivial, since then $\Omega(X^{(1)}, Y^{(1)}) = |X| + |Y| - 1 = \max(|X|, |Y|)$. Otherwise, it follows from Lemma (5.1). ■

Corollary 5.1. *Let \mathfrak{A} be a cancellative semigroup and X, Y non-empty subsets of \mathfrak{A} such that $\langle Y \rangle_{\mathfrak{A}}$ is commutative and $Y^\times \neq \emptyset$. Then $|X + Y| \geq \min(p(\mathfrak{A}), |X| + |Y| - 1)$.*

Proof. It is immediate by Lemma 5.2 and Theorem 5. ■

Clearly Corollary 5.1 contains Theorem 2 (and hence also Theorem 1) as a special case.

Corollary 5.2. *Let \mathfrak{A} be a cancellative semigroup and X, Y subsets of \mathfrak{A} such that $\langle X \rangle_{\mathfrak{A}}$ is commutative. Then $|X + Y| \geq \Omega(Y^{(1)}, X^{(1)})$.*

Proof. It is straightforward from point (i) of Lemma 2.1 and Theorem 5. ■

The bound in Theorem 5 can be slightly strengthened in the case where both summands generate commutative subsemigroups.

Corollary 5.3. *Let \mathfrak{A} be a cancellative semigroup and X, Y subsets of \mathfrak{A} such that $\langle X \rangle_{\mathfrak{A}}$ and $\langle Y \rangle_{\mathfrak{A}}$ are both commutative. Then $|X + Y| \geq \max(\Omega(X^{(1)}, Y^{(1)}), \Omega(Y^{(1)}, X^{(1)}))$.*

Proof. It is a trivial consequence of Corollary 5.2 and Theorem 5. ■

Theorem 5 also allows for an alternative proof of I. Chowla's theorem [3].

Corollary 5.4. *Let \mathfrak{A} be a cancellative unital semigroup with identity 0_A and X, Y non-empty subsets of \mathfrak{A} such that $\langle Y \rangle_{\mathfrak{A}}$ is commutative and $0_A \in Y$. Then that*

$$|X + Y| \geq \min(\min_{y \in Y \setminus \{0_A\}} \text{ord}_{\mathfrak{A}}(y), |X| + |Y| - 1).$$

Proof. If X or Y is a singleton or infinite, the claim is trivial, since then

$$|X + Y| = \max(|X|, |Y|) = |X| + |Y| - 1.$$

In all other cases, Theorem 5 implies that $|X + Y| \geq \min(\omega(Y), |X| + |Y| - 1)$, where

$$\omega(Y) := \sup_{y_0 \in Y^\times} \min_{y \in Y \setminus \{y_0\}} \geq \min_{y \in Y \setminus \{0_A\}} \text{ord}_{\mathfrak{A}}(y),$$

because $0 \in Y^\times$. Clearly, this suffices to complete the proof. \blacksquare

Theorem 6 (I. Chowla's theorem for composite moduli [3]). *Let $m \geq 2$ be an integer and denote by $\mathfrak{A} = (A, +, -, 0_A)$ the cyclic group of order m . If X, Y are subsets of \mathfrak{A} with $0_A \in Y$ and $\gcd(m, y) = 1$ for every $y \in Y \setminus \{0_A\}$, then $|X + Y| \geq \min(m, |X| + |Y| - 1)$.*

Proof of Theorem 6. It is straightforward from Corollary 5.4 that 5.4 since $\text{ord}_{\mathfrak{A}}(y) = m$ for each non-zero residue class $y \in Y$, from the fact that $\gcd(m, y) = 1$ by hypothesis. \blacksquare

We conclude with an example showing that Theorem 5 can actually be significantly sharper than Theorem 2.

Example 1. Pick $k, q \in \mathbb{N}^+$ with q prime, and let $\mathfrak{A} = (\mathbb{Z}/m\mathbb{Z}, +, -, 0_m)$ be the additive group of the integers modulo m for $m := kq$. Consider the subset $X := \{1 + ik : i = 0, 1, \dots, q-1\}$ of \mathfrak{A} . Then, $2X = \{2 + ik : i = 0, 1, \dots, 2q-2\}$ and $\Omega(X, X) = q$, while $p(\mathfrak{A})$ is the smallest natural prime p dividing m . It follows that $p(\mathfrak{A})$ is (much) smaller than $\Omega(X, X)$ if p is (much) smaller than q , while $|2X| = q + 1$ in all cases.

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