Rank-Nullity Theorem in Linear Algebra

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Abstract

In this contribution, we present some formalizations based on the HOL-Multivariate-Analysis session of Isabelle. Firstly, a generalization of several theorems of such library are presented. Secondly, some definitions and proofs involving Linear Algebra and the four fundamental subspaces of a matrix are shown. Finally, we present a proof of the result known in Linear Algebra as the “Rank-Nullity Theorem”, which states that, given any linear map f from a finite dimensional vector space V to a vector space W, then the dimension of V is equal to the dimension of the kernel of f (which is a subspace of V) and the dimension of the range of f (which is a subspace of W). The proof presented here is based on the one given in [1]. As a corollary of the previous theorem, and taking advantage of the relationship between linear maps and matrices, we prove that, for every matrix A (which has associated a linear map between finite dimensional vector spaces), the sum of its null space and its column space (which is equal to the range of the linear map) is equal to the number of columns of A.

Contents

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1 Dual Order

theory *Dual-Order*
  imports *Main*
begin

1.1 Interpretation of dual wellorder based on wellorder

lemma *wf-wellorderI2*:
  assumes *wf*: *wf* $\{(x{::}'a{::}ord,\ y).\ y < x\}$
  assumes *lin*: *class.linorder* $(\lambda(x{::}'a)\ y{::}'a.\ y \le x)$ $(\lambda(x{::}'a)\ y{::}'a.\ y < x)$
  shows *class.wellorder* $(\lambda(x{::}'a)\ y{::}'a.\ y \le x)$ $(\lambda(x{::}'a)\ y{::}'a.\ y < x)$
  using *lin* **unfolding** *class.wellorder-def* **apply** (*rule conjI*)
  apply (*rule class.wellorder-axioms.intro*) **by** (*blast intro*: *wf-induct-rule* [*OF wf*])

lemma (**in** *preorder*) *tranclp-less'*: $(>)^{++} = (>)$
  by(*auto simp add*: *fun-eq-iff intro*: *less-trans elim*: *tranclp.induct*)

interpretation *dual-wellorder*: *wellorder* $(\ge){::}('a{::}\{linorder,\ finite\}{=>}'a{=>}bool)$ $(>)$
proof (*rule wf-wellorderI2*)
  show *wf* $\{(x :: 'a,\ y).\ y < x\}$
    by(*auto simp add*: *trancl-def tranclp-less' intro*!: *finite-acyclic-wf acyclicI*)
  show *class.linorder* $(\lambda(x{::}'a)\ y{::}'a.\ y \le x)$ $(\lambda(x{::}'a)\ y{::}'a.\ y < x)$

unfolding *class.linorder-def* **unfolding** *class.linorder-axioms-def* **unfolding** *class.order-def*
unfolding *class.preorder-def* **unfolding** *class.order-axioms-def* **by** *auto*
qed

1.2 Properties of the Greatest operator

lemma *dual-wellorder-Least-eq-Greatest*[*simp*]: *dual-wellorder.Least* = *Greatest*
by (*auto simp add*: *Greatest-def dual-wellorder.Least-def*)

lemmas *GreatestI* = *dual-wellorder.LeastI*[*unfolded dual-wellorder-Least-eq-Greatest*]
lemmas *GreatestI2-ex* = *dual-wellorder.LeastI2-ex*[*unfolded dual-wellorder-Least-eq-Greatest*]
lemmas *GreatestI2-wellorder* = *dual-wellorder.LeastI2-wellorder*[*unfolded dual-wellorder-Least-eq-Greatest*]
lemmas *GreatestI-ex* = *dual-wellorder.LeastI-ex*[*unfolded dual-wellorder-Least-eq-Greatest*]
lemmas *not-greater-Greatest* = *dual-wellorder.not-less-Least*[*unfolded dual-wellorder-Least-eq-Greatest*]
lemmas *GreatestI2* = *dual-wellorder.LeastI2*[*unfolded dual-wellorder-Least-eq-Greatest*]
lemmas *Greatest-ge* = *dual-wellorder.Least-le*[*unfolded dual-wellorder-Least-eq-Greatest*]

end

2 Class for modular arithmetic

theory *Mod-Type*
imports
HOL−Library.Numeral-Type
HOL−Analysis.Cartesian-Euclidean-Space
Dual-Order
begin

2.1 Definition and properties

Class for modular arithmetic. It is inspired by the locale mod_type.

class *mod-type* = *times* + *wellorder* + *neg-numeral* +
fixes *Rep* :: *'a* => *int*
and *Abs* :: *int* => *'a*
assumes *type*: *type-definition Rep Abs* {*0..<int CARD* (*'a*)}
and *size1*: *1* < *int CARD* (*'a*)
and *zero-def*: *0* = *Abs 0*
and *one-def*: *1* = *Abs 1*
and *add-def*: *x* + *y* = *Abs* ((*Rep x* + *Rep y*) *mod* (*int CARD* (*'a*)))
and *mult-def*: *x* ∗ *y* = *Abs* ((*Rep x* ∗ *Rep y*) *mod* (*int CARD* (*'a*)))
and *diff-def*: *x* − *y* = *Abs* ((*Rep x* − *Rep y*) *mod* (*int CARD* (*'a*)))
and *minus-def*: − *x* = *Abs* ((− *Rep x*) *mod* (*int CARD* (*'a*)))
and *strict-mono-Rep*: *strict-mono Rep*
begin

lemma *size0*: *0* < *int CARD* (*'a*)
using *size1* **by** *simp*

lemmas *definitions* =
zero-def one-def add-def mult-def minus-def diff-def

lemma *Rep-less-n*: $Rep\ x < int\ CARD\ ('a)$
by (*rule type-definition.Rep* [*OF type*, *simplified*, *THEN conjunct2*])

lemma *Rep-le-n*: $Rep\ x \leq int\ CARD\ ('a)$
by (*rule Rep-less-n* [*THEN order-less-imp-le*])

lemma *Rep-inject-sym*: $x = y \longleftrightarrow Rep\ x = Rep\ y$
by (*rule type-definition.Rep-inject* [*OF type*, *symmetric*])

lemma *Rep-inverse*: $Abs\ (Rep\ x) = x$
by (*rule type-definition.Rep-inverse* [*OF type*])

lemma *Abs-inverse*: $m \in \{0..{<}int\ CARD\ ('a)\} \Longrightarrow Rep\ (Abs\ m) = m$
by (*rule type-definition.Abs-inverse* [*OF type*])

lemma *Rep-Abs-mod*: $Rep\ (Abs\ (m\ mod\ int\ CARD\ ('a))) = m\ mod\ int\ CARD\ ('a)$
by (*simp add*: *Abs-inverse pos-mod-conj* [*OF size0*])

lemma *Rep-Abs-0*: $Rep\ (Abs\ 0) = 0$
apply (*rule Abs-inverse* [*of 0*])
using *size0* **by** *simp*

lemma *Rep-0*: $Rep\ 0 = 0$
by (*simp add*: *zero-def Rep-Abs-0*)

lemma *Rep-Abs-1*: $Rep\ (Abs\ 1) = 1$
by (*simp add*: *Abs-inverse size1*)

lemma *Rep-1*: $Rep\ 1 = 1$
by (*simp add*: *one-def Rep-Abs-1*)

lemma *Rep-mod*: $Rep\ x\ mod\ int\ CARD\ ('a) = Rep\ x$
apply (*rule-tac x=x* **in** *type-definition.Abs-cases* [*OF type*])
apply (*simp add*: *type-definition.Abs-inverse* [*OF type*])
done

lemmas *Rep-simps* =
Rep-inject-sym Rep-inverse Rep-Abs-mod Rep-mod Rep-Abs-0 Rep-Abs-1

2.2 Conversion between a modular class and the subset of natural numbers associated.

Definitions to make transformations among elements of a modular class and naturals

```
definition to-nat :: 'a => nat
  where to-nat = nat ∘ Rep

definition Abs' :: int => 'a
  where Abs' x = Abs(x mod int CARD ('a))

definition from-nat :: nat ⇒ 'a
  where from-nat = (Abs' ∘ int)

lemma bij-Rep: bij-betw (Rep) (UNIV::'a set) {0..<int CARD('a)}
proof (unfold bij-betw-def, rule conjI)
  show inj Rep by (metis strict-mono-imp-inj-on strict-mono-Rep)
 show range Rep = {0..<int CARD('a)} using Typedef.type-definition.Rep-range[OF
type] .
qed

lemma mono-Rep: mono Rep by (metis strict-mono-Rep strict-mono-mono)

lemma Rep-ge-0: 0 ≤ Rep x using bij-Rep unfolding bij-betw-def by auto

lemma bij-Abs: bij-betw (Abs) {0..<int CARD('a)} (UNIV::'a set)
proof (unfold bij-betw-def, rule conjI)
 show inj-on Abs {0..<int CARD('a)} by (metis inj-on-inverseI type type-definition.Abs-inverse)
 show Abs ` {0..<int CARD('a)} = (UNIV::'a set) by (metis type type-definition.univ)
qed

corollary bij-Abs': bij-betw (Abs') {0..<int CARD('a)} (UNIV::'a set)
proof (unfold bij-betw-def, rule conjI)
  show inj-on Abs' {0..<int CARD('a)}
    unfolding inj-on-def Abs'-def
    by (auto, metis Rep-Abs-mod mod-pos-pos-trivial)
  show Abs' ` {0..<int CARD('a)} = (UNIV::'a set)
  proof (unfold image-def Abs'-def, auto)
    fix x show ∃xa∈{0..<int CARD('a)}. x = Abs xa
     by (rule bexI[of - Rep x], auto simp add: Rep-less-n[of x] Rep-ge-0[of x], metis
Rep-inverse)
  qed
qed

lemma bij-from-nat: bij-betw (from-nat) {0..<CARD('a)} (UNIV::'a set)
proof (unfold bij-betw-def, rule conjI)
  have set-eq: {0::int..<int CARD('a)} = int` {0..<CARD('a)} apply (auto)
  proof -
    fix x::int  assume x1: (0::int) ≤ x and x2: x < int CARD('a) show x ∈ int
` {0::nat..<CARD('a)}
    proof (unfold image-def, auto, rule bexI[of - nat x])
      show  x = int (nat x) using x1 by auto
      show nat x ∈ {0::nat..<CARD('a)} using x1 x2 by auto
    qed
```

qed
show *inj-on* (*from-nat*::*nat*⇒′*a*) {*0*::*nat*..<*CARD*(′*a*)}
proof (*unfold from-nat-def* , *rule comp-inj-on*)
show *inj-on int* {*0*::*nat*..<*CARD*(′*a*)} **by** (*metis inj-of-nat subset-inj-on top-greatest*)
show *inj-on* (*Abs*′::*int*=>′*a*) (*int* ‘ {*0*::*nat*..<*CARD*(′*a*)})
using *bij-Abs* **unfolding** *bij-betw-def set-eq*
by (*metis* (*opaque-lifting*, *no-types*) *Abs*′*-def Abs-inverse Rep-inverse Rep-mod inj-on-def set-eq*)
qed
show (*from-nat*::*nat*=>′*a*)‘ {*0*::*nat*..<*CARD*(′*a*)} = *UNIV*
unfolding *from-nat-def* **using** *bij-Abs*′
unfolding *bij-betw-def set-eq o-def* **by** *blast*
qed

