Cardinality of Multisets

Lukas Bulwahn

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Abstract

This entry provides three lemmas to count the number of multisets of a given size and finite carrier set. The first lemma provides a cardinality formula assuming that the multiset's elements are chosen from the given carrier set. The latter two lemmas provide formulas assuming that the multiset's elements also cover the given carrier set, i.e., each element of the carrier set occurs in the multiset at least once.

The proof of the first lemma uses the argument of the recurrence relation for counting multisets [1]. The proof of the second lemma is straightforward, and the proof of the third lemma is easily obtained using the first cardinality lemma. A challenge for the formalization is the derivation of the required induction rule, which is a special combination of the induction rules for finite sets and natural numbers. The induction rule is derived by defining a suitable inductive predicate and transforming the predicate's induction rule.

Contents

1 Cardinality of Multisets

theory *Card-Multisets*
imports
HOL−Library.Multiset
begin

1.1 Additions to Multiset Theory

lemma *mset-set-set-mset-subseteq*:

mset-set (*set-mset* M) $\subseteq\#$ M
proof (*induct* M)
case *empty*
show *?case* **by** *simp*
next
case (*add* x M)
from *this* **show** *?case*
proof (*cases* $x \in\#$ M)
assume $x \in\#$ M
from *this* **have** *mset-set* (*set-mset* (M + $\{\#x\#\}$)) = *mset-set* (*set-mset* M)
by (*simp add*: *insert-absorb*)
from *this add.hyps* **show** *?thesis*
using *subset-mset.order.trans* **by** *fastforce*
next
assume $\neg$ $x \in\#$ M
from *this add.hyps* **have** $\{\#x\#\}$ + *mset-set* (*set-mset* M) $\subseteq\#$ M + $\{\#x\#\}$
by (*simp add*: *insert-subset-eq-iff*)
from *this* ‹$\neg$ $x \in\#$ M› **show** *?thesis* **by** *simp*
qed
qed

lemma *size-mset-set-eq-card*:
assumes *finite* A
shows *size* (*mset-set* A) = *card* A
using *assms* **by** (*induct* A) *auto*

lemma *card-set-mset-leq*:
card (*set-mset* M) $\leq$ *size* M
by (*induct* M) (*auto simp add*: *card-insert-le-m1*)

1.2 Lemma to Enumerate Sets of Multisets

lemma *set-of-multisets-eq*:
assumes $x \notin A$
shows $\{M.$ *set-mset* $M \subseteq$ *insert* x A $\wedge$ *size* M = *Suc* $k\}$ =
$\{M.$ *set-mset* $M \subseteq A$ $\wedge$ *size* M = *Suc* $k\}$ $\cup$
($\lambda M.$ M + $\{\#x\#\}$) ‘ $\{M.$ *set-mset* $M \subseteq$ *insert* x A $\wedge$ *size* M = $k\}$
proof −
from ‹$x \notin A$› **have** $\{M.$ *set-mset* $M \subseteq$ *insert* x A $\wedge$ *size* M = *Suc* $k\}$ =
$\{M.$ *set-mset* $M \subseteq A$ $\wedge$ *size* M = *Suc* $k\}$ $\cup$
$\{M.$ *set-mset* $M \subseteq$ *insert* x A $\wedge$ *size* M = *Suc* k $\wedge$ $x \in\#$ $M\}$
by *auto*
moreover have $\{M.$ *set-mset* $M \subseteq$ *insert* x A $\wedge$ *size* M = *Suc* k $\wedge$ $x \in\#$ $M\}$ =
($\lambda M.$ M + $\{\#x\#\}$) ‘ $\{M.$ *set-mset* $M \subseteq$ *insert* x A $\wedge$ *size* M = $k\}$ (**is** *?S* =
?T)
proof
show *?S* $\subseteq$ *?T*
proof
fix M

assume $M \in ?S$
from *this* **have** $M = M - \{\#x\#\} + \{\#x\#\}$ **by** *auto*
moreover have $M - \{\#x\#\} \in \{M.\ \mathit{set\text{-}mset}\ M \subseteq \mathit{insert}\ x\ A \wedge \mathit{size}\ M = k\}$
proof −
have $\mathit{set\text{-}mset}\ (M - \{\#x\#\} + \{\#x\#\}) \subseteq \mathit{insert}\ x\ A$
using ‹$M \in ?S$› **by** *force*
moreover have $\mathit{size}\ (M - \{\#x\#\} + \{\#x\#\}) = \mathit{Suc}\ k \wedge x \in\# M - \{\#x\#\} + \{\#x\#\}$
using ‹$M \in ?S$› **by** *force*
ultimately show *?thesis* **by** *force*
qed
ultimately show $M \in ?T$ **by** *auto*
qed
next
show $?T \subseteq ?S$ **by** *force*
qed
ultimately show *?thesis* **by** *auto*
qed

