

# Khovanskii's Theorem

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## Abstract

We formalise the proof of an important theorem in additive combinatorics due to Khovanskii [2, 3], attesting that the cardinality of the set of all sums of  $n$  many elements of  $A$ , where  $A$  is a finite subset of an abelian group, is a polynomial in  $n$  for all sufficiently large  $n$ . We follow a proof of the theorem due to Nathanson and Ruzsa [4, 5] as presented in the notes “Introduction to Additive Combinatorics” by Timothy Gowers [1] for the University of Cambridge.

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# 1 Product Operator for Commutative Monoids

**theory** *FiniteProduct*

**imports**

*Jacobson-Basic-Algebra.Group-Theory*

**begin**

## 1.1 Products over Finite Sets

**context** *commutative-monoid* **begin**

**definition** *M-ify*  $x \equiv \text{if } x \in M \text{ then } x \text{ else } \mathbf{1}$

**definition** *fincomp*  $f A \equiv \text{if finite } A \text{ then } \text{Finite-Set.fold } (\lambda x y. f x \cdot M\text{-ify } y) \mathbf{1} A \text{ else } \mathbf{1}$

**lemma** *fincomp-empty* [*simp*]:  $\text{fincomp } f \ \{\} = \mathbf{1}$   
**by** (*simp add: fincomp-def*)

**lemma** *fincomp-infinite*[*simp*]:  $\text{infinite } A \implies \text{fincomp } f A = \mathbf{1}$   
**by** (*simp add: fincomp-def*)

**lemma** *left-commute*:  $\llbracket a \in M; b \in M; c \in M \rrbracket \implies b \cdot (a \cdot c) = a \cdot (b \cdot c)$   
**using** *commutative* **by** *force*

**lemma** *comp-fun-commute-onI*:

**assumes**  $f \in F \rightarrow M$

**shows** *comp-fun-commute-on*  $F \ (\lambda x y. f x \cdot M\text{-ify } y)$

**using** *assms*

**by** (*auto simp add: comp-fun-commute-on-def Pi-iff M-ify-def left-commute*)

**lemma** *fincomp-closed* [*simp*]:

**assumes**  $f \in F \rightarrow M$

**shows**  $\text{fincomp } f F \in M$

**proof** –

**interpret** *comp-fun-commute-on*  $F \ \lambda x y. f x \cdot M\text{-ify } y$

**by** (*simp add: assms comp-fun-commute-onI*)

**show** *?thesis*

**unfolding** *fincomp-def*

**by** (*smt (verit, ccfv-threshold) M-ify-def Pi-iff fold-graph-fold assms composition-closed equalityE fold-graph-closed-lemma unit-closed*)

**qed**

**lemma** *fincomp-insert* [*simp*]:

**assumes**  $F: \text{finite } F \ a \notin F$  **and**  $f: f \in F \rightarrow M \ f a \in M$

**shows**  $\text{fincomp } f (\text{insert } a F) = f a \cdot \text{fincomp } f F$

**proof** –

**interpret** *comp-fun-commute-on*  $\text{insert } a F \ \lambda x y. f x \cdot M\text{-ify } y$

by (simp add: comp-fun-commute-onI f)  
 show ?thesis  
 using assms fincomp-closed commutative-monoid.M-ify-def commutative-monoid-axioms  
 by (fastforce simp add: fincomp-def)  
 qed

**lemma** *fincomp-unit-eqI*:  $(\bigwedge x. x \in A \implies f x = \mathbf{1}) \implies \text{fincomp } f A = \mathbf{1}$

**proof** (induct A rule: infinite-finite-induct)

case empty show ?case by simp

next

case (insert a A)

have  $(\lambda i. \mathbf{1}) \in A \rightarrow M$  by auto

with insert show ?case by simp

qed simp

**lemma** *fincomp-unit [simp]*:  $\text{fincomp } (\lambda i. \mathbf{1}) A = \mathbf{1}$

by (simp add: fincomp-unit-eqI)

**lemma** *funcset-Int-left [simp, intro]*:

$\llbracket f \in A \rightarrow C; f \in B \rightarrow C \rrbracket \implies f \in A \text{ Int } B \rightarrow C$

by fast

**lemma** *funcset-Un-left [iff]*:

$(f \in A \text{ Un } B \rightarrow C) = (f \in A \rightarrow C \wedge f \in B \rightarrow C)$

by fast

**lemma** *fincomp-Un-Int*:

$\llbracket \text{finite } A; \text{finite } B; g \in A \rightarrow M; g \in B \rightarrow M \rrbracket \implies$

$\text{fincomp } g (A \cup B) \cdot \text{fincomp } g (A \cap B) =$

$\text{fincomp } g A \cdot \text{fincomp } g B$

— The reversed orientation looks more natural, but LOOPS as a simprule!

**proof** (induct set: finite)

case empty then show ?case by simp

next

case (insert a A)

then have  $g a \in M$   $g \in A \rightarrow M$  by blast+

with insert show ?case

by (simp add: Int-insert-left associative insert-absorb left-commute)

qed

**lemma** *fincomp-Un-disjoint*:

$\llbracket \text{finite } A; \text{finite } B; A \cap B = \{\}; g \in A \rightarrow M; g \in B \rightarrow M \rrbracket$

$\implies \text{fincomp } g (A \cup B) = \text{fincomp } g A \cdot \text{fincomp } g B$

by (metis Pi-split-domain fincomp-Un-Int fincomp-closed fincomp-empty right-unit)

**lemma** *fincomp-comp*:

$\llbracket f \in A \rightarrow M; g \in A \rightarrow M \rrbracket \implies \text{fincomp } (\lambda x. f x \cdot g x) A = (\text{fincomp } f A \cdot \text{fincomp } g A)$

**proof** (induct A rule: infinite-finite-induct)

```

  case empty show ?case by simp
next
  case (insert a A)
  then have  $f a \in M \ g \in A \rightarrow M \ g a \in M \ f \in A \rightarrow M \ (\lambda x. f x \cdot g x) \in A \rightarrow M$ 
    by blast+
  then show ?case
    by (simp add: insert associative left-commute)
qed simp

```

```

lemma fincomp-cong':
  assumes  $A = B \ g \in B \rightarrow M \ \bigwedge i. i \in B \implies f i = g i$ 
  shows  $\text{fincomp } f A = \text{fincomp } g B$ 
proof (cases finite B)
  case True
  then have ?thesis
    using assms
  proof (induct arbitrary: A)
    case empty thus ?case by simp
  next
    case (insert x B)
    then have  $\text{fincomp } f A = \text{fincomp } f (\text{insert } x B)$  by simp
    also from insert have  $\dots = f x \cdot \text{fincomp } f B$ 
      by (simp add: Pi-iff)
    also from insert have  $\dots = g x \cdot \text{fincomp } g B$  by fastforce
    also from insert have  $\dots = \text{fincomp } g (\text{insert } x B)$ 
      by (intro fincomp-insert [THEN sym]) auto
    finally show ?case .
  qed
  with assms show ?thesis by simp
next
  case False with assms show ?thesis by simp
qed

```

```

lemma fincomp-cong:
  assumes  $A = B \ g \in B \rightarrow M \ \bigwedge i. i \in B = \text{simp} \implies f i = g i$ 
  shows  $\text{fincomp } f A = \text{fincomp } g B$ 
  using assms unfolding simp-implies-def by (blast intro: fincomp-cong')

```

Usually, if this rule causes a failed congruence proof error, the reason is that the premise  $g \in B \rightarrow M$  cannot be shown. Adding *Pi-def* to the simpset is often useful. For this reason, *fincomp-cong* is not added to the simpset by default.

```

lemma fincomp-0 [simp]:
   $f \in \{0::\text{nat}\} \rightarrow M \implies \text{fincomp } f \{..0\} = f 0$ 
  by (simp add: Pi-def)

```

```

lemma fincomp-0':  $f \in \{..n\} \rightarrow M \implies (f 0) \cdot \text{fincomp } f \{\text{Suc } 0..n\} = \text{fincomp } f \{..n\}$ 
  by (metis Pi-split-insert-domain Suc-n-not-le-n atLeastAtMost-iff atLeastAtMost-insertL)

```

*atMost-atLeast0 finite-atLeastAtMost fincomp-insert le0)*

**lemma** *fincomp-Suc* [*simp*]:

$f \in \{..Suc\ n\} \rightarrow M \implies fincomp\ f\ \{..Suc\ n\} = (f\ (Suc\ n) \cdot fincomp\ f\ \{..n\})$   
**by** (*simp add: Pi-def atMost-Suc*)

**lemma** *fincomp-Suc2*:

$f \in \{..Suc\ n\} \rightarrow M \implies fincomp\ f\ \{..Suc\ n\} = (fincomp\ (\%i.\ f\ (Suc\ i))\ \{..n\} \cdot f\ 0)$

**proof** (*induct n*)

**case** 0 **thus** ?*case* **by** (*simp add: Pi-def*)

**next**

**case** *Suc* **thus** ?*case*

**by** (*simp add: associative Pi-def*)

**qed**

**lemma** *fincomp-Suc3*:

**assumes**  $f \in \{..n :: nat\} \rightarrow M$

**shows**  $fincomp\ f\ \{..n\} = (f\ n) \cdot fincomp\ f\ \{..< n\}$

**proof** (*cases n = 0*)

**case** *True* **thus** ?*thesis*

**using** *assms atMost-Suc* **by** *simp*

**next**

**case** *False*

**then obtain** *k* **where**  $n = Suc\ k$

**using** *not0-implies-Suc* **by** *blast*

**thus** ?*thesis*

**using** *fincomp-Suc[of f k]* *assms atMost-Suc lessThan-Suc-atMost* **by** *simp*

**qed**

**lemma** *fincomp-reindex*:

$f \in (h \text{ ' } A) \rightarrow M \implies$

$inj\text{-on}\ h\ A \implies fincomp\ f\ (h \text{ ' } A) = fincomp\ (\lambda x.\ f\ (h\ x))\ A$

**proof** (*induct A rule: infinite-finite-induct*)

**case** (*infinite A*)

**hence**  $\neg\ finite\ (h \text{ ' } A)$

**using** *finite-imageD* **by** *blast*

**with**  $\langle \neg\ finite\ A \rangle$  **show** ?*case* **by** *simp*

**qed** (*auto simp add: Pi-def*)

**lemma** *fincomp-const*:

**assumes**  $a$  [*simp*]:  $a \in M$

**shows**  $fincomp\ (\lambda x.\ a)\ A = rec\text{-nat}\ \mathbf{1}\ (\lambda u.\ (\cdot)\ a)\ (card\ A)$

**by** (*induct A rule: infinite-finite-induct*) *auto*

**lemma** *fincomp-singleton*:

**assumes** *i-in-A*:  $i \in A$  **and** *fin-A*: *finite A* **and** *f-Pi*:  $f \in A \rightarrow M$

**shows**  $fincomp\ (\lambda j.\ \text{if}\ i = j\ \text{then}\ f\ j\ \text{else}\ \mathbf{1})\ A = f\ i$

**using** *i-in-A fincomp-insert [of A - {i} i (\lambda j. if i = j then f j else 1)]*

$fin-A$   $f-Pi$   $fincomp-unit$  [of  $A - \{i\}$ ]  
 $fincomp-cong$  [of  $A - \{i\}$   $A - \{i\}$ ] ( $\lambda j. \text{if } i = j \text{ then } f j \text{ else } \mathbf{1}$ ) ( $\lambda i. \mathbf{1}$ )  
**unfolding**  $Pi-def$   $simp-implies-def$  **by** ( $force$   $simp$   $add: insert-absorb$ )

**lemma**  $fincomp-singleton-swap$ :

**assumes**  $i-in-A$ :  $i \in A$  **and**  $fin-A$ :  $finite\ A$  **and**  $f-Pi$ :  $f \in A \rightarrow M$   
**shows**  $fincomp$  ( $\lambda j. \text{if } j = i \text{ then } f j \text{ else } \mathbf{1}$ )  $A = f\ i$   
**using**  $fincomp-singleton$  [ $OF$   $assms$ ] **by** ( $simp$   $add: eq-commute$ )

**lemma**  $fincomp-mono-neutral-cong-left$ :

**assumes**  $finite\ B$   
**and**  $A \subseteq B$   
**and**  $1$ :  $\bigwedge i. i \in B - A \implies h\ i = \mathbf{1}$   
**and**  $gh$ :  $\bigwedge x. x \in A \implies g\ x = h\ x$   
**and**  $h$ :  $h \in B \rightarrow M$   
**shows**  $fincomp\ g\ A = fincomp\ h\ B$

