ZF

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theory *HOLZF*
imports *Main*
begin

typedecl *ZF*

axiomatization
  Empty :: *ZF* **and**
  Elem :: *ZF* ⇒ *ZF* ⇒ *bool* **and**
  Sum :: *ZF* ⇒ *ZF* **and**
  Power :: *ZF* ⇒ *ZF* **and**
  Repl :: *ZF* ⇒ (*ZF* ⇒ *ZF*) ⇒ *ZF* **and**
  Inf :: *ZF*

definition *Upair* :: *ZF* ⇒ *ZF* ⇒ *ZF* **where**
  Upair a b == *Repl* (*Power* (*Power Empty*)) (% *x*. *if x* = *Empty then a else b*)

definition *Singleton*:: *ZF* ⇒ *ZF* **where**
  Singleton x == *Upair x x*

definition *union* :: *ZF* ⇒ *ZF* ⇒ *ZF* **where**
  union A B == *Sum* (*Upair A B*)

definition *SucNat*:: *ZF* ⇒ *ZF* **where**
  SucNat x == *union x* (*Singleton x*)

definition *subset* :: *ZF* ⇒ *ZF* ⇒ *bool* **where**
  subset A B ≡ ∀ *x*. *Elem x A* ⟶ *Elem x B*

axiomatization where
  Empty: *Not* (*Elem x Empty*) **and**
  Ext: (*x* = *y*) = (∀ *z*. *Elem z x* = *Elem z y*) **and**
  Sum: *Elem z* (*Sum x*) = (∃ *y*. *Elem z y* ∧ *Elem y x*) **and**
  Power: *Elem y* (*Power x*) = (*subset y x*) **and**
  Repl: *Elem b* (*Repl A f*) = (∃ *a*. *Elem a A* ∧ *b* = *f a*) **and**
  Regularity: *A* ≠ *Empty* ⟶ (∃ *x*. *Elem x A* ∧ (∀ *y*. *Elem y x* ⟶ *Not* (*Elem y*

A))) **and**
Infinity: *Elem Empty Inf* $\wedge$ ($\forall$ *x*. *Elem x Inf* $\longrightarrow$ *Elem* (*SucNat x*) *Inf*)

definition *Sep* :: *ZF* $\Rightarrow$ (*ZF* $\Rightarrow$ *bool*) $\Rightarrow$ *ZF* **where**
Sep A p == (*if* ($\forall$ *x*. *Elem x A* $\longrightarrow$ *Not* (*p x*)) *then Empty else*
(*let z* = (ϵ *x*. *Elem x A* & *p x*) *in*
let f = λ*x*. (*if p x then x else z*) *in Repl A f*))

thm *Power*[*unfolded subset-def*]

theorem *Sep*: *Elem b* (*Sep A p*) = (*Elem b A* $\wedge$ *p b*)
⟨*proof*⟩

lemma *subset-empty*: *subset Empty A*
⟨*proof*⟩

theorem *Upair*: *Elem x* (*Upair a b*) = (*x* = *a* $\vee$ *x* = *b*)
⟨*proof*⟩

lemma *Singleton*: *Elem x* (*Singleton y*) = (*x* = *y*)
⟨*proof*⟩

definition *Opair* :: *ZF* $\Rightarrow$ *ZF* $\Rightarrow$ *ZF* **where**
Opair a b == *Upair* (*Upair a a*) (*Upair a b*)

lemma *Upair-singleton*: (*Upair a a* = *Upair c d*) = (*a* = *c* & *a* = *d*)
⟨*proof*⟩

lemma *Upair-fsteq*: (*Upair a b* = *Upair a c*) = ((*a* = *b* & *a* = *c*) | (*b* = *c*))
⟨*proof*⟩

lemma *Upair-comm*: *Upair a b* = *Upair b a*
⟨*proof*⟩

theorem *Opair*: (*Opair a b* = *Opair c d*) = (*a* = *c* & *b* = *d*)
⟨*proof*⟩

definition *Replacement* :: *ZF* $\Rightarrow$ (*ZF* $\Rightarrow$ *ZF option*) $\Rightarrow$ *ZF* **where**
Replacement A f == *Repl* (*Sep A* (% *a*. *f a* $\neq$ *None*)) (*the o f*)

theorem *Replacement*: *Elem y* (*Replacement A f*) = ($\exists$ *x*. *Elem x A* $\wedge$ *f x* = *Some y*)
⟨*proof*⟩

definition *Fst* :: *ZF* $\Rightarrow$ *ZF* **where**
Fst q == *SOME x*. $\exists$ *y*. *q* = *Opair x y*

definition *Snd* :: *ZF* $\Rightarrow$ *ZF* **where**
Snd q == *SOME y*. $\exists$ *x*. *q* = *Opair x y*

theorem *Fst*: *Fst* (*Opair x y*) = *x*
⟨*proof*⟩

theorem *Snd*: *Snd* (*Opair x y*) = *y*
⟨*proof*⟩

definition *isOpair* :: *ZF* ⇒ *bool* **where**
isOpair q == ∃ *x y*. *q* = *Opair x y*

lemma *isOpair*: *isOpair* (*Opair x y*) = *True*
⟨*proof*⟩

lemma *FstSnd*: *isOpair x* ⟹ *Opair* (*Fst x*) (*Snd x*) = *x*
⟨*proof*⟩

definition *CartProd* :: *ZF* ⇒ *ZF* ⇒ *ZF* **where**
CartProd A B == *Sum*(*Repl A* (% *a*. *Repl B* (% *b*. *Opair a b*)))

lemma *CartProd*: *Elem x* (*CartProd A B*) = (∃ *a b*. *Elem a A* ∧ *Elem b B* ∧ *x* = (*Opair a b*))
⟨*proof*⟩

definition *explode* :: *ZF* ⇒ *ZF set* **where**
explode z == { *x*. *Elem x z* }

lemma *explode-Empty*: (*explode x* = {}) = (*x* = *Empty*)
⟨*proof*⟩

lemma *explode-Elem*: (*x* ∈ *explode X*) = (*Elem x X*)
⟨*proof*⟩

lemma *Elem-explode-in*: ⟦ *Elem a A*; *explode A* ⊆ *B*⟧ ⟹ *a* ∈ *B*
⟨*proof*⟩

lemma *explode-CartProd-eq*: *explode* (*CartProd a b*) = (% (*x*,*y*). *Opair x y*) ‘ ((*explode a*) × (*explode b*))
⟨*proof*⟩

lemma *explode-Repl-eq*: *explode* (*Repl A f*) = *image f* (*explode A*)
⟨*proof*⟩

definition *Domain* :: *ZF* ⇒ *ZF* **where**
Domain f == *Replacement f* (% *p*. *if isOpair p then Some* (*Fst p*) *else None*)

definition *Range* :: *ZF* ⇒ *ZF* **where**
Range f == *Replacement f* (% *p*. *if isOpair p then Some* (*Snd p*) *else None*)

theorem *Domain*: *Elem x* (*Domain f*) = (∃ *y*. *Elem* (*Opair x y*) *f*)

