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# 1 Bool

```
(*****
(* Boolean *)
*****)

(* rename module to clash with existing list modules of targets *)

declare {isabelle, hol, ocaml, coq} rename module = lem_bool

(* The type bool is hard – coded, so are true and false *)

(* ----- *)
(* not *)
(* ----- *)

val not : BOOL → BOOL
let not b = match b with
| true → false
| false → true
end

declare hol target_rep function not x = '~' x
declare ocaml target_rep function not = 'not'
declare isabelle target_rep function not x = '\<not>' x
declare html target_rep function not = '&not;'
declare coq target_rep function not = 'negb'
declare tex target_rep function not b = '$\neg$' b

assert not1 :  $\neg (\neg \text{true})$ 
assert not2 :  $\neg \text{false}$ 

(* ----- *)
(* and *)
(* ----- *)

val && [and] : BOOL → BOOL → BOOL
let && b1 b2 = match (b1, b2) with
| (true, true) → true
| _ → false
end

declare hol target_rep function and = infix rightassoc0 '\&'
declare ocaml target_rep function and = infix '&&'
declare isabelle target_rep function and = infix '\<and>'
declare coq target_rep function and = infix '&&'
declare html target_rep function and = infix '&and;'
declare tex target_rep function and = infix '$\wedge$'

assert and1 :  $(\neg (\text{true} \wedge \text{false}))$ 
assert and2 :  $(\neg (\text{false} \wedge \text{true}))$ 
assert and3 :  $(\neg (\text{false} \wedge \text{false}))$ 
assert and4 :  $(\text{true} \wedge \text{true})$ 

(* ----- *)
(* or *)
(* ----- *)
```

```

val || [or] : BOOL → BOOL → BOOL
let || b1 b2 = match (b1, b2) with
| (false, false) → false
| _ → true
end

declare hol target_rep function or = infix '\/'
declare ocaml target_rep function or = infix '||'
declare isabelle target_rep function or = infix '\<or>'
declare coq target_rep function or = infix '||'
declare html target_rep function or = infix '&or;'
declare tex target_rep function or = infix '$\vee$'

assert or1 : (true ∨ false)
assert or2 : (false ∨ true)
assert or3 : (true ∨ true)
assert or4 : (¬ (false ∨ false))

(* ----- *)
(* implication *)
(* ----- *)

val --> [imp] : BOOL → BOOL → BOOL
let --> b1 b2 = match (b1, b2) with
| (true, false) → false
| _ → true
end

declare hol target_rep function imp = infix '==>'
declare isabelle target_rep function imp = infix '\<longrightarrow>'
(* declare coq target_rep function (-->) = 'imp' *)
declare html target_rep function imp = infix '&rarr;'
declare tex target_rep function imp = infix '$\longrightarrow$'

let inline {ocaml, coq} imp x y = ((¬ x) ∨ y)

assert imp1 : (¬ (true → false))
assert imp2 : (false → true)
assert imp3 : (false → false)
assert imp4 : (true → true)

(* ----- *)
(* equivalence *)
(* ----- *)

val <-> [equiv] : BOOL → BOOL → BOOL
let <-> b1 b2 = match (b1, b2) with
| (true, true) → true
| (false, false) → true
| _ → false
end

declare hol target_rep function equiv = infix '<=>'
declare isabelle target_rep function equiv = infix '\<longlefttrightarrow>'
declare coq target_rep function equiv = 'Bool.eqb'

```

```

declare ocaml target_rep function equiv = infix '='
declare html target_rep function equiv = infix '&harr;'
declare tex target_rep function equiv = infix '$\longleftarrow$'

```

```

assert equiv1 : (¬ (true  $\longleftrightarrow$  false))
assert equiv2 : (¬ (false  $\longleftrightarrow$  true))
assert equiv3 : (false  $\longleftrightarrow$  false)
assert equiv4 : (true  $\longleftrightarrow$  true)

```

```

(* ----- *)
(* xor      *)
(* ----- *)

```

```

val xor : BOOL → BOOL → BOOL
let inline xor b1 b2 = ¬ (b1  $\longleftrightarrow$  b2)

```

```

assert xor1 : (xor true false)
assert xor2 : (xor false true)
assert xor3 : (¬ (xor true true))
assert xor4 : (¬ (xor false false))

```

## 2 Basic\_classes

```

(*****
(* Basic Type Classes *)
(*****)

open import Bool

declare {isabelle, ocaml, hol, coq} rename module = lem_basic_classes

open import {coq} Coq.Strings.Ascii
open import {hol} ternaryComparisonsTheory

(* ===== *)
(* Equality *)
(* ===== *)

(* Lem's default equality (=) is defined by the following type – class Eq. This typeclass should define equal

class ( Eq  $\alpha$  )
  val = [isEqual] :  $\alpha \rightarrow \alpha \rightarrow \text{BOOL}$ 
  val <> [isInequal] :  $\alpha \rightarrow \alpha \rightarrow \text{BOOL}$ 
end

declare coq target_rep function isEqual = infix '='
(* declare coq target_rep function isEqual = infix '=' declare coq target_rep function isInequal = infix '<>' *)
declare tex target_rep function isInequal = infix '\neq'

(* (=) should for all instances be an equivalence relation The isEquivalence predicate of relations could b

(* TODO: add later, once lemmata can be assigned to classes lemma eq_equiv: ((forall x. (x = x)) &&

(* Structural equality *)

(* Sometimes, it is also handy to be able to use structural equality. This equality is mapped to the build –
val unsafe_structural_equality :  $\forall \alpha. \alpha \rightarrow \alpha \rightarrow \text{BOOL}$ 

declare hol target_rep function unsafe_structural_equality = infix '='
declare ocaml target_rep function unsafe_structural_equality = infix '='
declare isabelle target_rep function unsafe_structural_equality = infix '='
declare coq target_rep function unsafe_structural_equality = 'classical.boolean.equivalence'

val unsafe_structural_inequality :  $\forall \alpha. \alpha \rightarrow \alpha \rightarrow \text{BOOL}$ 
let unsafe_structural_inequality x y =  $\neg$  (unsafe_structural_equality x y)
declare isabelle target_rep function unsafe_structural_inequality = infix '\noteq'
declare hol target_rep function unsafe_structural_inequality = infix '<>'

(* The default for equality is the unsafe structural one. It can (and should) be overridden for concrete types

default_instance  $\forall \alpha. (Eq \alpha)$ 
  let == = unsafe_structural_equality
  let <> = unsafe_structural_inequality
end

(* for HOL and Isabelle, be even stronger and always(!) use standard equality *)
let inline {hol, isabelle} == = unsafe_structural_equality
let inline {hol, isabelle} <> = unsafe_structural_inequality

```

```

(* ===== *)
(* Orderings *)
(* ===== *)

(* The type - class Ord represents total orders (also called linear orders) *)
type ORDERING = LT | EQ | GT

declare ocaml target_rep type ORDERING = 'int'
declare ocaml target_rep function LT = '(-1)'
declare ocaml target_rep function EQ = '0'
declare ocaml target_rep function GT = '1'

declare coq target_rep type ORDERING = 'ordering'
declare coq target_rep function LT = 'LT'
declare coq target_rep function EQ = 'EQ'
declare coq target_rep function GT = 'GT'

declare hol target_rep type ORDERING = 'ordering'
declare hol target_rep function LT = 'LESS'
declare hol target_rep function EQ = 'EQUAL'
declare hol target_rep function GT = 'GREATER'

let orderingIsLess r = (match r with LT → true | _ → false end)
let orderingIsGreater r = (match r with GT → true | _ → false end)
let orderingIsEqual r = (match r with EQ → true | _ → false end)
let inline orderingIsLessEqual r = ¬ (orderingIsGreater r)
let inline orderingIsGreaterEqual r = ¬ (orderingIsLess r)

let ordering_cases r lt eq gt =
  if orderingIsLess r then lt else
  if orderingIsEqual r then eq else gt

declare ocaml target_rep function orderingIsLess = 'Lem.orderingIsLess'
declare ocaml target_rep function orderingIsGreater = 'Lem.orderingIsGreater'
declare ocaml target_rep function orderingIsEqual = 'Lem.orderingIsEqual'

declare ocaml target_rep function ordering_cases = 'Lem.ordering_cases'

declare {ocaml} pattern_match exhaustive ORDERING = [ LT; EQ; GT ] ordering_cases

assert ordering_cases_0 : (ordering_cases LT true false false)
assert ordering_cases_1 : (ordering_cases EQ false true false)
assert ordering_cases_2 : (ordering_cases GT false false true)
assert ordering_match_1 : (match LT with GT → false ∧ false | _ → true end)
assert ordering_match_2 : (match EQ with GT → false | _ → true end)
assert ordering_match_3 : (match GT with GT → true ∧ true | _ → false end)
assert ordering_match_4 : ((fun r → (match r with GT → false | _ → true end)) LT)
assert ordering_match_5 : ((fun r → (match r with GT → false | _ → true end)) EQ)
assert ordering_match_6 : ((fun r → (match r with GT → true ∧ true | _ → false end)) GT)

val orderingEqual : ORDERING → ORDERING → BOOL
let inline ~{ocaml, coq} orderingEqual = unsafe_structural_equality
declare coq target_rep function orderingEqual left right = ('ordering_equal' left right)
declare ocaml target_rep function orderingEqual = 'Lem.orderingEqual'

```

```
instance (Eq ORDERING)
  let == orderingEqual
  let <> x y = ¬ (orderingEqual x y)
end
```

```
class ( Ord  $\alpha$  )
  val compare :  $\alpha \rightarrow \alpha \rightarrow$  ORDERING
  val < [isLess] :  $\alpha \rightarrow \alpha \rightarrow$  BOOL
  val <= [isLessEqual] :  $\alpha \rightarrow \alpha \rightarrow$  BOOL
  val > [isGreater] :  $\alpha \rightarrow \alpha \rightarrow$  BOOL
  val >= [isGreaterEqual] :  $\alpha \rightarrow \alpha \rightarrow$  BOOL
end
```

```
declare coq target_rep function isLess = 'isLess'
declare coq target_rep function isLessEqual = 'isLessEqual'
declare coq target_rep function isGreater = 'isGreater'
declare coq target_rep function isGreaterEqual = 'isGreaterEqual'
declare tex target_rep function isLess = infix '$<$'
declare tex target_rep function isLessEqual = infix '$\le$'
declare tex target_rep function isGreater = infix '$>$'
declare tex target_rep function isGreaterEqual = infix '$\ge$'
```

```
(* Ocaml provides default, polymorphic compare functions. Let's use them as the default. However, because u
val defaultCompare :  $\forall \alpha. \alpha \rightarrow \alpha \rightarrow$  ORDERING
val defaultLess :  $\forall \alpha. \alpha \rightarrow \alpha \rightarrow$  BOOL
val defaultLessEq :  $\forall \alpha. \alpha \rightarrow \alpha \rightarrow$  BOOL
val defaultGreater :  $\forall \alpha. \alpha \rightarrow \alpha \rightarrow$  BOOL
val defaultGreaterEq :  $\forall \alpha. \alpha \rightarrow \alpha \rightarrow$  BOOL
```

```
declare ocaml target_rep function defaultCompare = 'compare'
declare hol target_rep function defaultCompare =
declare isabelle target_rep function defaultCompare =
declare coq target_rep function defaultCompare x y = EQ
```

```
declare ocaml target_rep function defaultLess = infix '<'
declare hol target_rep function defaultLess =
declare isabelle target_rep function defaultLess =
declare coq target_rep function defaultLess =
```

```
declare ocaml target_rep function defaultLessEq = infix '<='
declare hol target_rep function defaultLessEq =
declare isabelle target_rep function defaultLessEq =
declare coq target_rep function defaultLessEq =
```

```
declare ocaml target_rep function defaultGreater = infix '>'
declare hol target_rep function defaultGreater =
declare isabelle target_rep function defaultGreater =
declare coq target_rep function defaultGreater =
```

```
declare ocaml target_rep function defaultGreaterEq = infix '>='
declare hol target_rep function defaultGreaterEq =
declare isabelle target_rep function defaultGreaterEq =
declare coq target_rep function defaultGreaterEq =
```

```
let genericCompare (less :  $\alpha \rightarrow \alpha \rightarrow$  BOOL) (equal :  $\alpha \rightarrow \alpha \rightarrow$  BOOL) (x :  $\alpha$ ) (y :  $\alpha$ ) =
  if less x y then
```

```

    LT
  else if equal x y then
    EQ
  else
    GT

(*(* compare should really be a total order *)lemma ord_OK.1 : ( (forall x y. (compare x y = EQ) <-> (compare y x = EQ)) <-> (forall x y. (compare x y = EQ) <-> (compare y x = EQ)) *)

(* let's derive a compare function from the Ord type - class *)
val ordCompare : ∀ α. Eq α, Ord α ⇒ α → α → ORDERING
let ordCompare x y =
  if (x < y) then LT else
  if (x = y) then EQ else GT

class ( OrdMaxMin α )
  val max : α → α → α
  val min : α → α → α
end

val minByLessEqual : ∀ α. (α → α → BOOL) → α → α → α
let ~{isabelle} minByLessEqual le x y = if (le x y) then x else y
let inline {isabelle} minByLessEqual le x y = if (le x y) then x else y

val maxByLessEqual : ∀ α. (α → α → BOOL) → α → α → α
let ~{isabelle} maxByLessEqual le x y = if (le y x) then x else y
let inline {isabelle} maxByLessEqual le x y = if (le y x) then x else y

val defaultMax : ∀ α. Ord α ⇒ α → α → α
let inline defaultMax = maxByLessEqual (≤)
declare ocaml target_rep function defaultMax = 'max'

val defaultMin : ∀ α. Ord α ⇒ α → α → α
let inline defaultMin = minByLessEqual (≤)
declare ocaml target_rep function defaultMin = 'min'

default_instance ∀ α. Ord α ⇒ ( OrdMaxMin α )
  let max = defaultMax
  let min = defaultMin
end

(* ===== *)
(* SetTypes *)
(* ===== *)

(* Set implementations use often an order on the elements. This allows the OCaml implementation to use trees *)

class ( SetType α )
  val {ocaml, coq} setElemCompare : α → α → ORDERING
end

default_instance ∀ α. ( SetType α )
  let setElemCompare = defaultCompare
end

(* ===== *)
(* Instantiations *)
(* ===== *)

```



```

(* ===== *)

instance (Eq BOOL)
  let == (↔)
  let <> x y = ¬ ((↔) x y)
end

let boolCompare b1 b2 = match (b1, b2) with
| (true, true) → EQ
| (true, false) → GT
| (false, true) → LT
| (false, false) → EQ
end

instance (SetType BOOL)
  let setElemCompare = boolCompare
end

(* strings *)

val charEqual : CHAR → CHAR → BOOL
let inline ~{coq} charEqual = unsafe_structural_equality
declare coq target_rep function charEqual left right = ('char_equal' left right)

instance (Eq CHAR)
  let == charEqual
  let <> left right = ¬ (charEqual left right)
end

val stringEquality : STRING → STRING → BOOL
declare coq target_rep function stringEquality left right = ('string_equal' left right)
let inline {ocaml, hol, isabelle} stringEquality = unsafe_structural_equality

instance (Eq STRING)
  let == stringEquality
  let <> l r = ¬ (stringEquality l r)
end

(* pairs *)

val pairEqual : ∀ α β. Eq α, Eq β ⇒ (α * β) → (α * β) → BOOL
let pairEqual (a1, b1) (a2, b2) = (a1 = a2) ∧ (b1 = b2)

val pairEqualBy : ∀ α β. (α → α → BOOL) → (β → β → BOOL) → (α * β) → (α * β) → BOOL
declare ocaml target_rep function pairEqualBy = 'Lem.pair_equal'
declare coq target_rep function pairEqualBy leftEq rightEq left right = ('tuple_equal_by' leftEq rightEq left right)

let inline {hol, isabelle} pairEqual = unsafe_structural_equality
let inline {ocaml, coq} pairEqual = pairEqualBy (=) (=)

instance ∀ α β. Eq α, Eq β ⇒ (Eq (α * β))
  let == pairEqual
  let <> x y = ¬ (pairEqual x y)
end

val pairCompare : ∀ α β. (α → α → ORDERING) → (β → β → ORDERING) → (α * β) →
(α * β) → ORDERING

```

```

let pairCompare cmpa cmpb (a1, b1) (a2, b2) =
  match cmpa a1 a2 with
  | LT → LT
  | GT → GT
  | EQ → cmpb b1 b2
end

```

```

let pairLess (x1, x2) (y1, y2) = (x1 < y1) ∨ ((x1 ≤ y1) ∧ (x2 < y2))
let pairLessEq (x1, x2) (y1, y2) = (x1 < y1) ∨ ((x1 ≤ y1) ∧ (x2 ≤ y2))

```

```

let pairGreater x12 y12 = pairLess y12 x12
let pairGreaterEq x12 y12 = pairLessEq y12 x12

```

```

instance ∀ α β. Ord α, Ord β ⇒ (Ord (α * β))
  let compare = pairCompare compare compare
  let < = pairLess
  let <= = pairLessEq
  let > = pairGreater
  let >= = pairGreaterEq
end

```

```

instance ∀ α β. SetType α, SetType β ⇒ (SetType (α * β))
  let setElemCompare = pairCompare setElemCompare setElemCompare
end

```

(\* triples \*)

```

val tripleEqual : ∀ α β γ. Eq α, Eq β, Eq γ ⇒ (α * β * γ) → (α * β * γ) → BOOL
let tripleEqual (x1, x2, x3) (y1, y2, y3) = ((x1, (x2, x3)) = (y1, (y2, y3)))
let inline {hol, isabelle} tripleEqual = unsafe_structural_equality

```

```

instance ∀ α β γ. Eq α, Eq β, Eq γ ⇒ (Eq (α * β * γ))
  let == = tripleEqual
  let <> x y = ¬ (tripleEqual x y)
end

```

```

val tripleCompare : ∀ α β γ. (α → α → ORDERING) → (β → β → ORDERING) → (γ → γ → ORDERING) → (α * β * γ) → (α * β * γ) → ORDERING
let tripleCompare cmpa cmpb cmpc (a1, b1, c1) (a2, b2, c2) =
  pairCompare cmpa (pairCompare cmpb cmpc) (a1, (b1, c1)) (a2, (b2, c2))

```

```

let tripleLess (x1, x2, x3) (y1, y2, y3) = (x1, (x2, x3)) < (y1, (y2, y3))
let tripleLessEq (x1, x2, x3) (y1, y2, y3) = (x1, (x2, x3)) ≤ (y1, (y2, y3))

```

```

let tripleGreater x123 y123 = tripleLess y123 x123
let tripleGreaterEq x123 y123 = tripleLessEq y123 x123

```

```

instance ∀ α β γ. Ord α, Ord β, Ord γ ⇒ (Ord (α * β * γ))
  let compare = tripleCompare compare compare compare
  let < = tripleLess
  let <= = tripleLessEq
  let > = tripleGreater
  let >= = tripleGreaterEq
end

```

```

instance ∀ α β γ. SetType α, SetType β, SetType γ ⇒ (SetType (α * β * γ))
  let setElemCompare = tripleCompare setElemCompare setElemCompare setElemCompare

```

end

(\* quadruples \*)

val quadrupleEqual :  $\forall \alpha \beta \gamma \delta. Eq \alpha, Eq \beta, Eq \gamma, Eq \delta \Rightarrow (\alpha * \beta * \gamma * \delta) \rightarrow (\alpha * \beta * \gamma * \delta) \rightarrow \text{BOOL}$

let quadrupleEqual (x<sub>1</sub>, x<sub>2</sub>, x<sub>3</sub>, x<sub>4</sub>) (y<sub>1</sub>, y<sub>2</sub>, y<sub>3</sub>, y<sub>4</sub>) = ((x<sub>1</sub>, (x<sub>2</sub>, (x<sub>3</sub>, x<sub>4</sub>))) = (y<sub>1</sub>, (y<sub>2</sub>, (y<sub>3</sub>, y<sub>4</sub>))))  
let inline {hol, isabelle} quadrupleEqual = unsafe\_structural\_equality

instance  $\forall \alpha \beta \gamma \delta. Eq \alpha, Eq \beta, Eq \gamma, Eq \delta \Rightarrow (Eq (\alpha * \beta * \gamma * \delta))$

let == quadrupleEqual

let <> x y =  $\neg$  (quadrupleEqual x y)

end

val quadrupleCompare :  $\forall \alpha \beta \gamma \delta. (\alpha \rightarrow \alpha \rightarrow \text{ORDERING}) \rightarrow (\beta \rightarrow \beta \rightarrow \text{ORDERING}) \rightarrow (\gamma \rightarrow \gamma \rightarrow \text{ORDERING}) \rightarrow$   
 $(\delta \rightarrow \delta \rightarrow \text{ORDERING}) \rightarrow (\alpha * \beta * \gamma * \delta) \rightarrow (\alpha * \beta * \gamma * \delta) \rightarrow \text{ORDERING}$

let quadrupleCompare cmpa cmpb cmpc cmpd (a<sub>1</sub>, b<sub>1</sub>, c<sub>1</sub>, d<sub>1</sub>) (a<sub>2</sub>, b<sub>2</sub>, c<sub>2</sub>, d<sub>2</sub>) =  
pairCompare cmpa (pairCompare cmpb (pairCompare cmpc cmpd)) (a<sub>1</sub>, (b<sub>1</sub>, (c<sub>1</sub>, d<sub>1</sub>))) (a<sub>2</sub>, (b<sub>2</sub>, (c<sub>2</sub>, d<sub>2</sub>)))

let quadrupleLess (x<sub>1</sub>, x<sub>2</sub>, x<sub>3</sub>, x<sub>4</sub>) (y<sub>1</sub>, y<sub>2</sub>, y<sub>3</sub>, y<sub>4</sub>) = (x<sub>1</sub>, (x<sub>2</sub>, (x<sub>3</sub>, x<sub>4</sub>))) < (y<sub>1</sub>, (y<sub>2</sub>, (y<sub>3</sub>, y<sub>4</sub>)))  
let quadrupleLessEq (x<sub>1</sub>, x<sub>2</sub>, x<sub>3</sub>, x<sub>4</sub>) (y<sub>1</sub>, y<sub>2</sub>, y<sub>3</sub>, y<sub>4</sub>) = (x<sub>1</sub>, (x<sub>2</sub>, (x<sub>3</sub>, x<sub>4</sub>)))  $\leq$  (y<sub>1</sub>, (y<sub>2</sub>, (y<sub>3</sub>, y<sub>4</sub>)))

let quadrupleGreater x<sub>1234</sub> y<sub>1234</sub> = quadrupleLess y<sub>1234</sub> x<sub>1234</sub>

let quadrupleGreaterEq x<sub>1234</sub> y<sub>1234</sub> = quadrupleLessEq y<sub>1234</sub> x<sub>1234</sub>

instance  $\forall \alpha \beta \gamma \delta. Ord \alpha, Ord \beta, Ord \gamma, Ord \delta \Rightarrow (Ord (\alpha * \beta * \gamma * \delta))$

let compare = quadrupleCompare compare compare compare compare compare

let < = quadrupleLess

let <= = quadrupleLessEq

let > = quadrupleGreater

let >= = quadrupleGreaterEq

end

instance  $\forall \alpha \beta \gamma \delta. SetType \alpha, SetType \beta, SetType \gamma, SetType \delta \Rightarrow (SetType (\alpha * \beta * \gamma * \delta))$

let setElemCompare = quadrupleCompare setElemCompare setElemCompare setElemCompare setElemCompare  
end