**proof** –

**have**  $eq$ :  $A \cup (B - A) = B$  **using**  $\langle A \subseteq B \rangle$  **by**  $blast$   
**have**  $d$ :  $A \cap (B - A) = \{\}$  **using**  $\langle A \subseteq B \rangle$  **by**  $blast$   
**from**  $\langle finite\ B \rangle$   $\langle A \subseteq B \rangle$  **have**  $f$ :  $finite\ A$   $finite\ (B - A)$   
**by** ( $auto$   $intro: finite-subset$ )  
**have**  $h \in A \rightarrow M$   $h \in B - A \rightarrow M$   
**using**  $assms$  **by** ( $auto$   $simp: image-subset-iff-funcset$ )  
**moreover** **have**  $fincomp\ g\ A = fincomp\ h\ A \cdot fincomp\ h\ (B - A)$

**proof** –

**have**  $fincomp\ h\ (B - A) = \mathbf{1}$   
**using**  $1$   $fincomp-unit-eqI$  **by**  $blast$   
**moreover** **have**  $fincomp\ g\ A = fincomp\ h\ A$   
**using**  $\langle h \in A \rightarrow M \rangle$   $fincomp-cong'$   $gh$  **by**  $blast$   
**ultimately** **show**  $?thesis$   
**by** ( $simp$   $add: \langle h \in A \rightarrow M \rangle$ )

**qed**

**ultimately** **show**  $?thesis$

**by** ( $simp$   $add: fincomp-Un-disjoint$  [ $OF$   $f\ d$ ,  $unfolded\ eq$ ])

**qed**

**lemma**  $fincomp-mono-neutral-cong-right$ :

**assumes**  $finite\ B$   
**and**  $A \subseteq B$   $\bigwedge i. i \in B - A \implies g\ i = \mathbf{1}$   $\bigwedge x. x \in A \implies g\ x = h\ x$   $g \in B \rightarrow M$   
**shows**  $fincomp\ g\ B = fincomp\ h\ A$   
**using**  $assms$  **by** ( $auto$   $intro!: fincomp-mono-neutral-cong-left$  [ $symmetric$ ])

**lemma**  $fincomp-mono-neutral-cong$ :

**assumes** [ $simp$ ]:  $finite\ B$   $finite\ A$   
**and**  $*$ :  $\bigwedge i. i \in B - A \implies h\ i = \mathbf{1}$   $\bigwedge i. i \in A - B \implies g\ i = \mathbf{1}$   
**and**  $gh$ :  $\bigwedge x. x \in A \cap B \implies g\ x = h\ x$   
**and**  $g$ :  $g \in A \rightarrow M$   
**and**  $h$ :  $h \in B \rightarrow M$   
**shows**  $fincomp\ g\ A = fincomp\ h\ B$

**proof**–  
**have**  $\text{fincomp } g \ A = \text{fincomp } g \ (A \cap B)$   
**by** (*rule fincomp-mono-neutral-cong-right*) (*use assms in auto*)  
**also have**  $\dots = \text{fincomp } h \ (A \cap B)$   
**by** (*rule fincomp-cong*) (*use assms in auto*)  
**also have**  $\dots = \text{fincomp } h \ B$   
**by** (*rule fincomp-mono-neutral-cong-left*) (*use assms in auto*)  
**finally show** *?thesis* .  
**qed**

**lemma** *fincomp-UN-disjoint*:  
**assumes**  
 $\text{finite } I \ \wedge i. i \in I \implies \text{finite } (A \ i) \ \text{pairwise } (\lambda i \ j. \text{disjnt } (A \ i) \ (A \ j)) \ I$   
 $\wedge i \ x. i \in I \implies x \in A \ i \implies g \ x \in M$   
**shows**  $\text{fincomp } g \ (\bigcup (A \ ` I)) = \text{fincomp } (\lambda i. \text{fincomp } g \ (A \ i)) \ I$   
**using** *assms*  
**proof** (*induction set: finite*)  
**case empty**  
**then show** *?case*  
**by force**  
**next**  
**case (insert i I)**  
**then show** *?case*  
**unfolding** *pairwise-def disjnt-def*  
**apply** *clarsimp*  
**apply** (*subst fincomp-Un-disjoint*)  
**apply** (*fastforce intro!: funcsetI fincomp-closed*)  
**done**  
**qed**

**lemma** *fincomp-Union-disjoint*:  
 $\llbracket \text{finite } C; \wedge A. A \in C \implies \text{finite } A \ \wedge (\forall x \in A. f \ x \in M); \text{pairwise disjnt } C \rrbracket \implies$   
 $\text{fincomp } f \ (\bigcup C) = \text{fincomp } (\text{fincomp } f) \ C$   
**by** (*frule fincomp-UN-disjoint [of C id f]*) *auto*

**end**

## 1.2 Results for Abelian Groups

**context** *abelian-group* **begin**

**lemma** *fincomp-inverse*:  
 $f \in A \rightarrow G \implies \text{fincomp } (\lambda x. \text{inverse } (f \ x)) \ A = \text{inverse } (\text{fincomp } f \ A)$   
**proof** (*induct A rule: infinite-finite-induct*)  
**case empty** **show** *?case* **by simp**  
**next**  
**case (insert a A)**  
**then have**  $f \ a \in G \ f \in A \rightarrow G \ (\lambda x. \text{inverse } (f \ x)) \in A \rightarrow G$

```

    by blast+
  with insert show ?case
  by (simp add: commutative inverse-composition-commute)
qed simp

```

Jeremy Avigad. This should be generalized to arbitrary groups, not just Abelian ones, using Lagrange’s theorem.

```

lemma power-order-eq-one:
  assumes fin [simp]: finite G
  and a [simp]: a ∈ G
  shows rec-nat 1 (λu. (·) a) (card G) = 1
proof -
  have rec-G: rec-nat 1 (λu. (·) a) (card G) ∈ G
  by (metis Pi-I' a fincomp-closed fincomp-const)
  have ∧x. x ∈ G ⇒ x ∈ (·) a ‘ G
  by (metis a composition-closed imageI invertible invertible-inverse-closed invert-
  ible-right-inverse2)
  with a have (·) a ‘ G = G by blast
  then have 1 · fincomp (λx. x) G = fincomp (λx. x) ((·) a ‘ G)
  by simp
  also have ... = fincomp (λx. a · x) G
  using fincomp-reindex
  by (subst (2) fincomp-reindex [symmetric]) (auto simp: inj-on-def)
  also have ... = fincomp (λx. a) G · fincomp (λx. x) G
  by (simp add: fincomp-comp)
  also have fincomp (λx. a) G = rec-nat 1 (λu. (·) a) (card G)
  by (simp add: fincomp-const)
  finally show ?thesis
  by (metis commutative fincomp-closed funcset-id invertible invertible-left-cancel
  rec-G unit-closed)
qed

end

end

```

## 2 Khovanskii’s Theorem

We formalise the proof of an important theorem in additive combinatorics due to Khovanskii, attesting that the cardinality of the set of all sums of  $n$  many elements of  $A$ , where  $A$  is a finite subset of an abelian group, is a polynomial in  $n$  for all sufficiently large  $n$ . We follow a proof due to Nathanson and Ruzsa as presented in the notes “Introduction to Additive Combinatorics” by Timothy Gowers for the University of Cambridge.

```

theory Khovanskii
  imports
    FiniteProduct

```

*Pluenncke-Ruzsa-Inequality.Pluenncke-Ruzsa-Inequality*  
*Bernoulli.Bernoulli* — sums of a fixed power are polynomials  
*HOL-Analysis.Weierstrass-Theorems* — needed for polynomial function  
*HOL-Library.List-Lenlexorder* — lexicographic ordering for the type *nat*  
*list*

**begin**

The sum of the elements of a list

**abbreviation**  $\sigma \equiv \text{sum-list}$

Related to the nsets of Ramsey.thy, but simpler

**definition** *finsets* :: [*'a set, nat*]  $\Rightarrow$  *'a set set*  
**where** *finsets* *A n*  $\equiv \{N. N \subseteq A \wedge \text{card } N = n\}$

**lemma** *card-finsets*: *finite N*  $\implies \text{card } (\text{finsets } N \ k) = \text{card } N \ \text{choose } k$   
**by** (*simp add: finsets-def n-subsets*)

**lemma** *sorted-map-plus-iff* [*simp*]:  
**fixes** *a*::*'a::linordered-cancel-ab-semigroup-add*  
**shows** *sorted (map ((+) a) xs)*  $\longleftrightarrow$  *sorted xs*  
**by** (*induction xs*) *auto*

**lemma** *distinct-map-plus-iff* [*simp*]:  
**fixes** *a*::*'a::linordered-cancel-ab-semigroup-add*  
**shows** *distinct (map ((+) a) xs)*  $\longleftrightarrow$  *distinct xs*  
**by** (*induction xs*) *auto*

## 2.1 Arithmetic operations on lists, pointwise on the elements

Weak type class properties. Cancellation is difficult to arrange because of complications when lists differ in length.

**instantiation** *list* :: (*plus*) *plus*

**begin**

**definition** *plus-list*  $\equiv \text{map2 } (+)$

**instance..**

**end**

**lemma** *length-plus-list* [*simp*]:  
**fixes** *xs* :: *'a::plus list*  
**shows** *length (xs+ys)* = *min (length xs) (length ys)*  
**by** (*simp add: plus-list-def*)

**lemma** *plus-Nil* [*simp*]:  $[\ ] + \text{xs} = [\ ]$   
**by** (*simp add: plus-list-def*)

**lemma** *plus-Cons*:  $(y \# \text{ys}) + (x \# \text{xs}) = (y+x) \# (\text{ys}+\text{xs})$   
**by** (*simp add: plus-list-def*)

**lemma** *nth-plus-list* [*simp*]:

```

fixes  $xs :: 'a::plus\ list$ 
assumes  $i < length\ xs\ i < length\ ys$ 
shows  $(xs+ys)!i = xs!i + ys!i$ 
by (simp add: plus-list-def assms)

instantiation  $list :: (minus)\ minus$ 
begin
definition  $minus-list \equiv map2\ (-)$ 
instance..
end

lemma  $length-minus-list\ [simp]:$ 
  fixes  $xs :: 'a::minus\ list$ 
  shows  $length\ (xs-ys) = min\ (length\ xs)\ (length\ ys)$ 
  by (simp add: minus-list-def)

lemma  $minus-Nil\ [simp]:\ [] - xs = []$ 
  by (simp add: minus-list-def)

lemma  $minus-Cons: (y \# ys) - (x \# xs) = (y-x) \# (ys-xs)$ 
  by (simp add: minus-list-def)

lemma  $nth-minus-list\ [simp]:$ 
  fixes  $xs :: 'a::minus\ list$ 
  assumes  $i < length\ xs\ i < length\ ys$ 
  shows  $(xs-ys)!i = xs!i - ys!i$ 
  by (simp add: minus-list-def assms)

instance  $list :: (ab-semigroup-add)\ ab-semigroup-add$ 
proof
  have  $map2\ (+)\ (map2\ (+)\ xs\ ys)\ zs = map2\ (+)\ xs\ (map2\ (+)\ ys\ zs)$  for  $xs\ ys$ 
   $zs :: 'a\ list$ 
  proof (induction xs arbitrary: ys zs)
    case ( $Cons\ x\ xs$ )
    show ?case
    proof ( $cases\ ys=[] \vee\ zs=[]$ )
      case  $False$ 
      then obtain  $y\ ys'\ z\ zs'$  where  $ys = y\#\ ys'\ zs = z\ \#\ zs'$ 
      by (meson list.exhaust)
      then show ?thesis
      by (simp add: Cons add.assoc)
    qed auto
  qed auto
  then show  $a + b + c = a + (b + c)$  for  $a\ b\ c :: 'a\ list$ 
  by (auto simp: plus-list-def)
next
  have  $map2\ (+)\ xs\ ys = map2\ (+)\ ys\ xs$  for  $xs\ ys :: 'a\ list$ 
  proof (induction xs arbitrary: ys)

```

```

case (Cons x xs)
show ?case
proof (cases ys)
  case (Cons y ys')
  then show ?thesis
    by (simp add: Cons.IH add.commute)
qed auto
qed auto
then show a + b = b + a for a b :: 'a list
  by (auto simp: plus-list-def)
qed

```

## 2.2 The pointwise ordering on two equal-length lists of natural numbers

Gowers uses the usual symbol ( $\leq$ ) for his pointwise ordering. In our development,  $\leq$  is the lexicographic ordering and  $\leqslant$  is the pointwise ordering.

