Representations of Finite Groups

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Abstract

We provide a formal framework for the theory of representations of finite groups, as modules over the group ring. Along the way, we develop the general theory of groups (relying on the *group_add* class for the basics), modules, and vector spaces, to the extent required for theory of group representations. We then provide formal proofs of several important introductory theorems in the subject, including Maschke's theorem, Schur's lemma, and Frobenius reciprocity. We also prove that every irreducible representation is isomorphic to a submodule of the group ring, leading to the fact that for a finite group there are only finitely many isomorphism classes of irreducible representations. In all of this, no restriction is made on the characteristic of the ring or field of scalars until the definition of a group representation, and then the only restriction made is that the characteristic must not divide the order of the group.

Contents

Note: A number of the proofs in this theory were modelled on or inspired by proofs in the books listed in the bibliography.

theory *Rep-Fin-Groups*

imports
HOL−Library.Function-Algebras
HOL−Library.Set-Algebras
HOL−Computational-Algebra.Polynomial

begin

1 Preliminaries

In this section, we establish some basic facts about logic, sets, and functions that are not available in the HOL library. As well, we develop some theory for almost-everywhere-zero functions in preparation of the definition of the group ring.

1.1 Logic

lemma *conjcases* [*case-names BothTrue OneTrue OtherTrue BothFalse*] :
assumes *BothTrue*: $P \wedge Q \implies R$
and *OneTrue*: $P \wedge \neg Q \implies R$
and *OtherTrue*: $\neg P \wedge Q \implies R$
and *BothFalse*: $\neg P \wedge \neg Q \implies R$
shows R
⟨*proof*⟩

1.2 Sets

lemma *empty-set-diff-single* : $A - \{x\} = \{\} \implies A = \{\} \vee A = \{x\}$
⟨*proof*⟩

lemma *seteqI* : $(\bigwedge a.\ a \in A \implies a \in B) \implies (\bigwedge b.\ b \in B \implies b \in A) \implies A = B$
⟨*proof*⟩

lemma *prod-ballI* : $(\bigwedge a\ b.\ (a,b) \in AxB \implies P\ a\ b) \implies \forall (a,b) \in AxB.\ P\ a\ b$
⟨*proof*⟩

lemma *good-card-imp-finite* : *of-nat* (*card A*) $\neq$ (*0*::'*a*::*semiring-1*) $\implies$ *finite A*
⟨*proof*⟩

1.3 Lists

1.3.1 *zip*

lemma *zip-truncate-left* : *zip xs ys* = *zip* (*take* (*length ys*) *xs*) *ys*
⟨*proof*⟩

lemma *zip-truncate-right* : *zip xs ys* = *zip xs* (*take* (*length xs*) *ys*)
⟨*proof*⟩

Lemmas *zip-append1* and *zip-append2* in theory *HOL.List* have unnecessary *take* (*length* -) in them. Here are replacements.

lemma *zip-append-left* :
zip (*xs*@*ys*) *zs* = *zip xs zs* @ *zip ys* (*drop* (*length xs*) *zs*)
⟨*proof*⟩

lemma *zip-append-right* :
zip xs (*ys*@*zs*) = *zip xs ys* @ *zip* (*drop* (*length ys*) *xs*) *zs*

⟨*proof*⟩

lemma *length-concat-map-split-zip* :
length [*f x y*. (*x*,*y*)←*zip xs ys*] = *min* (*length xs*) (*length ys*)
⟨*proof*⟩

lemma *concat-map-split-eq-map-split-zip* :
[*f x y*. (*x*,*y*)←*zip xs ys*] = *map* (*case-prod f*) (*zip xs ys*)
⟨*proof*⟩

lemma *set-zip-map2* :
(*a*,*z*) ∈ *set* (*zip xs* (*map f ys*)) ⟹ ∃ *b*. (*a*,*b*) ∈ *set* (*zip xs ys*) ∧ *z* = *f b*
⟨*proof*⟩

1.3.2 *concat*

lemma *concat-eq* :
list-all2 (λ*xs ys*. *length xs* = *length ys*) *xss yss* ⟹ *concat xss* = *concat yss*
⟹ *xss* = *yss*
⟨*proof*⟩

lemma *match-concat* :
fixes *bss* :: *'b list list*
defines *eq-len*: *eq-len* ≡ λ*xs ys*. *length xs* = *length ys*
shows ∀ *as*::*'a list*. *length as* = *length* (*concat bss*)
⟶ (∃ *css*::*'a list list*. *as* = *concat css* ∧ *list-all2 eq-len css bss*)
⟨*proof*⟩

1.3.3 *strip-while*

lemma *strip-while-0-nnil* :
as ≠ [] ⟹ *set as* ≠ *0* ⟹ *strip-while* ((=) *0*) *as* ≠ []
⟨*proof*⟩

1.3.4 *sum-list*

lemma *const-sum-list* :
∀ *x* ∈ *set xs*. *f x* = *a* ⟹ *sum-list* (*map f xs*) = *a* ∗ (*length xs*)
⟨*proof*⟩

lemma *sum-list-prod-cong* :
∀ (*x*,*y*) ∈ *set xys*. *f x y* = *g x y*
⟹ (∑ (*x*,*y*)←*xys*. *f x y*) = (∑ (*x*,*y*)←*xys*. *g x y*)
⟨*proof*⟩

lemma *sum-list-prod-map2* :
(∑ (*a*,*y*)←*zip as* (*map f bs*). *g a y*) = (∑ (*a*,*b*)←*zip as bs*. *g a* (*f b*))
⟨*proof*⟩

lemma *sum-list-fun-apply* : (∑ *x*←*xs*. *f x*) *y* = (∑ *x*←*xs*. *f x y*)

⟨*proof*⟩

lemma *sum-list-prod-fun-apply* : $(\sum (x,y)\leftarrow xys.\ f\ x\ y)\ z = (\sum (x,y)\leftarrow xys.\ f\ x\ y\ z)$
⟨*proof*⟩

lemma (**in** *comm-monoid-add*) *sum-list-plus* :
$length\ xs = length\ ys$
$\Longrightarrow sum\text{-}list\ xs + sum\text{-}list\ ys = sum\text{-}list\ [a+b.\ (a,b)\leftarrow zip\ xs\ ys]$
⟨*proof*⟩

lemma *sum-list-const-mult-prod* :
fixes $f :: 'a \Rightarrow 'b \Rightarrow 'r$::*semiring-0*
shows $r * (\sum (x,y)\leftarrow xys.\ f\ x\ y) = (\sum (x,y)\leftarrow xys.\ r * (f\ x\ y))$
⟨*proof*⟩

lemma *sum-list-mult-const-prod* :
fixes $f :: 'a \Rightarrow 'b \Rightarrow 'r$::*semiring-0*
shows $(\sum (x,y)\leftarrow xys.\ f\ x\ y) * r = (\sum (x,y)\leftarrow xys.\ (f\ x\ y) * r)$
⟨*proof*⟩

lemma *sum-list-update* :
fixes $xs :: 'a$::*ab-group-add list*
shows $n < length\ xs \Longrightarrow sum\text{-}list\ (xs[n := y]) = sum\text{-}list\ xs - xs!n + y$
⟨*proof*⟩

lemma *sum-list-replicate0* : $sum\text{-}list\ (replicate\ n\ 0) = 0$
⟨*proof*⟩

1.3.5 *listset*

lemma *listset-ConsI* : $x \in X \Longrightarrow xs \in listset\ Xs \Longrightarrow x\#xs \in listset\ (X\#Xs)$
⟨*proof*⟩

lemma *listset-ConsD* : $x\#xs \in listset\ (A\ \#\ As) \Longrightarrow x \in A \wedge xs \in listset\ As$
⟨*proof*⟩

lemma *listset-Cons-conv* :
$xs \in listset\ (A\ \#\ As) \Longrightarrow (\exists\, y\ ys.\ y \in A \wedge ys \in listset\ As \wedge xs = y\#ys)$
⟨*proof*⟩

lemma *listset-length* : $xs \in listset\ Xs \Longrightarrow length\ xs = length\ Xs$
⟨*proof*⟩

lemma *set-sum-list-element* :
$x \in (\sum A\leftarrow As.\ A) \Longrightarrow \exists\, as \in listset\ As.\ x = (\sum a\leftarrow as.\ a)$
⟨*proof*⟩

lemma *set-sum-list-element-Cons* :
assumes $x \in (\sum X\leftarrow(A\#As).\ X)$

shows $\exists\, a\ as.\ a{\in}A \wedge as \in listset\ As \wedge x = a + (\sum b{\leftarrow}as.\ b)$
⟨*proof*⟩

lemma *sum-list-listset* : $as \in listset\ As \Longrightarrow sum\text{-}list\ as \in (\sum A{\leftarrow}As.\ A)$
⟨*proof*⟩

lemma *listsetI-nth* :
$length\ xs = length\ Xs \Longrightarrow \forall\, n{<}length\ xs.\ xs!n \in Xs!n \Longrightarrow xs \in listset\ Xs$
⟨*proof*⟩

lemma *listsetD-nth* : $xs \in listset\ Xs \Longrightarrow \forall\, n{<}length\ xs.\ xs!n \in Xs!n$
⟨*proof*⟩

lemma *set-listset-el-subset* :
$xs \in listset\ Xs \Longrightarrow \forall\, X{\in}set\ Xs.\ X \subseteq A \Longrightarrow set\ xs \subseteq A$
⟨*proof*⟩

1.4 Functions

1.4.1 Miscellaneous facts

lemma *sum-fun-apply* : $finite\ A \Longrightarrow (\sum a{\in}A.\ f\ a)\ x = (\sum a{\in}A.\ f\ a\ x)$
⟨*proof*⟩

lemma *sum-single-nonzero* :
$finite\ A \Longrightarrow (\forall\, x{\in}A.\ \forall\, y{\in}A.\ f\ x\ y = (if\ y = x\ then\ g\ x\ else\ 0))$
$\Longrightarrow (\forall\, x{\in}A.\ sum\ (f\ x)\ A = g\ x)$
⟨*proof*⟩

lemma *distrib-comp-sum-right* : $(T + T') \circ S = (T \circ S) + (T' \circ S)$
⟨*proof*⟩

1.4.2 Support of a function

definition *supp* :: $('a \Rightarrow 'b{::}zero) \Rightarrow 'a\ set$ **where** $supp\ f = \{x.\ f\ x \neq 0\}$

lemma *suppI*: $f\ x \neq 0 \Longrightarrow x \in supp\ f$
⟨*proof*⟩

lemma *suppI-contra*: $x \notin supp\ f \Longrightarrow f\ x = 0$
⟨*proof*⟩

lemma *suppD*: $x \in supp\ f \Longrightarrow f\ x \neq 0$
⟨*proof*⟩

lemma *suppD-contra*: $f\ x = 0 \Longrightarrow x \notin supp\ f$
⟨*proof*⟩

lemma *zerofun-imp-empty-supp* : $supp\ 0 = \{\}$
⟨*proof*⟩

lemma *supp-zerofun-subset-any* : $supp\ 0 \subseteq A$
⟨*proof*⟩

lemma *supp-sum-subset-union-supp* :
fixes $f\ g :: 'a \Rightarrow 'b::monoid\text{-}add$
shows $supp\ (f + g) \subseteq supp\ f \cup supp\ g$
⟨*proof*⟩

lemma *supp-neg-eq-supp* :
fixes $f :: 'a \Rightarrow 'b::group\text{-}add$
shows $supp\ (-f) = supp\ f$
⟨*proof*⟩

lemma *supp-diff-subset-union-supp* :
fixes $f\ g :: 'a \Rightarrow 'b::group\text{-}add$
shows $supp\ (f - g) \subseteq supp\ f \cup supp\ g$
⟨*proof*⟩

abbreviation *restrict0* :: $('a \Rightarrow 'b::zero) \Rightarrow 'a\ set \Rightarrow ('a \Rightarrow 'b)$ (**infix** ‹↓› *70*)
where $restrict0\ f\ A \equiv (\lambda a.\ if\ a \in A\ then\ f\ a\ else\ 0)$

lemma *supp-restrict0* : $supp\ (f{\downarrow}A) \subseteq A$
⟨*proof*⟩

lemma *bij-betw-restrict0* : $bij\text{-}betw\ f\ A\ B \Longrightarrow bij\text{-}betw\ (f \downarrow A)\ A\ B$
⟨*proof*⟩

1.4.3 Convolution

definition *convolution* ::
$('a::group\text{-}add \Rightarrow 'b::\{comm\text{-}monoid\text{-}add,times\}) \Rightarrow ('a \Rightarrow 'b) \Rightarrow ('a \Rightarrow 'b)$
where *convolution f g*
$= (\lambda x.\ \sum y | x - y \in supp\ f \wedge y \in supp\ g.\ (f\ (x - y)) * g\ y)$
— More often than not, this definition will be used in the case that $'b$ is of class *mult-zero*, in which case the conditions $x - y \in supp\ f$ and $y \in supp\ g$ are obviously mathematically unnecessary. However, they also serve to ensure that the sum is taken over a finite set in the case that at least one of f and g is almost everywhere zero.

lemma *convolution-zero* :
fixes $f\ g :: 'a::group\text{-}add \Rightarrow 'b::\{comm\text{-}monoid\text{-}add,mult\text{-}zero\}$
shows $f = 0 \vee g = 0 \Longrightarrow convolution\ f\ g = 0$
⟨*proof*⟩

lemma *convolution-symm* :
fixes $f\ g :: 'a::group\text{-}add \Rightarrow 'b::\{comm\text{-}monoid\text{-}add,times\}$
shows *convolution f g*
$= (\lambda x.\ \sum y | y \in supp\ f \wedge -y + x \in supp\ g.\ (f\ y) * g\ (-y + x))$

⟨*proof*⟩

lemma *supp-convolution-subset-sum-supp* :
fixes *f g* :: *'a*::*group-add* ⇒ *'b*::{*comm-monoid-add*,*times*}
shows *supp* (*convolution f g*) ⊆ *supp f* + *supp g*
⟨*proof*⟩

1.5 Almost-everywhere-zero functions

1.5.1 Definition and basic properties

definition *aezfun-set* = {*f*::*'a*⇒*'b*::*zero*. *finite* (*supp f*)}

lemma *aezfun-setD*: *f* ∈ *aezfun-set* ⟹ *finite* (*supp f*)
⟨*proof*⟩

lemma *aezfun-setI*: *finite* (*supp f*) ⟹ *f* ∈ *aezfun-set*
⟨*proof*⟩

lemma *zerofun-is-aezfun* : *0* ∈ *aezfun-set*
⟨*proof*⟩

lemma *sum-of-aezfun-is-aezfun* :
fixes *f g* :: *'a*⇒*'b*::*monoid-add*
shows *f* ∈ *aezfun-set* ⟹ *g* ∈ *aezfun-set* ⟹ *f* + *g* ∈ *aezfun-set*
⟨*proof*⟩

lemma *neg-of-aezfun-is-aezfun* :
fixes *f* :: *'a*⇒*'b*::*group-add*
shows *f* ∈ *aezfun-set* ⟹ − *f* ∈ *aezfun-set*
⟨*proof*⟩

lemma *diff-of-aezfun-is-aezfun* :
fixes *f g* :: *'a*⇒*'b*::*group-add*
shows *f* ∈ *aezfun-set* ⟹ *g* ∈ *aezfun-set* ⟹ *f* − *g* ∈ *aezfun-set*
⟨*proof*⟩

lemma *restrict-and-extend0-aezfun-is-aezfun* :
assumes *f* ∈ *aezfun-set*
shows *f*↓*A* ∈ *aezfun-set*
⟨*proof*⟩

1.5.2 Delta (impulse) functions

The notation is set up in the order output-input so that later when these are used to define the group ring RG, it will be in order ring-element-group-element.

definition *deltafun* :: *'b*::*zero* ⇒ *'a* ⇒ (*'a* ⇒ *'b*) (**infix** ‹*δ*› *70*)
where *b δ a* = (λ*x*. *if x* = *a then b else 0*)

lemma *deltafun-apply-eq* : $(b\ \delta\ a)\ a = b$
⟨*proof*⟩

lemma *deltafun-apply-neq* : $x \neq a \Longrightarrow (b\ \delta\ a)\ x = 0$
⟨*proof*⟩

lemma *deltafun0* : $0\ \delta\ a = 0$
⟨*proof*⟩

lemma *deltafun-plus* :
fixes $b\ c :: 'b{::}monoid\text{-}add$
shows $(b{+}c)\ \delta\ a = (b\ \delta\ a) + (c\ \delta\ a)$
⟨*proof*⟩

lemma *supp-delta0fun* : $supp\ (0\ \delta\ a) = \{\}$
⟨*proof*⟩

lemma *supp-deltafun* : $b \neq 0 \Longrightarrow supp\ (b\ \delta\ a) = \{a\}$
⟨*proof*⟩

lemma *deltafun-is-aezfun* : $b\ \delta\ a \in aezfun\text{-}set$
⟨*proof*⟩

lemma *aezfun-common-supp-spanning-set'* :
$finite\ A \Longrightarrow \exists\, as.\ distinct\ as \wedge set\ as = A$
$\wedge\ (\ \forall f{::}'a \Rightarrow 'b{::}semiring\text{-}1.\ supp\ f \subseteq A$
$\longrightarrow (\exists\, bs.\ length\ bs = length\ as \wedge f = (\sum (b,a){\leftarrow}zip\ bs\ as.\ b\ \delta\ a))\ )$
⟨*proof*⟩

1.5.3 Convolution of almost-everywhere-zero functions

lemma *convolution-eq-sum-over-supp-right* :
fixes $g\ f :: 'a{::}group\text{-}add \Rightarrow 'b{::}\{comm\text{-}monoid\text{-}add,mult\text{-}zero\}$
assumes $g \in aezfun\text{-}set$
shows $convolution\ f\ g = (\lambda x.\ \sum y{\in}supp\ g.\ (f\ (x - y)) * g\ y\ )$
⟨*proof*⟩

lemma *convolution-symm-eq-sum-over-supp-left* :
fixes $f\ g :: 'a{::}group\text{-}add \Rightarrow 'b{::}\{comm\text{-}monoid\text{-}add,mult\text{-}zero\}$
assumes $f \in aezfun\text{-}set$
shows $convolution\ f\ g = (\lambda x.\ \sum y{\in}supp\ f.\ (f\ y) * g\ (-y + x))$
⟨*proof*⟩

lemma *convolution-delta-left* :
fixes $b :: 'b{::}\{comm\text{-}monoid\text{-}add,mult\text{-}zero\}$
and $a :: 'a{::}group\text{-}add$
and $f :: 'a \Rightarrow 'b$
shows $convolution\ (b\ \delta\ a)\ f = (\lambda x.\ b * f\ (-a + x))$

⟨*proof*⟩

lemma *convolution-delta-right* :
fixes *b* :: *'b*::{*comm-monoid-add*,*mult-zero*}
and *f* :: *'a*::*group-add* ⇒ *'b* **and** *a*::*'a*
shows *convolution f* (*b δ a*) = (λ*x*. *f* (*x* − *a*) ∗ *b*)
⟨*proof*⟩

lemma *convolution-delta-delta* :
fixes *b1 b2* :: *'b*::{*comm-monoid-add*,*mult-zero*}
and *a1 a2* :: *'a*::*group-add*
shows *convolution* (*b1 δ a1*) (*b2 δ a2*) = (*b1* ∗ *b2*) *δ* (*a1* + *a2*)
⟨*proof*⟩

lemma *convolution-of-aezfun-is-aezfun* :
fixes *f g* :: *'a*::*group-add* ⇒ *'b*::{*comm-monoid-add*,*times*}
shows *f* ∈ *aezfun-set* ⟹ *g* ∈ *aezfun-set* ⟹ *convolution f g* ∈ *aezfun-set*
⟨*proof*⟩

lemma *convolution-assoc* :
fixes *f h g* :: *'a*::*group-add* ⇒ *'b*::*semiring-0*
assumes *f-aez*: *f* ∈ *aezfun-set* **and** *h-aez*: *h* ∈ *aezfun-set*
shows *convolution* (*convolution f g*) *h* = *convolution f* (*convolution g h*)
⟨*proof*⟩

lemma *convolution-distrib-left* :
fixes *g h f* :: *'a*::*group-add* ⇒ *'b*::*semiring-0*
assumes *g* ∈ *aezfun-set h* ∈ *aezfun-set*
shows *convolution f* (*g* + *h*) = *convolution f g* + *convolution f h*
⟨*proof*⟩

lemma *convolution-distrib-right* :
fixes *f g h* :: *'a*::*group-add* ⇒ *'b*::*semiring-0*
assumes *f* ∈ *aezfun-set g* ∈ *aezfun-set*
shows *convolution* (*f* + *g*) *h* = *convolution f h* + *convolution g h*
⟨*proof*⟩

1.5.4 Type definition, instantiations, and instances

typedef (**overloaded**) (*'a*::*zero*,*'b*) *aezfun* = *aezfun-set* :: (*'b*⇒*'a*) *set*
morphisms *aezfun Abs-aezfun*
⟨*proof*⟩

setup-lifting *type-definition-aezfun*

lemma *aezfun-finite-supp* : *finite* (*supp* (*aezfun a*))
⟨*proof*⟩

lemma *aezfun-transfer* : *aezfun a* = *aezfun b* ⟹ *a* = *b* ⟨*proof*⟩

instantiation *aezfun* :: (*zero*, *type*) *zero*
begin
  lift-definition *zero-aezfun* :: ('*a*,'*b*) *aezfun* **is** *0*::'*b*⇒'*a*
    ⟨*proof*⟩
  instance ⟨*proof*⟩
end

lemma *zero-aezfun-transfer* : *Abs-aezfun* ((*0*::'*b*::*zero*) *δ* (*0*::'*a*::*zero*)) = *0*
⟨*proof*⟩

lemma *zero-aezfun-apply* [*simp*]: *aezfun 0 x* = *0*
  ⟨*proof*⟩

instantiation *aezfun* :: (*monoid-add*, *type*) *plus*
begin
  lift-definition *plus-aezfun* :: ('*a*, '*b*) *aezfun* ⇒ ('*a*, '*b*) *aezfun* ⇒ ('*a*, '*b*) *aezfun*
    is λ*f g*. *f* + *g*
    ⟨*proof*⟩
  instance ⟨*proof*⟩
end

lemma *plus-aezfun-apply* [*simp*]: *aezfun* (*a*+*b*) *x* = *aezfun a x* + *aezfun b x*
  ⟨*proof*⟩

instance *aezfun* :: (*monoid-add*, *type*) *semigroup-add*
⟨*proof*⟩

instance *aezfun* :: (*monoid-add*, *type*) *monoid-add*
⟨*proof*⟩

lemma *sum-list-aezfun-apply* [*simp*] :
  aezfun (*sum-list as*) *x* = (∑ *a*←*as*. *aezfun a x*)
  ⟨*proof*⟩

lemma *sum-list-map-aezfun-apply* [*simp*] :
  aezfun (∑ *a*←*as*. *f a*) *x* = (∑ *a*←*as*. *aezfun* (*f a*) *x*)
  ⟨*proof*⟩

lemma *sum-list-map-aezfun* [*simp*] :
  aezfun (∑ *a*←*as*. *f a*) = (∑ *a*←*as*. *aezfun* (*f a*))
  ⟨*proof*⟩

lemma *sum-list-prod-map-aezfun-apply* :
  aezfun (∑ (*x*,*y*)←*xys*. *f x y*) *a* = (∑ (*x*,*y*)←*xys*. *aezfun* (*f x y*) *a*)
  ⟨*proof*⟩

lemma *sum-list-prod-map-aezfun* :
  aezfun (∑ (*x*,*y*)←*xys*. *f x y*) = (∑ (*x*,*y*)←*xys*. *aezfun* (*f x y*))

⟨*proof*⟩

instance *aezfun* :: (*comm-monoid-add*, *type*) *comm-monoid-add*
⟨*proof*⟩

lemma *sum-aezfun-apply* [*simp*] :
finite A ⟹ *aezfun* (∑ *A*) *x* = (∑ *a*∈*A*. *aezfun a x*)
⟨*proof*⟩

instantiation *aezfun* :: (*group-add*, *type*) *minus*
begin
lift-definition *minus-aezfun* :: ('*a*, '*b*) *aezfun* ⇒ ('*a*, '*b*) *aezfun* ⇒ ('*a*, '*b*) *aezfun*
is λ*f g*. *f* − *g*
⟨*proof*⟩
instance ⟨*proof*⟩
end

lemma *minus-aezfun-apply* [*simp*]: *aezfun* (*a*−*b*) *x* = *aezfun a x* − *aezfun b x*
⟨*proof*⟩

instantiation *aezfun* :: (*group-add*, *type*) *uminus*
begin
lift-definition *uminus-aezfun* :: ('*a*, '*b*) *aezfun* ⇒ ('*a*, '*b*) *aezfun* **is** λ*f*. − *f*
⟨*proof*⟩
instance ⟨*proof*⟩
end

lemma *uminus-aezfun-apply* [*simp*]: *aezfun* (−*a*) *x* = − *aezfun a x*
⟨*proof*⟩

lemma *aezfun-left-minus* [*simp*] :
fixes *a* :: ('*a*::*group-add*, '*b*) *aezfun*
shows − *a* + *a* = *0*
⟨*proof*⟩

lemma *aezfun-diff-minus* [*simp*] :
fixes *a b* :: ('*a*::*group-add*, '*b*) *aezfun*
shows *a* − *b* = *a* + − *b*
⟨*proof*⟩

instance *aezfun* :: (*group-add*, *type*) *group-add*
⟨*proof*⟩

instance *aezfun* :: (*ab-group-add*, *type*) *ab-group-add*
⟨*proof*⟩

instantiation *aezfun* :: ({*one*,*zero*}, *zero*) *one*
begin
lift-definition *one-aezfun* :: ('*a*,'*b*) *aezfun* **is** *1* δ *0*

⟨*proof*⟩
instance ⟨*proof*⟩
end

lemma *one-aezfun-transfer* : *Abs-aezfun* (*1* δ *0*) = *1*
⟨*proof*⟩

lemma *one-aezfun-apply* [*simp*]: *aezfun 1 x* = (*1* δ *0*) *x*
⟨*proof*⟩

lemma *one-aezfun-apply-eq* [*simp*]: *aezfun 1 0* = *1*
⟨*proof*⟩

lemma *one-aezfun-apply-neq* [*simp*]: *x* $\neq$ *0* $\Longrightarrow$ *aezfun 1 x* = *0*
⟨*proof*⟩

instance *aezfun* :: (*zero-neq-one*, *zero*) *zero-neq-one*
⟨*proof*⟩

instantiation *aezfun* :: ({*comm-monoid-add*,*times*}, *group-add*) *times*
begin
lift-definition *times-aezfun* :: ('*a*, '*b*) *aezfun* $\Rightarrow$ ('*a*, '*b*) *aezfun* $\Rightarrow$ ('*a*, '*b*) *aezfun*
is λ *f g*. *convolution f g*
⟨*proof*⟩
instance ⟨*proof*⟩
end

lemma *convolution-transfer* :
assumes *f* $\in$ *aezfun-set g* $\in$ *aezfun-set*
shows *Abs-aezfun* (*convolution f g*) = *Abs-aezfun f* $*$ *Abs-aezfun g*
⟨*proof*⟩

instance *aezfun* :: ({*comm-monoid-add*,*mult-zero*}, *group-add*) *mult-zero*
⟨*proof*⟩

instance *aezfun* :: (*semiring-0*, *group-add*) *semiring-0*
⟨*proof*⟩

instance *aezfun* :: (*ring*, *group-add*) *ring* ⟨*proof*⟩

instance *aezfun* :: ({*semiring-0*,*monoid-mult*,*zero-neq-one*}, *group-add*) *monoid-mult*
⟨*proof*⟩

instance *aezfun* :: (*ring-1*, *group-add*) *ring-1* ⟨*proof*⟩

1.5.5 Transfer facts

abbreviation *aezdeltafun* :: '*b*::*zero* $\Rightarrow$ '*a* $\Rightarrow$ ('*b*,'*a*) *aezfun* (**infix** ‹$\delta\delta$› *70*)
where *b* $\delta\delta$ *a* $\equiv$ *Abs-aezfun* (*b* δ *a*)

lemma *aezdeltafun* : *aezfun* (*b* *δδ* *a*) = *b* *δ* *a*
⟨*proof*⟩

lemma *aezdeltafun-plus* : (*b*+*c*) *δδ* *a* = (*b* *δδ* *a*) + (*c* *δδ* *a*)
⟨*proof*⟩

lemma *times-aezdeltafun-aezdeltafun* :
fixes *b1* *b2* :: *'b*::{*comm-monoid-add*,*mult-zero*}
shows (*b1* *δδ* *a1*) ∗ (*b2* *δδ* *a2*) = (*b1* ∗ *b2*) *δδ* (*a1* + *a2*)
⟨*proof*⟩

lemma *aezfun-restrict-and-extend0* : (*aezfun* *x*)↓*A* ∈ *aezfun-set*
⟨*proof*⟩

lemma *aezdeltafun-decomp* :
fixes *b* :: *'b*::*semiring-1*
shows *b* *δδ* *a* = (*b* *δδ* *0*) ∗ (*1* *δδ* *a*)
⟨*proof*⟩

lemma *aezdeltafun-decomp'* :
fixes *b* :: *'b*::*semiring-1*
shows *b* *δδ* *a* = (*1* *δδ* *a*) ∗ (*b* *δδ* *0*)
⟨*proof*⟩

lemma *supp-aezfun1* :
supp (*aezfun* (*1* :: (*'a*::*zero-neq-one*,*'b*::*zero*) *aezfun*)) = *0*
⟨*proof*⟩

lemma *supp-aezfun-diff* :
supp (*aezfun* (*x* − *y*)) ⊆ *supp* (*aezfun* *x*) ∪ *supp* (*aezfun* *y*)
⟨*proof*⟩

lemma *supp-aezfun-times* :
supp (*aezfun* (*x* ∗ *y*)) ⊆ *supp* (*aezfun* *x*) + *supp* (*aezfun* *y*)
⟨*proof*⟩

