ZF

Steven Obua

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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*)
  apply (*auto simp add*: *Sep-def Empty*)
  apply (*auto simp add*: *Let-def Repl*)
  apply (*rule someI2*, *auto*)+
  done

lemma *subset-empty*: *subset Empty A*
  by (*simp add*: *subset-def Empty*)

theorem *Upair*: *Elem x* (*Upair a b*) = (*x* = *a* $\vee$ *x* = *b*)
  apply (*auto simp add*: *Upair-def Repl*)
  apply (*rule exI*[**where** *x*=*Empty*])
  apply (*simp add*: *Power subset-empty*)
  apply (*rule exI*[**where** *x*=*Power Empty*])
  apply (*auto*)
  apply (*auto simp add*: *Ext Power subset-def Empty*)
  apply (*drule spec*[**where** *x*=*Empty*], *simp add*: *Empty*)+
  done

lemma *Singleton*: *Elem x* (*Singleton y*) = (*x* = *y*)
  by (*simp add*: *Singleton-def Upair*)

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*)
  by (*auto simp add*: *Ext*[**where** *x*=*Upair a a*] *Upair*)

lemma *Upair-fsteq*: (*Upair a b* = *Upair a c*) = ((*a* = *b* & *a* = *c*) | (*b* = *c*))
  by (*auto simp add*: *Ext*[**where** *x*=*Upair a b*] *Upair*)

lemma *Upair-comm*: *Upair a b* = *Upair b a*
  by (*auto simp add*: *Ext Upair*)

theorem *Opair*: (*Opair a b* = *Opair c d*) = (*a* = *c* & *b* = *d*)
  proof −
    have *fst*: (*Opair a b* = *Opair c d*) $\Longrightarrow$ *a* = *c*
      apply (*simp add*: *Opair-def*)
      apply (*simp add*: *Ext*[**where** *x*=*Upair* (*Upair a a*) (*Upair a b*)])

apply (*drule spec*[**where** *x*=*Upair a a*])
apply (*auto simp add*: *Upair Upair-singleton*)
done
show *?thesis*
apply (*auto*)
apply (*erule fst*)
apply (*frule fst*)
apply (*auto simp add*: *Opair-def Upair-fsteq*)
done
qed

definition *Replacement* :: *ZF* ⇒ (*ZF* ⇒ *ZF option*) ⇒ *ZF* **where**
Replacement A f == *Repl* (*Sep A* (% *a*. *f a* ≠ *None*)) (*the o f*)

theorem *Replacement*: *Elem y* (*Replacement A f*) = (∃ *x*. *Elem x A* ∧ *f x* = *Some y*)
by (*auto simp add*: *Replacement-def Repl Sep*)

definition *Fst* :: *ZF* ⇒ *ZF* **where**
Fst q == *SOME x*. ∃ *y*. *q* = *Opair x y*

definition *Snd* :: *ZF* ⇒ *ZF* **where**
Snd q == *SOME y*. ∃ *x*. *q* = *Opair x y*

theorem *Fst*: *Fst* (*Opair x y*) = *x*
apply (*simp add*: *Fst-def*)
apply (*rule someI2*)
apply (*simp-all add*: *Opair*)
done

theorem *Snd*: *Snd* (*Opair x y*) = *y*
apply (*simp add*: *Snd-def*)
apply (*rule someI2*)
apply (*simp-all add*: *Opair*)
done

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

lemma *isOpair*: *isOpair* (*Opair x y*) = *True*
by (*auto simp add*: *isOpair-def*)

lemma *FstSnd*: *isOpair x* ⟹ *Opair* (*Fst x*) (*Snd x*) = *x*
by (*auto simp add*: *isOpair-def Fst Snd*)

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*))
apply (*auto simp add*: *CartProd-def Sum Repl*)
apply (*rule-tac x*=*Repl B* (*Opair a*) **in** *exI*)
apply (*auto simp add*: *Repl*)
done

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

lemma *explode-Empty*: (*explode x* = {}) = (*x* = *Empty*)
by (*auto simp add*: *explode-def Ext Empty*)

lemma *explode-Elem*: (*x* ∈ *explode X*) = (*Elem x X*)
by (*simp add*: *explode-def*)

lemma *Elem-explode-in*: ⟦ *Elem a A*; *explode A* ⊆ *B*⟧ ⟹ *a* ∈ *B*
by (*auto simp add*: *explode-def*)

lemma *explode-CartProd-eq*: *explode* (*CartProd a b*) = (% (*x*,*y*). *Opair x y*) ‘
((*explode a*) × (*explode b*))
by (*simp add*: *explode-def set-eq-iff CartProd image-def*)

lemma *explode-Repl-eq*: *explode* (*Repl A f*) = *image f* (*explode A*)
by (*simp add*: *explode-def Repl image-def*)

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*)
apply (*auto simp add*: *Domain-def Replacement*)
apply (*rule-tac x*=*Snd xa* **in** *exI*)
apply (*simp add*: *FstSnd*)
apply (*rule-tac x*=*Opair x y* **in** *exI*)
apply (*simp add*: *isOpair Fst*)
done

theorem *Range*: *Elem y* (*Range f*) = (∃ *x*. *Elem* (*Opair x y*) *f*)
apply (*auto simp add*: *Range-def Replacement*)
apply (*rule-tac x*=*Fst x* **in** *exI*)
apply (*simp add*: *FstSnd*)
apply (*rule-tac x*=*Opair x y* **in** *exI*)
apply (*simp add*: *isOpair Snd*)
done

theorem *union*: *Elem x* (*union A B*) = (*Elem x A* | *Elem x B*)
by (*auto simp add*: *union-def Sum Upair*)

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*
by (*simp add*: *app-def Lambda-def Repl Opair*)

lemma *isFun-Lambda*: *isFun* (*Lambda A f*)
by (*auto simp add*: *isFun-def Lambda-def Repl Opair*)

lemma *domain-Lambda*: *Domain* (*Lambda A f*) = *A*
apply (*auto simp add*: *Domain-def*)
apply (*subst Ext*)
apply (*auto simp add*: *Replacement*)
apply (*simp add*: *Lambda-def Repl*)
apply (*auto simp add*: *Fst*)
apply (*simp add*: *Lambda-def Repl*)
apply (*rule-tac x*=*Opair z* (*f z*) **in** *exI*)
apply (*auto simp add*: *Fst isOpair-def*)
done

lemma *Lambda-ext*: (*Lambda s f* = *Lambda t g*) = (*s* = *t* ∧ (∀ *x*. *Elem x s* ⟶ *f x* = *g x*))
proof −
have *Lambda s f* = *Lambda t g* ⟹ *s* = *t*
apply (*subst domain-Lambda*[**where** *A* = *s* **and** *f* = *f*, *symmetric*])
apply (*subst domain-Lambda*[**where** *A* = *t* **and** *f* = *g*, *symmetric*])
apply *auto*
done
then show *?thesis*
apply *auto*
apply (*subst Lambda-app*[**where** *f*=*f*, *symmetric*], *simp*)
apply (*subst Lambda-app*[**where** *f*=*g*, *symmetric*], *simp*)
apply *auto*
apply (*auto simp add*: *Lambda-def Repl Ext*)
apply (*auto simp add*: *Ext*[*symmetric*])
done
qed

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*
apply (*simp add*: *Fun-def Sep PFun-def Power subset-def CartProd*)
apply (*auto simp add*: *Domain Range*)
apply (*erule-tac x*=*Opair xa x* **in** *allE*)
apply (*auto simp add*: *Opair*)
done

lemma *Elem-Elem-PFun*: *Elem F* (*PFun U V*) ⟹ *Elem p F* ⟹ *isOpair p* & *Elem* (*Fst p*) *U* & *Elem* (*Snd p*) *V*
apply (*simp add*: *PFun-def Sep Power subset-def*, *clarify*)
apply (*erule-tac x*=*p* **in** *allE*)
apply (*auto simp add*: *CartProd isOpair Fst Snd*)
done

lemma *Fun-implies-PFun*[*simp*]: *Elem f* (*Fun U V*) ⟹ *Elem f* (*PFun U V*)
by (*simp add*: *Fun-def Sep*)

lemma *Elem-Elem-Fun*: *Elem F* (*Fun U V*) ⟹ *Elem p F* ⟹ *isOpair p* & *Elem* (*Fst p*) *U* & *Elem* (*Snd p*) *V*
by (*auto simp add*: *Elem-Elem-PFun dest*: *Fun-implies-PFun*)

lemma *PFun-inj*: *Elem F* (*PFun U V*) ⟹ *Elem x F* ⟹ *Elem y F* ⟹ *Fst x* = *Fst y* ⟹ *Snd x* = *Snd y*
apply (*frule Elem-Elem-PFun*[**where** *p*=*x*], *simp*)
apply (*frule Elem-Elem-PFun*[**where** *p*=*y*], *simp*)
apply (*subgoal-tac isFun F*)
apply (*simp add*: *isFun-def isOpair-def*)
apply (*auto simp add*: *Fst Snd*)
apply (*auto simp add*: *PFun-def Sep*)
done

lemma *Fun-total*: ⟦*Elem F* (*Fun U V*); *Elem a U*⟧ ⟹ ∃ *x*. *Elem* (*Opair a x*) *F*
using [[*simp-depth-limit* = *2*]]
by (*auto simp add*: *Fun-def Sep Domain*)

lemma *unique-fun-value*: ⟦*isFun f*; *Elem x* (*Domain f*)⟧ ⟹ ∃!*y*. *Elem* (*Opair x y*) *f*
by (*auto simp add*: *Domain isFun-def*)

lemma *fun-value-in-range*: ⟦*isFun f*; *Elem x* (*Domain f*)⟧ ⟹ *Elem* (*f´x*) (*Range f*)
apply (*auto simp add*: *Range*)

apply (*drule unique-fun-value*)
apply *simp*
apply (*simp add*: *app-def*)
apply (*rule exI*[**where** *x*=*x*])
apply (*auto simp add*: *the-equality*)
done

lemma *fun-range-witness*: ⟦*isFun f*; *Elem y* (*Range f*)⟧ ⟹ ∃ *x*. *Elem x* (*Domain f*) & *f* ´ *x* = *y*
apply (*auto simp add*: *Range*)
apply (*rule-tac x*=*x* **in** *exI*)
apply (*auto simp add*: *app-def the-equality isFun-def Domain*)
done

lemma *Elem-Fun-Lambda*: *Elem F* (*Fun U V*) ⟹ ∃ *f*. *F* = *Lambda U f*
apply (*rule exI*[**where** *x*= % *x*. (*THE y*. *Elem* (*Opair x y*) *F*)])
apply (*simp add*: *Ext Lambda-def Repl Domain*)
apply (*simp add*: *Ext*[*symmetric*])
apply *auto*
apply (*frule Elem-Elem-Fun*)
apply *auto*
apply (*rule-tac x*=*Fst z* **in** *exI*)
apply (*simp add*: *isOpair-def*)
apply (*auto simp add*: *Fst Snd Opair*)
apply (*rule the1I2*)
apply *auto*
apply (*drule Fun-implies-PFun*)
apply (*drule-tac x*=*Opair x ya* **and** *y*=*Opair x yb* **in** *PFun-inj*)
apply (*auto simp add*: *Fst Snd*)
apply (*drule Fun-implies-PFun*)
apply (*drule-tac x*=*Opair x y* **and** *y*=*Opair x ya* **in** *PFun-inj*)
apply (*auto simp add*: *Fst Snd*)
apply (*rule the1I2*)
apply (*auto simp add*: *Fun-total*)
apply (*drule Fun-implies-PFun*)
apply (*drule-tac x*=*Opair a x* **and** *y*=*Opair a y* **in** *PFun-inj*)
apply (*auto simp add*: *Fst Snd*)
done