lemma *to-nat-is-inv*: *the-inv-into* {*0*..<*CARD*(′*a*)} (*from-nat*::*nat*=>′*a*) = (*to-nat*::′*a*=>*nat*)
proof (*unfold the-inv-into-def fun-eq-iff from-nat-def to-nat-def o-def*, *clarify*)
fix *x*::′*a* **show** (*THE y*::*nat*. *y* ∈ {*0*::*nat*..<*CARD*(′*a*)} ∧ *Abs*′ (*int y*) = *x*) = *nat* (*Rep x*)
proof (*rule the-equality*, *auto*)
show *Abs*′ (*Rep x*) = *x* **by** (*metis Abs*′*-def Rep-inverse Rep-mod*)
show *nat* (*Rep x*) < *CARD*(′*a*) **by** (*metis* (*full-types*) *Rep-less-n nat-int size0 zless-nat-conj*)
assume *x*: ¬ (*0*::*int*) ≤ *Rep x* **show** (*0*::*nat*) < *CARD*(′*a*) **and** *Abs*′ (*0*::*int*) = *x*
using *Rep-ge-0 x* **by** *auto*
next
fix *y*::*nat* **assume** *y*: *y* < *CARD*(′*a*)
have (*Rep*(*Abs*′(*int y*)::′*a*)) = (*Rep*((*Abs*(*int y mod int CARD*(′*a*)))::′*a*)) **unfolding** *Abs*′*-def* **..**
also have ... = (*Rep* (*Abs* (*int y*)::′*a*)) **using** *zmod-int*[*of y CARD*(′*a*)]
using *y mod-less* **by** *auto*
also have ... = (*int y*) **proof** (*rule Abs-inverse*) **show** *int y* ∈ {*0*::*int*..<*int CARD*(′*a*)}
using *y* **by** *auto* **qed**
finally show *y* = *nat* (*Rep* (*Abs*′ (*int y*)::′*a*)) **by** (*metis nat-int*)
qed
qed

lemma *bij-to-nat*: *bij-betw* (*to-nat*) (*UNIV*::′*a set*) {*0*..<*CARD*(′*a*)}
using *bij-betw-the-inv-into*[*OF bij-from-nat*] **unfolding** *to-nat-is-inv* **.**

lemma *finite-mod-type*: *finite* (*UNIV*::′*a set*)
using *finite-imageD*[*of to-nat UNIV*::′*a set*] **using** *bij-to-nat* **unfolding** *bij-betw-def* **by** *auto*

subclass (**in** *mod-type*) *finite* **by** (*intro-classes*, *rule finite-mod-type*)

lemma *least-0*: (*LEAST n*. *n* ∈ (*UNIV*::′*a set*)) = *0*
proof (*rule Least-equality*, *auto*)

fix *y*::′*a*
have (*0*::′*a*) ≤ *Abs* (*Rep y mod int CARD*(′*a*)) **using** *strict-mono-Rep* **unfolding** *strict-mono-def*
by (*metis* (*opaque-lifting*, *mono-tags*) *Rep-0 Rep-ge-0 strict-mono-Rep strict-mono-less-eq*)
also have ... = *y* **by** (*metis Rep-inverse Rep-mod*)
finally show (*0*::′*a*) ≤ *y* **.**
qed

lemma *add-to-nat-def*: *x* + *y* = *from-nat* (*to-nat x* + *to-nat y*)
unfolding *from-nat-def to-nat-def o-def* **using** *Rep-ge-0*[*of x*] **using** *Rep-ge-0*[*of y*]
using *Rep-less-n*[*of x*] *Rep-less-n*[*of y*]
unfolding *Abs*′*-def* **unfolding** *add-def*[*of x y*] **by** *auto*

lemma *to-nat-1*: *to-nat 1* = *1*
by (*simp add*: *to-nat-def Rep-1*)

lemma *add-def*′:
shows *x* + *y* = *Abs*′ (*Rep x* + *Rep y*) **unfolding** *Abs*′*-def* **using** *add-def* **by** *simp*

lemma *Abs*′*-0*:
shows *Abs*′ (*CARD*(′*a*))=(*0*::′*a*) **by** (*metis* (*opaque-lifting*, *mono-tags*) *Abs*′*-def mod-self zero-def*)

lemma *Rep-plus-one-le-card*:
assumes *a*: *a* + *1* ≠ *0*
shows (*Rep a*) + *1* < *CARD* (′*a*)
proof (*rule ccontr*)
assume ¬ *Rep a* + *1* < *CARD*(′*a*) **hence** *to-nat-eq-card*: *Rep a* + *1* = *CARD*(′*a*)
using *Rep-less-n*
by (*simp add*: *add1-zle-eq order-class.less-le*)
have *a*+*1* = *Abs*′ (*Rep a* + *Rep* (*1*::′*a*)) **using** *add-def*′ **by** *auto*
also have ... = *Abs*′ ((*Rep a*) + *1*) **using** *Rep-1* **by** *simp*
also have ... = *Abs*′ (*CARD*(′*a*)) **unfolding** *to-nat-eq-card* **..**
also have ... = *0* **using** *Abs*′*-0* **by** *auto*
finally show *False* **using** *a* **by** *contradiction*
qed

lemma *to-nat-plus-one-less-card*: ∀ *a*. *a*+*1* ≠ *0* −−> *to-nat a* + *1* < *CARD*(′*a*)
proof (*clarify*)
fix *a*
assume *a*: *a* + *1* ≠ *0*
have *Rep a* + *1* < *int CARD*(′*a*) **using** *Rep-plus-one-le-card*[*OF a*] **by** *auto*
hence *nat* (*Rep a* + *1*) < *nat* (*int CARD*(′*a*)) **unfolding** *zless-nat-conj* **using** *size0* **by** *fast*
thus *to-nat a* + *1* < *CARD*(′*a*) **unfolding** *to-nat-def o-def* **using** *nat-add-distrib*[*OF Rep-ge-0*] **by** *simp*
qed

corollary *to-nat-plus-one-less-card'*:
assumes $a+1 \neq 0$
shows *to-nat* $a + 1 < CARD('a)$ **using** *to-nat-plus-one-less-card assms* **by** *simp*

lemma *strict-mono-to-nat*: *strict-mono to-nat*
  using *strict-mono-Rep*
   unfolding *strict-mono-def to-nat-def* **using** *Rep-ge-0* **by** (*metis comp-apply nat-less-eq-zless*)

lemma *to-nat-eq* [*simp*]: *to-nat* $x =$ *to-nat* $y \longleftrightarrow x = y$
  using *injD* [*OF bij-betw-imp-inj-on*[*OF bij-to-nat*]] **by** *blast*

lemma *mod-type-forall-eq* [*simp*]: $(\forall j::'a.$ (*to-nat* $j) < CARD('a) \longrightarrow P\ j) = (\forall a.\ P\ a)$
proof (*auto*)
  fix *a* **assume** *a*: $\forall j.$ (*to-nat*::'a=>nat) $j < CARD('a) \longrightarrow P\ j$
  have (*to-nat*::'a=>nat) $a < CARD('a)$ **using** *bij-to-nat* **unfolding** *bij-betw-def* **by** *auto*
  thus $P\ a$ **using** *a* **by** *auto*
qed

lemma *to-nat-from-nat*:
  assumes *t*:*to-nat* $j = k$
  shows *from-nat* $k = j$
proof −
  have *from-nat* k = *from-nat* (*to-nat* j) **unfolding** *t* **..**
 also have ... = *from-nat* (*the-inv-into* $\{0..<CARD('a)\}$ (*from-nat*) j) **unfolding** *to-nat-is-inv* **..**
  also have ... = j
  proof (*rule f-the-inv-into-f*)
   show *inj-on from-nat* $\{0..<CARD('a)\}$ **by** (*metis bij-betw-imp-inj-on bij-from-nat*)
   show $j \in$ *from-nat* ‘ $\{0..<CARD('a)\}$ **by** (*metis UNIV-I bij-betw-def bij-from-nat*)
  qed
  finally show *from-nat* $k = j$ **.**
qed

lemma *to-nat-mono*:
  assumes *ab*: $a < b$
  shows *to-nat* $a <$ *to-nat* b
  using *strict-mono-to-nat* **unfolding** *strict-mono-def* **using** *assms* **by** *fast*

lemma *to-nat-mono'*:
  assumes *ab*: $a \leq b$
  shows *to-nat* $a \leq$ *to-nat* b
proof (*cases* $a=b$)
  case *True* **thus** *?thesis* **by** *auto*
next
  case *False*

hence $a<b$ **using** *ab* **by** *simp*
thus *?thesis* **using** *to-nat-mono* **by** *fastforce*
qed

lemma *least-mod-type*:
shows $0 \leq (n::'a)$
using *least-0* **by** (*metis* (*full-types*) *Least-le UNIV-I*)

lemma *to-nat-from-nat-id*:
assumes *x*: $x<CARD('a)$
shows *to-nat* ((*from-nat x*)::$'a$) = *x*
unfolding *to-nat-is-inv*[*symmetric*] **proof** (*rule the-inv-into-f-f*)
show *inj-on* (*from-nat*::*nat*=>$'a$) $\{0..<CARD('a)\}$ **using** *bij-from-nat* **unfolding** *bij-betw-def* **by** *auto*
show $x \in \{0..<CARD('a)\}$ **using** *x* **by** *simp*
qed

lemma *from-nat-to-nat-id*[*simp*]:
shows *from-nat* (*to-nat x*) = *x* **by** (*metis to-nat-from-nat*)

lemma *from-nat-to-nat*:
assumes *t*:*from-nat j* = *k* **and** *j*: $j<CARD('a)$
shows *to-nat k* = *j* **by** (*metis j t to-nat-from-nat-id*)

lemma *from-nat-mono*:
assumes *i-le-j*: $i<j$ **and** *j*: $j<CARD('a)$
shows (*from-nat i*::$'a$) < *from-nat j*
proof −
have *i*: $i<CARD('a)$ **using** *i-le-j j* **by** *simp*
obtain *a* **where** *a*: *i*=*to-nat a*
using *bij-to-nat* **unfolding** *bij-betw-def* **using** *i to-nat-from-nat-id* **by** *metis*
obtain *b* **where** *b*: *j*=*to-nat b*
using *bij-to-nat* **unfolding** *bij-betw-def* **using** *j to-nat-from-nat-id* **by** *metis*
show *?thesis* **by** (*metis a b from-nat-to-nat-id i-le-j strict-mono-less strict-mono-to-nat*)
qed

lemma *from-nat-mono'*:
assumes *i-le-j*: $i \leq j$ **and** $j<CARD\ ('a)$
shows (*from-nat i*::$'a$) $\leq$ *from-nat j*
proof (*cases i*=*j*)
case *True*
have (*from-nat i*::$'a$) = *from-nat j* **using** *True* **by** *simp*
thus *?thesis* **by** *simp*
next
case *False*
hence $i<j$ **using** *i-le-j* **by** *simp*
thus *?thesis* **by** (*metis assms*(*2*) *from-nat-mono less-imp-le*)
qed

lemma *to-nat-suc*:
 assumes *to-nat* (*x*)+*1* < *CARD* ('*a*)
 shows *to-nat* (*x* + *1*::'*a*) = (*to-nat* *x*) + *1*
proof −
 have (*x*::'*a*) + *1* = *from-nat* (*to-nat* *x* + *to-nat* (*1*::'*a*)) **unfolding** *add-to-nat-def* **..**
 hence *to-nat* ((*x*::'*a*) + *1*) = *to-nat* (*from-nat* (*to-nat* *x* + *to-nat* (*1*::'*a*))::'*a*) **by** *presburger*
 also have ... = *to-nat* (*from-nat* (*to-nat* *x* + *1*)::'*a*) **unfolding** *to-nat-1* **..**
 also have ... = (*to-nat* *x* + *1*) **by** (*metis* *assms* *to-nat-from-nat-id*)
 finally show *?thesis* **.**
qed