1.5.6 Almost-everywhere-zero functions with constrained support

The name of the next definition anticipates *aezfun-common-supp-spanning-set* below.

definition *aezfun-setspan* :: *'a* *set* ⇒ (*'b*::*zero*,*'a*) *aezfun* *set*
where *aezfun-setspan* *A* = {*x*. *supp* (*aezfun* *x*) ⊆ *A*}

lemma *aezfun-setspanD* : *x* ∈ *aezfun-setspan* *A* ⟹ *supp* (*aezfun* *x*) ⊆ *A*
⟨*proof*⟩

lemma *aezfun-setspanI* : *supp* (*aezfun* *x*) ⊆ *A* ⟹ *x* ∈ *aezfun-setspan* *A*

⟨*proof*⟩

lemma *aezfun-common-supp-spanning-set* :
assumes *finite A*
shows ∃ *as*. *distinct as* ∧ *set as* = *A* ∧ (
∀ *x*::('*b*::*semiring-1*,'*a*) *aezfun* ∈ *aezfun-setspan A*.
∃ *bs*. *length bs* = *length as* ∧ *x* = (∑ (*b*,*a*)←*zip bs as*. *b* δδ *a*)
)
⟨*proof*⟩

lemma *aezfun-common-supp-spanning-set-decomp* :
fixes *G* :: '*g*::*group-add set*
assumes *finite G*
shows ∃ *gs*. *distinct gs* ∧ *set gs* = *G* ∧ (
∀ *x*::('*r*::*semiring-1*,'*g*) *aezfun* ∈ *aezfun-setspan G*.
∃ *rs*. *length rs* = *length gs*
∧ *x* = (∑ (*r*,*g*)←*zip rs gs*. (*r* δδ *0*) ∗ (*1* δδ *g*))
)
⟨*proof*⟩

lemma *aezfun-decomp-aezdeltafun* :
fixes *c* :: ('*r*::*semiring-1*,'*a*) *aezfun*
shows ∃ *ras*. *set* (*map snd ras*) = *supp* (*aezfun c*) ∧ *c* = (∑ (*r*,*a*)←*ras*. *r* δδ *a*)
⟨*proof*⟩

lemma *aezfun-setspan-el-decomp-aezdeltafun* :
fixes *c* :: ('*r*::*semiring-1*,'*a*) *aezfun*
shows *c* ∈ *aezfun-setspan A*
⟹ ∃ *ras*. *set* (*map snd ras*) ⊆ *A* ∧ *c* = (∑ (*r*,*a*)←*ras*. *r* δδ *a*)
⟨*proof*⟩

lemma *aezdelta0fun-commutes'* :
fixes *b1 b2* :: '*b*::*comm-semiring-1*
shows *b1* δδ *a* ∗ (*b2* δδ *0*) = *b2* δδ *0* ∗ (*b1* δδ *a*)
⟨*proof*⟩

lemma *aezdelta0fun-commutes* :
fixes *b* :: '*b*::*comm-semiring-1*
shows *c* ∗ (*b* δδ *0*) = *b* δδ *0* ∗ *c*
⟨*proof*⟩

The following definition constrains the support of arbitrary almost-everywhere-zero functions, as a sort of projection onto a *aezfun-setspan*.

definition *aezfun-setspan-proj* :: '*a set* ⇒ ('*b*::*zero*,'*a*) *aezfun* ⇒ ('*b*::*zero*,'*a*) *aezfun*
where *aezfun-setspan-proj A x* ≡ *Abs-aezfun* ((*aezfun x*)↓*A*)

lemma *aezfun-setspan-projD1* :
a ∈ *A* ⟹ *aezfun* (*aezfun-setspan-proj A x*) *a* = *aezfun x a*
⟨*proof*⟩

lemma *aezfun-setspan-projD2* :
a ∉ *A* ⟹ *aezfun* (*aezfun-setspan-proj A x*) *a* = *0*
⟨*proof*⟩

lemma *aezfun-setspan-proj-in-setspan* :
aezfun-setspan-proj A x ∈ *aezfun-setspan A*
⟨*proof*⟩

lemma *aezfun-setspan-proj-zero* : *aezfun-setspan-proj A 0* = *0*
⟨*proof*⟩

lemma *aezfun-setspan-proj-aezdeltafun* :
aezfun-setspan-proj A (*b* *δδ* *a*) = (*if a* ∈ *A then b* *δδ* *a else 0*)
⟨*proof*⟩

lemma *aezfun-setspan-proj-add* :
aezfun-setspan-proj A (*x*+*y*)
= *aezfun-setspan-proj A x* + *aezfun-setspan-proj A y*
⟨*proof*⟩

lemma *aezfun-setspan-proj-sum-list* :
aezfun-setspan-proj A (∑ *x*←*xs*. *f x*) = (∑ *x*←*xs*. *aezfun-setspan-proj A* (*f x*))
⟨*proof*⟩

lemma *aezfun-setspan-proj-sum-list-prod* :
aezfun-setspan-proj A (∑ (*x*,*y*)←*xys*. *f x y*)
= (∑ (*x*,*y*)←*xys*. *aezfun-setspan-proj A* (*f x y*))
⟨*proof*⟩

1.6 Polynomials

lemma *nonzero-coeffs-nonzero-poly* : *as* ≠ [] ⟹ *set as* ≠ *0* ⟹ *Poly as* ≠ *0*
⟨*proof*⟩

lemma *const-poly-nonzero-coeff* :
assumes *degree p* = *0 p* ≠ *0*
shows *coeff p 0* ≠ *0*
⟨*proof*⟩

lemma *pCons-induct2* [*case-names 00 lpCons rpCons pCons2*]:
assumes *00*: *P 0 0*
and *lpCons*: ⋀*a p*. *a* ≠ *0* ∨ *p* ≠ *0* ⟹ *P* (*pCons a p*) *0*
and *rpCons*: ⋀*b q*. *b* ≠ *0* ∨ *q* ≠ *0* ⟹ *P 0* (*pCons b q*)
and *pCons2*: ⋀*a p b q*. *a* ≠ *0* ∨ *p* ≠ *0* ⟹ *b* ≠ *0* ∨ *q* ≠ *0* ⟹ *P p q*
⟹ *P* (*pCons a p*) (*pCons b q*)
shows *P p q*
⟨*proof*⟩

1.7 Algebra of sets

1.7.1 General facts

lemma *zeroset-eqI*: $0 \in A \Longrightarrow (\bigwedge a.\ a \in A \Longrightarrow a = 0) \Longrightarrow A = 0$
⟨*proof*⟩

lemma *sum-list-sets-single* : $(\sum X{\leftarrow}[A].\ X) = A$
⟨*proof*⟩

lemma *sum-list-sets-double* : $(\sum X{\leftarrow}[A,B].\ X) = A + B$
⟨*proof*⟩

1.7.2 Additive independence of sets

primrec *add-independentS* :: $'a$::*monoid-add set list* ⇒ *bool*
where *add-independentS* [] = *True*
| *add-independentS* (*A*#*As*) = (*add-independentS As*
$\wedge\ (\forall x{\in}(\sum B{\leftarrow}As.\ B).\ \forall a{\in}A.\ a + x = 0 \longrightarrow a = 0)$)

lemma *add-independentS-doubleI*:
assumes $\bigwedge b\ a.\ b{\in}B \Longrightarrow a{\in}A \Longrightarrow a + b = 0 \Longrightarrow a = 0$
shows *add-independentS* [*A*,*B*]
⟨*proof*⟩

lemma *add-independentS-doubleD*:
assumes *add-independentS* [*A*,*B*]
shows $\bigwedge b\ a.\ b{\in}B \Longrightarrow a{\in}A \Longrightarrow a + b = 0 \Longrightarrow a = 0$
⟨*proof*⟩

lemma *add-independentS-double-iff* :
add-independentS [*A*,*B*] = $(\forall b{\in}B.\ \forall a{\in}A.\ a + b = 0 \longrightarrow a = 0\ )$
⟨*proof*⟩

lemma *add-independentS-Cons-conv-sum-right* :
add-independentS (*A*#*As*)
= (*add-independentS* [*A*,$\sum B{\leftarrow}As.\ B$] ∧ *add-independentS As*)
⟨*proof*⟩

lemma *add-independentS-double-sum-conv-append* :
⟦ $\forall X{\in}$*set As*. *0* ∈ *X*; *add-independentS As*; *add-independentS Bs*;
add-independentS [$\sum X{\leftarrow}As.\ X$, $\sum X{\leftarrow}Bs.\ X$] ⟧
⟹ *add-independentS* (*As*@*Bs*)
⟨*proof*⟩

lemma *add-independentS-ConsI* :
assumes *add-independentS As*
$\bigwedge x\ a.$ ⟦ $x{\in}(\sum X{\leftarrow}As.\ X)$; $a \in A$; $a{+}x = 0$ ⟧ ⟹ $a = 0$
shows *add-independentS* (*A*#*As*)
⟨*proof*⟩

lemma *add-independentS-append-reduce-right* :
add-independentS (*As*@*Bs*) ⟹ *add-independentS Bs*
⟨*proof*⟩

lemma *add-independentS-append-reduce-left* :
add-independentS (*As*@*Bs*) ⟹ *0* ∈ (∑ *X*←*Bs*. *X*) ⟹ *add-independentS As*
⟨*proof*⟩

lemma *add-independentS-append-conv-double-sum* :
add-independentS (*As*@*Bs*) ⟹ *add-independentS* [∑ *X*←*As*. *X*, ∑ *X*←*Bs*. *X*]
⟨*proof*⟩

1.7.3 Inner direct sums

definition *inner-dirsum* :: *'a*::*monoid-add set list* ⇒ *'a set*
where *inner-dirsum As* = (*if add-independentS As then* ∑ *A*←*As*. *A else 0*)

Some syntactic sugar for *inner-dirsum*, borrowed from theory *HOL.List*.

syntax
-inner-dirsum :: *pttrn* => *'a list* => *'b* => *'b*
(‹(*3*⨁ -←-. -)› [*0*, *51*, *10*] *10*)
syntax-consts
-inner-dirsum == *inner-dirsum*
translations — Beware of argument permutation!
⨁ *M*←*Ms*. *b* == *CONST inner-dirsum* (*CONST map* (%*M*. *b*) *Ms*)

abbreviation *inner-dirsum-double* ::
'a::*monoid-add set* ⇒ *'a set* ⇒ *'a set* (**infixr** ‹⊕› *70*)
where *inner-dirsum-double A B* ≡ *inner-dirsum* [*A*,*B*]

lemma *inner-dirsumI* :
M = (∑ *N*←*Ns*. *N*) ⟹ *add-independentS Ns* ⟹ *M* = (⨁ *N*←*Ns*. *N*)
⟨*proof*⟩

lemma *inner-dirsum-doubleI* :
M = *A* + *B* ⟹ *add-independentS* [*A*,*B*] ⟹ *M* = *A* ⊕ *B*
⟨*proof*⟩

lemma *inner-dirsumD* :
add-independentS Ms ⟹ (⨁ *M*←*Ms*. *M*) = (∑ *M*←*Ms*. *M*)
⟨*proof*⟩

lemma *inner-dirsumD2* : ¬ *add-independentS Ms* ⟹ (⨁ *M*←*Ms*. *M*) = *0*
⟨*proof*⟩

lemma *inner-dirsum-Nil* : (⨁ *A*←[]. *A*) = *0*
⟨*proof*⟩

lemma *inner-dirsum-singleD* : $(\bigoplus N{\leftarrow}[M].\ N) = M$
⟨*proof*⟩

lemma *inner-dirsum-doubleD* : *add-independentS* $[M,N] \Longrightarrow M \oplus N = M + N$
⟨*proof*⟩

lemma *inner-dirsum-Cons* :
add-independentS $(A \# As) \Longrightarrow (\bigoplus X{\leftarrow}(A\#As).\ X) = A \oplus (\bigoplus X{\leftarrow}As.\ X)$
⟨*proof*⟩

lemma *inner-dirsum-append* :
add-independentS $(As@Bs) \Longrightarrow 0 \in (\sum X{\leftarrow}Bs.\ X)$
$\Longrightarrow (\bigoplus X{\leftarrow}(As@Bs).\ X) = (\bigoplus X{\leftarrow}As.\ X) \oplus (\bigoplus X{\leftarrow}Bs.\ X)$
⟨*proof*⟩

lemma *inner-dirsum-double-left0*: $0 \oplus A = A$
⟨*proof*⟩

lemma *add-independentS-Cons-conv-dirsum-right* :
add-independentS $(A\#As) = (add\text{-}independentS\ [A,\bigoplus B{\leftarrow}As.\ B]$
$\wedge$ *add-independentS As*)
⟨*proof*⟩

lemma *sum-list-listset-dirsum* :
add-independentS As $\Longrightarrow$ *as* $\in$ *listset As* $\Longrightarrow$ *sum-list as* $\in (\bigoplus A{\leftarrow}As.\ A)$
⟨*proof*⟩

2 Groups

2.1 Locales and basic facts

2.1.1 Locale *Group* and finite variant *FinGroup*

Define a *Group* to be a closed subset of *UNIV* for the *group-add* class.

locale *Group* =
fixes G :: *'g*::*group-add set*
assumes *nonempty* : $G \neq \{\}$
and *diff-closed*: $\bigwedge g\ h.\ g \in G \Longrightarrow h \in G \Longrightarrow g - h \in G$

lemma *trivial-Group* : *Group 0*
⟨*proof*⟩

locale *FinGroup* = *Group G*
for G :: *'g*::*group-add set*
+ **assumes** *finite*: *finite G*

lemma (**in** *FinGroup*) *Group* : *Group G* ⟨*proof*⟩

lemma (**in** *Group*) *FinGroupI* : *finite G* $\Longrightarrow$ *FinGroup G* ⟨*proof*⟩

context *Group*
begin

abbreviation *Subgroup* ::
  $'g\ set \Rightarrow bool$ **where** $Subgroup\ H \equiv Group\ H \wedge H \subseteq G$

lemma *SubgroupD1* : $Subgroup\ H \Longrightarrow Group\ H$ ⟨*proof*⟩

lemma *zero-closed* : $0 \in G$
⟨*proof*⟩

lemma *obtain-nonzero*: **assumes** $G \neq 0$ **obtains** g **where** $g \in G$ **and** $g \neq 0$
  ⟨*proof*⟩

lemma *zeroS-closed* : $0 \subseteq G$
  ⟨*proof*⟩

lemma *neg-closed* : $g \in G \Longrightarrow -g \in G$
  ⟨*proof*⟩

lemma *add-closed* : $g \in G \Longrightarrow h \in G \Longrightarrow g + h \in G$
  ⟨*proof*⟩

lemma *neg-add-closed* : $g \in G \Longrightarrow h \in G \Longrightarrow -g + h \in G$
  ⟨*proof*⟩

lemma *sum-list-closed* : $set\ (map\ f\ as) \subseteq G \Longrightarrow (\sum a{\leftarrow}as.\ f\ a) \in G$
  ⟨*proof*⟩

lemma *sum-list-closed-prod* :
  $set\ (map\ (case\text{-}prod\ f)\ xys) \subseteq G \Longrightarrow (\sum (x,y){\leftarrow}xys.\ f\ x\ y) \in G$
  ⟨*proof*⟩

lemma *set-plus-closed* : $A \subseteq G \Longrightarrow B \subseteq G \Longrightarrow A + B \subseteq G$
  ⟨*proof*⟩

lemma *zip-add-closed* :
  $set\ as \subseteq G \Longrightarrow set\ bs \subseteq G \Longrightarrow set\ [a + b.\ (a,b){\leftarrow}zip\ as\ bs] \subseteq G$
  ⟨*proof*⟩

lemma *list-diff-closed* :
  $set\ gs \subseteq G \Longrightarrow set\ hs \subseteq G \Longrightarrow set\ [x-y.\ (x,y){\leftarrow}zip\ gs\ hs] \subseteq G$
  ⟨*proof*⟩

lemma *add-closed-converse-right* : $g+x \in G \Longrightarrow g \in G \Longrightarrow x \in G$
  ⟨*proof*⟩

lemma *add-closed-inverse-right* : $x \notin G \Longrightarrow g \in G \Longrightarrow g+x \notin G$

⟨*proof*⟩

lemma *add-closed-converse-left* : $g+x \in G \Longrightarrow x \in G \Longrightarrow g \in G$
⟨*proof*⟩

lemma *add-closed-inverse-left* : $g \notin G \Longrightarrow x \in G \Longrightarrow g+x \notin G$
⟨*proof*⟩

lemma *right-translate-bij* :
assumes $g \in G$
shows *bij-betw* $(\lambda x.\ x + g)\ G\ G$
⟨*proof*⟩

lemma *right-translate-sum* : $g \in G \Longrightarrow (\sum h{\in}G.\ f\ h) = (\sum h{\in}G.\ f\ (h + g))$
⟨*proof*⟩

end

2.1.2 Abelian variant locale *AbGroup*

locale *AbGroup* = *Group G*
for *G* :: *'g*::*ab-group-add set*
begin

lemmas *nonempty* = *nonempty*
lemmas *zero-closed* = *zero-closed*
lemmas *diff-closed* = *diff-closed*
lemmas *add-closed* = *add-closed*
lemmas *neg-closed* = *neg-closed*

lemma *sum-closed* : *finite A* $\Longrightarrow f\ `\ A \subseteq G \Longrightarrow (\sum a{\in}A.\ f\ a) \in G$
⟨*proof*⟩

lemma *subset-plus-right* : $A \subseteq G + A$
⟨*proof*⟩

lemma *subset-plus-left* : $A \subseteq A + G$
⟨*proof*⟩

end

2.2 Right cosets

context *Group*
begin

definition *rcoset-rel* :: *'g set* ⇒ *('g*×*'g) set*
where *rcoset-rel H* ≡ $\{(g,g').\ g \in G \wedge g' \in G \wedge g - g' \in H\}$

lemma (**in** *Group*) *rcosets* :

assumes *subgrp*: *Subgroup H* **and** *g*: $g \in G$
shows $(rcoset\text{-}rel\ H)``\{g\} = H + \{g\}$
⟨*proof*⟩

lemma *rcoset-equiv* :
assumes *Subgroup H*
shows *equiv G* (*rcoset-rel H*)
⟨*proof*⟩

lemma *rcoset0* : *Subgroup H* $\Longrightarrow$ $(rcoset\text{-}rel\ H)``\{0\} = H$
⟨*proof*⟩

definition *is-rcoset-replist* :: *'g set* ⇒ *'g list* ⇒ *bool*
where *is-rcoset-replist H gs*
$\equiv$ *set gs* $\subseteq G \wedge$ *distinct* (*map* ($\lambda g.\ (rcoset\text{-}rel\ H)``\{g\}$) *gs*)
$\wedge\ G = (\bigcup g \in set\ gs.\ (rcoset\text{-}rel\ H)``\{g\})$

lemma *is-rcoset-replistD-set* : *is-rcoset-replist H gs* $\Longrightarrow$ *set gs* $\subseteq G$
⟨*proof*⟩

lemma *is-rcoset-replistD-distinct* :
is-rcoset-replist H gs $\Longrightarrow$ *distinct* (*map* ($\lambda g.\ (rcoset\text{-}rel\ H)``\{g\}$) *gs*)
⟨*proof*⟩

lemma *is-rcoset-replistD-cosets* :
is-rcoset-replist H gs $\Longrightarrow$ $G = (\bigcup g \in set\ gs.\ (rcoset\text{-}rel\ H)``\{g\})$
⟨*proof*⟩

lemma *group-eq-subgrp-rcoset-un* :
Subgroup H $\Longrightarrow$ *is-rcoset-replist H gs* $\Longrightarrow$ $G = (\bigcup g \in set\ gs.\ H + \{g\})$
⟨*proof*⟩

lemma *is-rcoset-replist-imp-nrelated-nth* :
assumes *Subgroup H is-rcoset-replist H gs*
shows $\bigwedge i\ j.\ i < length\ gs \Longrightarrow j < length\ gs \Longrightarrow i \neq j \Longrightarrow gs!i - gs!j \notin H$
⟨*proof*⟩

lemma *is-rcoset-replist-Cons* :
is-rcoset-replist H $(g \# gs) \longleftrightarrow$
$g \in G \wedge$ *set gs* $\subseteq G$
$\wedge\ (rcoset\text{-}rel\ H)``\{g\} \notin set\ (map\ (\lambda x.\ (rcoset\text{-}rel\ H)``\{x\})\ gs)$
$\wedge$ *distinct* (*map* ($\lambda x.\ (rcoset\text{-}rel\ H)``\{x\}$) *gs*)
$\wedge\ G = (rcoset\text{-}rel\ H)``\{g\} \cup (\bigcup x \in set\ gs.\ (rcoset\text{-}rel\ H)``\{x\})$
⟨*proof*⟩

lemma *rcoset-replist-Hrep* :
assumes *Subgroup H is-rcoset-replist H gs*
shows $\exists g \in set\ gs.\ g \in H$
⟨*proof*⟩

lemma *rcoset-replist-reorder* :
is-rcoset-replist H (*gs* @ *g* # *gs'*) ⟹ *is-rcoset-replist H* (*g* # *gs* @ *gs'*)
⟨*proof*⟩

lemma *rcoset-replist-replacehd* :
assumes *Subgroup H g'* ∈ (*rcoset-rel H*) ‘‘{*g*} *is-rcoset-replist H* (*g* # *gs*)
shows *is-rcoset-replist H* (*g'* # *gs*)
⟨*proof*⟩

end

lemma (**in** *FinGroup*) *ex-rcoset-replist* :
assumes *Subgroup H*
shows ∃ *gs*. *is-rcoset-replist H gs*
⟨*proof*⟩

lemma (**in** *FinGroup*) *ex-rcoset-replist-hd0* :
assumes *Subgroup H*
shows ∃ *gs*. *is-rcoset-replist H* (*0*#*gs*)
⟨*proof*⟩

2.3 Group homomorphisms

2.3.1 Preliminaries

definition *ker* :: (*'a*⇒*'b*::*zero*) ⇒ *'a set*
where *ker f* = {*a*. *f a* = *0*}

lemma *kerI* : *f a* = *0* ⟹ *a* ∈ *ker f*
⟨*proof*⟩

lemma *kerD* : *a* ∈ *ker f* ⟹ *f a* = *0*
⟨*proof*⟩

lemma *ker-im-iff* : (*A* ≠ {} ∧ *A* ⊆ *ker f*) = (*f* ‘ *A* = *0*)
⟨*proof*⟩

2.3.2 Locales

The *supp* condition is not strictly necessary, but helps with equality and uniqueness arguments.

locale *GroupHom* = *Group G*
for *G* :: *'g*::*group-add set*
+ **fixes** *T* :: *'g* ⇒ *'h*::*group-add*
assumes *hom* : ⋀*g g'*. *g* ∈ *G* ⟹ *g'* ∈ *G* ⟹ *T* (*g* + *g'*) = *T g* + *T g'*
and *supp*: *supp T* ⊆ *G*

abbreviation (**in** *GroupHom*) *Ker* ≡ *ker T* ∩ *G*

abbreviation (**in** *GroupHom*) *ImG* ≡ *T* ‘ *G*

locale *GroupEnd* = *GroupHom G T*
  for *G* :: *'g*::*group-add set*
  and *T* :: *'g* ⇒ *'g*
+ **assumes** *endomorph*: *ImG* ⊆ *G*

locale *GroupIso* = *GroupHom G T*
  for *G* :: *'g*::*group-add set*
  and *T* :: *'g* ⇒ *'h*::*group-add*
+ **fixes** *H* :: *'h set*
  assumes *bijective*: *bij-betw T G H*

2.3.3 Basic facts

lemma (**in** *Group*) *trivial-GroupHom* : *GroupHom G* (*0*::(*'g*⇒*'h*::*group-add*))
⟨*proof*⟩

lemma (**in** *Group*) *GroupHom-idhom* : *GroupHom G* (*id*↓*G*)
  ⟨*proof*⟩

context *GroupHom*
begin

lemma *im-zero* : *T 0* = *0*
  ⟨*proof*⟩

lemma *zero-in-Ker* : *0* ∈ *Ker*
  ⟨*proof*⟩

lemma *comp-zero* : *T* ∘ *0* = *0*
  ⟨*proof*⟩

lemma *im-neg* : *T* (− *g*) = − *T g*
  ⟨*proof*⟩

lemma *im-diff* : *g* ∈ *G* ⟹ *g'* ∈ *G* ⟹ *T* (*g* − *g'*) = *T g* − *T g'*
  ⟨*proof*⟩

lemma *eq-im-imp-diff-in-Ker* : ⟦ *g* ∈ *G*; *h* ∈ *G*; *T g* = *T h* ⟧ ⟹ *g* − *h* ∈ *Ker*
  ⟨*proof*⟩

lemma *im-sum-list-prod* :
  set (*map* (*case-prod f*) *xys*) ⊆ *G*
    ⟹ *T* (∑ (*x*,*y*)←*xys*. *f x y*) = (∑ (*x*,*y*)←*xys*. *T* (*f x y*))
⟨*proof*⟩

lemma *distrib-comp-sum-left* :
  range S ⊆ *G* ⟹ *range S'* ⊆ *G* ⟹ *T* ∘ (*S* + *S'*) = (*T* ∘ *S*) + (*T* ∘ *S'*)