lemma *Elem-Lambda-Fun*: *Elem* (*Lambda A f*) (*Fun U V*) = (*A* = *U* ∧ (∀ *x*. *Elem x A* ⟶ *Elem* (*f x*) *V*))
proof −
have *Elem* (*Lambda A f*) (*Fun U V*) ⟹ *A* = *U*
by (*simp add*: *Fun-def Sep domain-Lambda*)
then show *?thesis*
apply *auto*
apply (*drule Fun-Range*)
apply (*subgoal-tac f x* = ((*Lambda U f*) ´ *x*))
prefer *2*

```
    apply (simp add: Lambda-app)
    apply simp
    apply (subgoal-tac Elem (Lambda U f ´ x) (Range (Lambda U f)))
    apply (simp add: subset-def)
    apply (rule fun-value-in-range)
    apply (simp-all add: isFun-Lambda domain-Lambda)
    apply (simp add: Fun-def Sep PFun-def Power domain-Lambda isFun-Lambda)
    apply (auto simp add: subset-def CartProd)
    apply (rule-tac x=Fst x in exI)
    apply (auto simp add: Lambda-def Repl Fst)
    done
qed


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

lemma cond-wf-Elem:
  assumes hyps:∀ x. (∀ y. Elem y x ⟶ Elem y U ⟶ P y) ⟶ Elem x U ⟶ P
x Elem a U
  shows P a
proof −
  {
    fix P
    fix U
    fix a
    assume P-induct: (∀ x. (∀ y. Elem y x ⟶ Elem y U ⟶ P y) ⟶ (Elem x U
⟶ P x))
    assume a-in-U: Elem a U
    have P a
      proof −
        term P
        term Sep
        let ?Z = Sep U (Not o P)
        have ?Z = Empty ⟶ P a by (simp add: Ext Sep Empty a-in-U)
        moreover have ?Z ≠ Empty ⟶ False
          proof
            assume not-empty: ?Z ≠ Empty
          note thereis-x = Regularity[where A=?Z, simplified not-empty, simplified]
           then obtain x where x-def: Elem x ?Z ∧ (∀ y. Elem y x ⟶ Not (Elem
y ?Z)) ..
            then have x-induct:∀ y. Elem y x ⟶ Elem y U ⟶ P y by (simp add:
Sep)
            have Elem x U ⟶ P x
                 by (rule impE[OF spec[OF P-induct, where x=x], OF x-induct],
assumption)
            moreover have Elem x U & Not(P x)
              apply (insert x-def)
              apply (simp add: Sep)
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        done
      ultimately show False by auto
    qed
  ultimately show P a by auto
 qed
}
with hyps show ?thesis by blast
qed

lemma cond2-wf-Elem:
 assumes
   special-P: ∃ U. ∀ x. Not(Elem x U) ⟶ (P x)
   and P-induct: ∀ x. (∀ y. Elem y x ⟶ P y) ⟶ P x
 shows
   P a
proof −
 have ∃ U Q. P = (λ x. (Elem x U ⟶ Q x))
 proof −
  from special-P obtain U where U: ∀ x. Not(Elem x U) ⟶ (P x) ..
  show ?thesis
   apply (rule-tac exI[where x=U])
   apply (rule exI[where x=P])
   apply (rule ext)
   apply (auto simp add: U)
   done
 qed
 then obtain U where ∃ Q. P = (λ x. (Elem x U ⟶ Q x)) ..
 then obtain Q where UQ: P = (λ x. (Elem x U ⟶ Q x)) ..
 show ?thesis
  apply (auto simp add: UQ)
  apply (rule cond-wf-Elem)
  apply (rule P-induct[simplified UQ])
  apply simp
  done
qed

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
 apply (induct n)
 apply (simp-all add: Infinity)
 done

definition Nat :: ZF
```

where $Nat == Sep\ Inf\ (\lambda N.\ \exists n.\ nat2Nat\ n = N)$

lemma *Elem-nat2Nat-Nat*[*intro*]: $Elem\ (nat2Nat\ n)\ Nat$
by (*auto simp add*: *Nat-def Sep*)

lemma *Elem-Empty-Nat*: $Elem\ Empty\ Nat$
by (*auto simp add*: *Nat-def Sep Infinity*)

lemma *Elem-SucNat-Nat*: $Elem\ N\ Nat \Longrightarrow Elem\ (SucNat\ N)\ Nat$
by (*auto simp add*: *Nat-def Sep Infinity*)

lemma *no-infinite-Elem-down-chain*:
$Not\ (\exists f.\ isFun\ f \wedge Domain\ f = Nat \wedge (\forall N.\ Elem\ N\ Nat \longrightarrow Elem\ (f'(SucNat\ N))\ (f'N)))$
proof −
{
fix *f*
assume *f*: $isFun\ f \wedge Domain\ f = Nat \wedge (\forall N.\ Elem\ N\ Nat \longrightarrow Elem\ (f'(SucNat\ N))\ (f'N))$
let *?r* = $Range\ f$
have $?r \neq Empty$
apply (*auto simp add*: *Ext Empty*)
apply (*rule exI*[**where** *x*=*f' Empty*])
apply (*rule fun-value-in-range*)
apply (*auto simp add*: *f Elem-Empty-Nat*)
done
then have $\exists x.\ Elem\ x\ ?r \wedge (\forall y.\ Elem\ y\ x \longrightarrow Not(Elem\ y\ ?r))$
by (*simp add*: *Regularity*)
then obtain *x* **where** *x*: $Elem\ x\ ?r \wedge (\forall y.\ Elem\ y\ x \longrightarrow Not(Elem\ y\ ?r))$ **..**
then have $\exists N.\ Elem\ N\ (Domain\ f)\ \&\ f'N = x$
apply (*rule-tac fun-range-witness*)
apply (*simp-all add*: *f*)
done
then have $\exists N.\ Elem\ N\ Nat\ \&\ f'N = x$
by (*simp add*: *f*)
then obtain *N* **where** *N*: $Elem\ N\ Nat\ \&\ f'N = x$ **..**
from *N* **have** *N'*: $Elem\ N\ Nat$ **by** *auto*
let *?y* = $f'(SucNat\ N)$
have *Elem-y-r*: $Elem\ ?y\ ?r$
by (*simp-all add*: *f Elem-SucNat-Nat N fun-value-in-range*)
have $Elem\ ?y\ (f'N)$ **by** (*auto simp add*: *f N'*)
then have $Elem\ ?y\ x$ **by** (*simp add*: *N*)
with *x* **have** $Not\ (Elem\ ?y\ ?r)$ **by** *auto*
with *Elem-y-r* **have** *False* **by** *auto*
}
then show *?thesis* **by** *auto*
qed

lemma *Upair-nonEmpty*: $Upair\ a\ b \neq Empty$

```
  by (auto simp add: Ext Empty Upair)

lemma Singleton-nonEmpty: Singleton x ≠ Empty
  by (auto simp add: Singleton-def Upair-nonEmpty)

lemma notsym-Elem: Not(Elem a b & Elem b a)
proof −
  {
    fix a b
    assume ab: Elem a b
    assume ba: Elem b a
    let ?Z = Upair a b
    have ?Z ≠ Empty by (simp add: Upair-nonEmpty)
    then have ∃ x. Elem x ?Z ∧ (∀ y. Elem y x ⟶ Not(Elem y ?Z))
      by (simp add: Regularity)
    then obtain x where x:Elem x ?Z ∧ (∀ y. Elem y x ⟶ Not(Elem y ?Z)) ..
    then have x = a ∨ x = b by (simp add: Upair)
    moreover have x = a ⟶ Not (Elem b ?Z)
      by (auto simp add: x ba)
    moreover have x = b ⟶ Not (Elem a ?Z)
      by (auto simp add: x ab)
    ultimately have False
      by (auto simp add: Upair)
  }
  then show ?thesis by auto
qed

lemma irreflexiv-Elem: Not(Elem a a)
  by (simp add: notsym-Elem[of a a, simplified])

lemma antisym-Elem: Elem a b ⟹ Not (Elem b a)
  apply (insert notsym-Elem[of a b])
  apply auto
  done

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)
  apply (induct m)
  apply (auto simp add: Singleton union)
  apply (case-tac q <= m)
  apply auto
  apply (subgoal-tac q = Suc m)
  apply auto
  done
```

lemma *NatInterval-not-Empty*: *NatInterval n m* $\neq$ *Empty*
by (*auto intro*: *n-Elem-NatInterval*[**where** *q* = *0*, *simplified*] *simp add*: *Empty Ext*)

lemma *increasing-nat2Nat*[*rule-format*]: *0* < *n* $\longrightarrow$ *Elem* (*nat2Nat* (*n* − *1*)) (*nat2Nat n*)
apply (*case-tac* $\exists$ *m*. *n* = *Suc m*)
apply (*auto simp add*: *SucNat-def union Singleton*)
apply (*drule spec*[**where** *x*=*n* − *1*])
apply *arith*
done

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*)
apply (*induct m*)
apply (*auto simp add*: *Singleton union*)
apply (*rule-tac x*=*Suc* (*n*+*m*) **in** *exI*)
apply *auto*
done

lemma *inj-nat2Nat*: *inj nat2Nat*
proof −
{
fix *n m* :: *nat*
assume *nm*: *nat2Nat n* = *nat2Nat* (*n*+*m*)
assume *mg0*: *0* < *m*
let *?Z* = *NatInterval n m*
have *?Z* $\neq$ *Empty* **by** (*simp add*: *NatInterval-not-Empty*)
then have $\exists$ *x*. (*Elem x ?Z*) $\wedge$ ($\forall$ *y*. *Elem y x* $\longrightarrow$ *Not* (*Elem y ?Z*))
by (*auto simp add*: *Regularity*)
then obtain *x* **where** *x*:*Elem x ?Z* $\wedge$ ($\forall$ *y*. *Elem y x* $\longrightarrow$ *Not* (*Elem y ?Z*)) **..**
then have $\exists$ *u*. *n* $\leq$ *u* & *u* $\leq$ *n*+*m* & *nat2Nat u* = *x*
by (*simp add*: *represent-NatInterval*)
then obtain *u* **where** *u*: *n* $\leq$ *u* & *u* $\leq$ *n*+*m* $\wedge$ *nat2Nat u* = *x* **..**
have *n* < *u* $\longrightarrow$ *False*
proof
assume *n-less-u*: *n* < *u*
let *?y* = *nat2Nat* (*u* − *1*)
have *Elem ?y* (*nat2Nat u*)
apply (*rule increasing-nat2Nat*)
apply (*insert n-less-u*)
apply *arith*
done
with *u* **have** *Elem ?y x* **by** *auto*
with *x* **have** *Not* (*Elem ?y ?Z*) **by** *auto*
moreover have *Elem ?y ?Z*
apply (*insert n-Elem-NatInterval*[**where** *q* = *u* − *n* − *1* **and** *n*=*n* **and** *m*=*m*])
apply (*insert n-less-u*)

```
      apply (insert u)
      apply auto
      done
    ultimately show False by auto
  qed
  moreover have u = n ⟶ False
  proof
    assume u = n
    with u have nat2Nat n = x by auto
    then have nm-eq-x: nat2Nat (n+m) = x by (simp add: nm)
    let ?y = nat2Nat (n+m - 1)
    have Elem ?y (nat2Nat (n+m))
      apply (rule increasing-nat2Nat)
      apply (insert mg0)
      apply arith
      done
    with nm-eq-x have Elem ?y x by auto
    with x have Not (Elem ?y ?Z) by auto
    moreover have Elem ?y ?Z
     apply (insert n-Elem-NatInterval[where q = m - 1 and n=n and m=m])
      apply (insert mg0)
      apply auto
      done
    ultimately show False by auto
  qed
  ultimately have False using u by arith
 }
 note lemma-nat2Nat = this
 have th:⋀x y. ¬ (x < y ∧ (∀(m::nat). y ≠ x + m)) by presburger
 have th': ⋀x y. ¬ (x ≠ y ∧ (¬ x < y) ∧ (∀(m::nat). x ≠ y + m)) by presburger
 show ?thesis
  apply (auto simp add: inj-on-def)
  apply (case-tac x = y)
  apply auto
  apply (case-tac x < y)
  apply (case-tac ∃m. y = x + m & 0 < m)
  apply (auto intro: lemma-nat2Nat)
  apply (case-tac y < x)
  apply (case-tac ∃m. x = y + m & 0 < m)
  apply simp
  apply simp
  using th apply blast
  apply (case-tac ∃m. x = y + m)
  apply (auto intro: lemma-nat2Nat)
  apply (drule sym)
  using lemma-nat2Nat apply blast
  using th' apply blast
  done
qed
```