lemma *to-nat-le*:
 assumes *y* < *from-nat* *k*
 shows *to-nat* *y* < *k*
proof (*cases* *k*<*CARD*('*a*))
 case *True* **show** *?thesis* **by** (*metis* (*full-types*) *True* *assms* *to-nat-from-nat-id* *to-nat-mono*)
next
 case *False* **have** *to-nat* *y* < *CARD* ('*a*) **using** *bij-to-nat* **unfolding** *bij-betw-def* **by** *auto*
 thus *?thesis* **using** *False* **by** *auto*
qed

lemma *le-Suc*:
 assumes *ab*: *a* < (*b*::'*a*)
 shows *a* + *1* ≤ *b*
proof −
 have *a* + *1* = (*from-nat* (*to-nat* (*a* + *1*))::'*a*) **using** *from-nat-to-nat-id* [*of* *a*+*1*,*symmetric*] **.**
 also have ... ≤ (*from-nat* (*to-nat* (*b*::'*a*))::'*a*)
 proof (*rule* *from-nat-mono'*)
  have *to-nat* *a* < *to-nat* *b* **using** *ab* **by** (*metis* *to-nat-mono*)
  hence *to-nat* *a* + *1* ≤ *to-nat* *b* **by** *simp*
  thus *to-nat* *b* < *CARD* ('*a*) **using** *bij-to-nat* **unfolding** *bij-betw-def* **by** *auto*
  hence *to-nat* *a* + *1* < *CARD* ('*a*) **by** (*metis* ‹*to-nat* *a* + *1* ≤ *to-nat* *b*› *preorder-class.le-less-trans*)
  thus *to-nat* (*a* + *1*) ≤ *to-nat* *b* **by** (*metis* ‹*to-nat* *a* + *1* ≤ *to-nat* *b*› *to-nat-suc*)
 qed
 also have ... = *b* **by** (*metis* *from-nat-to-nat-id*)
 finally show *a* + (*1*::'*a*) ≤ *b* **.**
qed

lemma *le-Suc'*:
assumes *ab*: *a* + *1* ≤ *b*
 and *less-card*: (*to-nat* *a*) + *1* < *CARD* ('*a*)
 shows *a* < *b*
proof −

have $a = (from\text{-}nat\ (to\text{-}nat\ a)::'a)$ **using** *from-nat-to-nat-id* [*of a,symmetric*] **.**
also have ... $<$ (*from-nat* (*to-nat* b)::$'a$)
proof (*rule from-nat-mono*)
show *to-nat* $b <$ *CARD*($'a$) **using** *bij-to-nat* **unfolding** *bij-betw-def* **by** *auto*
have *to-nat* $(a + 1) \leq$ *to-nat* b **using** *ab* **by** (*metis to-nat-mono'*)
hence *to-nat* $(a) + 1 \leq$ *to-nat* b **using** *to-nat-suc*[*OF less-card*] **by** *auto*
thus *to-nat* $a <$ *to-nat* b **by** *simp*
qed
finally show $a < b$ **by** (*metis to-nat-from-nat*)
qed

lemma *Suc-le*:
assumes *less-card*: (*to-nat* a) $+ 1 <$ *CARD* ($'a$)
shows $a < a + 1$
proof $-$
have (*to-nat* a) $<$ (*to-nat* a) $+ 1$ **by** *simp*
hence (*to-nat* a) $<$ *to-nat* $(a + 1)$ **by** (*metis less-card to-nat-suc*)
hence (*from-nat* (*to-nat* a)::$'a$) $<$ *from-nat* (*to-nat* $(a + 1)$)
by (*rule from-nat-mono*, *metis less-card to-nat-suc*)
thus $a < a + 1$ **by** (*metis to-nat-from-nat*)
qed

lemma *Suc-le'*:
fixes $a::'a$
assumes $a + 1 \neq 0$
shows $a < a + 1$ **using** *Suc-le to-nat-plus-one-less-card assms* **by** *blast*

lemma *from-nat-not-eq*:
assumes *a-eq-to-nat*: $a \neq$ *to-nat* b
and *a-less-card*: $a<$*CARD*($'a$)
shows *from-nat* $a \neq b$
proof (*rule ccontr*)
assume $\neg$ *from-nat* $a \neq b$ **hence** *from-nat* $a = b$ **by** *simp*
hence *to-nat* ((*from-nat* a)::$'a$) $=$ *to-nat* b **by** *auto*
thus *False* **by** (*metis a-eq-to-nat a-less-card to-nat-from-nat-id*)
qed

lemma *Suc-less*:
fixes $i::'a$
assumes $i<j$
and $i+1 \neq j$
shows $i+1<j$ **by** (*metis assms le-Suc le-neq-trans*)

lemma *Greatest-is-minus-1*: $\forall\ a::'a.\ a \leq -1$
proof (*clarify*)
fix $a::'a$
have *zero-ge-card-1*: $0 \leq$ *int CARD*($'a$) $- 1$ **using** *size1* **by** *auto*
have *card-less*: *int CARD*($'a$) $- 1 <$ *int CARD*($'a$) **by** *auto*

have *not-zero*: *1 mod int CARD*('*a*) $\neq$ *0*
by (*metis* (*opaque-lifting*, *mono-tags*) *Rep-Abs-1 Rep-mod zero-neq-one*)
have *int-card*: *int* (*CARD*('*a*) − *1*) = *int CARD*('*a*) − *1* **using** *of-nat-diff*[*of 1 CARD* ('*a*)]
using *size1* **by** *simp*
have *a* = *Abs'* (*Rep a*) **by** (*metis* (*opaque-lifting*, *mono-tags*) *Rep-0 add-0-right add-def'*
monoid-add-class.add.right-neutral)
also have ... = *Abs'* (*int* (*nat* (*Rep a*))) **by** (*metis Rep-ge-0 int-nat-eq*)
also have ... $\leq$ *Abs'* (*int* (*CARD*('*a*) − *1*))
proof (*rule from-nat-mono'*[*unfolded from-nat-def o-def*, *of nat* (*Rep a*) *CARD*('*a*) − *1*])
show *nat* (*Rep a*) $\leq$ *CARD*('*a*) − *1* **using** *Rep-less-n*
using *int-card nat-le-iff* **by** *auto*
show *CARD*('*a*) − *1* < *CARD*('*a*) **using** *finite-UNIV-card-ge-0 finite-mod-type* **by** *fastforce*
qed
also have ... = − *1*
unfolding *Abs'-def* **unfolding** *minus-def zmod-zminus1-eq-if* **unfolding** *Rep-1*
apply (*rule cong* [*of Abs*], *rule refl*)
unfolding *if-not-P* [*OF not-zero*]
unfolding *int-card*
unfolding *mod-pos-pos-trivial*[*OF zero-ge-card-1 card-less*]
using *mod-pos-pos-trivial*[*OF - size1*] **by** *presburger*
finally show *a* $\leq$ −*1* **by** *fastforce*
qed

lemma *a-eq-minus-1*: ∀ *a*::'*a*. *a*+*1* = *0* ⟶ *a* = −*1*
by (*metis eq-neg-iff-add-eq-0*)

lemma *forall-from-nat-rw*:
shows (∀ *x*∈{*0*..<*CARD*('*a*)}. *P* (*from-nat x*::'*a*)) = (∀ *x*. *P* (*from-nat x*))
proof (*auto*)
fix *y* **assume** ∗: ∀ *x*∈{*0*..<*CARD*('*a*)}. *P* (*from-nat x*)
have *from-nat y* ∈ (*UNIV*::'*a set*) **by** *auto*
from *this* **obtain** *x* **where** *x1*: *from-nat y* = (*from-nat x*::'*a*) **and** *x2*: *x*∈{*0*..<*CARD*('*a*)}
using *bij-from-nat* **unfolding** *bij-betw-def*
by (*metis from-nat-to-nat-id rangeI the-inv-into-onto to-nat-is-inv*)
show *P* (*from-nat y*::'*a*) **unfolding** *x1* **using** ∗ *x2* **by** *simp*
qed

lemma *from-nat-eq-imp-eq*:
assumes *f-eq*: *from-nat x* = (*from-nat xa*::'*a*)
and *x*: *x*<*CARD*('*a*) **and** *xa*: *xa*<*CARD*('*a*)
shows *x*=*xa* **using** *assms from-nat-not-eq* **by** *metis*

lemma *to-nat-less-card*:
fixes *j*::'*a*

shows *to-nat j* < *CARD* (*'a*)
using *bij-to-nat* **unfolding** *bij-betw-def* **by** *auto*

lemma *from-nat-0*: *from-nat 0* = *0*
unfolding *from-nat-def o-def of-nat-0 Abs'-def mod-0 zero-def* **..**
lemma *to-nat-0*: *to-nat 0* = *0* **unfolding** *to-nat-def o-def Rep-0 nat-0* **..**
lemma *to-nat-eq-0*: (*to-nat x* = *0*) = (*x* = *0*)
by (*auto simp add*: *to-nat-0 from-nat-0 dest*: *to-nat-from-nat*)

lemma *suc-not-zero*:
assumes *to-nat a* + *1* ≠ *CARD*(*'a*)
shows *a*+*1* ≠ *0*
proof (*rule ccontr*, *simp*)
assume *a-plus-one-zero*: *a* + *1* = *0*
hence *rep-eq-card*: *Rep a* + *1* = *CARD*(*'a*)
using *assms to-nat-0 Suc-eq-plus1 Suc-lessI Zero-not-Suc to-nat-less-card to-nat-suc*
by (*metis* (*opaque-lifting*, *mono-tags*))
moreover have *Rep a* + *1* < *CARD*(*'a*)
using *Abs'-0 Rep-1 Suc-eq-plus1 Suc-lessI Suc-neq-Zero add-def' assms*
rep-eq-card to-nat-0 to-nat-less-card to-nat-suc **by** (*metis* (*opaque-lifting*, *mono-tags*))
ultimately show *False* **by** *fastforce*
qed

lemma *from-nat-suc*:
shows *from-nat* (*j* + *1*) = *from-nat j* + *1*
unfolding *from-nat-def o-def Abs'-def add-def' Rep-1 Rep-Abs-mod*
unfolding *of-nat-add* **apply** (*subst mod-add-left-eq*) **unfolding** *of-nat-1* **..**

lemma *to-nat-plus-1-set*:
shows *to-nat a* + *1* ∈ {*1*..<*CARD*(*'a*)+*1*}
using *to-nat-less-card* **by** *simp*

end

lemma *from-nat-CARD*:
shows *from-nat* (*CARD*(*'a*)) = (*0*::*'a*::{*mod-type*})
unfolding *from-nat-def o-def Abs'-def* **by** (*simp add*: *zero-def*)

