

ZERO-SUM PROBLEMS IN FINITE ABELIAN GROUPS AND AFFINE CAPS

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Abstract

For a finite abelian group G , let $\mathfrak{s}(G)$ denote the smallest integer l such that every sequence S over G of length $|S| \geq l$ has a zero-sum subsequence of length $\exp(G)$. We derive new upper and lower bounds for $\mathfrak{s}(G)$, and all our bounds are sharp for special types of groups. The results are not restricted to groups G of the form $G = C_n^r$, but they respect the structure of the group. In particular, we show $\mathfrak{s}(C_n^4) \geq 20n - 19$ for all odd n , which is sharp if n is a power of 3. Moreover, we investigate the relationship between extremal sequences and maximal caps in finite geometry.

1. Introduction and main results

Let G be a finite abelian group. We denote by $\mathfrak{s}(G)$ (or $\eta(G)$ respectively) the smallest integer $l \in \mathbb{N}$ such that every sequence S over G of length $|S| \geq l$ has a zero-sum subsequence T of length $|T| = \exp(G)$ (or a zero-sum subsequence T of length $|T| \in [1, \exp(G)]$ respectively); for details on

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terminology and notation we refer to section 2. The investigation of these invariants has a long tradition in combinatorial number theory as well as in finite geometry (for an overview, see [32, section 5.7] and section 5). As already pointed out by Harborth, $\mathfrak{s}(C_n^r)$ is the smallest integer l such that every set of l lattice points in r -dimensional euclidean space contains n elements which have a centroid with integral coordinates. This geometric interpretation was a main reason why emphasis was formerly placed on groups of the form C_n^r . In the meantime, new applications (for example, in the theory of non-unique factorizations [32]) caused the need for investigations of the invariants $\mathfrak{s}(G)$ and $\eta(G)$ for general finite abelian groups.

In the present paper, such investigations are carried out for the first time in a systematic way. In Theorems 1.1 and 1.2, we briefly summarize the present state of knowledge, and then we discuss the new results.

For finite abelian groups of rank at most 2, both invariants $\eta(G)$ and $\mathfrak{s}(G)$ are completely determined.

THEOREM 1.1 *Let $G = C_{n_1} \oplus C_{n_2}$ with $1 \leq n_1 | n_2$. Then*

$$\eta(G) = 2n_1 + n_2 - 2 \quad \text{and} \quad \mathfrak{s}(G) = 2n_1 + 2n_2 - 3.$$

A proof of Theorem 1.1 was recently given in [32, Theorem 5.8.3]. It contains the result by Reiher [56], which states that $\mathfrak{s}(C_p \oplus C_p) = 4p - 3$ for all $p \in \mathbb{P}$ [56, 59], and it contains the theorem of Erdős, Ginzburg and Ziv (set $n_1 = 1$; see [19] for the original paper; for various proofs see [1; 51, section 2.4]).

From now on we consider finite abelian groups of rank larger than 2, and we start with the discussion of lower bounds.

THEOREM 1.2 *Let $n, r \in \mathbb{N}$.*

- (1) $\eta(C_n^r) \geq (2^r - 1)(n - 1) + 1$ and $\mathfrak{s}(C_n^r) \geq 2^r(n - 1) + 1$.
- (2) *If n is odd, then there exists a sequence $T \in \mathcal{F}(C_n^3)$ of length $|T| = 9$ such that T^{n-1} has no zero-sum subsequence of length n . In particular, we have $\eta(C_n^3) \geq 8n - 7$ and $\mathfrak{s}(C_n^3) \geq 9n - 8$.*

The first result is due to Harborth (see [34, Hilfssatz 1] or Proposition 3.1 for a generalization) and the second due to Elsholtz ([17], see also Lemma 3.4 for a simpler alternative proof). Note that in these papers only the result for $\mathfrak{s}(C_n^r)$ is formulated, but the proofs and Lemma 2.3(2) show the lower bound for $\eta(C_n^r)$.

Gao and Thangadurai [27] conjecture that the lower bounds given in Theorem 1.2(2) are the precise values, that is,

$$\eta(C_n^3) = 8n - 7 \quad \text{and} \quad \mathfrak{s}(C_n^3) = 9n - 8 \quad \text{for all odd } n \in \mathbb{N}_{\geq 3}$$

(see also Corollary 4.5).

Before discussing our new results, we consider the inverse problems associated to invariants $\mathfrak{s}(G)$ and $\eta(G)$. In other words, we study the structure of sequences $S \in \mathcal{F}(G)$ of length $|S| = \mathfrak{s}(G) - 1$ (or $|S| = \eta(G) - 1$ respectively), which have no zero-sum subsequence T of length $|T| = \exp(G)$ (or no zero-sum subsequence T of length $|T| \in [1, \exp(G)]$ respectively). These problems were first studied for groups of the form $G = C_n \oplus C_n$ by van Emde Boas [18]. Suppose that $G = C_n^r$ with $n \geq 2$ and $r \in \mathbb{N}$. It is generally believed that G has the following two properties.

PROPERTY C Every sequence $S \in \mathcal{F}(G)$ of length $|S| = \eta(G) - 1$ which has no short zero-sum subsequence has the form $S = T^{n-1}$ for some sequence $T \in \mathcal{F}(G)$.

PROPERTY D Every sequence $S \in \mathcal{F}(G)$ of length $|S| = \mathfrak{s}(G) - 1$ which has no zero-sum subsequence of length n has the form $S = T^{n-1}$ for some sequence $T \in \mathcal{F}(G)$.

If $n \geq 2$ and $r = 1$, then Property C holds (trivially) and so does Property D, as was proved independently by several authors [4; 24, Theorem 1; 54]. For a detailed discussion of these two properties in the case $r = 2$, see [26]; in the case $r \geq 3$, see [28]. Clearly, if Property D holds then $n - 1$ divides $\mathfrak{s}(C_n^r) - 1$ and, by Lemma 2.3(2), we have $\eta(C_n^r) = \mathfrak{s}(C_n^r) - n + 1$.

In Theorem 1.3 we present new lower bounds for $\eta(C_n^4)$ and $\mathfrak{s}(C_n^4)$, and we conjecture that these lower bounds give the precise value for all odd $n \in \mathbb{N}_{\geq 3}$ (see Corollary 4.5). The sequence S we construct for the proof of Theorem 1.3 has the form $S = T^{n-1}$ for some $T \in \mathcal{F}(C_n^r)$, supporting the conjecture that Property D holds for C_n^4 . The proof of Theorem 1.3 is given in section 3, and subsequently we show how to lift the bounds of Theorem 1.3 and Theorem 1.2 to groups of higher rank (see Proposition 3.5 and Corollary 3.6).

THEOREM 1.3 *Let n be an odd integer with $n \geq 3$. Then there exists a sequence $T \in \mathcal{F}(C_n^4)$ of length $|T| = 20$ such that T^{n-1} has no zero-sum subsequence of length n . In particular, we have $\eta(C_n^4) \geq 19n - 18$ and $\mathfrak{s}(C_n^4) \geq 20n - 19$.*

Now we discuss the upper bounds. Gao and Yang (see [30] for the original paper (in Chinese) or [32, Theorem 5.7.4]) proved that $\mathfrak{s}(G) \leq |G| + \exp(G) - 1$ for every finite abelian group G . The upper bounds for groups G of the form $G = C_n^r$ were given by Alon, Dubiner and recently by Kubertin (see Remarks 3.7).

We derive new upper bounds for both $\eta(G)$ and $\mathfrak{s}(G)$. The first (Theorem 1.4) rests on upper bounds for $\mathfrak{s}(C_p^r)$ for primes $p \in \mathbb{P}$ dividing $\exp(G)$, and the second (Theorem 1.5) is valid for groups with large exponent (as usual, $\mathbf{D}(G)$ denotes the Davenport constant of G ; see Definition 2.1 and the subsequent remarks).

THEOREM 1.4 *Let $G = C_{n_1} \oplus \cdots \oplus C_{n_r}$ with $r = r(G)$ and $1 < n_1 | \cdots | n_r$. Let $c_1, \dots, c_r \in \mathbb{N}$ such that for all primes $p \in \mathbb{P}$ with $p | n_r$ and all $i \in [1, r]$, we have $\mathfrak{s}(C_p^i) \leq c_i(p - 1) + 1$. Then*

$$\mathfrak{s}(G) \leq \sum_{i=1}^r (c_{r+1-i} - c_{r-i})n_i - c_r + 1, \quad \text{where } c_0 = 0.$$

In particular, if $n_1 = \cdots = n_r = n$, then $\mathfrak{s}(G) \leq c_r(n - 1) + 1$.

THEOREM 1.5 *Let $G = H \oplus C_n$ be a finite abelian group where $H \subset G$ is a subgroup, $\exp(G) = n \geq 2$ and $\mathbf{D}(G) \leq 2n - 1$.*

- (1) *If $\mathbf{D}(G \oplus C_n) \leq 3n - 1$, then $2(\mathbf{D}(H) - 1) + n \leq \eta(G) \leq \mathbf{D}(G \oplus C_n)$.*
- (2) *If G is a p -group for some odd prime p , then*

$$\mathbf{D}(G \oplus C_n) + \mathbf{D}(H) - 1 \leq \mathfrak{s}(G) \leq \mathbf{D}(G \oplus C_n) + n.$$

The proofs of Theorems 1.4 and 1.5 will be given in section 4. Theorem 1.4 is proved by the induction method and provides the best known upper bound for groups G which are not of the form $G = C_n^r$. The main part of Theorem 1.5 is the upper bound in 1.5(2), which generalizes (for odd primes) the recent results of Gao and Zhou [31, Theorem 1.5; 23, Proposition 3.1]. Its proof uses the polynomial method, first developed by Rónyai [57] and later generalized by Sun [61], and Kubertin [45].

After the proof of Theorem 1.5 we present special types of groups for which the lower and upper bounds derived in this paper coincide (see Corollaries 4.4, 4.5 and 4.6). The quality of the bounds in Theorem 1.5 can immediately be seen by considering the following most simple case. If (in Theorem 1.5) $H = C_m$ for some m dividing n , then $2(\mathbf{D}(H) - 1) + n = 2m + n - 2 = \eta(G)$ (see Theorem 1.1). Moreover, if $H = C_n$ and n is a prime power, then (again by Theorem 1.1) $\eta(G) = 3n - 2 = \mathbf{D}(G \oplus C_n)$ and $\mathfrak{s}(G) = 4n - 3 = \mathbf{D}(G \oplus C_n) + n - 1 = \mathbf{D}(G \oplus C_n) + \mathbf{D}(H) - 1$.

In section 5 we discuss further applications of invariants $\mathfrak{s}(G)$ and $\eta(G)$. Special emphasis is given to the role of invariant $\mathfrak{s}(C_n^r)$ in finite geometry and problems on arithmetic progressions. We give a detailed discussion of the history of the associated geometric problems.

2. Notation and some preparatory results

Let \mathbb{N} denote the set of positive integers, $\mathbb{P} \subset \mathbb{N}$ the set of all prime numbers and let $\mathbb{N}_0 = \mathbb{N} \cup \{0\}$. For integers $a, b \in \mathbb{Z}$ we set $[a, b] = \{x \in \mathbb{Z} | a \leq x \leq b\}$, and for $c \in \mathbb{N}$ let $\mathbb{N}_{\geq c} = \mathbb{N} \setminus [1, c - 1]$. Throughout, all abelian groups will be written additively, and for $n \in \mathbb{N}$, let C_n denote a cyclic group with n elements. For $p \in \mathbb{P}$, let $\mathbb{F}_p = \mathbb{Z}/p\mathbb{Z}$, and for a power q of p , let \mathbb{F}_q denote a field with q elements such that $\mathbb{F}_q \supset \mathbb{F}_p$.

