

The Plünnecke-Ruzsa Inequality

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Abstract

We formalise Plünnecke's inequality and the Plünnecke-Ruzsa inequality, following the notes by Timothy Gowers: "Introduction to Additive Combinatorics" (2022) for the University of Cambridge. To this end, we first introduce basic definitions and prove elementary facts on sumsets and difference sets. Then, we show two versions of the Ruzsa triangle inequality. We follow with a proof due to Petridis [1].

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1 The Plünnecke-Ruzsa Inequality

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We formalise Plünnecke's inequality and the Plünnecke-Ruzsa inequality, following the notes by Timothy Gowers: "Introduction to Additive Combinatorics" (2022) for the University of Cambridge. To this end, we first introduce basic definitions and prove elementary facts on sumsets and difference sets. Then, we show (two versions of) the Ruzsa triangle inequality. We follow with a proof due to Petridis.

```
theory Pluenecke-Ruzsa-Inequality
imports
  Jacobson-Basic-Algebra.Ring-Theory
  Complex-Main
```

```
begin
```

```
notation plus (infixl  $\langle + \rangle$  65)
notation minus (infixl  $\langle - \rangle$  65)
unbundle uminus-syntax
```

1.1 Key definitions (sumset, difference set) and basic lemmas

Working in an arbitrary Abelian group, with additive syntax

```
locale additive-abelian-group = abelian-group  $G$  ( $\oplus$ )  $\mathbf{0}$ 
for  $G$  and addition (infixl  $\langle \oplus \rangle$  65) and zero ( $\langle \mathbf{0} \rangle$ )
```

```
begin
```

```
abbreviation G-minus:: 'a  $\Rightarrow$  'a  $\Rightarrow$  'a (infixl  $\langle \ominus \rangle$  70)
where  $x \ominus y \equiv x \oplus$  inverse  $y$ 
```

```
lemma inverse-closed:  $x \in G \implies$  inverse  $x \in G$ 
  <proof>
```

1.1.1 Sumsets

```
inductive-set sumset :: 'a set  $\Rightarrow$  'a set  $\Rightarrow$  'a set for  $A B$ 
where
  sumsetI[intro]:  $\llbracket a \in A; a \in G; b \in B; b \in G \rrbracket \implies a \oplus b \in$  sumset  $A B$ 
```

```
lemma sumset-eq: sumset  $A B = \{c. \exists a \in A \cap G. \exists b \in B \cap G. c = a \oplus b\}$ 
  <proof>
```

```
lemma sumset: sumset  $A B = (\bigcup a \in A \cap G. \bigcup b \in B \cap G. \{a \oplus b\})$ 
  <proof>
```

lemma *sumset-subset-carrier*: $\text{sumset } A \ B \subseteq G$

<proof>

lemma *sumset-Int-carrier [simp]*: $\text{sumset } A \ B \cap G = \text{sumset } A \ B$

<proof>

lemma *sumset-mono*: $[[A' \subseteq A; B' \subseteq B]] \implies \text{sumset } A' \ B' \subseteq \text{sumset } A \ B$

<proof>

lemma *sumset-insert1*: *NO-MATCH* $\{\} A \implies \text{sumset } (\text{insert } x \ A) \ B = \text{sumset } \{x\} \ B \cup \text{sumset } A \ B$

<proof>

lemma *sumset-insert2*: *NO-MATCH* $\{\} B \implies \text{sumset } A \ (\text{insert } x \ B) = \text{sumset } A \ \{x\} \cup \text{sumset } A \ B$

<proof>

lemma *sumset-subset-Un1*: $\text{sumset } (A \cup A') \ B = \text{sumset } A \ B \cup \text{sumset } A' \ B$

<proof>

lemma *sumset-subset-Un2*: $\text{sumset } A \ (B \cup B') = \text{sumset } A \ B \cup \text{sumset } A \ B'$

<proof>

lemma *sumset-subset-insert*: $\text{sumset } A \ B \subseteq \text{sumset } A \ (\text{insert } x \ B) \ \text{sumset } A \ B \subseteq \text{sumset } (\text{insert } x \ A) \ B$

<proof>

lemma *sumset-subset-Un*: $\text{sumset } A \ B \subseteq \text{sumset } A \ (B \cup C) \ \text{sumset } A \ B \subseteq \text{sumset } (A \cup C) \ B$

<proof>

lemma *sumset-empty [simp]*: $\text{sumset } A \ \{\} = \{\} \ \text{sumset } \{\} \ A = \{\}$