2.3 Instantiations

instantiation *bit0* **and** *bit1*:: (*finite*) *mod-type*
begin

definition (*Rep*::*'a bit0* => *int*) *x* = *Rep-bit0 x*
definition (*Abs*::*int* => *'a bit0*) *x* = *Abs-bit0' x*

definition (*Rep*::*'a bit1* => *int*) *x* = *Rep-bit1 x*
definition (*Abs*::*int* => *'a bit1*) *x* = *Abs-bit1' x*

instance
proof
 show (*0*::*'a bit0*) = *Abs* (*0*::*int*) **unfolding** *Abs-bit0-def Abs-bit0'-def zero-bit0-def*
by *auto*
  show (*1*::*int*) < *int CARD*(*'a bit0*) **by** (*metis bit0.size1*)
  show *type-definition* (*Rep*::*'a bit0* => *int*) (*Abs*:: *int* => *'a bit0*) {*0*::*int*..<*int*
CARD(*'a bit0*)}
  proof (*unfold type-definition-def Rep-bit0-def* [*abs-def*]
      Abs-bit0-def [*abs-def*] *Abs-bit0'-def*, *intro conjI*)
    show ∀ *x*::*'a bit0*. *Rep-bit0 x* ∈ {*0*::*int*..<*int CARD*(*'a bit0*)}
      unfolding *card-bit0* **unfolding** *of-nat-mult*
      using *Rep-bit0* [**where** *?'a* = *'a*] **by** *simp*
    show ∀ *x*::*'a bit0*. *Abs-bit0* (*Rep-bit0 x mod int CARD*(*'a bit0*)) = *x*
      by (*metis Rep-bit0-inverse bit0.Rep-mod*)
    show ∀ *y*::*int*. *y* ∈ {*0*::*int*..<*int CARD*(*'a bit0*)}
      ⟶ *Rep-bit0* ((*Abs-bit0*::*int* => *'a bit0*) (*y mod int CARD*(*'a bit0*))) = *y*
      by (*metis bit0.Abs-inverse bit0.Rep-mod*)
  qed
 show (*1*::*'a bit0*) = *Abs* (*1*::*int*) **unfolding** *Abs-bit0-def Abs-bit0'-def one-bit0-def*
    by (*metis bit0.of-nat-eq of-nat-1 one-bit0-def*)
  fix *x y* :: *'a bit0*
  show *x* + *y* = *Abs* ((*Rep x* + *Rep y*) *mod int CARD*(*'a bit0*))
    unfolding *Abs-bit0-def Rep-bit0-def plus-bit0-def Abs-bit0'-def* **by** *fastforce*
  show *x* ∗ *y* = *Abs* (*Rep x* ∗ *Rep y mod int CARD*(*'a bit0*))
    unfolding *Abs-bit0-def Rep-bit0-def times-bit0-def Abs-bit0'-def* **by** *fastforce*
  show *x* − *y* = *Abs* ((*Rep x* − *Rep y*) *mod int CARD*(*'a bit0*))
    unfolding *Abs-bit0-def Rep-bit0-def minus-bit0-def Abs-bit0'-def* **by** *fastforce*
  show − *x* = *Abs* (− *Rep x mod int CARD*(*'a bit0*))
    unfolding *Abs-bit0-def Rep-bit0-def uminus-bit0-def Abs-bit0'-def* **by** *fastforce*
 show (*0*::*'a bit1*) = *Abs* (*0*::*int*) **unfolding** *Abs-bit1-def Abs-bit1'-def zero-bit1-def*
by *auto*
  show (*1*::*int*) < *int CARD*(*'a bit1*) **by** (*metis bit1.size1*)
 show (*1*::*'a bit1*) = *Abs* (*1*::*int*) **unfolding** *Abs-bit1-def Abs-bit1'-def one-bit1-def*
    by (*metis bit1.of-nat-eq of-nat-1 one-bit1-def*)
  fix *x y* :: *'a bit1*
  show *x* + *y* = *Abs* ((*Rep x* + *Rep y*) *mod int CARD*(*'a bit1*))
    unfolding *Abs-bit1-def Abs-bit1'-def Rep-bit1-def plus-bit1-def* **by** *fastforce*
  show *x* ∗ *y* = *Abs* (*Rep x* ∗ *Rep y mod int CARD*(*'a bit1*))
    unfolding *Abs-bit1-def Rep-bit1-def times-bit1-def Abs-bit1'-def* **by** *fastforce*
  show *x* − *y* = *Abs* ((*Rep x* − *Rep y*) *mod int CARD*(*'a bit1*))
    unfolding *Abs-bit1-def Rep-bit1-def minus-bit1-def Abs-bit1'-def* **by** *fastforce*
  show − *x* = *Abs* (− *Rep x mod int CARD*(*'a bit1*))
    unfolding *Abs-bit1-def Rep-bit1-def uminus-bit1-def Abs-bit1'-def* **by** *fastforce*
  show *type-definition* (*Rep*::*'a bit1* => *int*) (*Abs*:: *int* => *'a bit1*) {*0*::*int*..<*int*
CARD(*'a bit1*)}
  proof (*unfold type-definition-def Rep-bit1-def* [*abs-def*]
      Abs-bit1-def [*abs-def*] *Abs-bit1'-def*, *intro conjI*)
    have *int-2*: *int 2* = *2* **by** *auto*

show $\forall x::'a\ bit1.\ Rep\text{-}bit1\ x \in \{0::int..<int\ CARD('a\ bit1)\}$
unfolding *card-bit1*
unfolding *of-nat-Suc of-nat-mult*
using *Rep-bit1* [**where** *?'a = 'a*]
unfolding *int-2* **..**
show $\forall x::'a\ bit1.\ Abs\text{-}bit1\ (Rep\text{-}bit1\ x\ mod\ int\ CARD('a\ bit1)) = x$
by (*metis Rep-bit1-inverse bit1.Rep-mod*)
show $\forall y::int.\ y \in \{0::int..<int\ CARD('a\ bit1)\}$
$\longrightarrow Rep\text{-}bit1\ ((Abs\text{-}bit1::int => 'a\ bit1)\ (y\ mod\ int\ CARD('a\ bit1))) = y$
by (*metis bit1.Abs-inverse bit1.Rep-mod*)
qed
show *strict-mono* (*Rep::'a bit0 => int*) **unfolding** *strict-mono-def*
by (*metis Rep-bit0-def less-bit0-def*)
show *strict-mono* (*Rep::'a bit1 => int*) **unfolding** *strict-mono-def*
by (*metis Rep-bit1-def less-bit1-def*)
qed
end

end

3 Miscellaneous

theory *Miscellaneous*
imports
HOL−Analysis.Determinants
Mod-Type
HOL−Library.Function-Algebras
begin

context *Vector-Spaces.linear* **begin**
sublocale *vector-space-pair* **by** *unfold-locales*— TODO: (re)move?
end

hide-const (**open**) *Real-Vector-Spaces.linear*
abbreviation *linear* ≡ *Vector-Spaces.linear*

In this file, we present some basic definitions and lemmas about linear algebra and matrices.

3.1 Definitions of number of rows and columns of a matrix

definition *nrows* :: $'a\widehat{~}'columns\widehat{~}'rows => nat$
where *nrows A = CARD('rows)*

definition *ncols* :: $'a\widehat{~}'columns\widehat{~}'rows => nat$
where *ncols A = CARD('columns)*

definition *matrix-scalar-mult* :: $'a::ab\text{-}semigroup\text{-}mult => 'a\ \widehat{~}'n\widehat{~}'m => 'a\ \widehat{~}'n\widehat{~}'m$
(**infixl** $*k$ *70*)

where $k *k\ A \equiv (\chi\ i\ j.\ k * A\ \$\ i\ \$\ j)$

3.2 Basic properties about matrices

lemma *nrows-not-0*[*simp*]:
shows $0 \neq nrows\ A$ **unfolding** *nrows-def* **by** *simp*

lemma *ncols-not-0*[*simp*]:
shows $0 \neq ncols\ A$ **unfolding** *ncols-def* **by** *simp*

lemma *nrows-transpose*: $nrows\ (transpose\ A) = ncols\ A$
unfolding *nrows-def ncols-def* **..**

lemma *ncols-transpose*: $ncols\ (transpose\ A) = nrows\ A$
unfolding *nrows-def ncols-def* **..**

lemma *finite-rows*: *finite* (*rows A*)
using *finite-Atleast-Atmost-nat*[*of* $\lambda i.\ row\ i\ A$] **unfolding** *rows-def* **.**

lemma *finite-columns*: *finite* (*columns A*)
using *finite-Atleast-Atmost-nat*[*of* $\lambda i.\ column\ i\ A$] **unfolding** *columns-def* **.**

lemma *transpose-vector*: $x\ v{*}\ A = transpose\ A *v\ x$
by *simp*

lemma *transpose-zero*[*simp*]: $(transpose\ A = 0) = (A = 0)$
unfolding *transpose-def zero-vec-def vec-eq-iff* **by** *auto*

3.3 Theorems obtained from the AFP

The following theorems and definitions have been obtained from the AFP http://isa-afp.org/browser_info/current/HOL/Tarskis_Geometry/Linear_Algebra2.html. I have removed some restrictions over the type classes.

lemma *vector-scalar-matrix-ac*:
fixes $k :: 'a::\{field\}$ **and** $x :: 'a::\{field\}\hat{}'n$ **and** $A :: 'a\hat{}'m\hat{}'n$
shows $x\ v{*}\ (k *k\ A) = k *s\ (x\ v{*}\ A)$
using *scalar-vector-matrix-assoc*
unfolding *vector-matrix-mult-def matrix-scalar-mult-def vec-eq-iff*
by (*auto simp add*: *sum-distrib-left vector-space-over-itself.scale-scale*)

lemma *transpose-scalar*: $transpose\ (k *k\ A) = k *k\ transpose\ A$
unfolding *transpose-def*
by (*vector*, *simp add*: *matrix-scalar-mult-def*)

lemma *scalar-matrix-vector-assoc*:
fixes $A :: 'a::\{field\}\hat{}'m\hat{}'n$
shows $k *s\ (A *v\ v) = k *k\ A *v\ v$
by (*metis transpose-scalar vector-scalar-matrix-ac vector-transpose-matrix*)

lemma *matrix-scalar-vector-ac*:
  fixes A :: $'a::\{field\}^{\frown}'m^{\frown}'n$
  shows $A *v\ (k *s\ v) = k *k\ A *v\ v$
  by (*simp add*: *Miscellaneous.scalar-matrix-vector-assoc vec.scale*)

definition
  is-basis :: $('a::\{field\}^{\frown}'n)$ *set* => *bool* **where**
  is-basis $S \equiv$ *vec.independent* $S \wedge$ *vec.span* $S = UNIV$

lemma *card-finite*:
  assumes *card* $S = CARD('n::finite)$
  shows *finite* S
proof −
  from ‹*card* $S = CARD('n)$› **have** *card* $S \neq 0$ **by** *simp*
  with *card-eq-0-iff* [*of* S] **show** *finite* S **by** *simp*
qed

lemma *independent-is-basis*:
  fixes B :: $('a::\{field\}^{\frown}'n)$ *set*
  shows *vec.independent* $B \wedge$ *card* $B = CARD('n) \longleftrightarrow$ *is-basis* B
proof
  assume *vec.independent* $B \wedge$ *card* $B = CARD('n)$
  hence *vec.independent* B **and** *card* $B = CARD('n)$ **by** *simp+*
  from *card-finite* [*of* B, **where** $'n = 'n$] **and** ‹*card* $B = CARD('n)$›
  have *finite* B **by** *simp*
  from ‹*card* $B = CARD('n)$›
  have *card* $B =$ *vec.dim* $(UNIV :: (('a^{\frown}'n)\ set))$ **unfolding** *vec-dim-card* **.**
  with *vec.card-eq-dim* [*of* B *UNIV*] **and** ‹*finite* B› **and** ‹*vec.independent* B›
  have *vec.span* $B = UNIV$ **by** *auto*
  with ‹*vec.independent* B› **show** *is-basis* B **unfolding** *is-basis-def* **..**
next
  assume *is-basis* B
  hence *vec.independent* B **unfolding** *is-basis-def* **..**
  moreover have *card* $B = CARD('n)$
  proof −
    have $B \subseteq UNIV$ **by** *simp*
    moreover
    { from ‹*is-basis* B› **have** $UNIV \subseteq$ *vec.span* B **and** *vec.independent* B
        unfolding *is-basis-def*
        by *simp+* **}**
    ultimately have *card* $B =$ *vec.dim* $(UNIV::((real^{\frown}'n)\ set))$
      using *vec.basis-card-eq-dim* [*of* B *UNIV*]
      unfolding *vec-dim-card*
      by *simp*
    then show *card* $B = CARD('n)$
      by (*metis vec-dim-card*)
  qed
  ultimately show *vec.independent* $B \wedge$ *card* $B = CARD('n)$ **..**

qed

lemma *basis-finite*:
  fixes B :: $('a::\{field\}^{\frown}'n)$ *set*
  assumes *is-basis* B
  shows *finite* B
proof −
  from *independent-is-basis* [*of* B] **and** ‹*is-basis* B› **have** *card* $B = CARD('n)$
    by *simp*
  with *card-finite* [*of* B, **where** $'n = 'n$] **show** *finite* B **by** *simp*
qed

Here ends the statements obtained from AFP: http://isa-afp.org/browser_info/current/HOL/Tarskis_Geometry/Linear_Algebra2.html which have been generalized.