**definition** *pointwise-le* :: [nat list, nat list]  $\Rightarrow$  bool (**infixr**  $\leqslant$  50 )  
**where**  $x \leqslant y \equiv \text{list-all2 } (\leq) x y$

**definition** *pointwise-less* :: [nat list, nat list]  $\Rightarrow$  bool (**infixr**  $\leqslant$  50 )  
**where**  $x \leqslant y \equiv x \leq y \wedge x \neq y$

**lemma** *pointwise-le-iff-nth*:  
 $x \leqslant y \longleftrightarrow \text{length } x = \text{length } y \wedge (\forall i < \text{length } x. x!i \leq y!i)$   
**by** (simp add: list-all2-conv-all-nth pointwise-le-def)

**lemma** *pointwise-le-iff*:  
 $x \leqslant y \longleftrightarrow \text{length } x = \text{length } y \wedge (\forall (i,j) \in \text{set } (\text{zip } x y). i \leq j)$   
**by** (simp add: list-all2-iff pointwise-le-def)

**lemma** *pointwise-append-le-iff* [simp]:  $u @ x \leqslant u @ y \longleftrightarrow x \leqslant y$   
**by** (auto simp: pointwise-le-iff-nth nth-append)

**lemma** *pointwise-le-refl* [iff]:  $x \leqslant x$   
**by** (simp add: list.rel-refl pointwise-le-def)

**lemma** *pointwise-le-antisym*:  $\llbracket x \leqslant y; y \leqslant x \rrbracket \Longrightarrow x = y$   
**by** (metis antisym list-all2-antisym pointwise-le-def)

**lemma** *pointwise-le-trans*:  $\llbracket x \leqslant y; y \leqslant z \rrbracket \Longrightarrow x \leqslant z$   
**by** (smt (verit, del-insts) le-trans list-all2-trans pointwise-le-def)

**lemma** *pointwise-le-Nil* [simp]:  $\text{Nil} \leqslant x \longleftrightarrow x = \text{Nil}$   
**by** (simp add: pointwise-le-def)

**lemma** *pointwise-le-Nil2* [simp]:  $x \leqslant \text{Nil} \longleftrightarrow x = \text{Nil}$   
**by** (simp add: pointwise-le-def)

**lemma** *pointwise-le-iff-less-equal*:  $x \sqsubseteq y \longleftrightarrow x \triangleleft y \vee x = y$   
**using** *pointwise-less-def* **by** *blast*

**lemma** *pointwise-less-iff*:  
 $x \triangleleft y \longleftrightarrow x \sqsubseteq y \wedge (\exists (i,j) \in \text{set } (\text{zip } x \ y). \ i < j)$   
**using** *list-eq-iff-zip-eq* *pointwise-le-iff* *pointwise-less-def* **by** *fastforce*

**lemma** *pointwise-less-iff2*:  $x \triangleleft y \longleftrightarrow x \sqsubseteq y \wedge (\exists k < \text{length } x. \ x!k < y!k)$   
**unfolding** *pointwise-less-def* *pointwise-le-iff-nth*  
**by** (*fastforce* *intro!*: *nth-equalityI*)

**lemma** *pointwise-less-Nil* [*simp*]:  $\neg \text{Nil} \triangleleft x$   
**by** (*simp* *add*: *pointwise-less-def*)

**lemma** *pointwise-less-Nil2* [*simp*]:  $\neg x \triangleleft \text{Nil}$   
**by** (*simp* *add*: *pointwise-less-def*)

**lemma** *zero-pointwise-le-iff* [*simp*]:  $\text{replicate } r \ 0 \sqsubseteq x \longleftrightarrow \text{length } x = r$   
**by** (*auto* *simp*: *pointwise-le-iff-nth*)

**lemma** *pointwise-le-imp- $\sigma$* :  
**assumes**  $xs \sqsubseteq ys$  **shows**  $\sigma \ xs \leq \sigma \ ys$   
**using** *assms*  
**proof** (*induction* *ys* *arbitrary*: *xs*)  
**case** *Nil*  
**then show** *?case*  
**by** (*simp* *add*: *pointwise-le-iff*)  
**next**  
**case** (*Cons* *y* *ys*)  
**then obtain**  $x \ xs'$  **where**  $x \sqsubseteq y \ xs = x \# \ xs' \ xs' \sqsubseteq ys$   
**by** (*auto* *simp*: *pointwise-le-def* *list-all2-Cons2*)  
**then show** *?case*  
**by** (*simp* *add*: *Cons.IH* *add-le-mono*)  
**qed**

**lemma** *sum-list-plus*:  
**fixes**  $xs :: 'a::\text{comm-monoid-add}$  *list*  
**assumes**  $\text{length } xs = \text{length } ys$  **shows**  $\sigma \ (xs + ys) = \sigma \ xs + \sigma \ ys$   
**using** *assms* **by** (*simp* *add*: *plus-list-def* *case-prod-unfold* *sum-list-addr*)

**lemma** *sum-list-minus*:  
**assumes**  $xs \sqsubseteq ys$  **shows**  $\sigma \ (ys - xs) = \sigma \ ys - \sigma \ xs$   
**using** *assms*  
**proof** (*induction* *ys* *arbitrary*: *xs*)  
**case** (*Cons* *y* *ys*)  
**then obtain**  $x \ xs'$  **where**  $x \sqsubseteq y \ xs = x \# \ xs' \ xs' \sqsubseteq ys$   
**by** (*auto* *simp*: *pointwise-le-def* *list-all2-Cons2*)  
**then show** *?case*  
**using** *pointwise-le-imp- $\sigma$*  **by** (*auto* *simp*: *Cons* *minus-Cons*)

qed (auto simp: in-set-conv-nth)

## 2.3 Pointwise minimum and maximum of a set of lists

**definition** *min-pointwise* :: [nat, nat list set]  $\Rightarrow$  nat list  
 where *min-pointwise*  $\equiv \lambda r U. \text{map } (\lambda i. \text{Min } ((\lambda u. u!i) ' U)) [0..<r]$

**lemma** *min-pointwise-le*:  $\llbracket u \in U; \text{finite } U \rrbracket \Longrightarrow \text{min-pointwise } (\text{length } u) U \trianglelefteq u$   
 by (simp add: min-pointwise-def pointwise-le-iff-nth)

**lemma** *min-pointwise-ge-iff*:  
 assumes *finite*  $U \ U \neq \{\}$   $\bigwedge u. u \in U \Longrightarrow \text{length } u = r \ \text{length } x = r$   
 shows  $x \trianglelefteq \text{min-pointwise } r U \longleftrightarrow (\forall u \in U. x \trianglelefteq u)$   
 by (auto simp: min-pointwise-def pointwise-le-iff-nth assms)

**definition** *max-pointwise* :: [nat, nat list set]  $\Rightarrow$  nat list  
 where *max-pointwise*  $\equiv \lambda r U. \text{map } (\lambda i. \text{Max } ((\lambda u. u!i) ' U)) [0..<r]$

**lemma** *max-pointwise-ge*:  $\llbracket u \in U; \text{finite } U \rrbracket \Longrightarrow u \trianglelefteq \text{max-pointwise } (\text{length } u) U$   
 by (simp add: max-pointwise-def pointwise-le-iff-nth)

**lemma** *max-pointwise-le-iff*:  
 assumes *finite*  $U \ U \neq \{\}$   $\bigwedge u. u \in U \Longrightarrow \text{length } u = r \ \text{length } x = r$   
 shows  $\text{max-pointwise } r U \trianglelefteq x \longleftrightarrow (\forall u \in U. u \trianglelefteq x)$   
 by (auto simp: max-pointwise-def pointwise-le-iff-nth assms)

**lemma** *max-pointwise-mono*:  
 assumes  $X' \subseteq X$  *finite*  $X \ X' \neq \{\}$   
 shows  $\text{max-pointwise } r X' \trianglelefteq \text{max-pointwise } r X$   
 using assms by (simp add: max-pointwise-def pointwise-le-iff-nth Max-mono image-mono)

**lemma** *pointwise-le-plus*:  $\llbracket xs \trianglelefteq ys; \text{length } ys \leq \text{length } zs \rrbracket \Longrightarrow xs \trianglelefteq ys+zs$

**proof** (induction *xs* arbitrary: *ys zs*)

case (Cons *x xs*)

then obtain *y ys' z zs'* where  $ys = y\#\#ys'$   $zs = z\#\#zs'$

unfolding *pointwise-le-iff* by (metis Suc-le-length-iff le-refl length-Cons)

with Cons show ?case

by (auto simp: plus-list-def pointwise-le-def)

qed (simp add: pointwise-le-iff)

**lemma** *pairwise-minus-cancel*:  $\llbracket z \trianglelefteq x; z \trianglelefteq y; x - z = y - z \rrbracket \Longrightarrow x = y$   
 unfolding *pointwise-le-iff-nth* by (metis eq-diff-iff nth-equalityI nth-minus-list)

## 2.4 A locale to fix the finite subset $A \subseteq G$

**locale** *Khovanskii* = additive-abelian-group +  
 fixes *A* :: 'a set  
 assumes *AsubG*:  $A \subseteq G$  and *finA*: finite *A*

**begin**

finite products of a group element

**definition**  $Gmult :: 'a \Rightarrow nat \Rightarrow 'a$   
**where**  $Gmult\ a\ n \equiv (((\oplus)a) \overset{\sim}{\sim} n)\ \mathbf{0}$

**lemma**  $Gmult-0$  [*simp*]:  $Gmult\ a\ 0 = \mathbf{0}$   
**by** (*simp add: Gmult-def*)

**lemma**  $Gmult-1$  [*simp*]:  $a \in G \Longrightarrow Gmult\ a\ (Suc\ 0) = a$   
**by** (*simp add: Gmult-def*)

**lemma**  $Gmult-Suc$  [*simp*]:  $Gmult\ a\ (Suc\ n) = a \oplus Gmult\ a\ n$   
**by** (*simp add: Gmult-def*)

**lemma**  $Gmult-in-G$  [*simp,intro*]:  $a \in G \Longrightarrow Gmult\ a\ n \in G$   
**by** (*induction n*) *auto*

**lemma**  $Gmult-add-add$ :  
**assumes**  $a \in G$   
**shows**  $Gmult\ a\ (m+n) = Gmult\ a\ m \oplus Gmult\ a\ n$   
**by** (*induction m*) (*use assms local.associative in fastforce*)<sup>+</sup>

**lemma**  $Gmult-add-diff$ :  
**assumes**  $a \in G$   
**shows**  $Gmult\ a\ (n+k) \ominus Gmult\ a\ n = Gmult\ a\ k$   
**by** (*metis Gmult-add-add Gmult-in-G assms commutative inverse-closed invertible invertible-left-inverse2*)

**lemma**  $Gmult-diff$ :  
**assumes**  $a \in G\ n \leq m$   
**shows**  $Gmult\ a\ m \ominus Gmult\ a\ n = Gmult\ a\ (m-n)$   
**by** (*metis Gmult-add-diff assms le-add-diff-inverse*)

Mapping elements of  $A$  to their numeric subscript

**abbreviation**  $idx \equiv to-nat-on\ A$

The elements of  $A$  in order

**definition**  $aA :: 'a\ list$   
**where**  $aA \equiv map\ (from-nat-into\ A)\ [0..<card\ A]$

**definition**  $\alpha :: nat\ list \Rightarrow 'a$   
**where**  $\alpha \equiv \lambda x. fincomp\ (\lambda i. Gmult\ (aA!i)\ (x!i))\ \{..<card\ A\}$

The underlying assumption is  $length\ y = length\ x$

**definition**  $useless :: nat\ list \Rightarrow bool$   
**where**  $useless\ x \equiv \exists y < x. \sigma\ y = \sigma\ x \wedge \alpha\ y = \alpha\ x \wedge length\ y = length\ x$

**abbreviation**  $useful\ x \equiv \neg\ useless\ x$

**lemma** *alpha-replicate-0* [simp]:  $\alpha$  (replicate (card A) 0) = 0  
 by (auto simp:  $\alpha$ -def intro: fincomp-unit-eqI)

**lemma** *idx-less-cardA*:  
 assumes  $a \in A$  shows  $\text{idx } a < \text{card } A$   
 by (metis assms bij-betw-def finA imageI lessThan-iff to-nat-on-finite)