⟨*proof*⟩

theorem *Range*: *Elem y* (*Range f*) = (∃ *x*. *Elem* (*Opair x y*) *f*)
⟨*proof*⟩

theorem *union*: *Elem x* (*union A B*) = (*Elem x A* | *Elem x B*)
⟨*proof*⟩

definition *Field* :: *ZF* ⇒ *ZF* **where**
Field A == *union* (*Domain A*) (*Range A*)

definition *app* :: *ZF* ⇒ *ZF* => *ZF* (**infixl´** *90*) — function application **where**
f´ x == (*THE y*. *Elem* (*Opair x y*) *f*)

definition *isFun* :: *ZF* ⇒ *bool* **where**
isFun f == (∀ *x y1 y2*. *Elem* (*Opair x y1*) *f* & *Elem* (*Opair x y2*) *f* ⟶ *y1* = *y2*)

definition *Lambda* :: *ZF* ⇒ (*ZF* ⇒ *ZF*) ⇒ *ZF* **where**
Lambda A f == *Repl A* (% *x*. *Opair x* (*f x*))

lemma *Lambda-app*: *Elem x A* ⟹ (*Lambda A f*)*x* = *f x*
⟨*proof*⟩

lemma *isFun-Lambda*: *isFun* (*Lambda A f*)
⟨*proof*⟩

lemma *domain-Lambda*: *Domain* (*Lambda A f*) = *A*
⟨*proof*⟩

lemma *Lambda-ext*: (*Lambda s f* = *Lambda t g*) = (*s* = *t* ∧ (∀ *x*. *Elem x s* ⟶ *f x* = *g x*))
⟨*proof*⟩

definition *PFun* :: *ZF* ⇒ *ZF* ⇒ *ZF* **where**
PFun A B == *Sep* (*Power* (*CartProd A B*)) *isFun*

definition *Fun* :: *ZF* ⇒ *ZF* ⇒ *ZF* **where**
Fun A B == *Sep* (*PFun A B*) (λ *f*. *Domain f* = *A*)

lemma *Fun-Range*: *Elem f* (*Fun U V*) ⟹ *subset* (*Range f*) *V*
⟨*proof*⟩

lemma *Elem-Elem-PFun*: *Elem F* (*PFun U V*) ⟹ *Elem p F* ⟹ *isOpair p* & *Elem* (*Fst p*) *U* & *Elem* (*Snd p*) *V*
⟨*proof*⟩

lemma *Fun-implies-PFun*[*simp*]: *Elem f* (*Fun U V*) ⟹ *Elem f* (*PFun U V*)
⟨*proof*⟩

lemma *Elem-Elem-Fun*: *Elem F (Fun U V)* $\Longrightarrow$ *Elem p F* $\Longrightarrow$ *isOpair p & Elem (Fst p) U & Elem (Snd p) V*
⟨*proof*⟩

lemma *PFun-inj*: *Elem F (PFun U V)* $\Longrightarrow$ *Elem x F* $\Longrightarrow$ *Elem y F* $\Longrightarrow$ *Fst x = Fst y* $\Longrightarrow$ *Snd x = Snd y*
⟨*proof*⟩

lemma *Fun-total*: $[\![$*Elem F (Fun U V)*; *Elem a U*$]\!]$ $\Longrightarrow$ $\exists\, x.$ *Elem (Opair a x) F*
⟨*proof*⟩

lemma *unique-fun-value*: $[\![$*isFun f*; *Elem x (Domain f)*$]\!]$ $\Longrightarrow$ $\exists!\, y.$ *Elem (Opair x y) f*
⟨*proof*⟩

lemma *fun-value-in-range*: $[\![$*isFun f*; *Elem x (Domain f)*$]\!]$ $\Longrightarrow$ *Elem (f x) (Range f)*
⟨*proof*⟩

lemma *fun-range-witness*: $[\![$*isFun f*; *Elem y (Range f)*$]\!]$ $\Longrightarrow$ $\exists\, x.$ *Elem x (Domain f) & f x = y*
⟨*proof*⟩

lemma *Elem-Fun-Lambda*: *Elem F (Fun U V)* $\Longrightarrow$ $\exists f.$ *F = Lambda U f*
⟨*proof*⟩

lemma *Elem-Lambda-Fun*: *Elem (Lambda A f) (Fun U V) = (A = U* $\wedge$ *(*$\forall\, x.$ *Elem x A* $\longrightarrow$ *Elem (f x) V))*
⟨*proof*⟩

definition *is-Elem-of* :: *(ZF * ZF) set* **where**
is-Elem-of == { *(a,b)* | *a b. Elem a b* }

lemma *cond-wf-Elem*:
assumes *hyps*:$\forall\, x.$ *(*$\forall\, y.$ *Elem y x* $\longrightarrow$ *Elem y U* $\longrightarrow$ *P y)* $\longrightarrow$ *Elem x U* $\longrightarrow$ *P x Elem a U*
shows *P a*
⟨*proof*⟩

lemma *cond2-wf-Elem*:
assumes
special-P: $\exists\, U.\ \forall\, x.$ *Not(Elem x U)* $\longrightarrow$ *(P x)*
and *P-induct*: $\forall\, x.$ *(*$\forall\, y.$ *Elem y x* $\longrightarrow$ *P y)* $\longrightarrow$ *P x*
shows
P a
⟨*proof*⟩