1.3 Derivation of Suitable Induction Rule

context
begin

private inductive $R :: 'a\ set \Rightarrow nat \Rightarrow bool$
where
finite $A \Longrightarrow R\ A\ 0$
| $R\ \{\}\ k$
| *finite* $A \Longrightarrow x \notin A \Longrightarrow R\ A\ (\mathit{Suc}\ k) \Longrightarrow R\ (\mathit{insert}\ x\ A)\ k \Longrightarrow R\ (\mathit{insert}\ x\ A)\ (\mathit{Suc}\ k)$

private lemma *R-eq-finite*:
$R\ A\ k \longleftrightarrow$ *finite* A
proof
assume $R\ A\ k$
from *this* **show** *finite* A **by** *cases auto*
next
assume *finite* A
from *this* **show** $R\ A\ k$
proof (*induct* A)
case *empty*
from *this* **show** *?case* **by** (*rule R.intros*(*2*))
next
case *insert*
from *this* **show** *?case*
proof (*induct* k)
case *0*
from *this* **show** *?case*

by (*intro R.intros*(*1*) *finite.insertI*)
next
case *Suc*
from *this* **show** *?case*
by (*metis R.simps Zero-neq-Suc diff-Suc-1*)
qed
qed
qed

lemma *finite-set-and-nat-induct*[*consumes 1*, *case-names zero empty step*]:
assumes *finite A*
assumes $\bigwedge A$. *finite A* $\Longrightarrow$ *P A 0*
assumes $\bigwedge k$. *P* {} *k*
assumes $\bigwedge A\ k\ x$. *finite A* $\Longrightarrow$ $x \notin A$ $\Longrightarrow$ *P A* (*Suc k*) $\Longrightarrow$ *P* (*insert x A*) *k* $\Longrightarrow$ *P* (*insert x A*) (*Suc k*)
shows *P A k*
proof −
from ‹*finite A*› **have** *R A k* **by** (*subst R-eq-finite*)
from *this assms*(*2*−*4*) **show** *?thesis* **by** (*induct A k*) *auto*
qed

end

1.4 Finiteness of Sets of Multisets

lemma *finite-multisets*:
assumes *finite A*
shows *finite* {*M*. *set-mset M* $\subseteq$ *A* $\wedge$ *size M* = *k*}
using *assms*
proof (*induct A k rule*: *finite-set-and-nat-induct*)
case *zero*
from *this* **show** *?case* **by** *auto*
next
case *empty*
from *this* **show** *?case* **by** *auto*
next
case (*step A k x*)
from *this* **show** *?case*
using *set-of-multisets-eq*[*OF* ‹$x \notin A$›] **by** *simp*
qed

1.5 Cardinality of Multisets

lemma *card-multisets*:
assumes *finite A*
shows *card* {*M*. *set-mset M* $\subseteq$ *A* $\wedge$ *size M* = *k*} = (*card A* + *k* − *1*) *choose k*
using *assms*
proof (*induct A k rule*: *finite-set-and-nat-induct*)
case (*zero A*)
assume *finite* (*A* :: *'a set*)