**lemma** *aA-idx-eq* [simp]:  
 assumes  $a \in A$  shows  $aA ! (\text{idx } a) = a$   
 by (simp add: aA-def assms countable-finite finA idx-less-cardA)

**lemma** *set-aA*:  $\text{set } aA = A$   
 using *bij-betw-from-nat-into-finite* [OF finA]  
 by (simp add: aA-def atLeast0LessThan bij-betw-def)

**lemma** *nth-aA-in-G* [simp]:  $i < \text{card } A \implies aA!i \in G$   
 using *AsubG* aA-def set-aA by auto

**lemma** *alpha-in-G* [iff]:  $\alpha x \in G$   
 using *nth-aA-in-G* fincomp-closed by (simp add:  $\alpha$ -def)

**lemma** *Gmult-in-PiG* [simp]:  $(\lambda i. \text{Gmult } (aA!i) (f i)) \in \{..<\text{card } A\} \rightarrow G$   
 by simp

**lemma** *alpha-plus*:  
 assumes  $\text{length } x = \text{card } A$   $\text{length } y = \text{card } A$   
 shows  $\alpha (x + y) = \alpha x \oplus \alpha y$   
**proof** –  
 have  $\alpha (x + y) = \text{fincomp } (\lambda i. \text{Gmult } (aA!i) (\text{map2 } (+) x y!i)) \{..<\text{card } A\}$   
 by (simp add:  $\alpha$ -def plus-list-def)  
 also have  $\dots = \text{fincomp } (\lambda i. \text{Gmult } (aA!i) (x!i + y!i)) \{..<\text{card } A\}$   
 by (intro fincomp-cong'; simp add: assms)  
 also have  $\dots = \text{fincomp } (\lambda i. \text{Gmult } (aA!i) (x!i) \oplus \text{Gmult } (aA!i) (y!i)) \{..<\text{card } A\}$   
 by (intro fincomp-cong'; simp add: Gmult-add-add)  
 also have  $\dots = \alpha x \oplus \alpha y$   
 by (simp add:  $\alpha$ -def fincomp-comp)  
 finally show ?thesis .  
**qed**

**lemma** *alpha-minus*:  
 assumes  $y \trianglelefteq x$   $\text{length } y = \text{card } A$   
 shows  $\alpha (x - y) = \alpha x \ominus \alpha y$   
**proof** –  
 have  $\alpha (x - y) = \text{fincomp } (\lambda i. \text{Gmult } (aA!i) (\text{map2 } (-) x y!i)) \{..<\text{card } A\}$   
 by (simp add:  $\alpha$ -def minus-list-def)  
 also have  $\dots = \text{fincomp } (\lambda i. \text{Gmult } (aA!i) (x!i - y!i)) \{..<\text{card } A\}$   
 using assms by (intro fincomp-cong') (auto simp: pointwise-le-iff)

**also have**  $\dots = \text{fincomp } (\lambda i. \text{Gmult } (aA!i) (x!i) \ominus \text{Gmult } (aA!i) (y!i)) \{..<\text{card } A\}$   
**using** *assms*  
**by** (*intro fincomp-cong'*) (*simp add: pointwise-le-iff-nth Gmult-diff*)+  
**also have**  $\dots = \alpha x \ominus \alpha y$   
**by** (*simp add:  $\alpha$ -def fincomp-comp fincomp-inverse*)  
**finally show** *?thesis* .  
**qed**

## 2.5 Adding one to a list element

**definition** *list-incr* ::  $\text{nat} \Rightarrow \text{nat list} \Rightarrow \text{nat list}$   
**where** *list-incr*  $i x \equiv x[i := \text{Suc } (x!i)]$

**lemma** *list-incr-Nil* [*simp*]: *list-incr*  $i [] = []$   
**by** (*simp add: list-incr-def*)

**lemma** *list-incr-Cons* [*simp*]: *list-incr* ( $\text{Suc } i$ ) ( $k\#ks$ ) =  $k \# \text{list-incr } i ks$   
**by** (*simp add: list-incr-def*)

**lemma** *sum-list-incr* [*simp*]:  $i < \text{length } x \implies \sigma (\text{list-incr } i x) = \text{Suc } (\sigma x)$   
**by** (*auto simp: list-incr-def sum-list-update*)

**lemma** *length-list-incr* [*simp*]:  $\text{length } (\text{list-incr } i x) = \text{length } x$   
**by** (*auto simp: list-incr-def*)

**lemma** *nth-le-list-incr*:  $i < \text{card } A \implies x!i \leq \text{list-incr } (iA) x!i$   
**unfolding** *list-incr-def*  
**by** (*metis Suc-leD linorder-not-less list-update-beyond nth-list-update-eq nth-list-update-neq order-refl*)

**lemma** *list-incr-nth-diff*:  $i < \text{length } x \implies \text{list-incr } j x!i - x!i = (\text{if } i = j \text{ then } 1 \text{ else } 0)$   
**by** (*simp add: list-incr-def*)

## 2.6 The set of all $r$ -tuples that sum to $n$

**definition** *length-sum-set* ::  $\text{nat} \Rightarrow \text{nat} \Rightarrow \text{nat list set}$   
**where** *length-sum-set*  $r n \equiv \{x. \text{length } x = r \wedge \sigma x = n\}$

**lemma** *length-sum-set-Nil* [*simp*]: *length-sum-set*  $0 n = (\text{if } n=0 \text{ then } \{[]\} \text{ else } \{\})$   
**by** (*auto simp: length-sum-set-def*)

**lemma** *length-sum-set-Suc* [*simp*]:  $k\#ks \in \text{length-sum-set } (Suc r) n \longleftrightarrow (\exists m. ks \in \text{length-sum-set } r m \wedge n = m+k)$   
**by** (*auto simp: length-sum-set-def*)

**lemma** *length-sum-set-Suc-epoll*:  $\text{length-sum-set } (Suc r) n \approx \text{Sigma } \{..n\} (\lambda i. \text{length-sum-set } r (n-i))$  (**is** *?L*  $\approx$  *?R*)  
**unfolding** *epoll-def*

**proof**  
**let**  $?f = (\lambda l. (hd\ l, tl\ l))$   
**show**  $bij\_betw\ ?f\ ?L\ ?R$   
**proof** (*intro bij-betw-imageI*)  
**show**  $inj\_on\ ?f\ ?L$   
**by** (*force simp: inj-on-def length-sum-set-def intro: list.expand*)  
**show**  $?f\ ' ?L = ?R$   
**by** (*force simp: length-sum-set-def length-Suc-conv*)  
**qed**  
**qed**

**lemma** *finite-length-sum-set: finite (length-sum-set r n)*  
**proof** (*induction r arbitrary: n*)  
**case**  $0$   
**then show**  $?case$   
**by** (*auto simp: length-sum-set-def*)  
**next**  
**case** ( $Suc\ r$ )  
**then show**  $?case$   
**using**  $length-sum-set-Suc-epoll\ eqpoll-finite-iff$  **by** *blast*  
**qed**

**lemma** *card-length-sum-set: card (length-sum-set (Suc r) n) = ( $\sum i \leq n. card (length-sum-set r (n-i))$ )*  
**proof** –  
**have**  $card (length-sum-set (Suc r) n) = card (Sigma\ \{..n\}\ (\lambda i. length-sum-set\ r\ (n-i)))$   
**by** (*metis eqpoll-finite-iff eqpoll-iff-card finite-length-sum-set length-sum-set-Suc-epoll*)  
**also have**  $\dots = ( $\sum i \leq n. card (length-sum-set r (n-i))$ )$   
**by** (*simp add: finite-length-sum-set*)  
**finally show**  $?thesis$  .  
**qed**

**lemma** *sum-up-index-split'*:  
**assumes**  $N \leq n$  **shows**  $(\sum i \leq n. f\ i) = (\sum i \leq n-N. f\ i) + (\sum i = Suc\ (n-N)..n. f\ i)$   
**by** (*metis diff-le-self ordered-cancel-comm-monoid-diff-class.add-diff-inverse sum-up-index-split*)

**lemma** *sum-invert:  $N \leq n \implies (\sum i = Suc\ (n - N)..n. f\ (n - i)) = (\sum j < N. f\ j)$*   
**proof** (*induction N*)  
**case** ( $Suc\ N$ )  
**then show**  $?case$   
**apply** (*auto simp: Suc-diff-Suc*)  
**by** (*metis sum.atLeast-Suc-atMost Suc-leD add commute diff-diff-cancel diff-le-self*)  
**qed** *auto*

**lemma** *real-polynomial-function-length-sum-set:*  
 $\exists p. real-polynomial-function\ p \wedge (\forall n > 0. real (card (length-sum-set r n)) = p$

```

(real n))
proof (induction r)
  case 0
  have  $\forall n > 0. \text{real} (\text{card} (\text{length-sum-set } 0 \ n)) = 0$ 
    by auto
  then show ?case
    by blast
next
  case (Suc r)
  then obtain p where poly: real-polynomial-function p
    and p:  $\bigwedge n. n > 0 \implies \text{real} (\text{card} (\text{length-sum-set } r \ n)) = p (\text{real } n)$ 
    by blast
  then obtain a n where p-eq:  $p = (\lambda x. \sum_{i \leq n}. a \ i * x^i)$ 
    using real-polynomial-function-iff-sum by auto
  define q where  $q \equiv \lambda x. \sum_{j \leq n}. a \ j * ((\text{bernpoly} (\text{Suc } j) (1 + x) - \text{bernpoly} (\text{Suc } j) 0) / (1 + \text{real } j) - 0^j)$ 
  have rp-q: real-polynomial-function q
    by (fastforce simp: bernpoly-def p-eq q-def)
  have q-eq:  $(\sum_{x \leq k-1}. p (k-x)) = q \ k$  if  $k > 0$  for  $k :: \text{nat}$ 
  proof -
    have  $(\sum_{x \leq k-1}. p (k-x)) = (\sum_{j \leq n}. a \ j * ((\sum_{x \leq k}. \text{real } x^j) - 0^j))$ 
      using that
    by (simp add: p-eq sum.swap
      flip: sum-distrib-left of-nat-diff sum-diff-split[where  $f = \lambda i. \text{real } i^j$ ])
    also have ... = q k
      by (simp add: sum-of-powers add commute q-def)
    finally show ?thesis .
  qed
  define p' where  $p' \equiv \lambda x. q \ x + \text{real} (\text{card} (\text{length-sum-set } r \ 0))$ 
  have real-polynomial-function p'
    using rp-q by (force simp: p'-def)
  moreover have  $(\sum_{x \leq n - \text{Suc } 0}. p (\text{real } (n - x))) + \text{real} (\text{card} (\text{length-sum-set } r \ 0)) = p' (\text{real } n)$  if  $n > 0$  for n
    using that q-eq by (auto simp: p'-def)
  ultimately show ?case
    unfolding card-length-sum-set
    by (force simp: sum-up-index-split' [of 1] p sum-invert)
qed

lemma all-zeroes-replicate:  $\text{length-sum-set } r \ 0 = \{\text{replicate } r \ 0\}$ 
  by (auto simp: length-sum-set-def replicate-eqI)

lemma length-sum-set-Suc-eq-UN:  $\text{length-sum-set } r \ (\text{Suc } n) = (\bigcup_{i < r}. \text{list-incr } i \text{ ' length-sum-set } r \ n)$ 
proof -
  have  $\exists i < r. x \in \text{list-incr } i \text{ ' length-sum-set } r \ n$ 
    if  $\sigma \ x = \text{Suc } n$  and  $r = \text{length } x$  for x
  proof -

```

**have**  $x \neq \text{replicate } r \ 0$   
**using** *that by* (*metis sum-list-replicate Zero-not-Suc mult-zero-right*)  
**then obtain**  $i$  **where**  $i < r$   $x!i \neq 0$   
**by** (*metis*  $\langle r = \text{length } x \rangle$  *in-set-conv-nth replicate-eqI*)  
**with** *that have*  $x[i := x!i - 1] \in \text{length-sum-set } r \ n$   
**by** (*simp add: sum-list-update length-sum-set-def*)  
**with**  $i$  **that show** *?thesis*  
**unfolding** *list-incr-def* **by force**  
**qed**  
**then show** *?thesis*  
**by** (*auto simp: length-sum-set-def Bex-def*)  
**qed**

