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On bases with an exact order

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Introduction. A set A of nonnegative integers is said to be an (*asymptotic*) *basis of order* r if every sufficiently large integer can be expressed as a sum of at most r integers taken from A (where repetition is allowed) and r is the least integer with this property. In this case we write $\operatorname{ord}(A) = r$. A basis A is said to have *exact order* s if every sufficiently large integer is the sum of *exactly* s elements taken from A (again, allowing repetition) where s is the least integer with this property. We indicate this by writing $\operatorname{ord}^*(A) = s$.

It is easy to find examples of bases A which do not have an exact order, e.g., the set of positive odd integers. Of course, if $0 \in A$ and $\operatorname{ord}(A) = r$ then $\operatorname{ord}^*(A) = r$ as well. However, it is not difficult to construct examples of bases A for which

$$\operatorname{ord}^*(A) > \operatorname{ord}(A).$$

For example, the set B defined by

$$B = \bigcup_{k=0}^{\infty} I_k$$

where

$$I_k = \{x: 2^{2k}+1 \leqslant x \leqslant 2^{2k+1}\}$$

has

$$\operatorname{ord}(B) = 2 \quad \text{and} \quad \operatorname{ord}^*(B) = 3.$$

In this note we characterize those bases A which have an exact order. It turns out that the only bases which do not have an exact order are those whose elements fail to satisfy a simple modular condition. We also estimate to within a constant factor the largest value $\operatorname{ord}^*(A)$ can attain given that $\operatorname{ord}(A) = r$. (The reader may consult [1] for a survey of results on bases.)

Bases with an exact order

THEOREM 1. *A basis $A = \{a_1, a_2, \dots\}$ has an exact order if and only if*

$$\text{g.c.d.}\{a_{k+1}-a_k\colon k = 1, 2, \dots\} = 1. \tag{$*$}$$

Proof. (Necessity). Suppose for some s that $\mathrm{ord}^*(A) = s$ and assume $(*)$ does not hold, i.e.,

$$\text{g.c.d.}\{a_{k+1}-a_k\colon k = 1, 2, \dots\} = d > 1.$$

Thus, for all k,

$$a_{k+1} \equiv a_k (\operatorname{mod} d).$$

Therefore, the sum of any s integers taken from A is always congruent to sa_1 modulo d which contradicts the assumption that $\mathrm{ord}^*(A) = s$.

(Sufficiency). Denote $\mathrm{ord}(A)$ by r and assume $(*)$ holds. Let mA denote the set

$$\{x_1+x_2+\dots+x_m\colon x_k \in A\}.$$

FACT. For some n,

$$nA \cap (n+1)A \neq \emptyset.$$

Proof of Fact. It follows from $(*)$ that for some t,

$$\text{g.c.d.}\{a_{k+1}-a_k\colon 1 \leqslant k \leqslant t\} = 1.$$

Thus, for suitable integers c_k we have

$$\sum_{k=1}^{t} c_k(a_{k+1}-a_k) = 1. \tag{1}$$

Define p_k and q_k by

$$p_k = \begin{cases} a_{k+1} & \text{if} \quad c_k \geqslant 0, \\ a_k & \text{if} \quad c_k < 0, \end{cases} \qquad q_k = \begin{cases} a_k & \text{if} \quad c_k \geqslant 0, \\ a_{k+1} & \text{if} \quad c_k < 0. \end{cases}$$

Then (1) can be rewritten as

$$\sum_{k=1}^{t} |c_k|(p_k - q_k) = 1,$$

i.e.,

$$\sum_{k=1}^{t} |c_k| p_k = 1 + \sum_{k=1}^{t} |c_k| q_k. \tag{2}$$

Now consider the integer

$$M = \sum_{k=1}^{t} |c_k| p_k q_k.$$

Since

$$M = \sum_{k=1}^{t} \sum_{i=1}^{|c_k|p_k} q_k \in \Big(\sum_{k=1}^{t} |c_k| p_k\Big) A \tag{3}$$

and also

$$M = \sum_{k=1}^{t} \sum_{j=1}^{|c_k|q_k} p_k \in \Big(\sum_{k=1}^{t} |c_k| q_k\Big) A, \tag{4}$$

the Fact follows from (2) by taking

$$n = \sum_{k=1}^{t} |c_k| q_k.$$

It follows immediately from (2), (3) and (4) that

$$2M = M + M \in 2nA \cap (2n+1)A \cap (2n+2)A$$

and, more generally, that for any $w \geqslant 1$,

$$wM \in \bigcap_{k=0}^{w} (wn+k)A. \tag{5}$$

However, by hypothesis, every sufficiently large integer x belongs to $\bigcup_{i=1}^{r} iA$. Thus, from (5) with $w = r-1$, we have

$$x + (r-1)M \in \big((r-1)n + r\big)A \tag{6}$$

for all sufficiently large x. This shows that A has an exact order and in fact, that

$$\mathrm{ord}^*(A) \leqslant (r-1)n + r.$$

This proves Theorem 1. ∎

Comparing $\mathrm{ord}(A)$ **and** $\mathrm{ord}^*(A)$. Define the function $g\colon \boldsymbol{Z}^+ \to \boldsymbol{Z}^+$ as follows:

$$g(r) = \max\{\mathrm{ord}^*(A)\colon \mathrm{ord}(A) = r \text{ and } A \text{ satisfies } (*)\}.$$