3.4 Basic properties involving span, linearity and dimensions

context *finite-dimensional-vector-space*
begin

This theorem is the reciprocal theorem of *local.independent* $?B \Longrightarrow$ *finite* $?B \wedge$ *card* $?B =$ *local.dim* (*local.span* $?B$)

lemma *card-eq-dim-span-indep*:
  assumes *dim* (*span* A) = *card* A **and** *finite* A
  shows *independent* A
  by (*metis assms card-le-dim-spanning dim-subset equalityE span-superset*)

lemma *dim-zero-eq*:
  assumes *dim-A*: *dim* $A = 0$
  shows $A = \{\} \vee A = \{0\}$
  using *dim-A local.card-ge-dim-independent local.independent-empty* **by** *force*

lemma *dim-zero-eq'*:
  assumes A: $A = \{\} \vee A = \{0\}$
  shows *dim* $A = 0$
using *assms local.dim-span local.indep-card-eq-dim-span local.independent-empty*
by *fastforce*

lemma *dim-zero-subspace-eq*:
  assumes *subs-A*: *subspace* A
  shows (*dim* $A = 0$) = ($A = \{0\}$)
  by (*metis dim-zero-eq dim-zero-eq' subspace-0*[*OF subs-A*] *empty-iff*)

lemma *span-0-imp-set-empty-or-0*:
  assumes *span* $A = \{0\}$
  shows $A = \{\} \vee A = \{0\}$ **by** (*metis assms span-superset subset-singletonD*)

end

context *Vector-Spaces.linear*
begin

lemma *linear-injective-ker-0*:
  shows $inj\ f = (\{x.\ f\ x = 0\} = \{0\})$
  using *inj-iff-eq-0* **by** *auto*

end

lemma *snd-if-conv*:
  shows $snd\ (if\ P\ then\ (A,B)\ else\ (C,D))=(if\ P\ then\ B\ else\ D)$ **by** *simp*

3.5 Basic properties about matrix multiplication

lemma *row-matrix-matrix-mult*:
  fixes $A::'a::\{comm\text{-}ring\text{-}1\}^{\frown}'n^{\frown}'m$
  shows $(P\ \$\ i)\ v*\ A = (P\ **\ A)\ \$\ i$
  unfolding *vec-eq-iff*
  unfolding *vector-matrix-mult-def* **unfolding** *matrix-matrix-mult-def*
  by (*auto intro*!: *sum.cong*)

corollary *row-matrix-matrix-mult'*:
  fixes $A::'a::\{comm\text{-}ring\text{-}1\}^{\frown}'n^{\frown}'m$
  shows $(row\ i\ P)\ v*\ A = row\ i\ (P\ **\ A)$
  using *row-matrix-matrix-mult* **unfolding** *row-def vec-nth-inverse* **.**

lemma *column-matrix-matrix-mult*:
  shows $column\ i\ (P**A) = P\ *v\ (column\ i\ A)$
 unfolding *column-def matrix-vector-mult-def matrix-matrix-mult-def* **by** *fastforce*

lemma *matrix-matrix-mult-inner-mult*:
  shows $(A\ **\ B)\ \$\ i\ \$\ j = row\ i\ A\ \cdot\ column\ j\ B$
  unfolding *inner-vec-def matrix-matrix-mult-def row-def column-def* **by** *auto*

lemma *matrix-vmult-column-sum*:
  fixes $A::'a::\{field\}^{\frown}'n^{\frown}'m$
  shows $\exists f.\ A\ *v\ x = sum\ (\lambda y.\ f\ y\ *s\ y)\ (columns\ A)$
proof (*rule exI*[*of* - $\lambda y.\ sum\ (\lambda i.\ x\ \$\ i)\ \{i.\ y = column\ i\ A\}$])
  let $?f=\lambda y.\ sum\ (\lambda i.\ x\ \$\ i)\ \{i.\ y = column\ i\ A\}$
  let $?g=(\lambda y.\ \{i.\ y=column\ i\ (A)\})$
  have *inj*: *inj-on* $?g$ (*columns* (*A*)) **unfolding** *inj-on-def* **unfolding** *columns-def*
by *auto*
  have *union-univ*: $\bigcup\ (?g\text{`}(columns\ (A))) = UNIV$ **unfolding** *columns-def* **by**
auto
  have $A\ *v\ x = (\sum i\in UNIV.\ x\ \$\ i\ *s\ column\ i\ A)$ **unfolding** *matrix-mult-sum*
..
  also have ... $= sum\ (\lambda i.\ x\ \$\ i\ *s\ column\ i\ A)\ (\bigcup (?g\text{`}(columns\ A)))$ **unfolding**

union-univ **..**
  also have ... = *sum* (*sum* ((λ*i*. *x* \$ *i* ∗*s* *column* *i* *A*))) (*?g*‘(*columns* *A*))
    by (*rule* *sum.Union-disjoint*[*unfolded* *o-def*], *auto*)
  also have ... = *sum* ((*sum* ((λ*i*. *x* \$ *i* ∗*s* *column* *i* *A*))) ∘ *?g*) (*columns* *A*)
    by (*rule* *sum.reindex*, *simp* *add*: *inj*)
  also have ... = *sum* (λ*y*. *?f* *y* ∗*s* *y*) (*columns* *A*)
  proof (*rule* *sum.cong*, *unfold* *o-def*)
    fix *xa*
    have *sum* (λ*i*. *x* \$ *i* ∗*s* *column* *i* *A*) {*i*. *xa* = *column* *i* *A*}
      = *sum* (λ*i*. *x* \$ *i* ∗*s* *xa*) {*i*. *xa* = *column* *i* *A*} **by** *simp*
    also have ... = *sum* (λ*i*. *x* \$ *i*) {*i*. *xa* = *column* *i* *A*} ∗*s* *xa*
      using *vec.scale-sum-left*[*of* (λ*i*. *x* \$ *i*) {*i*. *xa* = *column* *i* *A*} *xa*] **..**
     finally show ($\sum$*i* | *xa* = *column* *i* *A*. *x* \$ *i* ∗*s* *column* *i* *A*) = ($\sum$*i* | *xa* = *column* *i* *A*. *x* \$ *i*) ∗*s* *xa* **.**
  qed *rule*
  finally show *A* ∗*v* *x* = ($\sum$*y*∈*columns* *A*. ($\sum$*i* | *y* = *column* *i* *A*. *x* \$ *i*) ∗*s* *y*) **.**
qed

3.6 Properties about invertibility

lemma *matrix-inv*:
  assumes *invertible* *M*
  shows *matrix-inv-left*: *matrix-inv* *M* ∗∗ *M* = *mat* *1*
    and *matrix-inv-right*: *M* ∗∗ *matrix-inv* *M* = *mat* *1*
  using ‹*invertible* *M*› **and** *someI-ex* [*of* λ *N*. *M* ∗∗ *N* = *mat* *1* ∧ *N* ∗∗ *M* = *mat* *1*]
  unfolding *invertible-def* **and** *matrix-inv-def*
  by *simp-all*

In the library, *matrix-inv* *?A* = (*SOME* *A'*. *?A* ∗∗ *A'* = *mat* (*1*::*?'a*) ∧ *A'* ∗∗ *?A* = *mat* (*1*::*?'a*)) allows the use of non squary matrices. The following lemma can be also proved fixing *A*

lemma *matrix-inv-unique*:
  fixes *A*::*'a*::{*semiring-1*}^*'n*^*'n*
  assumes *AB*: *A* ∗∗ *B* = *mat* *1* **and** *BA*: *B* ∗∗ *A* = *mat* *1*
  shows *matrix-inv* *A* = *B*
  by (*metis* *AB* *BA* *invertible-def* *matrix-inv-right* *matrix-mul-assoc* *matrix-mul-lid*)

lemma *matrix-vector-mult-zero-eq*:
  assumes *P*: *invertible* *P*
  shows ((*P*∗∗*A*)∗*v* *x* = *0*) = (*A* ∗*v* *x* = *0*)
proof (*rule* *iffI*)
  assume *P* ∗∗ *A* ∗*v* *x* = *0*
  hence *matrix-inv* *P* ∗*v* (*P* ∗∗ *A* ∗*v* *x*) = *matrix-inv* *P* ∗*v* *0* **by** *simp*
  hence *matrix-inv* *P* ∗*v* (*P* ∗∗ *A* ∗*v* *x*) = *0* **by** (*metis* *matrix-vector-mult-0-right*)
  hence (*matrix-inv* *P* ∗∗ *P* ∗∗ *A*) ∗*v* *x* = *0* **by** (*metis* *matrix-vector-mul-assoc*)
  thus *A* ∗*v* *x* = *0* **by** (*metis* *assms* *matrix-inv-left* *matrix-mul-lid*)

next
assume *A *v x = 0*
thus *P ** A *v x = 0* **by** (*metis matrix-vector-mul-assoc matrix-vector-mult-0-right*)
qed

lemma *independent-image-matrix-vector-mult*:
fixes *P::'a::{field}^'n^'m*
assumes *ind-B*: *vec.independent B* **and** *inv-P*: *invertible P*
shows *vec.independent (((*v) P)‘ B)*
proof (*rule vec.independent-injective-image*)
show *vec.independent B* **using** *ind-B* **.**
show *inj-on ((*v) P) (vec.span B)*
using *inj-matrix-vector-mult[OF inv-P]* **unfolding** *inj-on-def* **by** *simp*
qed

lemma *independent-preimage-matrix-vector-mult*:
fixes *P::'a::{field}^'n^'n*
assumes *ind-B*: *vec.independent (((*v) P)‘ B)* **and** *inv-P*: *invertible P*
shows *vec.independent B*
proof −
have *vec.independent (((*v) (matrix-inv P))‘ (((*v) P)‘ B))*
proof (*rule independent-image-matrix-vector-mult*)
show *vec.independent ((*v) P ‘ B)* **using** *ind-B* **.**
show *invertible (matrix-inv P)*
by (*metis matrix-inv-left matrix-inv-right inv-P invertible-def*)
qed
moreover have *((*v) (matrix-inv P))‘ (((*v) P)‘ B) = B*
proof (*auto*)
fix *x* **assume** *x*: *x ∈ B* **show** *matrix-inv P *v (P *v x) ∈ B*
by (*metis (full-types) x inv-P matrix-inv-left matrix-vector-mul-assoc matrix-vector-mul-lid*)
thus *x ∈ (*v) (matrix-inv P) ‘ (*v) P ‘ B*
unfolding *image-def*
by (*auto, metis inv-P matrix-inv-left matrix-vector-mul-assoc matrix-vector-mul-lid*)
qed
ultimately show *?thesis* **by** *simp*
qed