<proof>

lemma *sumset-empty'*:

assumes $A \cap G = \{\}$

shows $\text{sumset } B \ A = \{\} \ \text{sumset } A \ B = \{\}$

<proof>

lemma *sumset-is-empty-iff [simp]*: $\text{sumset } A \ B = \{\} \longleftrightarrow A \cap G = \{\} \vee B \cap G = \{\}$

<proof>

lemma *sumset-D [simp]*: $\text{sumset } A \ \{\mathbf{0}\} = A \cap G \ \text{sumset } \{\mathbf{0}\} \ A = A \cap G$

<proof>

lemma *sumset-Int-carrier-eq [simp]*: $\text{sumset } A \ (B \cap G) = \text{sumset } A \ B \ \text{sumset } (A \cap G) \ B = \text{sumset } A \ B$

<proof>

lemma *sumset-assoc*:

shows $\text{sumset } (\text{sumset } A B) C = \text{sumset } A (\text{sumset } B C)$

<proof>

lemma *sumset-commute*:

shows $\text{sumset } A B = \text{sumset } B A$

<proof>

lemma *finite-sumset*:

assumes *finite* A *finite* B **shows** *finite* $(\text{sumset } A B)$

<proof>

lemma *finite-sumset'*:

assumes *finite* $(A \cap G)$ *finite* $(B \cap G)$

shows *finite* $(\text{sumset } A B)$

<proof>

lemma *sumsetdiff-sing*: $\text{sumset } (A - B) \{x\} = \text{sumset } A \{x\} - \text{sumset } B \{x\}$

<proof>

lemma *card-sumset-singleton-eq*:

assumes *finite* A **shows** $\text{card } (\text{sumset } A \{a\}) = (\text{if } a \in G \text{ then } \text{card } (A \cap G) \text{ else } 0)$

<proof>

lemma *card-sumset-le*:

assumes *finite* A **shows** $\text{card } (\text{sumset } A \{a\}) \leq \text{card } A$

<proof>

lemma *infinite-sumset-aux*:

assumes *infinite* $(A \cap G)$

shows $\text{infinite } (\text{sumset } A B) \longleftrightarrow B \cap G \neq \{\}$

<proof>

lemma *infinite-sumset-iff*:

shows $\text{infinite } (\text{sumset } A B) \longleftrightarrow \text{infinite } (A \cap G) \wedge B \cap G \neq \{\} \vee A \cap G \neq \{\} \wedge \text{infinite } (B \cap G)$

<proof>

lemma *card-le-sumset*:

assumes A : *finite* A $a \in A$ $a \in G$

and B : *finite* B $B \subseteq G$

shows $\text{card } B \leq \text{card } (\text{sumset } A B)$

<proof>

lemma *card-sumset-0-iff'*: $\text{card } (\text{sumset } A B) = 0 \longleftrightarrow \text{card } (A \cap G) = 0 \vee \text{card } (B \cap G) = 0$

<proof>

lemma *card-sumset-0-iff*:

assumes $A \subseteq G \ B \subseteq G$

shows $\text{card} (\text{sumset } A \ B) = 0 \iff \text{card } A = 0 \vee \text{card } B = 0$

<proof>

lemma *card-sumset-leq*:

assumes $A \subseteq G$

shows $\text{card}(\text{sumset } A \ A) \leq \text{Suc}(\text{card } A)$ *choose 2*

<proof>

1.1.2 Iterated sumsets

definition *sumset-iterated* :: 'a set \Rightarrow nat \Rightarrow 'a set

where *sumset-iterated* $A \ r \equiv \text{Finite-Set.fold} (\text{sumset} \circ (\lambda-. A)) \ \{\mathbf{0}\} \ \{..<r\}$

lemma *sumset-iterated-0 [simp]*: *sumset-iterated* $A \ 0 = \{\mathbf{0}\}$

<proof>

lemma *sumset-iterated-Suc [simp]*: *sumset-iterated* $A \ (\text{Suc } k) = \text{sumset } A \ (\text{sumset-iterated } A \ k)$

(is ?lhs = ?rhs)

<proof>

lemma *sumset-iterated-2*:

shows *sumset-iterated* $A \ 2 = \text{sumset } A \ A$

<proof>

lemma *sumset-iterated-r*: $r > 0 \implies \text{sumset-iterated } A \ r = \text{sumset } A \ (\text{sumset-iterated } A \ (r-1))$

<proof>

lemma *sumset-iterated-subset-carrier*: *sumset-iterated* $A \ k \subseteq G$

<proof>

lemma *finite-sumset-iterated*: *finite* $A \implies \text{finite} (\text{sumset-iterated } A \ r)$