⟨*proof*⟩

lemma *Ker-Im-iff* : (*Ker* = *G*) = (*ImG* = *0*)
⟨*proof*⟩

lemma *Ker0-imp-inj-on* :
assumes *Ker* ⊆ *0*
shows *inj-on T G*
⟨*proof*⟩

lemma *inj-on-imp-Ker0* :
assumes *inj-on T G*
shows *Ker* = *0*
⟨*proof*⟩

lemma *nonzero-Ker-el-imp-n-inj* :
g ∈ *G* ⟹ *g* ≠ *0* ⟹ *T g* = *0* ⟹ ¬ *inj-on T G*
⟨*proof*⟩

lemma *Group-Ker* : *Group Ker*
⟨*proof*⟩

lemma *Group-Im* : *Group ImG*
⟨*proof*⟩

lemma *GroupHom-restrict0-subgroup* :
assumes *Subgroup H*
shows *GroupHom H* (*T* ↓ *H*)
⟨*proof*⟩

lemma *im-subgroup* :
assumes *Subgroup H*
shows *Group.Subgroup ImG* (*T* ‘ *H*)
⟨*proof*⟩

lemma *GroupHom-composite-left* :
assumes *ImG* ⊆ *H GroupHom H S*
shows *GroupHom G* (*S* ∘ *T*)
⟨*proof*⟩

lemma *idhom-left* : *T* ‘ *G* ⊆ *H* ⟹ (*id*↓*H*) ∘ *T* = *T*
⟨*proof*⟩

end

2.3.4 Basic facts about endomorphisms

context *GroupEnd*
begin

lemmas *hom = hom*

lemma *range* : *range T* $\subseteq$ *G*
⟨*proof*⟩

lemma *proj-decomp* :
assumes $\bigwedge g.\ g \in G \Longrightarrow T\ (T\ g) = T\ g$
shows *G = Ker* $\oplus$ *ImG*
⟨*proof*⟩

end

2.3.5 Basic facts about isomorphisms

context *GroupIso*
begin

abbreviation *invT* $\equiv$ (*the-inv-into G T*) $\downarrow$ *H*

lemma *ImG* : *ImG = H* ⟨*proof*⟩

lemma *GroupH* : *Group H* ⟨*proof*⟩

lemma *invT-onto* : *invT* ‘ *H = G*
⟨*proof*⟩

lemma *inj-on-invT* : *inj-on invT H*
⟨*proof*⟩

lemma *bijective-invT* : *bij-betw invT H G*
⟨*proof*⟩

lemma *invT-into* : *h* $\in$ *H* $\Longrightarrow$ *invT h* $\in$ *G*
⟨*proof*⟩

lemma *T-invT* : *h* $\in$ *H* $\Longrightarrow$ *T* (*invT h*) = *h*
⟨*proof*⟩

lemma *invT-eq*: *g* $\in$ *G* $\Longrightarrow$ *T g = h* $\Longrightarrow$ *invT h = g*
⟨*proof*⟩

lemma *inv* : *GroupIso H invT G*
⟨*proof*⟩

end

2.3.6 Hom-sets

definition *GroupHomSet* :: *'g*::*group-add set* $\Rightarrow$ *'h*::*group-add set* $\Rightarrow$ (*'g* $\Rightarrow$ *'h*) *set*

where *GroupHomSet G H* ≡ {*T*. *GroupHom G T*} ∩ {*T*. *T* ‘ *G* ⊆ *H*}

lemma *GroupHomSetI* :
GroupHom G T ⟹ *T* ‘ *G* ⊆ *H* ⟹ *T* ∈ *GroupHomSet G H*
⟨*proof*⟩

lemma *GroupHomSetD-GroupHom* :
T ∈ *GroupHomSet G H* ⟹ *GroupHom G T*
⟨*proof*⟩

lemma *GroupHomSetD-Im* : *T* ∈ *GroupHomSet G H* ⟹ *T* ‘ *G* ⊆ *H*
⟨*proof*⟩

lemma (**in** *Group*) *Group-GroupHomSet* :
fixes *H* :: *'h*::*ab-group-add set*
assumes *AbGroup H*
shows *Group* (*GroupHomSet G H*)
⟨*proof*⟩

2.4 Facts about collections of groups

lemma *listset-Group-plus-closed* :
⟦ ∀ *G*∈*set Gs*. *Group G*; *as* ∈ *listset Gs*; *bs* ∈ *listset Gs*⟧
⟹ [*a*+*b*. (*a*,*b*)←*zip as bs*] ∈ *listset Gs*
⟨*proof*⟩

lemma *AbGroup-set-plus* :
assumes *AbGroup H AbGroup G*
shows *AbGroup* (*H* + *G*)
⟨*proof*⟩

lemma *AbGroup-sum-list* :
(∀ *G*∈*set Gs*. *AbGroup G*) ⟹ *AbGroup* (∑ *G*←*Gs*. *G*)
⟨*proof*⟩

lemma *AbGroup-subset-sum-list* :
∀ *G* ∈ *set Gs*. *AbGroup G* ⟹ *H* ∈ *set Gs* ⟹ *H* ⊆ (∑ *G*←*Gs*. *G*)
⟨*proof*⟩

lemma *independent-AbGroups-pairwise-int0* :
⟦ ∀ *G*∈*set Gs*. *AbGroup G*; *add-independentS Gs*; *G* ∈ *set Gs*; *G'* ∈ *set Gs*;
G ≠ *G'* ⟧ ⟹ *G* ∩ *G'* = *0*
⟨*proof*⟩

lemma *independent-AbGroups-pairwise-int0-double* :
assumes *AbGroup G AbGroup G' add-independentS* [*G*,*G'*]
shows *G* ∩ *G'* = *0*
⟨*proof*⟩

2.5 Inner direct sums of Abelian groups

2.5.1 General facts

lemma *AbGroup-inner-dirsum* :
$\forall\, G{\in}set\ Gs.\ AbGroup\ G \Longrightarrow AbGroup\ (\bigoplus G{\leftarrow}Gs.\ G)$
⟨*proof*⟩

lemma *inner-dirsum-double-leftfull-imp-right0*:
assumes $Group\ A\ B \neq \{\}\ A = A \oplus B$
shows $B = 0$
⟨*proof*⟩

lemma *AbGroup-subset-inner-dirsum* :
$[\![\ \forall\, G \in set\ Gs.\ AbGroup\ G;\ add\text{-}independentS\ Gs;\ H \in set\ Gs\ ]\!]$
$\Longrightarrow H \subseteq (\bigoplus G{\leftarrow}Gs.\ G)$
⟨*proof*⟩

lemma *AbGroup-nth-subset-inner-dirsum* :
$[\![\ \forall\, G \in set\ Gs.\ AbGroup\ G;\ add\text{-}independentS\ Gs;\ n < length\ Gs\ ]\!]$
$\Longrightarrow Gs!n \subseteq (\bigoplus G{\leftarrow}Gs.\ G)$
⟨*proof*⟩

lemma *AbGroup-inner-dirsum-el-decomp-ex1-double* :
assumes *AbGroup G AbGroup H add-independentS* $[G,H]$ $x \in G \oplus H$
shows $\exists!gh.\ fst\ gh \in G \wedge snd\ gh \in H \wedge x = fst\ gh + snd\ gh$
⟨*proof*⟩

lemma *AbGroup-inner-dirsum-el-decomp-ex1* :
$[\![\ \forall\, G \in set\ Gs.\ AbGroup\ G;\ add\text{-}independentS\ Gs\ ]\!]$
$\Longrightarrow \forall\, x \in (\bigoplus G{\leftarrow}Gs.\ G).\ \exists!gs{\in}listset\ Gs.\ x = sum\text{-}list\ gs$
⟨*proof*⟩

lemma *AbGroup-inner-dirsum-pairwise-int0* :
$[\![\ \forall\, G \in set\ Gs.\ AbGroup\ G;\ add\text{-}independentS\ Gs;\ G \in set\ Gs;\ G' \in set\ Gs;$
$G \neq G'\ ]\!] \Longrightarrow G \cap G' = 0$
⟨*proof*⟩

lemma *AbGroup-inner-dirsum-pairwise-int0-double* :
assumes *AbGroup G AbGroup G' add-independentS* $[G,G']$
shows $G \cap G' = 0$
⟨*proof*⟩

2.5.2 Element decomposition and projection

definition *inner-dirsum-el-decomp* ::
$'g{::}ab\text{-}group\text{-}add\ set\ list \Rightarrow ('g \Rightarrow 'g\ list)\ (\langle\bigoplus\text{-}{\leftarrow}\rangle)$
where $\bigoplus Gs{\leftarrow} = (\lambda x.\ if\ x \in (\bigoplus G{\leftarrow}Gs.\ G)$
$then\ THE\ gs.\ gs \in listset\ Gs \wedge x = sum\text{-}list\ gs\ else\ [])$

abbreviation *inner-dirsum-el-decomp-double* ::
'g::ab-group-add set ⇒ 'g set ⇒ ('g ⇒ 'g list) (‹-⊕-←›) **where** $G \oplus H \leftarrow \equiv \bigoplus [G,H] \leftarrow$

abbreviation *inner-dirsum-el-decomp-nth* ::
'g::ab-group-add set list ⇒ nat ⇒ ('g ⇒ 'g) (‹$\bigoplus$ -↓-›)
where $\bigoplus Gs \downarrow n \equiv$ *restrict0* $(\lambda x.\ (\bigoplus Gs \leftarrow x)!n)\ (\bigoplus G \leftarrow Gs.\ G)$

lemma *AbGroup-inner-dirsum-el-decompI* :
$[\![\forall G \in$ *set Gs. AbGroup G*; *add-independentS Gs*; $x \in (\bigoplus G \leftarrow Gs.\ G)]\!]$
$\Longrightarrow (\bigoplus Gs \leftarrow x) \in$ *listset Gs* $\wedge\ x =$ *sum-list* $(\bigoplus Gs \leftarrow x)$
⟨*proof*⟩

lemma (**in** *AbGroup*) *abSubgroup-inner-dirsum-el-decomp-set* :
$[\![\forall H \in$ *set Hs. Subgroup H*; *add-independentS Hs*; $x \in (\bigoplus H \leftarrow Hs.\ H)]\!]$
$\Longrightarrow$ *set* $(\bigoplus Hs \leftarrow x) \subseteq G$
⟨*proof*⟩

lemma *AbGroup-inner-dirsum-el-decomp-eq* :
$[\![\forall G \in$ *set Gs. AbGroup G*; *add-independentS Gs*; $x \in (\bigoplus G \leftarrow Gs.\ G)$;
gs $\in$ *listset Gs*; $x =$ *sum-list gs* $]\!] \Longrightarrow (\bigoplus Gs \leftarrow x) = gs$
⟨*proof*⟩

lemma *AbGroup-inner-dirsum-el-decomp-plus* :
assumes $\forall G \in$ *set Gs. AbGroup G add-independentS Gs* $x \in (\bigoplus G \leftarrow Gs.\ G)$
$y \in (\bigoplus G \leftarrow Gs.\ G)$
shows $(\bigoplus Gs \leftarrow (x+y)) = [a+b.\ (a,b) \leftarrow zip\ (\bigoplus Gs \leftarrow x)\ (\bigoplus Gs \leftarrow y)]$
⟨*proof*⟩

lemma *AbGroup-length-inner-dirsum-el-decomp* :
$[\![\forall G \in$ *set Gs. AbGroup G*; *add-independentS Gs*; $x \in (\bigoplus G \leftarrow Gs.\ G)]\!]$
$\Longrightarrow$ *length* $(\bigoplus Gs \leftarrow x) =$ *length Gs*
⟨*proof*⟩

lemma *AbGroup-inner-dirsum-el-decomp-in-nth* :
assumes $\forall G \in$ *set Gs. AbGroup G add-independentS Gs* $n <$ *length Gs*
$x \in Gs!n$
shows $(\bigoplus Gs \leftarrow x) =$ *(replicate (length Gs) 0)*$[n := x]$
⟨*proof*⟩

lemma *AbGroup-inner-dirsum-el-decomp-nth-in-nth* :
$[\![\forall G \in$ *set Gs. AbGroup G*; *add-independentS Gs*; $k <$ *length Gs*;
$n <$ *length Gs*; $x \in Gs!n$ $]\!] \Longrightarrow (\bigoplus Gs \downarrow k)\ x =$ *(if k = n then x else 0)*
⟨*proof*⟩

lemma *AbGroup-inner-dirsum-el-decomp-nth-id-on-nth* :
$[\![\forall G \in$ *set Gs. AbGroup G*; *add-independentS Gs*; $n <$ *length Gs*; $x \in Gs!n$ $]\!]$
$\Longrightarrow (\bigoplus Gs \downarrow n)\ x = x$
⟨*proof*⟩

lemma *AbGroup-inner-dirsum-el-decomp-nth-onto-nth* :
assumes $\forall\, G \in set\ Gs.\ AbGroup\ G\ add\text{-}independentS\ Gs\ n < length\ Gs$
shows $(\bigoplus Gs{\downarrow}n)\ `\ (\bigoplus G{\leftarrow}Gs.\ G) = Gs!n$
⟨*proof*⟩

lemma *AbGroup-inner-dirsum-subset-proj-eq-0* :
assumes $Gs \neq []\ \forall\, G \in set\ Gs.\ AbGroup\ G\ add\text{-}independentS\ Gs$
$X \subseteq (\bigoplus G{\leftarrow}Gs.\ G)\ \forall\, i < length\ Gs.\ (\bigoplus Gs{\downarrow}i)\ `\ X = 0$
shows $X = 0$
⟨*proof*⟩

lemma *GroupEnd-inner-dirsum-el-decomp-nth* :
assumes $\forall\, G \in set\ Gs.\ AbGroup\ G\ add\text{-}independentS\ Gs\ n < length\ Gs$
shows $GroupEnd\ (\bigoplus G{\leftarrow}Gs.\ G)\ (\bigoplus Gs{\downarrow}n)$
⟨*proof*⟩

2.6 Rings

2.6.1 Preliminaries

lemma (**in** *ring-1*) *map-times-neg1-eq-map-uminus* : $[(-1){*}r.\ r{\leftarrow}rs] = [-r.\ r{\leftarrow}rs]$
⟨*proof*⟩

2.6.2 Locale and basic facts

Define a *Ring1* to be a multiplicatively closed additive subgroup of *UNIV* for the *ring-1* class.

locale *Ring1* = *Group R*
for *R* :: *'r*::*ring-1 set*
+ **assumes** *one-closed* : $1 \in R$
and *mult-closed*: $\bigwedge r\ s.\ r \in R \Longrightarrow s \in R \Longrightarrow r * s \in R$
begin

lemma *AbGroup* : *AbGroup R*
⟨*proof*⟩

lemmas *zero-closed* = *zero-closed*
lemmas *add-closed* = *add-closed*
lemmas *neg-closed* = *neg-closed*
lemmas *diff-closed* = *diff-closed*
lemmas *zip-add-closed* = *zip-add-closed*
lemmas *sum-closed* = *AbGroup.sum-closed*[*OF AbGroup*]
lemmas *sum-list-closed* = *sum-list-closed*
lemmas *sum-list-closed-prod* = *sum-list-closed-prod*
lemmas *list-diff-closed* = *list-diff-closed*

abbreviation *Subring1* :: *'r set* ⇒ *bool* **where** $Subring1\ S \equiv Ring1\ S \wedge S \subseteq R$

lemma *Subring1D1* : *Subring1 S* $\Longrightarrow$ *Ring1 S* ⟨*proof*⟩

end

lemma (**in** *ring-1*) *full-Ring1* : *Ring1 UNIV*
⟨*proof*⟩

2.7 The group ring

2.7.1 Definition and basic facts

Realize the group ring as the set of almost-every-zero functions from group to ring. One can recover the usual notion of group ring element by considering such a function to send group elements to their coefficients. Here the codomain of such functions is not restricted to some *Ring1* subset since we will not be interested in having the ability to change the ring of scalars for a group ring.

context *Group*
begin

abbreviation *group-ring* :: (*'a*::*zero*, *'g*) *aezfun set*
where *group-ring* ≡ *aezfun-setspan G*

lemmas *group-ringD* = *aezfun-setspan-def*[*of G*]

lemma *RG-one-closed* : (*1*::(*'r*::*zero-neq-one*,*'g*) *aezfun*) ∈ *group-ring*
⟨*proof*⟩

lemma *RG-zero-closed* : (*0*::(*'r*::*zero*,*'g*) *aezfun*) ∈ *group-ring*
⟨*proof*⟩

lemma *RG-n0* : *group-ring* ≠ (*0*::(*'r*::*zero-neq-one*, *'g*) *aezfun set*)
⟨*proof*⟩

lemma *RG-mult-closed* :
defines *RG*: *RG* ≡ *group-ring* :: (*'r*::*ring-1*, *'g*) *aezfun set*
shows *x* ∈ *RG* $\Longrightarrow$ *y* ∈ *RG* $\Longrightarrow$ *x* ∗ *y* ∈ *RG*
⟨*proof*⟩

lemma *Ring1-RG* :
defines *RG*: *RG* ≡ *group-ring* :: (*'r*::*ring-1*, *'g*) *aezfun set*
shows *Ring1 RG*
⟨*proof*⟩

lemma *RG-aezdeltafun-closed* :
defines *RG*: *RG* ≡ *group-ring* :: (*'r*::*ring-1*, *'g*) *aezfun set*
assumes *g* ∈ *G*
shows *r* *δδ* *g* ∈ *RG*

⟨*proof*⟩

lemma *RG-aezdelta0fun-closed* : (*r*::'*r*::*ring-1*) *δδ 0* ∈ *group-ring*
⟨*proof*⟩

lemma *RG-sum-list-rddg-closed* :
defines *RG*: *RG* ≡ *group-ring* :: ('*r*::*ring-1*, '*g*) *aezfun set*
assumes *set* (*map snd rgs*) ⊆ *G*
shows (∑ (*r*,*g*)←*rgs*. *r δδ g*) ∈ *RG*
⟨*proof*⟩

lemmas *RG-el-decomp-aezdeltafun* = *aezfun-setspan-el-decomp-aezdeltafun*[*of* - *G*]

lemma *Subgroup-imp-Subring* :
fixes *H* :: '*g set*
and *FH* :: ('*r*::*ring-1*,'*g*) *aezfun set*
and *FG* :: ('*r*,'*g*) *aezfun set*
defines *FH* ≡ *Group.group-ring H*
and *FG* ≡ *group-ring*
shows *Subgroup H* ⟹ *Ring1.Subring1 FG FH*
⟨*proof*⟩

end

lemma (**in** *FinGroup*) *group-ring-spanning-set* :
∃ *gs*. *distinct gs* ∧ *set gs* = *G*
∧ (∀ *f*∈ (*group-ring* :: ('*b*::*semiring-1*, '*g*) *aezfun set*). ∃ *bs*.
length bs = *length gs* ∧ *f* = (∑ (*b*,*g*)←*zip bs gs*. (*b δδ 0*) ∗ (*1 δδ g*)))
⟨*proof*⟩

2.7.2 Projecting almost-everywhere-zero functions onto a group ring

context *Group*
begin

abbreviation *RG-proj* ≡ *aezfun-setspan-proj G*

lemmas *RG-proj-in-RG* = *aezfun-setspan-proj-in-setspan*
lemmas *RG-proj-sum-list-prod* = *aezfun-setspan-proj-sum-list-prod*[*of G*]

lemma *RG-proj-mult-leftdelta'* :
fixes *r s* :: '*r*::{*comm-monoid-add*,*mult-zero*}
shows *g* ∈ *G* ⟹ *RG-proj* (*r δδ g* ∗ (*s δδ g'*)) = *r δδ g* ∗ *RG-proj* (*s δδ g'*)
⟨*proof*⟩

lemma *RG-proj-mult-leftdelta* :
fixes *r* :: '*r*::*semiring-1*
assumes *g* ∈ *G*

shows *RG-proj ((r δδ g) ∗ x) = r δδ g ∗ RG-proj x*
⟨*proof*⟩

lemma *RG-proj-mult-rightdelta′* :
fixes *r s* :: *′r*::{*comm-monoid-add*,*mult-zero*}
assumes *g′* ∈ *G*
shows *RG-proj (r δδ g ∗ (s δδ g′)) = RG-proj (r δδ g) ∗ (s δδ g′)*
⟨*proof*⟩

lemma *RG-proj-mult-rightdelta* :
fixes *r* :: *′r*::*semiring-1*
assumes *g* ∈ *G*
shows *RG-proj (x ∗ (r δδ g)) = (RG-proj x) ∗ (r δδ g)*
⟨*proof*⟩

lemma *RG-proj-mult-right* :
x ∈ (*group-ring* :: (*′r*::*ring-1*, *′g*) *aezfun set*)
⟹ *RG-proj (y ∗ x) = RG-proj y ∗ x*
⟨*proof*⟩

end

3 Modules

3.1 Locales and basic facts

3.1.1 Locales

locale *scalar-mult* =
fixes *smult* :: *′r*::*ring-1* ⇒ *′m*::*ab-group-add* ⇒ *′m* (**infixr** ‹·› *70*)

locale *R-scalar-mult* = *scalar-mult smult* + *Ring1 R*
for *R* :: *′r*::*ring-1 set*
and *smult* :: *′r* ⇒ *′m*::*ab-group-add* ⇒ *′m* (**infixr** ‹·› *70*)

lemma (**in** *scalar-mult*) *R-scalar-mult* : *R-scalar-mult UNIV*
⟨*proof*⟩

lemma (**in** *R-scalar-mult*) *Ring1* : *Ring1 R* ⟨*proof*⟩

locale *RModule* = *R-scalars?*: *R-scalar-mult R smult* + *VecGroup?*: *Group M*
for *R* :: *′r*::*ring-1 set*
and *smult* :: *′r* ⇒ *′m*::*ab-group-add* ⇒ *′m* (**infixr** ‹·› *70*)
and *M* :: *′m set*
+ **assumes** *smult-closed* : ⟦ *r* ∈ *R*; *m* ∈ *M* ⟧ ⟹ *r* · *m* ∈ *M*
and *smult-distrib-left* [*simp*] : ⟦ *r* ∈ *R*; *m* ∈ *M*; *n* ∈ *M* ⟧
⟹ *r* · (*m* + *n*) = *r* · *m* + *r* · *n*
and *smult-distrib-right* [*simp*] : ⟦ *r* ∈ *R*; *s* ∈ *R*; *m* ∈ *M* ⟧
⟹ (*r* + *s*) · *m* = *r* · *m* + *s* · *m*

and *smult-assoc* [*simp*] : ⟦ $r \in R$; $s \in R$; $m \in M$ ⟧
$\Longrightarrow r \cdot s \cdot m = (r * s) \cdot m$
and *one-smult* [*simp*] : $m \in M \Longrightarrow 1 \cdot m = m$

lemmas *RModuleI* = *RModule.intro*[*OF R-scalar-mult.intro*]

locale *Module* = *RModule UNIV smult M*
for *smult* :: $'r$::*ring-1* ⇒ $'m$::*ab-group-add* ⇒ $'m$ (**infixr** ‹·› *70*)
and *M* :: $'m$ *set*

lemmas *ModuleI* = *RModuleI*[*of UNIV*, *OF full-Ring1*, *THEN Module.intro*]

3.1.2 Basic facts

lemma *trivial-RModule* :
fixes *smult* :: $'r$::*ring-1* ⇒ $'m$::*ab-group-add* ⇒ $'m$ (**infixr** ‹·› *70*)
assumes *Ring1 R* ∀ *r*∈*R*. *smult r* (*0*::$'m$::*ab-group-add*) = *0*
shows *RModule R smult* (*0*::$'m$ *set*)
⟨*proof*⟩

context *RModule*
begin

abbreviation *RSubmodule* :: $'m$ *set* ⇒ *bool*
where *RSubmodule N* ≡ *RModule R smult N* ∧ *N* ⊆ *M*

lemma *Group* : *Group M*
⟨*proof*⟩

lemma *Subgroup-RSubmodule* : *RSubmodule N* ⟹ *Subgroup N*
⟨*proof*⟩

lemma *AbGroup* : *AbGroup M*
⟨*proof*⟩

lemmas *zero-closed* = *zero-closed*
lemmas *diff-closed* = *diff-closed*
lemmas *set-plus-closed* = *set-plus-closed*
lemmas *sum-closed* = *AbGroup.sum-closed*[*OF AbGroup*]

lemma *map-smult-closed* :
r ∈ *R* ⟹ *set ms* ⊆ *M* ⟹ *set* (*map* ((·) *r*) *ms*) ⊆ *M*
⟨*proof*⟩

lemma *zero-smult* : *m* ∈ *M* ⟹ *0* · *m* = *0*
⟨*proof*⟩

lemma *smult-zero* : *r* ∈ *R* ⟹ *r* · *0* = *0*
⟨*proof*⟩

lemma *neg-smult* : $r \in R \Longrightarrow m \in M \Longrightarrow (-r) \cdot m = -(r \cdot m)$
⟨*proof*⟩

lemma *neg-eq-neg1-smult* : $m \in M \Longrightarrow (-1) \cdot m = -m$
⟨*proof*⟩

lemma *smult-neg* : $r \in R \Longrightarrow m \in M \Longrightarrow r \cdot (-m) = -(r \cdot m)$
⟨*proof*⟩

lemma *smult-distrib-left-diff* :
$[\![r \in R; m \in M; n \in M]\!] \Longrightarrow r \cdot (m - n) = r \cdot m - r \cdot n$
⟨*proof*⟩

lemma *smult-distrib-right-diff* :
$[\![r \in R; s \in R; m \in M]\!] \Longrightarrow (r - s) \cdot m = r \cdot m - s \cdot m$
⟨*proof*⟩

lemma *smult-sum-distrib* :
assumes $r \in R$
shows *finite* $A \Longrightarrow f \text{ ` } A \subseteq M \Longrightarrow r \cdot (\sum a{\in}A.\ f\ a) = (\sum a{\in}A.\ r \cdot f\ a)$
⟨*proof*⟩

lemma *sum-smult-distrib* :
assumes $m \in M$
shows *finite* $A \Longrightarrow f \text{ ` } A \subseteq R \Longrightarrow (\sum a{\in}A.\ f\ a) \cdot m = (\sum a{\in}A.\ (f\ a) \cdot m)$
⟨*proof*⟩

lemma *smult-sum-list-distrib* :
$r \in R \Longrightarrow$ *set ms* $\subseteq M \Longrightarrow r \cdot$ (*sum-list ms*) $= (\sum m{\leftarrow}ms.\ r \cdot m)$
⟨*proof*⟩

lemma *sum-list-prod-map-smult-distrib* :
$m \in M \Longrightarrow$ *set* (*map* (*case-prod f*) *xys*) $\subseteq R$
$\Longrightarrow (\sum (x,y){\leftarrow}xys.\ f\ x\ y) \cdot m = (\sum (x,y){\leftarrow}xys.\ f\ x\ y \cdot m)$
⟨*proof*⟩

lemma *RSubmoduleI* :
assumes *Subgroup* N $\bigwedge r\ n.\ r \in R \Longrightarrow n \in N \Longrightarrow r \cdot n \in N$
shows *RSubmodule N*
⟨*proof*⟩

end

lemma (**in** *R-scalar-mult*) *listset-RModule-Rsmult-closed* :
$[\![\forall M{\in}set\ Ms.\ RModule\ R\ smult\ M; r \in R; ms \in listset\ Ms]\!]$
$\Longrightarrow [r \cdot m.\ m{\leftarrow}ms] \in listset\ Ms$
⟨*proof*⟩

context *Module*
begin

abbreviation *Submodule* :: *'m set* ⇒ *bool*
  where *Submodule* ≡ *RModule.RSubmodule UNIV smult M*

lemmas *AbGroup* = *AbGroup*
lemmas *SubmoduleI* = *RSubmoduleI*

end

3.1.3 Module and submodule instances

lemma (**in** *R-scalar-mult*) *trivial-RModule* :
  (⋀*r*. *r* ∈ *R* ⟹ *r* · *0* = *0*) ⟹ *RModule R smult 0*
  ⟨*proof*⟩

context *RModule*
begin

lemma *trivial-RSubmodule* : *RSubmodule 0*
  ⟨*proof*⟩

lemma *RSubmodule-set-plus* :
  assumes *RSubmodule L RSubmodule N*
  shows *RSubmodule* (*L* + *N*)
⟨*proof*⟩

lemma *RSubmodule-sum-list* :
  (∀ *N*∈*set Ns*. *RSubmodule N*) ⟹ *RSubmodule* (∑ *N*←*Ns*. *N*)
  ⟨*proof*⟩

lemma *RSubmodule-inner-dirsum* :
  assumes (∀ *N*∈*set Ns*. *RSubmodule N*)
  shows *RSubmodule* (⨁ *N*←*Ns*. *N*)
⟨*proof*⟩

lemma *RModule-inner-dirsum* :
  (∀ *N*∈*set Ns*. *RSubmodule N*) ⟹ *RModule R smult* (⨁ *N*←*Ns*. *N*)
  ⟨*proof*⟩

lemma *SModule-restrict-scalars* :
  assumes *Subring1 S*
  shows *RModule S smult M*
⟨*proof*⟩

end

3.2 Linear algebra in modules

3.2.1 Linear combinations: *lincomb*

context *scalar-mult*
begin

definition *lincomb* :: *'r list* ⇒ *'m list* ⇒ *'m* (**infix** ‹··› *70*)
  where *rs ·· ms* = (∑ (*r*,*m*)←*zip rs ms*. *r* · *m*)

Note: *zip* will truncate if lengths of coefficient and vector lists differ.