A crude analysis of the proof of Theorem 1 shows that $g(r)$ exists and, for example, $g(r) < cr^4$ for a suitable constant c. The following result sharpens this estimate considerably.

THEOREM 2. *For all r,*

$$\tfrac{1}{4}\big(1+o(1)\big)r^2 \leqslant g(r) \leqslant \tfrac{5}{4}\big(1+o(1)\big)r^2. \tag{7}$$

Proof. We first prove the upper bound. Assume $\mathrm{ord}(A) = r$. Thus, all sufficiently large x satisfy

$$x \in \bigcup_{k=1}^{r} kA. \tag{8}$$

From (8) it follows that for any t,

$$tx \in \bigcup_{k=1}^{r} tkA \tag{9}$$

for x sufficiently large.

It also follows from (8) that for some m and some c, $1 \leqslant c \leqslant r$,

$$m \in cA \cap (r+1)A. \tag{10}$$

Thus, letting

$$d = r+1-c$$

we have

$$2m \in 2cA \cap (2c+d)A \cap (2c+2d)A$$

and, more generally,

$$um \in \bigcap_{i=0}^{u} (uc+id)A, \tag{11}$$

a special case being

$$udm \in \bigcap_{i=0}^{ud} (udc+id)A. \tag{12}$$

Setting $t = d$ in (9), we obtain

$$dx \in \bigcup_{k=1}^{r} dkA \tag{13}$$

for all sufficiently large x. Therefore,

$$dx+udm \in (dr+udc)A \tag{14}$$

for all sufficiently large x provided

$$ud \geqslant r-1 \tag{15}$$

since for each $dx \in dkA$, $1 \leqslant k \leqslant r$, we also have $udm \in \big(udc+(r-k)d\big)A$. In other words, if (15) holds then all sufficiently large multiples of d belong to $(r+uc)dA$.

Our next task is to find a number $w = o(r^2)$ so that wA contains a complete residue system mod d. Let $\bar{A} = \{l_1, \ldots, l_s\}$ denote the set of distinct residues modulo d which occur in A. Since A satisfies $(*)$ by hypothesis, we can assume that a_i and l_i are labelled so that $a_i \equiv l_i \pmod{d}$ and, for some t,

$$G_1 > G_2 > \ldots > G_t = 1 \tag{16}$$

where

$$G_i \equiv \text{g.c.d.}\,\{l_2-l_1, l_3-l_2, \ldots, l_{i+1}-l_i\}.$$

Since G_{i+1} divides G_i for all i, it follows at once that

$$t \leqslant \frac{\log s}{\log 2} \leqslant \frac{\log d}{\log 2} \leqslant \frac{\log r}{\log 2}. \tag{17}$$

Thus, for any $z \pmod{d}$ there exist integers $c_k = c_k(z)$ with $0 \leqslant c_k < d$ so that

$$\sum_{k=1}^{t} c_k(l_{k+1}-l_k) \equiv \sum_{k=1}^{t} c_k(a_{k+1}-a_k) \equiv z \pmod{d}. \tag{18}$$

It follows from (18) that all residue classes modulo d are in $(t+1)dA$.

Finally, using this together with (14), we see that (provided (15) holds) all sufficiently large integers belong to $d(r+uc+t+1)A$. To satisfy (15) it is enough to take $u = \left[\dfrac{r-1}{d}\right]$.

An easy calculation (using (17)) shows that the maximum value the coefficient $d\left(r+c\left[\dfrac{r-1}{d}\right]+t+1\right)$ achieves is $\big(1+o(1)\big)r^2$. Thus,

$$g(r) \leqslant \tfrac{5}{4}\big(1+o(1)\big)r^2$$

which is the upper bound of (7).

To obtain the lower bound of (7), consider the following set $A_r(m)$ defined by

$$A_r(m) \equiv \{x > 0:\ x \equiv i \pmod{n} \text{ for some } i,\ rm \leqslant i \leqslant (r+2)m\}$$

where $n = rm(r/2+2)$ and we assume r is even. Reduced modulo n, $A_r(m)$ is simply the *interval* of residues $\{rm, rm+1, \ldots, rm+2m\}$.