lemma *Nat2nat-nat2Nat*[*simp*]: *Nat2nat* (*nat2Nat n*) = *n*
by (*simp add*: *Nat2nat-def inv-f-f*[*OF inj-nat2Nat*])

lemma *nat2Nat-Nat2nat*[*simp*]: *Elem n Nat* ⟹ *nat2Nat* (*Nat2nat n*) = *n*
apply (*simp add*: *Nat2nat-def*)
apply (*rule-tac f-inv-into-f*)
apply (*auto simp add*: *image-def Nat-def Sep*)
done

lemma *Nat2nat-SucNat*: *Elem N Nat* ⟹ *Nat2nat* (*SucNat N*) = *Suc* (*Nat2nat N*)
apply (*auto simp add*: *Nat-def Sep Nat2nat-def*)
apply (*auto simp add*: *inv-f-f*[*OF inj-nat2Nat*])
apply (*simp only*: *nat2Nat.simps*[*symmetric*])
apply (*simp only*: *inv-f-f*[*OF inj-nat2Nat*])
done

lemma *Elem-Opair-exists*: ∃ *z*. *Elem x z* & *Elem y z* & *Elem z* (*Opair x y*)
apply (*rule exI*[**where** *x*=*Upair x y*])
by (*simp add*: *Upair Opair-def*)

lemma *UNIV-is-not-in-ZF*: *UNIV* ≠ *explode R*
proof
let *?Russell* = { *x*. *Not*(*Elem x x*) }
have *?Russell* = *UNIV* **by** (*simp add*: *irreflexiv-Elem*)
moreover assume *UNIV* = *explode R*
ultimately have *russell*: *?Russell* = *explode R* **by** *simp*
then show *False*
proof(*cases Elem R R*)
case *True*
then show *?thesis*
by (*insert irreflexiv-Elem*, *auto*)
next
case *False*
then have *R* ∈ *?Russell* **by** *auto*
then have *Elem R R* **by** (*simp add*: *russell explode-def*)
with *False* **show** *?thesis* **by** *auto*
qed
qed

definition *SpecialR* :: (*ZF* ∗ *ZF*) *set* **where**
SpecialR ≡ { (*x*, *y*) . *x* ≠ *Empty* ∧ *y* = *Empty*}

lemma *wf SpecialR*
apply (*subst wf-def*)

apply (*auto simp add*: *SpecialR-def*)
done

definition *Ext* :: (*'a* ∗ *'b*) *set* ⇒ *'b* ⇒ *'a set* **where**
Ext R y ≡ { *x* . (*x*, *y*) ∈ *R* }

lemma *Ext-Elem*: *Ext is-Elem-of* = *explode*
by (*auto simp add*: *Ext-def is-Elem-of-def explode-def*)

lemma *Ext SpecialR Empty* ≠ *explode z*
proof
have *Ext SpecialR Empty* = *UNIV* − {*Empty*}
by (*auto simp add*: *Ext-def SpecialR-def*)
moreover assume *Ext SpecialR Empty* = *explode z*
ultimately have *UNIV* = *explode*(*union z* (*Singleton Empty*))
by (*auto simp add*: *explode-def union Singleton*)
then show *False* **by** (*simp add*: *UNIV-is-not-in-ZF*)
qed

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

lemma *inj-explode*: *inj explode*
by (*auto simp add*: *inj-on-def explode-def Ext*)

lemma *implode-explode*[*simp*]: *implode* (*explode x*) = *x*
by (*simp add*: *implode-def inj-explode*)

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*
by (*simp add*: *regular-def is-Elem-of-def Regularity*)

lemma *set-like-Elem*: *set-like is-Elem-of*
by (*auto simp add*: *set-like-def image-def Ext-Elem*)

lemma *wfzf-is-Elem-of*: *wfzf is-Elem-of*
by (*auto simp add*: *wfzf-def regular-Elem set-like-Elem*)

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*))
apply (*auto simp add*: *SeqSum-def Sum Repl*)
apply (*rule-tac x* = *f n* **in** *exI*)
apply *auto*
done

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*)
apply (*auto*)
apply (*simp-all add*: *explode-def*)
done

lemma *Elem-Ext-ZF*: *set-like R* ⟹ *Elem x* (*Ext-ZF R s*) = ((*x*,*s*) ∈ *R*)
apply (*simp add*: *Ext-ZF-def*)
apply (*subst Elem-implode*)
apply (*simp add*: *set-like-def*)
apply (*simp add*: *Ext-def*)
done

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*))
by (*simp add*: *Ext-ZF-hull-def SeqSum*)

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 −
from *Elem-Ext-ZF-hull*[*OF set-like-R*] *x-hull*
have ∃ *n*. *Elem x* (*Ext-ZF-n R S n*) **by** *auto*
then obtain *n* **where** *n*:*Elem x* (*Ext-ZF-n R S n*) **..**
with *y-R-x* **have** *Elem y* (*Ext-ZF-n R S* (*Suc n*))
apply (*auto simp add*: *Repl Sum*)
apply (*rule-tac x*=*Ext-ZF R x* **in** *exI*)
apply (*auto simp add*: *Elem-Ext-ZF*[*OF set-like-R*])
done
with *Elem-Ext-ZF-hull*[*OF set-like-R*, **where** *x*=*y*] **show** *?thesis*

```
    by (auto simp del: Ext-ZF-n.simps)
qed

lemma wfzf-minimal:
  assumes hyps: wfzf R C ≠ {}
  shows ∃ x. x ∈ C ∧ (∀ y. (y, x) ∈ R ⟶ y ∉ C)
proof −
  from hyps have ∃ S. S ∈ C by auto
  then obtain S where S:S ∈ C by auto
  let ?T = Sep (Ext-ZF-hull R S) (λ s. s ∈ C)
  from hyps have set-like-R: set-like R by (simp add: wfzf-def)
  show ?thesis
  proof (cases ?T = Empty)
    case True
    then have ∀ z. ¬ (Elem z (Sep (Ext-ZF R S) (λ s. s ∈ C)))
      apply (auto simp add: Ext Empty Sep Ext-ZF-hull-def SeqSum)
      apply (erule-tac x=z in allE, auto)
      apply (erule-tac x=0 in allE, auto)
      done
    then show ?thesis
      apply (rule-tac exI[where x=S])
      apply (auto simp add: Sep Empty S)
      apply (erule-tac x=y in allE)
      apply (simp add: set-like-R Elem-Ext-ZF)
      done
  next
    case False
    from hyps have regular-R: regular R by (simp add: wfzf-def)
    from
      regular-R[simplified regular-def, rule-format, OF False, simplified Sep]
      Elem-Elem-Ext-ZF-hull[OF set-like-R]
    show ?thesis by blast
  qed
qed

lemma wfzf-implies-wf: wfzf R ⟹ wf R
proof (subst wf-def, rule allI)
  assume wfzf: wfzf R
  fix P :: ZF ⇒ bool
  let ?C = {x. P x}
  {
    assume induct: (∀ x. (∀ y. (y, x) ∈ R ⟶ P y) ⟶ P x)
    let ?C = {x. ¬ (P x)}
    have ?C = {}
    proof (rule ccontr)
      assume C: ?C ≠ {}
      from
        wfzf-minimal[OF wfzf C]
      obtain x where x: x ∈ ?C ∧ (∀ y. (y, x) ∈ R ⟶ y ∉ ?C) ..
```

```
    then have P x
      apply (rule-tac induct[rule-format])
      apply auto
      done
    with x show False by auto
  qed
  then have ∀ x. P x by auto
 }
 then show (∀ x. (∀ y. (y, x) ∈ R ⟶ P y) ⟶ P x) ⟶ (∀ x. P x) by blast
qed

lemma wf-is-Elem-of: wf is-Elem-of
 by (auto simp add: wfzf-is-Elem-of wfzf-implies-wf)

lemma in-Ext-RTrans-implies-Elem-Ext-ZF-hull:
 set-like R ⟹ x ∈ (Ext (R⁺) s) ⟹ Elem x (Ext-ZF-hull R s)
 apply (simp add: Ext-def Elem-Ext-ZF-hull)
 apply (erule converse-trancl-induct[where r=R])
 apply (rule exI[where x=0])
 apply (simp add: Elem-Ext-ZF)
 apply auto
 apply (rule-tac x=Suc n in exI)
 apply (simp add: Sum Repl)
 apply (rule-tac x=Ext-ZF R z in exI)
 apply (auto simp add: Elem-Ext-ZF)
 done

lemma implodeable-Ext-trancl: set-like R ⟹ set-like (R⁺)
 apply (subst set-like-def)
 apply (auto simp add: image-def)
 apply (rule-tac x=Sep (Ext-ZF-hull R y) (λ z. z ∈ (Ext (R⁺) y)) in exI)
 apply (auto simp add: explode-def Sep set-eqI
   in-Ext-RTrans-implies-Elem-Ext-ZF-hull)
 done

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)
 apply (induct-tac n)
 apply (auto simp add: Elem-Ext-ZF Ext-def Sum Repl)
 done

lemma set-like R ⟹ Ext-ZF (R⁺) s = Ext-ZF-hull R s
 apply (frule implodeable-Ext-trancl)
 apply (auto simp add: Ext)
 apply (erule in-Ext-RTrans-implies-Elem-Ext-ZF-hull)
 apply (simp add: Elem-Ext-ZF Ext-def)
 apply (auto simp add: Elem-Ext-ZF Elem-Ext-ZF-hull)
 apply (erule Elem-Ext-ZF-hull-implies-in-Ext-RTrans[simplified Ext-def, simplified], assumption)
```

done

lemma *wf-implies-regular*: *wf R* $\Longrightarrow$ *regular R*
proof (*simp add*: *regular-def*, *rule allI*)
assume *wf*: *wf R*
fix *A*
show *A* $\neq$ *Empty* $\longrightarrow$ ($\exists\, x.$ *Elem x A* $\wedge$ ($\forall\, y.$ $(y, x) \in R \longrightarrow \neg$ *Elem y A*))
proof
assume *A*: *A* $\neq$ *Empty*
then have $\exists\, x.$ *x* $\in$ *explode A*
by (*auto simp add*: *explode-def Ext Empty*)
then obtain *x* **where** *x*:*x* $\in$ *explode A* **..**
from *iffD1*[*OF wf-eq-minimal wf*, *rule-format*, **where** *Q*=*explode A*, *OF x*]
obtain *z* **where** *z* $\in$ *explode A* $\wedge$ ($\forall\, y.$ $(y, z) \in R \longrightarrow y \notin$ *explode A*) **by** *auto*

then show $\exists\, x.$ *Elem x A* $\wedge$ ($\forall\, y.$ $(y, x) \in R \longrightarrow \neg$ *Elem y A*)
apply (*rule-tac exI*[**where** *x* = *z*])
apply (*simp add*: *explode-def*)
done
qed
qed

lemma *wf-eq-wfzf*: (*wf R* $\wedge$ *set-like R*) = *wfzf R*
apply (*auto simp add*: *wfzf-implies-wf*)
apply (*auto simp add*: *wfzf-def wf-implies-regular*)
done

lemma *wfzf-trancl*: *wfzf R* $\Longrightarrow$ *wfzf* (R^+)
by (*auto simp add*: *wf-eq-wfzf*[*symmetric*] *implodeable-Ext-trancl wf-trancl*)

lemma *Ext-subset-mono*: *R* $\subseteq$ *S* $\Longrightarrow$ *Ext R y* $\subseteq$ *Ext S y*
by (*auto simp add*: *Ext-def*)

lemma *set-like-subset*: *set-like R* $\Longrightarrow$ *S* $\subseteq$ *R* $\Longrightarrow$ *set-like S*
apply (*auto simp add*: *set-like-def*)
apply (*erule-tac x*=*y* **in** *allE*)
apply (*drule-tac y*=*y* **in** *Ext-subset-mono*)
apply (*auto simp add*: *image-def*)
apply (*rule-tac x*=*Sep x* (% *z*. *z* $\in$ (*Ext S y*)) **in** *exI*)
apply (*auto simp add*: *explode-def Sep*)
done

lemma *wfzf-subset*: *wfzf S* $\Longrightarrow$ *R* $\subseteq$ *S* $\Longrightarrow$ *wfzf R*
by (*auto intro*: *set-like-subset wf-subset simp add*: *wf-eq-wfzf*[*symmetric*])

end

theory *Zet*

imports *HOLZF*
begin

definition *zet* = {*A* :: *'a set* | *A f z. inj-on f A* ∧ *f ' A* ⊆ *explode z*}

typedef *'a zet* = *zet* :: *'a set set*
  unfolding *zet-def* **by** *blast*

definition *zin* :: *'a* ⇒ *'a zet* ⇒ *bool* **where**
  zin x A == *x* ∈ (*Rep-zet A*)

lemma *zet-ext-eq*: (*A* = *B*) = (∀ *x. zin x A* = *zin x B*)
  by (*auto simp add*: *Rep-zet-inject*[*symmetric*] *zin-def*)