primrec *nat2Nat* :: *nat* ⇒ *ZF* **where**
  nat2Nat-0[*intro*]: *nat2Nat 0* = *Empty*
| *nat2Nat-Suc*[*intro*]: *nat2Nat* (*Suc n*) = *SucNat* (*nat2Nat n*)

definition *Nat2nat* :: *ZF* ⇒ *nat* **where**
  Nat2nat == *inv nat2Nat*

lemma *Elem-nat2Nat-inf*[*intro*]: *Elem* (*nat2Nat n*) *Inf*
  ⟨*proof*⟩

definition *Nat* :: *ZF*
 where *Nat* == *Sep Inf* (λ*N*. ∃ *n*. *nat2Nat n* = *N*)

lemma *Elem-nat2Nat-Nat*[*intro*]: *Elem* (*nat2Nat n*) *Nat*
  ⟨*proof*⟩

lemma *Elem-Empty-Nat*: *Elem Empty Nat*
  ⟨*proof*⟩

lemma *Elem-SucNat-Nat*: *Elem N Nat* ⟹ *Elem* (*SucNat N*) *Nat*
  ⟨*proof*⟩

lemma *no-infinite-Elem-down-chain*:
  Not (∃ *f*. *isFun f* ∧ *Domain f* = *Nat* ∧ (∀ *N*. *Elem N Nat* ⟶ *Elem* (*f*(*SucNat N*)) (*f N*)))
⟨*proof*⟩

lemma *Upair-nonEmpty*: *Upair a b* ≠ *Empty*
  ⟨*proof*⟩

lemma *Singleton-nonEmpty*: *Singleton x* ≠ *Empty*
  ⟨*proof*⟩

lemma *notsym-Elem*: *Not*(*Elem a b* & *Elem b a*)
⟨*proof*⟩

lemma *irreflexiv-Elem*: *Not*(*Elem a a*)
  ⟨*proof*⟩

lemma *antisym-Elem*: *Elem a b* ⟹ *Not* (*Elem b a*)
  ⟨*proof*⟩

primrec *NatInterval* :: *nat* ⇒ *nat* ⇒ *ZF* **where**
  NatInterval n 0 = *Singleton* (*nat2Nat n*)
| *NatInterval n* (*Suc m*) = *union* (*NatInterval n m*) (*Singleton* (*nat2Nat* (*n*+*m*+*1*)))

lemma *n-Elem-NatInterval*[*rule-format*]: ∀ *q*. *q* ≤ *m* ⟶ *Elem* (*nat2Nat* (*n*+*q*)) (*NatInterval n m*)
  ⟨*proof*⟩

lemma *NatInterval-not-Empty*: $NatInterval\ n\ m \neq Empty$
⟨*proof*⟩

lemma *increasing-nat2Nat*[*rule-format*]: $0 < n \longrightarrow Elem\ (nat2Nat\ (n - 1))\ (nat2Nat\ n)$
⟨*proof*⟩

lemma *represent-NatInterval*[*rule-format*]: $Elem\ x\ (NatInterval\ n\ m) \longrightarrow (\exists u.\ n \leq u \wedge u \leq n+m \wedge nat2Nat\ u = x)$
⟨*proof*⟩

lemma *inj-nat2Nat*: *inj nat2Nat*
⟨*proof*⟩

lemma *Nat2nat-nat2Nat*[*simp*]: $Nat2nat\ (nat2Nat\ n) = n$
⟨*proof*⟩

lemma *nat2Nat-Nat2nat*[*simp*]: $Elem\ n\ Nat \Longrightarrow nat2Nat\ (Nat2nat\ n) = n$
⟨*proof*⟩

lemma *Nat2nat-SucNat*: $Elem\ N\ Nat \Longrightarrow Nat2nat\ (SucNat\ N) = Suc\ (Nat2nat\ N)$
⟨*proof*⟩

lemma *Elem-Opair-exists*: $\exists z.\ Elem\ x\ z\ \&\ Elem\ y\ z\ \&\ Elem\ z\ (Opair\ x\ y)$
⟨*proof*⟩

lemma *UNIV-is-not-in-ZF*: $UNIV \neq explode\ R$
⟨*proof*⟩

definition *SpecialR* :: $(ZF * ZF)\ set$ **where**
$SpecialR \equiv \{\ (x,\ y)\ .\ x \neq Empty \wedge y = Empty\}$

lemma *wf SpecialR*
⟨*proof*⟩

definition *Ext* :: $('a * 'b)\ set \Rightarrow 'b \Rightarrow 'a\ set$ **where**
$Ext\ R\ y \equiv \{\ x\ .\ (x,\ y) \in R\ \}$

lemma *Ext-Elem*: $Ext\ is\text{-}Elem\text{-}of = explode$
⟨*proof*⟩

lemma *Ext SpecialR Empty* $\neq$ *explode z*
⟨*proof*⟩

definition *implode* :: *ZF set* ⇒ *ZF* **where**
implode == *inv explode*

lemma *inj-explode*: *inj explode*
⟨*proof*⟩

lemma *implode-explode*[*simp*]: *implode* (*explode x*) = *x*
⟨*proof*⟩

definition *regular* :: (*ZF* ∗ *ZF*) *set* ⇒ *bool* **where**
regular R == ∀ *A*. *A* ≠ *Empty* ⟶ (∃ *x*. *Elem x A* ∧ (∀ *y*. (*y*, *x*) ∈ *R* ⟶ *Not* (*Elem y A*)))

definition *set-like* :: (*ZF* ∗ *ZF*) *set* ⇒ *bool* **where**
set-like R == ∀ *y*. *Ext R y* ∈ *range explode*

definition *wfzf* :: (*ZF* ∗ *ZF*) *set* ⇒ *bool* **where**
wfzf R == *regular R* ∧ *set-like R*

lemma *regular-Elem*: *regular is-Elem-of*
⟨*proof*⟩

lemma *set-like-Elem*: *set-like is-Elem-of*
⟨*proof*⟩

lemma *wfzf-is-Elem-of*: *wfzf is-Elem-of*
⟨*proof*⟩

definition *SeqSum* :: (*nat* ⇒ *ZF*) ⇒ *ZF* **where**
SeqSum f == *Sum* (*Repl Nat* (*f o Nat2nat*))