Let G be an additive finite abelian group. If $|G| > 1$, then there are uniquely determined integers r, n_1, \dots, n_r with $1 < n_1 | \dots | n_r$ such that $G \cong C_{n_1} \oplus \dots \oplus C_{n_r}$. Then $r = r(G)$ is the rank of G , and $n_r = \exp(G)$ is the exponent of G . An r -tuple (e_1, \dots, e_r) in $G \setminus \{0\}$ is called a basis of G if $G = \langle e_1 \rangle \oplus \dots \oplus \langle e_r \rangle$. For $n \in \mathbb{N}$, we set $nG = \{ng | g \in G\}$.

We denote by $\mathcal{F}(G)$ the free (abelian, multiplicative) monoid with basis G . An element $S \in \mathcal{F}(G)$ is called a sequence over G and will be written in the form

$$S = \prod_{g \in G} g^{v_g(S)} = \prod_{i=1}^l g_i \in \mathcal{F}(G),$$

where $v_g(S)$ is called the multiplicity of g in S . A sequence $S' \in \mathcal{F}(G)$ is called a subsequence of S if there exists some $S'' \in \mathcal{F}(G)$ such that $S = S'S''$ (equivalently, $S'|S$ or $v_g(S') \leq v_g(S)$ for every $g \in G$). If this holds, then $S'' = S'^{-1}S$. As usual

$$\sigma(S) = \sum_{g \in G} v_g(S)g = \sum_{i=1}^l g_i \in G$$

denotes the sum of S ,

$$\text{supp}(S) = \{g \in G | v_g(S) > 0\} \subset G$$

is the support of S and

$$|S| = \sum_{g \in G} v_g(S) = l \in \mathbb{N}_0$$

denotes the length of S . Clearly, $|S| = 0$ if and only if $S = 1$ is the empty sequence. We say that sequence S is

- a zero-sum sequence (resp. has sum zero) if $\sigma(S) = 0$;
- short (in G) if $|S| \in [1, \exp(G)]$;
- square-free if $v_g(S) \leq 1$ for all $g \in G$.

DEFINITION 2.1 We denote by

- $D(G)$ the smallest integer $l \in \mathbb{N}$ such that every sequence $S \in \mathcal{F}(G)$ of length $|S| \geq l$ has a zero-sum subsequence. We call $D(G)$ the *Davenport constant of G* ;
- $\eta(G)$ the smallest integer $l \in \mathbb{N}$ such that every sequence $S \in \mathcal{F}(G)$ of length $|S| \geq l$ has a short zero-sum subsequence;
- $\mathfrak{s}(G)$ the smallest integer $l \in \mathbb{N}$ such that every sequence $S \in \mathcal{F}(G)$ of length $|S| \geq l$ has a zero-sum subsequence T of length $|T| = \exp(G)$;
- $\mathfrak{g}(G)$ the smallest integer $l \in \mathbb{N}$ such that every square-free sequence $S \in \mathcal{F}(G)$ of length $|S| \geq l$ has a zero-sum subsequence T of length $|T| = \exp(G)$.

A thorough treatment of the Davenport constant, a central invariant in zero-sum theory, may be found in [32, Chapter 5], and for some recent results we refer to [11]. Apart from basic properties, we use the following classical results on $D(G)$ (originally due to Kruyswijk and Olson): if $G = C_{n_1} \oplus \dots \oplus C_{n_r}$, where $r = r(G)$ and $1 < n_1 | \dots | n_r$, then

$$1 + \sum_{i=1}^r (n_i - 1) \leq D(G),$$

and equality holds if either $r \leq 2$ or G is a p -group [32, Theorems 5.5.9 and 5.8.3].

Let $\varphi: G \rightarrow G'$ be a map of abelian groups. Then there is a unique homomorphism $\bar{\varphi}: \mathcal{F}(G) \rightarrow \mathcal{F}(G')$ with $\bar{\varphi}|_G = \varphi$. We simply write φ instead of $\bar{\varphi}$, whence if $S = g_1 \cdot \dots \cdot g_l \in \mathcal{F}(G)$, then $\varphi(S) = \varphi(g_1) \cdot \dots \cdot \varphi(g_l) \in \mathcal{F}(G')$.

We start with a simple observation which will be used tacitly throughout the paper. Then we continue with a lemma relating invariants $\eta(G)$, $\mathfrak{s}(G)$ and $\mathfrak{g}(G)$. In sections 3 and 4 we concentrate on $\eta(G)$ and $\mathfrak{s}(G)$, and in section 5 we mainly deal with $\mathfrak{g}(G)$.

LEMMA 2.2 *Let G be a finite abelian group with $\exp(G) = n \geq 2$, $g \in G$, $\varphi: G \rightarrow G$ an automorphism, and $f: G \rightarrow G$ a map defined by $f(x) = \varphi(x) - g$ for every $x \in G$.*

- (1) *A sequence $S \in \mathcal{F}(G)$ has a zero-sum subsequence of length n if and only if $f(S)$ has a zero-sum subsequence of length n .*
- (2) *Let $S = h^{n-1}T \in \mathcal{F}(G)$ with $h \in G$, $f(h) = 0$ and $T \in \mathcal{F}(G)$. Then S has a zero-sum subsequence of length n if and only if $f(T)$ has a short zero-sum subsequence.*

Proof. (1) Let $S = g_1 \cdot \dots \cdot g_l \in \mathcal{F}(G)$ and $T = \prod_{i \in I} g_i$ be a subsequence of S , where $I \subset [1, l]$ with $|I| = n$. Then,

$$\sigma(f(T)) = \sum_{i \in I} (\varphi(g_i) - g) = \varphi(\sigma(T)),$$

whence $\sigma(T) = 0$ if and only if $\sigma(f(T)) = 0$.

- (2) By (1), S has a zero-sum subsequence of length n if and only if $f(S)$ has a zero-sum subsequence of length n . Since $f(S) = 0^{n-1}f(T)$, the assertion follows.

LEMMA 2.3 *Let G be a finite abelian group with $\exp(G) = n \geq 2$, $S \in \mathcal{F}(G)$, a sequence which has no zero-sum subsequence of length n , and $h = \max\{v_g(S) | g \in G\}$.*

- (1) $D(G) \leq \eta(G) \leq \mathfrak{s}(G) - n + 1$.
- (2) *If $h = n - 1$, then $\eta(G) \geq |S| - n + 2$. In particular, if $|S| = \mathfrak{s}(G) - 1$, then $\eta(G) = \mathfrak{s}(G) - n + 1$.*
- (3) $\mathfrak{g}(G) \leq \mathfrak{s}(G) \leq (\mathfrak{g}(G) - 1)(n - 1) + 1$. *If $G = C_n^r$, with $n \geq 2$ and $r \in \mathbb{N}$, and $\mathfrak{s}(G) = (\mathfrak{g}(G) - 1)(n - 1) + 1$, then G has Property D.*
- (4) *If H is a finite abelian group with $|H| \geq h$ and $f: [1, h] \rightarrow H$ an injective map, then*

$$\prod_{g \in G} \prod_{i=1}^{v_g(S)} (g + f(i)) \in \mathcal{F}(G \oplus H)$$

is a square-free sequence which has no zero-sum subsequence of length n . In particular, if $\exp(H)|n$, then $\mathfrak{g}(G \oplus H) \geq \mathfrak{s}(G)$, and $\mathfrak{g}(C_n^{r+1}) \geq \mathfrak{s}(C_n^r)$.

Proof. (1) Straightforward (for a detailed proof, see [32, Lemma 5.7.2]).

- (2) Let $S = g^{n-1}T$, with $g \in G$ and $T \in \mathcal{F}(G)$, and consider the map $f: G \rightarrow G$ defined by $f(x) = x - g$ for all $x \in G$. By Lemma 2.2(2), $f(T)$ has no short zero-sum subsequence whence $\eta(G) \geq |f(T)| + 1 = |S| - n + 2$. If $|S| = \mathfrak{s}(G) - 1$, then $\eta(G) \geq \mathfrak{s}(G) - n + 1$, whence (1) implies that $\eta(G) = \mathfrak{s}(G) - \exp(G) + 1$.
- (3) The first inequality follows by definition. Let

$$U = g_1^{k_1} \cdot \dots \cdot g_l^{k_l} \in \mathcal{F}(G), \quad \text{where } l, k_1, \dots, k_l \in \mathbb{N} \text{ and } g_1, \dots, g_l \in G \text{ are distinct,}$$

be a sequence of length $|U| = \mathfrak{s}(G) - 1$, which has no zero-sum subsequence of length n . Clearly, $T = g_1 \cdot \dots \cdot g_l$ is a square-free sequence which has no zero-sum subsequence of length n whence $l \leq \mathfrak{g}(G) - 1$. Therefore, we obtain that

$$\mathfrak{s}(G) - 1 = |U| = \sum_{i=1}^l k_i \leq l(n - 1) \leq (\mathfrak{g}(G) - 1)(n - 1).$$

Furthermore, if $G = C_n^r$ and equality holds, then $k_1 = \dots = k_l = n - 1$, whence G has Property D.

- (4) By construction, the given sequence has all the asserted properties.

All sequences S constructed in this paper, that have no zero-sum subsequence of length $\exp(G)$, have the additional property of Lemma 2.3(2). (That is, they have some element with multiplicity $\exp(G) - 1$) whence we always get $\eta(G) \geq |S| - \exp(G) + 2$. Gao [25] conjectured that for all finite abelian groups G we have $\eta(G) = \mathfrak{s}(G) - \exp(G) + 1$. Among others, this holds true for all groups G with $r(G) \leq 2$ (see Theorem 1.1) and $\exp(G) \leq 4$. Let $G = C_n^r$ with $n \geq 2$ and $r \in \mathbb{N}$ and consider the inequality $\mathfrak{s}(G) \leq (\mathfrak{g}(G) - 1)(n - 1) + 1$. Then the equality holds for $n = 2$ (trivial) and $n = 3$ [34, Hilfssatz 3]. If p is a prime with $p \geq 67$, then $\mathfrak{g}(C_p \oplus C_p) = \mathfrak{s}(C_p) = 2p - 1$; see Theorem 1.1 and [29].

3. Lower bounds

All lower bounds for invariants $\eta(G)$ and $\mathfrak{s}(G)$ are established by explicit constructions of sequences $S \in \mathcal{F}(G)$ having no zero-sum subsequences with the required properties. The first two results will be used several times, whereas the specific preparations for the proof of Theorem 1.3 start from Lemma 3.3 on. A geometric interpretation of the sequences given in Lemma 3.4 and Theorem 1.3 will be offered after Lemma 5.4. Note that in the special setting of p -groups, the bounds given in Lemma 3.2 were first proved in [31, Theorem 1.5].