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

lemma *zet-def'*: *zet* = {*A* :: *'a set* | *A f z. inj-on f A* ∧ *f ' A* = *explode z*}
  apply (*rule set-eqI*)
  apply (*auto simp add*: *zet-def*)
  apply (*rule-tac x*=*f* **in** *exI*)
  apply *auto*
  apply (*rule-tac x*=*Sep z* (λ *y. y* ∈ (*f ' x*)) **in** *exI*)
  apply (*auto simp add*: *explode-def Sep*)
  done

lemma *image-zet-rep*: *A* ∈ *zet* ⟹ ∃ *z* . *g ' A* = *explode z*
  apply (*auto simp add*: *zet-def'*)
  apply (*rule-tac x*=*Repl z* (*g o* (*inv-into A f*)) **in** *exI*)
  apply (*simp add*: *explode-Repl-eq*)
  apply (*subgoal-tac explode z* = *f ' A*)
  apply (*simp-all add*: *image-image cong*: *image-cong-simp*)
  done

lemma *zet-image-mem*:
  assumes *Azet*: *A* ∈ *zet*
  shows *g ' A* ∈ *zet*
proof −
  from *Azet* **have** ∃ (*f* :: - ⇒ *ZF*). *inj-on f A*
    by (*auto simp add*: *zet-def'*)
  then obtain *f* **where** *injf*: *inj-on* (*f* :: - ⇒ *ZF*) *A*
    by *auto*
  let *?w* = *f o* (*inv-into A g*)
  have *subset*: (*inv-into A g*) *'* (*g ' A*) ⊆ *A*
    by (*auto simp add*: *inv-into-into*)
  have *inj-on* (*inv-into A g*) (*g ' A*) **by** (*simp add*: *inj-on-inv-into*)
  then have *injw*: *inj-on ?w* (*g ' A*)
    apply (*rule comp-inj-on*)
    apply (*rule inj-on-subset*[**where** *A*=*A*])

```
    apply (auto simp add: subset injf)
    done
  show ?thesis
    apply (simp add: zet-def' image-comp)
    apply (rule exI[where x=?w])
    apply (simp add: injw image-zet-rep Azet)
    done
qed

lemma Rep-zimage-eq: Rep-zet (zimage f A) = image f (Rep-zet A)
  apply (simp add: zimage-def)
  apply (subst Abs-zet-inverse)
  apply (simp-all add: Rep-zet zet-image-mem)
  done

lemma zimage-iff: zin y (zimage f A) = (∃ x. zin x A ∧ y = f x)
  by (auto simp add: zin-def Rep-zimage-eq)

definition zimplode :: ZF zet ⇒ ZF where
  zimplode A == implode (Rep-zet A)

definition zexplode :: ZF ⇒ ZF zet where
  zexplode z == Abs-zet (explode z)

lemma Rep-zet-eq-explode: ∃ z. Rep-zet A = explode z
  by (rule image-zet-rep[where g=λ x. x,OF Rep-zet, simplified])

lemma zexplode-zimplode: zexplode (zimplode A) = A
  apply (simp add: zimplode-def zexplode-def)
  apply (simp add: implode-def)
  apply (subst f-inv-into-f[where y=Rep-zet A])
  apply (auto simp add: Rep-zet-inverse Rep-zet-eq-explode image-def)
  done

lemma explode-mem-zet: explode z ∈ zet
  apply (simp add: zet-def')
  apply (rule-tac x=% x. x in exI)
  apply (auto simp add: inj-on-def)
  done

lemma zimplode-zexplode: zimplode (zexplode z) = z
  apply (simp add: zimplode-def zexplode-def)
  apply (subst Abs-zet-inverse)
  apply (auto simp add: explode-mem-zet)
  done

lemma zin-zexplode-eq: zin x (zexplode A) = Elem x A
  apply (simp add: zin-def zexplode-def)
  apply (subst Abs-zet-inverse)
```

apply (*simp-all add*: *explode-Elem explode-mem-zet*)
done

lemma *comp-zimage-eq*: *zimage g* (*zimage f A*) = *zimage* (*g o f*) *A*
apply (*simp add*: *zimage-def*)
apply (*subst Abs-zet-inverse*)
apply (*simp-all add*: *image-comp zet-image-mem Rep-zet*)
done

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*)
apply (*rule set-eqI*)
apply (*simp add*: *explode-def union*)
done

lemma *Rep-zet-zunion*: *Rep-zet* (*zunion a b*) = (*Rep-zet a*) ∪ (*Rep-zet b*)
proof −
from *Rep-zet*[*of a*] **have** ∃ *f z*. *inj-on f* (*Rep-zet a*) ∧ *f* ‘ (*Rep-zet a*) = *explode z*
by (*auto simp add*: *zet-def'*)
then obtain *fa za* **where** *a*:*inj-on fa* (*Rep-zet a*) ∧ *fa* ‘ (*Rep-zet a*) = *explode za*
by *blast*
from *a* **have** *fa*: *inj-on fa* (*Rep-zet a*) **by** *blast*
from *a* **have** *za*: *fa* ‘ (*Rep-zet a*) = *explode za* **by** *blast*
from *Rep-zet*[*of b*] **have** ∃ *f z*. *inj-on f* (*Rep-zet b*) ∧ *f* ‘ (*Rep-zet b*) = *explode z*
by (*auto simp add*: *zet-def'*)
then obtain *fb zb* **where** *b*:*inj-on fb* (*Rep-zet b*) ∧ *fb* ‘ (*Rep-zet b*) = *explode zb*
by *blast*
from *b* **have** *fb*: *inj-on fb* (*Rep-zet b*) **by** *blast*
from *b* **have** *zb*: *fb* ‘ (*Rep-zet b*) = *explode zb* **by** *blast*
let *?f* = (λ *x*. *if x* ∈ (*Rep-zet a*) *then Opair* (*fa x*) (*Empty*) *else Opair* (*fb x*) (*Singleton Empty*))
let *?z* = *CartProd* (*union za zb*) (*Upair Empty* (*Singleton Empty*))
have *se*: *Singleton Empty* ≠ *Empty*
apply (*auto simp add*: *Ext Singleton*)
apply (*rule exI*[**where** *x*=*Empty*])
apply (*simp add*: *Empty*)
done
show *?thesis*
apply (*simp add*: *zunion-def*)
apply (*subst Abs-zet-inverse*)
apply (*auto simp add*: *zet-def*)
apply (*rule exI*[**where** *x* = *?f*])
apply (*rule conjI*)
apply (*auto simp add*: *inj-on-def Opair inj-onD*[*OF fa*] *inj-onD*[*OF fb*] *se*

se[*symmetric*])
  apply (*rule exI*[**where** *x* = *?z*])
  apply (*insert za zb*)
  apply (*auto simp add*: *explode-def CartProd union Upair Opair*)
  done
qed

lemma *zunion*: *zin x* (*zunion a b*) = ((*zin x a*) ∨ (*zin x b*))
  by (*auto simp add*: *zin-def Rep-zet-zunion*)

lemma *zimage-zexplode-eq*: *zimage f* (*zexplode z*) = *zexplode* (*Repl z f*)
  by (*simp add*: *zet-ext-eq zin-zexplode-eq Repl zimage-iff*)

lemma *range-explode-eq-zet*: *range explode* = *zet*
  apply (*rule set-eqI*)
  apply (*auto simp add*: *explode-mem-zet*)
  apply (*drule image-zet-rep*)
  apply (*simp add*: *image-def*)
  apply *auto*
  apply (*rule-tac x*=*z* **in** *exI*)
  apply *auto*
  done

lemma *Elem-zimplode*: (*Elem x* (*zimplode z*)) = (*zin x z*)
  apply (*simp add*: *zimplode-def*)
  apply (*subst Elem-implode*)
  apply (*simp-all add*: *zin-def Rep-zet range-explode-eq-zet*)
  done

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

lemma *zempty*[*simp*]: ¬ (*zin x zempty*)
  by (*auto simp add*: *zin-def zempty-def Abs-zet-inverse zet-def*)

lemma *zimage-zempty*[*simp*]: *zimage f zempty* = *zempty*
  by (*auto simp add*: *zet-ext-eq zimage-iff*)

lemma *zunion-zempty-left*[*simp*]: *zunion zempty a* = *a*
  by (*simp add*: *zet-ext-eq zunion*)

lemma *zunion-zempty-right*[*simp*]: *zunion a zempty* = *a*
  by (*simp add*: *zet-ext-eq zunion*)

lemma *zimage-id*[*simp*]: *zimage id A* = *A*
  by (*simp add*: *zet-ext-eq zimage-iff*)

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

by (*auto simp add*: *zet-ext-eq zimage-iff*)

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*
apply (*induct as bs rule*: *lprod.induct*)
apply *auto*
done

lemma (*as*, *bs*) ∈ *lprod R* ⟹ 1 ≤ *length as* ∧ 1 ≤ *length bs*
apply (*induct as bs rule*: *lprod.induct*)
apply *auto*
done

lemma *lprod-subset-elem*: (*as*, *bs*) ∈ *lprod S* ⟹ *S* ⊆ *R* ⟹ (*as*, *bs*) ∈ *lprod R*
apply (*induct as bs rule*: *lprod.induct*)
apply (*auto*)
done

lemma *lprod-subset*: *S* ⊆ *R* ⟹ *lprod S* ⊆ *lprod R*
by (*auto intro*: *lprod-subset-elem*)