On one hand, since

$$\frac{r}{2}(rm+2m) = \frac{r^2m}{2}+rm = \left(\frac{r}{2}+1\right)rm$$

and

$$r(rm+2m) = n+\tfrac{1}{2}r(rm)$$

then *all* residues modulo n belong to

$$\tfrac{1}{2}rA_r(m) \cup (r/2+1)A_r(m) \cup \ldots \cup rA_r(m)$$

and consequently

$$\operatorname{ord}\big(A_r(m)\big) \leqslant r. \tag{19}$$

On the other hand, for any k, $kA_r(m)$ reduced modulo n forms an interval of length $2mk+1$. Therefore,

$$\operatorname{ord}^*(A_r(m)) \geqslant \frac{n-1}{2m} = \frac{r^2}{4} + r - \frac{1}{2m}. \tag{20}$$

Taking m large, it follows from (19) and (20) that

$$g(r) \geqslant \tfrac{1}{4}(1+o(1))r^2$$

which is the lower bound of (7). This completes the proof of Theorem 2. ∎

Concluding remarks. We mention here several questions related to the preceding results which we were unable to settle.

1. Show that $\lim\limits_{r\to\infty} \frac{g(r)}{r^2}$ exists, and, if possible, determine its value. To obtain the exact value of $g(r)$ seems very difficult. It can be shown that $g(2) = 4$. However, at present we do not even know the value of $g(3)$. (It is at least 7.)

2. For a set A, let $A_m(x)$ denote $|mA \cap \{1, \ldots, x\}|$. If A is a basis and $A_1(x) = o(x)$ is it true that $\lim\limits_{x\to\infty} \frac{A_2(x)}{A_1(x)} = \infty$?

3. By the *restricted order* of A, denoted by $\operatorname{ord}_R(A)$, we mean the least integer t (if it exists) such that every sufficiently large integer is the sum of at most t *distinct* summands taken from A. As pointed out by Bateman, for $h \geqslant 3$ the set $A_h = \{x > 0 \colon x \equiv 1 \pmod h\}$ has $\operatorname{ord}(A) = h$ but has no restricted order. However, Kelly [2] has shown that $\operatorname{ord}(A) = 2$ implies $\operatorname{ord}_R(A) \leqslant 4$ and conjectures that, in fact, $\operatorname{ord}_R(A) \leqslant 3$ is true.

(i) What are necessary and sufficient conditions on a basis A to have a restricted order?

(ii) Is there a function $f(r)$ such that if $\operatorname{ord}(A) = r$ and $\operatorname{ord}_R(A)$ exists then $\operatorname{ord}_R(A) \leqslant f(r)$?

(iii) What are necessary and sufficient conditions that $\operatorname{ord}(A) = \operatorname{ord}_R(A)$? Even for sequences of polynomial values, the situation is not clear. For example, for the set $S_1 = \{n^2, n \geqslant 1\}$, $\operatorname{ord}(S_1) = 4$ (by Lagrange's theorem): and $\operatorname{ord}_R(S_1) = 5$ (by Pall [3]), whereas for the set $S_2 = \{(n^2+n)/2 \colon n \geqslant 1\}$,

$$\operatorname{ord}(S_2) = \operatorname{ord}_R(S_2) = 3.$$

(iv) Is it true that if for some r, $\operatorname{ord}(A - F) = r$ for all finite sets F, then $\operatorname{ord}_R(A)$ exists? What if we just assume $\operatorname{ord}(A-F)$ exists for all finite F?

4. Let $n \times A$ denote the set $\{a_{i_1} + \ldots + a_{i_n} \colon a_{i_k}$ are distinct elements of $A\}$. Is it true that if $\operatorname{ord}(A) = r$ then $r \times A$ has positive (lower) density? If sA has positive upper density then $s \times A$ must also have positive upper density?

5. Given k and m, when does there exist a set $A \subseteq Z_m$ so that $A, 2A, \ldots, kA$ form a disjoint cover of Z_m? For example, for $k = 2$, $m = 3t-1$, the set $A = \{t, t+1, \ldots, 2t-1\}$ works.

Of course, many of the preceding questions could be formulated for $\operatorname{ord}_R^*(A)$ (defined in the obvious way). However, we leave these for a later paper (IWL).

References

[1] H. Halberstam and K. Roth, *Sequences*, Vol. 1, Clarendon Press, Oxford 1966.

[2] John B. Kelly, *Restricted bases*, Amer. Journ. Math. 79 (1957), pp. 258–264.

[3] G. Pall, *On sums of squares*, Amer. Math. Monthly 40 (1933), pp. 10–18.

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