(\* quintuples \*)

val quintupleEqual :  $\forall \alpha \beta \gamma \delta 'e. Eq \alpha, Eq \beta, Eq \gamma, Eq \delta, Eq 'e \Rightarrow (\alpha * \beta * \gamma * \delta * 'e) \rightarrow$   
 $(\alpha * \beta * \gamma * \delta * 'e) \rightarrow \text{BOOL}$

let quintupleEqual (x<sub>1</sub>, x<sub>2</sub>, x<sub>3</sub>, x<sub>4</sub>, x<sub>5</sub>) (y<sub>1</sub>, y<sub>2</sub>, y<sub>3</sub>, y<sub>4</sub>, y<sub>5</sub>) = ((x<sub>1</sub>, (x<sub>2</sub>, (x<sub>3</sub>, (x<sub>4</sub>, x<sub>5</sub>)))) = (y<sub>1</sub>, (y<sub>2</sub>, (y<sub>3</sub>, (y<sub>4</sub>, y<sub>5</sub>))))))

let inline {hol, isabelle} quintupleEqual = unsafe\_structural\_equality

instance  $\forall \alpha \beta \gamma \delta 'e. Eq \alpha, Eq \beta, Eq \gamma, Eq \delta, Eq 'e \Rightarrow (Eq (\alpha * \beta * \gamma * \delta * 'e))$

let == quintupleEqual

let <> x y =  $\neg$  (quintupleEqual x y)

end

val quintupleCompare :  $\forall \alpha \beta \gamma \delta 'e. (\alpha \rightarrow \alpha \rightarrow \text{ORDERING}) \rightarrow (\beta \rightarrow \beta \rightarrow \text{ORDERING}) \rightarrow (\gamma \rightarrow \gamma \rightarrow \text{ORDERING}) \rightarrow$   
 $(\delta \rightarrow \delta \rightarrow \text{ORDERING}) \rightarrow ('e \rightarrow 'e \rightarrow \text{ORDERING}) \rightarrow$

$(\alpha * \beta * \gamma * \delta * 'e) \rightarrow (\alpha * \beta * \gamma * \delta * 'e) \rightarrow \text{ORDERING}$

let quintupleCompare cmpa cmpb cmpc cmpd cmpe (a<sub>1</sub>, b<sub>1</sub>, c<sub>1</sub>, d<sub>1</sub>, e<sub>1</sub>) (a<sub>2</sub>, b<sub>2</sub>, c<sub>2</sub>, d<sub>2</sub>, e<sub>2</sub>) =

```

pairCompare cmpa (pairCompare cmpb (pairCompare cmpc (pairCompare cmpd cmpe))) (a1, (b1, (c1, (d1, e1)))) (a2, (b2, (c2, (d2, e2))))

let quintupleLess (x1, x2, x3, x4, x5) (y1, y2, y3, y4, y5) = (x1, (x2, (x3, (x4, x5)))) < (y1, (y2, (y3, (y4, y5))))

let quintupleLessEq (x1, x2, x3, x4, x5) (y1, y2, y3, y4, y5) = (x1, (x2, (x3, (x4, x5)))) ≤ (y1, (y2, (y3, (y4, y5))))

let quintupleGreater x12345 y12345 = quintupleLess y12345 x12345
let quintupleGreaterEq x12345 y12345 = quintupleLessEq y12345 x12345

instance ∀ α β γ δ 'e. Ord α, Ord β, Ord γ, Ord δ, Ord 'e ⇒ (Ord (α * β * γ * δ * 'e))
  let compare = quintupleCompare compare compare compare compare compare compare
  let < = quintupleLess
  let <= = quintupleLessEq
  let > = quintupleGreater
  let >= = quintupleGreaterEq
end

instance ∀ α β γ δ 'e. SetType α, SetType β, SetType γ, SetType δ, SetType 'e ⇒ (SetType (α * β * γ * δ * 'e))
  let setElemCompare = quintupleCompare setElemCompare setElemCompare setElemCompare setElemCompare setElemCompare
end

(* sextuples *)

val sextupleEqual : ∀ α β γ δ 'e 'f. Eq α, Eq β, Eq γ, Eq δ, Eq 'e, Eq 'f ⇒ (α * β * γ * δ * 'e * 'f) →
(α * β * γ * δ * 'e * 'f) → BOOL
let sextupleEqual (x1, x2, x3, x4, x5, x6) (y1, y2, y3, y4, y5, y6) = ((x1, (x2, (x3, (x4, (x5, x6))))) = (y1, (y2, (y3, (y4, (y5, y6)))))

let inline {hol, isabelle} sextupleEqual = unsafe_structural_equality

instance ∀ α β γ δ 'e 'f. Eq α, Eq β, Eq γ, Eq δ, Eq 'e, Eq 'f ⇒ (Eq (α * β * γ * δ * 'e * 'f))
  let == = sextupleEqual
  let <> x y = ¬ (sextupleEqual x y)
end

val sextupleCompare : ∀ α β γ δ 'e 'f. (α → α → ORDERING) → (β → β → ORDERING) → (γ → γ → ORDERING) →
(δ → δ → ORDERING) → ('e → 'e → ORDERING) → ('f → 'f → ORDERING) →
(α * β * γ * δ * 'e * 'f) → (α * β * γ * δ * 'e * 'f) → ORDERING
let sextupleCompare cmpa cmpb cmpc cmpd cmpe cmpf (a1, b1, c1, d1, e1, f1) (a2, b2, c2, d2, e2, f2) =
  pairCompare cmpa (pairCompare cmpb (pairCompare cmpc (pairCompare cmpd (pairCompare cmpe cmpf)))) (a1, (b1, (c1, (d1, (e1, f1)))))

let sextupleLess (x1, x2, x3, x4, x5, x6) (y1, y2, y3, y4, y5, y6) = (x1, (x2, (x3, (x4, (x5, x6))))) < (y1, (y2, (y3, (y4, (y5, y6)))))

let sextupleLessEq (x1, x2, x3, x4, x5, x6) (y1, y2, y3, y4, y5, y6) = (x1, (x2, (x3, (x4, (x5, x6))))) ≤ (y1, (y2, (y3, (y4, (y5, y6)))))

let sextupleGreater x123456 y123456 = sextupleLess y123456 x123456
let sextupleGreaterEq x123456 y123456 = sextupleLessEq y123456 x123456

instance ∀ α β γ δ 'e 'f. Ord α, Ord β, Ord γ, Ord δ, Ord 'e, Ord 'f ⇒ (Ord (α * β * γ * δ * 'e * 'f))
  let compare = sextupleCompare compare compare compare compare compare compare compare
  let < = sextupleLess
  let <= = sextupleLessEq
  let > = sextupleGreater

```

```

    let >= = sextupleGreaterEq
end

```

```

instance ∀ α β γ δ 'e 'f. SetType α, SetType β, SetType γ, SetType δ, SetType 'e, SetType 'f ⇒
(SetType (α * β * γ * δ * 'e * 'f))
    let setElemCompare = sextupleCompare setElemCompare setElemCompare setElemCompare setElemCompare setElemC
end

```

### 3 Function

```
(*****
(* A library for common operations on functions *)
*****)

open import Bool Basic_classes

declare {isabelle, hol, ocaml, coq} rename module = lem_function

open import {coq} Program.Basics

(* ----- *)
(* identity function      *)
(* ----- *)

val id :  $\forall \alpha. \alpha \rightarrow \alpha$ 
let id x = x

let inline {coq} id x = x
declare isabelle target_rep function id = 'id'
declare hol target_rep function id = 'I'

(* ----- *)
(* constant function      *)
(* ----- *)

val const :  $\forall \alpha \beta. \alpha \rightarrow \beta \rightarrow \alpha$ 
let inline const x y = x

declare coq target_rep function const = 'const'
declare hol target_rep function const = 'K'

(* ----- *)
(* function composition    *)
(* ----- *)

val comb :  $\forall \alpha \beta \gamma. (\beta \rightarrow \gamma) \rightarrow (\alpha \rightarrow \beta) \rightarrow (\alpha \rightarrow \gamma)$ 
let comb f g = (fun x  $\rightarrow$  f (g x))

declare coq target_rep function comb = 'compose'
declare isabelle target_rep function comb = infix 'o'
declare hol target_rep function comb = infix 'o'

(* ----- *)
(* function application    *)
(* ----- *)

val $ [apply] :  $\forall \alpha \beta. (\alpha \rightarrow \beta) \rightarrow (\alpha \rightarrow \beta)$ 
let $ f = (fun x  $\rightarrow$  f x)

declare coq target_rep function apply = 'apply'
let inline {isabelle, ocaml, hol} apply f x = f x

val $> [rev_apply] :  $\forall \alpha \beta. \alpha \rightarrow (\alpha \rightarrow \beta) \rightarrow \beta$ 
```

```

let $> x f = f x
let inline {isabelle, ocaml, hol} rev_apply x f = f x

(* ----- *)
(* flipping argument order *)
(* ----- *)

val flip :  $\forall \alpha \beta \gamma. (\alpha \rightarrow \beta \rightarrow \gamma) \rightarrow (\beta \rightarrow \alpha \rightarrow \gamma)$ 
let flip f = (fun x y  $\rightarrow$  f y x)

declare coq target_rep function flip = 'flip'
let inline {isabelle} flip f x y = f y x
declare hol target_rep function flip = 'combin$C'

(* currying / uncurrying *)

val curry :  $\forall \alpha \beta \gamma. ((\alpha * \beta) \rightarrow \gamma) \rightarrow \alpha \rightarrow \beta \rightarrow \gamma$ 
let curry f = (fun a b  $\rightarrow$  f (a, b))

val uncurry :  $\forall \alpha \beta \gamma. (\alpha \rightarrow \beta \rightarrow \gamma) \rightarrow (\alpha * \beta \rightarrow \gamma)$ 
let uncurry f (a, b) = f a b

```

## 4 Maybe

```

(*****
(* A library for option
*)
(* It mainly follows the Haskell Maybe – library
*)
*****)

declare {hol, isabelle, ocaml, coq} rename module = lem_maybe

open import Bool Basic_classes Function

(* ===== *)
(* Basic stuff *)
(* ===== *)

type MAYBE  $\alpha$  =
| NOTHING
| JUST of  $\alpha$ 

declare hol target_rep type MAYBE  $\alpha$  = 'option'  $\alpha$ 
declare isabelle target_rep type MAYBE  $\alpha$  = 'option'  $\alpha$ 
declare coq target_rep type MAYBE  $\alpha$  = 'option'  $\alpha$ 
declare ocaml target_rep type MAYBE  $\alpha$  = 'option'  $\alpha$ 

declare hol target_rep function Just = 'SOME'
declare ocaml target_rep function Just = 'Some'
declare isabelle target_rep function Just = 'Some'
declare coq target_rep function Just = 'Some'

declare hol target_rep function Nothing = 'NONE'
declare ocaml target_rep function Nothing = 'None'
declare isabelle target_rep function Nothing = 'None'
declare coq target_rep function Nothing = 'None'

val maybeEqual :  $\forall \alpha. Eq \alpha \Rightarrow MAYBE \alpha \rightarrow MAYBE \alpha \rightarrow BOOL$ 
val maybeEqualBy :  $\forall \alpha. (\alpha \rightarrow \alpha \rightarrow BOOL) \rightarrow MAYBE \alpha \rightarrow MAYBE \alpha \rightarrow BOOL$ 

let maybeEqualBy eq x y = match (x, y) with
| (Nothing, Nothing)  $\rightarrow$  true
| (Nothing, Just _)  $\rightarrow$  false
| (Just _, Nothing)  $\rightarrow$  false
| (Just x', Just y')  $\rightarrow$  (eq x' y')
end
let inline maybeEqual = maybeEqualBy (=)

declare ocaml target_rep function maybeEqualBy = 'Lem.option.equal'
let inline {hol, isabelle} maybeEqual = unsafe_structural_equality

instance  $\forall \alpha. Eq \alpha \Rightarrow (Eq (MAYBE \alpha))$ 
let == maybeEqual
let <> x y =  $\neg$  (maybeEqual x y)
end

assert maybe_eq1 : ((Nothing : MAYBE BOOL) = Nothing)
assert maybe_eq2 : ((Just true)  $\neq$  Nothing)
assert maybe_eq3 : ((Just false)  $\neq$  (Just true))

```



```
assert maybe_eq4 : ((Just false) = (Just false))
```

```
let maybeCompare cmp x y = match (x, y) with
| (Nothing, Nothing) → EQ
| (Nothing, Just _) → LT
| (Just _, Nothing) → GT
| (Just x', Just y') → cmp x' y'
end
```

```
instance ∀ α. SetType α ⇒ (SetType (MAYBE α))
let setElemCompare = maybeCompare setElemCompare
end
```

```
instance ∀ α. Ord α ⇒ (Ord (MAYBE α))
let compare = maybeCompare compare
let <= fun m1 → (fun m2 → maybeCompare compare m1 m2 = LT)
let <= fun m1 → (fun m2 → (let r = maybeCompare compare m1 m2 in r = LT ∨ r = EQ))
let >= fun m1 → (fun m2 → maybeCompare compare m1 m2 = GT)
let >= fun m1 → (fun m2 → (let r = maybeCompare compare m1 m2 in r = GT ∨ r = EQ))
end
```

```
(* ----- *)
(* maybe          *)
(* ----- *)
```

```
val maybe : ∀ α β. β → (α → β) → MAYBE α → β
let maybe d f mb = match mb with
| Just a → f a
| Nothing → d
end
```

```
declare ocaml target_rep function maybe = 'Lem.option_case'
declare isabelle target_rep function maybe = 'case_option'
declare hol target_rep function maybe d f mb = 'option_CASE' mb d f
```

```
assert maybe1 : (maybe true (fun b → ¬ b) Nothing = true)
assert maybe2 : (maybe false (fun b → ¬ b) Nothing = false)
assert maybe3 : (maybe true (fun b → ¬ b) (Just true) = false)
assert maybe4 : (maybe true (fun b → ¬ b) (Just false) = true)
```

```
(* ----- *)
(* isJust / isNothing      *)
(* ----- *)
```

```
val isJust : ∀ α. MAYBE α → BOOL
let isJust mb = match mb with
| Just _ → true
| Nothing → false
end
```

```
declare hol target_rep function isJust = 'IS_SOME'
declare ocaml target_rep function isJust = 'Lem.is_some'
declare isabelle target_rep function isJust x = '$\neg$' (unsafe_structural_equality x Nothing)
```

```
assert isJust1 : (isJust (Just true))
assert isJust2 : (¬ (isJust (Nothing : MAYBE BOOL)))
```

```

val isNothing :  $\forall \alpha. \text{MAYBE } \alpha \rightarrow \text{BOOL}$ 
let isNothing mb = match mb with
| Just _  $\rightarrow$  false
| Nothing  $\rightarrow$  true
end

declare hol target_rep function isNothing = 'IS_NONE'
declare ocaml target_rep function isNothing = 'Lem.is_none'
declare isabelle target_rep function isNothing x = (unsafe_structural_equality x Nothing)

assert isNothing1 : ( $\neg$  (isNothing (Just true)))
assert isNothing2 : (isNothing (Nothing : MAYBE BOOL))

lemma isJustNothing : (
  ( $\forall x. \text{isNothing } x = \neg (\text{isJust } x)$ )  $\wedge$ 
  ( $\forall v. \text{isJust } (\text{Just } v)$ )  $\wedge$ 
  (isNothing Nothing))

(* ----- *)
(* fromMaybe *)
(* ----- *)

val fromMaybe :  $\forall \alpha. \alpha \rightarrow \text{MAYBE } \alpha \rightarrow \alpha$ 
let fromMaybe d mb = match mb with
| Just v  $\rightarrow$  v
| Nothing  $\rightarrow$  d
end

declare ocaml target_rep function fromMaybe = 'Lem.option_default'
let inline {isabelle, hol} fromMaybe d = maybe d id

lemma fromMaybe : (
  ( $\forall d v. \text{fromMaybe } d (\text{Just } v) = v$ )  $\wedge$ 
  ( $\forall d. \text{fromMaybe } d \text{ Nothing} = d$ ))

assert fromMaybe1 : (fromMaybe true Nothing = true)
assert fromMaybe2 : (fromMaybe false Nothing = false)
assert fromMaybe3 : (fromMaybe true (Just true) = true)
assert fromMaybe4 : (fromMaybe true (Just false) = false)

(* ----- *)
(* map *)
(* ----- *)

val map :  $\forall \alpha \beta. (\alpha \rightarrow \beta) \rightarrow \text{MAYBE } \alpha \rightarrow \text{MAYBE } \beta$ 
let map f = maybe Nothing (fun v  $\rightarrow$  Just (f v))

declare hol target_rep function map = 'OPTION_MAP'
declare ocaml target_rep function map = 'Lem.option_map'
declare isabelle target_rep function map = 'map_option'
declare coq target_rep function map = 'option_map'

lemma maybe_map : (
  ( $\forall f. \text{map } f \text{ Nothing} = \text{Nothing}$ )  $\wedge$ 
  ( $\forall f v. \text{map } f (\text{Just } v) = \text{Just } (f v)$ ))

assert map1 : (map (fun b  $\rightarrow$   $\neg b$ ) Nothing = Nothing)
assert map2 : (map (fun b  $\rightarrow$   $\neg b$ ) (Just true) = Just false)

```

```
assert map3 : (map (fun b → ¬ b) (Just false) = Just true)
```

```
(* ----- *)
(* bind          *)
(* ----- *)
```

```
val bind : ∀ α β. MAYBE α → (α → MAYBE β) → MAYBE β
let bind mb f = maybe Nothing f mb
```

```
declare isabelle target_rep function bind = 'Option.bind'
declare ocaml target_rep function bind = 'Lem.option.bind'
declare hol target_rep function bind = 'OPTION.BIND'
```

```
lemma maybe_bind : (
  (∀ f. bind Nothing f = Nothing) ∧
  (∀ f v. bind (Just v) f = (f v)))
```

```
assert bind1 : (bind Nothing (fun b → Just (¬ b)) = Nothing)
assert bind2 : (bind (Just true) (fun b → Just (¬ b)) = Just false)
assert bind3 : (bind (Just false) (fun b → Just (¬ b)) = Just true)
assert bind4 : (bind (Just false) (fun b → (Nothing : MAYBE BOOL)) = Nothing)
```

## 5 Num

```
(*****
(* A library for numbers
*)
(*
*)
(* It mainly follows the Haskell Maybe – library
*)
(*****

(* rename module to clash with existing list modules of targets  problem : renaming from inside the module i

declare {isabelle, ocaml, hol, coq} rename module = lem_num

open import Bool Basic_classes
open import {isabelle} HOL – Word.Word Complex_Main
open import {hol} integerTheory intReduce wordsTheory wordsLib ratTheory realTheory intrealTheory transcTheory

open import {coq} Coq.Numbers.BinNums Coq.ZArith.BinInt Coq.ZArith.Zpower Coq.ZArith.Zdiv Coq.ZArith.Zmax Coq.L

(* ===== *)
(* Numerals
*)
(* ===== *)

(* Numerals like 0, 1, 2, 42, 4543 are built – in. That’s the only use  of numerals. The following type – class

declare hol target_rep type NUMERAL = 'num'
declare coq target_rep type NUMERAL = 'nat'
declare ocaml target_rep type NUMERAL = 'int'

class inline ( Numeral  $\alpha$  )
  val fromNumeral : NUMERAL  $\rightarrow$   $\alpha$ 
end

(* ===== *)
(* Syntactic type – classes for common operations
*)
(* ===== *)

(* Typeclasses can be used as a mean to overload constants like ” + ”, ” – ”, etc *)

class ( NumNegate  $\alpha$  )
  val ~ [numNegate] :  $\alpha \rightarrow \alpha$ 
end
declare tex target_rep function numNegate = '$-$'

class ( NumAbs  $\alpha$  )
  val abs :  $\alpha \rightarrow \alpha$ 
end

class ( NumAdd  $\alpha$  )
  val + [numAdd] :  $\alpha \rightarrow \alpha \rightarrow \alpha$ 
end
declare tex target_rep function numAdd = infix '$+$'

class ( NumMinus  $\alpha$  )
  val – [numMinus] :  $\alpha \rightarrow \alpha \rightarrow \alpha$ 
end
declare tex target_rep function numMinus = infix '$-$'
```

```

class ( NumMult  $\alpha$  )
  val * [numMult] :  $\alpha \rightarrow \alpha \rightarrow \alpha$ 
end
declare tex target_rep function numMult = infix '$*$',

class ( NumPow  $\alpha$  )
  val ** [numPow] :  $\alpha \rightarrow \text{NAT} \rightarrow \alpha$ 
end
declare tex target_rep function numPow  $n\ m$  = special "{%e}^{%e}"  $n\ m$ 

class ( NumDivision  $\alpha$  )
  val / [numDivision] :  $\alpha \rightarrow \alpha \rightarrow \alpha$ 
end

class ( NumIntegerDivision  $\alpha$  )
  val div [numIntegerDivision] :  $\alpha \rightarrow \alpha \rightarrow \alpha$ 
end

```

```

class ( NumRemainder  $\alpha$  )
  val mod [numRemainder] :  $\alpha \rightarrow \alpha \rightarrow \alpha$ 
end

```

```

class ( NumSucc  $\alpha$  )
  val succ :  $\alpha \rightarrow \alpha$ 
end

```

```

class ( NumPred  $\alpha$  )
  val pred :  $\alpha \rightarrow \alpha$ 
end

```

```

(* ===== *)
(* Basic number types *)
(* ===== *)

```

```

(* ----- *)
(* nat *)
(* ----- *)

```

```

(* bounded size natural numbers, i.e. positive integers *)

```

(\* "nat" is the old type "num". It represents natural numbers. These numbers might be bounded, however no che

```

declare hol target_rep type NAT = 'num'
declare isabelle target_rep type NAT = 'nat'
declare coq target_rep type NAT = 'nat'
declare ocaml target_rep type NAT = 'int'

```

```

(* ----- *)
(* natural *)
(* ----- *)

```

```

(* unbounded size natural numbers *)
type NATURAL
declare hol target_rep type  $\mathbb{N}$  = 'num'
declare isabelle target_rep type  $\mathbb{N}$  = 'nat'
declare coq target_rep type  $\mathbb{N}$  = 'nat'

```

```

declare ocaml target_rep type  $\mathbb{N}$  = 'Nat.big_num.num'
declare tex target_rep type  $\mathbb{N}$  = '$\mathbb{N}$'

(* ----- *)
(* int *)
(* ----- *)

(* bounded size integers with uncertain length *)

type INT
declare ocaml target_rep type INT = 'int'
declare isabelle target_rep type INT = 'int'
declare hol target_rep type INT = 'int'
declare coq target_rep type INT = 'Z'

(* ----- *)
(* integer *)
(* ----- *)

(* unbounded size integers *)

type INTEGER
declare ocaml target_rep type  $\mathbb{Z}$  = 'Nat.big_num.num'
declare isabelle target_rep type  $\mathbb{Z}$  = 'int'
declare hol target_rep type  $\mathbb{Z}$  = 'int'
declare coq target_rep type  $\mathbb{Z}$  = 'Z'
declare tex target_rep type  $\mathbb{Z}$  = '$\mathbb{Z}$'

(* ----- *)
(* bint *)
(* ----- *)

(* TODO the bounded ints are only partially implemented, use with care. *)

(* 32 bit integers *)
type INT32
declare ocaml target_rep type INT32 = 'Int32.t'
declare coq target_rep type INT32 = 'Z' (* ??? : better type for this in Coq? *)
declare isabelle target_rep type INT32 = 'word' 32
declare hol target_rep type INT32 = 'word' 32

(* 64 bit integers *)
type INT64
declare ocaml target_rep type INT64 = 'Int64.t'
declare coq target_rep type INT64 = 'Z' (* ??? : better type for this in Coq? *)
declare isabelle target_rep type INT64 = 'word' 64
declare hol target_rep type INT64 = 'word' 64

(* ----- *)
(* rational *)
(* ----- *)

(* unbounded size and precision rational numbers *)

type RATIONAL