lemma *lprod-implies-mult*: (*as*, *bs*) ∈ *lprod R* ⟹ *trans R* ⟹ (*mset as*, *mset bs*) ∈ *mult R*
proof (*induct as bs rule*: *lprod.induct*)
case (*lprod-single a b*)
note *step* = *one-step-implies-mult*[
where *r*=*R* **and** *I*={#} **and** *K*={#*a*#} **and** *J*={#*b*#}, *simplified*]
show *?case* **by** (*auto intro*: *lprod-single step*)
next
case (*lprod-list ah at bh bt a b*)
then have *transR*: *trans R* **by** *auto*
have *as*: *mset* (*ah* @ *a* # *at*) = *mset* (*ah* @ *at*) + {#*a*#} (**is** - = *?ma* + -)
by (*simp add*: *algebra-simps*)
have *bs*: *mset* (*bh* @ *b* # *bt*) = *mset* (*bh* @ *bt*) + {#*b*#} (**is** - = *?mb* + -)
by (*simp add*: *algebra-simps*)

```
  from lprod-list have (?ma, ?mb) ∈ mult R
    by auto
  with mult-implies-one-step[OF transR] have
     ∃ I J K. ?mb = I + J ∧ ?ma = I + K ∧ J ≠ {#} ∧ (∀ k∈set-mset K.
∃ j∈set-mset J. (k, j) ∈ R)
    by blast
  then obtain I J K where
     decomposed: ?mb = I + J ∧ ?ma = I + K ∧ J ≠ {#} ∧ (∀ k∈set-mset K.
∃ j∈set-mset J. (k, j) ∈ R)
    by blast
  show ?case
  proof (cases a = b)
    case True
    have ((I + {#b#}) + K, (I + {#b#}) + J) ∈ mult R
      apply (rule one-step-implies-mult)
      apply (auto simp add: decomposed)
      done
    then show ?thesis
      apply (simp only: as bs)
      apply (simp only: decomposed True)
      apply (simp add: algebra-simps)
      done
  next
    case False
    from False lprod-list have False: (a, b) ∈ R by blast
    have (I + (K + {#a#}), I + (J + {#b#})) ∈ mult R
      apply (rule one-step-implies-mult)
      apply (auto simp add: False decomposed)
      done
    then show ?thesis
      apply (simp only: as bs)
      apply (simp only: decomposed)
      apply (simp add: algebra-simps)
      done
  qed
qed

lemma wf-lprod[simp,intro]:
  assumes wf-R: wf R
  shows wf (lprod R)
proof −
  have subset: lprod (R⁺) ⊆ inv-image (mult (R⁺)) mset
    by (auto simp add: lprod-implies-mult trans-trancl)
 note lprodtrancl = wf-subset[OF wf-inv-image[where r=mult (R⁺) and f=mset,

    OF wf-mult[OF wf-trancl[OF wf-R]]], OF subset]
  note lprod = wf-subset[OF lprodtrancl, where p=lprod R, OF lprod-subset, sim-
plified]
  show ?thesis by (auto intro: lprod)
```

qed

definition *gprod-2-2* :: $('a * 'a)$ *set* $\Rightarrow$ $(('a * 'a) * ('a * 'a))$ *set* **where**
gprod-2-2 R $\equiv$ { $((a,b), (c,d))$. $(a = c \wedge (b,d) \in R) \vee (b = d \wedge (a,c) \in R)$ }

definition *gprod-2-1* :: $('a * 'a)$ *set* $\Rightarrow$ $(('a * 'a) * ('a * 'a))$ *set* **where**
gprod-2-1 R $\equiv$ { $((a,b), (c,d))$. $(a = d \wedge (b,c) \in R) \vee (b = c \wedge (a,d) \in R)$ }

lemma *lprod-2-3*: $(a, b) \in R \Longrightarrow ([a, c], [b, c]) \in lprod\ R$
by (*auto intro*: *lprod-list*[**where** *a*=*c* **and** *b*=*c* **and**
ah = [*a*] **and** *at* = [] **and** *bh*=[*b*] **and** *bt*=[], *simplified*])

lemma *lprod-2-4*: $(a, b) \in R \Longrightarrow ([c, a], [c, b]) \in lprod\ R$
by (*auto intro*: *lprod-list*[**where** *a*=*c* **and** *b*=*c* **and**
ah = [] **and** *at* = [*a*] **and** *bh*=[] **and** *bt*=[*b*], *simplified*])

lemma *lprod-2-1*: $(a, b) \in R \Longrightarrow ([c, a], [b, c]) \in lprod\ R$
by (*auto intro*: *lprod-list*[**where** *a*=*c* **and** *b*=*c* **and**
ah = [] **and** *at* = [*a*] **and** *bh*=[*b*] **and** *bt*=[], *simplified*])

lemma *lprod-2-2*: $(a, b) \in R \Longrightarrow ([a, c], [c, b]) \in lprod\ R$
by (*auto intro*: *lprod-list*[**where** *a*=*c* **and** *b*=*c* **and**
ah = [*a*] **and** *at* = [] **and** *bh*=[] **and** *bt*=[*b*], *simplified*])

lemma [*simp*, *intro*]:
assumes *wfR*: *wf R* **shows** *wf* (*gprod-2-1 R*)
proof −
have *gprod-2-1 R* $\subseteq$ *inv-image* (*lprod R*) (λ (*a*,*b*). [*a*,*b*])
by (*auto simp add*: *gprod-2-1-def lprod-2-1 lprod-2-2*)
with *wfR* **show** *?thesis*
by (*rule-tac wf-subset*, *auto*)
qed

lemma [*simp*, *intro*]:
assumes *wfR*: *wf R* **shows** *wf* (*gprod-2-2 R*)
proof −
have *gprod-2-2 R* $\subseteq$ *inv-image* (*lprod R*) (λ (*a*,*b*). [*a*,*b*])
by (*auto simp add*: *gprod-2-2-def lprod-2-3 lprod-2-4*)
with *wfR* **show** *?thesis*
by (*rule-tac wf-subset*, *auto*)
qed

lemma *lprod-3-1*: **assumes** $(x', x) \in R$ **shows** $([y, z, x'], [x, y, z]) \in lprod\ R$
apply (*rule lprod-list*[**where** *a*=*y* **and** *b*=*y* **and** *ah*=[] **and** *at*=[*z*,*x'*] **and** *bh*=[*x*]
and *bt*=[*z*], *simplified*])
apply (*auto simp add*: *lprod-2-1 assms*)
done

lemma *lprod-3-2*: **assumes** $(z',z) \in R$ **shows** $([z', x, y], [x,y,z]) \in lprod\ R$

apply (*rule lprod-list*[**where** *a*=*y* **and** *b*=*y* **and** *ah*=[*z'*,*x*] **and** *at*=[] **and** *bh*=[*x*] **and** *bt*=[*z*], *simplified*])
apply (*auto simp add*: *lprod-2-2 assms*)
done

lemma *lprod-3-3*: **assumes** *xr*: (*xr*, *x*) ∈ *R* **shows** ([*xr*, *y*, *z*], [*x*, *y*, *z*]) ∈ *lprod R*
apply (*rule lprod-list*[**where** *a*=*y* **and** *b*=*y* **and** *ah*=[*xr*] **and** *at*=[*z*] **and** *bh*=[*x*] **and** *bt*=[*z*], *simplified*])
apply (*simp add*: *xr lprod-2-3*)
done

lemma *lprod-3-4*: **assumes** *yr*: (*yr*, *y*) ∈ *R* **shows** ([*x*, *yr*, *z*], [*x*, *y*, *z*]) ∈ *lprod R*
apply (*rule lprod-list*[**where** *a*=*x* **and** *b*=*x* **and** *ah*=[] **and** *at*=[*yr*,*z*] **and** *bh*=[] **and** *bt*=[*y*,*z*], *simplified*])
apply (*simp add*: *yr lprod-2-3*)
done

lemma *lprod-3-5*: **assumes** *zr*: (*zr*, *z*) ∈ *R* **shows** ([*x*, *y*, *zr*], [*x*, *y*, *z*]) ∈ *lprod R*
apply (*rule lprod-list*[**where** *a*=*x* **and** *b*=*x* **and** *ah*=[] **and** *at*=[*y*,*zr*] **and** *bh*=[] **and** *bt*=[*y*,*z*], *simplified*])
apply (*simp add*: *zr lprod-2-4*)
done

lemma *lprod-3-6*: **assumes** *y'*: (*y'*, *y*) ∈ *R* **shows** ([*x*, *z*, *y'*], [*x*, *y*, *z*]) ∈ *lprod R*
apply (*rule lprod-list*[**where** *a*=*z* **and** *b*=*z* **and** *ah*=[*x*] **and** *at*=[*y'*] **and** *bh*=[*x*,*y*] **and** *bt*=[], *simplified*])
apply (*simp add*: *y' lprod-2-4*)
done

lemma *lprod-3-7*: **assumes** *z'*: (*z'*,*z*) ∈ *R* **shows** ([*x*, *z'*, *y*], [*x*, *y*, *z*]) ∈ *lprod R*
apply (*rule lprod-list*[**where** *a*=*y* **and** *b*=*y* **and** *ah*=[*x*, *z'*] **and** *at*=[] **and** *bh*=[*x*] **and** *bt*=[*z*], *simplified*])
apply (*simp add*: *z' lprod-2-4*)
done

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*))
oops

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

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*)
  apply (*auto simp add*: *mono-def fixgames-def*)
  apply (*rule-tac x*=*l* **in** *exI*)
  apply (*rule-tac x*=*r* **in** *exI*)
  apply *auto*
  done

lemma *games-lfp-unfold*: *games-lfp* = *fixgames games-lfp*
  by (*auto simp add*: *def-lfp-unfold games-lfp-def mono-fixgames*)

lemma *games-gfp-unfold*: *games-gfp* = *fixgames games-gfp*
  by (*auto simp add*: *def-gfp-unfold games-gfp-def mono-fixgames*)

lemma *games-lfp-nonempty*: *Opair Empty Empty* ∈ *games-lfp*
proof −
  have *fixgames* {} ⊆ *games-lfp*
    apply (*subst games-lfp-unfold*)
    apply (*simp add*: *mono-fixgames*[*simplified mono-def*, *rule-format*])
    done
  moreover have *fixgames* {} = {*Opair Empty Empty*}
    by (*simp add*: *fixgames-def explode-Empty*)
  finally show *?thesis*
    by *auto*
qed

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 −
have *games-lfp* ⊆ *fixgames games-lfp*
by (*simp add*: *games-lfp-unfold*[*symmetric*])
then show *?thesis*
by (*simp add*: *games-gfp-def gfp-upperbound*)
qed

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 −
from *g fixgames* **have** *g* ∈ *fixgames games* **by** *auto*
then have ∃ *l r*. *g* = *Opair l r* ∧ *explode l* ⊆ *games* ∧ *explode r* ⊆ *games*
by (*simp add*: *fixgames-def*)
then obtain *l* **where** ∃ *r*. *g* = *Opair l r* ∧ *explode l* ⊆ *games* ∧ *explode r* ⊆ *games* **..**
then obtain *r* **where** *lr*: *g* = *Opair l r* ∧ *explode l* ⊆ *games* ∧ *explode r* ⊆ *games* **..**
with *opt* **show** *?thesis*
by (*auto intro*: *Elem-explode-in simp add*: *left-option-def right-option-def Fst Snd*)
qed

lemma *option2elem*: (*opt*,*g*) ∈ *is-option-of* ⟹ ∃ *u v*. *Elem opt u* ∧ *Elem u v* ∧ *Elem v g*
apply (*simp add*: *is-option-of-def*)
apply (*subgoal-tac* (*g* ∈ *games-gfp*) = (*g* ∈ (*fixgames games-gfp*)))
prefer *2*
apply (*simp add*: *games-gfp-unfold*[*symmetric*])
apply (*auto simp add*: *fixgames-def left-option-def right-option-def Fst Snd*)
apply (*rule-tac x*=*l* **in** *exI*, *insert Elem-Opair-exists*, *blast*)
apply (*rule-tac x*=*r* **in** *exI*, *insert Elem-Opair-exists*, *blast*)
done