lemma *SeqSum*: *Elem x* (*SeqSum f*) = (∃ *n*. *Elem x* (*f n*))
⟨*proof*⟩

definition *Ext-ZF* :: (*ZF* ∗ *ZF*) *set* ⇒ *ZF* ⇒ *ZF* **where**
Ext-ZF R s == *implode* (*Ext R s*)

lemma *Elem-implode*: *A* ∈ *range explode* ⟹ *Elem x* (*implode A*) = (*x* ∈ *A*)
⟨*proof*⟩

lemma *Elem-Ext-ZF*: *set-like R* ⟹ *Elem x* (*Ext-ZF R s*) = ((*x*,*s*) ∈ *R*)
⟨*proof*⟩

primrec *Ext-ZF-n* :: (*ZF* ∗ *ZF*) *set* ⇒ *ZF* ⇒ *nat* ⇒ *ZF* **where**
Ext-ZF-n R s 0 = *Ext-ZF R s*
| *Ext-ZF-n R s* (*Suc n*) = *Sum* (*Repl* (*Ext-ZF-n R s n*) (*Ext-ZF R*))

definition *Ext-ZF-hull* :: (*ZF* ∗ *ZF*) *set* ⇒ *ZF* ⇒ *ZF* **where**
Ext-ZF-hull R s == *SeqSum* (*Ext-ZF-n R s*)

lemma *Elem-Ext-ZF-hull*:
assumes *set-like-R*: *set-like R*
shows *Elem x* (*Ext-ZF-hull R S*) = (∃ *n*. *Elem x* (*Ext-ZF-n R S n*))
⟨*proof*⟩

lemma *Elem-Elem-Ext-ZF-hull*:
assumes *set-like-R*: *set-like R*
and *x-hull*: *Elem x* (*Ext-ZF-hull R S*)
and *y-R-x*: (*y*, *x*) ∈ *R*
shows *Elem y* (*Ext-ZF-hull R S*)
⟨*proof*⟩

lemma *wfzf-minimal*:
assumes *hyps*: *wfzf R C* ≠ {}
shows ∃ *x*. *x* ∈ *C* ∧ (∀ *y*. (*y*, *x*) ∈ *R* ⟶ *y* ∉ *C*)
⟨*proof*⟩

lemma *wfzf-implies-wf*: *wfzf R* ⟹ *wf R*
⟨*proof*⟩

lemma *wf-is-Elem-of*: *wf is-Elem-of*
⟨*proof*⟩

lemma *in-Ext-RTrans-implies-Elem-Ext-ZF-hull*:
set-like R ⟹ *x* ∈ (*Ext* (*R*⁺) *s*) ⟹ *Elem x* (*Ext-ZF-hull R s*)
⟨*proof*⟩

lemma *implodeable-Ext-trancl*: *set-like R* ⟹ *set-like* (*R*⁺)
⟨*proof*⟩

lemma *Elem-Ext-ZF-hull-implies-in-Ext-RTrans*[*rule-format*]:
set-like R ⟹ ∀ *x*. *Elem x* (*Ext-ZF-n R s n*) ⟶ *x* ∈ (*Ext* (*R*⁺) *s*)
⟨*proof*⟩

lemma *set-like R* ⟹ *Ext-ZF* (*R*⁺) *s* = *Ext-ZF-hull R s*
⟨*proof*⟩

lemma *wf-implies-regular*: *wf R* ⟹ *regular R*
⟨*proof*⟩

lemma *wf-eq-wfzf*: (*wf R* ∧ *set-like R*) = *wfzf R*
⟨*proof*⟩

lemma *wfzf-trancl*: *wfzf R* ⟹ *wfzf* (*R*⁺)
⟨*proof*⟩

lemma *Ext-subset-mono*: *R* ⊆ *S* ⟹ *Ext R y* ⊆ *Ext S y*
⟨*proof*⟩

lemma *set-like-subset*: *set-like* $R \Longrightarrow S \subseteq R \Longrightarrow$ *set-like* S
⟨*proof*⟩

lemma *wfzf-subset*: *wfzf* $S \Longrightarrow R \subseteq S \Longrightarrow$ *wfzf* R
⟨*proof*⟩

end

theory *Zet*
imports *HOLZF*
begin

definition *zet* = $\{A :: 'a\ set \mid A\ f\ z.\ inj\text{-}on\ f\ A \wedge f\ `\ A \subseteq explode\ z\}$

typedef $'a$ *zet* = *zet* :: $'a$ *set set*
⟨*proof*⟩

definition *zin* :: $'a \Rightarrow 'a$ *zet* $\Rightarrow$ *bool* **where**
zin x A == $x \in$ (*Rep-zet A*)

lemma *zet-ext-eq*: $(A = B) = (\forall x.\ zin\ x\ A = zin\ x\ B)$
⟨*proof*⟩

definition *zimage* :: $('a \Rightarrow 'b) \Rightarrow 'a$ *zet* $\Rightarrow 'b$ *zet* **where**
zimage f A == *Abs-zet* (*image f* (*Rep-zet A*))

lemma *zet-def'*: *zet* = $\{A :: 'a\ set \mid A\ f\ z.\ inj\text{-}on\ f\ A \wedge f\ `\ A = explode\ z\}$
⟨*proof*⟩

lemma *image-zet-rep*: $A \in zet \Longrightarrow \exists z\ .\ g\ `\ A = explode\ z$
⟨*proof*⟩

lemma *zet-image-mem*:
assumes *Azet*: $A \in zet$
shows $g\ `\ A \in zet$
⟨*proof*⟩

lemma *Rep-zimage-eq*: *Rep-zet* (*zimage f A*) = *image f* (*Rep-zet A*)
⟨*proof*⟩

lemma *zimage-iff*: *zin y* (*zimage f A*) = $(\exists x.\ zin\ x\ A \wedge y = f\ x)$
⟨*proof*⟩

definition *zimplode* :: *ZF zet* $\Rightarrow$ *ZF* **where**
zimplode A == *implode* (*Rep-zet A*)

definition *zexplode* :: *ZF* $\Rightarrow$ *ZF zet* **where**

zexplode z == Abs-zet (explode z)