**lemma** *alpha-list-incr:*  
**assumes**  $a \in A$   $x \in \text{length-sum-set } (\text{card } A) \ n$   
**shows**  $\alpha (\text{list-incr } (\text{idx } a) \ x) = a \oplus \alpha \ x$   
**proof** –  
**have** *lenx: length x = card A*  
**using** *assms length-sum-set-def by blast*  
**have**  $\alpha (\text{list-incr } (\text{idx } a) \ x) \ominus \alpha \ x = \text{fincomp } (\lambda i. \text{Gmult } (aA!i) (\text{list-incr } (\text{idx } a) \ x!i) \ominus \text{Gmult } (aA!i) (x!i)) \ \{.. < \text{card } A\}$   
**by** (*simp add: alpha-def fincomp-comp fincomp-inverse*)  
**also have**  $\dots = \text{fincomp } (\lambda i. \text{Gmult } (aA!i) (\text{list-incr } (\text{idx } a) \ x!i - x!i)) \ \{.. < \text{card } A\}$   
**by** (*intro fincomp-cong; simp add: Gmult-diff nth-le-list-incr*)  
**also have**  $\dots = \text{fincomp } (\lambda i. \text{if } i = \text{idx } a \text{ then } (aA!i) \text{ else } \mathbf{0}) \ \{.. < \text{card } A\}$   
**by** (*intro fincomp-cong'; simp add: list-incr-nth-diff lenx*)  
**also have**  $\dots = a$   
**using** *assms by (simp add: fincomp-singleton-swap idx-less-cardA)*  
**finally have**  $\alpha (\text{list-incr } (\text{idx } a) \ x) \ominus \alpha \ x = a$  .  
**then show** *?thesis*  
**by** (*metis alpha-in-G associative inverse-closed invertible invertible-left-inverse right-unit*)  
**qed**

**lemma** *sumset-iterated-enum:*  
**defines**  $r \equiv \text{card } A$   
**shows** *sumset-iterated*  $A \ n = \alpha \ ^{\prime} \text{length-sum-set } r \ n$   
**proof** (*induction n*)  
**case**  $0$   
**then show** *?case*  
**by** (*simp add: all-zeroes-replicate r-def*)  
**next**  
**case** (*Suc n*)  
**have** *eq: {..<r} = idx ^ A*  
**by** (*metis bij-betw-def finA r-def to-nat-on-finite*)  
**have** *sumset-iterated*  $A \ (\text{Suc } n) = (\bigcup a \in A. (\lambda i. a \oplus \alpha \ i) \ ^{\prime} \text{length-sum-set } r \ n)$   
**using** *AsubG by (auto simp: Suc sumset)*  
**also have**  $\dots = (\bigcup a \in A. (\lambda i. \alpha (\text{list-incr } (\text{idx } a) \ i)) \ ^{\prime} \text{length-sum-set } r \ n)$

by (*simp add: alpha-list-incr r-def*)  
 also have  $\dots = \alpha \text{ ` length-sum-set } r \text{ (Suc } n)$   
 by (*simp add: image-UN image-comp length-sum-set-Suc-eq-UN eq*)  
 finally show *?case* .  
 qed

## 2.7 Lemma 2.7 in Gowers's notes

The following lemma corresponds to a key fact about the cardinality of the set of all sums of  $n$  many elements of  $A$ , stated before Gowers's Lemma 2.7.

**lemma** *card-sumset-iterated-length-sum-set-useful:*

**defines**  $r \equiv \text{card } A$

**shows**  $\text{card}(\text{sumset-iterated } A \ n) = \text{card}(\text{length-sum-set } r \ n \cap \{x. \text{useful } x\})$   
*(is card ?L = card ?R)*

**proof** –

**have**  $\alpha \ x \in \alpha \text{ ` }(\text{length-sum-set } r \ n \cap \{x. \text{useful } x\})$

**if**  $x \in \text{length-sum-set } r \ n$  **for**  $x$

**proof** –

**define**  $y$  **where**  $y \equiv \text{LEAST } y. y \in \text{length-sum-set } r \ n \wedge \alpha \ y = \alpha \ x$

**have**  $y: y \in \text{length-sum-set } (\text{card } A) \ n \wedge \alpha \ y = \alpha \ x$

**by** (*metis (mono-tags, lifting) LeastI r-def y-def that*)

**moreover**

**have** *useful*  $y$

**proof** (*clarsimp simp: useless-def*)

**show** *False*

**if**  $\sigma \ z = \sigma \ y$   $\text{length } z = \text{length } y$  **and**  $z < y$   $\alpha \ z = \alpha \ y$  **for**  $z$

**using** *that Least-le length-sum-set-def not-less-Least r-def y y-def* **by** *fastforce*

qed

**ultimately show** *?thesis*

**unfolding** *image-iff length-sum-set-def r-def* **by** (*smt (verit) Int-Collect*)

qed

**then have**  $\text{sumset-iterated } A \ n = \alpha \text{ ` }(\text{length-sum-set } r \ n \cap \{x. \text{useful } x\})$

**by** (*auto simp: sumset-iterated-enum length-sum-set-def r-def*)

**moreover have** *inj-on*  $\alpha$   $(\text{length-sum-set } r \ n \cap \{x. \text{useful } x\})$

**apply** (*simp add: image-iff length-sum-set-def r-def inj-on-def useless-def Ball-def*)

**by** (*metis linorder-less-linear*)

**ultimately show** *?thesis*

**by** (*simp add: card-image length-sum-set-def*)

qed

The following lemma corresponds to Lemma 2.7 in Gowers's notes.

**lemma** *useless-leq-useless:*

**defines**  $r \equiv \text{card } A$

**assumes** *useless*  $x$  **and**  $x \leq y$  **and**  $\text{length } x = r$

**shows** *useless*  $y$

**proof** –

**have** *leny*:  $\text{length } y = r$

**using** *pointwise-le-iff assms* **by** *auto*

**obtain**  $x'$  **where**  $x' < x$  **and**  $\sigma x'$ :  $\sigma x' = \sigma x$  **and**  $\alpha x'$ :  $\alpha x' = \alpha x$  **and**  $\text{len}x'$ :  
 $\text{length } x' = \text{length } x$   
**using** *assms useless-def* **by** *blast*  
**obtain**  $i$  **where**  $i < \text{card } A$  **and**  $x_i$ :  $x'!i < x!i$  **and**  $\text{take}x'$ :  $\text{take } i \ x' = \text{take } i \ x$   
**using**  $\langle x' < x \rangle$   $\text{len}x'$  *assms* **by** (*auto simp: list-less-def lenlex-def elim!: lex-take-index*)  
**define**  $y'$  **where**  $y' \equiv y + x' - x$   
**have**  $\text{len}y'$ :  $\text{length } y' = \text{length } y$   
**using** *assms lenx' pointwise-le-iff* **by** (*simp add: y'-def*)  
**have**  $x!i \leq y!i$   
**using**  $\langle x \leq y \rangle$   $\langle i < \text{card } A \rangle$  *assms* **by** (*simp add: pointwise-le-iff-nth*)  
**then have**  $y'!i < y!i$   
**using**  $\langle i < \text{card } A \rangle$  *assms lenx' xi pointwise-le-iff* **by** (*simp add: y'-def plus-list-def minus-list-def*)  
**moreover have**  $\text{take } i \ y' = \text{take } i \ y$   
**proof** (*intro nth-equalityI*)  
**show**  $\text{length } (\text{take } i \ y') = \text{length } (\text{take } i \ y)$   
**by** (*simp add: leny'*)  
**show**  $\bigwedge k. k < \text{length } (\text{take } i \ y') \implies \text{take } i \ y' ! k = \text{take } i \ y ! k$   
**using**  $\text{take}x'$  **by** (*simp add: y'-def plus-list-def minus-list-def take-map take-zip*)  
**qed**  
**ultimately have**  $y' < y$   
**using**  $\text{len}y'$   $\langle i < \text{card } A \rangle$  *assms pointwise-le-iff*  
**by** (*auto simp: list-less-def lenlex-def lexord-lex lexord-take-index-conv*)  
**moreover have**  $\sigma y' = \sigma y$   
**using** *assms*  
**by** (*simp add:  $\sigma x'$  lenx' leny pointwise-le-plus sum-list-minus sum-list-plus y'-def*)  
**moreover have**  $\alpha y' = \alpha y$   
**using** *assms lenx'  $\alpha x'$  leny*  
**by** (*fastforce simp: y'-def pointwise-le-plus alpha-minus alpha-plus local.associative*)  
**ultimately show** *?thesis*  
**using**  $\text{len}y'$  *useless-def* **by** *blast*  
**qed**

**inductive-set** *minimal-elements* **for**  $U$

**where**  $\llbracket x \in U; \bigwedge y. y \in U \implies \neg y \triangleleft x \rrbracket \implies x \in \text{minimal-elements } U$

**lemma** *pointwise-less-imp- $\sigma$* :

**assumes**  $xs \triangleleft ys$  **shows**  $\sigma xs < \sigma ys$

**proof** –

**have** *eq*:  $\text{length } ys = \text{length } xs$  **and**  $xs \leq ys$

**using** *assms* **by** (*auto simp: pointwise-le-iff pointwise-less-iff*)

**have**  $\forall k < \text{length } xs. xs!k \leq ys!k$

**using**  $\langle xs \leq ys \rangle$  *list-all2-nthD pointwise-le-def* **by** *auto*

**moreover have**  $\exists k < \text{length } xs. xs!k < ys!k$

**using** *assms pointwise-less-iff2* **by** *force*

**ultimately show** *?thesis*

by (force simp: eq sum-list-sum-nth intro: sum-strict-mono-ex1)  
qed

**lemma** *wf-measure- $\sigma$ : wf (inv-image less-than  $\sigma$ )*  
by blast

**lemma** *WFP: wfP ( $\triangleleft$ )*  
by (auto simp: wfp-def pointwise-less-imp- $\sigma$  intro: wf-subset [OF wf-measure- $\sigma$ ])

The following is a direct corollary of the above lemma, i.e. a corollary of Lemma 2.7 in Gowers's notes.

**corollary** *useless-iff:*  
**assumes** *length  $x = \text{card } A$*   
**shows** *useless  $x \iff (\exists x' \in \text{minimal-elements } (\text{Collect } \text{useless}). x' \triangleleft x)$*  (is  
 $\text{-=?R}$ )

**proof**  
**assume** *useless  $x$*   
**obtain**  *$z$  where  $z$ : useless  $z$   $z \triangleleft x$  and  $z_{\text{min}}$ :  $\bigwedge y. y \triangleleft z \implies y \triangleleft x \implies \text{useful } y$*   
**using** *wfE-min [to-pred, where  $Q = \{z. \text{useless } z \wedge z \triangleleft x\}$ , OF WFP]*  
**by** (metis (no-types, lifting)  $\langle \text{useless } x \rangle$  mem-Collect-eq pointwise-le-refl)  
**then show**  $?R$   
**by** (smt (verit) mem-Collect-eq minimal-elements.intros pointwise-le-trans pointwise-less-def)  
**next**  
**assume**  $?R$   
**with** *useless-leq-useless minimal-elements.cases* **show** *useless  $x$*   
**by** (metis assms mem-Collect-eq pointwise-le-iff)  
qed

## 2.8 The set of minimal elements of a set of $r$ -tuples is finite

The following general finiteness claim corresponds to Lemma 2.8 in Gowers's notes and is key to the main proof.