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

```
    fix opt
    fix g
    assume (opt, g) ∈ is-option-of
    then have ∃ u v. (opt, u) ∈ (is-Elem-of⁺) ∧ (u,v) ∈ (is-Elem-of⁺) ∧ (v,g) ∈
(is-Elem-of⁺)
      apply −
      apply (drule option2elem)
      apply (auto simp add: r-into-trancl′ is-Elem-of-def)
      done
    then have (opt, g) ∈ (is-Elem-of⁺)
      by (blast intro: trancl-into-rtrancl trancl-rtrancl-trancl)
  }
  then show ?thesis by auto
qed

lemma wfzf-is-option-of: wfzf is-option-of
proof −
  have wfzf (is-Elem-of⁺) by (simp add: wfzf-trancl wfzf-is-Elem-of)
  then show ?thesis
    apply (rule wfzf-subset)
    apply (rule is-option-of-subset-is-Elem-of)
    done
  qed

lemma games-gfp-imp-lfp: g ∈ games-gfp ⟶ g ∈ games-lfp
proof −
  have unfold-gfp: ⋀ x. x ∈ games-gfp ⟹ x ∈ (fixgames games-gfp)
    by (simp add: games-gfp-unfold[symmetric])
  have unfold-lfp: ⋀ x. (x ∈ games-lfp) = (x ∈ (fixgames games-lfp))
    by (simp add: games-lfp-unfold[symmetric])
  show ?thesis
    apply (rule wf-induct[OF wfzf-implies-wf[OF wfzf-is-option-of]])
    apply (auto simp add: is-option-of-def)
    apply (drule-tac unfold-gfp)
    apply (simp add: fixgames-def)
    apply (auto simp add: left-option-def Fst right-option-def Snd)
    apply (subgoal-tac explode l ⊆ games-lfp)
    apply (subgoal-tac explode r ⊆ games-lfp)
    apply (subst unfold-lfp)
    apply (auto simp add: fixgames-def)
    apply (simp-all add: explode-Elem Elem-explode-in)
    done
qed

theorem games-lfp-eq-gfp: games-lfp = games-gfp
  apply (auto simp add: games-gfp-imp-lfp)
  apply (insert games-lfp-subset-gfp)
  apply auto
  done
```

theorem *unique-games*: $(g = \mathit{fixgames}\ g) = (g = \mathit{games\text{-}lfp})$
proof −
  {
    fix g
    assume *g*: $g = \mathit{fixgames}\ g$
    from g **have** $\mathit{fixgames}\ g \subseteq g$ **by** *auto*
    then have *l*:$\mathit{games\text{-}lfp} \subseteq g$
      by (*simp add*: *games-lfp-def lfp-lowerbound*)
    from g **have** $g \subseteq \mathit{fixgames}\ g$ **by** *auto*
    then have *u*:$g \subseteq \mathit{games\text{-}gfp}$
      by (*simp add*: *games-gfp-def gfp-upperbound*)
    from $l\ u$ *games-lfp-eq-gfp*[*symmetric*] **have** $g = \mathit{games\text{-}lfp}$
      by *auto*
  }
  note $\mathit{games} = \mathit{this}$
  show *?thesis*
    apply (*rule iffI*)
    apply (*erule games*)
    apply (*simp add*: *games-lfp-unfold*[*symmetric*])
    done
qed

lemma *games-lfp-option-stable*:
  assumes *g*: $g \in \mathit{games\text{-}lfp}$
  and *opt*: $\mathit{left\text{-}option}\ g\ \mathit{opt} \vee \mathit{right\text{-}option}\ g\ \mathit{opt}$
  shows $\mathit{opt} \in \mathit{games\text{-}lfp}$
  apply (*rule games-option-stable*[**where** *g*=*g*])
  apply (*simp add*: *games-lfp-unfold*[*symmetric*])
  apply (*simp-all add*: *assms*)
  done

lemma *is-option-of-imp-games*:
  assumes *hyp*: $(\mathit{opt}, g) \in \mathit{is\text{-}option\text{-}of}$
  shows $\mathit{opt} \in \mathit{games\text{-}lfp} \wedge g \in \mathit{games\text{-}lfp}$
proof −
  from *hyp* **have** *g-game*: $g \in \mathit{games\text{-}lfp}$
    by (*simp add*: *is-option-of-def games-lfp-eq-gfp*)
  from *hyp* **have** $\mathit{left\text{-}option}\ g\ \mathit{opt} \vee \mathit{right\text{-}option}\ g\ \mathit{opt}$
    by (*auto simp add*: *is-option-of-def*)
  with *g-game games-lfp-option-stable*[*OF g-game*, *OF this*] **show** *?thesis*
    by *auto*
qed

lemma *games-lfp-represent*: $x \in \mathit{games\text{-}lfp} \Longrightarrow \exists\ l\ r.\ x = \mathit{Opair}\ l\ r$
  apply (*rule exI*[**where** *x*=*Fst x*])
  apply (*rule exI*[**where** *x*=*Snd x*])
  apply (*subgoal-tac* $x \in (\mathit{fixgames\ games\text{-}lfp})$)
  apply (*simp add*: *fixgames-def*)

apply (*auto simp add*: *Fst Snd*)
apply (*simp add*: *games-lfp-unfold*[*symmetric*])
done

definition *game* = *games-lfp*

typedef *game* = *game*
unfolding *game-def* **by** (*blast intro*: *games-lfp-nonempty*)

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*
apply (*subst Ext*)
apply (*simp add*: *Repl*)
apply *auto*
apply (*subst Abs-game-inverse*, *simp-all add*: *game-def*)
apply (*rule-tac x*=*za* **in** *exI*)
apply (*subst Abs-game-inverse*, *simp-all add*: *game-def*)
done

lemma *game-split*: *g* = *Game* (*left-options g*) (*right-options g*)
proof −
have ∃ *l r*. *Rep-game g* = *Opair l r*
apply (*insert Rep-game*[*of g*])
apply (*simp add*: *game-def games-lfp-represent*)
done
then obtain *l r* **where** *lr*: *Rep-game g* = *Opair l r* **by** *auto*
have *partizan-g*: *Rep-game g* ∈ *games-lfp*
apply (*insert Rep-game*[*of g*])
apply (*simp add*: *game-def*)
done
have ∀ *e*. *Elem e l* ⟶ *left-option* (*Rep-game g*) *e*
by (*simp add*: *lr left-option-def Fst*)
then have *partizan-l*: ∀ *e*. *Elem e l* ⟶ *e* ∈ *games-lfp*
apply *auto*
apply (*rule games-lfp-option-stable*[**where** *g*=*Rep-game g*, *OF partizan-g*])
apply *auto*

```
    done
  have ∀ e. Elem e r ⟶ right-option (Rep-game g) e
    by (simp add: lr right-option-def Snd)
  then have partizan-r: ∀ e. Elem e r ⟶ e ∈ games-lfp
    apply auto
    apply (rule games-lfp-option-stable[where g=Rep-game g, OF partizan-g])
    apply auto
    done
  let ?L = zimage (Abs-game) (zexplode l)
  let ?R = zimage (Abs-game) (zexplode r)
  have L:?L = left-options g
    by (simp add: left-options-def lr Fst)
  have R:?R = right-options g
    by (simp add: right-options-def lr Snd)
  have g = Game ?L ?R
    apply (simp add: Game-def Rep-game-inject[symmetric] comp-zimage-eq zimage-zexplode-eq zimplode-zexplode)
    apply (simp add: Repl-Rep-game-Abs-game partizan-l partizan-r)
    apply (subst Abs-game-inverse)
    apply (simp-all add: lr[symmetric] Rep-game)
    done
  then show ?thesis
    by (simp add: L R)
qed

lemma Opair-in-games-lfp:
  assumes l: explode l ⊆ games-lfp
  and r: explode r ⊆ games-lfp
  shows Opair l r ∈ games-lfp
proof −
  note f = unique-games[of games-lfp, simplified]
  show ?thesis
    apply (subst f)
    apply (simp add: fixgames-def)
    apply (rule exI[where x=l])
    apply (rule exI[where x=r])
    apply (auto simp add: l r)
    done
qed

lemma left-options[simp]: left-options (Game l r) = l
  apply (simp add: left-options-def Game-def)
  apply (subst Abs-game-inverse)
  apply (simp add: game-def)
  apply (rule Opair-in-games-lfp)
 apply (auto simp add: explode-Elem Elem-zimplode zimage-iff Rep-game[simplified game-def])
  apply (simp add: Fst zexplode-zimplode comp-zimage-eq)
  apply (simp add: zet-ext-eq zimage-iff Rep-game-inverse)
```

done

lemma *right-options*[*simp*]: *right-options* (*Game l r*) = *r*
apply (*simp add*: *right-options-def Game-def*)
apply (*subst Abs-game-inverse*)
apply (*simp add*: *game-def*)
apply (*rule Opair-in-games-lfp*)
apply (*auto simp add*: *explode-Elem Elem-zimplode zimage-iff Rep-game*[*simplified game-def*])
apply (*simp add*: *Snd zexplode-zimplode comp-zimage-eq*)
apply (*simp add*: *zet-ext-eq zimage-iff Rep-game-inverse*)
done

lemma *Game-ext*: (*Game l1 r1* = *Game l2 r2*) = ((*l1* = *l2*) ∧ (*r1* = *r2*))
apply *auto*
apply (*subst left-options*[**where** *l*=*l1* **and** *r*=*r1*,*symmetric*])
apply (*subst left-options*[**where** *l*=*l2* **and** *r*=*r2*,*symmetric*])
apply *simp*
apply (*subst right-options*[**where** *l*=*l1* **and** *r*=*r1*,*symmetric*])
apply (*subst right-options*[**where** *l*=*l2* **and** *r*=*r2*,*symmetric*])
apply *simp*
done

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*) ∈ *option-of*) = ((*Rep-game option*, *Rep-game g*) ∈ *is-option-of*)
apply (*auto simp add*: *option-of-def*)
apply (*subst Abs-game-inverse*)
apply (*simp add*: *is-option-of-imp-games game-def*)
apply (*subst Abs-game-inverse*)
apply (*simp add*: *is-option-of-imp-games game-def*)
apply *simp*
apply (*auto simp add*: *Bex-def image-def*)
apply (*rule exI*[**where** *x*=*Rep-game option*])
apply (*rule exI*[**where** *x*=*Rep-game g*])
apply (*simp add*: *Rep-game-inverse*)
done

lemma *wf-is-option-of*: *wf is-option-of*
apply (*rule wfzf-implies-wf*)
apply (*simp add*: *wfzf-is-option-of*)
done

lemma *wf-option-of*[*simp*, *intro*]: *wf option-of*
proof −
have *option-of*: *option-of* = *inv-image is-option-of Rep-game*
apply (*rule set-eqI*)

```
    apply (case-tac x)
    by (simp add: option-to-is-option-of)
  show ?thesis
    apply (simp add: option-of)
    apply (auto intro: wf-is-option-of)
    done
qed

lemma right-option-is-option[simp, intro]: zin x (right-options g) ⟹ zin x (options
g)
  by (simp add: options-def zunion)

lemma left-option-is-option[simp, intro]: zin x (left-options g) ⟹ zin x (options
g)
  by (simp add: options-def zunion)

lemma zin-options[simp, intro]: zin x (options g) ⟹ (x, g) ∈ option-of
 apply (simp add: options-def zunion left-options-def right-options-def option-of-def

    image-def is-option-of-def zimage-iff zin-zexplode-eq)
  apply (cases g)
  apply (cases x)
  apply (auto simp add: Abs-game-inverse games-lfp-eq-gfp[symmetric] game-def
    right-option-def[symmetric] left-option-def[symmetric])
  done

function
  neg-game :: game ⇒ game
where
  [simp del]: neg-game g = Game (zimage neg-game (right-options g)) (zimage
neg-game (left-options g))
by auto
termination by (relation option-of) auto

lemma neg-game (neg-game g) = g
  apply (induct g rule: neg-game.induct)
  apply (subst neg-game.simps)+
  apply (simp add: comp-zimage-eq)
  apply (subgoal-tac zimage (neg-game o neg-game) (left-options g) = left-options
g)
 apply (subgoal-tac zimage (neg-game o neg-game) (right-options g) = right-options
g)
  apply (auto simp add: game-split[symmetric])
  apply (auto simp add: zet-ext-eq zimage-iff)
  done

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))
by auto
termination by (relation (gprod-2-1 option-of))
 (simp, auto simp: gprod-2-1-def)

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)))
  apply (subst ge-game.simps[where G=G and H=H])
  apply (auto)
  done

lemma ge-game-leftright-refl[rule-format]:
  ∀ y. (zin y (right-options x) ⟶ ¬ ge-game (x, y)) ∧ (zin y (left-options x) ⟶
¬ (ge-game (y, x))) ∧ ge-game (x, x)
proof (induct x rule: wf-induct[OF wf-option-of])
  case (1 g)
  {
    fix y
    assume y: zin y (right-options g)
    have ¬ ge-game (g, y)
    proof −
      have (y, g) ∈ option-of by (auto intro: y)
      with 1 have ge-game (y, y) by auto
      with y show ?thesis by (subst ge-game-eq, auto)
    qed
  }
  note right = this
  {
    fix y
    assume y: zin y (left-options g)
    have ¬ ge-game (y, g)
    proof −
      have (y, g) ∈ option-of by (auto intro: y)
      with 1 have ge-game (y, y) by auto
      with y show ?thesis by (subst ge-game-eq, auto)
    qed
  }
  note left = this
  from left right show ?case
    by (auto, subst ge-game-eq, auto)
qed

lemma ge-game-refl: ge-game (x,x) by (simp add: ge-game-leftright-refl)
```