lemma *lincomb-Nil* : *rs* = [] ∨ *ms* = [] ⟹ *rs ·· ms* = *0*
  ⟨*proof*⟩

lemma *lincomb-singles* : [*a*] ·· [*m*] = *a* · *m*
  ⟨*proof*⟩

lemma *lincomb-Cons* : (*r* # *rs*) ·· (*m* # *ms*) = *r* · *m* + *rs ·· ms*
  ⟨*proof*⟩

lemma *lincomb-append* :
  length rs = *length ms* ⟹ (*rs*@*ss*) ·· (*ms*@*ns*) = *rs ·· ms* + *ss ·· ns*
  ⟨*proof*⟩

lemma *lincomb-append-left* :
  (*rs* @ *ss*) ·· *ms* = *rs ·· ms* + *ss ·· drop* (*length rs*) *ms*
  ⟨*proof*⟩

lemma *lincomb-append-right* :
  rs ·· (*ms*@*ns*) = *rs ·· ms* + (*drop* (*length ms*) *rs*) ·· *ns*
  ⟨*proof*⟩

lemma *lincomb-conv-take-right* : *rs ·· ms* = *rs ·· take* (*length rs*) *ms*
  ⟨*proof*⟩

end

context *RModule*
begin

lemmas *lincomb-Nil* = *lincomb-Nil*
lemmas *lincomb-Cons* = *lincomb-Cons*

lemma *lincomb-closed* : *set rs* ⊆ *R* ⟹ *set ms* ⊆ *M* ⟹ *rs ·· ms* ∈ *M*
⟨*proof*⟩

lemma *smult-lincomb* :
  ⟦ *set rs* ⊆ *R*; *s* ∈ *R*; *set ms* ⊆ *M* ⟧ ⟹ *s* · (*rs ·· ms*) = [*s*∗*r*. *r*←*rs*] ·· *ms*
  ⟨*proof*⟩

lemma *neg-lincomb* :
set rs $\subseteq$ *R* $\Longrightarrow$ *set ms* $\subseteq$ *M* $\Longrightarrow$ $-$ (*rs* $\cdot\cdot$ *ms*) = [$-r$. *r*$\leftarrow$*rs*] $\cdot\cdot$ *ms*
⟨*proof*⟩

lemma *lincomb-sum-left* :
⟦ *set rs* $\subseteq$ *R*; *set ss* $\subseteq$ *R*; *set ms* $\subseteq$ *M*; *length rs* $\leq$ *length ss* ⟧
$\Longrightarrow$ [*r* + *s*. (*r*,*s*)$\leftarrow$*zip rs ss*] $\cdot\cdot$ *ms* = *rs* $\cdot\cdot$ *ms* + (*take* (*length rs*) *ss*) $\cdot\cdot$ *ms*
⟨*proof*⟩

lemma *lincomb-sum* :
assumes *set rs* $\subseteq$ *R set ss* $\subseteq$ *R set ms* $\subseteq$ *M length rs* $\leq$ *length ss*
shows *rs* $\cdot\cdot$ *ms* + *ss* $\cdot\cdot$ *ms*
= ([*a* + *b*. (*a*,*b*)$\leftarrow$*zip rs ss*] @ (*drop* (*length rs*) *ss*)) $\cdot\cdot$ *ms*
⟨*proof*⟩

lemma *lincomb-diff-left* :
⟦ *set rs* $\subseteq$ *R*; *set ss* $\subseteq$ *R*; *set ms* $\subseteq$ *M*; *length rs* $\leq$ *length ss* ⟧
$\Longrightarrow$ [*r* $-$ *s*. (*r*,*s*)$\leftarrow$*zip rs ss*] $\cdot\cdot$ *ms* = *rs* $\cdot\cdot$ *ms* $-$ (*take* (*length rs*) *ss*) $\cdot\cdot$ *ms*
⟨*proof*⟩

lemma *lincomb-replicate-left* :
r $\in$ *R* $\Longrightarrow$ *set ms* $\subseteq$ *M* $\Longrightarrow$ (*replicate k r*) $\cdot\cdot$ *ms* = *r* $\cdot$ ($\sum$ *m*$\leftarrow$(*take k ms*). *m*)
⟨*proof*⟩

lemma *lincomb-replicate0-left* : *set ms* $\subseteq$ *M* $\Longrightarrow$ (*replicate k 0*) $\cdot\cdot$ *ms* = *0*
⟨*proof*⟩

lemma *lincomb-0coeffs* : *set ms* $\subseteq$ *M* $\Longrightarrow$ $\forall$ *s*$\in$*set rs*. *s* = *0* $\Longrightarrow$ *rs* $\cdot\cdot$ *ms* = *0*
⟨*proof*⟩

lemma *delta-scalars-lincomb-eq-nth* :
set ms $\subseteq$ *M* $\Longrightarrow$ *n* < *length ms*
$\Longrightarrow$ ((*replicate* (*length ms*) *0*)[*n* := *1*]) $\cdot\cdot$ *ms* = *ms*!*n*
⟨*proof*⟩

lemma *lincomb-obtain-same-length-Rcoeffs* :
set rs $\subseteq$ *R* $\Longrightarrow$ *set ms* $\subseteq$ *M*
$\Longrightarrow$ $\exists$ *ss*. *set ss* $\subseteq$ *R* $\wedge$ *length ss* = *length ms*
$\wedge$ *take* (*length rs*) *ss* = *take* (*length ms*) *rs* $\wedge$ *rs* $\cdot\cdot$ *ms* = *ss* $\cdot\cdot$ *ms*
⟨*proof*⟩

lemma *lincomb-concat* :
list-all2 (λ*rs ms*. *length rs* = *length ms*) *rss mss*
$\Longrightarrow$ (*concat rss*) $\cdot\cdot$ (*concat mss*) = ($\sum$ (*rs*,*ms*)$\leftarrow$*zip rss mss*. *rs* $\cdot\cdot$ *ms*)
⟨*proof*⟩

lemma *lincomb-snoc0* : *set ms* $\subseteq$ *M* $\Longrightarrow$ (*as*@[*0*]) $\cdot\cdot$ *ms* = *as* $\cdot\cdot$ *ms*
⟨*proof*⟩

lemma *lincomb-strip-while-0coeffs* :
  assumes *set ms* $\subseteq$ *M*
  shows (*strip-while* ((=) *0*) *as*) $\cdot\cdot$ *ms* = *as* $\cdot\cdot$ *ms*
⟨*proof*⟩

end

lemmas (**in** *Module*) *lincomb-obtain-same-length-coeffs* = *lincomb-obtain-same-length-Rcoeffs*
lemmas (**in** *Module*) *lincomb-concat* = *lincomb-concat*

3.2.2 Spanning: *RSpan* and *Span*

context *R-scalar-mult*
begin

primrec *RSpan* :: *'m list* ⇒ *'m set*
  where *RSpan* [] = *0*
    | *RSpan* (*m*#*ms*) = { *r* · *m* | *r*. *r* ∈ *R* } + *RSpan ms*

lemma *RSpan-single* : *RSpan* [*m*] = { *r* · *m* | *r*. *r* ∈ *R* }
  ⟨*proof*⟩

lemma *RSpan-Cons* : *RSpan* (*m*#*ms*) = *RSpan* [*m*] + *RSpan ms*
  ⟨*proof*⟩

lemma *in-RSpan-obtain-same-length-coeffs* :
  n ∈ *RSpan ms* ⟹ ∃ *rs*. *set rs* ⊆ *R* ∧ *length rs* = *length ms* ∧ *n* = *rs* $\cdot\cdot$ *ms*
⟨*proof*⟩

lemma *in-RSpan-Cons-obtain-same-length-coeffs* :
  n ∈ *RSpan* (*m*#*ms*) ⟹ ∃ *r rs*. *set* (*r*#*rs*) ⊆ *R* ∧ *length rs* = *length ms*
    ∧ *n* = *r* · *m* + *rs* $\cdot\cdot$ *ms*
⟨*proof*⟩

lemma *RSpanD-lincomb* :
  RSpan ms = { *rs* $\cdot\cdot$ *ms* | *rs*. *set rs* ⊆ *R* ∧ *length rs* = *length ms*}
⟨*proof*⟩

lemma *RSpan-append* : *RSpan* (*ms* @ *ns*) = *RSpan ms* + *RSpan ns*
⟨*proof*⟩

end

context *scalar-mult*
begin

abbreviation *Span* ≡ *R-scalar-mult.RSpan UNIV smult*

lemmas *Span-append* = *R-scalar-mult.RSpan-append*[*OF R-scalar-mult*, *of smult*]

lemmas *SpanD-lincomb*
= *R-scalar-mult.RSpanD-lincomb* [*OF R-scalar-mult*, *of smult*]

lemmas *in-Span-obtain-same-length-coeffs*
= *R-scalar-mult.in-RSpan-obtain-same-length-coeffs*[
OF R-scalar-mult, *of - smult*
]

end

context *RModule*
begin

lemma *RSpan-contains-spanset-single* : $m \in M \Longrightarrow m \in RSpan\ [m]$
⟨*proof*⟩

lemma *RSpan-single-nonzero* : $m \in M \Longrightarrow m \neq 0 \Longrightarrow RSpan\ [m] \neq 0$
⟨*proof*⟩

lemma *Group-RSpan-single* :
assumes $m \in M$
shows *Group* (*RSpan* [*m*])
⟨*proof*⟩

lemma *Group-RSpan* : $set\ ms \subseteq M \Longrightarrow Group\ (RSpan\ ms)$
⟨*proof*⟩

lemma *RSpanD-lincomb-arb-len-coeffs* :
$set\ ms \subseteq M \Longrightarrow RSpan\ ms = \{\ rs \cdot\cdot ms \mid rs.\ set\ rs \subseteq R\ \}$
⟨*proof*⟩

lemma *RSpanI-lincomb-arb-len-coeffs* :
$set\ rs \subseteq R \Longrightarrow set\ ms \subseteq M \Longrightarrow rs \cdot\cdot ms \in RSpan\ ms$
⟨*proof*⟩

lemma *RSpan-contains-RSpans-Cons-left* :
$set\ ms \subseteq M \Longrightarrow RSpan\ [m] \subseteq RSpan\ (m\#ms)$
⟨*proof*⟩

lemma *RSpan-contains-RSpans-Cons-right* :
$m \in M \Longrightarrow RSpan\ ms \subseteq RSpan\ (m\#ms)$
⟨*proof*⟩

lemma *RSpan-contains-RSpans-append-left* :
$set\ ns \subseteq M \Longrightarrow RSpan\ ms \subseteq RSpan\ (ms@ns)$
⟨*proof*⟩

lemma *RSpan-contains-spanset* : $set\ ms \subseteq M \Longrightarrow set\ ms \subseteq RSpan\ ms$
⟨*proof*⟩

lemma *RSpan-contains-spanset-append-left* :
set ms $\subseteq$ *M* $\Longrightarrow$ *set ns* $\subseteq$ *M* $\Longrightarrow$ *set ms* $\subseteq$ *RSpan* (*ms*@*ns*)
⟨*proof*⟩

lemma *RSpan-contains-spanset-append-right* :
set ms $\subseteq$ *M* $\Longrightarrow$ *set ns* $\subseteq$ *M* $\Longrightarrow$ *set ns* $\subseteq$ *RSpan* (*ms*@*ns*)
⟨*proof*⟩

lemma *RSpan-zero-closed* : *set ms* $\subseteq$ *M* $\Longrightarrow$ *0* $\in$ *RSpan ms*
⟨*proof*⟩

lemma *RSpan-single-closed* : *m* $\in$ *M* $\Longrightarrow$ *RSpan* [*m*] $\subseteq$ *M*
⟨*proof*⟩

lemma *RSpan-closed* : *set ms* $\subseteq$ *M* $\Longrightarrow$ *RSpan ms* $\subseteq$ *M*
⟨*proof*⟩

lemma *RSpan-smult-closed* :
assumes *r* $\in$ *R set ms* $\subseteq$ *M n* $\in$ *RSpan ms*
shows *r* $\cdot$ *n* $\in$ *RSpan ms*
⟨*proof*⟩

lemma *RSpan-add-closed* :
assumes *set ms* $\subseteq$ *M n* $\in$ *RSpan ms n′* $\in$ *RSpan ms*
shows *n* + *n′* $\in$ *RSpan ms*
⟨*proof*⟩

lemma *RSpan-lincomb-closed* :
⟦ *set rs* $\subseteq$ *R*; *set ms* $\subseteq$ *M*; *set ns* $\subseteq$ *RSpan ms* ⟧ $\Longrightarrow$ *rs* $\cdot\cdot$ *ns* $\in$ *RSpan ms*
⟨*proof*⟩

lemma *RSpanI* : *set ms* $\subseteq$ *M* $\Longrightarrow$ *M* $\subseteq$ *RSpan ms* $\Longrightarrow$ *M* = *RSpan ms*
⟨*proof*⟩

lemma *RSpan-contains-RSpan-take* :
set ms $\subseteq$ *M* $\Longrightarrow$ *RSpan* (*take k ms*) $\subseteq$ *RSpan ms*
⟨*proof*⟩

lemma *RSubmodule-RSpan-single* :
assumes *m* $\in$ *M*
shows *RSubmodule* (*RSpan* [*m*])
⟨*proof*⟩

lemma *RSubmodule-RSpan* : *set ms* $\subseteq$ *M* $\Longrightarrow$ *RSubmodule* (*RSpan ms*)
⟨*proof*⟩

lemma *RSpan-RSpan-closed* :
set ms $\subseteq$ *M* $\Longrightarrow$ *set ns* $\subseteq$ *RSpan ms* $\Longrightarrow$ *RSpan ns* $\subseteq$ *RSpan ms*

⟨*proof*⟩

lemma *spanset-reduce-Cons* :
set ms ⊆ *M* ⟹ *m* ∈ *RSpan ms* ⟹ *RSpan* (*m*#*ms*) = *RSpan ms*
⟨*proof*⟩

lemma *RSpan-replace-hd* :
assumes *n* ∈ *M set ms* ⊆ *M m* ∈ *RSpan* (*n* # *ms*)
shows *RSpan* (*m* # *ms*) ⊆ *RSpan* (*n* # *ms*)
⟨*proof*⟩

end

lemmas (**in** *scalar-mult*)
Span-Cons = *R-scalar-mult.RSpan-Cons*[*OF R-scalar-mult*, *of smult*]

context *Module*
begin

lemmas *SpanD-lincomb-arb-len-coeffs* = *RSpanD-lincomb-arb-len-coeffs*
lemmas *SpanI* = *RSpanI*
lemmas *SpanI-lincomb-arb-len-coeffs* = *RSpanI-lincomb-arb-len-coeffs*
lemmas *Span-contains-Spans-Cons-right* = *RSpan-contains-RSpans-Cons-right*
lemmas *Span-contains-spanset* = *RSpan-contains-spanset*
lemmas *Span-contains-spanset-append-left* = *RSpan-contains-spanset-append-left*
lemmas *Span-contains-spanset-append-right* = *RSpan-contains-spanset-append-right*
lemmas *Span-closed* = *RSpan-closed*
lemmas *Span-smult-closed* = *RSpan-smult-closed*
lemmas *Span-contains-Span-take* = *RSpan-contains-RSpan-take*
lemmas *Span-replace-hd* = *RSpan-replace-hd*
lemmas *Submodule-Span* = *RSubmodule-RSpan*

end

3.2.3 Finitely generated modules

context *R-scalar-mult*
begin

abbreviation *R-fingen M* ≡ (∃ *ms*. *set ms* ⊆ *M* ∧ *RSpan ms* = *M*)

Similar to definition of *card* for finite sets, we default *dim* to 0 if no finite spanning set exists. Note that *RSpan* [] = *0* implies that *dim-R* {*0*} = *0*.

definition *dim-R* :: *'m set* ⇒ *nat*
where *dim-R M* = (*if R-fingen M then* (
LEAST n. ∃ *ms*. *length ms* = *n* ∧ *set ms* ⊆ *M* ∧ *RSpan ms* = *M*
) *else 0*)

lemma *dim-R-nonzero* :

assumes *dim-R M > 0*
shows *M ≠ 0*
⟨*proof*⟩

end

hide-const *real-vector.dim*
hide-const (**open**) *Real-Vector-Spaces.dim*

abbreviation (**in** *scalar-mult*) *fingen* ≡ *R-scalar-mult.R-fingen UNIV smult*
abbreviation (**in** *scalar-mult*) *dim* ≡ *R-scalar-mult.dim-R UNIV smult*

lemmas (**in** *Module*) *dim-nonzero* = *dim-R-nonzero*

3.2.4 *R*-linear independence

context *R-scalar-mult*
begin

primrec *R-lin-independent* :: *'m list* ⇒ *bool* **where**
R-lin-independent-Nil: *R-lin-independent* [] = *True* |
R-lin-independent-Cons:
R-lin-independent (*m*#*ms*) = (*R-lin-independent ms*
∧ (∀ *r rs*. (*set* (*r*#*rs*) ⊆ *R* ∧ (*r*#*rs*) ·· (*m*#*ms*) = *0*) ⟶ *r* = *0*))

lemma *R-lin-independent-ConsI* :
assumes *R-lin-independent ms*
⋀*r rs*. *set* (*r*#*rs*) ⊆ *R* ⟹ (*r*#*rs*) ·· (*m*#*ms*) = *0* ⟹ *r* = *0*
shows *R-lin-independent* (*m*#*ms*)
⟨*proof*⟩

lemma *R-lin-independent-ConsD1* :
R-lin-independent (*m*#*ms*) ⟹ *R-lin-independent ms*
⟨*proof*⟩

lemma *R-lin-independent-ConsD2* :
⟦ *R-lin-independent* (*m*#*ms*); *set* (*r*#*rs*) ⊆ *R*; (*r*#*rs*) ·· (*m*#*ms*) = *0* ⟧
⟹ *r* = *0*
⟨*proof*⟩

end

context *RModule*
begin

lemma *R-lin-independent-imp-same-scalars* :
⟦ *length rs* = *length ss*; *length rs* ≤ *length ms*; *set rs* ⊆ *R*; *set ss* ⊆ *R*;
set ms ⊆ *M*; *R-lin-independent ms*; *rs* ·· *ms* = *ss* ·· *ms* ⟧ ⟹ *rs* = *ss*

⟨*proof*⟩

lemma *R-lin-independent-obtain-unique-scalars* :
⟦ *set ms* ⊆ *M*; *R-lin-independent ms*; *n* ∈ *RSpan ms* ⟧
⟹ (∃! *rs*. *set rs* ⊆ *R* ∧ *length rs* = *length ms* ∧ *n* = *rs* ·· *ms*)
⟨*proof*⟩

lemma *R-lin-independentI-all-scalars* :
set ms ⊆ *M* ⟹
(∀ *rs*. *set rs* ⊆ *R* ∧ *length rs* = *length ms* ∧ *rs* ·· *ms* = *0* ⟶ *set rs* ⊆ *0*)
⟹ *R-lin-independent ms*
⟨*proof*⟩

lemma *R-lin-independentI-concat-all-scalars* :
defines *eq-len*: *eq-len* ≡ λ*xs ys*. *length xs* = *length ys*
assumes *set* (*concat mss*) ⊆ *M*
⋀*rss*. *set* (*concat rss*) ⊆ *R* ⟹ *list-all2 eq-len rss mss*
⟹ (*concat rss*) ·· (*concat mss*) = *0* ⟹ (∀ *rs* ∈ *set rss*. *set rs* ⊆ *0*)
shows *R-lin-independent* (*concat mss*)
⟨*proof*⟩

lemma *R-lin-independentD-all-scalars* :
⟦ *set rs* ⊆ *R*; *set ms* ⊆ *M*; *length rs* ≤ *length ms*; *R-lin-independent ms*;
rs ·· *ms* = *0* ⟧ ⟹ *set rs* ⊆ *0*
⟨*proof*⟩

lemma *R-lin-independentD-all-scalars-nth* :
assumes *set rs* ⊆ *R set ms* ⊆ *M R-lin-independent ms rs* ·· *ms* = *0*
k < *min* (*length rs*) (*length ms*)
shows *rs*!*k* = *0*
⟨*proof*⟩

lemma *R-lin-dependent-dependence-relation* :
set ms ⊆ *M* ⟹ ¬ *R-lin-independent ms*
⟹ ∃ *rs*. *set rs* ⊆ *R* ∧ *set rs* ≠ *0* ∧ *length rs* = *length ms* ∧ *rs* ·· *ms* = *0*
⟨*proof*⟩

lemma *R-lin-independent-imp-distinct* :
set ms ⊆ *M* ⟹ *R-lin-independent ms* ⟹ *distinct ms*
⟨*proof*⟩

lemma *R-lin-independent-imp-independent-take* :
set ms ⊆ *M* ⟹ *R-lin-independent ms* ⟹ *R-lin-independent* (*take n ms*)
⟨*proof*⟩

lemma *R-lin-independent-Cons-imp-independent-RSpans* :
assumes *m* ∈ *M R-lin-independent* (*m*#*ms*)
shows *add-independentS* [*RSpan* [*m*], *RSpan ms*]
⟨*proof*⟩

lemma *hd0-imp-R-lin-dependent* : ¬ *R-lin-independent* (*0*#*ms*)
⟨*proof*⟩

lemma *R-lin-independent-imp-hd-n0* : *R-lin-independent* (*m*#*ms*) ⟹ *m* ≠ *0*
⟨*proof*⟩

lemma *R-lin-independent-imp-hd-independent-from-RSpan* :
assumes *m* ∈ *M set ms* ⊆ *M R-lin-independent* (*m*#*ms*)
shows *m* ∉ *RSpan ms*
⟨*proof*⟩

lemma *R-lin-independent-reduce* :
assumes *n* ∈ *M*
shows *set ms* ⊆ *M* ⟹ *R-lin-independent* (*ms* @ *n* # *ns*)
⟹ *R-lin-independent* (*ms* @ *ns*)
⟨*proof*⟩

lemma *R-lin-independent-vs-lincomb0* :
assumes *set* (*ms*@*n*#*ns*) ⊆ *M R-lin-independent* (*ms* @ *n* # *ns*)
set (*rs*@*s*#*ss*) ⊆ *R length rs* = *length ms*
(*rs*@*s*#*ss*) ·· (*ms*@*n*#*ns*) = *0*
shows *s* = *0*
⟨*proof*⟩

lemma *R-lin-independent-append-imp-independent-RSpans* :
set ms ⊆ *M* ⟹ *R-lin-independent* (*ms*@*ns*)
⟹ *add-independentS* [*RSpan ms*, *RSpan ns*]
⟨*proof*⟩

end

3.2.5 Linear independence over *UNIV*

context *scalar-mult*
begin

abbreviation *lin-independent ms*
≡ *R-scalar-mult.R-lin-independent UNIV smult ms*

lemmas *lin-independent-ConsI*
= *R-scalar-mult.R-lin-independent-ConsI* [*OF R-scalar-mult*, *of smult*]
lemmas *lin-independent-ConsD1*
= *R-scalar-mult.R-lin-independent-ConsD1*[*OF R-scalar-mult*, *of smult*]

end

context *Module*
begin

lemmas *lin-independent-imp-independent-take* = *R-lin-independent-imp-independent-take*
lemmas *lin-independent-reduce* = *R-lin-independent-reduce*
lemmas *lin-independent-vs-lincomb0* = *R-lin-independent-vs-lincomb0*
lemmas *lin-dependent-dependence-relation* = *R-lin-dependent-dependence-relation*
lemmas *lin-independent-imp-distinct* = *R-lin-independent-imp-distinct*

lemmas *lin-independent-imp-hd-independent-from-Span*
= *R-lin-independent-imp-hd-independent-from-RSpan*
lemmas *lin-independent-append-imp-independent-Spans*
= *R-lin-independent-append-imp-independent-RSpans*

end

3.2.6 Rank

context *R-scalar-mult*
begin

definition *R-finrank* :: *'m set* ⇒ *bool*
where *R-finrank M* = (∃ *n*. ∀ *ms*. *set ms* ⊆ *M*
∧ *R-lin-independent ms* ⟶ *length ms* ≤ *n*)

lemma *R-finrankI* :
(⋀*ms*. *set ms* ⊆ *M* ⟹ *R-lin-independent ms* ⟹ *length ms* ≤ *n*)
⟹ *R-finrank M*
⟨*proof*⟩

lemma *R-finrankD* :
R-finrank M ⟹ ∃ *n*. ∀ *ms*. *set ms* ⊆ *M* ∧ *R-lin-independent ms*
⟶ *length ms* ≤ *n*
⟨*proof*⟩

lemma *submodule-R-finrank* : *R-finrank M* ⟹ *N* ⊆ *M* ⟹ *R-finrank N*
⟨*proof*⟩

end

context *scalar-mult*
begin

abbreviation *finrank* :: *'m set* ⇒ *bool*
where *finrank* ≡ *R-scalar-mult.R-finrank UNIV smult*

lemmas *finrankI* = *R-scalar-mult.R-finrankI*[*OF R-scalar-mult*, *of - smult*]
lemmas *finrankD* = *R-scalar-mult.R-finrankD*[*OF R-scalar-mult*, *of smult*]
lemmas *submodule-finrank*
= *R-scalar-mult.submodule-R-finrank* [*OF R-scalar-mult*, *of smult*]

end

3.3 Module homomorphisms

3.3.1 Locales

locale *RModuleHom* = *Domain?*: *RModule R smult M*
+ *Codomain?*: *scalar-mult smult′*
+ *GroupHom?*: *GroupHom M T*
  for *R* :: *′r*::*ring-1 set*
  and *smult* :: *′r* ⇒ *′m*::*ab-group-add* ⇒ *′m* (**infixr** ‹·› *70*)
  and *M* :: *′m set*
  and *smult′* :: *′r* ⇒ *′n*::*ab-group-add* ⇒ *′n* (**infixr** ‹⋆› *70*)
  and *T* :: *′m* ⇒ *′n*
+ **assumes** *R-map*: ⋀*r m*. *r* ∈ *R* ⟹ *m* ∈ *M* ⟹ *T* (*r* · *m*) = *r* ⋆ *T m*

abbreviation (**in** *RModuleHom*) *lincomb′* :: *′r list* ⇒ *′n list* ⇒ *′n* (**infix** ‹·⋆› *70*)
  where *lincomb′* ≡ *Codomain.lincomb*

lemma (**in** *RModule*) *RModuleHomI* :
  assumes *GroupHom M T*
    ⋀*r m*. *r* ∈ *R* ⟹ *m* ∈ *M* ⟹ *T* (*r* · *m*) = *smult′ r* (*T m*)
  shows *RModuleHom R smult M smult′ T*
  ⟨*proof*⟩

locale *RModuleEnd* = *RModuleHom R smult M smult T*
  for *R* :: *′r*::*ring-1 set*
  and *smult* :: *′r* ⇒ *′m*::*ab-group-add* ⇒ *′m* (**infixr** ‹·› *70*)
  and *M* :: *′m set*
  and *T* :: *′m* ⇒ *′m*
+ **assumes** *endomorph*: *ImG* ⊆ *M*

locale *ModuleHom* = *RModuleHom UNIV smult M smult′ T*
  for *smult* :: *′r*::*ring-1* ⇒ *′m*::*ab-group-add* ⇒ *′m* (**infixr** ‹·› *70*)
  and *M* :: *′m set*
  and *smult′* :: *′r* ⇒ *′n*::*ab-group-add* ⇒ *′n* (**infixr** ‹⋆› *70*)
  and *T* :: *′m* ⇒ *′n*

lemmas (**in** *ModuleHom*) *hom* = *hom*

lemmas (**in** *Module*) *ModuleHomI* = *RModuleHomI*[*THEN ModuleHom.intro*]

locale *ModuleEnd* = *ModuleHom smult M smult T*
  for *smult* :: *′r*::*ring-1* ⇒ *′m*::*ab-group-add* ⇒ *′m* (**infixr** ‹·› *70*)
  and *M* :: *′m set* **and** *T* :: *′m* ⇒ *′m*
+ **assumes** *endomorph*: *ImG* ⊆ *M*

locale *RModuleIso* = *RModuleHom R smult M smult′ T*
  for *R* :: *′r*::*ring-1 set*
  and *smult* :: *′r* ⇒ *′m*::*ab-group-add* ⇒ *′m* (**infixr** ‹·› *70*)

and M :: $'m$ *set*
and *smult'* :: $'r \Rightarrow 'n$::*ab-group-add* $\Rightarrow 'n$ (**infixr** ‹⋆› *70*)
and T :: $'m \Rightarrow 'n$
+ **fixes** N :: $'n$ *set*
assumes *bijective*: *bij-betw T M N*

lemma (**in** *RModule*) *RModuleIsoI* :
assumes *GroupIso M T N*
$\bigwedge r\ m.\ r \in R \Longrightarrow m \in M \Longrightarrow T\ (r \cdot m) = smult'\ r\ (T\ m)$
shows *RModuleIso R smult M smult' T N*
⟨*proof*⟩