lemma *Rep-zet-eq-explode*: $\exists z.$ *Rep-zet A = explode z*
⟨*proof*⟩

lemma *zexplode-zimplode*: *zexplode (zimplode A) = A*
⟨*proof*⟩

lemma *explode-mem-zet*: *explode z ∈ zet*
⟨*proof*⟩

lemma *zimplode-zexplode*: *zimplode (zexplode z) = z*
⟨*proof*⟩

lemma *zin-zexplode-eq*: *zin x (zexplode A) = Elem x A*
⟨*proof*⟩

lemma *comp-zimage-eq*: *zimage g (zimage f A) = zimage (g o f) A*
⟨*proof*⟩

definition *zunion* :: *'a zet ⇒ 'a zet ⇒ 'a zet* **where**
zunion a b ≡ Abs-zet ((Rep-zet a) ∪ (Rep-zet b))

definition *zsubset* :: *'a zet ⇒ 'a zet ⇒ bool* **where**
zsubset a b ≡ ∀ x. zin x a ⟶ zin x b

lemma *explode-union*: *explode (union a b) = (explode a) ∪ (explode b)*
⟨*proof*⟩

lemma *Rep-zet-zunion*: *Rep-zet (zunion a b) = (Rep-zet a) ∪ (Rep-zet b)*
⟨*proof*⟩

lemma *zunion*: *zin x (zunion a b) = ((zin x a) ∨ (zin x b))*
⟨*proof*⟩

lemma *zimage-zexplode-eq*: *zimage f (zexplode z) = zexplode (Repl z f)*
⟨*proof*⟩

lemma *range-explode-eq-zet*: *range explode = zet*
⟨*proof*⟩

lemma *Elem-zimplode*: *(Elem x (zimplode z)) = (zin x z)*
⟨*proof*⟩

definition *zempty* :: *'a zet* **where**
zempty ≡ Abs-zet {}

lemma *zempty*[*simp*]: *¬ (zin x zempty)*
⟨*proof*⟩

lemma *zimage-zempty*[*simp*]: *zimage f zempty = zempty*
⟨*proof*⟩

lemma *zunion-zempty-left*[*simp*]: *zunion zempty a = a*
⟨*proof*⟩

lemma *zunion-zempty-right*[*simp*]: *zunion a zempty = a*
⟨*proof*⟩

lemma *zimage-id*[*simp*]: *zimage id A = A*
⟨*proof*⟩

lemma *zimage-cong*[*fundef-cong*]: ⟦ *M = N*; !! *x*. *zin x N* ⟹ *f x = g x* ⟧ ⟹ *zimage f M = zimage g N*
⟨*proof*⟩

end

theory *LProd*
imports *HOL−Library.Multiset*
begin

inductive-set
lprod :: (*'a* ∗ *'a*) *set* ⇒ (*'a list* ∗ *'a list*) *set*
for *R* :: (*'a* ∗ *'a*) *set*
where
lprod-single[*intro*!]: (*a*, *b*) ∈ *R* ⟹ ([*a*], [*b*]) ∈ *lprod R*
| *lprod-list*[*intro*!]: (*ah*@*at*, *bh*@*bt*) ∈ *lprod R* ⟹ (*a*,*b*) ∈ *R* ∨ *a = b* ⟹ (*ah*@*a*#*at*, *bh*@*b*#*bt*) ∈ *lprod R*

lemma (*as*,*bs*) ∈ *lprod R* ⟹ *length as = length bs*
⟨*proof*⟩

lemma (*as*, *bs*) ∈ *lprod R* ⟹ *1* ≤ *length as* ∧ *1* ≤ *length bs*
⟨*proof*⟩

lemma *lprod-subset-elem*: (*as*, *bs*) ∈ *lprod S* ⟹ *S* ⊆ *R* ⟹ (*as*, *bs*) ∈ *lprod R*
⟨*proof*⟩

lemma *lprod-subset*: *S* ⊆ *R* ⟹ *lprod S* ⊆ *lprod R*
⟨*proof*⟩

lemma *lprod-implies-mult*: (*as*, *bs*) ∈ *lprod R* ⟹ *trans R* ⟹ (*mset as*, *mset bs*) ∈ *mult R*
⟨*proof*⟩

lemma *wf-lprod*[*simp*,*intro*]:

assumes *wf-R*: *wf R*
shows *wf* (*lprod R*)
⟨*proof*⟩

definition *gprod-2-2* :: (*'a* ∗ *'a*) *set* ⇒ ((*'a* ∗ *'a*) ∗ (*'a* ∗ *'a*)) *set* **where**
gprod-2-2 R ≡ { ((*a*,*b*), (*c*,*d*)) . (*a* = *c* ∧ (*b*,*d*) ∈ *R*) ∨ (*b* = *d* ∧ (*a*,*c*) ∈ *R*) }

definition *gprod-2-1* :: (*'a* ∗ *'a*) *set* ⇒ ((*'a* ∗ *'a*) ∗ (*'a* ∗ *'a*)) *set* **where**
gprod-2-1 R ≡ { ((*a*,*b*), (*c*,*d*)) . (*a* = *d* ∧ (*b*,*c*) ∈ *R*) ∨ (*b* = *c* ∧ (*a*,*d*) ∈ *R*) }

lemma *lprod-2-3*: (*a*, *b*) ∈ *R* ⟹ ([*a*, *c*], [*b*, *c*]) ∈ *lprod R*
⟨*proof*⟩

lemma *lprod-2-4*: (*a*, *b*) ∈ *R* ⟹ ([*c*, *a*], [*c*, *b*]) ∈ *lprod R*
⟨*proof*⟩

lemma *lprod-2-1*: (*a*, *b*) ∈ *R* ⟹ ([*c*, *a*], [*b*, *c*]) ∈ *lprod R*
⟨*proof*⟩

lemma *lprod-2-2*: (*a*, *b*) ∈ *R* ⟹ ([*a*, *c*], [*c*, *b*]) ∈ *lprod R*
⟨*proof*⟩

lemma [*simp*, *intro*]:
assumes *wfR*: *wf R* **shows** *wf* (*gprod-2-1 R*)
⟨*proof*⟩

lemma [*simp*, *intro*]:
assumes *wfR*: *wf R* **shows** *wf* (*gprod-2-2 R*)
⟨*proof*⟩

lemma *lprod-3-1*: **assumes** (*x'*, *x*) ∈ *R* **shows** ([*y*, *z*, *x'*], [*x*, *y*, *z*]) ∈ *lprod R*
⟨*proof*⟩