PROPOSITION 3.1 *Let $G = C_{n_1} \oplus \cdots \oplus C_{n_r}$, where $r = r(G)$ and $1 < n_1 | \cdots | n_r$, and let (e_1, \dots, e_r) be a basis of G with $\text{ord}(e_i) = n_i$ for every $i \in [1, r]$. For a subset $I \subset [1, r]$, we set $e_I = \sum_{i \in I} e_i$ (in particular, $e_\emptyset = 0$).*

(1) *Let*

$$U = \prod_{k=1}^r \prod_{I \subset [k+1, r]} (e_k + e_I)^{n_k-1} \in \mathcal{F}(G).$$

Then the following statements are equivalent:

- (a) *U has no short zero-sum subsequence;*
 - (b) *$r = 1$ or ($r \geq 2$ and $n_2 = n_r$).*
- (2) *Let H be a finite abelian group with $\exp(H) = n$ being a multiple of n_r and $T \in \mathcal{F}(H)$ such that T^{n-1} has no zero-sum subsequence of length n . Then the sequence*

$$S = \prod_{g \in T} \left(g^{n-1} \prod_{i=1}^r (g + e_i)^{n_i-1} \right) \in \mathcal{F}(G \oplus H)$$

has no zero-sum subsequence of length n , and hence

$$\mathfrak{s}(G \oplus H) \geq \eta(G \oplus H) + n - 1 \geq 1 + |T| \left(n - 1 + \sum_{i=1}^r (n_i - 1) \right).$$

Furthermore, if $m \in \mathbb{N}$ and $I_1, \dots, I_m \subset [1, r]$ are pairwise disjoint sets with $\sum_{i \in I_\mu} (n_i - 1) \geq n$ for all $\mu \in [1, m]$, then

$$\bar{S} = S \prod_{g \in T} \prod_{\mu=1}^m (g + e_{I_\mu}) \in \mathcal{F}(G \oplus H)$$

has no zero-sum subsequence of length n .

(3) *If $\bar{G} = G \oplus C_n^k$ with $k, n \in \mathbb{N}$ and $n_r | n$, then*

$$\mathfrak{s}(\bar{G}) \geq \eta(\bar{G}) + n - 1 \geq 1 + 2^k \left(n - 1 + \sum_{i=1}^r (n_i - 1) \right).$$

Proof. (1) (a) \Rightarrow (b) If $r \leq 2$, then there is nothing to show. If $r \geq 3$ and $n_2 < n_r$, then

$$U' = e_r^{n_r-n_2-1} (e_2 + e_r)^{n_2-n_1+1} (e_1 + e_r) (e_1 + e_2 + e_r)^{n_1-1}$$

is a short zero-sum subsequence of U , a contradiction.

(b) \Rightarrow (a) If $r = 1$, then the assertion is clear. Suppose that $r \geq 2$ and $n_2 = n_r = n$. Then

$$U = \prod_{I \subset [2, r]} (e_1 + e_I)^{n_1 - 1} \prod_{\emptyset \neq I \subset [2, r]} e_I^{n-1} \in \mathcal{F}(G)$$

and we consider a zero-sum subsequence

$$U' = \prod_{v=1}^k (e_1 + e_{I_v}) \prod_{v=k+1}^l e_{I_v}$$

of U with $0 \leq k \leq l \leq n$, subsets $I_1, \dots, I_k \subset [2, r]$ and non-empty subsets $I_{k+1}, \dots, I_l \subset [2, r]$. We have to show that $|U'| = l = 0$. Assume, on the contrary, that $l \geq 1$. Since $\mathbf{v}_{e_1}(U') \leq \mathbf{v}_{e_1}(U) = n_1 - 1$, there exists some $v \in [1, l]$ such that I_v is non-empty. Let $i \in I_v$ and

$$\alpha = |\{j \in [1, l] \mid i \in I_j\}|.$$

Since $\alpha \equiv 0 \pmod{n}$ and $1 \leq \alpha \leq l \leq n$, it follows that $\alpha = l = n$. Since U' has sum zero we infer that $I_1 = \dots = I_n$, whence

$$U' = (e_1 + e_{I_1})^k e_{I_1}^{n-k}.$$

Then $k \equiv 0 \pmod{n_1}$ and $k \leq \mathbf{v}_{e_1 + e_{I_1}}(U) = n_1 - 1$ imply that $k = 0$, whence $U' = e_{I_1}^n$ is a subsequence of U , a contradiction.

- (2) Assume, on the contrary, that S has a zero-sum subsequence S' of length n . Since every zero-sum subsequence of T^m , for any $m \geq n$, of length n has the form g^n for some $g \in \text{supp}(T)$ it follows that the sequence S' has the form

$$S' = g^{l_g} \prod_{i=1}^r (g + e_i)^{l_i},$$

with $g \in \text{supp}(T)$, $l_g \in [0, n-1]$ and $l_i \in [0, n_i-1]$ for all $i \in [1, r]$. But $l_g < n$ implies that there is some $i \in [1, r]$ with $l_i \in [1, n_i-1]$, and hence $\sigma(S') \neq 0$, a contradiction. Now the lower bounds for $\mathbf{s}(G \oplus H)$ and $\eta(G \oplus H)$ follow from Lemma 2.3.

If \bar{S} has a zero-sum subsequence \bar{S}' of length n , then

$$\bar{S}' = g^{l_g} \prod_{i=1}^r (g + e_i)^{l_i} \prod_{\mu=1}^m (g + e_{I_\mu})^{\delta_\mu},$$

with $\delta_\mu \in \{0, 1\}$ and all other parameters as before. Since \bar{S}' is not a subsequence of S , there is some $\mu \in [1, m]$ with $\delta_\mu = 1$. This implies that \bar{S}' must contain the sequence

$$\bar{S}'' = (g + e_{I_\mu}) \prod_{i \in I_\mu} (g + e_i)^{n_i - 1},$$

and hence $n = |\bar{S}'| \geq |\bar{S}''| \geq 1 + \sum_{i \in I_\mu} (n_i - 1) \geq n + 1$, a contradiction.

- (3) Applying (1) to the group C_n^k , we obtain a sequence $T = OT'$ of length $|T| = 2^k$ such that $U = T^{n-1}$ has no short zero-sum subsequence and hence T^{n-1} has no zero-sum subsequence of length n . Then (2) gives us a sequence $S \in \mathcal{F}(\overline{G})$ of length $|S| = |T|(n-1 + \sum_{i=1}^r (n_i - 1))$, which has no zero-sum subsequence of length n . Now the assertion follows from Lemma 2.3.

LEMMA 3.2 *Let G be a finite abelian group with $\exp(G) = n \geq 2$ and $G = H \oplus \langle e \rangle$, where $H \subset G$ is a subgroup and $e \in G$ with $\text{ord}(e) = n$. Then*

$$\eta(G) \geq 2(\mathbf{D}(H) - 1) + n \quad \text{and} \quad \mathbf{s}(G) \geq 2(\mathbf{D}(H) - 1) + 2n - 1.$$

Proof. If $T = g_1 \cdots g_l \in \mathcal{F}(H)$ is a sequence of length $|T| = l = \mathbf{D}(H) - 1$, which has no zero-sum subsequence, then obviously the sequence

$$S = e^{n-1} \prod_{i=1}^l g_i \prod_{i=1}^l (g_i + e) \in \mathcal{F}(G)$$

has no short zero-sum subsequence. This implies that

$$\eta(G) \geq |S| + 1 = 2(\mathbf{D}(H) - 1) + n,$$

and by Lemma 2.3(1) we have $\mathbf{s}(G) \geq 2(\mathbf{D}(H) - 1) + 2n - 1$.

For the rest of this section we introduce the following notation. Let $G = C_n^r$, with $n \geq 2$ and $r \in \mathbb{N}$, and let (e_1, \dots, e_r) be a basis of G . In order to stress the geometric aspect of the theory, we write the elements $g \in G$ as coordinate vectors; this means for an element $g \in G$ with $g = a_1 e_1 + \cdots + a_r e_r$, we set

$$\begin{pmatrix} a_1 \\ \vdots \\ a_r \end{pmatrix} = a_1 e_1 + \cdots + a_r e_r = g,$$

where $a_1, \dots, a_r \in [0, n-1]$. For $i \in [1, r]$, we call a_i the *i th coordinate of g* and $a_1 + \cdots + a_r \in \mathbb{N}_0$ the *weight of g* .

LEMMA 3.3 *Let $G = C_n^2$ with $n \geq 3$ odd,*

$$V_2 = \begin{pmatrix} 0 \\ 0 \end{pmatrix}^{n-1} S \quad \text{with} \quad S = \begin{pmatrix} 0 \\ 2 \end{pmatrix}^{n-1} \begin{pmatrix} 2 \\ 0 \end{pmatrix}^{n-1} \begin{pmatrix} 2 \\ 2 \end{pmatrix}^{n-1}$$

and

$$W_2 = \begin{pmatrix} 0 \\ 1 \end{pmatrix}^{n-1} \begin{pmatrix} 1 \\ 0 \end{pmatrix}^{n-1} \begin{pmatrix} 1 \\ 2 \end{pmatrix}^{n-1} \begin{pmatrix} 2 \\ 1 \end{pmatrix}^{n-1}.$$

Then neither V_2 nor W_2 has a zero-sum subsequence of length n .

Proof. Let $f : G \rightarrow G$ be defined by

$$\begin{pmatrix} a \\ b \end{pmatrix} \mapsto \begin{pmatrix} \frac{n+1}{2} & \frac{n+1}{2} \\ \frac{n-1}{2} & \frac{n+1}{2} \end{pmatrix} \begin{pmatrix} a \\ b \end{pmatrix} + \begin{pmatrix} 0 \\ 1 \end{pmatrix}.$$

Then it is easy to check that $f(V_2) = W_2$. By Proposition 3.1(1), S has no short zero-sum subsequence. Thus Lemma 2.2 implies that V_2 and $f(V_2)$ have no zero-sum subsequence of length n .

LEMMA 3.4 *Let $G = C_n^3$ with $n \geq 3$ odd,*

$$V_3 = \tilde{V}_3^{n-1} \quad \text{with} \quad \tilde{V}_3 = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 2 \end{pmatrix} \begin{pmatrix} 1 \\ 2 \\ 0 \end{pmatrix} \begin{pmatrix} 1 \\ 2 \\ 2 \end{pmatrix} \begin{pmatrix} 2 \\ 0 \\ 1 \end{pmatrix} \begin{pmatrix} 2 \\ 1 \\ 0 \end{pmatrix} \begin{pmatrix} 2 \\ 1 \\ 2 \end{pmatrix} \begin{pmatrix} 2 \\ 2 \\ 1 \end{pmatrix} \begin{pmatrix} 3 \\ 1 \\ 1 \end{pmatrix}$$

and

$$W_3 = \tilde{W}_3^{n-1} \quad \text{with} \quad \tilde{W}_3 = \begin{pmatrix} 2 \\ 0 \\ 0 \end{pmatrix} \begin{pmatrix} 2 \\ 0 \\ 2 \end{pmatrix} \begin{pmatrix} 2 \\ 2 \\ 0 \end{pmatrix} \begin{pmatrix} 2 \\ 2 \\ 2 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 1 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 2 \end{pmatrix} \begin{pmatrix} 1 \\ 2 \\ 1 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix}.$$

Then, neither V_3 nor W_3 has a zero-sum subsequence of length n . In particular, we have $\eta(C_n^3) \geq 8n - 7$ and $\mathfrak{S}(C_n^3) \geq 9n - 8$.

Proof. Let $f : G \rightarrow G$ be defined by

$$\begin{pmatrix} a \\ b \\ c \end{pmatrix} \mapsto \begin{pmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} a \\ b \\ c \end{pmatrix} + \begin{pmatrix} 3 \\ 0 \\ 0 \end{pmatrix}.$$

Then it is easy to verify that $f(V_3) = W_3$. Thus by Lemma 2.2(1) and Lemma 2.3(2), it suffices to prove that V_3 has no zero-sum subsequence of length n . Assume, on the contrary, that there is a zero-sum subsequence V'_3 of V_3 of length n .

We first suppose V'_3 contains only those elements of V_3 that have first coordinate 1 or 2. Then the sum of the first coordinates of the elements of V'_3 is n or $2n$. This is only possible if every element of V'_3 has the same entry in the first coordinate. If all elements of V'_3 have first coordinate 1, then the sequence formed by the remaining two coordinates is a zero-sum subsequence of V_2 of length n , a contradiction to Lemma 3.3. Similarly, if all elements of V'_3 have first coordinate 2, then the sequence formed by the remaining two coordinates is a zero-sum subsequence of W_2 of length n , a contradiction to Lemma 3.3.