3.3.2 Basic facts

lemma (**in** *RModule*) *trivial-RModuleHom* :
$\forall\, r{\in}R.\ smult'\ r\ 0 = 0 \Longrightarrow RModuleHom\ R\ smult\ M\ smult'\ 0$
⟨*proof*⟩

lemma (**in** *RModule*) *RModHom-idhom* : *RModuleHom R smult M smult* (*id*↓*M*)
⟨*proof*⟩

context *RModuleHom*
begin

lemmas *additive* = *hom*
lemmas *supp* = *supp*
lemmas *im-zero* = *im-zero*
lemmas *im-diff* = *im-diff*
lemmas *Ker-Im-iff* = *Ker-Im-iff*
lemmas *Ker0-imp-inj-on* = *Ker0-imp-inj-on*

lemma *GroupHom* : *GroupHom M T* ⟨*proof*⟩

lemma *codomain-smult-zero* : $r \in R \Longrightarrow r \star 0 = 0$
⟨*proof*⟩

lemma *RSubmodule-Ker* : *Domain.RSubmodule Ker*
⟨*proof*⟩

lemma *RModule-Im* : *RModule R smult' ImG*
⟨*proof*⟩

lemma *im-submodule* :
assumes *RSubmodule N*
shows *RModule.RSubmodule R smult' ImG* (*T* ‘ *N*)
⟨*proof*⟩

lemma *RModHom-composite-left* :
assumes *T* ‘ *M* ⊆ *N RModuleHom R smult' N smult'' S*

shows *RModuleHom R smult M smult''* $(S \circ T)$
⟨*proof*⟩

lemma *RModuleHom-restrict0-submodule* :
assumes *RSubmodule N*
shows *RModuleHom R smult N smult'* $(T \downarrow N)$
⟨*proof*⟩

lemma *distrib-lincomb* :
set rs $\subseteq$ *R* $\Longrightarrow$ *set ms* $\subseteq$ *M* $\Longrightarrow$ *T* (*rs* $\cdot\cdot$ *ms*) = *rs* $\cdot\star$ *map T ms*
⟨*proof*⟩

lemma *same-image-on-RSpanset-imp-same-hom* :
assumes *RModuleHom R smult M smult' S set ms* $\subseteq$ *M*
M = *Domain.R-scalars.RSpan ms* $\forall$ *m*$\in$*set ms. S m* = *T m*
shows *S* = *T*
⟨*proof*⟩

end

lemma *RSubmodule-eigenspace* :
fixes *smult* :: *'r*::*ring-1* $\Rightarrow$ *'m*::*ab-group-add* $\Rightarrow$ *'m* (**infixr** ‹·› *70*)
assumes *RModHom*: *RModuleHom R smult M smult T*
and *r*: *r* $\in$ *R* $\bigwedge$*s m. s* $\in$ *R* $\Longrightarrow$ *m* $\in$ *M* $\Longrightarrow$ *s* · *r* · *m* = *r* · *s* · *m*
defines *E*: *E* $\equiv$ $\{m \in M.\ T\ m = r \cdot m\}$
shows *RModule.RSubmodule R smult M E*
⟨*proof*⟩

3.3.3 Basic facts about endomorphisms

lemma (**in** *RModule*) *Rmap-endomorph-is-RModuleEnd* :
assumes *grpend*: *GroupEnd M T*
and *Rmap* : $\bigwedge$*r m. r* $\in$ *R* $\Longrightarrow$ *m* $\in$ *M* $\Longrightarrow$ *T* $(r \cdot m) = r \cdot (T\ m)$
shows *RModuleEnd R smult M T*
⟨*proof*⟩

lemma (**in** *RModuleEnd*) *GroupEnd* : *GroupEnd M T*
⟨*proof*⟩

lemmas (**in** *RModuleEnd*) *proj-decomp* = *GroupEnd.proj-decomp*[*OF GroupEnd*]

lemma (**in** *ModuleEnd*) *RModuleEnd* : *RModuleEnd UNIV smult M T*
⟨*proof*⟩

lemmas (**in** *ModuleEnd*) *GroupEnd* = *RModuleEnd.GroupEnd*[*OF RModuleEnd*]

lemma *RModuleEnd-over-UNIV-is-ModuleEnd* :
RModuleEnd UNIV rsmult M T $\Longrightarrow$ *ModuleEnd rsmult M T*
⟨*proof*⟩

3.3.4 Basic facts about isomorphisms

context *RModuleIso*
begin

abbreviation $invT \equiv (\textit{the-inv-into}\ M\ T) \downarrow N$

lemma *GroupIso* : *GroupIso M T N*
⟨*proof*⟩

lemmas *ImG* = *GroupIso.ImG* [*OF GroupIso*]
lemmas *GroupHom-inv* = *GroupIso.inv* [*OF GroupIso*]
lemmas *invT-into* = *GroupIso.invT-into* [*OF GroupIso*]
lemmas *T-invT* = *GroupIso.T-invT* [*OF GroupIso*]
lemmas *invT-eq* = *GroupIso.invT-eq* [*OF GroupIso*]

lemma *RModuleN* : *RModule R smult′ N* ⟨*proof*⟩

lemma *inv* : *RModuleIso R smult′ N smult invT M*
⟨*proof*⟩

end

3.4 Inner direct sums of RModules

lemma (**in** *RModule*) *RModule-inner-dirsum-el-decomp-Rsmult* :
assumes $\forall N{\in}\textit{set Ns}.\ \textit{RSubmodule N add-independentS Ns}\ r \in R$
$x \in (\bigoplus N{\leftarrow}\textit{Ns}.\ N)$
shows $(\bigoplus \textit{Ns}{\leftarrow}(r \cdot x)) = [r \cdot m.\ m{\leftarrow}(\bigoplus \textit{Ns}{\leftarrow}x)]$
⟨*proof*⟩

lemma (**in** *RModule*) *RModuleEnd-inner-dirsum-el-decomp-nth* :
assumes $\forall N \in \textit{set Ns}.\ \textit{RSubmodule N add-independentS Ns}\ n < \textit{length Ns}$
shows $\textit{RModuleEnd R smult}\ (\bigoplus N{\leftarrow}\textit{Ns}.\ N)\ (\bigoplus \textit{Ns}{\downarrow}n)$
⟨*proof*⟩

4 Vector Spaces

4.1 Locales and basic facts

Here we don't care about being able to switch scalars.

locale *fscalar-mult* = *scalar-mult smult*
for *smult* :: *'f*::*field* ⇒ *'v*::*ab-group-add* ⇒ *'v* (**infixr** ‹·› *70*)

abbreviation (**in** *fscalar-mult*) *findim* ≡ *fingen*

locale *VectorSpace* = *Module smult V*
for *smult* :: *'f*::*field* ⇒ *'v*::*ab-group-add* ⇒ *'v* (**infixr** ‹·› *70*)
and *V* :: *'v set*

lemmas *VectorSpaceI* = *ModuleI*[*THEN VectorSpace.intro*]

sublocale *VectorSpace* < *fscalar-mult* ⟨*proof*⟩

locale *FinDimVectorSpace* = *VectorSpace*
+ **assumes** *findim*: *findim V*

lemma (**in** *VectorSpace*) *FinDimVectorSpaceI* :
findim V ⟹ *FinDimVectorSpace* (·) *V*
⟨*proof*⟩

context *VectorSpace*
begin

abbreviation *Subspace* :: *'v set* ⇒ *bool* **where** *Subspace* ≡ *Submodule*

lemma *SubspaceD1* : *Subspace U* ⟹ *VectorSpace smult U*
⟨*proof*⟩

lemmas *AbGroup* = *AbGroup*
lemmas *add-closed* = *add-closed*
lemmas *smult-closed* = *smult-closed*
lemmas *one-smult* = *one-smult*
lemmas *smult-assoc* = *smult-assoc*
lemmas *smult-distrib-left* = *smult-distrib-left*
lemmas *smult-distrib-right* = *smult-distrib-right*
lemmas *zero-closed* = *zero-closed*
lemmas *zero-smult* = *zero-smult*
lemmas *smult-zero* = *smult-zero*
lemmas *smult-lincomb* = *smult-lincomb*
lemmas *smult-distrib-left-diff* = *smult-distrib-left-diff*
lemmas *smult-sum-distrib* = *smult-sum-distrib*
lemmas *sum-smult-distrib* = *sum-smult-distrib*
lemmas *lincomb-sum* = *lincomb-sum*
lemmas *lincomb-closed* = *lincomb-closed*
lemmas *lincomb-concat* = *lincomb-concat*
lemmas *lincomb-replicate0-left* = *lincomb-replicate0-left*
lemmas *delta-scalars-lincomb-eq-nth* = *delta-scalars-lincomb-eq-nth*
lemmas *SpanI* = *SpanI*
lemmas *Span-closed* = *Span-closed*
lemmas *SpanD-lincomb-arb-len-coeffs* = *SpanD-lincomb-arb-len-coeffs*
lemmas *SpanI-lincomb-arb-len-coeffs* = *SpanI-lincomb-arb-len-coeffs*
lemmas *in-Span-obtain-same-length-coeffs* = *in-Span-obtain-same-length-coeffs*
lemmas *SubspaceI* = *SubmoduleI*
lemmas *subspace-finrank* = *submodule-finrank*

lemma *cancel-scalar*: ⟦ *a* ≠ *0*; *u* ∈ *V*; *v* ∈ *V*; *a* · *u* = *a* · *v* ⟧ ⟹ *u* = *v*
⟨*proof*⟩

end

4.2 Linear algebra in vector spaces

4.2.1 Linear independence and spanning

context *VectorSpace*
begin

lemmas *Subspace-Span* = *Submodule-Span*
lemmas *lin-independent-Nil* = *R-lin-independent-Nil*
lemmas *lin-independentI-concat-all-scalars* = *R-lin-independentI-concat-all-scalars*
lemmas *lin-independentD-all-scalars* = *R-lin-independentD-all-scalars*
lemmas *lin-independent-obtain-unique-scalars* = *R-lin-independent-obtain-unique-scalars*

lemma *lincomb-Cons-0-imp-in-Span* :
$[\![v \in V; set\ vs \subseteq V; a \neq 0; (a\#as) \cdot\cdot (v\#vs) = 0]\!] \Longrightarrow v \in Span\ vs$
⟨*proof*⟩

lemma *lin-independent-Cons-conditions* :
$[\![v \in V; set\ vs \subseteq V; v \notin Span\ vs; lin\text{-}independent\ vs]\!]$
$\Longrightarrow lin\text{-}independent\ (v\#vs)$
⟨*proof*⟩

lemma *coeff-n0-imp-in-Span-others* :
assumes $v \in V$ *set us* $\subseteq V$ *set vs* $\subseteq V$ $b \neq 0$ *length as* = *length us*
$w = (as\ @\ b\ \#\ bs) \cdot\cdot (us\ @\ v\ \#\ vs)$
shows $v \in Span\ (w\ \#\ us\ @\ vs)$
⟨*proof*⟩

lemma *lin-independent-replace1-by-lincomb* :
assumes *set us* $\subseteq V$ $v \in V$ *set vs* $\subseteq V$ *lin-independent* $(us\ @\ v\ \#\ vs)$
length as = *length us* $b \neq 0$
shows *lin-independent* ($((as\ @\ b\ \#\ bs) \cdot\cdot (us\ @\ v\ \#\ vs))\ \#\ us\ @\ vs$)
⟨*proof*⟩

lemma *build-lin-independent-seq* :
assumes *us-V*: *set us* $\subseteq V$
and *indep-us*: *lin-independent us*
shows $\exists ws.\ set\ ws \subseteq V \wedge lin\text{-}independent\ (ws\ @\ us) \wedge (Span\ (ws\ @\ us) = V$
$\vee\ length\ ws = n)$
⟨*proof*⟩

end

4.2.2 Basis for a vector space: *basis-for*

abbreviation (**in** *fscalar-mult*) *basis-for* :: *'v set* ⇒ *'v list* ⇒ *bool*
where *basis-for V vs* ≡ (*set vs* $\subseteq V \wedge V = Span\ vs \wedge lin\text{-}independent\ vs$)

context *VectorSpace*
begin

lemma *spanset-contains-basis* :
set vs $\subseteq$ *V* $\Longrightarrow$ $\exists$ *us*. *set us* $\subseteq$ *set vs* $\wedge$ *basis-for* (*Span vs*) *us*
⟨*proof*⟩

lemma *basis-for-Span-ex* : *set vs* $\subseteq$ *V* $\Longrightarrow$ $\exists$ *us*. *basis-for* (*Span vs*) *us*
⟨*proof*⟩

lemma *replace-basis-one-step* :
assumes *closed*: *set vs* $\subseteq$ *V set us* $\subseteq$ *V* **and** *indep*: *lin-independent* (*us*@*vs*)
and *new-w*: *w* $\in$ *Span* (*us*@*vs*) − *Span us*
shows $\exists$ *xs y ys*. *vs* = *xs* @ *y* # *ys*
$\wedge$ *basis-for* (*Span* (*us*@*vs*)) (*w* # *us* @ *xs* @ *ys*)
⟨*proof*⟩

lemma *replace-basis* :
assumes *closed*: *set vs* $\subseteq$ *V* **and** *indep-vs*: *lin-independent vs*
shows ⟦ *length us* $\leq$ *length vs*; *set us* $\subseteq$ *Span vs*; *lin-independent us* ⟧
$\Longrightarrow$ $\exists$ *pvs*. *length pvs* = *length vs* $\wedge$ *set pvs* = *set vs*
$\wedge$ *basis-for* (*Span vs*) (*take* (*length vs*) (*us* @ *pvs*))
⟨*proof*⟩

lemma *replace-basis-completely* :
⟦ *set vs* $\subseteq$ *V*; *lin-independent vs*; *length us* = *length vs*;
set us $\subseteq$ *Span vs*; *lin-independent us* ⟧ $\Longrightarrow$ *basis-for* (*Span vs*) *us*
⟨*proof*⟩

lemma *basis-for-obtain-unique-scalars* :
basis-for V vs $\Longrightarrow$ *v* $\in$ *V* $\Longrightarrow$ $\exists!$ *as*. *length as* = *length vs* $\wedge$ *v* = *as* $\cdot\cdot$ *vs*
⟨*proof*⟩

lemma *add-unique-scalars* :
assumes *vs*: *basis-for V vs* **and** *v*: *v* $\in$ *V* **and** *v'*: *v'* $\in$ *V*
defines *as*: *as* $\equiv$ (*THE ds*. *length ds* = *length vs* $\wedge$ *v* = *ds* $\cdot\cdot$ *vs*)
and *bs*: *bs* $\equiv$ (*THE ds*. *length ds* = *length vs* $\wedge$ *v'* = *ds* $\cdot\cdot$ *vs*)
and *cs*: *cs* $\equiv$ (*THE ds*. *length ds* = *length vs* $\wedge$ *v*+*v'* = *ds* $\cdot\cdot$ *vs*)
shows *cs* = [*a*+*b*. (*a*,*b*)←*zip as bs*]
⟨*proof*⟩

lemma *smult-unique-scalars* :
fixes *a*::*'f*
assumes *vs*: *basis-for V vs* **and** *v*: *v* $\in$ *V*
defines *as*: *as* $\equiv$ (*THE cs*. *length cs* = *length vs* $\wedge$ *v* = *cs* $\cdot\cdot$ *vs*)
and *bs*: *bs* $\equiv$ (*THE cs*. *length cs* = *length vs* $\wedge$ *a* $\cdot$ *v* = *cs* $\cdot\cdot$ *vs*)
shows *bs* = *map* ((∗) *a*) *as*
⟨*proof*⟩

lemma *max-lin-independent-set-in-Span* :
assumes *set vs* $\subseteq$ *V set us* $\subseteq$ *Span vs lin-independent us*
shows *length us* $\leq$ *length vs*
⟨*proof*⟩

lemma *finrank-Span* : *set vs* $\subseteq$ *V* $\Longrightarrow$ *finrank* (*Span vs*)
⟨*proof*⟩

end

4.3 Finite dimensional spaces

context *VectorSpace*
begin

lemma *dim-eq-size-basis* : *basis-for V vs* $\Longrightarrow$ *length vs* = *dim V*
⟨*proof*⟩

lemma *finrank-imp-findim* :
assumes *finrank V*
shows *findim V*
⟨*proof*⟩

lemma *subspace-Span-is-findim* :
⟦ *set vs* $\subseteq$ *V*; *Subspace W*; *W* $\subseteq$ *Span vs* ⟧ $\Longrightarrow$ *findim W*
⟨*proof*⟩

end

context *FinDimVectorSpace*
begin

lemma *Subspace-is-findim* : *Subspace U* $\Longrightarrow$ *findim U*
⟨*proof*⟩

lemma *basis-ex* : $\exists$ *vs. basis-for V vs*
⟨*proof*⟩

lemma *lin-independent-length-le-dim* :
set us $\subseteq$ *V* $\Longrightarrow$ *lin-independent us* $\Longrightarrow$ *length us* $\leq$ *dim V*
⟨*proof*⟩

lemma *too-long-lin-dependent* :
set us $\subseteq$ *V* $\Longrightarrow$ *length us* > *dim V* $\Longrightarrow$ $\neg$ *lin-independent us*
⟨*proof*⟩

lemma *extend-lin-independent-to-basis* :
assumes *set us* $\subseteq$ *V lin-independent us*

shows $\exists vs.\ basis\text{-}for\ V\ (vs\ @\ us)$
⟨*proof*⟩

lemma *extend-Subspace-basis* :
$U \subseteq V \Longrightarrow basis\text{-}for\ U\ us \Longrightarrow \exists vs.\ basis\text{-}for\ V\ (vs@us)$
⟨*proof*⟩

lemma *Subspace-dim-le* :
assumes *Subspace U*
shows $dim\ U \leq dim\ V$
⟨*proof*⟩

lemma *Subspace-eqdim-imp-equal* :
assumes *Subspace U dim U* $= dim\ V$
shows $U = V$
⟨*proof*⟩

lemma *Subspace-dim-lt* : *Subspace* $U \Longrightarrow U \neq V \Longrightarrow dim\ U < dim\ V$
⟨*proof*⟩

lemma *semisimple* :
assumes *Subspace U*
shows $\exists W.\ Subspace\ W \wedge (V = W \oplus U)$
⟨*proof*⟩

end

4.4 Vector space homomorphisms

4.4.1 Locales

locale *VectorSpaceHom* = *ModuleHom smult V smult' T*
for *smult* :: *'f*::*field* ⇒ *'v*::*ab-group-add* ⇒ *'v* (**infixr** ‹·› *70*)
and *V* :: *'v set*
and *smult'* :: *'f* ⇒ *'w*::*ab-group-add* ⇒ *'w* (**infixr** ‹⋆› *70*)
and *T* :: *'v* ⇒ *'w*

sublocale *VectorSpaceHom* < *VectorSpace* ⟨*proof*⟩

lemmas (**in** *VectorSpace*)
VectorSpaceHomI = *ModuleHomI*[*THEN VectorSpaceHom.intro*]

lemma (**in** *VectorSpace*) *VectorSpaceHomI-fromaxioms* :
assumes $\bigwedge g\ g'.\ g \in V \Longrightarrow g' \in V \Longrightarrow T\ (g + g') = T\ g + T\ g'$
supp T $\subseteq V$
$\bigwedge r\ m.\ r \in UNIV \Longrightarrow m \in V \Longrightarrow T\ (r \cdot m) = smult'\ r\ (T\ m)$
shows *VectorSpaceHom smult V smult' T*
⟨*proof*⟩

locale *VectorSpaceEnd* = *VectorSpaceHom smult V smult T*

for *smult* :: *'f*::*field* ⇒ *'v*::*ab-group-add* ⇒ *'v* (**infixr** ‹·› *70*)
and *V* :: *'v set*
and *T* :: *'v* ⇒ *'v*
+ **assumes** *endomorph*: *ImG* ⊆ *V*

abbreviation (**in** *VectorSpace*) *VEnd* ≡ *VectorSpaceEnd smult V*

lemma *VectorSpaceEndI* :
fixes *smult* :: *'f*::*field* ⇒ *'v*::*ab-group-add* ⇒ *'v*
assumes *VectorSpaceHom smult V smult T T ' V* ⊆ *V*
shows *VectorSpaceEnd smult V T*
⟨*proof*⟩

lemma (**in** *VectorSpaceEnd*) *VectorSpaceHom*: *VectorSpaceHom smult V smult T*
⟨*proof*⟩

lemma (**in** *VectorSpaceEnd*) *ModuleEnd* : *ModuleEnd smult V T*
⟨*proof*⟩

locale *VectorSpaceIso* = *VectorSpaceHom smult V smult' T*
for *smult* :: *'f*::*field* ⇒ *'v*::*ab-group-add* ⇒ *'v* (**infixr** ‹·› *70*)
and *V* :: *'v set*
and *smult'* :: *'f* ⇒ *'w*::*ab-group-add* ⇒ *'w* (**infixr** ‹⋆› *70*)
and *T* :: *'v* ⇒ *'w*
+ **fixes** *W* :: *'w set*
assumes *bijective*: *bij-betw T V W*

abbreviation (**in** *VectorSpace*) *isomorphic* ::
(*'f* ⇒ *'w*::*ab-group-add* ⇒ *'w*) ⇒ *'w set* ⇒ *bool*
where *isomorphic smult' W* ≡ (∃ *T*. *VectorSpaceIso smult V smult' T W*)

4.4.2 Basic facts

lemma (**in** *VectorSpace*) *trivial-VectorSpaceHom* :
(⋀*a*. *smult' a 0* = *0*) ⟹ *VectorSpaceHom smult V smult' 0*
⟨*proof*⟩

lemma (**in** *VectorSpace*) *VectorSpaceHom-idhom* :
VectorSpaceHom smult V smult (*id*↓*V*)
⟨*proof*⟩

context *VectorSpaceHom*
begin

lemmas *hom* = *hom*
lemmas *supp* = *supp*
lemmas *f-map* = *R-map*
lemmas *im-zero* = *im-zero*
lemmas *im-sum-list-prod* = *im-sum-list-prod*

lemmas *additive* = *additive*
lemmas *GroupHom* = *GroupHom*
lemmas *distrib-lincomb* = *distrib-lincomb*

lemmas *same-image-on-spanset-imp-same-hom*
= *same-image-on-RSpanset-imp-same-hom*[
OF ModuleHom.axioms(*1*), *OF VectorSpaceHom.axioms*(*1*)
]

lemma *VectorSpace-Im* : *VectorSpace smult' ImG*
⟨*proof*⟩

lemma *VectorSpaceHom-scalar-mul* :
VectorSpaceHom smult V smult' (λ*v*. *a* ⋆ *T v*)
⟨*proof*⟩

lemma *VectorSpaceHom-composite-left* :
assumes *ImG* ⊆ *W VectorSpaceHom smult' W smult'' S*
shows *VectorSpaceHom smult V smult''* (*S* ∘ *T*)
⟨*proof*⟩

lemma *findim-domain-findim-image* :
assumes *findim V*
shows *fscalar-mult.findim smult' ImG*
⟨*proof*⟩

end

lemma (**in** *VectorSpace*) *basis-im-defines-hom* :
fixes *smult'* :: *'f* ⇒ *'w*::*ab-group-add* ⇒ *'w* (**infixr** ‹⋆› *70*)
and *lincomb'* :: *'f list* ⇒ *'w list* ⇒ *'w* (**infixr** ‹·⋆› *70*)
defines *lincomb'* : *lincomb'* ≡ *scalar-mult.lincomb smult'*
assumes *VSpW* : *VectorSpace smult' W*
and *basisV* : *basis-for V vs*
and *basisV-im* : *set ws* ⊆ *W length ws* = *length vs*
shows ∃! *T*. *VectorSpaceHom smult V smult' T* ∧ *map T vs* = *ws*
⟨*proof*⟩

4.4.3 Hom-sets

definition *VectorSpaceHomSet* ::
(*'f*::*field* ⇒ *'v*::*ab-group-add* ⇒ *'v*) ⇒ *'v set* ⇒ (*'f* ⇒ *'w*::*ab-group-add* ⇒ *'w*)
⇒ *'w set* ⇒ (*'v* ⇒ *'w*) *set*
where *VectorSpaceHomSet fsmult V fsmult' W*
≡ {*T*. *VectorSpaceHom fsmult V fsmult' T*} ∩ {*T*. *T* ‘ *V* ⊆ *W*}

abbreviation (**in** *VectorSpace*) *VectorSpaceEndSet* ≡ {*S*. *VEnd S*}

lemma *VectorSpaceHomSetI* :

VectorSpaceHom fsmult V fsmult′ T $\Longrightarrow$ *T ‘ V* $\subseteq$ *W*
$\Longrightarrow$ *T* $\in$ *VectorSpaceHomSet fsmult V fsmult′ W*
⟨*proof*⟩

lemma *VectorSpaceHomSetD-VectorSpaceHom* :
T $\in$ *VectorSpaceHomSet fsmult V fsmult′ N*
$\Longrightarrow$ *VectorSpaceHom fsmult V fsmult′ T*
⟨*proof*⟩

lemma *VectorSpaceHomSetD-Im* :
T $\in$ *VectorSpaceHomSet fsmult V fsmult′ W* $\Longrightarrow$ *T ‘ V* $\subseteq$ *W*
⟨*proof*⟩

context *VectorSpace*
begin

lemma *VectorSpaceHomSet-is-fmaps-in-GroupHomSet* :
fixes *smult′* :: *'f* $\Rightarrow$ *'w*::*ab-group-add* $\Rightarrow$ *'w* (**infixr** ‹$\star$› *70*)
shows *VectorSpaceHomSet smult V smult′ W*
= (*GroupHomSet V W*) $\cap$ {*T*. $\forall$ *a*. $\forall$ *v*$\in$*V*. *T* (*a* · *v*) = *a* $\star$ (*T v*)}
⟨*proof*⟩

lemma *Group-VectorSpaceHomSet* :
fixes *smult′* :: *'f* $\Rightarrow$ *'w*::*ab-group-add* $\Rightarrow$ *'w* (**infixr** ‹$\star$› *70*)
assumes *VectorSpace smult′ W*
shows *Group* (*VectorSpaceHomSet smult V smult′ W*)
⟨*proof*⟩

lemma *VectorSpace-VectorSpaceHomSet* :
fixes *smult′* :: *'f* $\Rightarrow$ *'w*::*ab-group-add* $\Rightarrow$ *'w* (**infixr** ‹$\star$› *70*)
and *hom-smult* :: *'f* $\Rightarrow$ (*'v* $\Rightarrow$ *'w*) $\Rightarrow$ (*'v* $\Rightarrow$ *'w*) (**infixr** ‹$\star$·› *70*)
defines *hom-smult*: *hom-smult* $\equiv$ λ*a T v*. *a* $\star$ *T v*
assumes *VSpW*: *VectorSpace smult′ W*
shows *VectorSpace hom-smult* (*VectorSpaceHomSet smult V smult′ W*)
⟨*proof*⟩

end

4.4.4 Basic facts about endomorphisms

lemma *ModuleEnd-over-field-is-VectorSpaceEnd* :
fixes *smult* :: *'f*::*field* $\Rightarrow$ *'v*::*ab-group-add* $\Rightarrow$ *'v*
assumes *ModuleEnd smult V T*
shows *VectorSpaceEnd smult V T*
⟨*proof*⟩

context *VectorSpace*
begin

lemmas *VectorSpaceEnd-inner-dirsum-el-decomp-nth* =
RModuleEnd-inner-dirsum-el-decomp-nth[
THEN RModuleEnd-over-UNIV-is-ModuleEnd,
THEN ModuleEnd-over-field-is-VectorSpaceEnd
]

abbreviation *end-smult* :: $'f \Rightarrow ('v \Rightarrow 'v) \Rightarrow ('v \Rightarrow 'v)$ (**infixr** $\langle\cdot\cdot\rangle$ *70*)
where $a \cdot\cdot T \equiv (\lambda v.\ a \cdot T\ v)$

abbreviation *end-lincomb*
:: $'f$ *list* $\Rightarrow$ (($'v \Rightarrow 'v$) *list*) $\Rightarrow$ ($'v \Rightarrow 'v$) (**infixr** $\langle\cdots\rangle$ *70*)
where *end-lincomb* $\equiv$ *scalar-mult.lincomb end-smult*

lemma *end-smult0*: $a \cdot\cdot 0 = 0$
⟨*proof*⟩

lemma *end-0smult*: *range* $T \subseteq V \Longrightarrow 0 \cdot\cdot T = 0$
⟨*proof*⟩

lemma *end-smult-distrib-left* :
assumes *range* $S \subseteq V$ *range* $T \subseteq V$
shows $a \cdot\cdot (S + T) = a \cdot\cdot S + a \cdot\cdot T$
⟨*proof*⟩

lemma *end-smult-distrib-right* :
assumes *range* $T \subseteq V$
shows $(a+b) \cdot\cdot T = a \cdot\cdot T + b \cdot\cdot T$
⟨*proof*⟩

lemma *end-smult-assoc* :
assumes *range* $T \subseteq V$
shows $a \cdot\cdot b \cdot\cdot T = (a * b) \cdot\cdot T$
⟨*proof*⟩

lemma *end-smult-comp-comm-left* : $(a \cdot\cdot T) \circ S = a \cdot\cdot (T \circ S)$
⟨*proof*⟩

lemma *end-idhom* : *VEnd* $(id{\downarrow}V)$
⟨*proof*⟩

lemma *VectorSpaceEndSet-is-VectorSpaceHomSet* :
VectorSpaceHomSet smult V smult V = $\{T.\ VEnd\ T\}$
⟨*proof*⟩

lemma *VectorSpace-VectorSpaceEndSet* : *VectorSpace end-smult VectorSpaceEnd-Set*
⟨*proof*⟩

end

context *VectorSpaceEnd*
begin

lemmas *f-map* = *R-map*
lemmas *supp* = *supp*
lemmas *GroupEnd* = *ModuleEnd.GroupEnd*[*OF ModuleEnd*]
lemmas *idhom-left* = *idhom-left*
lemmas *range* = *GroupEnd.range*[*OF GroupEnd*]
lemmas *Ker0-imp-inj-on* = *Ker0-imp-inj-on*
lemmas *inj-on-imp-Ker0* = *inj-on-imp-Ker0*
lemmas *nonzero-Ker-el-imp-n-inj* = *nonzero-Ker-el-imp-n-inj*
lemmas *VectorSpaceHom-composite-left*
= *VectorSpaceHom-composite-left*[*OF endomorph*]

lemma *in-VEndSet* : $T \in$ *VectorSpaceEndSet*
⟨*proof*⟩

lemma *end-smult-comp-comm-right* :
range $S \subseteq V \Longrightarrow T \circ (a \cdot\cdot S) = a \cdot\cdot (T \circ S)$
⟨*proof*⟩

lemma *VEnd-end-smult-VEnd* : *VEnd* $(a \cdot\cdot T)$
⟨*proof*⟩

lemma *VEnd-composite-left* :
assumes *VEnd S*
shows *VEnd* $(S \circ T)$
⟨*proof*⟩

lemma *VEnd-composite-right* : *VEnd* $S \Longrightarrow$ *VEnd* $(T \circ S)$
⟨*proof*⟩

end

lemma (**in** *VectorSpace*) *inj-comp-end* :
assumes *VEnd S inj-on S V VEnd T inj-on T V*
shows *inj-on* $(S \circ T)$ *V*
⟨*proof*⟩

lemma (**in** *VectorSpace*) *n-inj-comp-end* :
$[\![$ *VEnd S*; *VEnd T*; $\neg$ *inj-on* $(S \circ T)$ *V* $]\!] \Longrightarrow \neg$ *inj-on S V* $\vee \neg$ *inj-on T V*
⟨*proof*⟩