lemma *lprod-3-2*: **assumes** (*z'*,*z*) ∈ *R* **shows** ([*z'*, *x*, *y*], [*x*,*y*,*z*]) ∈ *lprod R*
⟨*proof*⟩

lemma *lprod-3-3*: **assumes** *xr*: (*xr*, *x*) ∈ *R* **shows** ([*xr*, *y*, *z*], [*x*, *y*, *z*]) ∈ *lprod R*
⟨*proof*⟩

lemma *lprod-3-4*: **assumes** *yr*: (*yr*, *y*) ∈ *R* **shows** ([*x*, *yr*, *z*], [*x*, *y*, *z*]) ∈ *lprod R*
⟨*proof*⟩

lemma *lprod-3-5*: **assumes** *zr*: (*zr*, *z*) ∈ *R* **shows** ([*x*, *y*, *zr*], [*x*, *y*, *z*]) ∈ *lprod R*
⟨*proof*⟩

lemma *lprod-3-6*: **assumes** *y'*: (*y'*, *y*) ∈ *R* **shows** ([*x*, *z*, *y'*], [*x*, *y*, *z*]) ∈ *lprod R*
⟨*proof*⟩

lemma *lprod-3-7*: **assumes** *z'*: (*z'*,*z*) ∈ *R* **shows** ([*x*, *z'*, *y*], [*x*, *y*, *z*]) ∈ *lprod R*

⟨*proof*⟩

definition *perm* :: ('*a* ⇒ '*a*) ⇒ '*a set* ⇒ *bool* **where**
perm f A ≡ *inj-on f A* ∧ *f* ' *A* = *A*

lemma ((*as*,*bs*) ∈ *lprod R*) =
(∃ *f*. *perm f* {*0* ..< (*length as*)} ∧
(∀ *j*. *j* < *length as* ⟶ ((*nth as j*, *nth bs* (*f j*)) ∈ *R* ∨ (*nth as j* = *nth bs* (*f j*))))
∧
(∃ *i*. *i* < *length as* ∧ (*nth as i*, *nth bs* (*f i*)) ∈ *R*))
⟨*proof*⟩

lemma *trans R* ⟹ (*ah*@*a*#*at*, *bh*@*b*#*bt*) ∈ *lprod R* ⟹ (*b*, *a*) ∈ *R* ∨ *a* = *b* ⟹
(*ah*@*at*, *bh*@*bt*) ∈ *lprod R*
⟨*proof*⟩

end

theory *MainZF*
imports *Zet LProd*
begin

end

theory *Games*
imports *MainZF*
begin

definition *fixgames* :: *ZF set* ⇒ *ZF set* **where**
fixgames A ≡ { *Opair l r* | *l r*. *explode l* ⊆ *A* & *explode r* ⊆ *A*}

definition *games-lfp* :: *ZF set* **where**
games-lfp ≡ *lfp fixgames*

definition *games-gfp* :: *ZF set* **where**
games-gfp ≡ *gfp fixgames*

lemma *mono-fixgames*: *mono* (*fixgames*)
⟨*proof*⟩

lemma *games-lfp-unfold*: *games-lfp* = *fixgames games-lfp*
⟨*proof*⟩

lemma *games-gfp-unfold*: *games-gfp* = *fixgames games-gfp*
⟨*proof*⟩

lemma *games-lfp-nonempty*: *Opair Empty Empty* ∈ *games-lfp*

⟨*proof*⟩

definition *left-option* :: *ZF* ⇒ *ZF* ⇒ *bool* **where**
left-option g opt ≡ (*Elem opt* (*Fst g*))

definition *right-option* :: *ZF* ⇒ *ZF* ⇒ *bool* **where**
right-option g opt ≡ (*Elem opt* (*Snd g*))

definition *is-option-of* :: (*ZF* ∗ *ZF*) *set* **where**
is-option-of ≡ { (*opt*, *g*) | *opt g*. *g* ∈ *games-gfp* ∧ (*left-option g opt* ∨ *right-option g opt*) }

lemma *games-lfp-subset-gfp*: *games-lfp* ⊆ *games-gfp*
⟨*proof*⟩

lemma *games-option-stable*:
assumes *fixgames*: *games* = *fixgames games*
and *g*: *g* ∈ *games*
and *opt*: *left-option g opt* ∨ *right-option g opt*
shows *opt* ∈ *games*
⟨*proof*⟩

lemma *option2elem*: (*opt*,*g*) ∈ *is-option-of* ⟹ ∃ *u v*. *Elem opt u* ∧ *Elem u v* ∧ *Elem v g*
⟨*proof*⟩

lemma *is-option-of-subset-is-Elem-of*: *is-option-of* ⊆ (*is-Elem-of*$^+$)
⟨*proof*⟩

lemma *wfzf-is-option-of*: *wfzf is-option-of*
⟨*proof*⟩

lemma *games-gfp-imp-lfp*: *g* ∈ *games-gfp* ⟶ *g* ∈ *games-lfp*
⟨*proof*⟩

theorem *games-lfp-eq-gfp*: *games-lfp* = *games-gfp*
⟨*proof*⟩

theorem *unique-games*: (*g* = *fixgames g*) = (*g* = *games-lfp*)
⟨*proof*⟩

lemma *games-lfp-option-stable*:
assumes *g*: *g* ∈ *games-lfp*
and *opt*: *left-option g opt* ∨ *right-option g opt*
shows *opt* ∈ *games-lfp*
⟨*proof*⟩

lemma *is-option-of-imp-games*:
assumes *hyp*: (*opt*, *g*) ∈ *is-option-of*

shows *opt* ∈ *games-lfp* ∧ *g* ∈ *games-lfp*
⟨*proof*⟩

lemma *games-lfp-represent*: *x* ∈ *games-lfp* ⟹ ∃ *l r*. *x* = *Opair l r*
⟨*proof*⟩

definition *game* = *games-lfp*

typedef *game* = *game*
⟨*proof*⟩

definition *left-options* :: *game* ⇒ *game zet* **where**
left-options g ≡ *zimage Abs-game* (*zexplode* (*Fst* (*Rep-game g*)))

definition *right-options* :: *game* ⇒ *game zet* **where**
right-options g ≡ *zimage Abs-game* (*zexplode* (*Snd* (*Rep-game g*)))