3.7 Properties about the dimension of vectors

lemma *dimension-vector[code-unfold]*: *vec.dimension TYPE('a::{field}) TYPE('rows::{mod-type})=CARD('r*
proof −
let *?f=λx. axis (from-nat x) 1::'a^'rows::{mod-type}*
have *vec.dimension TYPE('a::{field}) TYPE('rows::{mod-type}) = card (cart-basis::('a^'rows::{mod-type}) set)*
unfolding *vec.dimension-def* **..**
also have *... = card{..<CARD('rows)}* **unfolding** *cart-basis-def*
proof (*rule bij-betw-same-card[symmetric, of ?f], unfold bij-betw-def, unfold inj-on-def axis-eq-axis, auto*)

fix *x y* **assume** *x*: $x < CARD('rows)$ **and** *y*: $y < CARD('rows)$ **and** *eq*: *from-nat* x = (*from-nat* y::*'rows*)
show $x = y$ **using** *from-nat-eq-imp-eq*[*OF eq x y*] **.**
next
fix *i* **show** *axis i 1* ∈ (λ*x*. *axis* (*from-nat x*::*'rows*) *1*) ‘ {..<*CARD*(*'rows*)} **unfolding** *image-def*
by (*auto*, *metis lessThan-iff to-nat-from-nat to-nat-less-card*)
qed
also have ... = *CARD*(*'rows*) **by** (*metis card-lessThan*)
finally show *?thesis* **.**
qed

3.8 Instantiations and interpretations

Functions between two real vector spaces form a real vector

instantiation *fun* :: (*real-vector*, *real-vector*) *real-vector*
begin

definition *scaleR-fun a f* = (λ*i*. $a *_R f\ i$)

instance
by (*intro-classes*, *auto simp add*: *fun-eq-iff scaleR-fun-def scaleR-left.add scaleR-right.add*)
end

instantiation *vec* :: (*type*, *finite*) *equal*
begin
definition *equal-vec* :: (*'a*, *'b*::*finite*) *vec* => (*'a*, *'b*::*finite*) *vec* => *bool*
where *equal-vec x y* = (∀ *i*. *x*\$*i* = *y*\$*i*)
instance
proof (*intro-classes*)
fix *x y*::(*'a*, *'b*::*finite*) *vec*
show *equal-class.equal x y* = (*x* = *y*) **unfolding** *equal-vec-def* **using** *vec-eq-iff* **by** *auto*
qed
end

interpretation *matrix*: *vector-space* ((∗*k*))::*'a*::{*field*}=>*'a*^*'cols*^*'rows*=>*'a*^*'cols*^*'rows*
proof (*unfold-locales*)
fix *a*::*'a* **and** *x y*::*'a*^*'cols*^*'rows*
show *a* ∗*k* (*x* + *y*) = *a* ∗*k x* + *a* ∗*k y*
unfolding *matrix-scalar-mult-def vec-eq-iff*
by (*simp add*: *vector-space-over-itself.scale-right-distrib*)
next
fix *a b*::*'a* **and** *x*::*'a*^*'cols*^*'rows*
show (*a* + *b*) ∗*k x* = *a* ∗*k x* + *b* ∗*k x*
unfolding *matrix-scalar-mult-def vec-eq-iff*
by (*simp add*: *comm-semiring-class.distrib*)
show *a* ∗*k* (*b* ∗*k x*) = *a* ∗ *b* ∗*k x*

unfolding *matrix-scalar-mult-def vec-eq-iff* **by** *auto*
show *1* ∗*k x* = *x* **unfolding** *matrix-scalar-mult-def vec-eq-iff* **by** *auto*
qed

end

4 Fundamental Subspaces

theory *Fundamental-Subspaces*
imports
Miscellaneous
begin

4.1 The fundamental subspaces of a matrix

4.1.1 Definitions

definition *left-null-space* :: *'a*::{*semiring-1*}^*'n*^*'m* => (*'a*^*'m*) *set*
where *left-null-space A* = {*x*. *x v*∗ *A* = *0*}

definition *null-space* :: *'a*::{*semiring-1*}^*'n*^*'m* => (*'a*^*'n*) *set*
where *null-space A* = {*x*. *A* ∗*v x* = *0*}

definition *row-space* :: *'a*::{*field*}^*'n*^*'m*=>(*'a*^*'n*) *set*
where *row-space A* = *vec.span* (*rows A*)

definition *col-space* :: *'a*::{*field*}^*'n*^*'m*=>(*'a*^*'m*) *set*
where *col-space A* = *vec.span* (*columns A*)

4.1.2 Relationships among them

lemma *left-null-space-eq-null-space-transpose*: *left-null-space A* = *null-space* (*transpose A*)
unfolding *null-space-def left-null-space-def transpose-vector* **..**

lemma *null-space-eq-left-null-space-transpose*: *null-space A* = *left-null-space* (*transpose A*)
using *left-null-space-eq-null-space-transpose*[*of transpose A*]
unfolding *transpose-transpose* **..**

lemma *row-space-eq-col-space-transpose*:
fixes *A*::*'a*::{*field*}^*'columns*^*'rows*
shows *row-space A* = *col-space* (*transpose A*)
unfolding *col-space-def row-space-def columns-transpose*[*of A*] **..**

lemma *col-space-eq-row-space-transpose*:
fixes *A*::*'a*::{*field*}^*'n*^*'m*
shows *col-space A* = *row-space* (*transpose A*)
unfolding *col-space-def row-space-def* **unfolding** *rows-transpose*[*of A*] **..**

4.2 Proving that they are subspaces

lemma *subspace-null-space*:
  fixes $A::'a::\{field\}^\frown{}'n^\frown{}'m$
  shows *vec.subspace* (*null-space A*)
  by (*auto simp*: *vec.subspace-def null-space-def vec.scale vec.add*)

lemma *subspace-left-null-space*:
  fixes $A::'a::\{field\}^\frown{}'n^\frown{}'m$
  shows *vec.subspace* (*left-null-space A*)
  unfolding *left-null-space-eq-null-space-transpose* **using** *subspace-null-space* **.**

lemma *subspace-row-space*:
  shows *vec.subspace* (*row-space A*) **by** (*metis row-space-def vec.subspace-span*)

lemma *subspace-col-space*:
  shows *vec.subspace* (*col-space A*) **by** (*metis col-space-def vec.subspace-span*)

4.3 More useful properties and equivalences

lemma *col-space-eq*:
  fixes $A::'a::\{field\}^\frown{}'m::\{finite,\ wellorder\}^\frown{}'n$
  shows *col-space* $A = \{y.\ \exists x.\ A *v\ x = y\}$
proof (*unfold col-space-def vec.span-finite*[*OF finite-columns*], *auto*)
  fix x
  show $A *v\ x \in range\ (\lambda u.\ \sum v{\in}columns\ A.\ u\ v *s\ v)$ **using** *matrix-vmult-column-sum*[*of A x*] **by** *auto*
next
  fix $u::('a,\ 'n)\ vec \Rightarrow 'a$
  let $?g{=}\lambda y.\ \{i.\ y{=}column\ i\ A\}$
  let $?x{=}(\chi\ i.\ if\ i{=}(LEAST\ a.\ a \in\ ?g\ (column\ i\ A))\ then\ u\ (column\ i\ A)\ else\ 0)$
  show $\exists x.\ A *v\ x = (\sum v{\in}columns\ A.\ u\ v *s\ v)$
  proof (*unfold matrix-mult-sum*, *rule exI*[*of - ?x*], *auto*)
    have *inj*: *inj-on ?g* (*columns A*) **unfolding** *inj-on-def* **unfolding** *columns-def* **by** *auto*
    have *union-univ*: $\bigcup\ (?g`(columns\ A)) = UNIV$ **unfolding** *columns-def* **by** *auto*

    have $sum\ (\lambda i.(if\ i = (LEAST\ a.\ column\ i\ A = column\ a\ A)\ then\ u\ (column\ i\ A)\ else\ 0) *s\ column\ i\ A)\ UNIV$
      $= sum\ (\lambda i.\ (if\ i = (LEAST\ a.\ column\ i\ A = column\ a\ A)\ then\ u\ (column\ i\ A)\ else\ 0) *s\ column\ i\ A)\ (\bigcup\ (?g`(columns\ A)))$
      unfolding *union-univ* **..**
    also have $... = sum\ (sum\ (\lambda i.(if\ i = (LEAST\ a.\ column\ i\ A = column\ a\ A)\ then\ u\ (column\ i\ A)\ else\ 0) *s\ column\ i\ A))\ (?g`(columns\ A))$
      by (*rule sum.Union-disjoint*[*unfolded o-def*], *auto*)
    also have $... = sum\ ((sum\ (\lambda i.(if\ i = (LEAST\ a.\ column\ i\ A = column\ a\ A)\ then\ u\ (column\ i\ A)\ else\ 0) *s\ column\ i\ A)) \circ\ ?g)$
      (*columns A*) **by** (*rule sum.reindex*, *simp add*: *inj*)
    also have $... = sum\ (\lambda y.\ u\ y *s\ y)\ (columns\ A)$
    proof (*rule sum.cong*, *auto*)

```
      fix x
      assume x-in-cols: x ∈ columns A
      obtain b where b: x=column b A using x-in-cols unfolding columns-def by blast
      let ?f=(λi. (if i = (LEAST a. column i A = column a A) then u (column i A) else 0) *s column i A)
      have sum-rw: sum ?f ({i. x = column i A} − {LEAST a. x = column a A}) = 0
        by (rule sum.neutral, auto)
      have sum ?f {i. x = column i A} = ?f (LEAST a. x = column a A) + sum ?f ({i. x = column i A} − {LEAST a. x = column a A})
        apply (rule sum.remove, auto, rule LeastI-ex)
        using x-in-cols unfolding columns-def by auto
      also have ... = ?f (LEAST a. x = column a A) unfolding sum-rw by simp
      also have ... = u x *s x
      proof (auto, rule LeastI2)
        show x = column b A using b .
        fix xa
        assume x: x = column xa A
        show u (column xa A) *s column xa A = u x *s x unfolding x ..
      next
        assume (LEAST a. x = column a A) ≠ (LEAST a. column (LEAST c. x = column c A) A = column a A)
        moreover have (LEAST a. x = column a A) = (LEAST a. column (LEAST c. x = column c A) A = column a A)
          by (rule Least-equality[symmetric], rule LeastI2, simp-all add: b, rule Least-le, metis (lifting, full-types) LeastI)
        ultimately show u x = 0 by contradiction
      qed
      finally show (∑ i | x = column i A. (if i = (LEAST a. column i A = column a A) then u (column i A) else 0) *s column i A) = u x *s x .
    qed
    finally show (∑ i∈UNIV. (if i = (LEAST a. column i A = column a A) then u (column i A) else 0) *s column i A) = (∑ y∈columns A. u y *s y) .
  qed
qed


corollary col-space-eq':
  fixes A::'a::{field}^'m::{finite, wellorder}^'n
  shows col-space A = range (λx. A *v x)
  unfolding col-space-eq by auto

lemma row-space-eq:
  fixes A::'a::{field}^'m^'n::{finite, wellorder}
  shows row-space A = {w. ∃ y. (transpose A) *v y = w}
  unfolding row-space-eq-col-space-transpose col-space-eq ..

lemma null-space-eq-ker:
```