```

```

declare ocaml target_rep type RATIONAL = 'Rational.t'
declare coq target_rep type RATIONAL = 'Q' (* ??? : better type for this in Coq? *)
declare isabelle target_rep type RATIONAL = 'rat'
declare hol target_rep type RATIONAL = 'rat' (* ??? : better type for this in HOL? *)

(* ----- *)
(* real *)
(* ----- *)

(* real numbers *)
(* Note that for OCaml, this is mapped to floats with 64 bits. *)

type REAL
declare ocaml target_rep type REAL = 'float'
declare coq target_rep type REAL = 'R' (* ??? : better type for this in Coq? *)
declare isabelle target_rep type REAL = 'real'
declare hol target_rep type REAL = 'real' (* ??? : better type for this in HOL? *)

(* ----- *)
(* double *)
(* ----- *)

(* double precision floating point (64 bits) *)

type FLOAT64
declare ocaml target_rep type FLOAT64 = 'double'
declare coq target_rep type FLOAT64 = 'Q' (* ??? : better type for this in Coq? *)
declare isabelle target_rep type FLOAT64 = '???' (* ??? : better type for this in Isa? *)
declare hol target_rep type FLOAT64 = 'XXX' (* ??? : better type for this in HOL? *)

type FLOAT32
declare ocaml target_rep type FLOAT32 = 'float'
declare coq target_rep type FLOAT32 = 'Q' (* ??? : better type for this in Coq? *)
declare isabelle target_rep type FLOAT32 = '???' (* ??? : better type for this in Isa? *)
declare hol target_rep type FLOAT32 = 'XXX' (* ??? : better type for this in HOL? *)

(* ===== *)
(* Binding the standard operations for the number types *)
(* ===== *)

(* ----- *)
(* nat *)
(* ----- *)

val natFromNumeral : NUMERAL → NAT
declare hol target_rep function natFromNumeral x = (''x : NAT)
declare ocaml target_rep function natFromNumeral = ''
declare isabelle target_rep function natFromNumeral n = (''n : NAT)
declare coq target_rep function natFromNumeral = ''

instance (Numeral NAT)
  let fromNumeral n = natFromNumeral n
end

```

```

val natEq : NAT → NAT → BOOL
let inline natEq = unsafe_structural_equality
declare coq target_rep function natEq = 'beq_nat'
instance (Eq NAT)
  let == = natEq
  let <> n1 n2 = ¬ (natEq n1 n2)
end

val natLess : NAT → NAT → BOOL
val natLessEqual : NAT → NAT → BOOL
val natGreater : NAT → NAT → BOOL
val natGreaterEqual : NAT → NAT → BOOL

declare hol target_rep function natLess = infix '<'
declare ocaml target_rep function natLess = infix '<'
declare isabelle target_rep function natLess = infix '<'
declare coq target_rep function natLess = 'nat_ltb'

declare hol target_rep function natLessEqual = infix '<='
declare ocaml target_rep function natLessEqual = infix '<='
declare isabelle target_rep function natLessEqual = infix '\<le>'
declare coq target_rep function natLessEqual = 'nat_lteb'

declare hol target_rep function natGreater = infix '>'
declare ocaml target_rep function natGreater = infix '>'
declare isabelle target_rep function natGreater = infix '>'
declare coq target_rep function natGreater = 'nat_gtb'

declare hol target_rep function natGreaterEqual = infix '>='
declare ocaml target_rep function natGreaterEqual = infix '>='
declare isabelle target_rep function natGreaterEqual = infix '\<ge>'
declare coq target_rep function natGreaterEqual = 'nat_gteb'

val natCompare : NAT → NAT → ORDERING
let inline natCompare = defaultCompare
let inline {coq, hol, isabelle} natCompare = genericCompare natLess natEq

instance (Ord NAT)
  let compare = natCompare
  let < = natLess
  let <= = natLessEqual
  let > = natGreater
  let >= = natGreaterEqual
end

instance (SetType NAT)
  let setElemCompare = natCompare
end

val natAdd : NAT → NAT → NAT
declare hol target_rep function natAdd = infix '+'
declare ocaml target_rep function natAdd = infix '+'
declare isabelle target_rep function natAdd = infix '+'
declare coq target_rep function natAdd = 'Coq.Init.Peano.plus'

instance (NumAdd NAT)
  let + = natAdd
end

```



```

val natMinus : NAT → NAT → NAT
declare hol target_rep function natMinus = infix '-'
declare ocaml target_rep function natMinus = 'Nat.num.nat_minus'
declare isabelle target_rep function natMinus = infix '-'
declare coq target_rep function natMinus = 'Coq.Init.Peano.minus'

instance (NumMinus NAT)
  let - = natMinus
end

val natSucc : NAT → NAT
let natSucc n = n + 1
declare hol target_rep function natSucc = 'SUC'
declare isabelle target_rep function natSucc = 'Suc'
declare ocaml target_rep function natSucc = 'succ'
declare coq target_rep function natSucc = 'S'
instance (NumSucc NAT)
  let succ = natSucc
end

val natPred : NAT → NAT
let inline natPred n = n - 1
declare hol target_rep function natPred = 'PRE'
declare ocaml target_rep function natPred = 'Nat.num.nat_pred'
declare coq target_rep function natPred = 'Coq.Init.Peano.pred'
instance (NumPred NAT)
  let pred = natPred
end

val natMult : NAT → NAT → NAT
declare hol target_rep function natMult = infix '*'
declare ocaml target_rep function natMult = infix '*'
declare isabelle target_rep function natMult = infix '*'
declare coq target_rep function natMult = 'Coq.Init.Peano.mult'

instance (NumMult NAT)
  let * = natMult
end

val natDiv : NAT → NAT → NAT
declare hol target_rep function natDiv = infix 'DIV'
declare ocaml target_rep function natDiv = infix '/'
declare isabelle target_rep function natDiv = infix 'div'
declare coq target_rep function natDiv = 'Coq.Numbers.Natural.Peano.NPeano.div'

instance ( NumIntegerDivision NAT )
  let div = natDiv
end

instance ( NumDivision NAT )
  let / = natDiv
end

val natMod : NAT → NAT → NAT
declare hol target_rep function natMod = infix 'MOD'
declare ocaml target_rep function natMod = infix 'mod'
declare isabelle target_rep function natMod = infix 'mod'

```

```

declare coq target_rep function natMod = 'Coq.Numbers.Natural.Peano.NPeano.modulo'

instance ( NumRemainder NAT )
  let mod = natMod
end

val gen_pow_aux :  $\forall \alpha. (\alpha \rightarrow \alpha \rightarrow \alpha) \rightarrow \alpha \rightarrow \alpha \rightarrow \text{NAT} \rightarrow \alpha$ 
let rec gen_pow_aux (mul :  $\alpha \rightarrow \alpha \rightarrow \alpha$ ) (a :  $\alpha$ ) (b :  $\alpha$ ) (e : NAT) =
  match e with
  | 0  $\rightarrow$  a (* cannot happen, call discipline guarentees e >= 1 *)
  | 1  $\rightarrow$  mul a b
  | (e' + 2)  $\rightarrow$  let e'' = e / 2 in
    let a' = (if (e mod 2) = 0 then a else mul a b) in
    gen_pow_aux mul a' (mul b b) e''
  end
declare termination_argument gen_pow_aux = automatic

declare coq target_rep function gen_pow_aux = 'gen_pow_aux'

let gen_pow (one :  $\alpha$ ) (mul :  $\alpha \rightarrow \alpha \rightarrow \alpha$ ) (b :  $\alpha$ ) (e : NAT) :  $\alpha$  =
  if e < 0 then one else
  if (e = 0) then one else gen_pow_aux mul one b e

val natPow : NAT  $\rightarrow$  NAT  $\rightarrow$  NAT
let {ocaml} natPow = gen_pow 1 natMult

declare hol target_rep function natPow = infix '**'
declare isabelle target_rep function natPow = infix '^'
declare coq target_rep function natPow = 'nat_power'

instance ( NumPow NAT )
  let ** = natPow
end

val natMin : NAT  $\rightarrow$  NAT  $\rightarrow$  NAT
let inline natMin = defaultMin
declare ocaml target_rep function natMin = 'min'
declare isabelle target_rep function natMin = 'min'
declare hol target_rep function natMin = 'MIN'
declare coq target_rep function natMin = 'nat_min'

val natMax : NAT  $\rightarrow$  NAT  $\rightarrow$  NAT
let inline natMax = defaultMax
declare isabelle target_rep function natMax = 'max'
declare ocaml target_rep function natMax = 'max'
declare hol target_rep function natMax = 'MAX'
declare coq target_rep function natMax = 'nat_max'

instance ( OrdMaxMin NAT )
  let max = natMax
  let min = natMin
end

(* ----- *)
(* natural      *)
(* ----- *)

```

```

val naturalFromNumeral : NUMERAL →  $\mathbb{N}$ 
declare hol target_rep function naturalFromNumeral x = (''x :  $\mathbb{N}$ '' )
declare ocaml target_rep function naturalFromNumeral = 'Nat_big_num.of_int'
declare isabelle target_rep function naturalFromNumeral n = (''n :  $\mathbb{N}$ '' )
declare coq target_rep function naturalFromNumeral = ''

instance (Numeral  $\mathbb{N}$ )
  let fromNumeral n = naturalFromNumeral n
end

val naturalEq :  $\mathbb{N}$  →  $\mathbb{N}$  → BOOL
let inline naturalEq = unsafe_structural_equality
declare ocaml target_rep function naturalEq = 'Nat_big_num.equal'
declare coq target_rep function naturalEq = 'beq_nat'
instance (Eq  $\mathbb{N}$ )
  let == = naturalEq
  let <> n1 n2 = ¬ (naturalEq n1 n2)
end

val naturalLess :  $\mathbb{N}$  →  $\mathbb{N}$  → BOOL
val naturalLessEqual :  $\mathbb{N}$  →  $\mathbb{N}$  → BOOL
val naturalGreater :  $\mathbb{N}$  →  $\mathbb{N}$  → BOOL
val naturalGreaterEqual :  $\mathbb{N}$  →  $\mathbb{N}$  → BOOL

declare hol target_rep function naturalLess = infix '<'
declare ocaml target_rep function naturalLess = 'Nat_big_num.less'
declare isabelle target_rep function naturalLess = infix '<'
declare coq target_rep function naturalLess = 'nat_ltb'

declare hol target_rep function naturalLessEqual = infix '<='
declare ocaml target_rep function naturalLessEqual = 'Nat_big_num.less_equal'
declare isabelle target_rep function naturalLessEqual = infix '\<le>'
declare coq target_rep function naturalLessEqual = 'nat_lteb'

declare hol target_rep function naturalGreater = infix '>'
declare ocaml target_rep function naturalGreater = 'Nat_big_num.greater'
declare isabelle target_rep function naturalGreater = infix '>'
declare coq target_rep function naturalGreater = 'nat_gtb'

declare hol target_rep function naturalGreaterEqual = infix '>='
declare ocaml target_rep function naturalGreaterEqual = 'Nat_big_num.greater_equal'
declare isabelle target_rep function naturalGreaterEqual = infix '\<ge>'
declare coq target_rep function naturalGreaterEqual = 'nat_gteb'

val naturalCompare :  $\mathbb{N}$  →  $\mathbb{N}$  → ORDERING
let inline naturalCompare = defaultCompare
let inline {coq, isabelle, hol} naturalCompare = genericCompare naturalLess naturalEq
declare ocaml target_rep function naturalCompare = 'Nat_big_num.compare'

instance (Ord  $\mathbb{N}$ )
  let compare = naturalCompare
  let < = naturalLess
  let <= = naturalLessEqual
  let > = naturalGreater
  let >= = naturalGreaterEqual
end

```

```

instance (SetType  $\mathbb{N}$ )
  let setElemCompare = naturalCompare
end

val naturalAdd :  $\mathbb{N}$   $\rightarrow$   $\mathbb{N}$   $\rightarrow$   $\mathbb{N}$ 
declare hol target_rep function naturalAdd = infix '+'
declare ocaml target_rep function naturalAdd = 'Nat_big_num.add'
declare isabelle target_rep function naturalAdd = infix '+'
declare coq target_rep function naturalAdd = 'Coq.Init.Peano.plus'

instance (NumAdd  $\mathbb{N}$ )
  let + = naturalAdd
end

val naturalMinus :  $\mathbb{N}$   $\rightarrow$   $\mathbb{N}$   $\rightarrow$   $\mathbb{N}$ 
declare hol target_rep function naturalMinus = infix '-'
declare ocaml target_rep function naturalMinus = 'Nat_big_num.sub_nat'
declare isabelle target_rep function naturalMinus = infix '-'
declare coq target_rep function naturalMinus = 'Coq.Init.Peano.minus'

instance (NumMinus  $\mathbb{N}$ )
  let - = naturalMinus
end

val naturalSucc :  $\mathbb{N}$   $\rightarrow$   $\mathbb{N}$ 
let naturalSucc n = n + 1
declare hol target_rep function naturalSucc = 'SUC'
declare isabelle target_rep function naturalSucc = 'Suc'
declare ocaml target_rep function naturalSucc = 'Nat_big_num.succ'
declare coq target_rep function naturalSucc = 'S'
instance (NumSucc  $\mathbb{N}$ )
  let succ = naturalSucc
end

val naturalPred :  $\mathbb{N}$   $\rightarrow$   $\mathbb{N}$ 
let inline naturalPred n = n - 1
declare hol target_rep function naturalPred = 'PRE'
declare ocaml target_rep function naturalPred = 'Nat_big_num.pred_nat'
declare coq target_rep function naturalPred = 'Coq.Init.Peano.pred'
instance (NumPred  $\mathbb{N}$ )
  let pred = naturalPred
end

val naturalMult :  $\mathbb{N}$   $\rightarrow$   $\mathbb{N}$   $\rightarrow$   $\mathbb{N}$ 
declare hol target_rep function naturalMult = infix '*'
declare ocaml target_rep function naturalMult = 'Nat_big_num.mul'
declare isabelle target_rep function naturalMult = infix '*'
declare coq target_rep function naturalMult = 'Coq.Init.Peano.mult'

instance (NumMult  $\mathbb{N}$ )
  let * = naturalMult
end

val naturalPow :  $\mathbb{N}$   $\rightarrow$  NAT  $\rightarrow$   $\mathbb{N}$ 
declare hol target_rep function naturalPow = infix '**'
declare ocaml target_rep function naturalPow = 'Nat_big_num.pow_int'
declare isabelle target_rep function naturalPow = infix '^'

```

```

declare coq target_rep function naturalPow = 'nat_power'

instance ( NumPow  $\mathbb{N}$  )
  let ** = naturalPow
end

val naturalDiv :  $\mathbb{N}$   $\rightarrow$   $\mathbb{N}$   $\rightarrow$   $\mathbb{N}$ 
declare hol target_rep function naturalDiv = infix 'DIV'
declare ocaml target_rep function naturalDiv = 'Nat_big_num.div'
declare isabelle target_rep function naturalDiv = infix 'div'
declare coq target_rep function naturalDiv = 'Coq.Numbers.Natural.Peano.NPeano.div'

instance ( NumIntegerDivision  $\mathbb{N}$  )
  let div = naturalDiv
end

instance ( NumDivision  $\mathbb{N}$  )
  let / = naturalDiv
end

val naturalMod :  $\mathbb{N}$   $\rightarrow$   $\mathbb{N}$   $\rightarrow$   $\mathbb{N}$ 
declare hol target_rep function naturalMod = infix 'MOD'
declare ocaml target_rep function naturalMod = 'Nat_big_num.modulus'
declare isabelle target_rep function naturalMod = infix 'mod'
declare coq target_rep function naturalMod = 'Coq.Numbers.Natural.Peano.NPeano.modulo'

instance ( NumRemainder  $\mathbb{N}$  )
  let mod = naturalMod
end

val naturalMin :  $\mathbb{N}$   $\rightarrow$   $\mathbb{N}$   $\rightarrow$   $\mathbb{N}$ 
let inline naturalMin = defaultMin
declare isabelle target_rep function naturalMin = 'min'
declare ocaml target_rep function naturalMin = 'Nat_big_num.min'
declare hol target_rep function naturalMin = 'MIN'
declare coq target_rep function naturalMin = 'nat_min'

val naturalMax :  $\mathbb{N}$   $\rightarrow$   $\mathbb{N}$   $\rightarrow$   $\mathbb{N}$ 
let inline naturalMax = defaultMax
declare isabelle target_rep function naturalMax = 'max'
declare ocaml target_rep function naturalMax = 'Nat_big_num.max'
declare hol target_rep function naturalMax = 'MAX'
declare coq target_rep function naturalMax = 'nat_max'

instance ( OrdMaxMin  $\mathbb{N}$  )
  let max = naturalMax
  let min = naturalMin
end

(* ----- *)
(* int      *)
(* ----- *)

val intFromNumeral : NUMERAL  $\rightarrow$  INT
declare ocaml target_rep function intFromNumeral = ''
declare isabelle target_rep function intFromNumeral n = (''n : INT)
declare hol target_rep function intFromNumeral n = (''n : INT)

```

```

declare coq target_rep function intFromNumeral n = ('Zpred' ('Zpos' ('P_of_succ_nat' n)))

instance (Numeral INT)
  let fromNumeral n = intFromNumeral n
end

val intEq : INT → INT → BOOL
let inline intEq = unsafe_structural_equality
declare coq target_rep function intEq = 'Z.eqb'
instance (Eq INT)
  let == = intEq
  let <> n1 n2 = ¬ (intEq n1 n2)
end

val intLess : INT → INT → BOOL
val intLessEqual : INT → INT → BOOL
val intGreater : INT → INT → BOOL
val intGreaterEqual : INT → INT → BOOL

declare hol target_rep function intLess = infix '<'
declare ocaml target_rep function intLess = infix '<'
declare isabelle target_rep function intLess = infix '<'
declare coq target_rep function intLess = 'int_ltb'

declare hol target_rep function intLessEqual = infix '<='
declare ocaml target_rep function intLessEqual = infix '<='
declare isabelle target_rep function intLessEqual = infix '\<le>'
declare coq target_rep function intLessEqual = 'int_lteb'

declare hol target_rep function intGreater = infix '>'
declare ocaml target_rep function intGreater = infix '>'
declare isabelle target_rep function intGreater = infix '>'
declare coq target_rep function intGreater = 'int_gtb'

declare hol target_rep function intGreaterEqual = infix '>='
declare ocaml target_rep function intGreaterEqual = infix '>='
declare isabelle target_rep function intGreaterEqual = infix '\<ge>'
declare coq target_rep function intGreaterEqual = 'int_gteb'

val intCompare : INT → INT → ORDERING
let inline intCompare = defaultCompare
let inline {coq, isabelle, hol} intCompare = genericCompare intLess intEq
declare ocaml target_rep function intCompare = 'compare'

instance (Ord INT)
  let compare = intCompare
  let < = intLess
  let <= = intLessEqual
  let > = intGreater
  let >= = intGreaterEqual
end

instance (SetType INT)
  let setElemCompare = intCompare
end

val intNegate : INT → INT
declare hol target_rep function intNegate i = '~' i

```

```

declare ocaml target_rep function intNegate i = (~- i)
declare isabelle target_rep function intNegate i = '- ' i
declare coq target_rep function intNegate i = ('Coq.ZArith.BinInt.Zminus' 'Z'₀ i)

instance (NumNegate INT)
  let ~ = intNegate
end

val intAbs : INT → INT
declare hol target_rep function intAbs = 'ABS'
declare ocaml target_rep function intAbs = 'abs'
declare isabelle target_rep function intAbs = 'abs'
declare coq target_rep function intAbs input = ('Zpred' ('Zpos' ('P.of_succ_nat' ('Zabs_nat' input))))
(* TODO: check *)

instance (NumAbs INT)
  let abs = intAbs
end

val intAdd : INT → INT → INT
declare hol target_rep function intAdd = infix '+'
declare ocaml target_rep function intAdd = infix '+'
declare isabelle target_rep function intAdd = infix '+'
declare coq target_rep function intAdd = 'Coq.ZArith.BinInt.Zplus'

instance (NumAdd INT)
  let + = intAdd
end

val intMinus : INT → INT → INT
declare hol target_rep function intMinus = infix '-'
declare ocaml target_rep function intMinus = infix '-'
declare isabelle target_rep function intMinus = infix '-'
declare coq target_rep function intMinus = 'Coq.ZArith.BinInt.Zminus'

instance (NumMinus INT)
  let - = intMinus
end

val intSucc : INT → INT
let inline intSucc n = n + 1
declare ocaml target_rep function intSucc = 'succ'
instance (NumSucc INT)
  let succ = intSucc
end

val intPred : INT → INT
let inline intPred n = n - 1
declare ocaml target_rep function intPred = 'pred'
instance (NumPred INT)
  let pred = intPred
end

val intMult : INT → INT → INT
declare hol target_rep function intMult = infix '*'
declare ocaml target_rep function intMult = infix '*'
declare isabelle target_rep function intMult = infix '*'
declare coq target_rep function intMult = 'Coq.ZArith.BinInt.Zmult'

```

```

instance (NumMult INT)
  let * = intMult
end

val intPow : INT → NAT → INT
let {ocaml} intPow = gen_pow 1 intMult
declare hol target_rep function intPow = infix '**'
declare isabelle target_rep function intPow = infix '^'
declare coq target_rep function intPow = 'Coq.ZArith.Zpower.Zpower_nat'

instance ( NumPow INT )
  let ** = intPow
end

val intDiv : INT → INT → INT
declare hol target_rep function intDiv = infix '/'
declare ocaml target_rep function intDiv = 'Nat_num.int_div'
declare isabelle target_rep function intDiv = infix 'div'
declare coq target_rep function intDiv = 'Coq.ZArith.Zdiv.Zdiv'

instance ( NumIntegerDivision INT )
  let div = intDiv
end

instance ( NumDivision INT )
  let / = intDiv
end

val intMod : INT → INT → INT
declare hol target_rep function intMod = infix '%'
declare ocaml target_rep function intMod = 'Nat_num.int_mod'
declare isabelle target_rep function intMod = infix 'mod'
declare coq target_rep function intMod = 'Coq.ZArith.Zdiv.Zmod'

instance ( NumRemainder INT )
  let mod = intMod
end

val intMin : INT → INT → INT
let inline intMin = defaultMin
declare isabelle target_rep function intMin = 'min'
declare ocaml target_rep function intMin = 'min'
declare hol target_rep function intMin = 'int_min'
declare coq target_rep function intMin = 'Zmin'

val intMax : INT → INT → INT
let inline intMax = defaultMax
declare isabelle target_rep function intMax = 'max'
declare ocaml target_rep function intMax = 'max'
declare hol target_rep function intMax = 'int_max'
declare coq target_rep function intMax = 'Zmax'

instance ( OrdMaxMin INT )
  let max = intMax
  let min = intMin
end