definition *options* :: *game* ⇒ *game zet* **where**
options g ≡ *zunion* (*left-options g*) (*right-options g*)

definition *Game* :: *game zet* ⇒ *game zet* ⇒ *game* **where**
Game L R ≡ *Abs-game* (*Opair* (*zimplode* (*zimage Rep-game L*)) (*zimplode* (*zimage Rep-game R*)))

lemma *Repl-Rep-game-Abs-game*: ∀ *e*. *Elem e z* ⟶ *e* ∈ *games-lfp* ⟹ *Repl z* (*Rep-game o Abs-game*) = *z*
⟨*proof*⟩

lemma *game-split*: *g* = *Game* (*left-options g*) (*right-options g*)
⟨*proof*⟩

lemma *Opair-in-games-lfp*:
assumes *l*: *explode l* ⊆ *games-lfp*
and *r*: *explode r* ⊆ *games-lfp*
shows *Opair l r* ∈ *games-lfp*
⟨*proof*⟩

lemma *left-options*[*simp*]: *left-options* (*Game l r*) = *l*
⟨*proof*⟩

lemma *right-options*[*simp*]: *right-options* (*Game l r*) = *r*
⟨*proof*⟩

lemma *Game-ext*: (*Game l1 r1* = *Game l2 r2*) = ((*l1* = *l2*) ∧ (*r1* = *r2*))
⟨*proof*⟩

definition *option-of* :: (*game* ∗ *game*) *set* **where**
option-of ≡ *image* (λ (*option*, *g*). (*Abs-game option*, *Abs-game g*)) *is-option-of*

lemma *option-to-is-option-of*: $((option,\ g) \in option\text{-}of) = ((Rep\text{-}game\ option,\ Rep\text{-}game\ g) \in is\text{-}option\text{-}of)$
⟨*proof*⟩

lemma *wf-is-option-of*: *wf is-option-of*
⟨*proof*⟩

lemma *wf-option-of*[*simp*, *intro*]: *wf option-of*
⟨*proof*⟩

lemma *right-option-is-option*[*simp*, *intro*]: *zin x* (*right-options g*) ⟹ *zin x* (*options g*)
⟨*proof*⟩

lemma *left-option-is-option*[*simp*, *intro*]: *zin x* (*left-options g*) ⟹ *zin x* (*options g*)
⟨*proof*⟩

lemma *zin-options*[*simp*, *intro*]: *zin x* (*options g*) ⟹ $(x,\ g) \in option\text{-}of$
⟨*proof*⟩

function
neg-game :: *game* ⇒ *game*
where
[*simp del*]: *neg-game g* = *Game* (*zimage neg-game* (*right-options g*)) (*zimage neg-game* (*left-options g*))
⟨*proof*⟩
termination ⟨*proof*⟩

lemma *neg-game* (*neg-game g*) = *g*
⟨*proof*⟩

function
ge-game :: (*game* ∗ *game*) ⇒ *bool*
where
[*simp del*]: *ge-game* (*G*, *H*) = (∀ *x*. *if zin x* (*right-options G*) *then* (
if zin x (*left-options H*) *then* ¬ (*ge-game* (*H*, *x*) ∨ (*ge-game* (*x*, *G*)))
else ¬ (*ge-game* (*H*, *x*)))
else (*if zin x* (*left-options H*) *then* ¬ (*ge-game* (*x*, *G*)) *else True*))
⟨*proof*⟩
termination ⟨*proof*⟩

lemma *ge-game-eq*: *ge-game* (*G*, *H*) = (∀ *x*. (*zin x* (*right-options G*) ⟶ ¬ *ge-game* (*H*, *x*)) ∧ (*zin x* (*left-options H*) ⟶ ¬ *ge-game* (*x*, *G*)))
⟨*proof*⟩

lemma *ge-game-leftright-refl*[*rule-format*]:

$\forall\ y.\ (zin\ y\ (right\text{-}options\ x) \longrightarrow \neg\ ge\text{-}game\ (x,\ y)) \wedge (zin\ y\ (left\text{-}options\ x) \longrightarrow \neg\ (ge\text{-}game\ (y,\ x))) \wedge ge\text{-}game\ (x,\ x)$
⟨*proof*⟩

lemma *ge-game-refl*: *ge-game* (*x*,*x*) ⟨*proof*⟩

lemma $\forall\ y.\ (zin\ y\ (right\text{-}options\ x) \longrightarrow \neg\ ge\text{-}game\ (x,\ y)) \wedge (zin\ y\ (left\text{-}options\ x) \longrightarrow \neg\ (ge\text{-}game\ (y,\ x))) \wedge ge\text{-}game\ (x,\ x)$
⟨*proof*⟩

definition *eq-game* :: *game* ⇒ *game* ⇒ *bool* **where**
eq-game G H ≡ *ge-game* (*G*, *H*) ∧ *ge-game* (*H*, *G*)

lemma *eq-game-sym*: (*eq-game G H*) = (*eq-game H G*)
⟨*proof*⟩

lemma *eq-game-refl*: *eq-game G G*
⟨*proof*⟩

lemma *induct-game*: (⋀*x*. ∀ *y*. (*y*, *x*) ∈ *lprod option-of* ⟶ *P y* ⟹ *P x*) ⟹ *P a*
⟨*proof*⟩

lemma *ge-game-trans*:
assumes *ge-game* (*x*, *y*) *ge-game* (*y*, *z*)
shows *ge-game* (*x*, *z*)
⟨*proof*⟩

lemma *eq-game-trans*: *eq-game a b* ⟹ *eq-game b c* ⟹ *eq-game a c*
⟨*proof*⟩

definition *zero-game* :: *game*
where *zero-game* ≡ *Game zempty zempty*

function
plus-game :: *game* ⇒ *game* ⇒ *game*
where
[*simp del*]: *plus-game G H* = *Game* (*zunion* (*zimage* (λ *g*. *plus-game g H*) (*left-options G*))
(*zimage* (λ *h*. *plus-game G h*) (*left-options H*)))
(*zunion* (*zimage* (λ *g*. *plus-game g H*) (*right-options G*))
(*zimage* (λ *h*. *plus-game G h*) (*right-options H*)))
⟨*proof*⟩
termination ⟨*proof*⟩

lemma *plus-game-comm*: *plus-game G H* = *plus-game H G*
⟨*proof*⟩

lemma *game-ext-eq*: (*G* = *H*) = (*left-options G* = *left-options H* ∧ *right-options G* = *right-options H*)