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 (*induct x rule*: *wf-induct*[*OF wf-option-of*])
  case (*1 g*)
  show *?case*
  proof (*auto*, *goal-cases*)
    {case *prems*: (*1 y*)
      from *prems* **have** (*y*, *g*) ∈ *option-of* **by** (*auto*)
      with *1* **have** *ge-game* (*y*, *y*) **by** *auto*
      with *prems* **have** ¬ *ge-game* (*g*, *y*)
        by (*subst ge-game-eq*, *auto*)
      with *prems* **show** *?case* **by** *auto***}**
    note *right* = *this*
    {case *prems*: (*2 y*)
      from *prems* **have** (*y*, *g*) ∈ *option-of* **by** (*auto*)
      with *1* **have** *ge-game* (*y*, *y*) **by** *auto*
      with *prems* **have** ¬ *ge-game* (*y*, *g*)
        by (*subst ge-game-eq*, *auto*)
      with *prems* **show** *?case* **by** *auto***}**
    note *left* = *this*
    {case *3*
      from *left right* **show** *?case*
        by (*subst ge-game-eq*, *auto*)
    }
  qed
qed

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*)
  by (*auto simp add*: *eq-game-def*)

lemma *eq-game-refl*: *eq-game G G*
  by (*simp add*: *ge-game-refl eq-game-def*)

lemma *induct-game*: (⋀*x*. ∀ *y*. (*y*, *x*) ∈ *lprod option-of* ⟶ *P y* ⟹ *P x*) ⟹ *P a*
  by (*erule wf-induct*[*OF wf-lprod*[*OF wf-option-of*]])

lemma *ge-game-trans*:
  assumes *ge-game* (*x*, *y*) *ge-game* (*y*, *z*)
  shows *ge-game* (*x*, *z*)
proof −
  {
    fix *a*
    have ∀ *x y z*. *a* = [*x*,*y*,*z*] ⟶ *ge-game* (*x*,*y*) ⟶ *ge-game* (*y*,*z*) ⟶ *ge-game* (*x*, *z*)
    proof (*induct a rule*: *induct-game*)
      case (*1 a*)

```
      show ?case
      proof ((rule allI | rule impI)+, goal-cases)
        case prems: (1 x y z)
        show ?case
        proof −
          { fix xr
            assume xr:zin xr (right-options x)
            assume a: ge-game (z, xr)
            have ge-game (y, xr)
              apply (rule 1[rule-format, where y=[y,z,xr]])
              apply (auto intro: xr lprod-3-1 simp add: prems a)
              done
            moreover from xr have ¬ ge-game (y, xr)
               by (simp add: prems(2)[simplified ge-game-eq[of x y], rule-format, of
xr, simplified xr])
            ultimately have False by auto
          }
          note xr = this
          { fix zl
            assume zl:zin zl (left-options z)
            assume a: ge-game (zl, x)
            have ge-game (zl, y)
              apply (rule 1[rule-format, where y=[zl,x,y]])
              apply (auto intro: zl lprod-3-2 simp add: prems a)
              done
            moreover from zl have ¬ ge-game (zl, y)
               by (simp add: prems(3)[simplified ge-game-eq[of y z], rule-format, of
zl, simplified zl])
            ultimately have False by auto
          }
          note zl = this
          show ?thesis
            by (auto simp add: ge-game-eq[of x z] intro: xr zl)
        qed
      qed
    qed
  }
  note trans = this[of [x, y, z], simplified, rule-format]
  with assms show ?thesis by blast
qed

lemma eq-game-trans: eq-game a b ⟹ eq-game b c ⟹ eq-game a c
  by (auto simp add: eq-game-def intro: ge-game-trans)

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*)))
by *auto*
termination by (*relation gprod-2-2 option-of*)
(*simp*, *auto simp*: *gprod-2-2-def*)

lemma *plus-game-comm*: *plus-game G H* = *plus-game H G*
proof (*induct G H rule*: *plus-game.induct*)
case (*1 G H*)
show *?case*
by (*auto simp add*:
plus-game.simps[**where** *G*=*G* **and** *H*=*H*]
plus-game.simps[**where** *G*=*H* **and** *H*=*G*]
Game-ext zet-ext-eq zunion zimage-iff 1)
qed

lemma *game-ext-eq*: (*G* = *H*) = (*left-options G* = *left-options H* ∧ *right-options G* = *right-options H*)
proof −
have (*G* = *H*) = (*Game* (*left-options G*) (*right-options G*) = *Game* (*left-options H*) (*right-options H*))
by (*simp add*: *game-split*[*symmetric*])
then show *?thesis* **by** *auto*
qed

lemma *left-zero-game*[*simp*]: *left-options* (*zero-game*) = *zempty*
by (*simp add*: *zero-game-def*)

lemma *right-zero-game*[*simp*]: *right-options* (*zero-game*) = *zempty*
by (*simp add*: *zero-game-def*)

lemma *plus-game-zero-right*[*simp*]: *plus-game G zero-game* = *G*
proof −
have *H* = *zero-game* ⟶ *plus-game G H* = *G* **for** *G H*
proof (*induct G H rule*: *plus-game.induct*, *rule impI*, *goal-cases*)
case *prems*: (*1 G H*)
note *induct-hyp* = *this*[*simplified prems*, *simplified*] **and** *this*
show *?case*
apply (*simp only*: *plus-game.simps*[**where** *G*=*G* **and** *H*=*H*])
apply (*simp add*: *game-ext-eq prems*)
apply (*auto simp add*:
zimage-cong [**where** *f* = λ *g*. *plus-game g zero-game* **and** *g* = *id*]
induct-hyp)
done
qed

then show *?thesis* **by** *auto*
qed

lemma *plus-game-zero-left*: *plus-game zero-game G* = *G*
by (*simp add*: *plus-game-comm*)

lemma *left-imp-options*[*simp*]: *zin opt* (*left-options g*) ⟹ *zin opt* (*options g*)
by (*simp add*: *options-def zunion*)

lemma *right-imp-options*[*simp*]: *zin opt* (*right-options g*) ⟹ *zin opt* (*options g*)
by (*simp add*: *options-def zunion*)

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*))
by (*subst plus-game.simps*, *simp*)

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*))
by (*subst plus-game.simps*, *simp*)

lemma *left-options-neg*: *left-options* (*neg-game u*) = *zimage neg-game* (*right-options u*)
by (*subst neg-game.simps*, *simp*)

lemma *right-options-neg*: *right-options* (*neg-game u*) = *zimage neg-game* (*left-options u*)
by (*subst neg-game.simps*, *simp*)

lemma *plus-game-assoc*: *plus-game* (*plus-game F G*) *H* = *plus-game F* (*plus-game G H*)
proof −
have ∀ *F G H*. *a* = [*F*, *G*, *H*] ⟶ *plus-game* (*plus-game F G*) *H* = *plus-game F* (*plus-game G H*) **for** *a*
proof (*induct a rule*: *induct-game*, (*rule impI* | *rule allI*)+, *goal-cases*)
case *prems*: (*1 x F G H*)
let *?L* = *plus-game* (*plus-game F G*) *H*
let *?R* = *plus-game F* (*plus-game G H*)
note *options-plus* = *left-options-plus right-options-plus*
{
fix *opt*
note *hyp* = *prems*(*1*)[*simplified prems*(*2*), *rule-format*]
have *F*: *zin opt* (*options F*) ⟹ *plus-game* (*plus-game opt G*) *H* = *plus-game opt* (*plus-game G H*)
by (*blast intro*: *hyp lprod-3-3*)
have *G*: *zin opt* (*options G*) ⟹ *plus-game* (*plus-game F opt*) *H* = *plus-game F* (*plus-game opt H*)
by (*blast intro*: *hyp lprod-3-4*)

```
    have H: zin opt (options H) ⟹ plus-game (plus-game F G) opt = plus-game
F (plus-game G opt)
      by (blast intro: hyp lprod-3-5)
    note F and G and H
   }
   note induct-hyp = this
   have left-options ?L = left-options ?R ∧ right-options ?L = right-options ?R
    by (auto simp add:
      plus-game.simps[where G=plus-game F G and H=H]
      plus-game.simps[where G=F and H=plus-game G H]
      zet-ext-eq zunion zimage-iff options-plus
      induct-hyp left-imp-options right-imp-options)
   then show ?case
    by (simp add: game-ext-eq)
  qed
  then show ?thesis by auto
qed

lemma neg-plus-game: neg-game (plus-game G H) = plus-game (neg-game G)
(neg-game H)
proof (induct G H rule: plus-game.induct)
  case (1 G H)
  note opt-ops =
   left-options-plus right-options-plus
   left-options-neg right-options-neg
  show ?case
   by (auto simp add: opt-ops
     neg-game.simps[of plus-game G H]
     plus-game.simps[of neg-game G neg-game H]
     Game-ext zet-ext-eq zunion zimage-iff 1)
qed

lemma eq-game-plus-inverse: eq-game (plus-game x (neg-game x)) zero-game
proof (induct x rule: wf-induct[OF wf-option-of], goal-cases)
  case prems: (1 x)
  then have ihyp: eq-game (plus-game y (neg-game y)) zero-game if zin y (options
x) for y
   using that by (auto simp add: prems)
  have case1: ¬ (ge-game (zero-game, plus-game y (neg-game x)))
   if y: zin y (right-options x) for y
   apply (subst ge-game.simps, simp)
   apply (rule exI[where x=plus-game y (neg-game y)])
   apply (auto simp add: ihyp[of y, simplified y right-imp-options eq-game-def])
   apply (auto simp add: left-options-plus left-options-neg zunion zimage-iff intro:
y)
   done
  have case2: ¬ (ge-game (zero-game, plus-game x (neg-game y)))
   if y: zin y (left-options x) for y
   apply (subst ge-game.simps, simp)
```

```
    apply (rule exI[where x=plus-game y (neg-game y)])
    apply (auto simp add: ihyp[of y, simplified y left-imp-options eq-game-def])
    apply (auto simp add: left-options-plus zunion zimage-iff intro: y)
    done
  have case3: ¬ (ge-game (plus-game y (neg-game x), zero-game))
    if y: zin y (left-options x) for y
    apply (subst ge-game.simps, simp)
    apply (rule exI[where x=plus-game y (neg-game y)])
    apply (auto simp add: ihyp[of y, simplified y left-imp-options eq-game-def])
     apply (auto simp add: right-options-plus right-options-neg zunion zimage-iff
intro: y)
    done
  have case4: ¬ (ge-game (plus-game x (neg-game y), zero-game))
    if y: zin y (right-options x) for y
    apply (subst ge-game.simps, simp)
    apply (rule exI[where x=plus-game y (neg-game y)])
    apply (auto simp add: ihyp[of y, simplified y right-imp-options eq-game-def])
    apply (auto simp add: right-options-plus zunion zimage-iff intro: y)
    done
  show ?case
    apply (simp add: eq-game-def)
    apply (simp add: ge-game.simps[of plus-game x (neg-game x) zero-game])
    apply (simp add: ge-game.simps[of zero-game plus-game x (neg-game x)])
   apply (simp add: right-options-plus left-options-plus right-options-neg left-options-neg
zunion zimage-iff)
    apply (auto simp add: case1 case2 case3 case4)
    done
qed

lemma ge-plus-game-left: ge-game (y,z) = ge-game (plus-game x y, plus-game x
z)
proof −
  have ∀ x y z. a = [x,y,z] ⟶ ge-game (y,z) = ge-game (plus-game x y, plus-game
x z) for a
  proof (induct a rule: induct-game, (rule impI | rule allI)+, goal-cases)
    case prems: (1 a x y z)
    note induct-hyp = prems(1)[rule-format, simplified prems(2)]
    {
      assume hyp: ge-game(plus-game x y, plus-game x z)
      have ge-game (y, z)
      proof −
        { fix yr
          assume yr: zin yr (right-options y)
          from hyp have ¬ (ge-game (plus-game x z, plus-game x yr))
            by (auto simp add: ge-game-eq[of plus-game x y plus-game x z]
              right-options-plus zunion zimage-iff intro: yr)
          then have ¬ (ge-game (z, yr))
            apply (subst induct-hyp[where y=[x, z, yr], of x z yr])
            apply (simp-all add: yr lprod-3-6)
```