```



```

(* ----- *)
(* int32      *)
(* ----- *)
val int32FromNumeral : NUMERAL → INT32

declare ocaml target_rep function int32FromNumeral = 'Int32.of_int'
declare isabelle target_rep function int32FromNumeral n = (('word_of_int' n) : INT32)
declare hol target_rep function int32FromNumeral n = (('n2w' n) : INT32)
declare coq target_rep function int32FromNumeral n = ('Zpred' ('Zpos' ('P_of_succ_nat' n))) (* TODO : check *)

instance (Numeral INT32)
  let fromNumeral n = int32FromNumeral n
end

val int32Eq : INT32 → INT32 → BOOL
let inline int32Eq = unsafe_structural_equality
declare coq target_rep function int32Eq = 'Z.eqb'

instance (Eq INT32)
  let == = int32Eq
  let <> n1 n2 = ¬ (int32Eq n1 n2)
end

val int32Less : INT32 → INT32 → BOOL
val int32LessEqual : INT32 → INT32 → BOOL
val int32Greater : INT32 → INT32 → BOOL
val int32GreaterEqual : INT32 → INT32 → BOOL

declare ocaml target_rep function int32Less = infix '<'
declare isabelle target_rep function int32Less = 'word_sless'
declare hol target_rep function int32Less = infix '<'
(*TODO: Implement the following correctly. *)
declare coq target_rep function int32Less = 'int_ltb'

declare ocaml target_rep function int32LessEqual = infix '<='
declare isabelle target_rep function int32LessEqual = 'word_sle'
declare hol target_rep function int32LessEqual = infix '<='
(*TODO: Implement the following correctly. *)
declare coq target_rep function int32LessEqual = 'int_lteb'

declare ocaml target_rep function int32Greater = infix '>'
let inline {isabelle} int32Greater x y = int32Less y x
declare hol target_rep function int32Greater = infix '>'
(*TODO: Implement the following correctly. *)
declare coq target_rep function int32Greater = 'int_gtb'

declare ocaml target_rep function int32GreaterEqual = infix '>='
let inline {isabelle} int32GreaterEqual x y = int32LessEqual y x
declare hol target_rep function int32GreaterEqual = infix '>='
(*TODO: Implement the following correctly. *)
declare coq target_rep function int32GreaterEqual = 'int_gteb'

val int32Compare : INT32 → INT32 → ORDERING
let inline int32Compare = defaultCompare
let inline {coq, isabelle, hol} int32Compare = genericCompare int32Less int32Eq
declare ocaml target_rep function int32Compare = 'Int32.compare'

```

```

instance (Ord INT32)
  let compare = int32Compare
  let < = int32Less
  let <= = int32LessEqual
  let > = int32Greater
  let >= = int32GreaterEqual
end

instance (SetType INT32)
  let setElemCompare = int32Compare
end

val int32Negate : INT32 → INT32
declare ocaml target_rep function int32Negate = 'Int32.neg'
declare isabelle target_rep function int32Negate i = '-' i
declare hol target_rep function int32Negate i = (('-' i) : INT32)
(*TODO: Implement the following correctly. *)
declare coq target_rep function int32Negate i = ('Coq.ZArith.BinInt.Zminus' 'Z'0 i)

instance (NumNegate INT32)
  let ~ = int32Negate
end

val int32Abs : INT32 → INT32
let int32Abs i = (if 0 ≤ i then i else -i)
declare ocaml target_rep function int32Abs = 'Int32.abs'

instance (NumAbs INT32)
  let abs = int32Abs
end

val int32Add : INT32 → INT32 → INT32
declare ocaml target_rep function int32Add = 'Int32.add'
declare isabelle target_rep function int32Add = infix '+'
(*TODO: Implement the following two correctly. *)
declare hol target_rep function int32Add i1 i2 = (('word_add' i1 i2) : INT32)
declare coq target_rep function int32Add = 'Coq.ZArith.BinInt.Zplus'

instance (NumAdd INT32)
  let + = int32Add
end

val int32Minus : INT32 → INT32 → INT32
declare ocaml target_rep function int32Minus = 'Int32.sub'
declare isabelle target_rep function int32Minus = infix '-'
(*TODO: Implement the following two correctly. *)
declare hol target_rep function int32Minus i1 i2 = (('word_sub' i1 i2) : INT32)
declare coq target_rep function int32Minus = 'Coq.ZArith.BinInt.Zminus'

instance (NumMinus INT32)
  let - = int32Minus
end

val int32Succ : INT32 → INT32
let inline int32Succ n = n + 1
declare ocaml target_rep function int32Succ = 'Int32.succ'

```

```

instance (NumSucc INT32)
  let succ = int32Succ
end

val int32Pred : INT32 → INT32
let inline int32Pred n = n - 1
declare ocaml target_rep function int32Pred = 'Int32.pred'
instance (NumPred INT32)
  let pred = int32Pred
end

val int32Mult : INT32 → INT32 → INT32
declare ocaml target_rep function int32Mult = 'Int32.mul'
declare isabelle target_rep function int32Mult = infix '*'
declare hol target_rep function int32Mult i1 i2 = (('word_mul' i1 i2) : INT32)
(*TODO: Implement the following correctly. *)
declare coq target_rep function int32Mult = 'Coq.ZArith.BinInt.Zmult'

instance (NumMult INT32)
  let * = int32Mult
end

val int32Pow : INT32 → NAT → INT32
let {ocaml, hol} int32Pow = gen_pow 1 int32Mult
declare isabelle target_rep function int32Pow = infix '^'
(*TODO: Implement the following two correctly. *)
declare coq target_rep function int32Pow = 'Coq.ZArith.Zpower.Zpower_nat'

instance ( NumPow INT32 )
  let ** = int32Pow
end

val int32Div : INT32 → INT32 → INT32
declare ocaml target_rep function int32Div = 'Nat_num.int32_div'
declare isabelle target_rep function int32Div = infix 'div'
declare hol target_rep function int32Div i1 i2 = (('word_div' i1 i2) : INT32)
(*TODO: Implement the following correctly. *)
declare coq target_rep function int32Div = 'Coq.ZArith.Zdiv.Zdiv'

instance ( NumIntegerDivision INT32 )
  let div = int32Div
end

instance ( NumDivision INT32 )
  let / = int32Div
end

val int32Mod : INT32 → INT32 → INT32
declare ocaml target_rep function int32Mod = 'Nat_num.int32_mod'
declare isabelle target_rep function int32Mod = infix 'mod'
declare hol target_rep function int32Mod i1 i2 = (('word_mod' i1 i2) : INT32)
(*TODO: Implement the following correctly. *)
declare coq target_rep function int32Mod = 'Coq.ZArith.Zdiv.Zmod'

instance ( NumRemainder INT32 )
  let mod = int32Mod
end

```

```

val int32Min : INT32 → INT32 → INT32
let inline int32Min = defaultMin
declare hol target_rep function int32Min = 'word_smin'
(*TODO: Implement the following correctly. *)
declare coq target_rep function int32Min = 'Zmin'

val int32Max : INT32 → INT32 → INT32
let inline int32Max = defaultMax
declare hol target_rep function int32Max = 'word_smax'
(*TODO: Implement the following correctly. *)
declare coq target_rep function int32Max = 'Zmax'

instance ( OrdMaxMin INT32 )
  let max = int32Max
  let min = int32Min
end

(* ----- *)
(* int64 *)
(* ----- *)
val int64FromNumeral : NUMERAL → INT64

declare ocaml target_rep function int64FromNumeral = 'Int64.of_int'
declare isabelle target_rep function int64FromNumeral n = (('word_of_int' n) : INT64)
declare hol target_rep function int64FromNumeral n = (('n2w' n) : INT64)
declare coq target_rep function int64FromNumeral n = ('Zpred' ('Zpos' ('P_of_succ_nat' n))) (* TODO : check *)

instance ( Numeral INT64 )
  let fromNumeral n = int64FromNumeral n
end

val int64Eq : INT64 → INT64 → BOOL
let inline int64Eq = unsafe_structural_equality
declare coq target_rep function int64Eq = 'Z.eqb'

instance ( Eq INT64 )
  let == = int64Eq
  let <> n1 n2 = ¬ (int64Eq n1 n2)
end

val int64Less : INT64 → INT64 → BOOL
val int64LessEqual : INT64 → INT64 → BOOL
val int64Greater : INT64 → INT64 → BOOL
val int64GreaterEqual : INT64 → INT64 → BOOL

declare ocaml target_rep function int64Less = infix '<'
declare isabelle target_rep function int64Less = 'word_sless'
declare hol target_rep function int64Less = infix '<'
(*TODO: Implement the following correctly. *)
declare coq target_rep function int64Less = 'int_ltb'

declare ocaml target_rep function int64LessEqual = infix '<='
declare isabelle target_rep function int64LessEqual = 'word_sle'
declare hol target_rep function int64LessEqual = infix '<='
(*TODO: Implement the following correctly. *)

```

```

declare coq target_rep function int64LessEqual = 'int_lteb'

declare ocaml target_rep function int64Greater = infix '>'
let inline {isabelle} int64Greater x y = int64Less y x
declare hol target_rep function int64Greater = infix '>'
(*TODO: Implement the following correctly. *)
declare coq target_rep function int64Greater = 'int_gtb'

declare ocaml target_rep function int64GreaterEqual = infix '>='
let inline {isabelle} int64GreaterEqual x y = int64LessEqual y x
declare hol target_rep function int64GreaterEqual = infix '>='
(*TODO: Implement the following correctly. *)
declare coq target_rep function int64GreaterEqual = 'int_gteb'

val int64Compare : INT64 → INT64 → ORDERING
let inline int64Compare = defaultCompare
let inline {coq, isabelle, hol} int64Compare = genericCompare int64Less int64Eq
declare ocaml target_rep function int64Compare = 'Int64.compare'

instance (Ord INT64)
  let compare = int64Compare
  let < = int64Less
  let <= = int64LessEqual
  let > = int64Greater
  let >= = int64GreaterEqual
end

instance (SetType INT64)
  let setElemCompare = int64Compare
end

val int64Negate : INT64 → INT64
declare ocaml target_rep function int64Negate = 'Int64.neg'
declare isabelle target_rep function int64Negate i = '-' i
declare hol target_rep function int64Negate i = (('-' i) : INT64)
(*TODO: Implement the following one correctly. *)
declare coq target_rep function int64Negate i = ('Coq.ZArith.BinInt.Zminus' 'Z'0 i)

instance (NumNegate INT64)
  let ~ = int64Negate
end

val int64Abs : INT64 → INT64
let int64Abs i = (if 0 ≤ i then i else -i)
declare ocaml target_rep function int64Abs = 'Int64.abs'

instance (NumAbs INT64)
  let abs = int64Abs
end

val int64Add : INT64 → INT64 → INT64
declare ocaml target_rep function int64Add = 'Int64.add'
declare isabelle target_rep function int64Add = infix '+'
declare hol target_rep function int64Add i1 i2 = (('word_add' i1 i2) : INT64)
(*TODO: Implement the following one correctly. *)
declare coq target_rep function int64Add = 'Coq.ZArith.BinInt.Zplus'

```

```

instance (NumAdd INT64)
  let + = int64Add
end

val int64Minus : INT64 → INT64 → INT64
declare ocaml target_rep function int64Minus = 'Int64.sub'
declare isabelle target_rep function int64Minus = infix '-'
declare hol target_rep function int64Minus  $i_1 i_2$  = (('word_sub'  $i_1 i_2$ ) : INT64)
(*TODO: Implement the following one correctly. *)
declare coq target_rep function int64Minus = 'Coq.ZArith.BinInt.Zminus'

instance (NumMinus INT64)
  let - = int64Minus
end

val int64Succ : INT64 → INT64
let inline int64Succ  $n$  =  $n + 1$ 
declare ocaml target_rep function int64Succ = 'Int64.succ'

instance (NumSucc INT64)
  let succ = int64Succ
end

val int64Pred : INT64 → INT64
let inline int64Pred  $n$  =  $n - 1$ 
declare ocaml target_rep function int64Pred = 'Int64.pred'
instance (NumPred INT64)
  let pred = int64Pred
end

val int64Mult : INT64 → INT64 → INT64
declare ocaml target_rep function int64Mult = 'Int64.mul'
declare isabelle target_rep function int64Mult = infix '*'
declare hol target_rep function int64Mult  $i_1 i_2$  = (('word_mul'  $i_1 i_2$ ) : INT64)
(*TODO: Implement the following one correctly. *)
declare coq target_rep function int64Mult = 'Coq.ZArith.BinInt.Zmult'

instance (NumMult INT64)
  let * = int64Mult
end

val int64Pow : INT64 → NAT → INT64
let {ocaml, hol} int64Pow = gen_pow 1 int64Mult
declare isabelle target_rep function int64Pow = infix '^'
(*TODO: Implement the following one correctly. *)
declare coq target_rep function int64Pow = 'Coq.ZArith.Zpower.Zpower_nat'

instance ( NumPow INT64 )
  let ** = int64Pow
end

val int64Div : INT64 → INT64 → INT64
declare ocaml target_rep function int64Div = 'Nat_num.int64_div'
declare isabelle target_rep function int64Div = infix 'div'
(*TODO: Implement the following two correctly. *)
declare hol target_rep function int64Div  $i_1 i_2$  = (('word_div'  $i_1 i_2$ ) : INT64)
declare coq target_rep function int64Div = 'Coq.ZArith.Zdiv.Zdiv'

```

```

instance ( NumIntegerDivision INT64 )
  let div = int64Div
end

instance ( NumDivision INT64 )
  let / = int64Div
end

val int64Mod : INT64 → INT64 → INT64
declare ocaml target_rep function int64Mod = 'Nat.num.int64_mod'
declare isabelle target_rep function int64Mod = infix 'mod'
(*TODO: Implement the following two correctly. *)
declare hol target_rep function int64Mod i1 i2 = (('word_mod' i1 i2) : INT64)
declare coq target_rep function int64Mod = 'Coq.ZArith.Zdiv.Zmod'

instance ( NumRemainder INT64 )
  let mod = int64Mod
end

val int64Min : INT64 → INT64 → INT64
let inline int64Min = defaultMin
declare hol target_rep function int64Min = 'word_smin'
(*TODO: Implement the following one correctly. *)
declare coq target_rep function int64Min = 'Zmin'

val int64Max : INT64 → INT64 → INT64
let inline int64Max = defaultMax
declare hol target_rep function int64Max = 'word_smax'
(*TODO: Implement the following one correctly. *)
declare coq target_rep function int64Max = 'Zmax'

instance ( OrdMaxMin INT64 )
  let max = int64Max
  let min = int64Min
end

(* ----- *)
(* integer      *)
(* ----- *)

val integerFromNumeral : NUMERAL →  $\mathbb{Z}$ 
declare ocaml target_rep function integerFromNumeral = 'Nat.big_num.of_int'
declare isabelle target_rep function integerFromNumeral n = (''n :  $\mathbb{Z}$ )
declare hol target_rep function integerFromNumeral n = (''n :  $\mathbb{Z}$ )
declare coq target_rep function integerFromNumeral n = ('Zpred' ('Zpos' ('P_of_succ_nat' n)))

instance (Numeral  $\mathbb{Z}$ )
  let fromNumeral n = integerFromNumeral n
end

val integerFromNat : NAT →  $\mathbb{Z}$ 
declare hol target_rep function integerFromNat = 'int_of_num'
declare ocaml target_rep function integerFromNat = 'Nat.big_num.of_int'
declare isabelle target_rep function integerFromNat = 'int'
declare coq target_rep function integerFromNat n = ('Zpred' ('Zpos' ('P_of_succ_nat' n))) (* TODO: check *)

```

```

val integerEq :  $\mathbb{Z}$  →  $\mathbb{Z}$  → BOOL
let inline integerEq = unsafe_structural_equality
declare ocaml target_rep function integerEq = 'Nat_big_num.equal'
declare coq target_rep function integerEq = 'Z.eqb'
instance (Eq  $\mathbb{Z}$ )
  let == = integerEq
  let <> n1 n2 = ¬ (integerEq n1 n2)
end

val integerLess :  $\mathbb{Z}$  →  $\mathbb{Z}$  → BOOL
val integerLessEqual :  $\mathbb{Z}$  →  $\mathbb{Z}$  → BOOL
val integerGreater :  $\mathbb{Z}$  →  $\mathbb{Z}$  → BOOL
val integerGreaterEqual :  $\mathbb{Z}$  →  $\mathbb{Z}$  → BOOL

declare hol target_rep function integerLess = infix '<'
declare ocaml target_rep function integerLess = 'Nat_big_num.less'
declare isabelle target_rep function integerLess = infix '<'
declare coq target_rep function integerLess = 'int.ltb'

declare hol target_rep function integerLessEqual = infix '<='
declare ocaml target_rep function integerLessEqual = 'Nat_big_num.less_equal'
declare isabelle target_rep function integerLessEqual = infix '<=le>'
declare coq target_rep function integerLessEqual = 'int.lteb'

declare hol target_rep function integerGreater = infix '>'
declare ocaml target_rep function integerGreater = 'Nat_big_num.greater'
declare isabelle target_rep function integerGreater = infix '>'
declare coq target_rep function integerGreater = 'int.gt'

declare hol target_rep function integerGreaterEqual = infix '>='
declare ocaml target_rep function integerGreaterEqual = 'Nat_big_num.greater_equal'
declare isabelle target_rep function integerGreaterEqual = infix '<=ge>'
declare coq target_rep function integerGreaterEqual = 'int.geb'

val integerCompare :  $\mathbb{Z}$  →  $\mathbb{Z}$  → ORDERING
let inline integerCompare = defaultCompare
let inline {coq, isabelle, hol} integerCompare = genericCompare integerLess integerEq
declare ocaml target_rep function integerCompare = 'Nat_big_num.compare'

instance (Ord  $\mathbb{Z}$ )
  let compare = integerCompare
  let < = integerLess
  let <= = integerLessEqual
  let > = integerGreater
  let >= = integerGreaterEqual
end

instance (SetType  $\mathbb{Z}$ )
  let setElemCompare = integerCompare
end

val integerNegate :  $\mathbb{Z}$  →  $\mathbb{Z}$ 
declare hol target_rep function integerNegate i = '~' i
declare ocaml target_rep function integerNegate = 'Nat_big_num.negate'
declare isabelle target_rep function integerNegate i = '-' i
declare coq target_rep function integerNegate i = ('Coq.ZArith.BinInt.Zminus' 'Z'0 i)

instance (NumNegate  $\mathbb{Z}$ )

```



```

    let ~ = integerNegate
end

val integerAbs :  $\mathbb{Z}$  →  $\mathbb{Z}$ 
declare hol target_rep function integerAbs = 'ABS'
declare ocaml target_rep function integerAbs = 'Nat_big_num.abs'
declare isabelle target_rep function integerAbs = 'abs'
declare coq target_rep function integerAbs input = ('Zpred' ('Zpos' ('P_of_succ_nat' ('Zabs_nat' input))))
(* TODO: check *)

instance (NumAbs  $\mathbb{Z}$ )
  let abs = integerAbs
end

val integerAdd :  $\mathbb{Z}$  →  $\mathbb{Z}$  →  $\mathbb{Z}$ 
declare hol target_rep function integerAdd = infix '+'
declare ocaml target_rep function integerAdd = 'Nat_big_num.add'
declare isabelle target_rep function integerAdd = infix '+'
declare coq target_rep function integerAdd = 'Coq.ZArith.BinInt.Zplus'

instance (NumAdd  $\mathbb{Z}$ )
  let + = integerAdd
end

val integerMinus :  $\mathbb{Z}$  →  $\mathbb{Z}$  →  $\mathbb{Z}$ 
declare hol target_rep function integerMinus = infix '-'
declare ocaml target_rep function integerMinus = 'Nat_big_num.sub'
declare isabelle target_rep function integerMinus = infix '-'
declare coq target_rep function integerMinus = 'Coq.ZArith.BinInt.Zminus'

instance (NumMinus  $\mathbb{Z}$ )
  let - = integerMinus
end

val integerSucc :  $\mathbb{Z}$  →  $\mathbb{Z}$ 
let inline integerSucc n = n + 1
declare ocaml target_rep function integerSucc = 'Nat_big_num.succ'
instance (NumSucc  $\mathbb{Z}$ )
  let succ = integerSucc
end

val integerPred :  $\mathbb{Z}$  →  $\mathbb{Z}$ 
let inline integerPred n = n - 1
declare ocaml target_rep function integerPred = 'Nat_big_num.pred'
instance (NumPred  $\mathbb{Z}$ )
  let pred = integerPred
end

val integerMult :  $\mathbb{Z}$  →  $\mathbb{Z}$  →  $\mathbb{Z}$ 
declare hol target_rep function integerMult = infix '*'
declare ocaml target_rep function integerMult = 'Nat_big_num.mul'
declare isabelle target_rep function integerMult = infix '*'
declare coq target_rep function integerMult = 'Coq.ZArith.BinInt.Zmult'

instance (NumMult  $\mathbb{Z}$ )
  let * = integerMult
end

```

```

val integerPow :  $\mathbb{Z} \rightarrow \text{NAT} \rightarrow \mathbb{Z}$ 
declare hol target_rep function integerPow = infix '**'
declare ocaml target_rep function integerPow = 'Nat.big_num.pow_int'
declare isabelle target_rep function integerPow = infix '^'
declare coq target_rep function integerPow = 'Coq.ZArith.Zpower.Zpower_nat'

instance ( NumPow  $\mathbb{Z}$  )
  let ** = integerPow
end

val integerDiv :  $\mathbb{Z} \rightarrow \mathbb{Z} \rightarrow \mathbb{Z}$ 
declare hol target_rep function integerDiv = infix '/'
declare ocaml target_rep function integerDiv = 'Nat.big_num.div'
declare isabelle target_rep function integerDiv = infix 'div'
declare coq target_rep function integerDiv = 'Coq.ZArith.Zdiv.Zdiv'

instance ( NumIntegerDivision  $\mathbb{Z}$  )
  let div = integerDiv
end

instance ( NumDivision  $\mathbb{Z}$  )
  let / = integerDiv
end

val integerMod :  $\mathbb{Z} \rightarrow \mathbb{Z} \rightarrow \mathbb{Z}$ 
declare hol target_rep function integerMod = infix '%'
declare ocaml target_rep function integerMod = 'Nat.big_num.modulus'
declare isabelle target_rep function integerMod = infix 'mod'
declare coq target_rep function integerMod = 'Coq.ZArith.Zdiv.Zmod'

instance ( NumRemainder  $\mathbb{Z}$  )
  let mod = integerMod
end

val integerMin :  $\mathbb{Z} \rightarrow \mathbb{Z} \rightarrow \mathbb{Z}$ 
let inline integerMin = defaultMin
declare isabelle target_rep function integerMin = 'min'
declare ocaml target_rep function integerMin = 'Nat.big_num.min'
declare hol target_rep function integerMin = 'int_min'
declare coq target_rep function integerMin = 'Zmin'

val integerMax :  $\mathbb{Z} \rightarrow \mathbb{Z} \rightarrow \mathbb{Z}$ 
let inline integerMax = defaultMax
declare isabelle target_rep function integerMax = 'max'
declare ocaml target_rep function integerMax = 'Nat.big_num.max'
declare hol target_rep function integerMax = 'int_max'
declare coq target_rep function integerMax = 'Zmax'

instance ( OrdMaxMin  $\mathbb{Z}$  )
  let max = integerMax
  let min = integerMin
end

(* ----- *)
(* rational      *)