⟨*proof*⟩

lemma *left-zero-game*[*simp*]: *left-options* (*zero-game*) = *zempty*
⟨*proof*⟩

lemma *right-zero-game*[*simp*]: *right-options* (*zero-game*) = *zempty*
⟨*proof*⟩

lemma *plus-game-zero-right*[*simp*]: *plus-game G zero-game* = *G*
⟨*proof*⟩

lemma *plus-game-zero-left*: *plus-game zero-game G* = *G*
⟨*proof*⟩

lemma *left-imp-options*[*simp*]: *zin opt* (*left-options g*) ⟹ *zin opt* (*options g*)
⟨*proof*⟩

lemma *right-imp-options*[*simp*]: *zin opt* (*right-options g*) ⟹ *zin opt* (*options g*)
⟨*proof*⟩

lemma *left-options-plus*:
left-options (*plus-game u v*) = *zunion* (*zimage* (λ*g*. *plus-game g v*) (*left-options u*)) (*zimage* (λ*h*. *plus-game u h*) (*left-options v*))
⟨*proof*⟩

lemma *right-options-plus*:
right-options (*plus-game u v*) = *zunion* (*zimage* (λ*g*. *plus-game g v*) (*right-options u*)) (*zimage* (λ*h*. *plus-game u h*) (*right-options v*))
⟨*proof*⟩

lemma *left-options-neg*: *left-options* (*neg-game u*) = *zimage neg-game* (*right-options u*)
⟨*proof*⟩

lemma *right-options-neg*: *right-options* (*neg-game u*) = *zimage neg-game* (*left-options u*)
⟨*proof*⟩

lemma *plus-game-assoc*: *plus-game* (*plus-game F G*) *H* = *plus-game F* (*plus-game G H*)
⟨*proof*⟩

lemma *neg-plus-game*: *neg-game* (*plus-game G H*) = *plus-game* (*neg-game G*) (*neg-game H*)
⟨*proof*⟩

lemma *eq-game-plus-inverse*: *eq-game* (*plus-game x* (*neg-game x*)) *zero-game*
⟨*proof*⟩

lemma *ge-plus-game-left*: *ge-game* (*y*,*z*) = *ge-game* (*plus-game x y*, *plus-game x z*)
⟨*proof*⟩

lemma *ge-plus-game-right*: *ge-game* (*y*,*z*) = *ge-game*(*plus-game y x*, *plus-game z x*)
⟨*proof*⟩

lemma *ge-neg-game*: *ge-game* (*neg-game x*, *neg-game y*) = *ge-game* (*y*, *x*)
⟨*proof*⟩

definition *eq-game-rel* :: (*game* ∗ *game*) *set* **where**
eq-game-rel ≡ { (*p*, *q*) . *eq-game p q* }

definition *Pg* = *UNIV*//*eq-game-rel*

typedef *Pg* = *Pg*
⟨*proof*⟩

lemma *equiv-eq-game*[*simp*]: *equiv UNIV eq-game-rel*
⟨*proof*⟩

instantiation *Pg* :: {*ord*, *zero*, *plus*, *minus*, *uminus*}
begin

definition
Pg-zero-def: *0* = *Abs-Pg* (*eq-game-rel* `` {*zero-game*})

definition
Pg-le-def: *G* ≤ *H* ⟷ (∃ *g h*. *g* ∈ *Rep-Pg G* ∧ *h* ∈ *Rep-Pg H* ∧ *ge-game* (*h*, *g*))

definition
Pg-less-def: *G* < *H* ⟷ *G* ≤ *H* ∧ *G* ≠ (*H*::*Pg*)

definition
Pg-minus-def: − *G* = *the-elem* (⋃ *g* ∈ *Rep-Pg G*. {*Abs-Pg* (*eq-game-rel* `` {*neg-game g*})})

definition
Pg-plus-def: *G* + *H* = *the-elem* (⋃ *g* ∈ *Rep-Pg G*. ⋃ *h* ∈ *Rep-Pg H*. {*Abs-Pg* (*eq-game-rel* `` {*plus-game g h*})})

definition
Pg-diff-def: *G* − *H* = *G* + (− (*H*::*Pg*))

instance ⟨*proof*⟩

end

lemma *Rep-Abs-eq-Pg*[*simp*]: *Rep-Pg* (*Abs-Pg* (*eq-game-rel* `` {*g*})) = *eq-game-rel*

‘‘ $\{g\}$
⟨*proof*⟩

lemma *char-Pg-le*[*simp*]: (*Abs-Pg* (*eq-game-rel* ‘‘ $\{g\}$) ≤ *Abs-Pg* (*eq-game-rel* ‘‘ $\{h\}$)) = (*ge-game* (*h*, *g*))
⟨*proof*⟩

lemma *char-Pg-eq*[*simp*]: (*Abs-Pg* (*eq-game-rel* ‘‘ $\{g\}$) = *Abs-Pg* (*eq-game-rel* ‘‘ $\{h\}$)) = (*eq-game g h*)
⟨*proof*⟩

lemma *char-Pg-plus*[*simp*]: *Abs-Pg* (*eq-game-rel* ‘‘ $\{g\}$) + *Abs-Pg* (*eq-game-rel* ‘‘ $\{h\}$) = *Abs-Pg* (*eq-game-rel* ‘‘ $\{$*plus-game g h*$\}$)
⟨*proof*⟩

lemma *char-Pg-minus*[*simp*]: − *Abs-Pg* (*eq-game-rel* ‘‘ $\{g\}$) = *Abs-Pg* (*eq-game-rel* ‘‘ $\{$*neg-game g*$\}$)
⟨*proof*⟩

lemma *eq-Abs-Pg*[*rule-format*, *cases type*: *Pg*]: (∀ *g*. *z* = *Abs-Pg* (*eq-game-rel* ‘‘ $\{g\}$) ⟶ *P*) ⟶ *P*
⟨*proof*⟩

instance *Pg* :: *ordered-ab-group-add*
⟨*proof*⟩

end