```
      done
    }
    note yr = this
    { fix zl
      assume zl: zin zl (left-options z)
      from hyp have ¬ (ge-game (plus-game x zl, plus-game x y))
        by (auto simp add: ge-game-eq[of plus-game x y plus-game x z]
          left-options-plus zunion zimage-iff intro: zl)
      then have ¬ (ge-game (zl, y))
        apply (subst prems(1)[rule-format, where y=[x, zl, y], of x zl y])
        apply (simp-all add: prems(2) zl lprod-3-7)
        done
    }
    note zl = this
    show ge-game (y, z)
      apply (subst ge-game-eq)
      apply (auto simp add: yr zl)
      done
  qed
}
note right-imp-left = this
{
  assume yz: ge-game (y, z)
  {
    fix x'
    assume x': zin x' (right-options x)
    assume hyp: ge-game (plus-game x z, plus-game x' y)
    then have n: ¬ (ge-game (plus-game x' y, plus-game x' z))
      by (auto simp add: ge-game-eq[of plus-game x z plus-game x' y]
        right-options-plus zunion zimage-iff intro: x')
    have t: ge-game (plus-game x' y, plus-game x' z)
      apply (subst induct-hyp[symmetric])
      apply (auto intro: lprod-3-3 x' yz)
      done
    from n t have False by blast
  }
  note case1 = this
  {
    fix x'
    assume x': zin x' (left-options x)
    assume hyp: ge-game (plus-game x' z, plus-game x y)
    then have n: ¬ (ge-game (plus-game x' y, plus-game x' z))
      by (auto simp add: ge-game-eq[of plus-game x' z plus-game x y]
        left-options-plus zunion zimage-iff intro: x')
    have t: ge-game (plus-game x' y, plus-game x' z)
      apply (subst induct-hyp[symmetric])
      apply (auto intro: lprod-3-3 x' yz)
      done
    from n t have False by blast
```

```
    }
    note case3 = this
    {
      fix y'
      assume y': zin y' (right-options y)
      assume hyp: ge-game (plus-game x z, plus-game x y')
      then have ge-game(z, y')
        apply (subst induct-hyp[of [x, z, y'] x z y'])
        apply (auto simp add: hyp lprod-3-6 y')
        done
      with yz have ge-game (y, y')
        by (blast intro: ge-game-trans)
      with y' have False by (auto simp add: ge-game-leftright-refl)
    }
    note case2 = this
    {
      fix z'
      assume z': zin z' (left-options z)
      assume hyp: ge-game (plus-game x z', plus-game x y)
      then have ge-game(z', y)
        apply (subst induct-hyp[of [x, z', y] x z' y])
        apply (auto simp add: hyp lprod-3-7 z')
        done
      with yz have ge-game (z', z)
        by (blast intro: ge-game-trans)
      with z' have False by (auto simp add: ge-game-leftright-refl)
    }
    note case4 = this
    have ge-game(plus-game x y, plus-game x z)
      apply (subst ge-game-eq)
     apply (auto simp add: right-options-plus left-options-plus zunion zimage-iff)
      apply (auto intro: case1 case2 case3 case4)
      done
  }
  note left-imp-right = this
  show ?case by (auto intro: right-imp-left left-imp-right)
 qed
 from this[of [x, y, z]] show ?thesis by blast
qed

lemma ge-plus-game-right: ge-game (y,z) = ge-game(plus-game y x, plus-game z
x)
 by (simp add: ge-plus-game-left plus-game-comm)

lemma ge-neg-game: ge-game (neg-game x, neg-game y) = ge-game (y, x)
proof −
 have ∀ x y. a = [x, y] ⟶ ge-game (neg-game x, neg-game y) = ge-game (y, x)
for a
 proof (induct a rule: induct-game, (rule impI | rule allI)+, goal-cases)
```

```
    case prems: (1 a x y)
    note ihyp = prems(1)[rule-format, simplified prems(2)]
    { fix xl
      assume xl: zin xl (left-options x)
      have ge-game (neg-game y, neg-game xl) = ge-game (xl, y)
        apply (subst ihyp)
        apply (auto simp add: lprod-2-1 xl)
        done
    }
    note xl = this
    { fix yr
      assume yr: zin yr (right-options y)
      have ge-game (neg-game yr, neg-game x) = ge-game (x, yr)
        apply (subst ihyp)
        apply (auto simp add: lprod-2-2 yr)
        done
    }
    note yr = this
    show ?case
      by (auto simp add: ge-game-eq[of neg-game x neg-game y] ge-game-eq[of y x]
        right-options-neg left-options-neg zimage-iff  xl yr)
  qed
  from this[of [x,y]] show ?thesis by blast
qed

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
  unfolding Pg-def by (auto simp add: quotient-def)

lemma equiv-eq-game[simp]: equiv UNIV eq-game-rel
proof (rule equivI)
  show eq-game-rel ⊆ UNIV × UNIV
    by simp
next
  show refl eq-game-rel
    by (auto simp only: eq-game-rel-def intro: reflI eq-game-refl)
next
  show sym eq-game-rel
    by (auto simp only: eq-game-rel-def eq-game-sym intro: symI)
next
  show trans eq-game-rel
    by (auto simp only: eq-game-rel-def intro: transI eq-game-trans)
qed

instantiation Pg :: {ord, zero, plus, minus, uminus}
```

begin

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

definition
Pg-le-def: $G \leq H \longleftrightarrow (\exists\ g\ h.\ g \in Rep\text{-}Pg\ G \wedge h \in Rep\text{-}Pg\ H \wedge ge\text{-}game\ (h,\ g))$

definition
Pg-less-def: $G < H \longleftrightarrow G \leq H \wedge G \neq (H::Pg)$

definition
Pg-minus-def: $- G = the\text{-}elem\ (\bigcup g \in Rep\text{-}Pg\ G.\ \{Abs\text{-}Pg\ (eq\text{-}game\text{-}rel\ ``\ \{neg\text{-}game\ g\})\})$

definition
Pg-plus-def: $G + H = the\text{-}elem\ (\bigcup g \in Rep\text{-}Pg\ G.\ \bigcup h \in Rep\text{-}Pg\ H.\ \{Abs\text{-}Pg\ (eq\text{-}game\text{-}rel\ ``\ \{plus\text{-}game\ g\ h\})\})$

definition
Pg-diff-def: $G - H = G + (-\ (H::Pg))$

instance ..

end

lemma *Rep-Abs-eq-Pg*[*simp*]: $Rep\text{-}Pg\ (Abs\text{-}Pg\ (eq\text{-}game\text{-}rel\ ``\ \{g\})) = eq\text{-}game\text{-}rel\ ``\ \{g\}$
apply (*subst Abs-Pg-inverse*)
apply (*auto simp add*: *Pg-def quotient-def*)
done

lemma *char-Pg-le*[*simp*]: $(Abs\text{-}Pg\ (eq\text{-}game\text{-}rel\ ``\ \{g\}) \leq Abs\text{-}Pg\ (eq\text{-}game\text{-}rel\ ``\ \{h\})) = (ge\text{-}game\ (h,\ g))$
apply (*simp add*: *Pg-le-def*)
apply (*auto simp add*: *eq-game-rel-def eq-game-def intro*: *ge-game-trans ge-game-refl*)
done

lemma *char-Pg-eq*[*simp*]: $(Abs\text{-}Pg\ (eq\text{-}game\text{-}rel\ ``\ \{g\}) = Abs\text{-}Pg\ (eq\text{-}game\text{-}rel\ ``\ \{h\})) = (eq\text{-}game\ g\ h)$
apply (*simp add*: *Rep-Pg-inject* [*symmetric*])
apply (*subst eq-equiv-class-iff*[*of UNIV*])
apply (*simp-all*)
apply (*simp add*: *eq-game-rel-def*)
done

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

```
  have (λ g h. {Abs-Pg (eq-game-rel `` {plus-game g h})}) respects2 eq-game-rel
    apply (simp add: congruent2-def)
    apply (auto simp add: eq-game-rel-def eq-game-def)
    apply (rule-tac y=plus-game a ba in ge-game-trans)
   apply (simp add: ge-plus-game-left[symmetric] ge-plus-game-right[symmetric])+
    apply (rule-tac y=plus-game b aa in ge-game-trans)
   apply (simp add: ge-plus-game-left[symmetric] ge-plus-game-right[symmetric])+
    done
  then show ?thesis
    by (simp add: Pg-plus-def UN-equiv-class2[OF equiv-eq-game equiv-eq-game])
qed

lemma char-Pg-minus[simp]: − Abs-Pg (eq-game-rel `` {g}) = Abs-Pg (eq-game-rel
`` {neg-game g})
proof −
  have (λ g. {Abs-Pg (eq-game-rel `` {neg-game g})}) respects eq-game-rel
    apply (simp add: congruent-def)
    apply (auto simp add: eq-game-rel-def eq-game-def ge-neg-game)
    done
  then show ?thesis
    by (simp add: Pg-minus-def UN-equiv-class[OF equiv-eq-game])
qed

lemma eq-Abs-Pg[rule-format, cases type: Pg]: (∀ g. z = Abs-Pg (eq-game-rel ``
{g}) ⟶ P) ⟶ P
  apply (cases z, simp)
  apply (simp add: Rep-Pg-inject[symmetric])
  apply (subst Abs-Pg-inverse, simp)
  apply (auto simp add: Pg-def quotient-def)
  done

instance Pg :: ordered-ab-group-add
proof
  fix a b c :: Pg
  show a − b = a + (− b) by (simp add: Pg-diff-def)
  {
    assume ab: a ≤ b
    assume ba: b ≤ a
    from ab ba show a = b
      apply (cases a, cases b)
      apply (simp add: eq-game-def)
      done
  }
  then show (a < b) = (a ≤ b ∧ ¬ b ≤ a) by (auto simp add: Pg-less-def)
  show a + b = b + a
    apply (cases a, cases b)
    apply (simp add: eq-game-def plus-game-comm)
    done
  show a + b + c = a + (b + c)
```

```
    apply (cases a, cases b, cases c)
    apply (simp add: eq-game-def plus-game-assoc)
    done
  show 0 + a = a
    apply (cases a)
    apply (simp add: Pg-zero-def plus-game-zero-left)
    done
  show − a + a = 0
    apply (cases a)
    apply (simp add: Pg-zero-def eq-game-plus-inverse plus-game-comm)
    done
  show a ≤ a
    apply (cases a)
    apply (simp add: ge-game-refl)
    done
  {
    assume ab: a ≤ b
    assume bc: b ≤ c
    from ab bc show a ≤ c
      apply (cases a, cases b, cases c)
      apply (auto intro: ge-game-trans)
      done
  }
  {
    assume ab: a ≤ b
    from ab show c + a ≤ c + b
      apply (cases a, cases b, cases c)
      apply (simp add: ge-plus-game-left[symmetric])
      done
  }
qed

end
```