4.4.5 Polynomials of endomorphisms

context *VectorSpaceEnd*
begin

primrec *endpow* :: *nat* ⇒ (*'v*⇒*'v*)
  where *endpow0*: *endpow 0 = id↓V*
  | *endpowSuc*: *endpow* (*Suc n*) = *T* ∘ (*endpow n*)

definition *polymap* :: *'f poly* ⇒ (*'v*⇒*'v*)
  where *polymap p* ≡ (*coeffs p*) ··· (*map endpow* [*0..<Suc* (*degree p*)])

lemma *VEnd-endpow* : *VEnd* (*endpow n*)
⟨*proof*⟩

lemma *endpow-list-apply-closed* :
  v ∈ *V* ⟹ *set* (*map* (λ*S*. *S v*) (*map endpow* [*0..<k*])) ⊆ *V*
  ⟨*proof*⟩

lemma *map-endpow-Suc* :
  map endpow [*0..<Suc n*] = (*id↓V*) # *map* ((∘) *T*) (*map endpow* [*0..<n*])
⟨*proof*⟩

lemma *T-endpow-list-apply-commute* :
  map T (*map* (λ*S*. *S v*) (*map endpow* [*0..<n*]))
      = *map* (λ*S*. *S v*) (*map* ((∘) *T*) (*map endpow* [*0..<n*]))
  ⟨*proof*⟩

lemma *polymap0* : *polymap 0 = 0*
  ⟨*proof*⟩

lemma *VEnd-polymap* : *VEnd* (*polymap p*)
⟨*proof*⟩

lemma *polymap-pCons* : *polymap* (*pCons a p*) = *a* ·· (*id↓V*) + (*T* ∘ (*polymap p*))
⟨*proof*⟩

lemma *polymap-plus* : *polymap* (*p* + *q*) = *polymap p* + *polymap q*
⟨*proof*⟩

lemma *polymap-polysmult* : *polymap* (*Polynomial.smult a p*) = *a* ·· *polymap p*
⟨*proof*⟩

lemma *polymap-times* : *polymap* (*p* ∗ *q*) = (*polymap p*) ∘ (*polymap q*)
⟨*proof*⟩

lemma *polymap-apply* :
  assumes *v* ∈ *V*
  shows *polymap p v* = (*coeffs p*)
        ·· (*map* (λ*S*. *S v*) (*map endpow* [*0..<Suc* (*degree p*)]))
⟨*proof*⟩

lemma *polymap-apply-linear* : *v* ∈ *V* ⟹ *polymap* [:−*c*, *1*:] *v* = *T v* − *c* · *v*
  ⟨*proof*⟩

lemma *polymap-const-inj* :
assumes *degree p = 0 p ≠ 0*
shows *inj-on (polymap p) V*
⟨*proof*⟩

lemma *n-inj-polymap-times* :
¬ *inj-on (polymap (p * q)) V*
⟹ ¬ *inj-on (polymap p) V* ∨ ¬ *inj-on (polymap q) V*
⟨*proof*⟩

In the following lemma, [:− *c*, *1*:] is the linear polynomial $x - c$.

lemma *n-inj-polymap-findlinear* :
assumes *alg-closed*: ⋀*p*::'*f poly. degree p > 0* ⟹ ∃ *c. poly p c = 0*
shows *p ≠ 0* ⟹ ¬ *inj-on (polymap p) V*
⟹ ∃ *c*. ¬ *inj-on (polymap* [:−*c*, *1*:]*) V*
⟨*proof*⟩

end

4.4.6 Existence of eigenvectors of endomorphisms of finite-dimensional vector spaces

lemma (**in** *FinDimVectorSpace*) *endomorph-has-eigenvector* :
assumes *alg-closed*: ⋀*p*::'*a poly. degree p > 0* ⟹ ∃ *c. poly p c = 0*
and *dim* : *dim V > 0*
and *endo* : *VectorSpaceEnd smult V T*
shows ∃ *c u. u* ∈ *V* ∧ *u* ≠ *0* ∧ *T u = c* · *u*
⟨*proof*⟩

5 Modules Over a Group Ring

5.1 Almost-everywhere-zero functions as scalars

locale *aezfun-scalar-mult = scalar-mult smult*
for *smult* ::
('*r*::*ring-1*, '*g*::*group-add*) *aezfun* ⇒ '*v*::*ab-group-add* ⇒ '*v* (**infixr** ‹·› *70*)
begin

definition *fsmult* :: '*r* ⇒ '*v* ⇒ '*v* (**infixr** ‹♯·› *70*) **where** *a* ♯· *v* ≡ (*a* *δδ* *0*) · *v*
abbreviation *flincomb* :: '*r list* ⇒ '*v list* ⇒ '*v* (**infixr** ‹·♯·› *70*)
where *as* ·♯· *vs* ≡ *scalar-mult.lincomb fsmult as vs*
abbreviation *f-lin-independent* :: '*v list* ⇒ *bool*
where *f-lin-independent* ≡ *scalar-mult.lin-independent fsmult*
abbreviation *fSpan* :: '*v list* ⇒ '*v set* **where** *fSpan* ≡ *scalar-mult.Span fsmult*
definition *Gmult* :: '*g* ⇒ '*v* ⇒ '*v* (**infixr** ‹*·› *70*) **where** *g* *· *v* ≡ (*1* *δδ* *g*) · *v*

lemmas *R-scalar-mult* = *R-scalar-mult*

lemma *fsmultD* : $a \sharp\cdot v = (a \ \delta\delta \ 0) \cdot v$
⟨*proof*⟩

lemma *GmultD* : $g *\cdot v = (1 \ \delta\delta \ g) \cdot v$
⟨*proof*⟩

definition *negGorbit-list* :: $'g$ *list* ⇒ ($'a$ ⇒ $'v$) ⇒ $'a$ *list* ⇒ $'v$ *list list*
where *negGorbit-list gs T as* ≡ *map* (λ*g*. *map* (*Gmult* (−*g*) ∘ *T*) *as*) *gs*

lemma *negGorbit-Cons* :
negGorbit-list (*g*#*gs*) *T as*
= (*map* (*Gmult* (−*g*) ∘ *T*) *as*) # *negGorbit-list gs T as*
⟨*proof*⟩

lemma *length-negGorbit-list* : *length* (*negGorbit-list gs T as*) = *length gs*
⟨*proof*⟩

lemma *length-negGorbit-list-sublist* :
fs ∈ *set* (*negGorbit-list gs T as*) ⟹ *length fs* = *length as*
⟨*proof*⟩

lemma *length-concat-negGorbit-list* :
length (*concat* (*negGorbit-list gs T as*)) = (*length gs*) ∗ (*length as*)
⟨*proof*⟩

lemma *negGorbit-list-nth* :
⋀*i*. *i* < *length gs* ⟹ (*negGorbit-list gs T as*)!*i* = *map* (*Gmult* (−*gs*!*i*) ∘ *T*) *as*
⟨*proof*⟩

end

5.2 Locale and basic facts

locale *FGModule* = *ActingGroup?*: *Group G*
+ *FGMod?*: *RModule ActingGroup.group-ring smult V*
for *G* :: $'g$::*group-add set*
and *smult* :: ($'f$::*field*, $'g$) *aezfun* ⇒ $'v$::*ab-group-add* ⇒ $'v$ (**infixr** ‹·› *70*)
and *V* :: $'v$ *set*

sublocale *FGModule* < *aezfun-scalar-mult* ⟨*proof*⟩

lemma (**in** *Group*) *trivial-FGModule* :
fixes *smult* :: ($'f$::*field*, $'g$) *aezfun* ⇒ $'v$::*ab-group-add* ⇒ $'v$
assumes *smult-zero*: ∀ *a*∈*group-ring*. *smult a* (*0*::$'v$) = *0*
shows *FGModule G smult* (*0*::$'v$ *set*)
⟨*proof*⟩

context *FGModule*
begin

abbreviation *FG* :: (*'f*,*'g*) *aezfun set* **where** *FG* ≡ *ActingGroup.group-ring*
abbreviation *FGSubmodule* ≡ *RSubmodule*
abbreviation *FG-proj* ≡ *ActingGroup.RG-proj*

lemma *GroupG*: *Group G* ⟨*proof*⟩

lemmas *zero-closed* = *zero-closed*
lemmas *neg-closed* = *neg-closed*
lemmas *diff-closed* = *diff-closed*
lemmas *zero-smult* = *zero-smult*
lemmas *smult-zero* = *smult-zero*
lemmas *AbGroup* = *AbGroup*
lemmas *sum-closed* = *AbGroup.sum-closed*[*OF AbGroup*]
lemmas *FGSubmoduleI* = *RSubmoduleI*
lemmas *FG-proj-mult-leftdelta* = *ActingGroup.RG-proj-mult-leftdelta*
lemmas *FG-proj-mult-right* = *ActingGroup.RG-proj-mult-right*
lemmas *FG-el-decomp* = *ActingGroup.RG-el-decomp-aezdeltafun*

lemma *FG-n0*: *FG* ≠ *0* ⟨*proof*⟩

lemma *FG-proj-in-FG* : *FG-proj x* ∈ *FG*
⟨*proof*⟩

lemma *FG-fddg-closed* : *g* ∈ *G* ⟹ *a δδ g* ∈ *FG*
⟨*proof*⟩

lemma *FG-fdd0-closed* : *a δδ 0* ∈ *FG*
⟨*proof*⟩

lemma *Gmult-closed* : *g* ∈ *G* ⟹ *v* ∈ *V* ⟹ *g* ∗· *v* ∈ *V*
⟨*proof*⟩

lemma *map-Gmult-closed* :
g ∈ *G* ⟹ *set vs* ⊆ *V* ⟹ *set* (*map* ((∗·) *g*) *vs*) ⊆ *V*
⟨*proof*⟩

lemma *Gmult0* :
assumes *v* ∈ *V*
shows *0* ∗· *v* = *v*
⟨*proof*⟩

lemma *Gmult-assoc* :
assumes *g* ∈ *G h* ∈ *G v* ∈ *V*
shows *g* ∗· *h* ∗· *v* = (*g* + *h*) ∗· *v*
⟨*proof*⟩

lemma *Gmult-distrib-left* :
⟦ *g* ∈ *G*; *v* ∈ *V*; *v'* ∈ *V* ⟧ ⟹ *g* ∗· (*v* + *v'*) = *g* ∗· *v* + *g* ∗· *v'*

⟨*proof*⟩

lemma *neg-Gmult* : $g \in G \Longrightarrow v \in V \Longrightarrow g *\cdot (- v) = - (g *\cdot v)$
⟨*proof*⟩

lemma *Gmult-neg-left* : $g \in G \Longrightarrow v \in V \Longrightarrow (- g) *\cdot g *\cdot v = v$
⟨*proof*⟩

lemma *fddg-smult-decomp* : $g \in G \Longrightarrow v \in V \Longrightarrow (f\ \delta\delta\ g) \cdot v = f \sharp\cdot g *\cdot v$
⟨*proof*⟩

lemma *sum-list-aezdeltafun-smult-distrib* :
assumes $v \in V$ *set* (*map snd fgs*) $\subseteq G$
shows $(\sum (f,g) \leftarrow fgs.\ f\ \delta\delta\ g) \cdot v = (\sum (f,g) \leftarrow fgs.\ f \sharp\cdot g *\cdot v)$
⟨*proof*⟩

abbreviation *GSubspace* ≡ *RSubmodule*
abbreviation *GSpan* ≡ *RSpan*
abbreviation *G-fingen* ≡ *R-fingen*

lemma *GSubspaceI* : *FGModule G smult U* $\Longrightarrow U \subseteq V \Longrightarrow$ *GSubspace U*
⟨*proof*⟩

lemma *GSubspace-is-FGModule* :
assumes *GSubspace U*
shows *FGModule G smult U*
⟨*proof*⟩

lemma *restriction-to-subgroup-is-module* :
fixes $H :: 'g\ set$
assumes *subgrp*: *Group.Subgroup G H*
shows *FGModule H smult V*
⟨*proof*⟩

lemma *negGorbit-list-V* :
assumes *set gs* $\subseteq G$ *T* ‘ (*set as*) $\subseteq V$
shows *set* (*concat* (*negGorbit-list gs T as*)) $\subseteq V$
⟨*proof*⟩

lemma *negGorbit-list-Cons0* :
T ‘ (*set as*) $\subseteq V$
$\Longrightarrow$ *negGorbit-list* (*0#gs*) *T as* = (*map T as*) # (*negGorbit-list gs T as*)
⟨*proof*⟩

end

5.3 Modules over a group ring as a vector spaces

context *FGModule*

begin

lemma *fVectorSpace* : *VectorSpace fsmult V*
⟨*proof*⟩

abbreviation *fSubspace* ≡ *VectorSpace.Subspace fsmult V*
abbreviation *fbasis-for* ≡ *fscalar-mult.basis-for fsmult*
abbreviation *fdim* ≡ *scalar-mult.dim fsmult V*

lemma *VectorSpace-fSubspace* : *fSubspace W* ⟹ *VectorSpace fsmult W*
⟨*proof*⟩

lemma *fsmult-closed* : *v* ∈ *V* ⟹ *a* ♯· *v* ∈ *V*
⟨*proof*⟩

lemmas *one-fsmult* [*simp*] = *VectorSpace.one-smult* [*OF fVectorSpace*]
lemmas *fsmult-assoc* [*simp*] = *VectorSpace.smult-assoc* [*OF fVectorSpace*]
lemmas *fsmult-zero* [*simp*] = *VectorSpace.smult-zero* [*OF fVectorSpace*]
lemmas *fsmult-distrib-left* [*simp*] = *VectorSpace.smult-distrib-left*
[*OF fVectorSpace*]
lemmas *flincomb-closed* = *VectorSpace.lincomb-closed* [*OF fVectorSpace*]
lemmas *fsmult-sum-distrib* = *VectorSpace.smult-sum-distrib* [*OF fVectorSpace*]
lemmas *sum-fsmult-distrib* = *VectorSpace.sum-smult-distrib* [*OF fVectorSpace*]
lemmas *flincomb-concat* = *VectorSpace.lincomb-concat* [*OF fVectorSpace*]
lemmas *fSpan-closed* = *VectorSpace.Span-closed* [*OF fVectorSpace*]
lemmas *flin-independentD-all-scalars*
= *VectorSpace.lin-independentD-all-scalars*[*OF fVectorSpace*]
lemmas *in-fSpan-obtain-same-length-coeffs*
= *VectorSpace.in-Span-obtain-same-length-coeffs* [*OF fVectorSpace*]

lemma *fsmult-smult-comm* : *r* ∈ *FG* ⟹ *v* ∈ *V* ⟹ *a* ♯· *r* · *v* = *r* · *a* ♯· *v*
⟨*proof*⟩

lemma *fsmult-Gmult-comm* : *g* ∈ *G* ⟹ *v* ∈ *V* ⟹ *a* ♯· *g* ∗· *v* = *g* ∗· *a* ♯· *v*
⟨*proof*⟩

lemma *Gmult-flincomb-comm* :
assumes *g* ∈ *G set vs* ⊆ *V*
shows *g* ∗· *as* ·♯· *vs* = *as* ·♯· (*map* (*Gmult g*) *vs*)
⟨*proof*⟩

lemma *GSubspace-is-Subspace* :
GSubspace U ⟹ *VectorSpace.Subspace fsmult V U*
⟨*proof*⟩

end

5.4 Homomorphisms of modules over a group ring

5.4.1 Locales

locale *FGModuleHom* = *ActingGroup?*: *Group G*
+ *RModHom?*: *RModuleHom ActingGroup.group-ring smult V smult′ T*
  for *G* :: *'g*::*group-add set*
  and *smult* :: (*'f*::*field*, *'g*) *aezfun* ⇒ *'v*::*ab-group-add* ⇒ *'v* (**infixr** ‹·› *70*)
  and *V* :: *'v set*
  and *smult′* :: (*'f*, *'g*) *aezfun* ⇒ *'w*::*ab-group-add* ⇒ *'w* (**infixr** ‹⋆› *70*)
  and *T* :: *'v* ⇒ *'w*

sublocale *FGModuleHom* < *FGModule* ⟨*proof*⟩

lemma (**in** *FGModule*) *FGModuleHomI-fromaxioms* :
  assumes ⋀*v v′*. *v* ∈ *V* ⟹ *v′* ∈ *V* ⟹ *T* (*v* + *v′*) = *T v* + *T v′*
    supp T ⊆ *V* ⋀*r m*. *r* ∈ *FG* ⟹ *m* ∈ *V* ⟹ *T* (*r* · *m*) = *smult′ r* (*T m*)
  shows *FGModuleHom G smult V smult′ T*
  ⟨*proof*⟩

locale *FGModuleEnd* = *FGModuleHom G smult V smult T*
  for *G* :: *'g*::*group-add set*
  and *FG* :: (*'f*::*field*,*'g*) *aezfun set*
  and *smult* :: (*'f*, *'g*) *aezfun* ⇒ *'v*::*ab-group-add* ⇒ *'v* (**infixr** ‹·› *70*)
  and *V* :: *'v set*
  and *T* :: *'v* ⇒ *'v*
+ **assumes** *endomorph*: *ImG* ⊆ *V*

locale *FGModuleIso* = *FGModuleHom G smult V smult′ T*
  for *G* :: *'g*::*group-add set*
  and *smult* :: (*'f*::*field*, *'g*) *aezfun* ⇒ *'v*::*ab-group-add* ⇒ *'v* (**infixr** ‹·› *70*)
  and *V* :: *'v set*
  and *smult′* :: (*'f*, *'g*) *aezfun* ⇒ *'w*::*ab-group-add* ⇒ *'w* (**infixr** ‹⋆› *70*)
  and *T* :: *'v* ⇒ *'w*
+ **fixes** *W* :: *'w set*
  assumes *bijective*: *bij-betw T V W*

abbreviation (**in** *FGModule*) *isomorphic* ::
  ((*'f*,*'g*) *aezfun* ⇒ *'w*::*ab-group-add* ⇒ *'w*) ⇒ *'w set* ⇒ *bool*
  where *isomorphic smult′ W* ≡ (∃ *T*. *FGModuleIso G smult V smult′ T W*)

5.4.2 Basic facts

context *FGModule*
begin

lemma *trivial-FGModuleHom* :
  assumes ⋀*r*. *r* ∈ *FG* ⟹ *smult′ r 0* = *0*
  shows *FGModuleHom G smult V smult′ 0*
⟨*proof*⟩

lemma *FGModHom-idhom* : *FGModuleHom G smult V smult* (*id*↓*V*)
⟨*proof*⟩

lemma *VecHom-GMap-is-FGModuleHom* :
fixes *smult′* :: ('*f*, '*g*) *aezfun* ⇒ '*w*::*ab-group-add* ⇒ '*w* (**infixr** ‹⋆› 70)
and *fsmult′* :: '*f* ⇒ '*w* ⇒ '*w* (**infixr** ‹♯⋆› 70)
and *Gmult′* :: '*g* ⇒ '*w* ⇒ '*w* (**infixr** ‹∗⋆› 70)
defines *fsmult′*: *fsmult′* ≡ *aezfun-scalar-mult.fsmult smult′*
and *Gmult′* : *Gmult′* ≡ *aezfun-scalar-mult.Gmult smult′*
assumes *hom* : *VectorSpaceHom fsmult V fsmult′ T*
and *Im-W* : *FGModule G smult′ W T ‘ V* ⊆ *W*
and *G-map* : ⋀*g v*. *g* ∈ *G* ⟹ *v* ∈ *V* ⟹ *T* (*g* ∗· *v*) = *g* ⋆∗ (*T v*)
shows *FGModuleHom G smult V smult′ T*
⟨*proof*⟩

lemma *VecHom-GMap-on-fbasis-is-FGModuleHom* :
fixes *smult′* :: ('*f*, '*g*) *aezfun* ⇒ '*w*::*ab-group-add* ⇒ '*w* (**infixr** ‹⋆› 70)
and *fsmult′* :: '*f* ⇒ '*w* ⇒ '*w* (**infixr** ‹♯⋆› 70)
and *Gmult′* :: '*g* ⇒ '*w* ⇒ '*w* (**infixr** ‹∗⋆› 70)
and *flincomb′* :: '*f list* ⇒ '*w list* ⇒ '*w* (**infixr** ‹·♯⋆› 70)
defines *fsmult′* : *fsmult′* ≡ *aezfun-scalar-mult.fsmult smult′*
and *Gmult′* : *Gmult′* ≡ *aezfun-scalar-mult.Gmult smult′*
and *flincomb′* : *flincomb′* ≡ *aezfun-scalar-mult.flincomb smult′*
assumes *fbasis* : *fbasis-for V vs*
and *hom* : *VectorSpaceHom fsmult V fsmult′ T*
and *Im-W* : *FGModule G smult′ W T ‘ V* ⊆ *W*
and *G-map* : ⋀*g v*. *g* ∈ *G* ⟹ *v* ∈ *set vs* ⟹ *T* (*g* ∗· *v*) = *g* ⋆∗ (*T v*)
shows *FGModuleHom G smult V smult′ T*
⟨*proof*⟩

end

context *FGModuleHom*
begin

abbreviation *fsmult′* :: '*f* ⇒ '*w* ⇒ '*w* (**infixr** ‹♯⋆› 70)
where *fsmult′* ≡ *aezfun-scalar-mult.fsmult smult′*
abbreviation *Gmult′* :: '*g* ⇒ '*w* ⇒ '*w* (**infixr** ‹∗⋆› 70)
where *Gmult′* ≡ *aezfun-scalar-mult.Gmult smult′*

lemmas *supp* = *supp*
lemmas *additive* = *additive*
lemmas *FG-map* = *R-map*
lemmas *FG-fdd0-closed* = *FG-fdd0-closed*
lemmas *fsmult-smult-domain-comm* = *fsmult-smult-comm*
lemmas *GSubspace-Ker* = *RSubmodule-Ker*
lemmas *Ker-Im-iff* = *Ker-Im-iff*
lemmas *Ker0-imp-inj-on* = *Ker0-imp-inj-on*

lemmas *eq-im-imp-diff-in-Ker* = *eq-im-imp-diff-in-Ker*
lemmas *im-submodule* = *im-submodule*
lemmas *fsmultD'* = *aezfun-scalar-mult.fsmultD*[*of smult'*]
lemmas *GmultD'* = *aezfun-scalar-mult.GmultD*[*of smult'*]

lemma *f-map* : $v \in V \Longrightarrow T\ (a\ \sharp\cdot\ v) = a\ \sharp\star\ T\ v$
⟨*proof*⟩

lemma *G-map* : $g \in G \Longrightarrow v \in V \Longrightarrow T\ (g\ *\cdot\ v) = g\ **\star\ T\ v$
⟨*proof*⟩

lemma *VectorSpaceHom* : *VectorSpaceHom fsmult V fsmult' T*
⟨*proof*⟩

lemmas *distrib-flincomb* = *VectorSpaceHom.distrib-lincomb*[*OF VectorSpaceHom*]

lemma *FGModule-Im* : *FGModule G smult' ImG*
⟨*proof*⟩

lemma *FGModHom-composite-left* :
assumes *FGModuleHom G smult' W smult'' S T* ‘ $V \subseteq W$
shows *FGModuleHom G smult V smult'' (S* ∘ *T)*
⟨*proof*⟩

lemma *restriction-to-subgroup-is-hom* :
fixes *H* :: *'g set*
assumes *subgrp*: *Group.Subgroup G H*
shows *FGModuleHom H smult V smult' T*
⟨*proof*⟩

lemma *FGModuleHom-restrict0-GSubspace* :
assumes *GSubspace U*
shows *FGModuleHom G smult U smult' (T* ↓ *U)*
⟨*proof*⟩

lemma *FGModuleHom-fscalar-mul* :
FGModuleHom G smult V smult' (λ*v. a* ♯⋆ *T v*)
⟨*proof*⟩

end

lemma *GSubspace-eigenspace* :
fixes *e* :: *'f*::*field*
and *E* :: *'v*::*ab-group-add set*
and *smult* :: (*'f*::*field*, *'g*::*group-add*) *aezfun* ⇒ *'v* ⇒ *'v* (**infixr** ‹·› *70*)
assumes *FGModHom*: *FGModuleHom G smult V smult T*
defines *E* : $E \equiv \{v \in V.\ T\ v = aezfun\text{-}scalar\text{-}mult.fsmult\ smult\ e\ v\}$
shows *FGModule.GSubspace G smult V E*
⟨*proof*⟩