Thus V'_3 must contain the element $g = \begin{pmatrix} 3 \\ 1 \\ 1 \end{pmatrix}$. Since the second coordinate of g equals 1, the sum of the second coordinates of the elements of V'_3 must be n . The same is true for the third coordinate. Since the first coordinate of g equals 3, the sum of the first coordinates of the elements of V'_3 must

be $2n$. Thus the sum of all coordinates of the n elements of V_3' equals $n + n + 2n$, which is even. On the other hand, since all elements of V_3 have odd weight, this is the sum of an odd number of odd weights whence it should be odd, a contradiction.

Proof of Theorem 1.3 Let $G = C_n^4$ with $n \geq 3$ odd. We set

$$T(n) = T = \begin{pmatrix} 1 \\ 1 \\ 0 \\ 0 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 0 \\ 2 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 2 \\ 0 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 2 \\ 2 \end{pmatrix} \begin{pmatrix} 1 \\ 2 \\ 0 \\ 1 \end{pmatrix} \begin{pmatrix} 1 \\ 2 \\ 1 \\ 0 \end{pmatrix} \begin{pmatrix} 1 \\ 2 \\ 1 \\ 2 \end{pmatrix} \begin{pmatrix} 1 \\ 2 \\ 2 \\ 1 \end{pmatrix} \begin{pmatrix} 1 \\ 2 \\ 2 \\ 1 \end{pmatrix} \begin{pmatrix} 1 \\ 2 \\ 2 \\ 1 \end{pmatrix} \begin{pmatrix} 0 \\ 2 \\ 1 \\ 1 \end{pmatrix} \begin{pmatrix} 3 \\ 1 \\ 1 \\ 1 \end{pmatrix}$$

and assert that $V_4 = T^{n-1}$ has no zero-sum subsequence of length n . Then $\mathfrak{s}(G) \geq |S| + 1 = 20n - 19$, and Lemma 2.3(2) implies that $\eta(G) \geq 19n - 18$. Assume, on the contrary, that there is a zero-sum subsequence V_4' of V_4 of length n . We consider the elements

$$g = \begin{pmatrix} 0 \\ 2 \\ 1 \\ 1 \end{pmatrix}, \quad h = \begin{pmatrix} 3 \\ 1 \\ 1 \\ 1 \end{pmatrix}, \quad g' = \begin{pmatrix} 2 \\ 0 \\ 1 \\ 1 \end{pmatrix} \quad \text{and} \quad h' = \begin{pmatrix} 1 \\ 3 \\ 1 \\ 1 \end{pmatrix}.$$

We first suppose that $\mathbf{v}_g(V_4') + \mathbf{v}_h(V_4') = 0$, whence V_4' contains only those elements of V_4 that have the first coordinate 1 or 2. Then the sum of the first coordinates of the elements of V_4' is n or $2n$. This is only possible if all the elements of V_4' have the same entry in the first coordinate. If all elements of V_4' have first coordinate 1, then the sequence formed by the remaining three coordinates is a zero-sum subsequence of V_3 of length n , a contradiction to Lemma 3.4. Similarly, if all elements of V_4' have first coordinate 2, then the sequence formed by the remaining three coordinates is a zero-sum subsequence of W_3 of length n , a contradiction to Lemma 3.4.

Thus it follows that $\mathbf{v}_g(V_4') + \mathbf{v}_h(V_4') > 0$. Since both g and h have a 1 in the third coordinate and all other elements of V_4 have a 0, 1 or 2 in the third coordinate, the sum of the third coordinates of the elements of V_4' must be n . The same is true for the fourth coordinate. The sum of the first coordinates of the elements of V_4' can be neither 0 nor $3n$, hence it must be either n or $2n$. The same is true for the second coordinate. We distinguish three cases.

Case 1. *The sum of the first coordinates and the sum of the second coordinates are both n .* Since for all elements of V_4 the sum of the first and the second coordinates is at least 2, V_4' can only contain elements whose first two coordinates sum to exactly 2. This implies that $\mathbf{v}_g(V_4') = \mathbf{v}_{g'}(V_4')$. Any other elements of V_4' have an even number in the third coordinate. Thus the sum of the third coordinates is even, contradicting n is odd.

Case 2. *The sum of the first coordinates and the sum of the second coordinates are both $2n$.* Since for all elements of V_4 the sum of the first and the second coordinates is at most 4, V_4'

can only contain elements whose first two coordinates sum to exactly 4. This implies that $\mathbf{v}_h(V'_4) = \mathbf{v}_{h'}(V'_4)$. Any other elements of V'_4 have an even number in the third coordinate. Thus the sum of the third coordinates is even, contradicting n is odd.

Case 3. *The sum of the first coordinates equals n and the sum of the second coordinates equals $2n$, or conversely.* Then the sum of all coordinates of the n elements of V'_4 equals $n + n + n + 2n = 5n$, which is odd. On the other hand, since all elements of V_4 have even weight, the sum of all coordinates of the n elements of V'_4 should be even, a contradiction.

Next, we show how to lift lower bounds for $\mathfrak{s}(C_n^2)$, $\mathfrak{s}(C_n^3)$ and $\mathfrak{s}(C_n^4)$ to lower bounds for $\mathfrak{s}(C_n^r)$ with $r \geq 5$. Then we compare these bounds with upper bounds for $\mathfrak{s}(C_n^r)$. Although these lifting results give the best lower bounds that are currently available, a lifting of a sharp bound for $\mathfrak{s}(C_n^r)$ will in general not give sharp bounds for larger ranks.

PROPOSITION 3.5 *Let G be a finite abelian group with $\exp(G) = n \geq 2$.*

- (1) *Let $G = G_1 \oplus G_2$ with subgroups $G_1, G_2 \subset G$ such that $\exp(G_1) = \exp(G_2) = n$. If for every $i \in \{1, 2\}$ there is some $T_i = g_{i,1} \cdot \dots \cdot g_{i,l_i} \in \mathcal{F}(G_i)$ such that T_i^{n-1} has no zero-sum subsequence of length n , then sequence T^{n-1} , where*

$$T = \prod_{\substack{\lambda \in [1, l_1] \\ \nu \in [1, l_2]}} (g_{1,\lambda} + g_{2,\nu}) \in \mathcal{F}(G),$$

has no zero-sum subsequence of length n . In particular,

$$\mathfrak{s}(G) \geq |T|(n-1) + 1 \quad \text{and} \quad \eta(G) \geq (|T| - 1)(n-1) + 1.$$

- (2) *Let $G = C_n^r$ with $r \geq 2$ and let $r = r_1 + \dots + r_s$ be any partition of r with $s, r_1, \dots, r_s \in \mathbb{N}$. If for every $i \in [1, s]$ there exists some $T_i \in \mathcal{F}(C_n^{r_i})$ such that T_i^{n-1} has no zero-sum subsequence of length n , then*

$$\mathfrak{s}(G) \geq \left(\prod_{i=1}^s |T_i| \right) (n-1) + 1 \quad \text{and} \quad \eta(G) \geq \left(\prod_{i=1}^s |T_i| - 1 \right) (n-1) + 1.$$

Proof. (1) Assume, on the contrary, that T^{n-1} has a zero-sum subsequence T' of length n , say

$$T' = \prod_{j=1}^n (g_{1,\lambda_j} + g_{2,\nu_j}), \quad \text{where } \lambda_1, \dots, \lambda_n \in [1, l_1] \text{ and } \nu_1, \dots, \nu_n \in [1, l_2].$$

Then the sequences

$$T'_1 = \prod_{j=1}^n g_{1,\lambda_j} \quad \text{and} \quad T'_2 = \prod_{j=1}^n g_{2,\nu_j}$$

have sum zero. Thus for every $i \in \{1, 2\}$, the sequence T'_i is not a subsequence of T_i^{n-1} , whence $\lambda_1 = \dots = \lambda_n, \nu_1 = \dots = \nu_n$ and

$$T' = (g_{1,\lambda_1} + g_{2,\nu_1})^n,$$

a contradiction to the assumption that T' is a subsequence of T^{n-1} .

Now, the lower bound for $\mathfrak{s}(G)$ follows from the very definition, and the lower bound for $\eta(G)$ follows from Lemma 2.3(2).

- (2) This follows from (1) by induction on s .

COROLLARY 3.6 *Let $n \geq 3$ be an odd integer and $r \in \mathbb{N}$.*

- (1) *For $r \in [5, 12]$, we have $\mathfrak{s}(C_n^r) \geq c_r(n - 1) + 1$, where $c_5 = 40$, $c_6 = 81$, $c_7 = 180$, $c_8 = 400$, $c_9 = 800$, $c_{10} = 1620$, $c_{11} = 3600$ and $c_{12} = 8000$.*
- (2) *If $r = 4s + d$ with $s \in \mathbb{N}_0$ and $d \in [1, 4]$ and if $\mathfrak{s}(C_n^d) \geq c_d(n - 1) + 1$ with $c_1, c_2, c_3, c_4 \in \mathbb{N}$, then $\mathfrak{s}(C_n^r) \geq 20^s c_d(n - 1) + 1$.*

Proof. Let $d \in [1, 4]$. We assert that there is some sequence $T \in \mathcal{F}(C_n^d)$ such that T^{n-1} has no zero-sum subsequence of length n and $|T| = c_d$ with $c_1 = 2$, $c_2 = 4$, $c_3 = 9$ and $c_4 = 20$. For $d = 1$, the sequence $T = 0g$ has this property for every $g \in C_n$ with $\text{ord}(g) = n$. For $d = 2$, this follows from Proposition 3.1(2) with $G = H = C_n$. For $d = 3$, this follows from Lemma 3.4 and for $d = 4$, this follows by Theorem 1.3. Now (1) and (2) follow from Proposition 3.5(2) (for (1), use the partitions $5 = 1 + 4$, $6 = 3 + 3$, $7 = 4 + 3$, $8 = 4 + 4$, $9 = 1 + 4 + 4$, $10 = 3 + 3 + 4$, $11 = 3 + 4 + 4$, $12 = 4 + 4 + 4$).

- REMARKS 3.7** (1) Alon and Dubiner proved the following upper bounds for $\mathfrak{s}(C_n^r)$: for every $r \in \mathbb{N}$ and every prime p one has $\mathfrak{s}(C_p^r) \leq c_r p$, where c_r is recursively defined as follows: $c_1 = 2$ and $c_r = 256r(\log_2 r + 5)c_{r-1} + (r + 1)$ for $r \geq 2$ (note that there is a misprint in formula (6) in [2, p. 306]; since, in the meantime, it is known that $\mathfrak{s}(C_p^2) \leq 4p$, one can also start the recursion with $c_2 = 4$). Furthermore, there exists an absolute constant $M > 0$ such that $\mathfrak{s}(C_n^r) \leq (Mr \log_2 r)^r n$ for all $r, n \in \mathbb{N}$ [2, Theorem 1.1].
- (2) Using some refinements, Kubertin [44, Satz 5.2] gave the following upper bounds: for sufficiently large p and n , we have $\mathfrak{s}(C_p^r) \leq c_r p$ and $\mathfrak{s}(C_n^r) \leq 2c_r n$ with $c_1 = 2$, $c_2 = 4$ and $c_r = 79.3224 \log(4.2637(1.4715r)^r)c_{r-1} + (r + 3)/2$.
 - (3) Upper and lower bounds for $\mathfrak{s}(C_3^r)$ (equivalently, bounds for the maximal size of affine caps) are discussed in detail in section 5.