fixes f::('a::$field$^'n) => ('a^'m)
assumes lf: *Vector-Spaces.linear* (∗s) (∗s) f
shows *null-space* (*matrix f*) = {x. f x = 0}
unfolding *null-space-def* **using** *matrix-works* [*OF lf*] **by** *auto*

lemma *col-space-eq-range*:
fixes f::('a::$field$^'n::{*finite*, *wellorder*}) ⇒ ('a^'m)
assumes lf: *Vector-Spaces.linear* (∗s) (∗s) f
shows *col-space* (*matrix f*) = *range f*
unfolding *col-space-eq* **unfolding** *matrix-works*[*OF lf*] **by** *blast*

lemma *null-space-is-preserved*:
fixes A::'a::{*field*}^'*cols*^'*rows*
assumes P: *invertible* P
shows *null-space* (P∗∗A) = *null-space* A
unfolding *null-space-def*
using P *matrix-inv-left matrix-left-invertible-ker matrix-vector-mul-assoc matrix-vector-mult-0-right*
by *metis*

lemma *row-space-is-preserved*:
fixes A::'a::{*field*}^'*cols*^'*rows*::{*finite*, *wellorder*}
and P::'a::{*field*}^'*rows*::{*finite*, *wellorder*}^'*rows*::{*finite*, *wellorder*}
assumes P: *invertible* P
shows *row-space* (P∗∗A) = *row-space* A
proof (*auto*)
fix w
assume w: w ∈ *row-space* (P∗∗A)
from *this* **obtain** y **where** *w-By*: w=(*transpose* (P∗∗A)) ∗v y
unfolding *row-space-eq*[*of P* ∗∗ *A*] **by** *fast*
have w = (*transpose* (P∗∗A)) ∗v y **using** *w-By* **.**
also have ... = ((*transpose* A) ∗∗ (*transpose* P)) ∗v y **unfolding** *matrix-transpose-mul*
..
also have ... = (*transpose* A) ∗v ((*transpose* P) ∗v y) **unfolding** *matrix-vector-mul-assoc*
..
finally show w ∈ *row-space* A **unfolding** *row-space-eq* **by** *blast*
next
fix w
assume w: w ∈ *row-space* A
from *this* **obtain** y **where** *w-Ay*: w=(*transpose* A) ∗v y **unfolding** *row-space-eq*
by *fast*
have w = (*transpose* A) ∗v y **using** *w-Ay* **.**
also have ... = (*transpose* ((*matrix-inv* P) ∗∗ (P∗∗A))) ∗v y
by (*metis P matrix-inv-left matrix-mul-assoc matrix-mul-lid*)
also have ... = (*transpose* (P∗∗A) ∗∗ (*transpose* (*matrix-inv* P))) ∗v y
unfolding *matrix-transpose-mul* **..**
also have ... = *transpose* (P∗∗A) ∗v (*transpose* (*matrix-inv* P) ∗v y)
unfolding *matrix-vector-mul-assoc* **..**
finally show w ∈ *row-space* (P∗∗A) **unfolding** *row-space-eq* **by** *blast*

qed
end

5 Rank Nullity Theorem of Linear Algebra

theory *Dim-Formula*
  imports *Fundamental-Subspaces*
begin

context *vector-space*
begin

5.1 Previous results

Linear dependency is a monotone property, based on the monotonocity of linear independence:

lemma *dependent-mono*:
  assumes *d*:*dependent A*
  and *A-in-B*: $A \subseteq B$
  shows *dependent B*
  using *independent-mono* [*OF* - *A-in-B*] *d* **by** *auto*

Given a finite independent set, a linear combination of its elements equal to zero is possible only if every coefficient is zero:

lemma *scalars-zero-if-independent*:
  assumes *fin-A*: *finite A*
  and *ind*: *independent A*
  and *sum*: $(\sum x{\in}A.\ scale\ (f\ x)\ x) = 0$
  shows $\forall x \in A.\ f\ x = 0$
  using *fin-A ind local.dependent-finite sum* **by** *blast*

end

context *finite-dimensional-vector-space*
begin

In an finite dimensional vector space, every independent set is finite, and thus

$[\![finite\ A;\ local.independent\ A;\ (\sum x{\in}A.\ f\ x *s\ x) = (0::'b)]\!]$
$\Longrightarrow \forall x{\in}A.\ f\ x = (0::'a)$

holds:

corollary *scalars-zero-if-independent-euclidean*:
  assumes *ind*: *independent A*
    and *sum*: $(\sum x{\in}A.\ scale\ (f\ x)\ x) = 0$
  shows $\forall x \in A.\ f\ x = 0$

using *finiteI-independent ind scalars-zero-if-independent sum* **by** *blast*

end

The following lemma states that every linear form is injective over the elements which define the basis of the range of the linear form. This property is applied later over the elements of an arbitrary basis which are not in the basis of the nullifier or kernel set (*i.e.*, the candidates to be the basis of the range space of the linear form).

Thanks to this result, it can be concluded that the cardinal of the elements of a basis which do not belong to the kernel of a linear form f is equal to the cardinal of the set obtained when applying f to such elements.

The application of this lemma is not usually found in the pencil and paper proofs of the "rank nullity theorem", but will be crucial to know that, being f a linear form from a finite dimensional vector space V to a vector space V', and given a basis B of *ker f*, when B is completed up to a basis of V with a set W, the cardinal of this set is equal to the cardinal of its range set:

context *vector-space*
begin

lemma *inj-on-extended*:
  assumes *lf*: *Vector-Spaces.linear scaleB scaleC f*
  and *f*: *finite C*
  and *ind-C*: *independent C*
  and *C-eq*: $C = B \cup W$
  and *disj-set*: $B \cap W = \{\}$
  and *span-B*: $\{x.\ f\ x = 0\} \subseteq$ *span B*
  shows *inj-on f W*
  — The proof is carried out by reductio ad absurdum
proof (*unfold inj-on-def*, *rule+*, *rule ccontr*)
  interpret *lf*: *Vector-Spaces.linear scaleB scaleC f* **using** *lf* **by** *simp*
  — Some previous consequences of the premises that are used later:
  have *fin-B*: *finite B* **using** *finite-subset* [*OF - f*] *C-eq* **by** *simp*
  have *ind-B*: *independent B* **and** *ind-W*: *independent W*
    using *independent-mono*[*OF ind-C*] *C-eq* **by** *simp-all*
  — The proof starts here; we assume that there exist two different elements
  — with the same image:
  fix $x::'b$ **and** $y::'b$
  assume *x*: $x \in W$ **and** *y*: $y \in W$ **and** *f-eq*: $f\ x = f\ y$ **and** *x-not-y*: $x \neq y$
  have *fin-yB*: *finite* (*insert y B*) **using** *fin-B* **by** *simp*
  have $f\ (x - y) = 0$ **by** (*metis diff-self f-eq lf.diff*)
  hence $x - y \in \{x.\ f\ x = 0\}$ **by** *simp*
  hence $\exists\, g.\ (\sum v{\in}B.\ scale\ (g\ v)\ v) = (x - y)$ **using** *span-B*
    unfolding *span-finite* [*OF fin-B*] **by** *force*
  then obtain *g* **where** *sum*: $(\sum v{\in}B.\ scale\ (g\ v)\ v) = (x - y)$ **by** *blast*
  — We define one of the elements as a linear combination of the second element and the ones in B

define $h :: 'b \Rightarrow 'a$ **where** $h\ a = (if\ a = y\ then\ 1\ else\ g\ a)$ **for** a
have $x = y + (\sum v{\in}B.\ scale\ (g\ v)\ v)$ **using** *sum* **by** *auto*
also have ... $= scale\ (h\ y)\ y\ + (\sum v{\in}B.\ scale\ (g\ v)\ v)$ **unfolding** *h-def* **by** *simp*
also have ... $= scale\ (h\ y)\ y + (\sum v{\in}B.\ scale\ (h\ v)\ v)$
apply (*unfold add-left-cancel*, *rule sum.cong*)
using *y h-def empty-iff disj-set* **by** *auto*
also have ... $= (\sum v{\in}(insert\ y\ B).\ scale\ (h\ v)\ v)$
by (*rule sum.insert*[*symmetric*], *rule fin-B*)
(*metis* (*lifting*) *IntI disj-set empty-iff y*)
finally have *x-in-span-yB*: $x \in span\ (insert\ y\ B)$
unfolding *span-finite*[*OF fin-yB*] **by** *auto*
— We have that a subset of elements of C is linearly dependent
have *dep*: *dependent* (*insert x* (*insert y B*))
by (*unfold dependent-def*, *rule bexI* [*of - x*])
(*metis Diff-insert-absorb Int-iff disj-set empty-iff insert-iff*
x x-in-span-yB x-not-y, *simp*)
— Therefore, the set C is also dependent:
hence *dependent C* **using** *C-eq x y*
by (*metis Un-commute Un-upper2 dependent-mono insert-absorb insert-subset*)
— This yields the contradiction, since C is independent:
thus *False* **using** *ind-C* **by** *contradiction*
qed
end

5.2 The proof

Now the rank nullity theorem can be proved; given any linear form f, the sum of the dimensions of its kernel and range subspaces is equal to the dimension of the source vector space.

The statement of the "rank nullity theorem for linear algebra", as well as its proof, follow the ones on [1]. The proof is the traditional one found in the literature. The theorem is also named "fundamental theorem of linear algebra" in some texts (for instance, in [2]).

context *finite-dimensional-vector-space*
begin

theorem *rank-nullity-theorem*:
assumes *l*: *Vector-Spaces.linear scale scaleC f*
shows $dimension = dim\ \{x.\ f\ x = 0\} + vector\text{-}space.dim\ scaleC\ (range\ f)$
proof $-$
— For convenience we define abbreviations for the universe set, V, and the kernel of f
interpret *l*: *Vector-Spaces.linear scale scaleC f* **by** *fact*
define $V :: 'b\ set$ **where** $V = UNIV$
define *ker-f* **where** $ker\text{-}f = \{x.\ f\ x = 0\}$
— The kernel is a proper subspace:
have *sub-ker*: $subspace\ \{x.\ f\ x = 0\}$ **using** *l.subspace-kernel* **.**