<proof>

lemma *sumset-iterated-empty*: $r > 0 \implies \text{sumset-iterated } \{\} \ r = \{\}$

<proof>

1.1.3 Difference sets

inductive-set *minusset* :: 'a set \Rightarrow 'a set **for** A

where

minussetI[intro]: $\llbracket a \in A; a \in G \rrbracket \implies \text{inverse } a \in \text{minusset } A$

lemma *minusset-eq*: *minusset* $A = \text{inverse} \ ` (A \cap G)$

<proof>

abbreviation *differenceset* $A B \equiv \text{sumset } A (\text{minusset } B)$

lemma *minusset-is-empty-iff* [simp]: $\text{minusset } A = \{\}$ $\longleftrightarrow A \cap G = \{\}$
<proof>

lemma *minusset-triv* [simp]: $\text{minusset } \{\mathbf{0}\} = \{\mathbf{0}\}$
<proof>

lemma *minusset-subset-carrier*: $\text{minusset } A \subseteq G$
<proof>

lemma *minus-minusset* [simp]: $\text{minusset } (\text{minusset } A) = A \cap G$
<proof>

lemma *card-minusset* [simp]: $\text{card } (\text{minusset } A) = \text{card } (A \cap G)$
<proof>

lemma *card-minusset'*: $A \subseteq G \implies \text{card } (\text{minusset } A) = \text{card } A$
<proof>

lemma *diff-minus-set*:
 $\text{differenceset } (\text{minusset } A) B = \text{minusset } (\text{sumset } A B)$ (is ?lhs = ?rhs)
<proof>

lemma *differenceset-commute* [simp]:
shows $\text{minusset } (\text{differenceset } B A) = \text{differenceset } A B$
<proof>

lemma *card-differenceset-commute*: $\text{card } (\text{differenceset } B A) = \text{card } (\text{differenceset } A B)$
<proof>

lemma *minusset-distrib-sum*:
shows $\text{minusset } (\text{sumset } A B) = \text{sumset } (\text{minusset } A) (\text{minusset } B)$
<proof>

lemma *minusset-iterated-minusset*: $\text{sumset-iterated } (\text{minusset } A) k = \text{minusset } (\text{sumset-iterated } A k)$
<proof>

lemma *card-sumset-iterated-minusset*:
 $\text{card } (\text{sumset-iterated } (\text{minusset } A) k) = \text{card } (\text{sumset-iterated } A k)$
<proof>

lemma *finite-minusset*: $\text{finite } A \implies \text{finite } (\text{minusset } A)$
<proof>

lemma *finite-differenceset*: $finite\ A \implies finite\ B \implies finite\ (differenceset\ A\ B)$
 ⟨proof⟩

1.2 The Ruzsa triangle inequality

lemma *Ruzsa-triangle-ineq1*:
 assumes U : $finite\ U\ U \subseteq G$
 and V : $finite\ V\ V \subseteq G$
 and W : $finite\ W\ W \subseteq G$
 shows $(card\ U) * card(differenceset\ V\ W) \leq card\ (differenceset\ U\ V) * card\ (differenceset\ U\ W)$
 ⟨proof⟩

definition *Ruzsa-distance*:: 'a set \Rightarrow 'a set \Rightarrow real
 where $Ruzsa-distance\ A\ B \equiv card(differenceset\ A\ B) / (sqrt(card\ A) * sqrt(card\ B))$

lemma *Ruzsa-triangle-ineq2*:
 assumes U : $finite\ U\ U \subseteq G\ U \neq \{\}$
 and V : $finite\ V\ V \subseteq G$
 and W : $finite\ W\ W \subseteq G$
 shows $Ruzsa-distance\ V\ W \leq (Ruzsa-distance\ V\ U) * (Ruzsa-distance\ U\ W)$
 ⟨proof⟩

1.3 Petridis's proof of the Plünnecke-Ruzsa inequality

lemma *Plu-2-2*:
 assumes $K0$: $card\ (sumset\ A0\ B) \leq K0 * real\ (card\ A0)$
 and $A0$: $finite\ A0\ A0 \subseteq G\ A0 \neq \{\}$
 and B : $finite\ B\ B \subseteq G\ B \neq \{\}$
 obtains $A\ K$
 where $A \subseteq A0\ A \neq \{\}\ 0 < K\ K \leq K0$
 and $\bigwedge C. C \subseteq G \implies finite\ C \implies card\ (sumset\ A\ (sumset\ B\ C)) \leq K * real\ (card\ (sumset\ A\ C))$
 ⟨proof⟩

lemma *Cor-Plu-2-3*:
 assumes K : $card\ (sumset\ A\ B) \leq K * real\ (card\ A)$
 and A : $finite\ A\ A \subseteq G\ A \neq \{\}$
 and B : $finite\ B\ B \subseteq G$
 obtains A' where $A' \subseteq A\ A' \neq \{\}$
 $\bigwedge r. card\ (sumset\ A'\ (sumset-iterated\ B\ r)) \leq K^{\wedge r} * real\ (card\ A')$
 ⟨proof⟩