5.4.3 Basic facts about endomorphisms

lemma *RModuleEnd-over-group-ring-is-FGModuleEnd* :
fixes G :: $'g$::*group-add set*
and *smult* :: ($'f$::*field*, $'g$) *aezfun* ⇒ $'v$::*ab-group-add* ⇒ $'v$
assumes *G* : *Group G* **and** *endo*: *RModuleEnd* (*Group.group-ring G*) *smult V T*
shows *FGModuleEnd G smult V T*
⟨*proof*⟩

lemma (**in** *FGModule*) *VecEnd-GMap-is-FGModuleEnd* :
assumes *endo* : *VectorSpaceEnd fsmult V T*
and *G-map*: ⋀*g v*. *g* ∈ *G* ⟹ *v* ∈ *V* ⟹ *T* (*g* ∗· *v*) = *g* ∗· (*T v*)
shows *FGModuleEnd G smult V T*
⟨*proof*⟩

lemma (**in** *FGModule*) *GEnd-inner-dirsum-el-decomp-nth* :
⟦ ∀ *U*∈*set Us*. *GSubspace U*; *add-independentS Us*; *n* < *length Us* ⟧
⟹ *FGModuleEnd G smult* (⨁ *U*←*Us*. *U*) (⨁ *Us*↓*n*)
⟨*proof*⟩

context *FGModuleEnd*
begin

lemma *RModuleEnd* : *RModuleEnd ActingGroup.group-ring smult V T*
⟨*proof*⟩

lemma *VectorSpaceEnd* : *VectorSpaceEnd fsmult V T*
⟨*proof*⟩

lemmas *proj-decomp* = *RModuleEnd.proj-decomp*[*OF RModuleEnd*]
lemmas *GSubspace-Ker* = *GSubspace-Ker*
lemmas *FGModuleHom-restrict0-GSubspace* = *FGModuleHom-restrict0-GSubspace*

end

5.4.4 Basic facts about isomorphisms

context *FGModuleIso*
begin

lemmas *VectorSpaceHom* = *VectorSpaceHom*

abbreviation *invT* ≡ (*the-inv-into V T*) ↓ *W*

lemma *RModuleIso* : *RModuleIso FG smult V smult′ T W*
⟨*proof*⟩

lemmas *ImG* = *RModuleIso.ImG*[*OF RModuleIso*]

lemma *FGModuleIso-restrict0-GSubspace* :

assumes *GSubspace U*
shows *FGModuleIso G smult U smult' (T ↓ U) (T ‘ U)*
⟨*proof*⟩

lemma *inv* : *FGModuleIso G smult' W smult invT V*
⟨*proof*⟩

lemma *FGModIso-composite-left* :
assumes *FGModuleIso G smult' W smult'' S X*
shows *FGModuleIso G smult V smult'' (S ∘ T) X*
⟨*proof*⟩

lemma *isomorphic-sym* : *FGModule.isomorphic G smult' W smult V*
⟨*proof*⟩

lemma *isomorphic-trans* :
FGModule.isomorphic G smult' W smult'' X
⟹ *FGModule.isomorphic G smult V smult'' X*
⟨*proof*⟩

lemma *isomorphic-to-zero-left* : *V = 0 ⟹ W = 0*
⟨*proof*⟩

lemma *isomorphic-to-zero-right* : *W = 0 ⟹ V = 0*
⟨*proof*⟩

lemma *isomorphic-to-irr-right'* :
assumes ⋀*U*. *FGModule.GSubspace G smult' W U ⟹ U = 0 ∨ U = W*
shows ⋀*U*. *GSubspace U ⟹ U = 0 ∨ U = V*
⟨*proof*⟩

end

context *FGModule*
begin

lemma *isomorphic-sym* :
isomorphic smult' W ⟹ FGModule.isomorphic G smult' W smult V
⟨*proof*⟩

lemma *isomorphic-trans* :
isomorphic smult' W ⟹ FGModule.isomorphic G smult' W smult'' X
⟹ *isomorphic smult'' X*
⟨*proof*⟩

lemma *isomorphic-to-zero-left* : *V = 0 ⟹ isomorphic smult' W ⟹ W = 0*
⟨*proof*⟩

lemma *isomorphic-to-zero-right* : *isomorphic smult' 0 ⟹ V = 0*

⟨*proof*⟩

lemma *FGModIso-idhom* : *FGModuleIso G smult V smult* (*id*↓*V*) *V*
⟨*proof*⟩

lemma *isomorphic-refl* : *isomorphic smult V* ⟨*proof*⟩

end

5.4.5 Hom-sets

definition *FGModuleHomSet* ::
'g::*group-add set* ⇒ ((*'f*::*field*,*'g*) *aezfun* ⇒ *'v*::*ab-group-add* ⇒ *'v*) ⇒ *'v set*
⇒ ((*'f*,*'g*) *aezfun* ⇒ *'w*::*ab-group-add* ⇒ *'w*) ⇒ *'w set*
⇒ (*'v* ⇒ *'w*) *set*
where *FGModuleHomSet G fgsmult V fgsmult' W*
≡ {*T*. *FGModuleHom G fgsmult V fgsmult' T*} ∩ {*T*. *T* ‘ *V* ⊆ *W*}

lemma *FGModuleHomSetI* :
FGModuleHom G fgsmult V fgsmult' T ⟹ *T* ‘ *V* ⊆ *W*
⟹ *T* ∈ *FGModuleHomSet G fgsmult V fgsmult' W*
⟨*proof*⟩

lemma *FGModuleHomSetD-FGModuleHom* :
T ∈ *FGModuleHomSet G fgsmult V fgsmult' W*
⟹ *FGModuleHom G fgsmult V fgsmult' T*
⟨*proof*⟩

lemma *FGModuleHomSetD-Im* :
T ∈ *FGModuleHomSet G fgsmult V fgsmult' W* ⟹ *T* ‘ *V* ⊆ *W*
⟨*proof*⟩

context *FGModule*
begin

lemma *FGModuleHomSet-is-Gmaps-in-VectorSpaceHomSet* :
fixes *smult'* :: (*'f*, *'g*) *aezfun* ⇒ *'w*::*ab-group-add* ⇒ *'w* (**infixr** ‹⋆› *70*)
and *fsmult'* :: *'f* ⇒ *'w* ⇒ *'w* (**infixr** ‹♯⋆› *70*)
and *Gmult'* :: *'g* ⇒ *'w* ⇒ *'w* (**infixr** ‹∗⋆› *70*)
defines *fsmult'* : *fsmult'* ≡ *aezfun-scalar-mult.fsmult smult'*
and *Gmult'* : *Gmult'* ≡ *aezfun-scalar-mult.Gmult smult'*
assumes *FGModW* : *FGModule G smult' W*
shows *FGModuleHomSet G smult V smult' W*
= (*VectorSpaceHomSet fsmult V fsmult' W*)
∩ {*T*. ∀ *g*∈*G*. ∀ *v*∈*V*. *T* (*g* ∗· *v*) = *g* ∗⋆ (*T v*)}
⟨*proof*⟩

lemma *Group-FGModuleHomSet* :
fixes *smult'* :: (*'f*, *'g*) *aezfun* ⇒ *'w*::*ab-group-add* ⇒ *'w* (**infixr** ‹⋆› *70*)

and *fsmult'* :: *'f* ⇒ *'w* ⇒ *'w* (**infixr** ‹♯⋆› *70*)
and *Gmult'* :: *'g* ⇒ *'w* ⇒ *'w* (**infixr** ‹∗⋆› *70*)
defines *fsmult'* : *fsmult' ≡ aezfun-scalar-mult.fsmult smult'*
and *Gmult'* : *Gmult' ≡ aezfun-scalar-mult.Gmult smult'*
assumes *FGModW* : *FGModule G smult' W*
shows *Group* (*FGModuleHomSet G smult V smult' W*)
⟨*proof*⟩

lemma *Subspace-FGModuleHomSet* :
fixes *smult'* :: (*'f*, *'g*) *aezfun* ⇒ *'w*::*ab-group-add* ⇒ *'w* (**infixr** ‹⋆› *70*)
and *fsmult'* :: *'f* ⇒ *'w* ⇒ *'w* (**infixr** ‹♯⋆› *70*)
and *Gmult'* :: *'g* ⇒ *'w* ⇒ *'w* (**infixr** ‹∗⋆› *70*)
and *hom-fsmult* :: *'f* ⇒ (*'v* ⇒ *'w*) ⇒ (*'v* ⇒ *'w*) (**infixr** ‹♯⋆·› *70*)
defines *fsmult'* : *fsmult' ≡ aezfun-scalar-mult.fsmult smult'*
and *Gmult'* : *Gmult' ≡ aezfun-scalar-mult.Gmult smult'*
defines *hom-fsmult* : *hom-fsmult ≡ λa T v. a ♯⋆ T v*
assumes *FGModW* : *FGModule G smult' W*
shows *VectorSpace.Subspace hom-fsmult*
(*VectorSpaceHomSet fsmult V fsmult' W*)
(*FGModuleHomSet G smult V smult' W*)
⟨*proof*⟩

lemma *VectorSpace-FGModuleHomSet* :
fixes *smult'* :: (*'f*, *'g*) *aezfun* ⇒ *'w*::*ab-group-add* ⇒ *'w* (**infixr** ‹⋆› *70*)
and *fsmult'* :: *'f* ⇒ *'w* ⇒ *'w* (**infixr** ‹♯⋆› *70*)
and *hom-fsmult* :: *'f* ⇒ (*'v* ⇒ *'w*) ⇒ (*'v* ⇒ *'w*) (**infixr** ‹♯⋆·› *70*)
defines *fsmult' ≡ aezfun-scalar-mult.fsmult smult'*
defines *hom-fsmult ≡ λa T v. a ♯⋆ T v*
assumes *FGModule G smult' W*
shows *VectorSpace hom-fsmult* (*FGModuleHomSet G smult V smult' W*)
⟨*proof*⟩

end

5.5 Induced modules

5.5.1 Additive function spaces

definition *addfunset* ::
'a::*monoid-add set* ⇒ *'m*::*monoid-add set* ⇒ (*'a* ⇒ *'m*) *set*
where *addfunset A M* ≡ {*f*. *supp f* ⊆ *A* ∧ *range f* ⊆ *M*
∧ (∀ *x*∈*A*. ∀ *y*∈*A*. *f* (*x*+*y*) = *f x* + *f y*) }

lemma *addfunsetI* :
⟦ *supp f* ⊆ *A*; *range f* ⊆ *M*; ∀ *x*∈*A*. ∀ *y*∈*A*. *f* (*x*+*y*) = *f x* + *f y* ⟧
⟹ *f* ∈ *addfunset A M*
⟨*proof*⟩

lemma *addfunsetD-supp* : *f* ∈ *addfunset A M* ⟹ *supp f* ⊆ *A*
⟨*proof*⟩

lemma *addfunsetD-range* : $f \in addfunset\ A\ M \Longrightarrow range\ f \subseteq M$
⟨*proof*⟩

lemma *addfunsetD-range'* : $f \in addfunset\ A\ M \Longrightarrow f\ x \in M$
⟨*proof*⟩

lemma *addfunsetD-add* :
$[\![f \in addfunset\ A\ M;\ x{\in}A;\ y{\in}A\ ]\!] \Longrightarrow f\ (x{+}y) = f\ x + f\ y$
⟨*proof*⟩

lemma *addfunset0* : $addfunset\ A\ (0{::}'m{::}monoid\text{-}add\ set) = 0$
⟨*proof*⟩

lemma *Group-addfunset* :
fixes $M{::}'g{::}ab\text{-}group\text{-}add\ set$
assumes $Group\ M$
shows $Group\ (addfunset\ R\ M)$
⟨*proof*⟩

5.5.2 Spaces of functions which transform under scalar multiplication by almost-everywhere-zero functions

context *aezfun-scalar-mult*
begin

definition *smultfunset* :: $'g\ set \Rightarrow ('r,'g)\ aezfun\ set \Rightarrow (('r,'g)\ aezfun \Rightarrow 'v)\ set$
where $smultfunset\ G\ FH \equiv \{f.\ (\forall\, a{::}'r.\ \forall\, g{\in}G.\ \forall\, x{\in}FH.$
$f\ (\ a\ \delta\delta\ g * x\ ) = (a\ \delta\delta\ g) \cdot (f\ x))\}$

lemma *smultfunsetD* :
$[\![f \in smultfunset\ G\ FH;\ g{\in}G;\ x{\in}FH\ ]\!] \Longrightarrow f\ (\ a\ \delta\delta\ g * x\ ) = (a\ \delta\delta\ g) \cdot (f\ x)$
⟨*proof*⟩

lemma *smultfunsetI* :
$\forall\, a{::}'r.\ \forall\, g{\in}G.\ \forall\, x{\in}FH.\ f\ (\ a\ \delta\delta\ g * x\ ) = (a\ \delta\delta\ g) \cdot (f\ x)$
$\Longrightarrow f \in smultfunset\ G\ FH$
⟨*proof*⟩

end

5.5.3 General induced spaces of functions on a group ring

context *aezfun-scalar-mult*
begin

definition *indspace* ::
$'g\ set \Rightarrow ('r,'g)\ aezfun\ set \Rightarrow 'v\ set \Rightarrow (('r,'g)\ aezfun \Rightarrow 'v)\ set$
where $indspace\ G\ FH\ V = addfunset\ FH\ V \cap smultfunset\ G\ FH$

lemma *indspaceD* :
$f \in indspace\ G\ FH\ V \Longrightarrow f \in addfunset\ FH\ V \cap smultfunset\ G\ FH$
⟨*proof*⟩

lemma *indspaceD-supp* : $f \in indspace\ G\ FH\ V \Longrightarrow supp\ \ f \subseteq FH$
⟨*proof*⟩

lemma *indspaceD-supp'* : $f \in indspace\ G\ FH\ V \Longrightarrow x \notin FH \Longrightarrow f\ x = 0$
⟨*proof*⟩

lemma *indspaceD-range* : $f \in indspace\ G\ FH\ V \Longrightarrow range\ f \subseteq V$
⟨*proof*⟩

lemma *indspaceD-range'*: $f \in indspace\ G\ FH\ V \Longrightarrow f\ x \in V$
⟨*proof*⟩

lemma *indspaceD-add* :
$[\![f \in indspace\ G\ FH\ V;\ x{\in}FH;\ y{\in}FH\ ]\!] \Longrightarrow f\ (x{+}y) = f\ x + f\ y$
⟨*proof*⟩

lemma *indspaceD-transform* :
$[\![f \in indspace\ G\ FH\ V;\ g{\in}G;\ x{\in}FH\ ]\!] \Longrightarrow f\ (\ a\ \delta\delta\ g * x\ ) = (a\ \delta\delta\ g) \cdot (f\ x)$
⟨*proof*⟩

lemma *indspaceI* :
$f \in addfunset\ FH\ V \Longrightarrow f \in smultfunset\ G\ FH \Longrightarrow f \in indspace\ G\ FH\ V$
⟨*proof*⟩

lemma *indspaceI'* :
$[\![\ supp\ f \subseteq FH;\ range\ f \subseteq V;\ \forall\, x{\in}FH.\ \forall\, y{\in}FH.\ f\ (x{+}y) = f\ x + f\ y;$
$\forall\, a{::}'r.\ \forall\, g{\in}G.\ \forall\, x{\in}FH.\ f\ (\ a\ \delta\delta\ g * x\ ) = (a\ \delta\delta\ g) \cdot (f\ x)\ ]\!]$
$\Longrightarrow f \in indspace\ G\ FH\ V$
⟨*proof*⟩

lemma *mono-indspace* : *mono* (*indspace G FH*)
⟨*proof*⟩

end

context *FGModule*
begin

lemma *zero-transforms* : $0 \in smultfunset\ G\ FH$
⟨*proof*⟩

lemma *indspace0* : $indspace\ G\ FH\ 0 = 0$
⟨*proof*⟩

lemma *Group-indspace* :

assumes *Ring1 FH*
shows *Group* (*indspace G FH V*)
⟨*proof*⟩

end

5.5.4 The right regular action

context *Ring1*
begin

definition *rightreg-scalar-mult* ::
'r::*ring-1* ⇒ (*'r* ⇒ *'m*::*ab-group-add*) ⇒ (*'r* ⇒ *'m*) (**infixr** ‹¤› *70*)
where *rightreg-scalar-mult r f* = (λ*x*. *if x* ∈ *R then f* (*x*∗*r*) *else 0*)

lemma *rightreg-scalar-multD1* : *x* ∈ *R* ⟹ (*r* ¤ *f*) *x* = *f* (*x*∗*r*)
⟨*proof*⟩

lemma *rightreg-scalar-multD2* : *x* ∉ *R* ⟹ (*r* ¤ *f*) *x* = *0*
⟨*proof*⟩

lemma *rrsmult-supp* : *supp* (*r* ¤ *f*) ⊆ *R*
⟨*proof*⟩

lemma *rrsmult-range* : *range* (*r* ¤ *f*) ⊆ {*0*} ∪ *range f*
⟨*proof*⟩

lemma *rrsmult-distrib-left* : *r* ¤ (*f* + *g*) = *r* ¤ *f* + *r* ¤ *g*
⟨*proof*⟩

lemma *rrsmult-distrib-right* :
assumes ⋀*x y*. *x* ∈ *R* ⟹ *y* ∈ *R* ⟹ *f* (*x*+*y*) = *f x* + *f y r* ∈ *R s* ∈ *R*
shows (*r* + *s*) ¤ *f* = *r* ¤ *f* + *s* ¤ *f*
⟨*proof*⟩

lemma *RModule-addfunset* :
fixes *M*::*'g*::*ab-group-add set*
assumes *Group M*
shows *RModule R rightreg-scalar-mult* (*addfunset R M*)
⟨*proof*⟩

end

5.5.5 Locale and basic facts

In the following locale, G is a subgroup of H, V is a module over the group ring for G, and the induced space $indV$ will be shown to be a module over the group ring for H under the right regular scalar multiplication *rrsmult*.

locale *InducedFHModule* = *Supgroup?*: *Group H*

+ *BaseFGMod?* : *FGModule G smult V*
+ *induced-smult?*: *aezfun-scalar-mult rrsmult*
  for *H* :: *'g*::*group-add set*
  and *G* :: *'g set*
  and *FG* :: (*'f*::*field*, *'g*) *aezfun set*
  and *smult* :: (*'f*, *'g*) *aezfun* ⇒ *'v*::*ab-group-add* ⇒ *'v* (**infixl** ‹·› *70*)
  and *V* :: *'v set*
  and *rrsmult* :: (*'f*,*'g*) *aezfun* ⇒ ((*'f*,*'g*) *aezfun* ⇒ *'v*) ⇒ ((*'f*,*'g*) *aezfun* ⇒ *'v*)
    (**infixl** ‹¤› *70*)
+ **fixes** *FH* :: (*'f*, *'g*) *aezfun set*
  and *indV* :: ((*'f*, *'g*) *aezfun* ⇒ *'v*) *set*
  defines *FH* : *FH* ≡ *Supgroup.group-ring*
  and *indV* : *indV* ≡ *BaseFGMod.indspace G FH V*
  assumes *rrsmult* : *rrsmult* = *Ring1.rightreg-scalar-mult FH*
  and *Subgroup*: *Supgroup.Subgroup G*
begin

abbreviation *indfsmult* ::
  'f ⇒ ((*'f*, *'g*) *aezfun* ⇒ *'v*) ⇒ ((*'f*, *'g*) *aezfun* ⇒ *'v*) (**infixl** ‹¤¤› *70*)
  where *indfsmult* ≡ *induced-smult.fsmult*
abbreviation *indftincomb* ::
  'f list ⇒ ((*'f*, *'g*) *aezfun* ⇒ *'v*) *list* ⇒ ((*'f*, *'g*) *aezfun* ⇒ *'v*) (**infixl** ‹·¤¤› *70*)
  where *indftincomb* ≡ *induced-smult.ftincomb*
abbreviation *Hmult* ::
  'g ⇒ ((*'f*, *'g*) *aezfun* ⇒ *'v*) ⇒ ((*'f*, *'g*) *aezfun* ⇒ *'v*) (**infixl** ‹*¤› *70*)
  where *Hmult* ≡ *induced-smult.Gmult*

lemma *Ring1-FH* : *Ring1 FH* ⟨*proof*⟩

lemma *FG-subring-FH* : *Ring1.Subring1 FH BaseFGMod.FG*
  ⟨*proof*⟩

lemma *rrsmultD1* : *x* ∈ *FH* ⟹ (*r* ¤ *f*) *x* = *f* (*x*∗*r*)
  ⟨*proof*⟩

lemma *rrsmultD2* : *x* ∉ *FH* ⟹ (*r* ¤ *f*) *x* = *0*
  ⟨*proof*⟩

lemma *rrsmult-supp* : *supp* (*r* ¤ *f*) ⊆ *FH*
  ⟨*proof*⟩

lemma *rrsmult-range* : *range* (*r* ¤ *f*) ⊆ {*0*} ∪ *range f*
  ⟨*proof*⟩

lemma *FHModule-addfunset* : *FGModule H rrsmult* (*addfunset FH V*)
⟨*proof*⟩

lemma *FHSubmodule-indspace* :
  FGModule.FGSubmodule H rrsmult (*addfunset FH V*) *indV*

⟨*proof*⟩

lemma *FHModule-indspace* : *FGModule H rrsmult indV*
⟨*proof*⟩

lemmas *fVectorSpace-indspace* = *FGModule.fVectorSpace*[*OF FHModule-indspace*]
lemmas *restriction-is-FGModule*
= *FGModule.restriction-to-subgroup-is-module*[*OF FHModule-indspace*]

definition *induced-vector* :: *'v* ⇒ ((*'f*, *'g*) *aezfun* ⇒ *'v*)
where *induced-vector v* ≡ (*if v* ∈ *V*
then (λ*y*. *if y* ∈ *FH then* (*FG-proj y*) · *v else 0*) *else 0*)

lemma *induced-vector-apply1* :
v ∈ *V* ⟹ *x* ∈ *FH* ⟹ *induced-vector v x* = (*FG-proj x*) · *v*
⟨*proof*⟩

lemma *induced-vector-apply2* : *v* ∈ *V* ⟹ *x* ∉ *FH* ⟹ *induced-vector v x* = *0*
⟨*proof*⟩

lemma *induced-vector-indV* :
assumes *v*: *v* ∈ *V*
shows *induced-vector v* ∈ *indV*
⟨*proof*⟩

lemma *induced-vector-additive* :
v ∈ *V* ⟹ *v'* ∈ *V*
⟹ *induced-vector* (*v*+*v'*) = *induced-vector v* + *induced-vector v'*
⟨*proof*⟩

lemma *hom-induced-vector* : *FGModuleHom G smult V rrsmult induced-vector*
⟨*proof*⟩

lemma *indspace-sum-list-fddh*:
⟦ *fhs* ≠ []; *set* (*map snd fhs*) ⊆ *H*; *f* ∈ *indV* ⟧
⟹ *f* (∑ (*a*,*h*)←*fhs*. *a* δδ *h*) = (∑ (*a*,*h*)←*fhs*. *f* (*a* δδ *h*))
⟨*proof*⟩

lemma *induced-fsmult-conv-fsmult-1ddh* :
f ∈ *indV* ⟹ *h* ∈ *H* ⟹ (*r* ¤¤ *f*) (*1* δδ *h*) = *r* ♯· (*f* (*1* δδ *h*))
⟨*proof*⟩

lemma *indspace-el-eq-on-1ddh-imp-eq-on-rddh* :
assumes *HmodG* ⊆ *H H* = (⋃ *h*∈*HmodG*. *G* + {*h*}) *f* ∈ *indV f'* ∈ *indV*
∀ *h*∈*HmodG*. *f* (*1* δδ *h*) = *f'* (*1* δδ *h*) *h* ∈ *H*
shows *f* (*r* δδ *h*) = *f'* (*r* δδ *h*)
⟨*proof*⟩

lemma *indspace-el-eq* :

assumes $HmodG \subseteq H$ $H = (\bigcup h{\in}HmodG.\ G + \{h\})$ $f \in indV$ $f' \in indV$
$\forall\, h{\in}HmodG.\ f\ (1\ \delta\delta\ h) = f'\ (1\ \delta\delta\ h)$
shows $f = f'$
⟨*proof*⟩

lemma *indspace-el-eq'* :
assumes *set hs* $\subseteq H$ $H = (\bigcup h{\in}set\ hs.\ G + \{h\})$ $f \in indV$ $f' \in indV$
$\forall\, i{<}length\ hs.\ f\ (1\ \delta\delta\ (hs!i)) = f'\ (1\ \delta\delta\ (hs!i))$
shows $f = f'$
⟨*proof*⟩

end

6 Representations of Finite Groups

6.1 Locale and basic facts

Define a group representation to be a module over the group ring that is finite-dimensional as a vector space. The only restriction on the characteristic of the field is that it does not divide the order of the group. Also, we don't explicitly assume that the group is finite; instead, the *good-char* assumption implies that the cardinality of G is not zero, which implies G is finite. (See lemma *good-card-imp-finite*.)

locale *FinGroupRepresentation* = *FGModule G smult V*
for *G* :: *'g*::*group-add set*
and *smult* :: (*'f*::*field*, *'g*) *aezfun* ⇒ *'v*::*ab-group-add* ⇒ *'v* (**infixl** ‹·› *70*)
and *V* :: *'v set*
+
assumes *good-char*: *of-nat* (*card G*) ≠ (*0*::*'f*)
and *findim* : *fscalar-mult.findim fsmult V*

lemma (**in** *Group*) *trivial-FinGroupRep* :
fixes *smult* :: (*'f*::*field*, *'g*) *aezfun* ⇒ *'v*::*ab-group-add* ⇒ *'v*
assumes *good-char* : *of-nat* (*card G*) ≠ (*0*::*'f*)
and *smult-zero* : ∀ *a*∈*group-ring*. *smult a* (*0*::*'v*) = *0*
shows *FinGroupRepresentation G smult* (*0*::*'v set*)
⟨*proof*⟩

context *FinGroupRepresentation*
begin

abbreviation *ordG* :: *'f* **where** *ordG* ≡ *of-nat* (*card G*)
abbreviation *GRepHom* ≡ *FGModuleHom G smult V*
abbreviation *GRepIso* ≡ *FGModuleIso G smult V*
abbreviation *GRepEnd* ≡ *FGModuleEnd G smult V*

lemmas *zero-closed* = *zero-closed*
lemmas *Group* = *Group*

lemmas *GSubmodule-GSpan-single* = *RSubmodule-RSpan-single*
lemmas *GSpan-single-nonzero* = *RSpan-single-nonzero*

lemma *finiteG*: *finite G*
⟨*proof*⟩

lemma *FinDimVectorSpace*: *FinDimVectorSpace fsmult V*
⟨*proof*⟩

lemma *GSubspace-is-FinGroupRep* :
assumes *GSubspace U*
shows *FinGroupRepresentation G smult U*
⟨*proof*⟩

lemma *isomorphic-imp-GRep* :
assumes *isomorphic smult′ W*
shows *FinGroupRepresentation G smult′ W*
⟨*proof*⟩

end

6.2 Irreducible representations

locale *IrrFinGroupRepresentation* = *FinGroupRepresentation*
+ **assumes** *irr*: *GSubspace U* ⟹ *U* = *0* ∨ *U* = *V*
begin

lemmas *AbGroup* = *AbGroup*

lemma *zero-isomorphic-to-FG-zero* :
assumes *V* = *0*
shows *isomorphic* (∗) (*0*::('*b*,'*a*) *aezfun set*)
⟨*proof*⟩

lemma *eq-GSpan-single* : *v* ∈ *V* ⟹ *v* ≠ *0* ⟹ *V* = *GSpan* [*v*]
⟨*proof*⟩

end

lemma (**in** *Group*) *trivial-IrrFinGroupRepI* :
fixes *smult* :: ('*f*::*field*, '*g*) *aezfun* ⇒ '*v*::*ab-group-add* ⇒ '*v*
assumes *of-nat* (*card G*) ≠ (*0*::'*f*)
and ∀ *a*∈*group-ring*. *smult a* (*0*::'*v*) = *0*
shows *IrrFinGroupRepresentation G smult* (*0*::'*v set*)
⟨*proof*⟩

lemma (**in** *Group*) *trivial-IrrFinGroupRepresentation-in-FG* :
of-nat (*card G*) ≠ (*0*::'*f*::*field*)
⟹ *IrrFinGroupRepresentation G* (∗) (*0*::('*f*,'*g*) *aezfun set*)