4. Upper bounds and consequences

We first deal with Theorem 1.4. Note that the results of Alon, Dubiner and Kubertin (discussed in Remarks 3.7) provide the starting values c_1, \dots, c_r mentioned in the assumption of Theorem 1.4. Although the proof of this theorem is straightforward, it provides the first reasonable upper bound for $\mathfrak{s}(G)$ in the case where G has not the form C_n^r (see Corollary 4.6). We start with the following lemma which generalizes [34, Hilfssatz 2] (see also [12]).

LEMMA 4.1 *Let G be a finite abelian group, $H \subset G$ a subgroup and $S \in \mathcal{F}(G)$ a sequence of length $|S| \geq (\mathfrak{s}(H) - 1) \exp(G/H) + \mathfrak{s}(G/H)$. Then S has a zero-sum subsequence of length $\exp(H) \exp(G/H)$. In particular, if $\exp(G) = \exp(H) \exp(G/H)$, then*

$$\mathfrak{s}(G) \leq (\mathfrak{s}(H) - 1) \exp\left(\frac{G}{H}\right) + \mathfrak{s}\left(\frac{G}{H}\right).$$

Proof. This follows from [32, Proposition 5.7.11].

Proof of Theorem 1.4 We proceed by induction on $\exp(G)$. If $\exp(G) = p \in \mathbb{P}$, then $G = C_p^r$ and the assertion holds by assumption.

Let $p \in \mathbb{P}$ with $p|n_1$, $p < n_r$, and let $m_i = p^{-1}n_i$ for $i \in [1, r]$. We consider the groups

$$pG \cong C_{m_1} \oplus \cdots \oplus C_{m_r} \quad \text{and} \quad \frac{G}{pG} \cong C_p^r.$$

Note that we may have $m_1 = 1$, but in any case the induction hypothesis implies that

$$\mathfrak{s}(pG) \leq \sum_{i=1}^r (c_{r+1-i} - c_{r-i})m_i - c_r + 1.$$

By Lemma 4.1 (with $H = pG$), we infer that

$$\begin{aligned} \mathfrak{s}(G) &\leq (\mathfrak{s}(H) - 1) \exp\left(\frac{G}{H}\right) + \mathfrak{s}\left(\frac{G}{H}\right) \\ &\leq \left(\sum_{i=1}^r (c_{r+1-i} - c_{r-i})m_i - c_r\right) p + c_r(p - 1) + 1 \\ &\leq \sum_{i=1}^r (c_{r+1-i} - c_{r-i})n_i - c_r + 1. \end{aligned}$$

For the proof of Theorem 1.5 we need the following two well-known lemmas. For convenience, we provide a short proof for the second one.

LEMMA 4.2 *Let G be a finite abelian group, $k, n \in \mathbb{N}$, $\mathbf{D}(G \oplus C_n) \leq 3n - 1$ and $S \in \mathcal{F}(G)$ a zero-sum sequence of length $|S| = (2k - 1)n$. Then S has a zero-sum subsequence of length n .*

Proof. This follows from [32, Proposition 5.7.7.3].

We introduce some more notation. Let R be a commutative ring and $l \in \mathbb{N}$. We set $R[\mathbf{X}] = R[X_1, \dots, X_l]$, and if

$$f = \sum_{\mathbf{m}=(m_1, \dots, m_l) \in \mathbb{N}_0^l} a_{\mathbf{m}} X_1^{m_1} \cdots X_l^{m_l} \in R[\mathbf{X}]$$

is a non-zero polynomial, then we denote by

$$\deg(f) = \max\{m_1 + \cdots + m_l \mid \mathbf{m} \in \mathbb{N}_0^l \text{ with } a_{\mathbf{m}} \neq 0\} \in \mathbb{N}_0$$

the total degree of f .

LEMMA 4.3 *Let R be a commutative ring, $l \in \mathbb{N}$, $M = \langle \prod_{i \in I} X_i \mid I \subset [1, l] \rangle_R \subset R[\mathbf{X}]$ the submodule generated by the multilinear monomials, $C = \{0_R, 1_R\}^l \subset R^l$ the cube in R^l and R^C the set of all*

maps $\varphi: C \rightarrow R$. Then the map

$$\theta: M \rightarrow R^C \text{ defined by } f \mapsto \theta(f): \begin{cases} C & \longrightarrow R \\ \mathbf{c} & \longmapsto f(\mathbf{c}) \end{cases}$$

is an R -module isomorphism.

Proof. Clearly, M is a free R -module of rank 2^l and R^C is a free R -module of rank 2^l having the set of all characteristic functions as an R -basis. If $\mathbf{c} = (c_1, \dots, c_l) \in C$, $\chi_{\mathbf{c}} \in R^C$ the characteristic function of \mathbf{c} and

$$f = \prod_{\substack{j \in [1, l] \\ c_j = 1}} X_j \prod_{\substack{j \in [1, l] \\ c_j = 0}} (1 - X_j) \in M,$$

then $\theta(f) = \chi_{\mathbf{c}}$, whence θ is an isomorphism.

Proof of Theorem 1.5 (1) The lower bound follows from Lemma 3.2 and the upper bound from [32, Proposition 5.7.7.2].

(2) Since $D(G \oplus C_n) = (D(H) - 1) + D(C_n \oplus C_n) = (D(H) - 1) + 2n - 1$, the lower bound follows from Lemma 3.2, and it remains to prove the upper bound.

Let $p \in \mathbb{P}$ be an odd prime, $G = C_{n_1} \oplus \dots \oplus C_{n_r}$ a p -group, where $r = r(G)$ and $1 < n_1 | \dots | n_r$, and let (e_1, \dots, e_r) be a basis of G with $\text{ord}(e_i) = n_i$ for every $i \in [1, r]$. Then

$$D(G) = 1 + \sum_{i=1}^r (n_i - 1) \quad \text{and} \quad D(G \oplus C_n) = n + \sum_{i=1}^r (n_i - 1).$$

Assume, on the contrary, that there exists a sequence $S = g_1 \cdot \dots \cdot g_l \in \mathcal{F}(G)$ of length $|S| = l = D(G \oplus C_n) + n$, which has no zero-sum subsequence of length n . Since $D(G) \leq 2n - 1$ by assumption, Lemma 4.2 implies that S has no zero-sum subsequence of length $3n$. For every $i \in [1, l]$ we set

$$g_i = a_{i,1}e_1 + \dots + a_{i,r}e_r \quad \text{with } a_{i,\rho} \in [0, n_\rho - 1] \text{ for all } \rho \in [1, r]$$

We define the polynomial

$$P = \left(\binom{\sum_{i=1}^l X_i}{n} - 2 \right) Q \prod_{\rho=1}^r R_\rho \in \mathbb{Q}[X]$$

where, for all $\rho \in [1, r]$,

$$R_\rho = \binom{\sum_{i=1}^l a_{i,\rho} X_i - 1}{n_\rho - 1} \in \mathbb{Q}[X] \quad \text{and} \quad Q = \binom{\sum_{i=1}^l X_i - 1}{n - 1} \in \mathbb{Q}[X].$$

We set $C = \{0, 1\}^l \subset \mathbb{Q}^l$ and start with the following assertion.

ASSERTION $P(C) \subset \mathbb{Z}$, $P(\mathbf{0}) \not\equiv 0 \pmod{p}$ and $P(\mathbf{c}) \equiv 0 \pmod{p}$ for all $\mathbf{c} \in C \setminus \{\mathbf{0}\}$.

Proof of the assertion. Clearly, $P(\mathbf{0}) \in \{-2, 2\}$, whence $P(\mathbf{0}) \not\equiv 0 \pmod p$ because p is odd.

Let $\mathbf{0} \neq \mathbf{c} = (c_1, \dots, c_l) \in \{0, 1\}^l \subset \mathbb{Q}^l$. We have to show that $P(\mathbf{c}) \equiv 0 \pmod p$. We need the following two facts on binomial coefficients. Let $k, m \in \mathbb{N}$.

$$(F1) \text{ If } p^k \nmid m, \text{ then } \binom{m-1}{p^k-1} \equiv 0 \pmod p.$$

$$(F2) \binom{mn}{n} \equiv m \pmod p.$$

We consider the sequence

$$S_{\mathbf{c}} = \prod_{i=1}^l g_i^{c_i} \in \mathcal{F}(G).$$

Clearly, $S_{\mathbf{c}}$ is a subsequence of S of length $|\mathbf{c}| = c_1 + \dots + c_l \leq l$. We distinguish two cases.

Case 1. $S_{\mathbf{c}}$ is not a zero-sum sequence. Then there exists some $\rho \in [1, r]$ such that

$$\sum_{\substack{i=1 \\ c_i=1}}^l a_{i,\rho} \not\equiv 0 \pmod{n_{\rho}}.$$

Then (F1) implies that $R_{\rho}(\mathbf{c}) \equiv 0 \pmod p$, whence $P(\mathbf{c}) \equiv 0 \pmod p$.

Case 2. $S_{\mathbf{c}}$ is a zero-sum sequence. If $|S_{\mathbf{c}}|$ is not divisible by n , then (F1) implies that $Q(\mathbf{c}) \equiv 0 \pmod p$ whence $P(\mathbf{c}) \equiv 0 \pmod p$. Suppose that $|S_{\mathbf{c}}|$ is divisible by n . Then, by assumption, we have $|S_{\mathbf{c}}| = 2n$, whence (F2) and the first factor of P imply that $P(\mathbf{c}) \equiv 0 \pmod p$. Thus the proof of the assertion is complete.

Now we use Lemma 4.3 with $R = \mathbb{Q}$ and with θ and M as defined there.

Let $P_0 \in \mathbb{Q}[X]$ be the polynomial arising from P after replacing the powers X_i^k by X_i for all $i \in [1, l]$ and all $k \in \mathbb{N}$. Then, $P_0 \in M$, $\deg(P_0) \leq \deg(P)$ and $P(\mathbf{c}) = P_0(\mathbf{c})$ for all $\mathbf{c} \in C$.

For every $\mathbf{c} = (c_1, \dots, c_l) \in C$ we define

$$\chi_{\mathbf{c}} = \prod_{\substack{i=1 \\ c_i=1}}^l X_i \prod_{\substack{i=1 \\ c_i=0}}^l (1 - X_i) \in M \subset \mathbb{Q}[X]$$

and

$$\tilde{P}_0 = \sum_{\mathbf{c} \in C} P_0(\mathbf{c}) \chi_{\mathbf{c}} \in M \subset \mathbb{Q}[X].$$

Then $\theta(\chi_{\mathbf{c}}): C \rightarrow \mathbb{Q}$ is the characteristic function of \mathbf{c} , and we have $\theta(\tilde{P}_0)(\mathbf{c}) = \theta(P_0)(\mathbf{c})$ for all $\mathbf{c} \in C$. Therefore, by Lemma 4.3, we get $\tilde{P}_0 = P_0$. The assertion implies that the coefficient of $\prod_{i=1}^l X_i$ in \tilde{P}_0 and the coefficient of $\prod_{i=1}^l X_i$ in $P_0(\mathbf{0})\chi_{\mathbf{0}}$ are both integers which are congruent modulo p but not divisible by p . In particular, the coefficient of $\prod_{i=1}^l X_i$ in \tilde{P}_0 is non-zero, whence

$\deg(\tilde{P}_0) = l$, and we get

$$\begin{aligned} l &= \deg(\tilde{P}_0) = \deg(P_0) \leq \deg(P) \\ &\leq n + \deg(Q) + \sum_{\rho=1}^r \deg(R_\rho) \leq 2n - 1 + \sum_{\rho=1}^r (n_\rho - 1) \\ &= \mathbf{D}(G \oplus C_n) + n - 1 < l, \end{aligned}$$

a contradiction.