```

```

(* ----- *)

val rationalFromNumeral : NUMERAL → RATIONAL
declare ocaml target_rep function rationalFromNumeral n = ('Rational.of_int' n)
declare isabelle target_rep function rationalFromNumeral n = ('Fract' (''n :  $\mathbb{Z}$ '$) (1 :  $\mathbb{Z}$ $)))
declare hol target_rep function rationalFromNumeral n = (''n : RATIONAL)
declare coq target_rep function rationalFromNumeral n = ('inject_Z' ('Zpred' ('Zpos' ('P_of_succ_nat' n))))

instance (Numeral RATIONAL)
  let fromNumeral n = rationalFromNumeral n
end

val rationalFromInt : INT → RATIONAL
declare ocaml target_rep function rationalFromInt n = ('Rational.of_int' n)
declare isabelle target_rep function rationalFromInt n = ('Fract' n (1 :  $\mathbb{Z}$ $)))
declare hol target_rep function rationalFromInt n = ('rat_of_int' n)
declare coq target_rep function rationalFromInt n = ('inject_Z' n)

val rationalFromInteger :  $\mathbb{Z}$ $ → RATIONAL
declare ocaml target_rep function rationalFromInteger n = ('Rational.of_big_int' n)
declare isabelle target_rep function rationalFromInteger n = ('Fract' n (1 :  $\mathbb{Z}$ $)))
declare hol target_rep function rationalFromInteger n = ('rat_of_int' n)
declare coq target_rep function rationalFromInteger n = ('inject_Z' n)

val rationalEq : RATIONAL → RATIONAL → BOOL
let inline rationalEq = unsafe_structural_equality
declare ocaml target_rep function rationalEq = 'Rational.equal'
declare coq target_rep function rationalEq = 'Qeq_bool'
instance (Eq RATIONAL)
  let = = rationalEq
  let <> n1 n2 = ¬ (rationalEq n1 n2)
end

val rationalLess : RATIONAL → RATIONAL → BOOL
val rationalLessEqual : RATIONAL → RATIONAL → BOOL
val rationalGreater : RATIONAL → RATIONAL → BOOL
val rationalGreaterEqual : RATIONAL → RATIONAL → BOOL

declare hol target_rep function rationalLess = infix '<'
declare ocaml target_rep function rationalLess = 'Rational.lt'
declare isabelle target_rep function rationalLess = infix '<'
declare coq target_rep function rationalLess = 'Qlt_bool'

declare hol target_rep function rationalLessEqual = infix '<='
declare ocaml target_rep function rationalLessEqual = 'Rational.leq'
declare isabelle target_rep function rationalLessEqual = infix '\<le>'
declare coq target_rep function rationalLessEqual = 'Qle_bool'

declare hol target_rep function rationalGreater = infix '>'
declare ocaml target_rep function rationalGreater = 'Rational.gt'
declare isabelle target_rep function rationalGreater = infix '>'
declare coq target_rep function rationalGreater = 'Qgt_bool'

declare hol target_rep function rationalGreaterEqual = infix '>='
declare ocaml target_rep function rationalGreaterEqual = 'Rational.geq'
declare isabelle target_rep function rationalGreaterEqual = infix '\<ge>'

```

```

declare coq target_rep function rationalGreaterEqual = 'Qge_bool'

val rationalCompare : RATIONAL → RATIONAL → ORDERING
let inline rationalCompare = defaultCompare
let inline {coq, isabelle, hol, ocaml} rationalCompare = genericCompare rationalLess rationalEq

instance (Ord RATIONAL)
  let compare = rationalCompare
  let < = rationalLess
  let <= = rationalLessEqual
  let > = rationalGreater
  let >= = rationalGreaterEqual
end

instance (SetType RATIONAL)
  let setElemCompare = rationalCompare
end

val rationalAdd : RATIONAL → RATIONAL → RATIONAL
declare hol target_rep function rationalAdd = infix '+'
declare ocaml target_rep function rationalAdd = 'Rational.add'
declare isabelle target_rep function rationalAdd = infix '+'
declare coq target_rep function rationalAdd = 'Qplus'

instance (NumAdd RATIONAL)
  let + = rationalAdd
end

val rationalMinus : RATIONAL → RATIONAL → RATIONAL
declare hol target_rep function rationalMinus = infix '-'
declare ocaml target_rep function rationalMinus = 'Rational.sub'
declare isabelle target_rep function rationalMinus = infix '-'
declare coq target_rep function rationalMinus = 'Qminus'

instance (NumMinus RATIONAL)
  let - = rationalMinus
end

val rationalNegate : RATIONAL → RATIONAL
let inline rationalNegate n = 0 - n
declare ocaml target_rep function rationalNegate = 'Rational.neg'
declare isabelle target_rep function rationalNegate i = '-' i

instance (NumNegate RATIONAL)
  let ~ = rationalNegate
end

val rationalAbs : RATIONAL → RATIONAL
let inline rationalAbs n = (if n > 0 then n else -n)
declare ocaml target_rep function rationalAbs = 'Rational.abs'
declare isabelle target_rep function rationalAbs = 'abs'

instance (NumAbs RATIONAL)
  let abs = rationalAbs
end

val rationalSucc : RATIONAL → RATIONAL
let inline rationalSucc n = n + 1

```

```

instance (NumSucc RATIONAL)
  let succ = rationalSucc
end

val rationalPred : RATIONAL → RATIONAL
let inline rationalPred n = n - 1
instance (NumPred RATIONAL)
  let pred = rationalPred
end

val rationalMult : RATIONAL → RATIONAL → RATIONAL
declare hol target_rep function rationalMult = infix '*'
declare ocaml target_rep function rationalMult = 'Rational.mul'
declare isabelle target_rep function rationalMult = infix '*'
declare coq target_rep function rationalMult = 'Qmult'

instance (NumMult RATIONAL)
  let * = rationalMult
end

val rationalDiv : RATIONAL → RATIONAL → RATIONAL
declare hol target_rep function rationalDiv = infix '/'
declare ocaml target_rep function rationalDiv = 'Rational.div'
declare isabelle target_rep function rationalDiv = infix 'div'
declare coq target_rep function rationalDiv = 'Qdiv'

instance ( NumDivision RATIONAL )
  let / = rationalDiv
end

val rationalFromFrac : INT → INT → RATIONAL
let rationalFromFrac n d = (rationalFromInt n) / (rationalFromInt d)
declare ocaml target_rep function rationalFromFrac n d = ('Rational.of_ints' n d)
declare isabelle target_rep function rationalFromFrac n d = ('Fract' n d)
declare hol target_rep function rationalFromFrac n d = ('rat_cons' n d)

val rationalNumerator : RATIONAL →  $\mathbb{Z}$ 
declare ocaml target_rep function rationalNumerator r = ('Rational.num' r)
declare isabelle target_rep function rationalNumerator r = ('fst' ('quotient_of' r))
declare hol target_rep function rationalNumerator r = ('Numerator' r)
declare coq target_rep function rationalNumerator r = ('Qnum' r) (* TODO : test *)

val rationalDenominator : RATIONAL →  $\mathbb{Z}$ 
declare ocaml target_rep function rationalDenominator r = ('Rational.den' r)
declare isabelle target_rep function rationalDenominator r = ('snd' ('quotient_of' r))
declare hol target_rep function rationalDenominator r = ('Denominator' r)
declare coq target_rep function rationalDenominator r = ('QDen' r) (* TODO : test *)

val rationalPowInteger : RATIONAL →  $\mathbb{Z}$  → RATIONAL
let rec rationalPowInteger b e =
  if e = 0 then 1 else
  if e > 0 then rationalPowInteger b (e - 1) * b else
  rationalPowInteger b (e + 1) / b
declare coq target_rep function rationalPowInteger = 'Qpower'
declare {isabelle} termination_argument rationalPowInteger = automatic

val rationalPowNat : RATIONAL → NAT → RATIONAL
let rationalPowNat r e = rationalPowInteger r (integerFromNat e)

```

```

declare isabelle target_rep function rationalPowNat = 'power'
declare coq target_rep function rationalPowNat r e = ('Qpower' r ('Z.of_nat' e))

instance ( NumPow RATIONAL )
  let ** = rationalPowNat
end

val rationalMin : RATIONAL → RATIONAL → RATIONAL
let inline rationalMin = defaultMin
declare isabelle target_rep function rationalMin = 'min'
declare ocaml target_rep function rationalMin = 'Rational.min'
declare coq target_rep function rationalMin = 'Qmin'

val rationalMax : RATIONAL → RATIONAL → RATIONAL
let inline rationalMax = defaultMax
declare isabelle target_rep function rationalMax = 'max'
declare ocaml target_rep function rationalMax = 'Rational.max'
declare coq target_rep function rationalMax = 'Qmax'

instance ( OrdMaxMin RATIONAL )
  let max = rationalMax
  let min = rationalMin
end

(* ----- *)
(* real      *)
(* ----- *)

val realFromNumeral : NUMERAL → REAL
declare ocaml target_rep function realFromNumeral n = ('float_of_int' n)
declare isabelle target_rep function realFromNumeral n = (''n : REAL)
declare hol target_rep function realFromNumeral n = ('real_of_num' n)
declare coq target_rep function realFromNumeral n = ('IZR' ('Zpred' ('Zpos' ('P_of_succ_nat' n))))

instance (Numeral REAL)
  let fromNumeral n = realFromNumeral n
end

val realFromInteger :  $\mathbb{Z}$  → REAL
declare ocaml target_rep function realFromInteger n = ('float_of_int' ('Nat_big_num.to_int' n))
declare isabelle target_rep function realFromInteger n = ('real_of_int' n)
declare hol target_rep function realFromInteger n = ('real_of_int' n)
declare coq target_rep function realFromInteger n = ('IZR' n)

val realEq : REAL → REAL → BOOL
let inline realEq = unsafe_structural_equality
declare coq target_rep function realEq = 'Reqb'
instance (Eq REAL)
  let = = realEq
  let <> n1 n2 = ¬ (realEq n1 n2)
end

val realLess : REAL → REAL → BOOL
val realLessEqual : REAL → REAL → BOOL
val realGreater : REAL → REAL → BOOL
val realGreaterEqual : REAL → REAL → BOOL

```

```

declare hol target_rep function realLess = infix '<'
declare ocaml target_rep function realLess = infix '<'
declare isabelle target_rep function realLess = infix '<'
declare coq target_rep function realLess = 'Rlt_bool'

declare hol target_rep function realLessEqual = infix '<='
declare ocaml target_rep function realLessEqual = infix '<='
declare isabelle target_rep function realLessEqual = infix '\<le>'
declare coq target_rep function realLessEqual = 'Rle_bool'

declare hol target_rep function realGreater = infix '>'
declare ocaml target_rep function realGreater = infix '>'
declare isabelle target_rep function realGreater = infix '>'
declare coq target_rep function realGreater = 'Rgt_bool'

declare hol target_rep function realGreaterEqual = infix '>='
declare ocaml target_rep function realGreaterEqual = infix '>='
declare isabelle target_rep function realGreaterEqual = infix '\<ge>'
declare coq target_rep function realGreaterEqual = 'Rge_bool'

val realCompare : REAL → REAL → ORDERING
let inline realCompare = defaultCompare
let inline {coq, isabelle, hol, ocaml} realCompare = genericCompare realLess realEq

instance (Ord REAL)
  let compare = realCompare
  let < = realLess
  let <= = realLessEqual
  let > = realGreater
  let >= = realGreaterEqual
end

instance (SetType REAL)
  let setElemCompare = realCompare
end

val realAdd : REAL → REAL → REAL
declare hol target_rep function realAdd = infix '+'
declare ocaml target_rep function realAdd = 'Lem.plus_float'
declare isabelle target_rep function realAdd = infix '+'
declare coq target_rep function realAdd = 'Rplus'

instance (NumAdd REAL)
  let + = realAdd
end

val realMinus : REAL → REAL → REAL
declare hol target_rep function realMinus = infix '-'
declare ocaml target_rep function realMinus = 'Lem.minus_float'
declare isabelle target_rep function realMinus = infix '-'
declare coq target_rep function realMinus = 'Rminus'

instance (NumMinus REAL)
  let - = realMinus
end

val realNegate : REAL → REAL

```

```

let inline realNegate n = 0 - n
declare ocaml target_rep function realNegate = 'Lem.neg_float'
declare isabelle target_rep function realNegate i = '-' i
declare coq target_rep function realNegate = 'Ropp'

instance (NumNegate REAL)
  let ~ = realNegate
end

val realAbs : REAL → REAL
let inline realAbs n = (if n > 0 then n else -n)
declare ocaml target_rep function realAbs = 'abs_float'
declare isabelle target_rep function realAbs = 'abs'
declare coq target_rep function realAbs = 'Rabs'

instance (NumAbs REAL)
  let abs = realAbs
end

val realSucc : REAL → REAL
let inline realSucc n = n + 1
instance (NumSucc REAL)
  let succ = realSucc
end

val realPred : REAL → REAL
let inline realPred n = n - 1
instance (NumPred REAL)
  let pred = realPred
end

val realMult : REAL → REAL → REAL
declare hol target_rep function realMult = infix '*'
declare ocaml target_rep function realMult = 'Lem.mult_float'
declare isabelle target_rep function realMult = infix '*'
declare coq target_rep function realMult = 'Rmult'

instance (NumMult REAL)
  let * = realMult
end

val realDiv : REAL → REAL → REAL
declare hol target_rep function realDiv = infix '/'
declare ocaml target_rep function realDiv = 'Lem.div_float'
declare isabelle target_rep function realDiv = infix 'div'
declare coq target_rep function realDiv = 'Rdiv'

instance ( NumDivision REAL )
  let / = realDiv
end

val realFromFrac :  $\mathbb{Z}$  →  $\mathbb{Z}$  → REAL
let realFromFrac n d = realDiv (realFromInteger n) (realFromInteger d)
declare ocaml target_rep function realFromFrac n d = ('Lem.div_float' (realFromInteger n) (realFromInteger d))

val realPowInteger : REAL →  $\mathbb{Z}$  → REAL
let rec realPowInteger b e =

```



```

    if  $e = 0$  then 1 else
    if  $e > 0$  then  $\text{realPowInteger } b (e - 1) * b$  else
     $\text{realPowInteger } b (e + 1) / b$ 
declare ocaml target_rep function  $\text{realPowInteger } r e = (\text{'Lem.pow\_float' } r (\text{realFromInteger } e))$ 
declare coq target_rep function  $\text{realPowInteger} = \text{'powerRZ'}$ 
declare {isabelle} termination_argument  $\text{realPowInteger} = \text{automatic}$ 

```

```

val realPowNat :  $\text{REAL} \rightarrow \text{NAT} \rightarrow \text{REAL}$ 
let realPowNat  $r e = \text{realPowInteger } r (\text{integerFromNat } e)$ 
declare isabelle target_rep function  $\text{realPowNat} = \text{'power'}$ 
declare coq target_rep function  $\text{realPowNat} = \text{'pow'}$ 
declare hol target_rep function  $\text{realPowNat} = \text{infix 'pow'}$ 

```

```

instance ( NumPow  $\text{REAL}$  )
  let  $** = \text{realPowNat}$ 
end

```

```

val realSqrt :  $\text{REAL} \rightarrow \text{REAL}$ 
declare hol target_rep function  $\text{realSqrt} = \text{'sqrt'}$ 
declare ocaml target_rep function  $\text{realSqrt} = \text{'sqrt'}$ 
declare isabelle target_rep function  $\text{realSqrt} = \text{'sqrt'}$ 
declare coq target_rep function  $\text{realSqrt} = \text{'Rsqrt'}$ 

```

```

val realMin :  $\text{REAL} \rightarrow \text{REAL} \rightarrow \text{REAL}$ 
let inline realMin = defaultMin
declare hol target_rep function  $\text{realMin} = \text{'min'}$ 
declare isabelle target_rep function  $\text{realMin} = \text{'min'}$ 
declare ocaml target_rep function  $\text{realMin} = \text{'min'}$ 
declare coq target_rep function  $\text{realMin} = \text{'Rmin'}$ 

```

```

val realMax :  $\text{REAL} \rightarrow \text{REAL} \rightarrow \text{REAL}$ 
let inline realMax = defaultMax
declare hol target_rep function  $\text{realMax} = \text{'max'}$ 
declare isabelle target_rep function  $\text{realMax} = \text{'max'}$ 
declare ocaml target_rep function  $\text{realMax} = \text{'max'}$ 
declare coq target_rep function  $\text{realMax} = \text{'Rmax'}$ 

```

```

instance ( OrdMaxMin  $\text{REAL}$  )
  let  $\text{max} = \text{realMax}$ 
  let  $\text{min} = \text{realMin}$ 
end

```

```

val realCeiling :  $\text{REAL} \rightarrow \mathbb{Z}$ 
declare isabelle target_rep function  $\text{realCeiling} = \text{'ceiling'}$ 
declare ocaml target_rep function  $\text{realCeiling} = \text{'Lem.big\_num\_of\_ceil'}$ 
declare hol target_rep function  $\text{realCeiling} = \text{'clg'}$ 
declare coq target_rep function  $\text{realCeiling} = \text{'up'}$ 

```

```

val realFloor :  $\text{REAL} \rightarrow \mathbb{Z}$ 
declare isabelle target_rep function  $\text{realFloor} = \text{'floor'}$ 
declare ocaml target_rep function  $\text{realFloor} = \text{'Lem.big\_num\_of\_floor'}$ 
declare hol target_rep function  $\text{realFloor} = \text{'flr'}$ 
declare coq target_rep function  $\text{realFloor} = \text{'Rdown'}$ 

```

```

val integerSqrt :  $\mathbb{Z} \rightarrow \mathbb{Z}$ 
let integerSqrt  $i = \text{realFloor } (\text{realSqrt } (\text{realFromInteger } i))$ 
declare ocaml target_rep function  $\text{integerSqrt} = \text{'Nat.big\_num.sqrt'}$ 

```

```
declare coq target_rep function integerSqrt = 'Z.sqrt'
```

```
(* ===== *)
(* Tests *)
(* ===== *)

assert nat_test1 : (2 + (5 : NAT) = 7)
assert nat_test2 : (8 - (7 : NAT) = 1)
assert nat_test3 : (7 - (8 : NAT) = 0)
assert nat_test4 : (7 * (8 : NAT) = 56)
assert nat_test5 : ((7 : NAT)2 = 49)
assert nat_test6 : (div 11 (4 : NAT) = 2)
assert nat_test7 : (11 / (4 : NAT) = 2)
assert nat_test8 : (11 mod (4 : NAT) = 3)
assert nat_test9 : (11 < (12 : NAT))
assert nat_test10 : (11 ≤ (12 : NAT))
assert nat_test11 : (12 ≤ (12 : NAT))
assert nat_test12 : (¬ (12 < (12 : NAT)))
assert nat_test13 : (12 > (11 : NAT))
assert nat_test14 : (12 ≥ (11 : NAT))
assert nat_test15 : (12 ≥ (12 : NAT))
assert nat_test16 : (¬ (12 > (12 : NAT)))
assert nat_test17 : (min 12 (12 : NAT) = 12)
assert nat_test18 : (min 10 (12 : NAT) = 10)
assert nat_test19 : (min 12 (10 : NAT) = 10)
assert nat_test20 : (max 12 (12 : NAT) = 12)
assert nat_test21 : (max 10 (12 : NAT) = 12)
assert nat_test22 : (max 12 (10 : NAT) = 12)
assert nat_test23 : (succ 12 = (13 : NAT))
assert nat_test24 : (succ 0 = (1 : NAT))
assert nat_test25 : (pred 12 = (11 : NAT))
assert nat_test26 : (pred 0 = (0 : NAT))
assert nat_test27 : (match (27 : NAT) with
  | 0 → false
  | x + 2 → (x = 25)
  | x + 1 → (x = 26)
end)
assert nat_test28a : (match (27 : NAT) with
  | n + 50 → "50 <= x"
  | 40 → "x = 40"
  | n + 31 → "x <> 40 && 31 <= x < 50"
  | 29 → "x = 29"
  | n + 30 → "x = 30"
  | 4 → "x = 4"
  | _ → "x <> 4 && x <> 29 && x < 30"
end = "x <> 4 && x <> 29 && x < 30")
assert nat_test28b : (match (30 : NAT) with
  | n + 50 → "50 <= x"
  | 40 → "x = 40"
  | n + 31 → "x <> 40 && 31 <= x < 50"
  | 29 → "x = 29"
  | n + 30 → "x = 30"
  | 4 → "x = 4"
  | _ → "x <> 4 && x <> 29 && x < 30"
end = "x = 30")
```

```

assert natural_test1 : (2 + (5 :  $\mathbb{N}$ ) = 7)
assert natural_test2 : (8 - (7 :  $\mathbb{N}$ ) = 1)
assert natural_test3 : (7 - (8 :  $\mathbb{N}$ ) = 0)
assert natural_test4 : (7 * (8 :  $\mathbb{N}$ ) = 56)
assert natural_test5 : ((7 :  $\mathbb{N}$ )2 = 49)
assert natural_test6 : (div 11 (4 :  $\mathbb{N}$ ) = 2)
assert natural_test7 : (11 / (4 :  $\mathbb{N}$ ) = 2)
assert natural_test8 : (11 mod (4 :  $\mathbb{N}$ ) = 3)
assert natural_test9 : (11 < (12 :  $\mathbb{N}$ ))
assert natural_test10 : (11 ≤ (12 :  $\mathbb{N}$ ))
assert natural_test11 : (12 ≤ (12 :  $\mathbb{N}$ ))
assert natural_test12 : (¬ (12 < (12 :  $\mathbb{N}$ )))
assert natural_test13 : (12 > (11 :  $\mathbb{N}$ ))
assert natural_test14 : (12 ≥ (11 :  $\mathbb{N}$ ))
assert natural_test15 : (12 ≥ (12 :  $\mathbb{N}$ ))
assert natural_test16 : (¬ (12 > (12 :  $\mathbb{N}$ )))
assert natural_test17 : (min 12 (12 :  $\mathbb{N}$ ) = 12)
assert natural_test18 : (min 10 (12 :  $\mathbb{N}$ ) = 10)
assert natural_test19 : (min 12 (10 :  $\mathbb{N}$ ) = 10)
assert natural_test20 : (max 12 (12 :  $\mathbb{N}$ ) = 12)
assert natural_test21 : (max 10 (12 :  $\mathbb{N}$ ) = 12)
assert natural_test22 : (max 12 (10 :  $\mathbb{N}$ ) = 12)
assert natural_test23 : (succ 12 = (13 :  $\mathbb{N}$ ))
assert natural_test24 : (succ 0 = (1 :  $\mathbb{N}$ ))
assert natural_test25 : (pred 12 = (11 :  $\mathbb{N}$ ))
assert natural_test26 : (pred 0 = (0 :  $\mathbb{N}$ ))
assert natural_test27 : (match (27 :  $\mathbb{N}$ ) with
  | 0 → false
  | x + 2 → (x = 25)
  | x + 1 → (x = 26)
end)
assert natural_test28a : (match (27 :  $\mathbb{N}$ ) with
  | n + 50 → "50 ≤ x"
  | 40 → "x = 40"
  | n + 31 → "x < 40 ∧ 31 ≤ x < 50"
  | 29 → "x = 29"
  | n + 30 → "x = 30"
  | 4 → "x = 4"
  | _ → "x < 4 ∧ 29 ≤ x < 30"
end = "x < 4 ∧ 29 ≤ x < 30")
assert natural_test28b : (match (30 :  $\mathbb{N}$ ) with
  | n + 50 → "50 ≤ x"
  | 40 → "x = 40"
  | n + 31 → "x < 40 ∧ 31 ≤ x < 50"
  | 29 → "x = 29"
  | n + 30 → "x = 30"
  | 4 → "x = 4"
  | _ → "x < 4 ∧ 29 ≤ x < 30"
end = "x = 30")