The following Corollary of the above is an important special case, also referred to as the original version of Plünnecke's inequality first shown by Plünnecke.

lemma *Cor-Plu-2-3-Pluenecke-ineq*:

assumes $K: \text{card}(\text{sumset } A B) \leq K * \text{real}(\text{card } A)$
and $A: \text{finite } A \ A \subseteq G \ A \neq \{\}$
and $B: \text{finite } B \ B \subseteq G$
shows $\text{real}(\text{card}(\text{sumset-iterated } B r)) \leq K \wedge r * \text{real}(\text{card } A)$
 <proof>

Special case where $B = A$

lemma *Cor-Plu-2-3-1*:
assumes $K: \text{card}(\text{sumset } A A) \leq K * \text{real}(\text{card } A)$
and $A: \text{finite } A \ A \subseteq G \ A \neq \{\}$
shows $\text{card}(\text{sumset-iterated } A r) \leq K \wedge r * \text{real}(\text{card } A)$
 <proof>

Special case where $B = - A$

lemma *Cor-Plu-2-3-2*:
assumes $K: \text{card}(\text{differenceset } A A) \leq K * \text{real}(\text{card } A)$
and $A: \text{finite } A \ A \subseteq G \ A \neq \{\}$
shows $\text{card}(\text{sumset-iterated } A r) \leq K \wedge r * \text{real}(\text{card } A)$
 <proof>

The following result is known as the Plünnecke-Ruzsa inequality (Theorem 2.5 in Gowers's notes). The proof will make use of the Ruzsa triangle inequality.

theorem *Pluenncke-Ruzsa-ineq*:
assumes $K: \text{card}(\text{sumset } A B) \leq K * \text{real}(\text{card } A)$
and $A: \text{finite } A \ A \subseteq G \ A \neq \{\}$
and $B: \text{finite } B \ B \subseteq G$
and $0 < r \ 0 < s$
shows $\text{card}(\text{differenceset}(\text{sumset-iterated } B r) (\text{sumset-iterated } B s)) \leq K \wedge (r+s) * \text{real}(\text{card } A)$
 <proof>

The following is an alternative version of the Plünnecke-Ruzsa inequality (Theorem 2.1 in Gowers's notes).

theorem *Pluenncke-Ruzsa-ineq-alt*:
assumes $\text{finite } A \ A \subseteq G$
and $\text{card}(\text{sumset } A A) \leq K * \text{real}(\text{card } A) \ r > 0 \ s > 0$
shows $\text{card}(\text{differenceset}(\text{sumset-iterated } A r) (\text{sumset-iterated } A s)) \leq K \wedge (r+s) * \text{real}(\text{card } A)$
 <proof>

theorem *Pluenncke-Ruzsa-ineq-alt-2*:
assumes $\text{finite } A \ A \subseteq G$
and $\text{card}(\text{differenceset } A A) \leq K * \text{real}(\text{card } A) \ r > 0 \ s > 0$
shows $\text{card}(\text{differenceset}(\text{sumset-iterated } A r) (\text{sumset-iterated } A s)) \leq K \wedge (r+s) * \text{real}(\text{card } A)$
 <proof>

end

1.4 Supplementary material on sumsets for sets of integers: basic inequalities

lemma *moninv-int: monoid.invertible UNIV (+) 0 u for u::int*
<proof>

interpretation *int: additive-abelian-group UNIV (+) 0::int*
<proof>

lemma *card-sumset-geq1:*
assumes *A: A ≠ {} finite A and B: B ≠ {} finite B*
shows *card(int.sumset A B) ≥ (card A) + (card B) - 1*
<proof>

lemma *card-sumset-geq2:*
shows *card(int.sumset A A) ≥ 2 * (card A) - 1*
<proof>

end

References

- [1] G. Petridis. The Plünnecke–Ruzsa inequality: An overview. In M. B. Nathanson, editor, *Combinatorial and Additive Number Theory*, pages 229–241. Springer, 2014.