We end this section with a series of corollaries. Among others, they provide some special types of groups for which the lower bounds derived in section 3 and the upper bounds of this section give the precise values of $\eta(G)$ and $\mathbf{s}(G)$. The first corollary generalizes [34, Satz 1].

COROLLARY 4.4 *Let $G = C_{2^{k_1}} \oplus C_{2^k}^{r-1}$, where $k, r \in \mathbb{N}$, $r \geq 2$ and $k_1 \in [1, k]$. Then*

$$\eta(G) + 2^k - 1 = \mathbf{s}(G) = 2^{r-1}(2^{k_1} + 2^k - 2) + 1.$$

Proof. For every $i \in [1, r]$, we have $\mathbf{s}(C_2^i) = 2^i + 1 = c_i(2 - 1) + 1$ with $c_i = 2^i$ (this can be seen directly from the definition or [32, Corollary 5.7.6]). Thus Theorem 1.4 implies that

$$\begin{aligned} \mathbf{s}(G) &\leq (2^r - 2^{r-1})2^{k_1} + \sum_{i=2}^{r-1} (2^{r+1-i} - 2^{r-i})2^k + 2 \cdot 2^k - 2^r + 1 \\ &= 2^{r-1}2^{k_1} + 2^k 2^{r-1} - 2^r + 1 \\ &= 2^{r-1}(2^{k_1} + 2^k - 2) + 1. \end{aligned}$$

On the other hand, Proposition 3.1(3) (with $G = C_{2^{k_1}}$ and $C_n^k = C_{2^k}^{r-1}$) implies that

$$1 + 2^{r-1}(2^k - 1 + 2^{k_1} - 1) \leq \eta(G) + 2^k - 1,$$

whence the assertion follows from Lemma 2.3(1).

COROLLARY 4.5 *Let $P \subset \mathbb{P}$ be a non-empty set of odd primes and let $n \in \mathbb{N}$ be a product of prime powers with primes from P .*

- (1) *If $\mathbf{s}(C_p^3) = 9p - 8$ for all $p \in P$, then $8n - 7 = \eta(C_n^3) = \mathbf{s}(C_n^3) - n + 1$.*
- (2) *If $\mathbf{s}(C_p^4) = 20p - 19$ for all $p \in P$, then $19n - 18 = \eta(C_n^4) = \mathbf{s}(C_n^4) - n + 1$.*
- (3) *Let $r, c_r \in \mathbb{N}$ and let m be a power of 2. If $\mathbf{s}(C_p^r) \leq c_r(p - 1) + 1$ for all $p \in P$, then $\mathbf{s}(C_{mn}^r) \leq 2^r(m - 1)n + c_r(n - 1) + 1$.*

Proof. (1) By Lemma 3.4 and Lemma 2.3(1) we have

$$8n - 7 \leq \eta(C_n^3) \leq \mathbf{s}(C_n^3) - n + 1.$$

On the other hand, Theorem 1.4 (with $r = 3$ and $c_r = 9$) implies that $\mathbf{s}(C_n^3) \leq 9n - 8$.

(2) By Theorem 1.3 and Lemma 2.3(1), we have

$$19n - 18 \leq \eta(C_n^4) \leq \mathfrak{s}(C_n^4) - n + 1.$$

On the other hand, Theorem 1.4 (with $r = 4$ and $c_r = 20$) implies that $\mathfrak{s}(C_n^4) \leq 20n - 19$.

(3) We set $G = C_{mn}^r$ and $H = nG \cong C_m^r$, whence $G/H \cong C_n^r$. Since $\mathfrak{s}(C_p) \leq \mathfrak{s}(C_p^2) \leq \dots \leq \mathfrak{s}(C_p^r) \leq c_r(p-1) + 1$, Theorem 1.4 implies that $\mathfrak{s}(G/H) \leq c_r(n-1) + 1$, and Corollary 4.4 implies that $\mathfrak{s}(H) = 2^r(m-1) + 1$. Using Lemma 4.1 we infer that

$$\begin{aligned} \mathfrak{s}(G) &\leq (\mathfrak{s}(H) - 1) \exp\left(\frac{G}{H}\right) + \mathfrak{s}\left(\frac{G}{H}\right) \\ &= 2^r(m-1)n + c_r(n-1) + 1. \end{aligned}$$

COROLLARY 4.6 *Let $G = C_{n_1} \oplus C_{n_2} \oplus C_{n_3}$, where $1 < n_1 | n_2 | n_3$, and let $P \subset \mathbb{P}$ denote the set of primes dividing n_3 .*

(1) *If $\mathfrak{s}(C_p^3) \leq 9p - 8$ for all $p \in P$, then $\mathfrak{s}(G) \leq 5n_1 + 2n_2 + 2n_3 - 8$. If $n_2 = n_3$, then $4n_1 + 4n_3 - 7 \leq \mathfrak{s}(G)$.*

(2) *If G is a 2-group, then $\mathfrak{s}(G) \leq 4n_1 + 2n_2 + 2n_3 - 7$, and equality holds if $n_2 = n_3$.*

Proof. For every prime p , we have $\mathfrak{s}(C_p) = 2p - 1$ and $\mathfrak{s}(C_p^2) = 4p - 3$ by Theorem 1.1. Corollary 4.4 shows that $\mathfrak{s}(C_2^3) = 8(2 - 1) + 1$. Thus Theorem 1.4 implies the upper bounds. The lower bound in (1) follows from Proposition 3.1(3) (with $k = 2$ and $n = n_3$). If G is a 2-group and $n_2 = n_3$, then Corollary 4.4 implies equality in (2).

REMARKS 4.7 (1) For $r \in \{3, 4, 5\}$, the precise values of $\mathfrak{s}(C_3^r)$ and $\mathfrak{g}(C_3^r)$ (see the discussion after Lemma 2.3) were found (independently) by many authors (see the historical remarks after Lemma 5.2). We have $\mathfrak{s}(C_3^3) = 19$, $\mathfrak{s}(C_3^4) = 41$ and $\mathfrak{s}(C_3^5) = 91$, whence $P = \{3\}$ satisfies both assumptions in Corollary 4.5 and $P = \{2, 3\}$ satisfies the assumption in Corollary 4.6(1). Note that the sequence $(2, 4, 9, 20, 45) = (\mathfrak{g}(C_3) - 1, \dots, \mathfrak{g}(C_3^5) - 1)$ has number A090245 in the On-Line Encyclopedia of Integer Sequences [60].

(2) Applying Corollary 4.5(3) (with $P = \{3\}$, $r = 3$, $m = 2$, $c_3 = 9$) and Proposition 3.1, we obtain $41 \leq \mathfrak{s}(C_6^3) \leq 43$. Thus if the group C_6^3 has Property D, then $\mathfrak{s}(C_6^3) = 41$.

(3) In general, neither the upper bound in Theorem 1.4 nor the upper bound in Corollary 4.6(1) are sharp. Indeed, for certain groups, the upper bound from Theorem 1.5(2) is smaller than the upper bound from Corollary 4.6(1).

5. On a geometric aspect of invariant $\mathfrak{s}(G)$

It seems conceivable that all phenomena controlling invariant $\mathfrak{s}(C_n^r)$, for $n \geq 3$ odd and $r \in \mathbb{N}$, already occur in the special case where $n = 3$ (see the discussion after Lemma 5.4 and note that in all situations known so far we have

$$\mathfrak{s}(C_n^r) = \frac{\mathfrak{s}(C_3^r) - 1}{2}(n - 1) + 1.$$

But the problem to determine $\mathfrak{s}(C_3^r)$ is equivalent to the (well-investigated) problem of maximal caps in affine geometry (see Lemma 5.2 and the subsequent remarks). Even though this relationship

may have been implicitly known, we hope that the discussion below gives directions for future research.

We start with some elementary facts from finite geometry. For a short introduction and collection of basic properties of finite geometries, we refer to [48, Appendix B] and for more material to [39]. A recent survey on extremal problems in finite geometry is given in [40].

Let q be a prime power and $r \in \mathbb{N}$. Recall that the s -dimensional subspaces of a projective space $\text{PG}(r, q)$ can be identified with the $(s + 1)$ -dimensional subspaces of the vector space \mathbb{F}_q^{r+1} . The incidence in the projective geometry is defined by the inclusion of the corresponding vector spaces. The zero-dimensional subspaces of a projective space $\text{PG}(r, q)$ are called the *points*, so $\text{PG}(r, q)$ has $q^r + q^{r-1} + \dots + q + 1$ points. The one-dimensional subspaces are called the *lines* and the $(r - 1)$ -dimensional subspaces are called the *hyperplanes*. The points of a set $S \subset \text{PG}(r, q)$ are called *collinear* if there is a line L such that $S \subset L$.

One of the hyperplanes of $\text{PG}(r, q)$ can be thought of as the hyperplane at infinity. The complement of this hyperplane in $\text{PG}(r, q)$ is the affine geometry $\text{AG}(r, q)$ which consists of q^r points. These points can be thought of as lying on q parallel hyperplanes of q^{r-1} points. As the automorphism group of $\text{PG}(r, q)$, $\text{PGL}(r, q)$, operates transitively on the hyperplanes, we can assume without loss of generality that the hyperplane at infinity is the hyperplane $x_{r+1} = 0$. So, we can always choose this standard embedding of $\text{AG}(r, q)$, that is, the points $(x : 1)$ in $\text{PG}(r, q)$.

So, one can also think of $\text{AG}(r, q)$ as \mathbb{F}_q^r , since the point $(x : 1)$ is uniquely determined by $x \in \mathbb{F}_q^r$. It is also convenient to call x itself a point of $\text{AG}(r, q)$. The geometric structure of $\text{AG}(r, q)$ is induced from $\text{PG}(r, q)$ by restriction. A line in the projective space has $q + 1$ points, and a line in the affine space has q points. One of the classic objects of interest in finite geometry consists of caps.

- DEFINITION 5.1 (1) An m -cap $C \subset \text{PG}(r, q)$ is a set of $|C| = m$ points, three of which are not collinear.
- (2) An m -cap in $\text{PG}(r, q)$ is called *maximal* if there exists no $m + 1$ -cap in $\text{PG}(r, q)$.
- (3) A cap $C \subset \text{PG}(r, q)$ is called *affine* if there is a hyperplane H such that $C \cap H = \emptyset$.
- (4) An m -cap in $\text{PG}(r, q)$ is called *maximal affine* if there exists no affine $m + 1$ -cap in $\text{PG}(r, q)$.

LEMMA 5.2 Let $G = \mathbb{F}_3^r$ with $r \in \mathbb{N}$.

- (1) The map f , defined by $f(T) = \text{supp}(T)$, is a bijection from the set

$$\{T \in \mathcal{F}(G) \mid T \text{ is square-free and has no zero-sum subsequence of length } 3\}$$

onto the set $\{C \subset G \mid C \text{ is a cap}\}$.

- (2) The maximal size of a cap in $\text{AG}(r, 3)$ is $\mathfrak{g}(G) - 1$.
- (3) $\mathfrak{s}(G) = 2\mathfrak{g}(G) - 1$, and every sequence $S \in \mathcal{F}(G)$ of length $|S| = \mathfrak{s}(G) - 1$, which has no zero-sum subsequence of length 3, has the form $S = T^2$, where $\text{supp}(T)$ is a maximal cap in G . Conversely, if $T \in \mathcal{F}(G)$ is square free and has no zero-sum subsequence of length 3, then T^2 has no zero-sum subsequence of length 3.

Proof. We identify G with the affine space $\text{AG}(r, 3) \subset \text{PG}(r, 3)$.