**lemma** *minimal-elements-set-tuples-finite:*  
**assumes**  *$Ur: \bigwedge x. x \in U \implies \text{length } x = r$*   
**shows** *finite (minimal-elements  $U$ )*  
**using** *assms*  
**proof** (induction  $r$  arbitrary:  $U$ )  
**case**  $0$   
**then have**  $U \subseteq \{\{\}\}$   
**by** *auto*  
**then show**  $?case$   
**by** (metis finite.simps minimal-elements.cases finite-subset subset-eq)  
**next**  
**case** (Suc  $r$ )  
**show**  $?case$   
**proof** (cases  $U = \{\}$ )  
**case** *True*  
**with** *Suc.IH* **show**  $?thesis$  **by** *blast*

**next**  
**case** *False*  
**then obtain**  $u$  **where**  $u: u \in U$  **and**  $zmin: \bigwedge y. y \triangleleft u \implies y \notin U$   
**using** *wfE-min [to-pred, where  $Q = U$ , OF WFP]* **by** *blast*  
**define**  $V$  **where**  $V = \{v \in U. \neg u \sqsubseteq v\}$   
**define**  $VF$  **where**  $VF \equiv \lambda i t. \{v \in V. v!i = t\}$   
**have** [*simp*]:  $length\ v = Suc\ r$  **if**  $v \in VF\ i\ t$  **for**  $v\ i\ t$   
**using** *that by (simp add: Suc.premis VF-def V-def)*  
**have** \*:  $\exists i \leq r. v!i < u!i$  **if**  $v \in V$  **for**  $v$   
**using** *that u Suc.premis*  
**by** (*force simp: V-def pointwise-le-iff-nth not-le less-Suc-eq-le*)  
**with**  $u$  **have** *minimal-elements  $U \leq insert\ u\ (\bigcup_{i \leq r}. \bigcup_{t < u!i}. minimal-elements\ (VF\ i\ t))$*   
**by** (*force simp: VF-def V-def minimal-elements.simps pointwise-less-def*)  
**moreover**  
**have** *finite (minimal-elements (VF i t)) if  $i \leq r$   $t < u!i$  for  $i\ t$*   
**proof** –  
**define** *delete* **where**  $delete \equiv \lambda v::nat\ list. take\ i\ v @ drop\ (Suc\ i)\ v$  — deletion  
of  $i$   
**have** *len-delete*[*simp*]:  $length\ (delete\ u) = r$  **if**  $u \in VF\ i\ t$  **for**  $u$   
**using** *Suc.premis VF-def V-def  $\langle i \leq r \rangle$  delete-def that by auto*  
**have** *nth-delete*:  $delete\ u!k = (if\ k < i\ then\ u!k\ else\ u!Suc\ k)$  **if**  $u \in VF\ i\ t$   $k < r$   
**for**  $u\ k$   
**using** *that by (simp add: delete-def nth-append)*  
**have** *delete-le-iff* [*simp*]:  $delete\ u \sqsubseteq delete\ v \iff u \sqsubseteq v$  **if**  $u \in VF\ i\ t$   $v \in VF$   
 $i\ t$  **for**  $u\ v$   
**proof**  
**assume**  $delete\ u \sqsubseteq delete\ v$   
**then** **have**  $\forall j. (j < i \implies u!j \leq v!j) \wedge (j < r \implies i \leq j \implies u!Suc\ j \leq$   
 $v!Suc\ j)$   
**using** *that  $\langle i \leq r \rangle$*   
**by** (*force simp: pointwise-le-iff-nth nth-delete split: if-split-asm cong:*  
*conj-cong*)  
**then** **show**  $u \sqsubseteq v$   
**using** *that  $\langle i \leq r \rangle$*   
**apply** (*simp add: pointwise-le-iff-nth VF-def*)  
**by** (*metis eq-iff le-Suc-eq less-Suc-eq-0-disj linorder-not-less*)  
**next**  
**assume**  $u \sqsubseteq v$  **then** **show**  $delete\ u \sqsubseteq delete\ v$   
**using** *that by (simp add: pointwise-le-iff-nth nth-delete)*  
**qed**  
**then** **have** *delete-eq-iff*:  $delete\ u = delete\ v \iff u = v$  **if**  $u \in VF\ i\ t$   $v \in VF$   
 $i\ t$  **for**  $u\ v$   
**by** (*metis that pointwise-le-antisym pointwise-le-refl*)  
**have** *delete-less-iff*:  $delete\ u \triangleleft delete\ v \iff u \triangleleft v$  **if**  $u \in VF\ i\ t$   $v \in VF\ i\ t$   
**for**  $u\ v$   
**by** (*metis delete-le-iff pointwise-le-antisym pointwise-less-def that*)  
**have**  $length\ (delete\ v) = r$  **if**  $v \in V$  **for**  $v$   
**using** *id-take-nth-drop Suc.premis V-def  $\langle i \leq r \rangle$  delete-def that by auto*

```

then have finite (minimal-elements (delete ‘ V))
  by (metis (mono-tags, lifting) Suc.IH image-iff)
moreover have inj-on delete (minimal-elements (VF i t))
  by (simp add: delete-eq-iff inj-on-def minimal-elements.simps)
moreover have delete ‘ (minimal-elements (VF i t))  $\subseteq$  minimal-elements
(delete ‘ (VF i t))
  by (auto simp: delete-less-iff minimal-elements.simps)
ultimately show ?thesis
  by (metis (mono-tags, lifting) Suc.IH image-iff inj-on-finite len-delete)
qed
ultimately show ?thesis
  by (force elim: finite-subset)
qed
qed

```

## 2.9 Towards Lemma 2.9 in Gowers’s notes

Increasing sequences

```

fun augmentum :: nat list  $\Rightarrow$  nat list
  where augmentum [] = []
  | augmentum (n#ns) = n # map ((+)n) (augmentum ns)

```

```

definition dementum:: nat list  $\Rightarrow$  nat list
  where dementum xs  $\equiv$  xs - (0#xs)

```

```

lemma dementum-Nil [simp]: dementum [] = []
  by (simp add: dementum-def)

```

```

lemma zero-notin-augmentum [simp]: 0  $\notin$  set ns  $\implies$  0  $\notin$  set (augmentum ns)
  by (induction ns) auto

```

```

lemma length-augmentum [simp]: length (augmentum xs) = length xs
  by (induction xs) auto

```

```

lemma sorted-augmentum [simp]: 0  $\notin$  set ns  $\implies$  sorted (augmentum ns)
  by (induction ns) auto

```

```

lemma distinct-augmentum [simp]: 0  $\notin$  set ns  $\implies$  distinct (augmentum ns)
  by (induction ns) (simp-all add: image-iff)

```

```

lemma augmentum-subset-sum-list: set (augmentum ns)  $\subseteq$  {.. $\sigma$  ns}
  by (induction ns) auto

```

```

lemma sum-list-augmentum:  $\sigma$  ns  $\in$  set (augmentum ns)  $\iff$  length ns > 0
  by (induction ns) auto

```

```

lemma length-dementum [simp]: length (dementum xs) = length xs
  by (simp add: dementum-def)

```

**lemma** *sorted-imp-pointwise*:  
**assumes** *sorted* (*xs@*[*n*])  
**shows**  $0 \# xs \leq xs @ [n]$   
**using** *assms*  
**by** (*simp add: pointwise-le-iff-nth nth-Cons' nth-append sorted-append sorted-wrt-append sorted-wrt-nth-less*)

**lemma** *sum-list-dementum*:  
**assumes** *sorted* (*xs@*[*n*])  
**shows**  $\sigma$  (*dementum* (*xs@*[*n*])) = *n*  
**proof** –  
**have** *dementum* (*xs@*[*n*]) = (*xs@*[*n*]) – ( $0 \# xs$ )  
**by** (*rule nth-equalityI; simp add: nth-append dementum-def nth-Cons'*)  
**then show** *?thesis*  
**by** (*simp add: sum-list-minus sorted-imp-pointwise assms*)  
**qed**

**lemma** *augmentum-cancel*:  $\text{map } ((+)k) (\text{augmentum } ns) - (k \# \text{map } ((+)k) (\text{augmentum } ns)) = ns$   
**proof** (*induction ns arbitrary: k*)  
**case** *Nil*  
**then show** *?case*  
**by** *simp*  
**next**  
**case** (*Cons n ns*)  
**have**  $(+) k \circ (+) n = (+) (k+n)$  **by** *auto*  
**then show** *?case*  
**by** (*simp add: minus-Cons Cons*)  
**qed**

**lemma** *dementum-augmentum* [*simp*]:  
**assumes**  $0 \notin \text{set } ns$   
**shows** (*dementum*  $\circ$  *sorted-list-of-set*) ((*set*  $\circ$  *augmentum*) *ns*) = *ns* (**is** *?L ns = -*)  
**using** *assms augmentum-cancel [of 0]*  
**by** (*simp add: dementum-def map-idI sorted-list-of-set.idem-if-sorted-distinct*)

**lemma** *dementum-nonzero*:  
**assumes** *ns: sorted-wrt* ( $<$ ) *ns* **and**  $0: 0 \notin \text{set } ns$   
**shows**  $0 \notin \text{set} (\text{dementum } ns)$   
**unfolding** *dementum-def minus-list-def*  
**using** *sorted-wrt-nth-less [OF ns] 0*  
**by** (*auto simp: in-set-conv-nth image-iff set-zip nth-Cons' dest: leD*)

**lemma** *nth-augmentum* [*simp*]:  $i < \text{length } ns \implies \text{augmentum } ns!i = (\sum_{j \leq i. ns!j})$   
**proof** (*induction ns arbitrary: i*)  
**case** *Nil*  
**then show** *?case*  
**by** *simp*

```

next
case (Cons a ns)
show ?case
proof (cases i=0)
  case False
  then have augmentum (a # ns)!i = a + sum (!) ns {..i-1}
    using Cons.IH Cons.premis by auto
  also have ... = a + (∑ j∈{0<..i}. ns!(j-1))
    using sum.reindex [of Suc {..i - Suc 0} λj. ns!(j-1), symmetric] False
    by (simp add: image-Suc-atMost atLeastSucAtMost-greaterThanAtMost del:
sum.cl-ivl-Suc)
  also have ... = (∑ j = 0..i. if j=0 then a else ns!(j-1))
    by (simp add: sum.head)
  also have ... = sum (!) (a # ns) {..i}
    by (simp add: nth-Cons' atMost-atLeast0)
  finally show ?thesis .
qed auto
qed

lemma augmentum-dementum [simp]:
  assumes 0 ∉ set ns sorted ns
  shows augmentum (dementum ns) = ns
proof (rule nth-equalityI)
  fix i
  assume i < length (augmentum (dementum ns))
  then have i: i < length ns
    by simp
  show augmentum (dementum ns)!i = ns!i
  proof (cases i=0)
    case True
    then show ?thesis
      using nth-augmentum dementum-def i by auto
  next
  case False
  have ns-le: ∧j. [0 < j; j ≤ i] ⇒ ns ! (j - Suc 0) ≤ ns ! j
    using ‹sorted ns› i by (simp add: sorted-iff-nth-mono)
  have augmentum (dementum ns)!i = (∑ j≤i. ns!j - (if j = 0 then 0 else
ns!(j-1)))
    using i by (simp add: dementum-def nth-Cons')
  also have ... = (∑ j=0..i. if j = 0 then ns!0 else ns!j - ns!(j-1))
    by (smt (verit, del-insts) diff-zero sum.cong atMost-atLeast0)
  also have ... = ns!0 + (∑ j∈{0<..i}. ns!j - ns!(j-1))
    by (simp add: sum.head)
  also have ... = ns!0 + ((∑ j∈{0<..i}. ns!j) - (∑ j∈{0<..i}. ns!(j-1)))
    by (auto simp: ns-le intro: sum-subtractf-nat)
  also have ... = ns!0 + (∑ j∈{0<..i}. ns!j) - (∑ j∈{0<..i}. ns!(j-1))
  proof -
  have (∑ j∈{0<..i}. ns ! (j - 1)) ≤ sum (!) ns {0<..i}
    by (metis One-nat-def greaterThanAtMost-iff ns-le sum-mono)

```

**then show** *?thesis* **by** *simp*  
**qed**  
**also have**  $\dots = ns!0 + (\sum_{j \in \{0 <..i\}} ns!j) - (\sum_{j \leq i - Suc\ 0} ns!j)$   
**using** *sum.reindex [of Suc {..i - Suc 0}  $\lambda j. ns!(j-1)$ , symmetric] False*  
**by** (*simp add: image-Suc-atMost atLeastSucAtMost-greaterThanAtMost*)  
**also have**  $\dots = (\sum_{j=0..i} ns!j) - (\sum_{j \leq i - Suc\ 0} ns!j)$   
**by** (*simp add: sum.head [of 0 i]*)  
**also have**  $\dots = (\sum_{j=0..i - Suc\ 0} ns!j) + ns!i - (\sum_{j \leq i - Suc\ 0} ns!j)$   
**by** (*metis False Suc-pred less-Suc0 not-less-eq sum.atLeast0-atMost-Suc*)  
**also have**  $\dots = ns!i$   
**by** (*simp add: atLeast0AtMost*)  
**finally show** *augmentum (dementum ns)!i = ns!i* .  
**qed**  
**qed** *auto*

The following lemma corresponds to Lemma 2.9 in Gowers's notes. The proof involves introducing bijective maps between r-tuples that fulfill certain properties/r-tuples and subsets of naturals, so as to show the cardinality claim.