```

```

assert int_test1 : (2 + (5 :  $\mathbb{INT}$ ) = 7)
assert int_test2 : (8 - (7 :  $\mathbb{INT}$ ) = 1)
assert int_test3 : (7 - (8 :  $\mathbb{INT}$ ) = -1)
assert int_test4 : (7 * (8 :  $\mathbb{INT}$ ) = 56)
assert int_test5 : ((7 :  $\mathbb{INT}$ )2 = 49)
assert int_test6 : (div 11 (4 :  $\mathbb{INT}$ ) = 2)

```

```

assert int_test6a : (div (- 11) (4 : INT) = -3)
assert int_test7 : (11 / (4 : INT) = 2)
assert int_test7a : (-11 / (4 : INT) = -3)
assert int_test8 : (11 mod (4 : INT) = 3)
assert int_test8at : (-11 mod (4 : INT) = 1)
assert int_test9 : (11 < (12 : INT))
assert int_test10 : (11 ≤ (12 : INT))
assert int_test11 : (12 ≤ (12 : INT))
assert int_test12 : (¬ (12 < (12 : INT)))
assert int_test13 : (12 > (11 : INT))
assert int_test14 : (12 ≥ (11 : INT))
assert int_test15 : (12 ≥ (12 : INT))
assert int_test16 : (¬ (12 > (12 : INT)))
assert int_test17 : (min 12 (12 : INT) = 12)
assert int_test18 : (min 10 (12 : INT) = 10)
assert int_test19 : (min 12 (10 : INT) = 10)
assert int_test20 : (max 12 (12 : INT) = 12)
assert int_test21 : (max 10 (12 : INT) = 12)
assert int_test22 : (max 12 (10 : INT) = 12)
assert int_test23 : (succ 12 = (13 : INT))
assert int_test24 : (succ 0 = (1 : INT))
assert int_test25 : (pred 12 = (11 : INT))
assert int_test26 : (pred 0 = -(1 : INT))
assert int_test27 : (abs 42 = (42 : INT))
assert int_test28 : (abs (-42) = (42 : INT))

assert int32_test1 : (2 + (5 : INT32) = 7)
assert int32_test2 : (8 - (7 : INT32) = 1)
assert int32_test3 : (7 - (8 : INT32) = -1)
assert int32_test4 : (7 * (8 : INT32) = 56)
assert int32_test5 : ((7 : INT32)2 = 49)
assert int32_test6 : (div 11 (4 : INT32) = 2)
assert int32_test7 : (11 / (4 : INT32) = 2)
assert int32_test8 : (11 mod (4 : INT32) = 3)
assert int32_test9 : (11 < (12 : INT32))
assert int32_test10 : (11 ≤ (12 : INT32))
assert int32_test11 : (12 ≤ (12 : INT32))
assert int32_test12 : (¬ (12 < (12 : INT32)))
assert int32_test13 : (12 > (11 : INT32))
assert int32_test13a : (12 > -(11 : INT32))
assert int32_test14 : (12 ≥ (11 : INT32))
assert int32_test15 : (12 ≥ (12 : INT32))
assert int32_test16 : (¬ (12 > (12 : INT32)))
assert int32_test17 : (min 12 (12 : INT32) = 12)
assert int32_test18 : (min 10 (12 : INT32) = 10)
assert int32_test19 : (min 12 (10 : INT32) = 10)
assert int32_test20 : (max 12 (12 : INT32) = 12)
assert int32_test21 : (max (-10) (12 : INT32) = 12)
assert int32_test22 : (max 12 (10 : INT32) = 12)
assert int32_test23 : (succ 12 = (13 : INT32))
assert int32_test24 : (succ 0 = (1 : INT32))
assert int32_test25 : (pred 12 = (11 : INT32))
assert int32_test26 : (pred 0 = -(1 : INT32))
assert int32_test27 : (abs 42 = (42 : INT32))
assert int32_test28 : (abs (-42) = (42 : INT32))

assert int64_test1 : (2 + (5 : INT64) = 7)
assert int64_test2 : (8 - (7 : INT64) = 1)

```

```

assert int64_test3 : (7 - (8 : INT64) = -1)
assert int64_test4 : (7 * (8 : INT64) = 56)
assert int64_test5 : ((7 : INT64)2 = 49)
assert int64_test6 : (div 11 (4 : INT64) = 2)
assert int64_test7 : (11 / (4 : INT64) = 2)
assert int64_test8 : (11 mod (4 : INT64) = 3)
assert int64_test9 : (11 < (12 : INT64))
assert int64_test10 : (11 ≤ (12 : INT64))
assert int64_test11 : (12 ≤ (12 : INT64))
assert int64_test12 : (¬ (12 < (12 : INT64)))
assert int64_test13 : (12 > (11 : INT64))
assert int64_test13a : (12 > -(11 : INT64)))
assert int64_test14 : (12 ≥ (11 : INT64))
assert int64_test15 : (12 ≥ (12 : INT64))
assert int64_test16 : (¬ (12 > (12 : INT64)))
assert int64_test17 : (min 12 (12 : INT64) = 12)
assert int64_test18 : (min 10 (12 : INT64) = 10)
assert int64_test19 : (min 12 (10 : INT64) = 10)
assert int64_test20 : (max 12 (12 : INT64) = 12)
assert int64_test21 : (max (-10) (12 : INT64) = 12)
assert int64_test22 : (max 12 (10 : INT64) = 12)
assert int64_test23 : (succ 12 = (13 : INT64))
assert int64_test24 : (succ 0 = (1 : INT64))
assert int64_test25 : (pred 12 = (11 : INT64))
assert int64_test26 : (pred 0 = -(1 : INT64))
assert int64_test27 : (abs 42 = (42 : INT64))
assert int64_test28 : (abs (-42) = (42 : INT64))

assert integer_test1 : (2 + (5 :  $\mathbb{Z}$ ) = 7)
assert integer_test2 : (8 - (7 :  $\mathbb{Z}$ ) = 1)
assert integer_test3 : (7 - (8 :  $\mathbb{Z}$ ) = -1)
assert integer_test4 : (7 * (8 :  $\mathbb{Z}$ ) = 56)
assert integer_test5 : ((7 :  $\mathbb{Z}$ )2 = 49)
assert integer_test6 : (div 11 (4 :  $\mathbb{Z}$ ) = 2)
assert integer_test6a : (div (-11) (4 :  $\mathbb{Z}$ ) = -3)
assert integer_test7 : (11 / (4 :  $\mathbb{Z}$ ) = 2)
assert integer_test7a : (-11 / (4 :  $\mathbb{Z}$ ) = -3)
assert integer_test8 : (11 mod (4 :  $\mathbb{Z}$ ) = 3)
assert integer_test8a : (-11 mod (4 :  $\mathbb{Z}$ ) = 1)
assert integer_test9 : (11 < (12 :  $\mathbb{Z}$ ))
assert integer_test10 : (11 ≤ (12 :  $\mathbb{Z}$ ))
assert integer_test11 : (12 ≤ (12 :  $\mathbb{Z}$ ))
assert integer_test12 : (¬ (12 < (12 :  $\mathbb{Z}$ )))
assert integer_test13 : (12 > (11 :  $\mathbb{Z}$ ))
assert integer_test14 : (12 ≥ (11 :  $\mathbb{Z}$ ))
assert integer_test15 : (12 ≥ (12 :  $\mathbb{Z}$ ))
assert integer_test16 : (¬ (12 > (12 :  $\mathbb{Z}$ )))
assert integer_test17 : (min 12 (12 :  $\mathbb{Z}$ ) = 12)
assert integer_test18 : (min 10 (12 :  $\mathbb{Z}$ ) = 10)
assert integer_test19 : (min 12 (10 :  $\mathbb{Z}$ ) = 10)
assert integer_test20 : (max 12 (12 :  $\mathbb{Z}$ ) = 12)
assert integer_test21 : (max 10 (12 :  $\mathbb{Z}$ ) = 12)
assert integer_test22 : (max 12 (10 :  $\mathbb{Z}$ ) = 12)
assert integer_test23 : (succ 12 = (13 :  $\mathbb{Z}$ ))
assert integer_test24 : (succ 0 = (1 :  $\mathbb{Z}$ ))
assert integer_test25 : (pred 12 = (11 :  $\mathbb{Z}$ ))
assert integer_test26 : (pred 0 = -(1 :  $\mathbb{Z}$ ))
assert integer_test27 : (abs 42 = (42 :  $\mathbb{Z}$ ))

```

```

assert integer_test28 : (abs (-42) = (42 :  $\mathbb{Z}$ ))
assert integer_test29 : (integerSqrt 5 = 2)

assert rational_test1 : (2 + (5 : RATIONAL) = 7)
assert rational_test2 : ((rationalFromFrac 3 2) + (rationalFromFrac 1 2) = 2)
assert rational_test3 : (7 - (8 : RATIONAL) = -1)
assert rational_test4 : (7 * (8 : RATIONAL) = 56)
assert rational_test5 : ((7 : RATIONAL)2 = 49)
assert rational_test5a : (rationalPowInteger (2 : RATIONAL) (-3) = rationalFromFrac 1 8)
assert rational_test5b : (rationalPowInteger (-2 : RATIONAL) (-3) = rationalFromFrac (-1) 8)
assert rational_test5c : (rationalPowInteger (-2 : RATIONAL) (-2) = rationalFromFrac 1 4)
assert rational_test6 : (11 / (4 : RATIONAL) = (rationalFromFrac 11 4))
assert rational_test6a : ((- 11) / (4 : RATIONAL) = (rationalFromFrac (-11) 4))
assert rational_test7 : (11 < (12 : RATIONAL))
assert rational_test8 : (11 ≤ (12 : RATIONAL))
assert rational_test9 : (12 ≤ (12 : RATIONAL))
assert rational_test10 : (¬ (12 < (12 : RATIONAL)))
assert rational_test11 : (12 > (11 : RATIONAL))
assert rational_test12 : (12 ≥ (11 : RATIONAL))
assert rational_test13 : (12 ≥ (12 : RATIONAL))
assert rational_test14 : (¬ (12 > (12 : RATIONAL)))
assert rational_test15 : (min 12 (12 : RATIONAL) = 12)
assert rational_test16 : (min 10 (12 : RATIONAL) = 10)
assert rational_test17 : (min 12 (10 : RATIONAL) = 10)
assert rational_test18 : (max 12 (12 : RATIONAL) = 12)
assert rational_test19 : (max 10 (12 : RATIONAL) = 12)
assert rational_test20 : (max 12 (10 : RATIONAL) = 12)
assert rational_test21 : (succ 12 = (13 : RATIONAL))
assert rational_test22 : (succ 0 = (1 : RATIONAL))
assert rational_test23 : (pred 12 = (11 : RATIONAL))
assert rational_test24 : (pred 0 = -(1 : RATIONAL))
assert rational_test25 : (abs 42 = (42 : RATIONAL))
assert rational_test26 : (abs (-42) = (42 : RATIONAL))
assert rational_test27 : ((rationalFromFrac 1 2) * 2 = 1)
assert rational_test28 :
  (let r = rationalFromFrac (-11) 4 in
    (rationalFromInteger (rationalNumerator r) / rationalFromInteger (rationalDenominator r) = r))
assert rational_test29 :
  (let r = rationalFromFrac 8 4 in
    (rationalFromInteger (rationalNumerator r) / rationalFromInteger (rationalDenominator r) = rationalFromInt 2))

assert real_test1 : (2 + (5 : REAL) = 7)
assert real_test2 : ((3 / (2 : REAL)) + (1 / 2) = 2)
assert real_test3 : (7 - (8 : REAL) = -1)
assert real_test4 : (7 * (8 : REAL) = 56)
assert real_test5 : ((7 : REAL)2 = 49)
assert real_test5a : (realPowInteger (2 : REAL) (-3) = realFromFrac 1 8)
assert real_test5b : (realPowInteger (-2 : REAL) (-3) = realFromFrac (-1) 8)
assert real_test5c : (realPowInteger (-2 : REAL) (-2) = realFromFrac 1 4)
assert real_test6 : (11 / (4 : REAL) = (realFromFrac 11 4))
assert real_test6a : ((- 11) / (4 : REAL) = (realFromFrac (-11) 4))
assert real_test7 : (11 < (12 : REAL))
assert real_test8 : (11 ≤ (12 : REAL))
assert real_test9 : (12 ≤ (12 : REAL))
assert real_test10 : (¬ (12 < (12 : REAL)))
assert real_test11 : (12 > (11 : REAL))

```

```

assert real_test12 : (12 ≥ (11 : REAL))
assert real_test13 : (12 ≥ (12 : REAL))
assert real_test14 : (¬ (12 > (12 : REAL)))
assert real_test15 : (min 12 (12 : REAL) = 12)
assert real_test16 : (min 10 (12 : REAL) = 10)
assert real_test17 : (min 12 (10 : REAL) = 10)
assert real_test18 : (max 12 (12 : REAL) = 12)
assert real_test19 : (max 10 (12 : REAL) = 12)
assert real_test20 : (max 12 (10 : REAL) = 12)
assert real_test21 : (succ 12 = (13 : REAL))
assert real_test22 : (succ 0 = (1 : REAL))
assert real_test23 : (pred 12 = (11 : REAL))
assert real_test24 : (pred 0 = -(1 : REAL))
assert real_test25 : (abs 42 = (42 : REAL))
assert real_test26 : (abs (-42) = (42 : REAL))
assert real_test27 : ((1 / (2 : REAL)) * 2 = 1)
assert real_test28 : (realFloor (realFromFrac 11 4) = 2)
assert real_test29 : (realCeiling (realFromFrac 11 4) = 3)
assert real_test30 : (realFloor (realFromFrac 12 4) = 3)
assert real_test31 : (realCeiling (realFromFrac 12 4) = 3)
assert real_test32 : (realFloor (realFromFrac (-3) 2) = -2)
assert real_test33 : (realCeiling (realFromFrac (-3) 2) = -1)

(* ===== *)
(* Translation between number types *)
(* ===== *)

(*****
(* integerFrom... *)
(*****)

val integerFromInt : INT →  $\mathbb{Z}$ 
declare hol target_rep function integerFromInt = '' (* remove natFromNumeral, as it is the identify function *)
declare ocaml target_rep function integerFromInt = 'Nat_big_num.of_int'
declare isabelle target_rep function integerFromInt = ''
declare coq target_rep function integerFromInt = ''

assert integer_from_int0 : integerFromInt 0 = 0
assert integer_from_int1 : integerFromInt 1 = 1
assert integer_from_int2 : integerFromInt (-2) = (-2)

assert integer_from_nat0 : integerFromNat 0 = 0
assert integer_from_nat1 : integerFromNat 1 = 1
assert integer_from_nat2 : integerFromNat 12 = 12

val integerFromNatural :  $\mathbb{N}$  →  $\mathbb{Z}$ 
declare hol target_rep function integerFromNatural = 'int_of_num'
declare ocaml target_rep function integerFromNatural n = ''n
declare isabelle target_rep function integerFromNatural = 'int'
declare coq target_rep function integerFromNatural n = ('Zpred' ('Zpos' ('P_of_succ_nat' n))) (* TODO : check *)

assert integerFromNatural0 : integerFromNatural 0 = 0
assert integerFromNatural1 : integerFromNatural 822 = 822
assert integerFromNatural2 : integerFromNatural 12 = 12

val integerFromInt32 : INT32 →  $\mathbb{Z}$ 
declare ocaml target_rep function integerFromInt32 = 'Nat_big_num.of_int'32

```

```

declare isabelle target_rep function integerFromInt32 = 'sint'
declare hol target_rep function integerFromInt32 = 'w2int'
declare coq target_rep function integerFromInt32 = ''

assert integer_from_int32_0 : integerFromInt32 0 = 0
assert integer_from_int32_1 : integerFromInt32 1 = 1
assert integer_from_int32_2 : integerFromInt32 123 = 123
assert integer_from_int32_3 : integerFromInt32 (-0) = -0
assert integer_from_int32_4 : integerFromInt32 (-1) = -1
assert integer_from_int32_5 : integerFromInt32 (-123) = -123

val integerFromInt64 : INT64 →  $\mathbb{Z}$ 
declare ocaml target_rep function integerFromInt64 = 'Nat_big_num.of_int'64
declare isabelle target_rep function integerFromInt64 = 'sint'
declare hol target_rep function integerFromInt64 = 'w2int'
declare coq target_rep function integerFromInt64 = ''

assert integer_from_int64_0 : integerFromInt64 0 = 0
assert integer_from_int64_1 : integerFromInt64 1 = 1
assert integer_from_int64_2 : integerFromInt64 123 = 123
assert integer_from_int64_3 : integerFromInt64 (-0) = -0
assert integer_from_int64_4 : integerFromInt64 (-1) = -1
assert integer_from_int64_5 : integerFromInt64 (-123) = -123

(*****)
(* naturalFrom... *)
(*****)

val naturalFromNat : NAT →  $\mathbb{N}$ 
declare hol target_rep function naturalFromNat x = (''x :  $\mathbb{N}$ '' )
declare ocaml target_rep function naturalFromNat = 'Nat_big_num.of_int'
declare isabelle target_rep function naturalFromNat = ''
declare coq target_rep function naturalFromNat = ''

assert natural_from_nat0 : naturalFromNat 0 = 0
assert natural_from_nat1 : naturalFromNat 1 = 1
assert natural_from_nat2 : naturalFromNat 2 = 2

val naturalFromInteger :  $\mathbb{Z}$  →  $\mathbb{N}$ 
declare compile_message naturalFromInteger = "naturalFromInteger is undefined for negative integers"

declare hol target_rep function naturalFromInteger i = 'Num' ('ABS' i)
declare ocaml target_rep function naturalFromInteger = 'Nat_big_num.abs'
declare coq target_rep function naturalFromInteger = 'Zabs_nat'
declare isabelle target_rep function naturalFromInteger i = 'nat' ('abs' i)

assert natural_from_integer0 : naturalFromInteger 0 = 0
assert natural_from_integer1 : naturalFromInteger 1 = 1
assert natural_from_integer2 : naturalFromInteger (- 2) = 2

(*****)
(* intFrom ... *)
(*****)

val intFromInteger :  $\mathbb{Z}$  → INT

```



```

declare compile_message naturalFromInteger = “naturalFromInteger is undefined for negative integers and might fail for n”

declare hol target_rep function intFromInteger = 'I' (* remove natFromNumeral, as it is the identify function *)
declare ocaml target_rep function intFromInteger = 'Nat_big_num.to_int'
declare isabelle target_rep function intFromInteger = ''
declare coq target_rep function intFromInteger = ''

assert int_from_integer_0 : intFromInteger 0 = 0
assert int_from_integer_1 : intFromInteger 1 = 1
assert int_from_integer_2 : intFromInteger (-2) = (-2)

val intFromNat : NAT → INT
declare hol target_rep function intFromNat = 'int_of_num'
declare ocaml target_rep function intFromNat n = ''n
declare isabelle target_rep function intFromNat = 'int'
declare coq target_rep function intFromNat n = ('Zpred' ('Zpos' ('P_of_succ_nat' n)))

assert int_from_nat_0 : intFromNat 0 = 0
assert int_from_nat_1 : intFromNat 1 = 1
assert int_from_nat_2 : intFromNat 2 = 2

(*****)
(* natFrom ... *)
(*****)

val natFromNatural :  $\mathbb{N}$  → NAT
declare compile_message naturalFromInteger = “x natFromNatural might fail for too big values. The values allowed are sys.”

declare hol target_rep function natFromNatural x = (''x : NAT)
declare ocaml target_rep function natFromNatural = 'Nat_big_num.to_int'
declare isabelle target_rep function natFromNatural = ''
declare coq target_rep function natFromNatural = ''

assert nat_from_natural_0 : natFromNatural 0 = 0
assert nat_from_natural_1 : natFromNatural 1 = 1
assert nat_from_natural_2 : natFromNatural 2 = 2

val natFromInt : INT → NAT
declare hol target_rep function natFromInt i = 'Num' ('ABS' i)
declare ocaml target_rep function natFromInt = 'abs'
declare coq target_rep function natFromInt = 'Zabs_nat'
declare isabelle target_rep function natFromInt i = 'nat' ('abs' i)

assert nat_from_int_0 : natFromInt 0 = 0
assert nat_from_int_1 : natFromInt 1 = 1
assert nat_from_int_2 : natFromInt (- 2) = 2

(*****)
(* int32From ... *)
(*****)

val int32FromNat : NAT → INT32
declare hol target_rep function int32FromNat n = (('n2w' n) : INT32)
declare ocaml target_rep function int32FromNat = 'Int32.of_int'
declare coq target_rep function int32FromNat n = ('Zpred' ('Zpos' ('P_of_succ_nat' n))) (* TODO check *)
declare isabelle target_rep function int32FromNat n = (('word_of_int' ('int' n)) : INT32)

```

```

assert int32_from_nat0 : int32FromNat 0 = 0
assert int32_from_nat1 : int32FromNat 1 = 1
assert int32_from_nat2 : int32FromNat 123 = 123

val int32FromNatural :  $\mathbb{N} \rightarrow \text{INT}_{32}$ 
declare hol target_rep function int32FromNatural  $n = ((\text{'n2w' } n) : \text{INT}_{32})$ 
declare ocaml target_rep function int32FromNatural = 'Nat.big_num.to_int'32
declare coq target_rep function int32FromNatural  $n = (\text{'Zpred' } (\text{'Zpos' } (\text{'P.of_succ_nat' } n)))$  (* TODO check *)
declare isabelle target_rep function int32FromNatural  $n = ((\text{'word.of_int' } (\text{'int' } n)) : \text{INT}_{32})$ 

assert int32_from_natural0 : int32FromNatural 0 = 0
assert int32_from_natural1 : int32FromNatural 1 = 1
assert int32_from_natural2 : int32FromNatural 123 = 123

val int32FromInteger :  $\mathbb{Z} \rightarrow \text{INT}_{32}$ 
let int32FromInteger  $i =$  (
  let abs_int32 = int32FromNatural (naturalFromInteger  $i$ ) in
  if ( $i < 0$ ) then ( $- \text{abs\_int}_{32}$ ) else abs_int32
)

declare ocaml target_rep function int32FromInteger = 'Nat.big_num.to_int'32
declare isabelle target_rep function int32FromInteger  $i = ((\text{'word.of_int' } i) : \text{INT}_{32})$ 

assert int32_from_integer0 : int32FromInteger 0 = 0
assert int32_from_integer1 : int32FromInteger 1 = 1
assert int32_from_integer2 : int32FromInteger 123 = 123
assert int32_from_integer3 : int32FromInteger  $(-0) = -0$ 
assert int32_from_integer4 : int32FromInteger  $(-1) = -1$ 
assert int32_from_integer5 : int32FromInteger  $(-123) = -123$ 

val int32FromInt :  $\text{INT} \rightarrow \text{INT}_{32}$ 
let int32FromInt  $i =$  int32FromInteger (integerFromInt  $i$ )
declare ocaml target_rep function int32FromInt = 'Int32.of_int'
declare isabelle target_rep function int32FromInt  $i = ((\text{'word.of_int' } i) : \text{INT}_{32})$ 

assert int32_from_int0 : int32FromInt 0 = 0
assert int32_from_int1 : int32FromInt 1 = 1
assert int32_from_int2 : int32FromInt 123 = 123
assert int32_from_int3 : int32FromInt  $(-0) = -0$ 
assert int32_from_int4 : int32FromInt  $(-1) = -1$ 
assert int32_from_int5 : int32FromInt  $(-123) = -123$ 

val int32FromInt64 :  $\text{INT}_{64} \rightarrow \text{INT}_{32}$ 
let int32FromInt64  $i =$  int32FromInteger (integerFromInt64  $i$ )
declare ocaml target_rep function int32FromInt64 = 'Int64.to_int'32
declare hol target_rep function int32FromInt64  $i = ((\text{'sw2sw' } i) : \text{INT}_{32})$ 
declare isabelle target_rep function int32FromInt64  $i = ((\text{'scast' } i) : \text{INT}_{32})$ 

assert int32_from_int64-0 : int32FromInt64 0 = 0
assert int32_from_int64-1 : int32FromInt64 1 = 1
assert int32_from_int64-2 : int32FromInt64 123 = 123
assert int32_from_int64-3 : int32FromInt64  $(-0) = -0$ 
assert int32_from_int64-4 : int32FromInt64  $(-1) = -1$ 
assert int32_from_int64-5 : int32FromInt64  $(-123) = -123$ 