have $\{M.\ \textit{set-mset}\ M \subseteq A \wedge \textit{size}\ M = 0\} = \{\{\#\}\}$ **by** *auto*
from *this* **show** *card* $\{M.\ \textit{set-mset}\ M \subseteq A \wedge \textit{size}\ M = 0\} = \textit{card}\ A + 0 - 1\ \textit{choose}\ 0$
by *simp*
next
case (*empty k*)
show *card* $\{M.\ \textit{set-mset}\ M \subseteq \{\} \wedge \textit{size}\ M = k\} = \textit{card}\ \{\} + k - 1\ \textit{choose}\ k$
by (*cases k*) (*auto simp add*: *binomial-eq-0*)
next
case (*step A k x*)
let $?S_1 = \{M.\ \textit{set-mset}\ M \subseteq A \wedge \textit{size}\ M = \textit{Suc}\ k\}$
and $?S_2 = \{M.\ \textit{set-mset}\ M \subseteq \textit{insert}\ x\ A \wedge \textit{size}\ M = k\}$
assume *hyps1*: *card* $?S_1 = \textit{card}\ A + \textit{Suc}\ k - 1\ \textit{choose}\ \textit{Suc}\ k$
assume *hyps2*: *card* $?S_2 = \textit{card}\ (\textit{insert}\ x\ A) + k - 1\ \textit{choose}\ k$
have *finite-sets*: *finite* $?S_1$ *finite* $((\lambda M.\ M + \{\#x\#\})\ `\ ?S_2)$
using ⟨*finite A*⟩ **by** (*auto simp add*: *finite-multisets*)
have *inj*: *inj-on* $(\lambda M.\ M + \{\#x\#\})\ ?S_2$ **by** (*rule inj-onI*) *auto*
have *card* $\{M.\ \textit{set-mset}\ M \subseteq \textit{insert}\ x\ A \wedge \textit{size}\ M = \textit{Suc}\ k\} =$
card $(?S_1 \cup (\lambda M.\ M + \{\#x\#\})\ `\ ?S_2)$
using *set-of-multisets-eq* ⟨$x \notin A$⟩ **by** *fastforce*
also have $\ldots = \textit{card}\ ?S_1 + \textit{card}\ ((\lambda M.\ M + \{\#x\#\})\ `\ ?S_2)$
using *finite-sets* ⟨$x \notin A$⟩ **by** (*subst card-Un-disjoint*) *auto*
also have $\ldots = \textit{card}\ ?S_1 + \textit{card}\ ?S_2$
using *inj* **by** (*auto intro*: *card-image*)
also have $\ldots = \textit{card}\ A + \textit{Suc}\ k - 1\ \textit{choose}\ \textit{Suc}\ k + (\textit{card}\ (\textit{insert}\ x\ A) + k - 1\ \textit{choose}\ k)$
using *hyps1 hyps2* **by** *simp*
also have $\ldots = \textit{card}\ (\textit{insert}\ x\ A) + \textit{Suc}\ k - 1\ \textit{choose}\ \textit{Suc}\ k$
using ⟨$x \notin A$⟩ ⟨*finite A*⟩ **by** *simp*
finally show *?case* **.**
qed

lemma *card-too-small-multisets-covering-set*:
assumes *finite A*
assumes $k < \textit{card}\ A$
shows *card* $\{M.\ \textit{set-mset}\ M = A \wedge \textit{size}\ M = k\} = 0$
proof −
from ⟨$k < \textit{card}\ A$⟩ **have** *eq*: $\{M.\ \textit{set-mset}\ M = A \wedge \textit{size}\ M = k\} = \{\}$
using *card-set-mset-leq Collect-empty-eq leD* **by** *auto*
from *this* **show** *?thesis* **by** (*metis card-empty*)
qed

lemma *card-multisets-covering-set*:
assumes *finite A*
assumes $\textit{card}\ A \le k$
shows *card* $\{M.\ \textit{set-mset}\ M = A \wedge \textit{size}\ M = k\} = (k - 1)\ \textit{choose}\ (k - \textit{card}\ A)$
proof −
have $\{M.\ \textit{set-mset}\ M = A \wedge \textit{size}\ M = k\} = (\lambda M.\ M + \textit{mset-set}\ A)\ `$

$\{M.\ set\text{-}mset\ M \subseteq A \wedge size\ M = k - card\ A\}$ (**is** $?S = ?f\ `\ ?T$)
proof
show $?S \subseteq ?f\ `\ ?T$
proof
fix M
assume $M \in ?S$
from *this* **have** $M = M - mset\text{-}set\ A + mset\text{-}set\ A$
by (*auto simp add*: *mset-set-set-mset-subseteq subset-mset.diff-add*)
moreover from ‹$M \in ?S$› **have** $M - mset\text{-}set\ A \in ?T$
by (*auto simp add*: *mset-set-set-mset-subseteq size-Diff-submset size-mset-set-eq-card in-diffD*)
ultimately show $M \in ?f\ `\ ?T$ **by** *auto*
qed
next
from ‹*finite A*› ‹$card\ A \leq k$› **show** $?f\ `\ ?T \subseteq ?S$
by (*auto simp add*: *size-mset-set-eq-card*)+
qed
moreover have *inj-on ?f ?T* **by** (*rule inj-onI*) *auto*
ultimately have $card\ ?S = card\ ?T$ **by** (*simp add*: *card-image*)
also have $\ldots = card\ A + (k - card\ A) - 1\ choose\ (k - card\ A)$
using ‹*finite A*› **by** (*simp only*: *card-multisets*)
also have $\ldots = (k - 1)\ choose\ (k - card\ A)$
using ‹$card\ A \leq k$› **by** *auto*
finally show *?thesis* **.**
qed

end

References

[1] Wikipedia. Multiset — wikipedia, the free encyclopedia, 2016. [Online; accessed 23-June-2016].