**lemma** *bound-sum-list-card*:

**assumes**  $r > 0$  **and**  $n \geq \sigma\ x'$  **and**  $len\ x' = r$

**defines**  $S \equiv \{x. x' \trianglelefteq x \wedge \sigma\ x = n\}$

**shows**  $card\ S = (n - \sigma\ x' + r - 1)$  *choose (r-1)*

**proof** –

**define**  $m$  **where**  $m \equiv n - \sigma\ x'$

**define**  $f$  **where**  $f \equiv \lambda x::nat\ list. x - x'$

**have**  $f$ : *bij-betw f S (length-sum-set r m)*

**proof** (*intro bij-betw-imageI*)

**show** *inj-on f S*

**using** *pairwise-minus-cancel* **by** (*force simp: S-def f-def inj-on-def*)

**have**  $\bigwedge x. x \in S \implies f\ x \in length-sum-set\ r\ m$

**by** (*simp add: S-def f-def length-sum-set-def lenx' m-def pointwise-le-iff sum-list-minus*)

**moreover have**  $x \in f^{-1}\ S$  **if**  $x \in length-sum-set\ r\ m$  **for**  $x$

**proof**

**have**  $x[simp]$ :  $length\ x = r$   $\sigma\ x = m$

**using** *that* **by** (*auto simp: length-sum-set-def*)

**have**  $x = x' + x - x'$

**by** (*rule nth-equalityI; simp add: lenx'*)

**then show**  $x = f\ (x' + x)$

**unfolding** *f-def* **by** *fastforce*

**have**  $x' \trianglelefteq x' + x$

**by** (*simp add: lenx' pointwise-le-plus*)

**moreover have**  $\sigma\ (x' + x) = n$

**by** (*simp add: lenx' m-def n sum-list-plus*)

**ultimately show**  $x' + x \in S$

**using** *S-def* **by** *blast*

**qed**

**ultimately show**  $f^{-1}\ S = length-sum-set\ r\ m$  **by** *auto*

```

qed
define g where g ≡ λx::nat list. map Suc x
define g' where g' ≡ λx::nat list. x - replicate (length x) 1
define T where T ≡ length-sum-set r (m+r) ∩ lists(-{0})
have g: bij-betw g (length-sum-set r m) T
proof (intro bij-betw-imageI)
  show inj-on g (length-sum-set r m)
  by (auto simp: g-def inj-on-def)
  have ∧x. x ∈ length-sum-set r m ⇒ g x ∈ T
  by (auto simp: g-def length-sum-set-def sum-list-Suc T-def)
  moreover have x ∈ g ' length-sum-set r m if x ∈ T for x
  proof
    have [simp]: length x = r
    using length-sum-set-def that T-def by auto
    have r1-x: replicate r (Suc 0) ≤ x
    using that unfolding T-def pointwise-le-iff-nth
    by (simp add: lists-def in-listsp-conv-set Suc-leI)
    show x = g (g' x)
    using that by (intro nth-equalityI) (auto simp: g-def g'-def T-def)
    show g' x ∈ length-sum-set r m
    using that T-def by (simp add: g'-def r1-x sum-list-minus length-sum-set-def
sum-list-replicate)
  qed
  ultimately show g ' (length-sum-set r m) = T by auto
qed
define U where U ≡ (insert (m+r)) ' finsets {0<..

```

**from that**  
**obtain**  $N$  **where**  $u: u = \text{insert } (m + r) N$  **and**  $Nsub: N \subseteq \{0 <..< m + r\}$   
**and**  $[simp]: \text{card } N = r - \text{Suc } 0$   
**by**  $(\text{auto simp: } U\text{-def finsets-def})$   
**have**  $[simp]: 0 \notin N \ m+r \notin N$   $\text{finite } N$   
**using**  $\text{finite-subset } Nsub$  **by**  $\text{auto}$   
**have**  $[simp]: \text{card } u = r$   
**using**  $Nsub \langle r > 0 \rangle$  **by**  $(\text{auto simp: } u \text{ card-insert-if})$   
**have**  $ssN: \text{sorted } (\text{sorted-list-of-set } N @ [m + r])$   
**using**  $Nsub$  **by**  $(\text{simp add: less-imp-le-nat sorted-wrt-append subset-eq})$   
**have**  $so-u-N: \text{sorted-list-of-set } u = \text{insort } (m+r) (\text{sorted-list-of-set } N)$   
**by**  $(\text{simp add: } u)$   
**also have**  $\dots = \text{sorted-list-of-set } N @ [m+r]$   
**using**  $Nsub$  **by**  $(\text{force intro: sorted-insort-is-snoc})$   
**finally have**  $so-u: \text{sorted-list-of-set } u = \text{sorted-list-of-set } N @ [m+r]$  .  
**have**  $0: 0 \notin \text{set } (\text{sorted-list-of-set } u)$   
**by**  $(\text{simp add: } \langle r > 0 \rangle \text{ set-insort-key so-u-N})$   
**show**  $u = (\text{set} \circ \text{augmentum}) ((\text{dementum} \circ \text{sorted-list-of-set})u)$   
**using**  $0 \text{ so-u } ssN \ u$  **by**  $\text{force}$   
**have**  $\text{sortd-wrt-u: sorted-wrt } (<) (\text{sorted-list-of-set } u)$   
**by**  $\text{simp}$   
**show**  $(\text{dementum} \circ \text{sorted-list-of-set}) u \in T$   
**apply**  $(\text{simp add: } T\text{-def length-sum-set-def})$   
**using**  $\text{sum-list-dementum } [OF \ ssN] \ \text{sortd-wrt-u } 0$  **by**  $(\text{force simp: so-u}$   
 $\text{dementum-nonzero})+$   
**qed**  
**ultimately show**  $(\text{set} \circ \text{augmentum}) ' T = U$  **by**  $\text{auto}$   
**qed**  
**obtain**  $\varphi$  **where**  $\text{bij-betw } \varphi \ S \ U$   
**by**  $(\text{meson bij-betw-trans } f \ g \ h)$   
**moreover have**  $\text{card } U = (n - \sigma \ x' + r - 1)$   $\text{choose } (r - 1)$   
**proof** –  
**have**  $\text{inj-on } (\text{insert } (m + r)) (\text{finsets } \{0 <..< m + r\} (r - \text{Suc } 0))$   
**by**  $(\text{simp add: inj-on-def finsets-def subset-iff}) (\text{meson insert-ident order-less-le})$   
**then have**  $\text{card } U = \text{card } (\text{finsets } \{0 <..< m + r\} (r - 1))$   
**unfolding**  $U\text{-def}$  **by**  $(\text{simp add: card-image})$   
**also have**  $\dots = (n - \sigma \ x' + r - 1)$   $\text{choose } (r - 1)$   
**by**  $(\text{simp add: card-finsets m-def})$   
**finally show**  $?thesis$  .  
**qed**  
**ultimately show**  $?thesis$   
**by**  $(\text{metis bij-betw-same-card})$   
**qed**

## 2.10 Towards the main theorem

lemma *extend-tuple*:

assumes  $\sigma \ xs \leq n$   $\text{length } xs \neq 0$

obtains  $ys$  **where**  $\sigma \ ys = n$   $xs \leq ys$

```

proof –
  obtain  $x\ xs'$  where  $xs: xs = x\#\ xs'$ 
    using assms list.exhaust by auto
  define  $y$  where  $y \equiv x + n - \sigma\ xs$ 
  show thesis
proof
  show  $\sigma\ (y\#\ xs') = n$ 
    using assms xs y-def by auto
  show  $xs \sqsubseteq y\#\ xs'$ 
    using assms y-def pointwise-le-def xs by auto
qed
qed

```

**lemma** *extend-preserving*:

```

assumes  $\sigma\ xs \leq n$   $length\ xs > 1$   $i < length\ xs$ 
obtains  $ys$  where  $\sigma\ ys = n$   $xs \sqsubseteq ys$   $ys!i = xs!i$ 
proof –
  define  $j$  where  $j \equiv Suc\ i\ mod\ length\ xs$ 
  define  $xs1$  where  $xs1 = take\ j\ xs$ 
  define  $xs2$  where  $xs2 = drop\ (Suc\ j)\ xs$ 
  define  $x$  where  $x = xs!j$ 
  have  $xs: xs = xs1\ @\ [x]\ @\ xs2$ 
    using assms
    apply (simp add: Cons-nth-drop-Suc assms x-def xs1-def xs2-def j-def)
    by (meson Suc-lessD id-take-nth-drop mod-less-divisor)
  define  $y$  where  $y \equiv x + n - \sigma\ xs$ 
  define  $ys$  where  $ys \equiv xs1\ @\ [y]\ @\ xs2$ 
  have  $x \leq y$ 
    using assms y-def by linarith
  show thesis
proof
  show  $\sigma\ ys = n$ 
    using assms(1) xs y-def ys-def by auto
  show  $xs \sqsubseteq ys$ 
    using xs ys-def  $\langle x \leq y \rangle$  pointwise-append-le-iff pointwise-le-def by fastforce
  have  $length\ xs1 \neq i$ 
    using assms by (simp add: xs1-def j-def min-def mod-Suc)
  then show  $ys!i = xs!i$ 
    by (auto simp: ys-def xs nth-append nth-Cons')
qed
qed

```

The proof of the main theorem will make use of the inclusion-exclusion formula, in addition to the previously shown results.

**theorem** *Khovanskii*:

```

assumes  $card\ A > 1$ 
defines  $f \equiv \lambda n. card(sumset-iterated\ A\ n)$ 
obtains  $N\ p$  where real-polynomial-function  $p \wedge n. n \geq N \implies real\ (f\ n) = p$ 
(real n)

```

**proof** –

**define**  $r$  **where**  $r \equiv \text{card } A$

**define**  $C$  **where**  $C \equiv \lambda n x'. \{x. x' \leq x \wedge \sigma x = n\}$

**define**  $X$  **where**  $X \equiv \text{minimal-elements } \{x. \text{useless } x \wedge \text{length } x = r\}$

**have**  $r > 1 \ r \neq 0$

**using**  $\text{assms } r\text{-def}$  **by**  $\text{auto}$

**have**  $C\text{sub}: C \ n \ x' \subseteq \text{length-sum-set } (\text{length } x') \ n$  **for**  $n \ x'$

**by**  $(\text{auto simp: } C\text{-def length-sum-set-def pointwise-le-iff})$

**then have**  $\text{fin}C: \text{finite } (C \ n \ x')$  **for**  $n \ x'$

**by**  $(\text{meson finite-length-sum-set finite-subset})$

**have**  $\text{finite } X$

**using**  $\text{minimal-elements-set-tuples-finite } X\text{-def}$  **by**  $\text{force}$

**then have**  $\text{max-}X: \bigwedge x'. x' \in X \implies \sigma x' \leq \sigma (\text{max-pointwise } r \ X)$

**using**  $X\text{-def max-pointwise-ge minimal-elements.simps pointwise-le-imp-}\sigma$  **by**

$\text{force}$

**let**  $?z0 = \text{replicate } r \ 0$

**have**  $Cn0: C \ n \ ?z0 = \text{length-sum-set } r \ n$  **for**  $n$

**by**  $(\text{auto simp: } C\text{-def length-sum-set-def})$

**then obtain**  $p0$  **where**  $\text{pf-p}0: \text{real-polynomial-function } p0$  **and**  $p0: \bigwedge n. n > 0$

$\implies p0 \ (\text{real } n) = \text{real } (\text{card } (C \ n \ ?z0))$

**by**  $(\text{metis real-polynomial-function-length-sum-set})$

**obtain**  $q$  **where**  $\text{pf-q}: \text{real-polynomial-function } q$  **and**  $q: \bigwedge x. q \ x = x \ \text{gchoose}$

$(r-1)$

**using**  $\text{real-polynomial-function-gchoose}$  **by**  $\text{metis}$

**define**  $p$  **where**  $p \equiv \lambda x::\text{real}. p0 \ x - (\sum Y \mid Y \subseteq X \wedge Y \neq \{\}. (-1) \wedge (\text{card } Y + 1) * q((x - \text{real}(\sigma (\text{max-pointwise } r \ Y)) + \text{real } r - 1)))$

**show**  $\text{thesis}$

**proof**

**note**  $\text{pf-q}' = \text{real-polynomial-function-compose } [OF \ - \ \text{pf-q}, \ \text{unfolded } o\text{-def}]$

**note**  $\text{pf-intros} = \text{real-polynomial-function-sum real-polynomial-function-diff}$

$\text{real-polynomial-function.intros}$

**show**  $\text{real-polynomial-function } p$

**unfolding**  $p\text{-def}$  **using**  $\langle \text{finite } X \rangle$  **by**  $(\text{intro pf-p}0 \ \text{pf-q}' \ \text{pf-intros} \mid \text{force})+$