⟨*proof*⟩

context *FinGroupRepresentation*
begin

lemma *IrrFinGroupRep-trivialGSubspace* :
IrrFinGroupRepresentation G smult (*0*::*'v set*)
⟨*proof*⟩

lemma *IrrI* :
assumes $\bigwedge U.$ *FGModule.GSubspace G smult V U* $\Longrightarrow$ $U = 0 \vee U = V$
shows *IrrFinGroupRepresentation G smult V*
⟨*proof*⟩

lemma *notIrr* :
$\neg$ *IrrFinGroupRepresentation G smult V*
$\Longrightarrow \exists U.$ *GSubspace* $U \wedge U \neq 0 \wedge U \neq V$
⟨*proof*⟩

end

6.3 Maschke's theorem

6.3.1 Averaged projection onto a G-subspace

context *FinGroupRepresentation*
begin

lemma *avg-proj-eq-id-on-right* :
assumes *VectorSpace fsmult W add-independentS* $[W,V]$ $v \in V$
defines P : $P \equiv (\bigoplus [W,V]{\downarrow}1)$
defines *CP*: $CP \equiv (\lambda g.\ Gmult\ (-\ g) \circ P \circ Gmult\ g)$
defines T : $T \equiv fsmult\ (1/ordG) \circ (\sum g{\in}G.\ CP\ g)$
shows $T\ v = v$
⟨*proof*⟩

lemma *avg-proj-onto-right* :
assumes *VectorSpace fsmult W GSubspace U add-independentS* $[W,U]$
$V = W \oplus U$
defines P : $P \equiv (\bigoplus [W,U]{\downarrow}1)$
defines *CP*: $CP \equiv (\lambda g.\ Gmult\ (-\ g) \circ P \circ Gmult\ g)$
defines T : $T \equiv fsmult\ (1/ordG) \circ (\sum g{\in}G.\ CP\ g)$
shows T ‘ $V = U$
⟨*proof*⟩

lemma *FGModuleEnd-avg-proj-right* :
assumes *fSubspace W GSubspace U add-independentS* $[W,U]$ $V = W \oplus U$
defines P : $P \equiv (\bigoplus [W,U]{\downarrow}1)$
defines *CP*: $CP \equiv (\lambda g.\ Gmult\ (-\ g) \circ P \circ Gmult\ g)$
defines T : $T \equiv (fsmult\ (1/ordG) \circ (\sum g{\in}G.\ CP\ g)){\downarrow}V$

shows *FGModuleEnd G smult V T*
⟨*proof*⟩

lemma *avg-proj-is-proj-right* :
assumes *VectorSpace fsmult W GSubspace U add-independentS* [*W*,*U*]
$V = W \oplus U$ $v \in V$
defines *P* : $P \equiv (\bigoplus [W,U]\downarrow 1)$
defines *CP*: $CP \equiv (\lambda g.\ Gmult\ (-\ g) \circ P \circ Gmult\ g)$
defines *T* : $T \equiv fsmult\ (1/ordG) \circ (\sum g{\in}G.\ CP\ g)$
shows $T\ (T\ v) = T\ v$
⟨*proof*⟩

end

6.3.2 The theorem

context *FinGroupRepresentation*
begin

theorem *Maschke* :
assumes *GSubspace U*
shows $\exists W.\ GSubspace\ W \wedge V = W \oplus U$
⟨*proof*⟩

corollary *Maschke-proper* :
assumes *GSubspace U* $U \neq 0$ $U \neq V$
shows $\exists W.\ GSubspace\ W \wedge W \neq 0 \wedge W \neq V \wedge V = W \oplus U$
⟨*proof*⟩

end

6.3.3 Consequence: complete reducibility

lemma (**in** *FinGroupRepresentation*) *notIrr-decompose* :
$\neg$ *IrrFinGroupRepresentation G smult V*
$\Longrightarrow \exists U\ W.\ GSubspace\ U \wedge U \neq 0 \wedge U \neq V \wedge GSubspace\ W \wedge W \neq 0$
$\wedge\ W \neq V \wedge V = U \oplus W$
⟨*proof*⟩

In the following decomposition lemma, we do not need to explicitly include the condition that all *U* in *set Us* are subsets of *V*. (See lemma *AbGroup-subset-inner-dirsum.*)

lemma *FinGroupRepresentation-reducible′* :
fixes *n*::*nat*
shows $\bigwedge V.\ FinGroupRepresentation\ G\ fgsmult\ V$
$\wedge\ n = FGModule.fdim\ fgsmult\ V$
$\Longrightarrow (\exists\ Us.\ Ball\ (set\ Us)\ (IrrFinGroupRepresentation\ G\ fgsmult)$
$\wedge\ (0 \notin set\ Us) \wedge V = (\bigoplus U{\leftarrow}Us.\ U)\ )$
⟨*proof*⟩

theorem (**in** *FinGroupRepresentation*) *reducible* :
$\exists\, Us.\ (\forall\, U{\in}set\ Us.\ IrrFinGroupRepresentation\ G\ smult\ U) \wedge (0 \notin set\ Us)$
$\quad \wedge\ V = (\bigoplus U{\leftarrow}Us.\ U)$
⟨*proof*⟩

6.3.4 Consequence: decomposition relative to a homomomorphism

lemma (**in** *FinGroupRepresentation*) *GRepHom-decomp* :
fixes T :: $'v \Rightarrow 'w$::*ab-group-add*
defines *KerT* : $KerT \equiv (ker\ T \cap V)$
assumes *hom* : *GRepHom smult′ T* **and** *nonzero*: $V \neq 0$
shows $\exists\, U.\ GSubspace\ U \wedge V = U \oplus KerT$
$\quad \wedge\ FGModule.isomorphic\ G\ smult\ U\ smult'\ (T\ `\ V)$
⟨*proof*⟩

6.4 Schur's lemma

lemma (**in** *IrrFinGroupRepresentation*) *Schur-Ker* :
GRepHom smult′ T $\Longrightarrow$ $T\ `\ V \neq 0 \Longrightarrow$ *inj-on T V*
⟨*proof*⟩

lemma (**in** *FinGroupRepresentation*) *Schur-Im* :
assumes *IrrFinGroupRepresentation G smult′ W GRepHom smult′ T*
$T\ `\ V \subseteq W$
$T\ `\ V \neq 0$
shows $T\ `\ V = W$
⟨*proof*⟩

theorem (**in** *IrrFinGroupRepresentation*) *Schur1* :
assumes *IrrFinGroupRepresentation G smult′ W*
GRepHom smult′ T $T\ `\ V \subseteq W\ T\ `\ V \neq 0$
shows *GRepIso smult′ T W*
⟨*proof*⟩

theorem (**in** *IrrFinGroupRepresentation*) *Schur2* :
assumes *GRep* : *GRepEnd T*
and *fdim* : *fdim* > 0
and *alg-closed*: $\bigwedge p{::}'b\ poly.\ degree\ p > 0 \Longrightarrow \exists\, c.\ poly\ p\ c = 0$
shows $\exists\, c.\ \forall\, v \in V.\ T\ v = c\ \sharp{\cdot}\ v$
⟨*proof*⟩

6.5 The group ring as a representation space

6.5.1 The group ring is a representation space

lemma (**in** *Group*) *FGModule-FG* :
defines *FG*: $FG \equiv$ *group-ring* :: ($'f$::*field*, $'g$) *aezfun set*
shows *FGModule G* $(*)$ *FG*
⟨*proof*⟩

theorem (**in** *Group*) *FinGroupRepresentation-FG* :
defines *FG*: $FG \equiv$ *group-ring* :: ('*f*::*field*, '*g*) *aezfun set*
assumes *good-char*: *of-nat* (*card G*) $\neq$ (*0*::'*f*)
shows *FinGroupRepresentation G* (∗) *FG*
⟨*proof*⟩

lemma (**in** *FinGroupRepresentation*) *FinGroupRepresentation-FG* :
FinGroupRepresentation G (∗) *FG*
⟨*proof*⟩

lemma (**in** *Group*) *FG-reducible* :
assumes *of-nat* (*card G*) $\neq$ (*0*::'*f*::*field*)
shows ∃ *Us*::('*f*,'*g*) *aezfun set list*.
(∀ *U*∈*set Us*. *IrrFinGroupRepresentation G* (∗) *U*) ∧ *0* ∉ *set Us*
∧ *group-ring* = ($\bigoplus$ *U*←*Us*. *U*)
⟨*proof*⟩

6.5.2 Irreducible representations are constituents of the group ring

lemma (**in** *FGModuleIso*) *isomorphic-to-irr-right* :
assumes *IrrFinGroupRepresentation G smult' W*
shows *IrrFinGroupRepresentation G smult V*
⟨*proof*⟩

lemma (**in** *FinGroupRepresentation*) *IrrGSubspace-iso-constituent* :
assumes *nonzero* : *V* $\neq$ *0*
and *subsp* : *W* ⊆ *V W* $\neq$ *0 IrrFinGroupRepresentation G smult W*
and *V-decomp*: ∀ *U*∈*set Us*. *IrrFinGroupRepresentation G smult U*
0 ∉ *set Us V* = ($\bigoplus$ *U*←*Us*. *U*)
shows ∃ *U*∈*set Us*. *FGModule.isomorphic G smult W smult U*
⟨*proof*⟩

theorem (**in** *IrrFinGroupRepresentation*) *iso-FG-constituent* :
assumes *nonzero* : *V* $\neq$ *0*
and *FG-decomp*: ∀ *U*∈*set Us*. *IrrFinGroupRepresentation G* (∗) *U*
0 ∉ *set Us FG* = ($\bigoplus$ *U*←*Us*. *U*)
shows ∃ *U*∈*set Us*. *isomorphic* (∗) *U*
⟨*proof*⟩

6.6 Isomorphism classes of irreducible representations

We have already demonstrated that the relation *FGModule.isomorphic* is reflexive (lemma *FGModule.isomorphic-refl*), symmetric (lemma *FGModule.isomorphic-sym*), and transitive (lemma *FGModule.isomorphic-trans*). In this section, we provide a finite set of representatives for the resulting isomorphism classes of irreducible representations.

context *Group*
begin

primrec *remisodups* :: (*'f*::*field*,*'g*) *aezfun set list* ⇒ (*'f*,*'g*) *aezfun set list* **where**
  remisodups [] = []
| *remisodups* (*U* # *Us*) = (*if*
      (∃ *W*∈*set Us*. *FGModule.isomorphic G* (∗) *U* (∗) *W*)
       then remisodups Us else U # *remisodups Us*)

lemma *set-remisodups* : *set* (*remisodups Us*) ⊆ *set Us*
  ⟨*proof*⟩

lemma *isodistinct-remisodups* :
  ⟦ ∀ *U*∈*set Us*. *FGModule G* (∗) *U*; *V* ∈ *set* (*remisodups Us*);
      W ∈ *set* (*remisodups Us*); *V* ≠ *W* ⟧
       ⟹ ¬ (*FGModule.isomorphic G* (∗) *V* (∗) *W*)
⟨*proof*⟩

definition *FG-constituents* ≡ *SOME Us*.
                (∀ *U*∈*set Us*. *IrrFinGroupRepresentation G* (∗) *U*)
                  ∧ *0* ∉ *set Us* ∧ *group-ring* = (⨁ *U*←*Us*. *U*)

lemma *FG-constituents-irr* :
  of-nat (*card G*) ≠ (*0*::*'f*::*field*)
      ⟹ ∀ *U*∈*set* (*FG-constituents*::(*'f*,*'g*) *aezfun set list*).
        IrrFinGroupRepresentation G (∗) *U*
  ⟨*proof*⟩

lemma *FG-consitutents-n0*:
  of-nat (*card G*) ≠ (*0*::*'f*::*field*)
      ⟹ *0* ∉ *set* (*FG-constituents*::(*'f*,*'g*) *aezfun set list*)
  ⟨*proof*⟩

lemma *FG-constituents-constituents* :
  of-nat (*card G*) ≠ (*0*::*'f*::*field*)
      ⟹ (*group-ring*::(*'f*,*'g*) *aezfun set*) = (⨁ *U*←*FG-constituents*. *U*)
  ⟨*proof*⟩

definition *GIrrRep-repset* ≡ *0* ∪ *set* (*remisodups FG-constituents*)

lemma *finite-GIrrRep-repset* : *finite GIrrRep-repset*
  ⟨*proof*⟩

lemma *all-irr-GIrrRep-repset* :
  assumes *of-nat* (*card G*) ≠ (*0*::*'f*::*field*)
  shows ∀ *U*∈(*GIrrRep-repset*::(*'f*,*'g*) *aezfun set set*).
            IrrFinGroupRepresentation G (∗) *U*
⟨*proof*⟩

lemma *isodistinct-GIrrRep-repset* :
defines *GIRRS* ≡ *GIrrRep-repset* :: ('*f*::*field*,'*g*) *aezfun set set*
assumes *of-nat* (*card G*) ≠ (*0*::'*f*) *V* ∈ *GIRRS W* ∈ *GIRRS V* ≠ *W*
shows ¬ (*FGModule.isomorphic G* (∗) *V* (∗) *W*)
⟨*proof*⟩

end

lemma (**in** *FGModule*) *iso-in-list-imp-iso-in-remisodups* :
∃ *U*∈*set Us*. *isomorphic* (∗) *U*
⟹ ∃ *U*∈*set* (*ActingGroup.remisodups Us*). *isomorphic* (∗) *U*
⟨*proof*⟩

lemma (**in** *IrrFinGroupRepresentation*) *iso-to-GIrrRep-rep* :
∃ *U*∈*ActingGroup.GIrrRep-repset*. *isomorphic* (∗) *U*
⟨*proof*⟩

theorem (**in** *Group*) *iso-class-reps* :
defines *GIRRS* ≡ *GIrrRep-repset* :: ('*f*::*field*,'*g*) *aezfun set set*
assumes *of-nat* (*card G*) ≠ (*0*::'*f*)
shows *finite GIRRS*
∀ *U*∈*GIRRS*. *IrrFinGroupRepresentation G* (∗) *U*
⋀*U W*. ⟦ *U* ∈ *GIRRS*; *W* ∈ *GIRRS*; *U* ≠ *W* ⟧
⟹ ¬ (*FGModule.isomorphic G* (∗) *U* (∗) *W*)
⋀*fgsmult V*. *IrrFinGroupRepresentation G fgsmult V*
⟹ ∃ *U*∈*GIRRS*. *FGModule.isomorphic G fgsmult V* (∗) *U*
⟨*proof*⟩

6.7 Induced representations

6.7.1 Locale and basic facts

locale *InducedFinGroupRepresentation* = *Supgroup?*: *Group H*
+ *BaseRep?*: *FinGroupRepresentation G smult V*
+ *induced-smult?*: *aezfun-scalar-mult rrsmult*
for *H* :: '*g*::*group-add set*
and *G* :: '*g set*
and *smult* :: ('*f*::*field*, '*g*) *aezfun* ⇒ '*v*::*ab-group-add* ⇒ '*v* (**infixl** ‹·› *70*)
and *V* :: '*v set*
and *rrsmult* :: ('*f*,'*g*) *aezfun* ⇒ (('*f*,'*g*) *aezfun* ⇒'*v*)
⇒ (('*f*,'*g*) *aezfun* ⇒'*v*) (**infixl** ‹¤› *70*)
+ **fixes** *FH* :: ('*f*, '*g*) *aezfun set*
and *indV* :: (('*f*, '*g*) *aezfun* ⇒ '*v*) *set*
defines *FH* : *FH* ≡ *Supgroup.group-ring*
and *indV* : *indV* ≡ *BaseRep.indspace G FH V*
assumes *rrsmult* : *rrsmult* = *Ring1.rightreg-scalar-mult FH*
and *good-ordSupgrp*: *of-nat* (*card H*) ≠ (*0*::'*f*)
and *Subgroup* : *Supgroup.Subgroup G*

sublocale *InducedFinGroupRepresentation* < *InducedFHModule*

⟨*proof*⟩

context *InducedFinGroupRepresentation*
begin

abbreviation *ordH* :: *'f* **where** *ordH* ≡ *of-nat* (*card H*)
abbreviation *is-Vfbasis* ≡ *fbasis-for V*
abbreviation *GRepHomSet* ≡ *FGModuleHomSet G smult V*
abbreviation *HRepHom* ≡ *FGModuleHom H rrsmult indV*
abbreviation *HRepHomSet* ≡ *FGModuleHomSet H rrsmult indV*

lemma *finiteSupgroup*: *finite H*
⟨*proof*⟩

lemma *FinGroupSupgroup* : *FinGroup H*
⟨*proof*⟩

lemmas *fVectorSpace* = *fVectorSpace*
lemmas *FinDimVectorSpace* = *FinDimVectorSpace*
lemmas *ex-rcoset-replist-hd0*
= *FinGroup.ex-rcoset-replist-hd0*[*OF FinGroupSupgroup Subgroup*]

end

6.7.2 A basis for the induced space

context *InducedFinGroupRepresentation*
begin

abbreviation *negHorbit-list* ≡ *induced-smult.negGorbit-list*

lemmas *ex-rcoset-replist*
= *FinGroup.ex-rcoset-replist*[*OF FinGroupSupgroup Subgroup*]
lemmas *length-negHorbit-list* = *induced-smult.length-negGorbit-list*
lemmas *length-negHorbit-list-sublist* = *induced-smult.length-negGorbit-list-sublist*
lemmas *negHorbit-list-indV* = *FGModule.negGorbit-list-V*[*OF FHModule-indspace*]

lemma *flincomb-Horbit-induced-veclist-reduce* :
fixes *vs* :: *'v list*
and *hs* :: *'g list*
defines *hfvss* : *hfvss* ≡ *negHorbit-list hs induced-vector vs*
assumes *vs* : *set vs* ⊆ *V* **and** *i*: *i* < *length hs*
and *scalars* : *list-all2* (λ*rs ms*. *length rs* = *length ms*) *css hfvss*
and *rcoset-reps* : *Supgroup.is-rcoset-replist G hs*
shows ((*concat css*) •¤ ¤ (*concat hfvss*)) (*1* δδ (*hs*!*i*)) = (*css*!*i*) •♯· *vs*
⟨*proof*⟩

lemma *indspace-fspanning-set* :

fixes *vs* :: *'v list*
and *hs* :: *'g list*
defines *hfvss* : *hfvss* ≡ *negHorbit-list hs induced-vector vs*
assumes *base-spset* : *set vs* ⊆ *V V* = *BaseRep.fSpan vs*
and *rcoset-reps* : *Supgroup.is-rcoset-replist G hs*
shows *indV* = *induced-smult.fSpan* (*concat hfvss*)
⟨*proof*⟩

lemma *indspace-basis* :
fixes *vs* :: *'v list*
and *hs* :: *'g list*
defines *hfvss* : *hfvss* ≡ *negHorbit-list hs induced-vector vs*
assumes *base-spset* : *BaseRep.fbasis-for V vs*
and *rcoset-reps* : *Supgroup.is-rcoset-replist G hs*
shows *fscalar-mult.basis-for induced-smult.fsmult indV* (*concat hfvss*)
⟨*proof*⟩

lemma *induced-vector-decomp* :
fixes *vs* :: *'v list*
and *hs* :: *'g list*
and *cs* :: *'f list*
defines *hfvss* : *hfvss* ≡ *negHorbit-list* (*0*#*hs*) *induced-vector vs*
and *extrazeros* : *extrazeros* ≡ *replicate* ((*length hs*)∗(*length vs*)) *0*
assumes *base-spset* : *BaseRep.fbasis-for V vs*
and *rcoset-reps* : *Supgroup.is-rcoset-replist G* (*0*#*hs*)
and *cs* : *length cs* = *length vs*
and *v* : *v* = *cs* ·♯· *vs*
shows *induced-vector v* = (*cs*@*extrazeros*) ·¤ ¤ (*concat hfvss*)
⟨*proof*⟩

end

6.7.3 The induced space is a representation space

context *InducedFinGroupRepresentation*
begin

lemma *indspace-findim* :
fscalar-mult.findim induced-smult.fsmult indV
⟨*proof*⟩

theorem *FinGroupRepresentation-indspace* :
FinGroupRepresentation H rrsmult indV
⟨*proof*⟩

end

6.8 Frobenius reciprocity

6.8.1 Locale and basic facts

There are a number of defined objects and lemmas concerning those objects leading up to the theorem of Frobenius reciprocity, so we create a locale to contain it all.

locale *FrobeniusReciprocity*
= *GRep?*: *InducedFinGroupRepresentation H G smult V rrsmult*
+ *HRep?*: *FinGroupRepresentation H smult' W*
  for *H* :: *'g::group-add set*
  and *G* :: *'g set*
  and *smult* :: *('f::field, 'g) aezfun ⇒ 'v::ab-group-add ⇒ 'v* (**infixl** ‹·› *70*)
  and *V* :: *'v set*
  and *rrsmult* :: *('f,'g) aezfun ⇒ (('f,'g) aezfun ⇒ 'v)*
    ⇒ (('f,'g) aezfun ⇒ 'v) (**infixl** ‹¤› *70*)
  and *smult'* :: *('f, 'g) aezfun ⇒ 'w::ab-group-add ⇒ 'w* (**infixr** ‹⋆› *70*)
  and *W* :: *'w set*
begin

abbreviation *fsmult'* :: *'f ⇒ 'w ⇒ 'w* (**infixr** ‹♯⋆› *70*)
  where *fsmult' ≡ HRep.fsmult*
abbreviation *flincomb'* :: *'f list ⇒ 'w list ⇒ 'w* (**infixr** ‹·♯⋆› *70*)
  where *flincomb' ≡ HRep.flincomb*
abbreviation *Hmult'* :: *'g ⇒ 'w ⇒ 'w* (**infixr** ‹∗⋆› *70*)
  where *Hmult' ≡ HRep.Gmult*

definition *Tsmult1* ::
  'f ⇒ ((('f, 'g) aezfun ⇒ 'v)⇒'w) ⇒ ((('f, 'g) aezfun ⇒ 'v)⇒'w) (**infixr** ‹⋆¤› *70*)
  where *Tsmult1 ≡ λa T. λf. a ♯⋆ (T f)*

definition *Tsmult2* :: *'f ⇒ ('v⇒'w) ⇒ ('v⇒'w)* (**infixr** ‹⋆·› *70*)
  where *Tsmult2 ≡ λa T. λv. a ♯⋆ (T v)*

lemma *FHModuleW* : *FGModule H (⋆) W* ⟨*proof*⟩

lemma *FGModuleW*: *FGModule G smult' W*
⟨*proof*⟩

In order to build an inverse for the required isomorphism of Hom-sets, we will need a basis for the induced H-space.

definition *Vfbasis* :: *'v list* **where** *Vfbasis ≡ (SOME vs. is-Vfbasis vs)*

lemma *Vfbasis* : *is-Vfbasis Vfbasis*
  ⟨*proof*⟩

lemma *Vfbasis-V* : *set Vfbasis ⊆ V*
  ⟨*proof*⟩

definition *nonzero-H-rcoset-reps* :: *'g list*
where *nonzero-H-rcoset-reps* ≡ (*SOME hs. Group.is-rcoset-replist H G* (*0*#*hs*))

definition *H-rcoset-reps* :: *'g list* **where** *H-rcoset-reps* ≡ *0* # *nonzero-H-rcoset-reps*

lemma *H-rcoset-reps* : *Group.is-rcoset-replist H G H-rcoset-reps*
⟨*proof*⟩

lemma *H-rcoset-reps-H* : *set H-rcoset-reps* ⊆ *H*
⟨*proof*⟩

lemma *nonzero-H-rcoset-reps-H* : *set nonzero-H-rcoset-reps* ⊆ *H*
⟨*proof*⟩

abbreviation *negHorbit-homVfbasis* :: (*'v* ⇒ *'w*) ⇒ *'w list list*
where *negHorbit-homVfbasis T* ≡ *HRep.negGorbit-list H-rcoset-reps T Vfbasis*

lemma *negHorbit-Hom-indVfbasis-W* :
T ‘ *V* ⊆ *W* ⟹ *set* (*concat* (*negHorbit-homVfbasis T*)) ⊆ *W*
⟨*proof*⟩

lemma *negHorbit-HomSet-indVfbasis-W* :
T ∈ *GRepHomSet smult' W* ⟹ *set* (*concat* (*negHorbit-homVfbasis T*)) ⊆ *W*
⟨*proof*⟩

definition *indVfbasis* :: ((*'f*, *'g*) *aezfun* ⇒ *'v*) *list list*
where *indVfbasis* ≡ *GRep.negHorbit-list H-rcoset-reps induced-vector Vfbasis*

lemma *indVfbasis* :
fscalar-mult.basis-for induced-smult.fsmult indV (*concat indVfbasis*)
⟨*proof*⟩

lemma *indVfbasis-indV* : *hfvs* ∈ *set indVfbasis* ⟹ *set hfvs* ⊆ *indV*
⟨*proof*⟩

end

6.8.2 The required isomorphism of Hom-sets

context *FrobeniusReciprocity*
begin

The following function will demonstrate the required isomorphism of Hom-sets (as vector spaces).

definition *φ* :: (((*'f*, *'g*) *aezfun* ⇒ *'v*) ⇒ *'w*) ⇒ (*'v* ⇒ *'w*)
where *φ* ≡ *restrict0* (λ*T*. *T* ∘ *GRep.induced-vector*) (*HRepHomSet smult' W*)

lemma *φ-im* : *φ* ‘ *HRepHomSet* (⋆) *W* ⊆ *GRepHomSet* (⋆) *W*

⟨*proof*⟩

end

6.8.3 The inverse map of Hom-sets

In this section we build an inverse for the required isomorphism, φ.

context *FrobeniusReciprocity*
begin

definition ψ-*condition* :: $('v \Rightarrow 'w) \Rightarrow ((('f, 'g)\ aezfun \Rightarrow 'v) \Rightarrow 'w) \Rightarrow bool$
  where ψ-*condition* $T\ S$
    $\equiv$ *VectorSpaceHom induced-smult.fsmult indV fsmult' S*
      $\wedge$ *map* (*map S*) *indVfbasis* = *negHorbit-homVfbasis T*

lemma *inverse-im-exists'* :
  assumes $T \in$ *GRepHomSet* $(\star)$ *W*
  shows $\exists!$ *S*. *VectorSpaceHom induced-smult.fsmult indV fsmult' S*
      $\wedge$ *map S* (*concat indVfbasis*) = *concat* (*negHorbit-homVfbasis T*)
⟨*proof*⟩

lemma *inverse-im-exists* :
  assumes $T \in$ *GRepHomSet* $(\star)$ *W*
  shows $\exists!$ *S*. ψ-*condition T S*
⟨*proof*⟩

definition $\psi :: ('v \Rightarrow 'w) \Rightarrow ((('f, 'g)\ aezfun \Rightarrow 'v) \Rightarrow 'w)$
  where $\psi \equiv$ *restrict0* $(\lambda T.\ THE\ S.\ \psi\text{-}condition\ T\ S)$ (*GRepHomSet* $(\star)$ *W*)

lemma ψD : $T \in$ *GRepHomSet* $(\star)$ *W* $\Longrightarrow$ ψ-*condition T* $(\psi\ T)$
  ⟨*proof*⟩

lemma ψD-*VectorSpaceHom* :
  $T \in$ *GRepHomSet* $(\star)$ *W*
    $\Longrightarrow$ *VectorSpaceHom induced-smult.fsmult indV fsmult'* $(\psi\ T)$
  ⟨*proof*⟩

lemma ψD-*im* :
  $T \in$ *GRepHomSet* $(\star)$ *W* $\Longrightarrow$ *map* (*map* $(\psi\ T)$) *indVfbasis*
    = *aezfun-scalar-mult.negGorbit-list* $(\star)$ *H-rcoset-reps T Vfbasis*
  ⟨*proof*⟩

lemma ψD-*im-single* :
  assumes $T \in$ *GRepHomSet* $(\star)$ *W h* $\in$ *set H-rcoset-reps v* $\in$ *set Vfbasis*
  shows $\psi\ T\ ((-\ h) *¤ (induced\text{-}vector\ v)) = (-h) *\star (T\ v)$
⟨*proof*⟩

lemma ψT-*W* :
  assumes $T \in$ *GRepHomSet* $(\star)$ *W*

shows $\psi\ T\ `\ indV \subseteq W$
⟨*proof*⟩

lemma *ψT-Hmap-on-indVfbasis* :
assumes $T \in GRepHomSet\ (\star)\ W$
shows $\bigwedge x\ f.\ x \in H \Longrightarrow f \in set\ (concat\ indVfbasis)$
$\Longrightarrow \psi\ T\ (x *¤ f) = x **\star (\psi\ T\ f)$
⟨*proof*⟩

lemma *ψT-hom* :
assumes $T \in GRepHomSet\ (\star)\ W$
shows $HRepHom\ (\star)\ (\psi\ T)$
⟨*proof*⟩

lemma *ψ-im* : $\psi\ `\ GRepHomSet\ (\star)\ W \subseteq HRepHomSet\ (\star)\ W$
⟨*proof*⟩

end

6.8.4 Demonstration of bijectivity

Now we demonstrate that φ is bijective via the inverse ψ.

context *FrobeniusReciprocity*
begin

lemma *φψ* :
assumes $T \in GRepHomSet\ smult'\ W$
shows $(\varphi \circ \psi)\ T = T$
⟨*proof*⟩

lemma *φ-inverse-im* : $\varphi\ `\ HRepHomSet\ (\star)\ W \supseteq GRepHomSet\ (\star)\ W$
⟨*proof*⟩

lemma *bij-φ* : *bij-betw* $\varphi\ (HRepHomSet\ (\star)\ W)\ (GRepHomSet\ (\star)\ W)$
⟨*proof*⟩

end

6.8.5 The theorem

Finally we demonstrate that φ is an isomorphism of vector spaces between the two hom-sets, leading to Frobenius reciprocity.

context *FrobeniusReciprocity*
begin

lemma *VectorSpaceIso-φ* :
VectorSpaceIso Tsmult1 $(HRepHomSet\ (\star)\ W)$ *Tsmult2* φ
$(GRepHomSet\ (\star)\ W)$

⟨*proof*⟩

theorem *FrobeniusReciprocity* :
  VectorSpace.isomorphic Tsmult1 (*HRepHomSet smult′ W*) *Tsmult2*
      (*GRepHomSet smult′ W*)
  ⟨*proof*⟩

end

end

7 Bibliography

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