```

```

(*****)
(* int64From ... *)
(*****)

val int64FromNat : NAT → INT64
declare hol target_rep function int64FromNat n = (('n2w' n) : INT64)
declare ocaml target_rep function int64FromNat = 'Int64.of_int'
declare coq target_rep function int64FromNat n = ('Zpred' ('Zpos' ('P.of_succ_nat' n))) (* TODO check *)
declare isabelle target_rep function int64FromNat n = (('word_of_int' ('int' n)) : INT64)

assert int64_from_nat0 : int64FromNat 0 = 0
assert int64_from_nat1 : int64FromNat 1 = 1
assert int64_from_nat2 : int64FromNat 123 = 123

val int64FromNatural :  $\mathbb{N}$  → INT64
declare hol target_rep function int64FromNatural n = (('n2w' n) : INT64)
declare ocaml target_rep function int64FromNatural = 'Nat.big_num.to_int'64
declare coq target_rep function int64FromNatural n = ('Zpred' ('Zpos' ('P.of_succ_nat' n))) (* TODO check *)
declare isabelle target_rep function int64FromNatural n = (('word_of_int' ('int' n)) : INT64)

assert int64_from_natural0 : int64FromNatural 0 = 0
assert int64_from_natural1 : int64FromNatural 1 = 1
assert int64_from_natural2 : int64FromNatural 123 = 123

val int64FromInteger :  $\mathbb{Z}$  → INT64
let int64FromInteger i = (
  let abs_int64 = int64FromNatural (naturalFromInteger i) in
  if (i < 0) then (- abs_int64) else abs_int64
)

declare ocaml target_rep function int64FromInteger = 'Nat.big_num.to_int'64
declare isabelle target_rep function int64FromInteger i = (('word_of_int' i) : INT64)

assert int64_from_integer0 : int64FromInteger 0 = 0
assert int64_from_integer1 : int64FromInteger 1 = 1
assert int64_from_integer2 : int64FromInteger 123 = 123
assert int64_from_integer3 : int64FromInteger (-0) = -0
assert int64_from_integer4 : int64FromInteger (-1) = -1
assert int64_from_integer5 : int64FromInteger (-123) = -123

val int64FromInt : INT → INT64
let int64FromInt i = int64FromInteger (integerFromInt i)
declare ocaml target_rep function int64FromInt = 'Int64.of_int'
declare isabelle target_rep function int64FromInt i = (('word_of_int' i) : INT64)

assert int64_from_int0 : int64FromInt 0 = 0
assert int64_from_int1 : int64FromInt 1 = 1
assert int64_from_int2 : int64FromInt 123 = 123
assert int64_from_int3 : int64FromInt (-0) = -0
assert int64_from_int4 : int64FromInt (-1) = -1
assert int64_from_int5 : int64FromInt (-123) = -123

val int64FromInt32 : INT32 → INT64
let int64FromInt32 i = int64FromInteger (integerFromInt32 i)
declare ocaml target_rep function int64FromInt32 = 'Int64.of_int'32

```

```

declare hol target_rep function int64FromInt32 i = (('sw2sw' i) : INT64)
declare isabelle target_rep function int64FromInt32 i = (('scast' i) : INT64)

assert int64_from_int32_0 : int64FromInt32 0 = 0
assert int64_from_int32_1 : int64FromInt32 1 = 1
assert int64_from_int32_2 : int64FromInt32 123 = 123
assert int64_from_int32_3 : int64FromInt32 (-0) = -0
assert int64_from_int32_4 : int64FromInt32 (-1) = -1
assert int64_from_int32_5 : int64FromInt32 (-123) = -123

(*****)
(* what's missing *)
(*****)

val naturalFromInt : INT →  $\mathbb{N}$ 
val naturalFromInt32 : INT32 →  $\mathbb{N}$ 
val naturalFromInt64 : INT64 →  $\mathbb{N}$ 

let inline naturalFromInt i = naturalFromNat (natFromInt i)
let inline naturalFromInt32 i = naturalFromInteger (integerFromInt32 i)
let inline naturalFromInt64 i = naturalFromInteger (integerFromInt64 i)

assert natural_from_int_0 : naturalFromInt 0 = 0
assert natural_from_int_1 : naturalFromInt 1 = 1
assert natural_from_int_2 : naturalFromInt (- 2) = 2
assert natural_from_int32_0 : naturalFromInt32 0 = 0
assert natural_from_int32_1 : naturalFromInt32 1 = 1
assert natural_from_int32_2 : naturalFromInt32 (- 2) = 2
assert natural_from_int64_0 : naturalFromInt64 0 = 0
assert natural_from_int64_1 : naturalFromInt64 1 = 1
assert natural_from_int64_2 : naturalFromInt64 (- 2) = 2

val intFromNatural :  $\mathbb{N}$  → INT
val intFromInt32 : INT32 → INT
val intFromInt64 : INT64 → INT

let inline intFromNatural n = intFromNat (natFromNatural n)
let inline intFromInt32 i = intFromInteger (integerFromInt32 i)
let inline intFromInt64 i = intFromInteger (integerFromInt64 i)

assert int_from_natural_0 : intFromNatural 0 = 0
assert int_from_natural_1 : intFromNatural 1 = 1
assert int_from_natural_2 : intFromNatural 122 = 122
assert int_from_int32_0 : intFromInt32 0 = 0
assert int_from_int32_1 : intFromInt32 1 = 1
assert int_from_int32_2 : intFromInt32 (- 2) = (-2)
assert int_from_int64_0 : intFromInt64 0 = 0
assert int_from_int64_1 : intFromInt64 1 = 1
assert int_from_int64_2 : intFromInt64 (- 2) = (-2)

val natFromInteger :  $\mathbb{Z}$  → NAT
val natFromInt32 : INT32 → NAT
val natFromInt64 : INT64 → NAT

let inline natFromInteger n = natFromInt (intFromInteger n)
let inline natFromInt32 i = natFromInteger (integerFromInt32 i)

```

```
let inline natFromInt64 i = natFromInteger (integerFromInt64 i)
```

```
assert nat_from_integer0 : natFromInteger 0 = 0  
assert nat_from_integer1 : natFromInteger 1 = 1  
assert nat_from_integer2 : natFromInteger 122 = 122  
assert nat_from_int32_0 : natFromInt32 0 = 0  
assert nat_from_int32_1 : natFromInt32 1 = 1  
assert nat_from_int32_2 : natFromInt32 (− 2) = 2  
assert nat_from_int64_0 : natFromInt64 0 = 0  
assert nat_from_int64_1 : natFromInt64 1 = 1  
assert nat_from_int64_2 : natFromInt64 (− 2) = 2
```

## 6 Tuple

```
(*****
(* Tuples *)
*****)

(* The type for tuples (pairs) is hard-coded, so here only a few functions are used *)

declare {isabelle, hol, ocaml, coq} rename module = lem_tuple

open import Bool Basic_classes

(* ----- *)
(* fst *)
(* ----- *)

val fst :  $\forall \alpha \beta. \alpha * \beta \rightarrow \alpha$ 
let fst (v1, v2) = v1

declare hol target_rep function fst = 'FST'
declare ocaml target_rep function fst = 'fst'
declare isabelle target_rep function fst = 'fst'
declare coq target_rep function fst = ('@' 'fst' '_' '_')

assert fst1 : (fst (true, false) = true)
assert fst2 : (fst (false, true) = false)

(* ----- *)
(* snd *)
(* ----- *)

val snd :  $\forall \alpha \beta. \alpha * \beta \rightarrow \beta$ 
let snd (v1, v2) = v2

declare hol target_rep function snd = 'SND'
declare ocaml target_rep function snd = 'snd'
declare isabelle target_rep function snd = 'snd'
declare coq target_rep function snd = ('@' 'snd' '_' '_')

lemma fst_snd : ( $\forall v. v = (\text{fst } v, \text{snd } v)$ )

assert snd1 : (snd (true, false) = false)
assert snd2 : (snd (false, true) = true)

(* ----- *)
(* curry *)
(* ----- *)

val curry :  $\forall \alpha \beta \gamma. (\alpha * \beta \rightarrow \gamma) \rightarrow (\alpha \rightarrow \beta \rightarrow \gamma)$ 
let inline curry f v1 v2 = f (v1, v2)

declare hol target_rep function curry = 'CURRY'
declare isabelle target_rep function curry = 'curry'
declare ocaml target_rep function curry = 'Lem.curry'
declare coq target_rep function curry = 'prod.curry'

assert curry1 : (curry (fun (x, y)  $\rightarrow x \wedge y$ ) true false = false)
```

```

(* ----- *)
(* uncurry          *)
(* ----- *)

val uncurry :  $\forall \alpha \beta \gamma. (\alpha \rightarrow \beta \rightarrow \gamma) \rightarrow (\alpha * \beta \rightarrow \gamma)$ 
let inline uncurry f = (fun (v1, v2) → f v1 v2)

declare hol target_rep function uncurry = 'UNCURRY'
declare isabelle target_rep function uncurry = 'case_prod'
declare ocaml target_rep function uncurry = 'Lem.uncurry'
declare coq target_rep function uncurry = 'prod_uncurry'

lemma curry_uncurry : ( $\forall f xy. \text{uncurry} (\text{curry } f) xy = f xy$ )
lemma uncurry_curry : ( $\forall f x y. \text{curry} (\text{uncurry } f) x y = f x y$ )

assert uncurry1 : (uncurry (fun x y → x ∧ y) (true, false) = false)

(* ----- *)
(* swap            *)
(* ----- *)

val swap :  $\forall \alpha \beta. (\alpha * \beta) \rightarrow (\beta * \alpha)$ 
let swap (v1, v2) = (v2, v1)

let inline {isabelle, coq} swap = (fun (v1, v2) → (v2, v1))
declare hol target_rep function swap = 'SWAP'
declare ocaml target_rep function swap = 'Lem.pair_swap'

assert swap1 : (swap (false, true) = (true, false))

```

## 7 List

```
(*****
(* A library for lists *)
(*
(* It mainly follows the Haskell List – library *)
(*****

(* ===== *)
(* Header *)
(* ===== *)

declare {isabelle, ocaml, hol, coq} rename module = lem_list

open import Bool Maybe Basic_classes Function Tuple Num

open import {coq} Coq.Lists.List
open import {isabelle} $LIB_DIR/Lem
open import {hol} lemTheory listTheory rich_listTheory sortingTheory

(* ===== *)
(* Basic list functions *)
(* ===== *)

(* The type of lists as well as list literals like [], [1;2], ... are hardcoded. Thus, we can directly dive into

(* ----- *)
(* cons *)
(* ----- *)

val :: : ∀ α. α → LIST α → LIST α

declare ascii_rep function :: = cons
declare hol target_rep function cons = infix '::'
declare ocaml target_rep function cons = infix '::'
declare isabelle target_rep function cons = infix '#'
declare coq target_rep function cons = infix '::'

(* ----- *)
(* Emptiness check *)
(* ----- *)

val null : ∀ α. LIST α → BOOL
let null l = match l with [] → true | _ → false end

declare hol target_rep function null = 'NULL'
declare {ocaml} rename function null = list_null
let inline {isabelle} null l = (l = [])

assert null_simple1 : (null ([] : LIST NAT))
assert null_simple2 : (¬ (null [(2 : NAT); 3; 4]))
assert null_simple3 : (¬ (null [(2 : NAT)]))
```



```

(* ----- *)
(* Length *)
(* ----- *)

val length :  $\forall \alpha. \text{LIST } \alpha \rightarrow \text{NAT}$ 
let rec length l =
  match l with
  | []  $\rightarrow$  0
  | x :: xs  $\rightarrow$  length xs + 1
end

declare termination_argument length = automatic

declare hol target_rep function length = 'LENGTH'
declare ocaml target_rep function length = 'List.length'
declare isabelle target_rep function length = 'List.length'
declare coq target_rep function length = 'List.length'

assert length0 : (length [] : LIST NAT) = 0
assert length1 : (length ([2] : LIST NAT) = 1)
assert length2 : (length ([2; 3] : LIST NAT) = 2)

lemma length_spec : ((length [] = 0)  $\wedge$  ( $\forall x \text{ xs}. \text{length } (x :: \text{xs}) = \text{length } \text{xs} + 1$ ))

(* ----- *)
(* Equality *)
(* ----- *)

val listEqual :  $\forall \alpha. \text{Eq } \alpha \Rightarrow \text{LIST } \alpha \rightarrow \text{LIST } \alpha \rightarrow \text{BOOL}$ 
val listEqualBy :  $\forall \alpha. (\alpha \rightarrow \alpha \rightarrow \text{BOOL}) \rightarrow \text{LIST } \alpha \rightarrow \text{LIST } \alpha \rightarrow \text{BOOL}$ 

let rec listEqualBy eq l1 l2 = match (l1, l2) with
| ([], [])  $\rightarrow$  true
| ([], (_ :: _))  $\rightarrow$  false
| ((_ :: _), [])  $\rightarrow$  false
| (x :: xs, y :: ys)  $\rightarrow$  (eq x y  $\wedge$  listEqualBy eq xs ys)
end
declare termination_argument listEqualBy = automatic

let inline listEqual = listEqualBy (=)
declare hol target_rep function listEqual = infix '='
declare isabelle target_rep function listEqual = infix '='
declare coq target_rep function listEqualBy = 'list_equal_by'

instance  $\forall \alpha. \text{Eq } \alpha \Rightarrow (\text{Eq } (\text{LIST } \alpha))$ 
  let == = listEqual
  let <> l1 l2 =  $\neg$  (listEqual l1 l2)
end

(* ----- *)
(* compare *)
(* ----- *)

val lexicographicCompare :  $\forall \alpha. \text{Ord } \alpha \Rightarrow \text{LIST } \alpha \rightarrow \text{LIST } \alpha \rightarrow \text{ORDERING}$ 
val lexicographicCompareBy :  $\forall \alpha. (\alpha \rightarrow \alpha \rightarrow \text{ORDERING}) \rightarrow \text{LIST } \alpha \rightarrow \text{LIST } \alpha \rightarrow \text{ORDERING}$ 

let rec lexicographicCompareBy cmp l1 l2 = match (l1, l2) with

```

```

| ([], []) → EQ
| ([], _ :: _) → LT
| (_ :: _, []) → GT
| (x :: xs, y :: ys) → begin
  match cmp x y with
  | LT → LT
  | GT → GT
  | EQ → lexicographicCompareBy cmp xs ys
end
end
end
declare termination_argument lexicographicCompareBy = automatic

let inline lexicographicCompare = lexicographicCompareBy compare
declare {ocaml, hol} rename function lexicographicCompareBy = lexicographic_compare

val lexicographicLess : ∀ α. Ord α ⇒ LIST α → LIST α → BOOL
val lexicographicLessBy : ∀ α. (α → α → BOOL) → (α → α → BOOL) → LIST α → LIST α → BOOL

let rec lexicographicLessBy less less_eq l₁ l₂ = match (l₁, l₂) with
| ([], []) → false
| ([], _ :: _) → true
| (_ :: _, []) → false
| (x :: xs, y :: ys) → ((less x y) ∨ ((less_eq x y) ∧ (lexicographicLessBy less less_eq xs ys)))
end
declare termination_argument lexicographicLessBy = automatic

let inline lexicographicLess = lexicographicLessBy (<) (≤)
declare {ocaml, hol} rename function lexicographicLessBy = lexicographic_less

val lexicographicLessEq : ∀ α. Ord α ⇒ LIST α → LIST α → BOOL
val lexicographicLessEqBy : ∀ α. (α → α → BOOL) → (α → α → BOOL) → LIST α → LIST α →
BOOL
let rec lexicographicLessEqBy less less_eq l₁ l₂ = match (l₁, l₂) with
| ([], []) → true
| ([], _ :: _) → true
| (_ :: _, []) → false
| (x :: xs, y :: ys) → (less x y ∨ (less_eq x y ∧ lexicographicLessEqBy less less_eq xs ys))
end
declare termination_argument lexicographicLessEqBy = automatic

let inline lexicographicLessEq = lexicographicLessEqBy (<) (≤)
declare {ocaml, hol} rename function lexicographicLessEqBy = lexicographic_less_eq

instance ∀ α. Ord α ⇒ (Ord (LIST α))
let compare = lexicographicCompare
let < = lexicographicLess
let <= = lexicographicLessEq
let > x y = lexicographicLess y x
let >= x y = lexicographicLessEq y x
end

assert list_ord₁ : ([] < [(2 : NAT)])
assert list_ord₂ : ([] ≤ [(2 : NAT)])
assert list_ord₃ : ([1] ≤ [(2 : NAT)])
assert list_ord₄ : ([2] ≤ [(2 : NAT)])

```

```

assert list_ord5 : ([2;3] > [(2 : NAT)])
assert list_ord6 : ([2;3;4;5] > [(2 : NAT)])
assert list_ord7 : ([2;3;4] > [(2 : NAT); 1;5;67])
assert list_ord8 : ([4] > [(3 : NAT);56])
assert list_ord9 : ([5] ≥ [(5 : NAT)])

```

```

(* ----- *)
(* Append      *)
(* ----- *)

```

```

val ++ : ∀ α. LIST α → LIST α → LIST α (* originally append *)
let rec ++ xs ys = match xs with
  | [] → ys
  | x :: xs' → x :: (append xs' ys)
end

```

```

declare ascii_rep function ++ = append
declare termination_argument append = automatic

```

```

declare hol target_rep function append = infix '++'
declare ocaml target_rep function append l1 l2 = 'List.rev_append' ('List.rev' l1) l2
declare isabelle target_rep function append = infix '@'
declare tex target_rep function append = infix '$+\!+$'
declare coq target_rep function append = ('@' 'List.app' '_')

```

```

assert append1 : ([0;1;2;3] ++ [4;5] = [(0 : NAT); 1;2;3;4;5])
lemma append_nil1 : (∀ l. l ++ [] = l)
lemma append_nil2 : (∀ l. [] ++ l = l)

```

```

(* ----- *)
(* snoc        *)
(* ----- *)

```

```

val snoc : ∀ α. α → LIST α → LIST α
let snoc e l = l ++ [e]

```

```

declare hol target_rep function snoc = 'SNOC'
let inline {isabelle, coq} snoc e l = l ++ [e]

```

```

assert snoc1 : snoc (2 : NAT) [] = [2]
assert snoc2 : snoc (2 : NAT) [3;4] = [3;4;2]
assert snoc3 : snoc (2 : NAT) [1] = [1;2]
lemma snoc_length : ∀ e l. length (snoc e l) = succ (length l)
lemma snoc_append : ∀ e l1 l2. (snoc e (l1 ++ l2) = l1 ++ (snoc e l2))

```

```

(* ----- *)
(* Reverse      *)
(* ----- *)

```

(\* First lets define the function [reverse\_append], which is closely related to reverse. [reverse\_append l1 l2] is the reverse of the concatenation of l1 and l2.

```

val reverseAppend : ∀ α. LIST α → LIST α → LIST α (* originally named rev_append *)
let rec reverseAppend l1 l2 = match l1 with
  | [] → l2
  | x :: xs → reverseAppend xs (x :: l2)
end

```

```

declare termination_argument reverseAppend = automatic

declare hol target_rep function reverseAppend = 'REV'
declare ocaml target_rep function reverseAppend = 'List.rev_append'

assert reverseAppend1 : (reverseAppend [(0 : NAT); 1; 2; 3] [4; 5] = [3; 2; 1; 0; 4; 5])

(* Reversing a list *)
val reverse : ∀ α. LIST α → LIST α (* originally named rev *)
let reverse l = reverseAppend l []

declare hol target_rep function reverse = 'REVERSE'
declare ocaml target_rep function reverse = 'List.rev'
declare isabelle target_rep function reverse = 'List.rev'
declare coq target_rep function reverse = 'List.rev'

assert reverse_nil : (reverse ([] : LIST NAT) = [])
assert reverse1 : (reverse [(1 : NAT)] = [1])
assert reverse2 : (reverse [(1 : NAT); 2] = [2; 1])
assert reverse5 : (reverse [(1 : NAT); 2; 3; 4; 5] = [5; 4; 3; 2; 1])

lemma reverseAppend : (∀ l1 l2. reverseAppend l1 l2 = (++) (reverse l1) l2)
let inline {isabelle} reverseAppend l1 l2 = ((reverse l1) ++ l2)

(* ----- *)
(* Map *)
(* ----- *)

val map_tr : ∀ α β. LIST β → (α → β) → LIST α → LIST β
let rec map_tr rev_acc f l = match l with
| [] → reverse rev_acc
| x :: xs → map_tr ((f x) :: rev_acc) f xs
end

(* taken from: https://blogs.janestreet.com/optimizing-list-map/ *)
val count_map : ∀ α β. (α → β) → LIST α → NAT → LIST β
let rec count_map f l ctr =
  match l with
  | [] → []
  | hd :: tl → f hd ::
    (if ctr < 5000 then count_map f tl (ctr + 1)
     else map_tr [] f tl)
end

val map : ∀ α β. (α → β) → LIST α → LIST β
let map f l = count_map f l 0

declare termination_argument map = automatic

declare hol target_rep function map = 'MAP'
(** DPM: for standard List.map replace line below, otherwise uses imperative * version supplied with Lem t
(*declare ocaml target_rep function map = 'List.map'*)
declare isabelle target_rep function map = 'List.map'
declare coq target_rep function map = 'List.map'

assert map_nil : (map (fun x → x + (1 : NAT)) [] = [])
assert map1 : (map (fun x → x + (1 : NAT)) [0] = [1])
assert map2 : (map (fun x → x + (1 : NAT)) [0; 1] = [1; 2])

```

```

assert map3 : (map (fun x → x + (1 : NAT)) [0; 1; 2] = [1; 2; 3])
assert map4 : (map (fun x → x + (1 : NAT)) [0; 1; 2; 3] = [1; 2; 3; 4])
assert map5 : (map (fun x → x + (1 : NAT)) [0; 1; 2; 3; 4] = [1; 2; 3; 4; 5])
assert map6 : (map (fun x → x + (1 : NAT)) [0; 1; 2; 3; 4; 5] = [1; 2; 3; 4; 5; 6])

```

```

(* ----- *)
(* Reverse Map *)
(* ----- *)

```

```

val reverseMap : ∀ α β. (α → β) → LIST α → LIST β
let inline reverseMap f l = reverse (map f l)

```

```

declare ocaml target_rep function reverseMap = 'List.rev_map'

```

```

(* ===== *)
(* Folding *)
(* ===== *)

```

```

(* ----- *)
(* fold left *)
(* ----- *)

```

```

val foldl : ∀ α β. (α → β → α) → α → LIST β → α (* originally foldl *)

```

```

let rec foldl f b l = match l with
| [] → b
| x :: xs → foldl f (f b x) xs
end
declare termination_argument foldl = automatic