— The kernel has its proper basis, B:
obtain B **where** *B-in-ker*: $B \subseteq \{x.\ f\ x = 0\}$
and *independent-B*: *independent B*
and *ker-in-span*:$\{x.\ f\ x = 0\} \subseteq$ *span B*
and *card-B*: *card* $B =$ *dim* $\{x.\ f\ x = 0\}$ **using** *basis-exists* **by** *blast*
— The space V has a (finite dimensional) basis, C:
obtain C **where** *B-in-C*: $B \subseteq C$ **and** *C-in-V*: $C \subseteq V$
and *independent-C*: *independent C*
and *span-C*: $V =$ *span C*
unfolding *V-def*
by (*metis independent-B extend-basis-superset independent-extend-basis span-extend-basis span-superset*)
— The basis of V, C, can be decomposed in the disjoint union of the basis of the kernel, B, and its complementary set, $C - B$
have *C-eq*: $C = B \cup (C - B)$ **by** (*rule Diff-partition* [*OF B-in-C*, *symmetric*])
have *eq-fC*: f ‘ $C = f$ ‘ $B \cup f$ ‘ $(C - B)$
by (*subst C-eq*, *unfold image-Un*, *simp*)
— The basis C, and its image, are finite, since V is finite-dimensional
have *finite-C*: *finite C*
using *finiteI-independent*[*OF independent-C*] **.**
have *finite-fC*: *finite* (f ‘ C) **by** (*rule finite-imageI* [*OF finite-C*])
— The basis B of the kernel of f, and its image, are also finite
have *finite-B*: *finite B* **by** (*rule rev-finite-subset* [*OF finite-C B-in-C*])
have *finite-fB*: *finite* (f ‘ B) **by** (*rule finite-imageI*[*OF finite-B*])
— The set $C - B$ is also finite
have *finite-CB*: *finite* $(C - B)$ **by** (*rule finite-Diff* [*OF finite-C*, *of B*])
have *dim-ker-le-dim-V*:*dim* (*ker-f*) $\leq$ *dim V*
using *dim-subset* [*of ker-f V*] **unfolding** *V-def* **by** *simp*
— Here it starts the proof of the theorem: the sets B and $C - B$ must be proven to be bases, respectively, of the kernel of f and its range
show *?thesis*
proof –
have *dimension* = *dim V* **unfolding** *V-def dim-UNIV dimension-def*
by (*metis basis-card-eq-dim dimension-def independent-Basis span-Basis top-greatest*)
also have *dim V* = *dim C* **unfolding** *span-C dim-span* **..**
also have ... = *card C*
using *basis-card-eq-dim* [*of C C*, *OF - span-superset independent-C*] **by** *simp*
also have ... = *card* $(B \cup (C - B))$ **using** *C-eq* **by** *simp*
also have ... = *card B* + *card* $(C-B)$
by (*rule card-Un-disjoint*[*OF finite-B finite-CB*], *fast*)
also have ... = *dim ker-f* + *card* $(C-B)$ **unfolding** *ker-f-def card-B* **..**
— Now it has to be proved that the elements of $C - B$ are a basis of the range of f
also have ... = *dim ker-f* + *l.vs2.dim* (*range f*)
proof (*unfold add-left-cancel*)
define W **where** $W = C - B$
have *finite-W*: *finite W* **unfolding** *W-def* **using** *finite-CB* **.**
have *finite-fW*: *finite* (f ‘ W) **using** *finite-imageI*[*OF finite-W*] **.**

have *card W* = *card* (*f* ‘ *W*)
by (*rule card-image* [*symmetric*], *rule inj-on-extended*[*OF l*, *of C B*], *rule finite-C*)
(*rule independent-C*,*unfold W-def*, *subst C-eq*, *rule refl*, *simp*, *rule ker-in-span*)
also have ... = *l.vs2.dim* (*range f*)
— The image set of W is independent and its span contains the range of f, so it is a basis of the range:
proof (*rule l.vs2.basis-card-eq-dim*)
— 1. The image set of W generates the range of f:
show *range f* ⊆ *l.vs2.span* (*f* ‘ *W*)
proof (*unfold l.vs2.span-finite* [*OF finite-fW*], *auto*)
— Given any element v in V, its image can be expressed as a linear combination of elements of the image by f of C:
fix *v* :: *'b*
have *fV-span*: *f* ‘ *V* ⊆ *l.vs2.span* (*f* ‘ *C*)
by (*simp add*: *span-C l.span-image*)
have ∃ *g*. (∑ *x*∈*f*‘*C*. *scaleC* (*g x*) *x*) = *f v*
using *fV-span* **unfolding** *V-def*
using *l.vs2.span-finite*[*OF finite-fC*]
by (*metis* (*no-types*, *lifting*) *V-def rangeE rangeI span-C l.span-image*)
then obtain *g* **where** *fv*: *f v* = (∑ *x*∈*f* ‘ *C*. *scaleC* (*g x*) *x*) **by** *metis*
— We recall that C is equal to B union $(C - B)$, and B is the basis of the kernel; thus, the image of the elements of B will be equal to zero:
have *zero-fB*: (∑ *x*∈*f* ‘ *B*. *scaleC* (*g x*) *x*) = *0*
using *B-in-ker* **by** (*auto intro*!: *sum.neutral*)
have *zero-inter*: (∑ *x*∈(*f* ‘ *B* ∩ *f* ‘ *W*). *scaleC* (*g x*) *x*) = *0*
using *B-in-ker* **by** (*auto intro*!: *sum.neutral*)
have *f v* = (∑ *x*∈*f* ‘ *C*. *scaleC* (*g x*) *x*) **using** *fv* **.**
also have ... = (∑ *x*∈(*f* ‘ *B* ∪ *f* ‘ *W*). *scaleC* (*g x*) *x*)
using *eq-fC W-def* **by** *simp*
also have ... =
(∑ *x*∈*f* ‘ *B*. *scaleC* (*g x*) *x*) + (∑ *x*∈*f* ‘ *W*. *scaleC* (*g x*) *x*)
− (∑ *x*∈(*f* ‘ *B* ∩ *f* ‘ *W*). *scaleC* (*g x*) *x*)
using *sum-Un* [*OF finite-fB finite-fW*] **by** *simp*
also have ... = (∑ *x*∈*f* ‘ *W*. *scaleC* (*g x*) *x*)
unfolding *zero-fB zero-inter* **by** *simp*
— We have proved that the image set of W is a generating set of the range of f
finally show *f v* ∈ *range* (λ*u*. ∑ *v*∈*f* ‘ *W*. *scaleC* (*u v*) *v*) **by** *auto*
qed
— 2. The image set of W is linearly independent:
show *l.vs2.independent* (*f* ‘ *W*)
using *finite-fW*
proof (*rule l.vs2.independent-if-scalars-zero*)
— Every linear combination (given by gx) of the elements of the image set of W equal to zero, requires every coefficient to be zero:
fix *g* :: *'c* => *'a* **and** *w* :: *'c*
assume *sum*: (∑ *x*∈*f* ‘ *W*. *scaleC* (*g x*) *x*) = *0* **and** *w*: *w* ∈ *f* ‘ *W*

have $0 = (\sum x{\in}f \text{ ` } W.\ scaleC\ (g\ x)\ x)$ **using** *sum* **by** *simp*
also have ... $=$ *sum* $((\lambda x.\ scaleC\ (g\ x)\ x) \circ f)\ W$
by (*rule sum.reindex*, *rule inj-on-extended*[*OF l*, *of C B*])
(*unfold W-def*, *rule finite-C*, *rule independent-C*, *rule C-eq*, *simp*,
rule ker-in-span)
also have ... $= (\sum x{\in}W.\ scaleC\ ((g \circ f)\ x)\ (f\ x))$ **unfolding** *o-def* **..**
also have ... $= f\ (\sum x{\in}W.\ scale\ ((g \circ f)\ x)\ x)$
unfolding *l.sum*[*symmetric*] *l.scale*[*symmetric*] **by** *simp*
finally have *f-sum-zero*:$f\ (\sum x{\in}W.\ scale\ ((g \circ f)\ x)\ x) = 0$ **by** (*rule sym*)
hence $(\sum x{\in}W.\ scale\ ((g \circ f)\ x)\ x) \in$ *ker-f* **unfolding** *ker-f-def* **by** *simp*
hence $\exists\, h.\ (\sum v{\in}B.\ scale\ (h\ v)\ v) = (\sum x{\in}W.\ scale\ ((g \circ f)\ x)\ x)$
using *span-finite*[*OF finite-B*] **using** *ker-in-span*
unfolding *ker-f-def* **by** *force*
then obtain h **where**
sum-h: $(\sum v{\in}B.\ scale\ (h\ v)\ v) = (\sum x{\in}W.\ scale\ ((g \circ f)\ x)\ x)$ **by** *blast*
define t **where** $t\ a = (\mathit{if}\ a \in B\ \mathit{then}\ h\ a\ \mathit{else}\ -\ ((g \circ f)\ a))$ **for** a
have $0 = (\sum v{\in}B.\ scale\ (h\ v)\ v) + -\ (\sum x{\in}W.\ scale\ ((g \circ f)\ x)\ x)$
using *sum-h* **by** *simp*
also have ... $=\ (\sum v{\in}B.\ scale\ (h\ v)\ v) + (\sum x{\in}W.\ -\ (scale\ ((g \circ f)\ x)$
$x))$
unfolding *sum-negf* **..**
also have ... $= (\sum v{\in}B.\ scale\ (t\ v)\ v) + (\sum x{\in}W.\ -(scale((g \circ f)\ x)\ x))$
unfolding *add-right-cancel* **unfolding** *t-def* **by** *simp*
also have ... $=\ (\sum v{\in}B.\ scale\ (t\ v)\ v) + (\sum x{\in}W.\ scale\ (t\ x)\ x)$
by (*unfold add-left-cancel t-def W-def*, *rule sum.cong*) *simp+*
also have ... $= (\sum v{\in}B \cup W.\ scale\ (t\ v)\ v)$
by (*rule sum.union-inter-neutral* [*symmetric*], *rule finite-B*, *rule finite-W*)

(*simp add*: *W-def*)
finally have $(\sum v{\in}B \cup W.\ scale\ (t\ v)\ v) = 0$ **by** *simp*
hence *coef-zero*: $\forall\, x{\in}B \cup W.\ t\ x = 0$
using *C-eq scalars-zero-if-independent* [*OF finite-C independent-C*]
unfolding *W-def* **by** *simp*
obtain y **where** *w-fy*: $w = f\ y$ **and** *y-in-W*: $y \in W$ **using** w **by** *fast*
have $-\ g\ w = t\ y$
unfolding *t-def w-fy* **using** *y-in-W* **unfolding** *W-def* **by** *simp*
also have ... $= 0$ **using** *coef-zero y-in-W* **unfolding** *W-def* **by** *simp*
finally show $g\ w = 0$ **by** *simp*
qed
qed *auto*
finally show *card* $(C - B) =$ *l.vs2.dim* (*range f*) **unfolding** *W-def* **.**
qed
finally show *?thesis* **unfolding** *V-def ker-f-def* **unfolding** *dim-UNIV* **.**
qed
qed

end

5.3 The rank nullity theorem for matrices

The proof of the theorem for matrices is direct, as a consequence of the "rank nullity theorem".

lemma *rank-nullity-theorem-matrices*:
  fixes A::$'a$::{*field*}^$'$*cols*::{*finite*, *wellorder*}^$'$*rows*
  shows *ncols* A = *vec.dim* (*null-space* A) + *vec.dim* (*col-space* A)
  using *vec.rank-nullity-theorem*[*OF matrix-vector-mul-linear-gen*, *of* A]
  apply (*subst* (*2 3*) *matrix-of-matrix-vector-mul* [*of* A, *symmetric*])
  unfolding *null-space-eq-ker*[*OF matrix-vector-mul-linear-gen*]
  unfolding *col-space-eq-range* [*OF matrix-vector-mul-linear-gen*]
  unfolding *vec.dimension-def ncols-def card-cart-basis*
  by *simp*

end

References

[1] S. Axler. *Linear Algebra Done Right.* Springer, 2nd edition, 1997.

[2] M. S. Gockenbach. *Finite Dimensional Linear Algebra.* CRC Press, 2010.