**next**

**fix**  $n$

**assume**  $n \geq \text{max } 1 \ (\sigma (\text{max-pointwise } r \ X))$

**then have**  $n\text{large}: n \geq \sigma (\text{max-pointwise } r \ X)$  **and**  $n > 0$

**by**  $\text{auto}$

**define**  $U$  **where**  $U \equiv \lambda n. \text{length-sum-set } r \ n \cap \{x. \text{useful } x\}$

**have**  $2: (\text{length-sum-set } r \ n \cap \{x. \text{useless } x\}) = (\bigcup x' \in X. C \ n \ x')$

**unfolding**  $C\text{-def } X\text{-def length-sum-set-def } r\text{-def}$

**using**  $\text{useless-leq-useless}$  **by**  $(\text{force simp: minimal-elements.simps pointwise-le-iff}$

$\text{useless-iff})$

**define**  $SUM1$  **where**  $SUM1 \equiv \sum I \mid I \subseteq C \ n \ ' \ X \wedge I \neq \{\}. (-1) \wedge (\text{card } I$

$+ 1) * \text{int } (\text{card } (\bigcap I))$

**define**  $SUM2$  **where**  $SUM2 \equiv \sum Y \mid Y \subseteq X \wedge Y \neq \{\}. (-1) \wedge (\text{card } Y +$

$1) * \text{int } (\text{card } (\bigcap (C \ n \ ' \ Y)))$

**have**  $SUM1\text{-card}: \text{card}(\text{length-sum-set } r \ n \cap \{x. \text{useless } x\}) = \text{nat } SUM1$

**unfolding**  $SUM1\text{-def } 2$  **using**  $\langle \text{finite } X \rangle \ \text{fin}C$  **by**  $(\text{intro card-UNION}; \text{force})$

**have**  $SUM1 \geq 0$   
**unfolding**  $SUM1$ -def **using**  $card$ -UNION-nonneg  $finC$   $\langle finite X \rangle$  **by** *auto*  
**have**  $C$ -empty-iff:  $C n x' = \{\}$   $\leftrightarrow \sigma x' > n$  **if**  $length x' \neq 0$  **for**  $x'$   
**by** (*simp add: set-eq-iff C-def*) (*meson extend-tuple linorder-not-le pointwise-le-imp- $\sigma$  that*)  
**have**  $C$ -eq-1:  $C n x' = \{[n]\}$  **if**  $\sigma x' \leq n$   $length x' = 1$  **for**  $x'$   
**using** *that* **by** (*auto simp: C-def length-Suc-conv pointwise-le-def elim!: list.rel-cases*)  
**have**  $n$ -ge- $X$ :  $\sigma x \leq n$  **if**  $x \in X$  **for**  $x$   
**by** (*meson le-trans max-X nlarge that*)  
**have**  $len$ - $X$ - $r$ :  $x \in X \implies length x = r$  **for**  $x$   
**by** (*auto simp: X-def minimal-elements.simps*)

**have**  $min$ -pointwise  $r (C n x') = x'$  **if**  $r > 1$   $x' \in X$  **for**  $x'$   
**proof** (*rule pointwise-le-antisym*)  
**have** [*simp*]:  $length x' = r$   $\sigma x' \leq n$   
**using**  $X$ -def *minimal-elements.cases that*( $\mathcal{Q}$ )  $n$ -ge- $X$  **by** *auto*  
**have** [*simp*]:  $length (min$ -pointwise  $r (C n x')) = r$   
**by** (*simp add: min-pointwise-def*)  
**show**  $min$ -pointwise  $r (C n x') \trianglelefteq x'$   
**proof** (*clarsimp simp add: pointwise-le-iff-nth*)  
**fix**  $i$   
**assume**  $i < r$   
**then obtain**  $y$  **where**  $\sigma y = n \wedge x' \trianglelefteq y \wedge y!i \leq x'!i$   
**by** (*metis extend-preserving  $\langle 1 < r \rangle \langle length x' = r \rangle \langle x' \in X \rangle order.refl n$ -ge- $X$* )  
**then have**  $\exists y \in C n x'. y!i \leq x'!i$   
**using**  $C$ -def **by** *blast*  
**with**  $\langle i < r \rangle$  **show**  $min$ -pointwise  $r (C n x')!i \leq x'!i$   
**by** (*simp add: min-pointwise-def Min-le-iff finC C-empty-iff leD*)  
**qed**  
**have**  $x' \trianglelefteq min$ -pointwise  $r (C n x')$  **if**  $\sigma x' \leq n$   $length x' = r$  **for**  $x'$   
**by** (*smt (verit, del-insts) C-def C-empty-iff  $\langle r \neq 0 \rangle finC leD mem-Collect-eq min$ -pointwise-ge-iff pointwise-le-iff that*)  
**then show**  $x' \trianglelefteq min$ -pointwise  $r (C n x')$   
**using**  $X$ -def *minimal-elements.cases that* **by** *force*  
**qed**  
**then have**  $inj$ - $C$ :  $inj$ -on  $(C n) X$   
**by** (*smt (verit, best) inj-onI mem-Collect-eq  $\langle r > 1 \rangle$* )  
**have**  $inj$ -on-image $C$ :  $inj$ -on (*image*  $(C n)$ ) ( $Pow X - \{\{\}\}$ )  
**by** (*simp add: inj-C inj-on-diff inj-on-image-Pow*)

**have**  $Pow (C n ' X) - \{\{\}\} \subseteq (image (C n)) ' (Pow X - \{\{\}\})$   
**by** (*metis Pow-empty image-Pow-surj image-diff-subset image-empty*)  
**then have** (*image*  $(C n)$ ) ' ( $Pow X - \{\{\}\}$ ) =  $Pow (C n ' X) - \{\{\}\}$   
**by** *blast*  
**then have**  $SUM1 = sum (\lambda I. (- 1) ^ (card I + 1) * int (card (\bigcap I))) ((image (C n)) ' (Pow X - \{\{\}\}))$   
**unfolding**  $SUM1$ -def **by** (*auto intro: sum.cong*)

**also have**  $\dots = \text{sum } ((\lambda I. (- 1) \wedge (\text{card } I + 1) * \text{int } (\text{card } (\bigcap I))) \circ (\text{image } (C\ n))) (Pow\ X - \{\{\}\})$   
**by** (*simp add: sum.reindex inj-on-imageC*)  
**also have**  $\dots = SUM2$   
**unfolding** *SUM2-def* **using** *inj-on-subset [OF inj-C]* **by** (*force simp: card-image intro: sum.cong*)  
**finally have**  $SUM1 = SUM2$  .

**have**  $\text{length-sum-set } r\ n = (\text{length-sum-set } r\ n \cap \{x. \text{useful } x\}) \cup (\text{length-sum-set } r\ n \cap \{x. \text{useless } x\})$   
**by** *auto*  
**then have**  $\text{card } (\text{length-sum-set } r\ n) =$   
 $\text{card } (\text{length-sum-set } r\ n \cap \{x. \text{useful } x\}) +$   
 $\text{card } (\text{length-sum-set } r\ n \cap \text{Collect } \text{useless})$   
**by** (*simp add: finite-length-sum-set disjnt-iff flip: card-Un-disjnt*)  
**moreover have**  $C\ n\ ?z0 = \text{length-sum-set } r\ n$   
**by** (*auto simp: C-def length-sum-set-def*)  
**ultimately have**  $\text{card } (C\ n\ ?z0) = \text{card } (U\ n) + \text{nat } SUM2$   
**by** (*simp add: U-def flip: <SUM1 = SUM2> SUM1-card*)  
**then have**  $SUM2\text{-le: } \text{nat } SUM2 \leq \text{card } (C\ n\ ?z0)$   
**by** *arith*  
**have**  $\sigma\text{-max-pointwise-le: } \bigwedge Y. [Y \subseteq X; Y \neq \{\}] \implies \sigma (\text{max-pointwise } r\ Y)$   
 $\leq n$   
**by** (*meson <finite X> le-trans max-pointwise-mono nlarge pointwise-le-imp-σ*)

**have**  $\text{card-C-max: } \text{card } (C\ n (\text{max-pointwise } r\ Y)) =$   
 $(n - \sigma (\text{max-pointwise } r\ Y) + r - \text{Suc } 0 \text{ choose } (r - \text{Suc } 0))$   
**if**  $Y \subseteq X\ Y \neq \{\}$  **for**  $Y$   
**proof** -  
**have** [*simp*]:  $\text{length } (\text{max-pointwise } r\ Y) = r$   
**by** (*simp add: max-pointwise-def*)  
**then show** *?thesis*  
**using**  $\langle r \neq 0 \rangle$  **that** *C-def* **by** (*simp add: bound-sum-list-card [of r]*)  
 $\sigma\text{-max-pointwise-le}$   
**qed**

**define**  $SUM3$  **where**  $SUM3 \equiv (\sum Y \mid Y \subseteq X \wedge Y \neq \{\}.$   
 $- ((- 1) \wedge (\text{card } Y) * ((n - \sigma (\text{max-pointwise } r\ Y) + r - 1 \text{ choose } (r -$   
 $1))))))$   
**have**  $\bigcap (C\ n\ \text{' } Y) = C\ n (\text{max-pointwise } r\ Y)$  **if**  $Y \subseteq X\ Y \neq \{\}$  **for**  $Y$   
**proof**  
**show**  $\bigcap (C\ n\ \text{' } Y) \subseteq C\ n (\text{max-pointwise } r\ Y)$   
**unfolding** *C-def*  
**proof** *clarsimp*  
**fix**  $x$   
**assume**  $\forall y \in Y. y \trianglelefteq x \wedge \sigma\ x = n$   
**moreover have** *finite Y*  
**using**  $\langle \text{finite } X \rangle$  *infinite-super that* **by** *blast*  
**moreover have**  $\bigwedge u. u \in Y \implies \text{length } u = r$

```

    using len-X-r that by blast
    ultimately show max-pointwise r Y  $\leq$  x  $\wedge$   $\sigma$  x = n
      by (smt (verit, del-Insts) all-not-in-conv max-pointwise-le-iff point-
wise-le-iff-nth that(2))
    qed
  next
  show C n (max-pointwise r Y)  $\subseteq$   $\bigcap$  (C n ‘ Y)
    apply (clarsimp simp: C-def)
    by (metis ⟨finite X⟩ finite-subset len-X-r max-pointwise-ge pointwise-le-trans
subsetD that(1))
  qed
  then have SUM2 = SUM3
    by (simp add: SUM2-def SUM3-def card-C-max)
  have U n = C n ?z0 - (length-sum-set r n  $\cap$  {x. useless x})
    by (auto simp: U-def C-def length-sum-set-def)
  then have card (U n) = card (C n ?z0) - card(length-sum-set r n  $\cap$  {x. useless
x})
    using finite-length-sum-set
    by (simp add: C-def Collect-mono-iff inf.coboundedI1 length-sum-set-def flip:
card-Diff-subset)
  then have card-U-eq-diff: card (U n) = card (C n ?z0) - nat SUM1
    using SUM1-card by presburger
  have SUM3  $\geq$  0
    using ⟨0  $\leq$  SUM1⟩ ⟨SUM1 = SUM2⟩ ⟨SUM2 = SUM3⟩ by blast
  have **:  $\bigwedge Y. \llbracket Y \subseteq X; Y \neq \{\} \rrbracket \implies \text{Suc } (\sigma (\text{max-pointwise } r Y)) \leq n + r$ 
    by (metis ⟨1 < r⟩  $\sigma$ -max-pointwise-le add commute add-le-mono less-or-eq-imp-le
plus-1-eq-Suc)
  have real (f n) = card (U n)
    unfolding f-def r-def U-def length-sum-set-def
    using card-sumset-iterated-length-sum-set-useful length-sum-set-def by pres-
burger
  also have ... = card (C n ?z0) - nat SUM3
    using card-U-eq-diff ⟨SUM1 = SUM2⟩ ⟨SUM2 = SUM3⟩ by presburger
  also have ... = real (card (C n (replicate r 0))) - real (nat SUM3)
    using SUM2-le ⟨SUM2 = SUM3⟩ of-nat-diff by blast
  also have ... = p (real n)
    using ⟨1 < r⟩ ⟨n > 0⟩
    apply (simp add: p-def p0 q ⟨SUM3  $\geq$  0⟩)
    apply (simp add: SUM3-def binomial-gbinomial of-nat-diff  $\sigma$ -max-pointwise-le
algebra-simps **)
  done
  finally show real (f n) = p (real n) .
  qed
qed
end
end

```

## References

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