- (1) Three different points, $(x : 1), (y : 1), (z : 1) \in \text{AG}(r, 3)$, are not on a line if and only if the vectors $(x, 1), (y, 1), (z, 1) \in \mathbb{F}_3^{r+1}$ are linearly independent, that is, if there is no non-trivial linear combination $\lambda x + \mu y + \nu z = 0$ with $\lambda + \mu + \nu = 0$. The only possible coefficients $\{\lambda, \mu, \nu\}$ are $\{1, 1, 1\}, \{2, 2, 2\}$ or permutations of $\{0, 1, 2\}$. The case $\{0, 1, 2\}$ is impossible,

as it would imply that two points are equal. An affine relation with respect to coefficients $\{2, 2, 2\}$ is equivalent to the relation with respect to $\{1, 1, 1\}$ by a scalar multiplication. So, three different points are not on a line if and only if the corresponding sequence has no zero-sum of length 3.

(2) This follows from (1).

(3) In [34, Hilfssatz 3] it is proved that $\mathfrak{s}(G) = 2\mathfrak{g}(G) - 1$. Therefore, Lemma 2.3(3) implies that G has Property D, whence the first assertion follows from (1). Let $T \in \mathcal{F}(G)$ be a square-free sequence without a zero-sum subsequence of length 3. Assume, on the contrary, that T^2 has a zero-sum subsequence S' of length 3. Since S' is not a subsequence of T , we have $S' = h^2h'$ for some $h, h' \in G$. But then $2h + h' = 0$ implies that $h = h'$, a contradiction.

Let us briefly discuss some further connections to related problems. As Lemma 5.2 already shows, the same type of problem has been studied in various different parts of mathematics, such as number theory, combinatorics and finite geometry.

(1) A sequence $g_1 \dots g_l \in \mathcal{F}(\mathbb{F}_p^r)$ is called an arithmetic progression of length l if there exist $a, b \in \mathbb{F}_p^r$ such that $g_i = a + ib$ for all $i \in [0, l - 1]$. The problem of studying sets without arithmetic progressions in \mathbb{F}_p^r has been studied, for example, by Green [33] and Lev [47].

In analogy to Lemma 5.2, one can state that the map f , defined by $f(T) = \text{supp}(T)$, is a bijection from the set

$$\{T \in \mathcal{F}(G) \mid T \text{ is square-free and has no zero-sum subsequence of length 3}\}$$

onto the set $\{C \subset G \mid C \text{ does not contain an arithmetic progression of length 3}\}$. Thus $\mathfrak{g}(G) - 1$ is the maximal size of a set in G without an arithmetic progression of length 3.

This follows from Lemma 5.2(1) by observing that the three points in \mathbb{F}_3^r define an arithmetic progression of length 3 if and only if they are collinear.

The problem of sets without progressions in \mathbb{F}_3^r is closely connected to the famous Erdős–Turán problem on sets of integers without arithmetic progressions. Using harmonic analysis, Roth [58] was the first to show that the maximal cardinality, $r_3(n)$, of sets without a progression of length 3 in $[1, n]$ is $r_3(n) = O(n/\log \log n)$. Further progress was due to Heath-Brown [35], Szemerédi [62] and Bourgain [8], leading to $r_3(n) = O(n(\log \log n)^{1/2}/(\log n)^{1/2})$.

As Green [33] shows, all four proofs can be adapted to give an upper bound of $O(3^r/r)$ for the cardinality of maximal sets in \mathbb{F}_3^r without an arithmetic progression of length 3. This bound was first proved by Meshulam [49], based on Roth's method; for precursors, see [10, 21, 22] and for a generalization see [47]. Explicit bounds on $\mathfrak{g}(C_3^r)$ are given below.

(2) Davis and Maclagan [13] wrote an interesting paper on the card game SET, which carefully explains the connections between this card game and affine caps. In short, cards have several properties such as colour and symbol. A 'SET' is a set of three cards in which these properties are either the same (like the same colour three times) or all different (like three different colours). This corresponds to an arithmetic progression of length three or three collinear points. Since this card game is very popular, a growing number of manuscripts have appeared on the Internet, rediscovering results that are equivalent to the values of $\mathfrak{g}(C_3^3) = 10$ or $\mathfrak{g}(C_3^4) = 21$; here, we only mention the computer programme by Knuth [43].

(3) The problem of finding lattice points with no three collinear has an interesting application to graph drawings. Given a finite simple graph G , a drawing of G represents each vertex by an integer gridpoint in \mathbb{Z}^3 , in which the edges are drawn as straight line segments between the adjacent vertices. Edges are not allowed to pass through other vertices. The interest is in drawings with minimal volume of the bounding box of the vertices. The connection to the problem of no three collinear points follows from the observation that a set $V \subset \mathbb{Z}^3$ of n points induces a drawing of the complete graph K_n if and only if no three points of V are collinear; for more details, see Pór and Wood [55]. Also, their open Problem 3 on $\text{vol}(n, d, 1)$ is a question on dense d -dimensional point configurations without three points on a line, and their comment that this problem is trivial for $d \geq \log_2 n$ follows from the trivial cap consisting of 2^d points with coordinates 0 and 1 only.

We now describe the connection to caps in more detail and discuss explicit bounds on $\mathfrak{g}(C_3^r)$.

The determination of the maximal size of caps in projective geometry $\text{PG}(r, q)$ or affine geometry $\text{AG}(r, q)$, as well as their complete characterization, appears to be a difficult problem. Few exact results are known. We refer to [5, 40] for known results and here only summarize some details we need for caps in $\text{AG}(r, 3)$.

Let q be an odd prime power. In $\text{PG}(2, q)$ there are $(q + 1)$ -caps, the ovals, known to be maximal [7]. An oval avoids several hyperplanes, so the maximal size of a cap in $\text{AG}(2, 3)$ is 4. In $\text{PG}(3, q)$ there is a unique maximal $(q^2 + 1)$ -cap, the ovoid; see [3, 7, 52]. The ovoid contains an affine q^2 -cap. As every q^2 -cap in $\text{PG}(3, q)$ can be embedded in the unique $(q^2 + 1)$ -cap [20] and as the automorphism group of the ovoid is transitive, the affine q^2 -cap is also projectively unique. In $\text{PG}(4, 3)$ there exist exactly nine types of maximal 20-caps, and one of these is affine [38, 53].

The values $\mathfrak{s}(C_3^3) = 19$, $\mathfrak{g}(C_3^3) = 10$, $\mathfrak{s}(C_3^4) = 41$ and $\mathfrak{g}(C_3^4) = 21$ have been rediscovered several times. It appears that they were first found by finite geometers. Bose [7] found the size of the maximal affine caps in dimension 3, and uniqueness was proved by Barlotti [3] and Panella [52]. In $\text{AG}(4, 3)$ the existence and the maximality of a cap of size 20 were proved by Pellegrino [53], and uniqueness was proved by Hill [38]. The size of the unique maximal cap in $\text{AG}(5, 3)$ is 45, as proved by Edel *et al.* [16]. In $\text{AG}(6, 3)$, a 112-cap can be constructed by applying the elementary doubling construction due to Mukhopadhyay [50] to the 56 points of the Hill cap in $\text{PG}(5, 3)$ [36, 37]. The size of a cap in $\text{AG}(6, 3)$ can be at most 114 [6]. Frankl *et al.* [21] connected the problem of no three points in arithmetic progression in \mathbb{F}_3^r to sunflowers and proved, on the basis of a construction in $r = 18$, that there are affine caps in $\text{AG}(3, r)$ of size at least $2 \cdot 179^r$, for sufficiently large r .

In the combinatorics community, the problem of determining invariants $\mathfrak{s}(C_n^r)$ and $\mathfrak{g}(C_n^r)$ was posed and popularized by Harborth and Kemnitz. Harborth verified that $\mathfrak{s}(C_3^3) = 19$, and Kemnitz proved that $\mathfrak{s}(C_3^4) = 41$ [9, 10, 34, 41, 42, 63].

For larger r , lower bounds for the size of an affine cap in $\text{AG}(r, 3)$, that is, bounds for $\mathfrak{g}(C_3^r) - 1$, can be obtained from projective caps by choosing a hyperplane (which will be the hyperplane at infinity of the affine cap) and deleting all points of the projective cap in this hyperplane.

The lower bounds for $r \leq 12$ in the following table are obtained by choosing a hyperplane that contains the minimal number of points of the projective caps found at [14]. The bounds for $r = 62$ and $r = 480$ are constructed in [15]. The latter shows that there are affine caps in $\text{AG}(3, r)$ of size at least $2 \cdot 217389^r$, for sufficiently large r .

For the upper bounds, we recursively use Lemma 5.3, which is an adaptation of [6, Theorem 2] (see also [49]) to our situation. The upper bounds in the table are obtained by starting with the maximal cap in $\text{AG}(5, 3)$, that is, with $\mathfrak{g}(C_3^5) - 1 = 45$ [16].

LEMMA 5.3 *If $r \geq 3$, then*

$$\begin{aligned}
 (\mathbf{g}(C_3^r) - 1) &\leq 3^r \frac{3(\mathbf{g}(C_3^{r-1}) - 1) + 1}{3(\mathbf{g}(C_3^{r-1}) - 1) + 3^r}, \\
 236 &\leq \mathbf{g}(C_3^7) - 1 \leq 296, \\
 476 &\leq \mathbf{g}(C_3^8) - 1 \leq 783, \\
 1068 &\leq \mathbf{g}(C_3^9) - 1 \leq 2099, \\
 2228 &\leq \mathbf{g}(C_3^{10}) - 1 \leq 5691, \\
 5232 &\leq \mathbf{g}(C_3^{11}) - 1 \leq 15573, \\
 10848 &\leq \mathbf{g}(C_3^{12}) - 1 \leq 42944, \\
 2.57342 \times 10^{21} &\sim 2^{41} 7^9 29 \leq \mathbf{g}(C_3^{62}) - 1 \leq 6.11654 \times 10^{27}, \\
 1.0095 \times 10^{166} &\sim 32^{80} + 8^5 \binom{10}{5} 112^{75} 12^5 \leq \mathbf{g}(C_3^{480}) - 1 \leq 2.17081 \times 10^{226}.
 \end{aligned}$$

The upper bound coming from Lemma 5.3 tends to $3^r/r$, as r tends to infinity. Note that Meshulam [49] states this bound with an extra factor of 2.

LEMMA 5.4 *For $r \in \{3, 4, 5\}$, the maximal affine cap in $\text{AG}(r, 3)$ is unique up to affine transformation (which means that every maximal cap can be written as $MC + a$, where C is a fixed example of the maximal cap, M is a non-singular $r \times r$ matrix over \mathbb{F}_3 and $a \in \mathbb{F}_3^r$).*

Proof. In the preceding discussion we have seen that the caps in question are projectively unique. These caps avoid only one hyperplane (easily verified by a computer). As there is only one hyperplane avoided, a projective homomorphism fixing the cap must also fix this hyperplane.

This hyperplane must be the ‘hyperplane at infinity’ that defines the embedding of the affine geometry into the projective geometry. As was motivated in the introduction, we can use the standard embedding of $\text{AG}(r, 3)$ (that is, all points are of the form $(x : 1)$ in $\text{PG}(r, 3)$).

A projective homomorphism fixing the hyperplane at infinity, $x_{r+1} = 0$, must be equivalent to a multiplication with a matrix of the form

$$\begin{pmatrix} M & a \\ 0 & 1 \end{pmatrix},$$

with M a non-singular $r \times r$ matrix over \mathbb{F}_3 and $a \in \mathbb{F}_3^r$, that is, be an affine transformation.

In the remainder of this section we discuss some geometric aspects of the sequence constructed in [17] and that given in Theorem 1.3 (we use the notation introduced before Lemma 3.3). If $n \geq 3$ is odd and

$$T = \begin{pmatrix} 2 \\ 1 \\ 2 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 1 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 2 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 2 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix},$$

then the sequence $T^{n-1} \in \mathcal{F}(C_n^3)$ has no zero-sum subsequence of length n . This was first proved in [17] for all odd $n \geq 3$. The case $n = 3$ was studied in [34, proof of Satz 4]. In that case, the underlying

set $\text{supp}(T)$ is a cap in $\text{AG}(3, 3)$ and hence unique up to affine transformation (see Lemma 5.2(1) and Lemma 5.4). A computer-based search produced six further square-free sequences T_1, \dots, T_6 with the following properties: in the case $n = 3$, all underlying sets are representations of the cap in $\text{AG}(3, 3)$ and for all odd $n \geq 3$, sequences $T_1^{n-1}, \dots, T_6^{n-1}$ have no zero-sum subsequence of length n :

$$T_1 = \begin{pmatrix} 2 \\ 0 \\ 2 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix} \begin{pmatrix} 2 \\ 2 \\ 1 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \begin{pmatrix} 2 \\ 1 \\ 1 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 2 \end{pmatrix} \begin{pmatrix} 2 \\ 1 \\ 2 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix},$$

$$T_2 = \begin{pmatrix} 2 \\ 1 \\ 2 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 1 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix} \begin{pmatrix} 2 \\ 1 \\ 1 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \begin{pmatrix} 2 \\ 0 \\ 1 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 2 \end{pmatrix} \begin{pmatrix} 2 \\ 2 \\ 2 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix},$$

$$T_3 = \begin{pmatrix} 1 \\ 1 \\ 2 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \begin{pmatrix} 2 \\ 1 \\ 0 \end{pmatrix} \begin{pmatrix} 2 \\ 1 \\ 1 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 1 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \\ 2 \end{pmatrix} \begin{pmatrix} 2 \\ 2 \\ 2 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix},$$

$$T_4 = \begin{pmatrix} 1 \\ 1 \\ 2 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 1 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \begin{pmatrix} 2 \\ 0 \\ 1 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \\ 2 \end{pmatrix} \begin{pmatrix} 0 \\ 2 \\ 2 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix},$$

$$T_5 = \begin{pmatrix} 2 \\ 0 \\ 2 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \begin{pmatrix} 0 \\ 2 \\ 1 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 2 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 2 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix},$$

$$T_6 = \begin{pmatrix} 2 \\ 1 \\ 1 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 2 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 2 \end{pmatrix} \begin{pmatrix} 2 \\ 0 \\ 0 \end{pmatrix} \begin{pmatrix} 2 \\ 0 \\ 2 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix} \begin{pmatrix} 1 \\ 2 \\ 1 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}.$$

Of these seven examples, the sequence T is distinguished by being the only one with the canonical affine basis (containing $0, e_1, e_2, e_3$) and moreover is one of those sequences with a minimal sum of entries.

We now come back to the example in C_n^4 . Consider the support

$$S(n) = \text{supp}(T(n)) \subset (\mathbb{Z}/n\mathbb{Z})^4, \text{ where } n \geq 3 \text{ is odd,}$$

of the square-free sequence given in the proof of Theorem 1.3.

By Lemma 5.2(1), $S(3)$ is a cap in $\text{AG}(4, 3)$, and by Lemma 5.4, it is unique up to affine transformation. However, there are representations \mathbb{T} of $S(3)$ such that sequence $S = T^{n-1}$ (now considered as a sequence in C_n^r), with $\text{supp}(T) = \mathbb{T}$, has a zero-sum subsequence of length n . For example,

by [13] the set

$$\left\{ \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}, \begin{pmatrix} 2 \\ 0 \\ 0 \\ 0 \end{pmatrix}, \begin{pmatrix} 0 \\ 2 \\ 0 \\ 0 \end{pmatrix}, \begin{pmatrix} 2 \\ 2 \\ 0 \\ 0 \end{pmatrix}, \begin{pmatrix} 1 \\ 0 \\ 2 \\ 0 \end{pmatrix}, \begin{pmatrix} 0 \\ 1 \\ 2 \\ 0 \end{pmatrix}, \begin{pmatrix} 1 \\ 2 \\ 2 \\ 0 \end{pmatrix}, \begin{pmatrix} 2 \\ 1 \\ 2 \\ 0 \end{pmatrix}, \begin{pmatrix} 1 \\ 1 \\ 1 \\ 0 \end{pmatrix}, \begin{pmatrix} 1 \\ 1 \\ 0 \\ 1 \end{pmatrix}, \right. \\ \left. \begin{pmatrix} 0 \\ 0 \\ 2 \\ 2 \end{pmatrix}, \begin{pmatrix} 2 \\ 0 \\ 2 \\ 2 \end{pmatrix}, \begin{pmatrix} 0 \\ 2 \\ 2 \\ 2 \end{pmatrix}, \begin{pmatrix} 2 \\ 2 \\ 2 \\ 2 \end{pmatrix}, \begin{pmatrix} 1 \\ 0 \\ 0 \\ 2 \end{pmatrix}, \begin{pmatrix} 0 \\ 1 \\ 0 \\ 2 \end{pmatrix}, \begin{pmatrix} 1 \\ 2 \\ 0 \\ 2 \end{pmatrix}, \begin{pmatrix} 2 \\ 1 \\ 0 \\ 2 \end{pmatrix}, \begin{pmatrix} 1 \\ 1 \\ 1 \\ 2 \end{pmatrix}, \begin{pmatrix} 1 \\ 1 \\ 2 \\ 1 \end{pmatrix} \right\}$$

is a representation of the cap $S(3)$. For every odd $n > 3$, the sequence S consisting of $n - 1$ copies of any of the above points has the zero-sum subsequence S' of length n , where

$$S' = \begin{pmatrix} 1 \\ 0 \\ 2 \\ 0 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 1 \\ 0 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 0 \\ 1 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \\ 0 \\ 2 \end{pmatrix} \begin{pmatrix} 2 \\ 2 \\ 2 \\ 2 \end{pmatrix}^{(n-3)/2} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}^{(n-5)/2}.$$

Actually, using a computer, we tried many representations of the cap $S(3)$, but we did not find any that have no zero sums of length n modulo other odd integers n and use the entries 0, 1, 2 only. As the proof of Theorem 1.3 shows, the example can be thought of as two twisted copies of caps in $AG(3, 3)$ and two further points. The example we found may be one of the easiest, since it uses only four entries, 0, 1, 2, 3, with only two 3s, and because of the symmetry discussed in the proof of Theorem 1.3 and in what follows.

Finally, we study the automorphism group of the set $S(n)$ (that is, the group of all affine transformations $f : (\mathbb{Z}/n\mathbb{Z})^4 \rightarrow (\mathbb{Z}/n\mathbb{Z})^4$ with $f(S(n)) = S(n)$). It is hoped that the study of the automorphism group helps to construct maximal caps in $AG(r, q)$ for $r > 4$.

The following automorphisms are easy to spot:

$$\begin{aligned} S(n) &\longmapsto S(n), \\ (a, b, c, d) &\longmapsto (b, a, c, d), \\ (a, b, c, d) &\longmapsto (a, b, d, c), \\ (a, b, c, d) &\longmapsto (3, 3, 2, 2) - (a, b, c, d). \end{aligned}$$

Combinations of these already generate up to eight points for one given point (a, b, c, d) . A complete computer-based search revealed that the full automorphism group of $S(5) \subset \mathbb{F}_3^4$ and

$S(7) \subset \mathbb{F}_7^4$ has 96 elements. The maps

$$\begin{aligned}
 g_1 &: (a, b, c, d) \mapsto (0, 0, 2, 2) + (b, a, -c, -d), \\
 g_2 &: (a, b, c, d) \mapsto (3, 3, 2, 2) - (a, b, c, d), \\
 g_3 &: (a, b, c, d) \mapsto (f, f, f, f + 2) - (d, c, b, d + c + b), \\
 &\text{with } f := \frac{(a + b + c + d)(n + 1)}{2} \\
 g_4 &: (a, b, c, d) \mapsto (0, 0, 2, 0) + (a, b, -d, c)
 \end{aligned}$$

fix the set $S(n)$, as can be seen by explicit verification. The map g_1 as well as g_2 is of order 2 and commutes with all other maps. The maps g_3 and g_4 are of orders 3 and 4, respectively. The maps g_3 and g_4 generate a group of order 24 without a centre and with more than two elements of order 3. Thus, $\langle g_3, g_4 \rangle$ is a group which is isomorphic to the symmetric group S_4 [46, Lemma 4.3.4]. Therefore, the automorphism group of $S(n)$ must contain group $C_2 \oplus C_2 \oplus S_4$ as a subgroup. It is well known that in the case $n = 3$, the full automorphism group has order 2880. For $n \in \{5, 7\}$, a computer search shows that $G = C_2 \oplus C_2 \oplus S_4$ is the full automorphism group, and we do not expect any further automorphisms for $n > 7$. Under the group action of $\langle g_1, g_2, g_3, g_4 \rangle$, the set $S(n)$ is split into two orbits, which are given in Lemma 5.5.

LEMMA 5.5 *Let $n \geq 3$ be odd.*

- (1) *The group $G(n) = \langle g_1, g_2, g_3, g_4 \rangle$ is isomorphic to $C_2 \oplus C_2 \oplus S_4$. $G(n)$ is a subgroup of the automorphism group of $S(n)$, and for $n \in \{5, 7\}$ it is the full automorphism group.*
- (2) *Under the group action of $G(n)$, the set $S(n)$ is split into two orbits of lengths 12 (the first 12 below) and 8 (the last 8), respectively.*

$$\begin{pmatrix} 1 \\ 1 \\ 0 \\ 0 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 0 \\ 2 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 2 \\ 0 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 2 \\ 2 \end{pmatrix} \begin{pmatrix} 2 \\ 2 \\ 0 \\ 0 \end{pmatrix} \begin{pmatrix} 2 \\ 2 \\ 0 \\ 2 \end{pmatrix} \begin{pmatrix} 2 \\ 2 \\ 2 \\ 0 \end{pmatrix} \begin{pmatrix} 2 \\ 2 \\ 2 \\ 2 \end{pmatrix} \begin{pmatrix} 1 \\ 3 \\ 1 \\ 1 \end{pmatrix} \begin{pmatrix} 3 \\ 1 \\ 1 \\ 1 \end{pmatrix} \begin{pmatrix} 0 \\ 2 \\ 1 \\ 1 \end{pmatrix} \begin{pmatrix} 2 \\ 0 \\ 1 \\ 1 \end{pmatrix} \\
 \begin{pmatrix} 1 \\ 2 \\ 0 \\ 1 \end{pmatrix} \begin{pmatrix} 1 \\ 2 \\ 1 \\ 0 \end{pmatrix} \begin{pmatrix} 1 \\ 2 \\ 1 \\ 2 \end{pmatrix} \begin{pmatrix} 1 \\ 2 \\ 2 \\ 1 \end{pmatrix} \begin{pmatrix} 2 \\ 1 \\ 0 \\ 1 \end{pmatrix} \begin{pmatrix} 2 \\ 1 \\ 1 \\ 0 \end{pmatrix} \begin{pmatrix} 2 \\ 1 \\ 1 \\ 2 \end{pmatrix} \begin{pmatrix} 2 \\ 1 \\ 2 \\ 1 \end{pmatrix}$$

Proof. Point (1) has been outlined above and point (2) can be checked by a direct computation.

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