```

```

declare hol target_rep function foldl = 'FOLDL'
declare ocaml target_rep function foldl = 'List.fold_left'
declare isabelle target_rep function foldl = 'List.foldl'
declare coq target_rep function foldl f e l = 'List.fold_left' f l e

```

```

assert foldl0 : (foldl (+) (0 : NAT) [] = 0)
assert foldl1 : (foldl (+) (0 : NAT) [4] = 4)
assert foldl4 : (foldl (fun l e → e::l) [] [(1 : NAT); 2; 3; 4] = [4; 3; 2; 1])

```

```

(* ----- *)
(* fold right *)
(* ----- *)

```

```

val foldr : ∀ α β. (α → β → β) → β → LIST α → β (* originally foldr with different argument order *)

```

```

let rec foldr f b l = match l with
| [] → b
| x :: xs → f x (foldr f b xs)
end
declare termination_argument foldr = automatic

```

```

declare hol target_rep function foldr = 'FOLDR'
declare ocaml target_rep function foldr f b l = 'List.fold_right' f l b
declare isabelle target_rep function foldr f b l = 'List.foldr' f l b
declare coq target_rep function foldr = 'List.fold_right'

```

```

assert foldr0 : (foldr (+) (0 : NAT) [] = 0)

```

```

assert foldr1 : (foldr (+) 1 [(4 : NAT)] = 5)
assert foldr4 : (foldr (fun e l → e::l) [] [(1 : NAT); 2; 3; 4] = [1; 2; 3; 4])

(* ----- *)
(* concatenating lists *)
(* ----- *)

val concat : ∀ α. LIST (LIST α) → LIST α (* before also called "flatten" *)
let concat = foldr (++) []

declare hol target_rep function concat = 'FLAT'
declare ocaml target_rep function concat = 'List.concat'
declare isabelle target_rep function concat = 'List.concat'

assert concat_nil : (concat ([] : LIST (LIST NAT)) = [])
assert concat1 : (concat [[(1 : NAT)]] = [1])
assert concat2 : (concat [(1 : NAT); [2]] = [1; 2])
assert concat3 : (concat [(1 : NAT); [], [2]] = [1; 2])

lemma concat_emp_thm : (concat [] = [])
lemma concat_cons_thm : (∀ l ll. (concat (l::ll) = (++) l (concat ll)))

(* ----- *)
(* concatenating with mapping *)
(* ----- *)

val concatMap : ∀ α β. (α → LIST β) → LIST α → LIST β
let inline concatMap f l = concat (map f l)

assert concatMap_nil : (concatMap (fun (x : NAT) → [x; x]) [] = [])
assert concatMap1 : (concatMap (fun x → [x; x]) [(1 : NAT)] = [1; 1])
assert concatMap2 : (concatMap (fun x → [x; x]) [(1 : NAT); 2] = [1; 1; 2; 2])
assert concatMap3 : (concatMap (fun x → [x; x]) [(1 : NAT); 2; 3] = [1; 1; 2; 2; 3; 3])
lemma concatMap_concat : (∀ ll. concat ll = concatMap (fun l → l) ll)
lemma concatMap_alt_def : (∀ f l. concatMap f l = foldr (fun l ll → f l ++ ll) [] l)

(* ----- *)
(* universal qualification *)
(* ----- *)

val all : ∀ α. (α → BOOL) → LIST α → BOOL (* originally for_all *)
let all P l = foldl (fun r e → P e ∧ r) true l

declare hol target_rep function all = 'EVERY'
declare ocaml target_rep function all = 'List.for_all'
declare isabelle target_rep function all P l = (∀ x ∈ ('set' l). P x)
declare coq target_rep function all = 'List.forallb'

assert all0 : (all (fun x → x > (2 : NAT)) [])
assert all4 : (all (fun x → x > (2 : NAT)) [4; 5; 6; 7])
assert all4_neg : (¬ (all (fun x → x > (2 : NAT)) [4; 5; 2; 7]))

lemma all_nil_thm : (∀ P. all P [])
lemma all_cons_thm : (∀ P e l. all P (e::l) = (P e ∧ all P l))

```

```

(* ----- *)
(* existential qualification *)
(* ----- *)

val any :  $\forall \alpha. (\alpha \rightarrow \text{BOOL}) \rightarrow \text{LIST } \alpha \rightarrow \text{BOOL}$  (* originally exist *)
let any P l = foldl (fun r e  $\rightarrow$  P e  $\vee$  r) false l

declare hol target_rep function any = 'EXISTS'
declare ocaml target_rep function any = 'List.exists'
declare isabelle target_rep function any P l = ( $\exists x \in ('set' l). P x$ )
declare coq target_rep function any = 'List.existsb'

assert any_0 : ( $\neg$  (any (fun x  $\rightarrow$  (x < (3 : NAT))) []))
assert any_4 : ( $\neg$  (any (fun x  $\rightarrow$  (x < (3 : NAT))) [4; 5; 6; 7]))
assert any_4_neg : (any (fun x  $\rightarrow$  (x < (3 : NAT))) [4; 5; 2; 7])

lemma any_nil_thm : ( $\forall P. \neg$  (any P []))
lemma any_cons_thm : ( $\forall P e l. \text{any } P (e::l) = (P e \vee \text{any } P l)$ )

(* ----- *)
(* dest_init *)
(* ----- *)

(* get the initial part and the last element of the list in a safe way *)

val dest_init :  $\forall \alpha. \text{LIST } \alpha \rightarrow \text{MAYBE } (\text{LIST } \alpha * \alpha)$ 

let rec dest_init_aux rev_init last_elem_seen to_process =
  match to_process with
  | []  $\rightarrow$  (reverse rev_init, last_elem_seen)
  | x :: xs  $\rightarrow$  dest_init_aux (last_elem_seen::rev_init) x xs
end
declare termination_argument dest_init_aux = automatic

let dest_init l = match l with
| []  $\rightarrow$  Nothing
| x :: xs  $\rightarrow$  Just (dest_init_aux [] x xs)
end

assert dest_init_0 : (dest_init ([] : LIST NAT) = Nothing)
assert dest_init_1 : (dest_init [(1 : NAT)] = Just ([], 1))
assert dest_init_2 : (dest_init [(1 : NAT); 2; 3; 4; 5] = Just ([1; 2; 3; 4], 5))

lemma dest_init_nil : (dest_init [] = Nothing)
lemma dest_init_snoc : ( $\forall x xs. \text{dest\_init } (xs ++ [x]) = \text{Just } (xs, x)$ )

(* ===== *)
(* Indexing lists *)
(* ===== *)

(* ----- *)
(* index / nth with maybe *)
(* ----- *)

```

```
val index :  $\forall \alpha. \text{LIST } \alpha \rightarrow \text{NAT} \rightarrow \text{MAYBE } \alpha$ 
```

```
let rec index l n = match l with
| []  $\rightarrow$  Nothing
| x :: xs  $\rightarrow$  if n = 0 then Just x else index xs (n-1)
end
```

```
declare termination_argument index = automatic
```

```
declare isabelle target_rep function index = 'index'
declare {ocaml, hol} rename function index = list_index
```

```
assert index0 : (index [(0 : NAT); 1; 2; 3; 4; 5] 0 = Just 0)
assert index1 : (index [(0 : NAT); 1; 2; 3; 4; 5] 1 = Just 1)
assert index2 : (index [(0 : NAT); 1; 2; 3; 4; 5] 2 = Just 2)
assert index3 : (index [(0 : NAT); 1; 2; 3; 4; 5] 3 = Just 3)
assert index4 : (index [(0 : NAT); 1; 2; 3; 4; 5] 4 = Just 4)
assert index5 : (index [(0 : NAT); 1; 2; 3; 4; 5] 5 = Just 5)
assert index6 : (index [(0 : NAT); 1; 2; 3; 4; 5] 6 = Nothing)
```

```
lemma index_is_none : ( $\forall l n. (\text{index } l n = \text{Nothing}) \longleftrightarrow (n \geq \text{length } l)$ )
lemma index_list_eq : ( $\forall l_1 l_2. ((\forall n. \text{index } l_1 n = \text{index } l_2 n) \longleftrightarrow (l_1 = l_2))$ )
```

```
(* ----- *)
(* findIndices *)
(* ----- *)
```

```
(* [findIndices P l] returns the indices of all elements of list [l] that satisfy predicate [P]. Counting starts at 0. *)
val findIndices :  $\forall \alpha. (\alpha \rightarrow \text{BOOL}) \rightarrow \text{LIST } \alpha \rightarrow \text{LIST NAT}$ 
```

```
let rec findIndices_aux (i : NAT) P l =
  match l with
  | []  $\rightarrow$  []
  | x :: xs  $\rightarrow$  if P x then i :: findIndices_aux (i + 1) P xs else findIndices_aux (i + 1) P xs
end
let findIndices P l = findIndices_aux 0 P l
declare termination_argument findIndices_aux = automatic
```

```
declare isabelle target_rep function findIndices = 'find_indices'
declare {ocaml, hol} rename function findIndices = find_indices
declare {ocaml, hol} rename function findIndices_aux = find_indices_aux
```

```
assert findIndices1 : (findIndices (fun (n : NAT)  $\rightarrow$  n > 3) [] = [])
assert findIndices2 : (findIndices (fun (n : NAT)  $\rightarrow$  n > 3) [4] = [0])
assert findIndices3 : (findIndices (fun (n : NAT)  $\rightarrow$  n > 3) [1; 5; 3; 1; 2; 6] = [1; 5])
```

```
(* ----- *)
(* findIndex *)
(* ----- *)
```

```
(* findIndex returns the first index of a list that satisfies a given predicate. *)
val findIndex :  $\forall \alpha. (\alpha \rightarrow \text{BOOL}) \rightarrow \text{LIST } \alpha \rightarrow \text{MAYBE NAT}$ 
let findIndex P l = match findIndices P l with
| []  $\rightarrow$  Nothing
| x :: _  $\rightarrow$  Just x
end
```



```

declare isabelle target_rep function findIndex = 'find_index'
declare {ocaml, hol} rename function findIndex = find_index

assert find_index_0 : (findIndex (fun (n : NAT) → n > 3) [1; 2] = Nothing)
assert find_index_1 : (findIndex (fun (n : NAT) → n > 3) [1; 2; 4] = Just 2)
assert find_index_2 : (findIndex (fun (n : NAT) → n > 3) [1; 2; 4; 5; 67; 1] = Just 2)

(* ----- *)
(* elemIndices *)
(* ----- *)

val elemIndices : ∀ α. Eq α ⇒ α → LIST α → LIST NAT
let inline elemIndices e l = findIndices ((=) e) l

assert elemIndices_0 : (elemIndices (2 : NAT) [] = [])
assert elemIndices_1 : (elemIndices (2 : NAT) [2] = [0])
assert elemIndices_2 : (elemIndices (2 : NAT) [2; 3; 4; 2; 4; 2] = [0; 3; 5])

(* ----- *)
(* elemIndex *)
(* ----- *)

val elemIndex : ∀ α. Eq α ⇒ α → LIST α → MAYBE NAT
let inline elemIndex e l = findIndex ((=) e) l

assert elemIndex_0 : (elemIndex (2 : NAT) [] = Nothing)
assert elemIndex_1 : (elemIndex (2 : NAT) [2] = Just 0)
assert elemIndex_2 : (elemIndex (2 : NAT) [3; 4; 2; 4; 2] = Just 2)

(* ===== *)
(* Creating lists *)
(* ===== *)

(* ----- *)
(* genlist *)
(* ----- *)

(* [genlist f n] generates the list [f 0; f 1; ... (f (n - 1))] *)
val genlist : ∀ α. (NAT → α) → NAT → LIST α

let rec genlist f n =
  match n with
  | 0 → []
  | n' + 1 → snoc (f n') (genlist f n')
end
declare termination_argument genlist = automatic

assert genlist_0 : (genlist (fun n → n) 0 = [])
assert genlist_1 : (genlist (fun n → n) 1 = [0])
assert genlist_2 : (genlist (fun n → n) 2 = [0; 1])
assert genlist_3 : (genlist (fun n → n) 3 = [0; 1; 2])
lemma genlist_length : (∀ f n. (length (genlist f n) = n))
lemma genlist_index : (∀ f n i. i < n → index (genlist f n) i = Just (f i))

```

```

declare hol target_rep function genlist = 'GENLIST'
declare isabelle target_rep function genlist = 'genlist'

```

```

(* ----- *)
(* replicate      *)
(* ----- *)

```

```

val replicate : ∀ α. NAT → α → LIST α
let rec replicate n x =
  match n with
  | 0 → []
  | n' + 1 → x :: replicate n' x
end
declare termination_argument replicate = automatic

```

```

declare isabelle target_rep function replicate = 'List.replicate'
declare hol target_rep function replicate = 'REPLICATE'

```

```

assert replicate_0 : (replicate 0 (2 : NAT) = [])
assert replicate_1 : (replicate 1 (2 : NAT) = [2])
assert replicate_2 : (replicate 2 (2 : NAT) = [2; 2])
assert replicate_3 : (replicate 3 (2 : NAT) = [2; 2; 2])
lemma replicate_length : (∀ n x. (length (replicate n x) = n))
lemma replicate_index : (∀ n x i. i < n → index (replicate n x) i = Just x)

```

```

(* ===== *)
(* Sublists                                     *)
(* ===== *)

```

```

(* ----- *)
(* splitAt      *)
(* ----- *)

```

(\* [splitAt n xs] returns a tuple (xs1, xs2), with "append xs1 xs2 = xs" and "length xs1 = n". If there are not

```

val splitAtAcc : ∀ α. LIST α → NAT → LIST α → (LIST α * LIST α)

```

```

let rec splitAtAcc revAcc n l =
  match l with
  | [] → (reverse revAcc, [])
  | x :: xs → if n ≤ 0 then (reverse revAcc, l) else splitAtAcc (x::revAcc) (n-1) xs
end

```

```

val splitAt : ∀ α. NAT → LIST α → (LIST α * LIST α)
let splitAt n l =
  splitAtAcc [] n l

```

```

(* match l with | [] -> ([], []) | x :: xs -> if n <= 0 then ([], l) else begin let (l1, l2) = sp

```

```

declare termination_argument splitAt = automatic

```

```

declare isabelle target_rep function splitAt = 'split_at'
declare {ocaml, hol} rename function splitAt = split_at

```

```

assert splitAt_1 : (splitAt 0 [(1 : NAT); 2; 3; 4; 5; 6] = ([], [1; 2; 3; 4; 5; 6]))
assert splitAt_2 : (splitAt 2 [(1 : NAT); 2; 3; 4; 5; 6] = ([1; 2], [3; 4; 5; 6]))
assert splitAt_3 : (splitAt 100 [(1 : NAT); 2; 3; 4; 5; 6] = ([1; 2; 3; 4; 5; 6], []))

```

```
lemma splitAt_append : (∀ n xs.
  let (xs1, xs2) = splitAt n xs in
  (xs = xs1 ++ xs2))
```

```
lemma splitAt_length : (∀ n xs.
  let (xs1, xs2) = splitAt n xs in
  ((length xs1 = n) ∨
   (length xs1 = length xs ∧ null xs2)))
```

```
(* ----- *)
(* take                *)
(* ----- *)
```

```
(* take n xs returns the prefix of xs of length n, or xs itself if n > length xs *)
val take : ∀ α. NAT → LIST α → LIST α
let take n l = fst (splitAt n l)
```

```
declare hol target_rep function take = 'TAKE'
declare isabelle target_rep function take = 'List.take'
```

```
assert take1 : (take 0 [(1 : NAT); 2; 3; 4; 5; 6] = [])
assert take2 : (take 2 [(1 : NAT); 2; 3; 4; 5; 6] = [1; 2])
assert take3 : (take 100 [(1 : NAT); 2; 3; 4; 5; 6] = [1; 2; 3; 4; 5; 6])
```

```
(* ----- *)
(* drop                *)
(* ----- *)
```

```
(* [drop n xs] drops the first [n] elements of [xs]. It returns the empty list, if [n] > [length xs]. *)
val drop : ∀ α. NAT → LIST α → LIST α
let drop n l = snd (splitAt n l)
```

```
declare hol target_rep function drop = 'DROP'
declare isabelle target_rep function drop = 'List.drop'
```

```
assert drop1 : (drop 0 [(1 : NAT); 2; 3; 4; 5; 6] = [1; 2; 3; 4; 5; 6])
assert drop2 : (drop 2 [(1 : NAT); 2; 3; 4; 5; 6] = [3; 4; 5; 6])
assert drop3 : (drop 100 [(1 : NAT); 2; 3; 4; 5; 6] = [])
```

```
lemma splitAt_take_drop : (∀ n xs. splitAt n xs = (take n xs, drop n xs))
```

```
let inline {hol} splitAt n xs = (take n xs, drop n xs)
```

```
(* ----- *)
(* splitWhile, takeWhile, and dropWhile *)
(* ----- *)
```

```
val splitWhile_tr : ∀ α. (α → BOOL) → LIST α → LIST α → (LIST α * LIST α)
let rec splitWhile_tr p xs acc = match xs with
| [] →
  (reverse acc, [])
| x :: xs →
  if p x then
    splitWhile_tr p xs (x::acc)
  else
    (reverse acc, x::xs)
```

end

declare termination\_argument splitWhile\_tr = automatic

val splitWhile :  $\forall \alpha. (\alpha \rightarrow \text{BOOL}) \rightarrow \text{LIST } \alpha \rightarrow (\text{LIST } \alpha * \text{LIST } \alpha)$   
 let splitWhile p xs = splitWhile\_tr p xs []

assert splitWhile<sub>1</sub> : (splitWhile ((>) 3) [(1 : NAT); 2; 3; 4; 5; 6] = ([1; 2], [3; 4; 5; 6]))  
 assert splitWhile<sub>2</sub> : (splitWhile ((≤) 6) ([] : LIST NAT) = ([], []))

(\* [takeWhile p xs] takes the first elements of [xs] that satisfy [p]. \*)  
 val takeWhile :  $\forall \alpha. (\alpha \rightarrow \text{BOOL}) \rightarrow \text{LIST } \alpha \rightarrow \text{LIST } \alpha$   
 let takeWhile p l = fst (splitWhile p l)

(\* [dropWhile p xs] drops the first elements of [xs] that satisfy [p]. \*)  
 val dropWhile :  $\forall \alpha. (\alpha \rightarrow \text{BOOL}) \rightarrow \text{LIST } \alpha \rightarrow \text{LIST } \alpha$   
 let dropWhile p l = snd (splitWhile p l)

assert dropWhile<sub>0</sub> : (dropWhile ((>) 3) [(1 : NAT); 2; 3; 4; 5; 6] = [3; 4; 5; 6])  
 assert dropWhile<sub>1</sub> : (dropWhile ((≥) 5) [(1 : NAT); 2; 3; 4; 5; 6] = [6])  
 assert dropWhile<sub>2</sub> : (dropWhile ((>) 100) [(1 : NAT); 2; 3; 4; 5; 6] = [])  
 assert dropWhile<sub>3</sub> : (dropWhile ((<) 10) [(1 : NAT); 2; 3; 4; 5; 6] = [1; 2; 3; 4; 5; 6])

assert takeWhile<sub>0</sub> : (takeWhile ((>) 3) [(1 : NAT); 2; 3; 4; 5; 6] = [1; 2])  
 assert takeWhile<sub>1</sub> : (takeWhile ((≥) 5) [(1 : NAT); 2; 3; 4; 5; 6] = [1; 2; 3; 4; 5])  
 assert takeWhile<sub>2</sub> : (takeWhile ((>) 100) [(1 : NAT); 2; 3; 4; 5; 6] = [1; 2; 3; 4; 5; 6])  
 assert takeWhile<sub>3</sub> : (takeWhile ((<) 10) [(1 : NAT); 2; 3; 4; 5; 6] = [])

(\* ----- \*)  
 (\* isPrefixOf \*)  
 (\* ----- \*)

val isPrefixOf :  $\forall \alpha. Eq \alpha \Rightarrow \text{LIST } \alpha \rightarrow \text{LIST } \alpha \rightarrow \text{BOOL}$   
 let rec isPrefixOf l<sub>1</sub> l<sub>2</sub> = match (l<sub>1</sub>, l<sub>2</sub>) with  
 | ([], \_) → true  
 | (\_ :: \_, []) → false  
 | (x :: xs, y :: ys) → (x = y) ∧ isPrefixOf xs ys  
 end  
 declare termination\_argument isPrefixOf = automatic

declare hol target\_rep function isPrefixOf = 'isPREFIX'

assert isPrefixOf<sub>0</sub> : (isPrefixOf [] [(0 : NAT); 1; 2; 3; 4])  
 assert isPrefixOf<sub>1</sub> : (isPrefixOf [0] [(0 : NAT); 1; 2; 3; 4])  
 assert isPrefixOf<sub>2</sub> : (isPrefixOf [0; 1; 2] [(0 : NAT); 1; 2; 3; 4])  
 assert isPrefixOf<sub>3</sub> :  $\neg$  (isPrefixOf [0; 2] [(0 : NAT); 1; 2; 3; 4])  
 assert isPrefixOf<sub>4</sub> :  $\neg$  (isPrefixOf [(0 : NAT); 1; 2; 3; 4] [])

lemma isPrefixOf\_alt\_def :  $\forall l_1 l_2. \text{isPrefixOf } l_1 l_2 \longleftrightarrow (\exists l_3. l_2 = (l_1 ++ l_3))$   
 lemma isPrefixOf\_sym :  $\forall l. \text{isPrefixOf } l l$   
 lemma isPrefixOf\_trans :  $\forall l_1 l_2 l_3. \text{isPrefixOf } l_1 l_2 \longrightarrow \text{isPrefixOf } l_2 l_3 \longrightarrow \text{isPrefixOf } l_1 l_3$   
 lemma isPrefixOf\_antisym :  $\forall l_1 l_2. \text{isPrefixOf } l_1 l_2 \longrightarrow \text{isPrefixOf } l_2 l_1 \longrightarrow (l_1 = l_2)$

(\* ----- \*)  
 (\* update \*)  
 (\* ----- \*)  
 val update :  $\forall \alpha. \text{LIST } \alpha \rightarrow \text{NAT} \rightarrow \alpha \rightarrow \text{LIST } \alpha$   
 let rec update l n e =

```

match l with
| [] → []
| x :: xs → if n = 0 then e :: xs else x :: (update xs (n - 1) e)
end
declare termination_argument update = automatic

```

```

declare isabelle target_rep function update = 'List.list_update'
declare hol target_rep function update l n e = 'LUPDATE' e n l
declare {ocaml} rename function update = list_update

```

```

assert list_update1 : (update [] 2 (3 : NAT) = [])
assert list_update2 : (update [1; 2; 3; 4; 5] 0 (0 : NAT) = [0; 2; 3; 4; 5])
assert list_update3 : (update [1; 2; 3; 4; 5] 1 (0 : NAT) = [1; 0; 3; 4; 5])
assert list_update4 : (update [1; 2; 3; 4; 5] 2 (0 : NAT) = [1; 2; 0; 4; 5])
assert list_update5 : (update [1; 2; 3; 4; 5] 5 (0 : NAT) = [1; 2; 3; 4; 5])

```

```

lemma list_update_length : (∀ l n e. length (update l n e) = length l)
lemma list_update_index : (∀ i l n e.
  (index (update l n e) i = ((if i = n ∧ n < length l then Just e else index l e))))

```

```

(* ===== *)
(* Searching lists *)
(* ===== *)

```

```

(* ----- *)
(* Membership test *)
(* ----- *)

```

(\* The membership test, one of the basic list functions, is actually tricky for Lem, because it is tricky, w

```

val elem : ∀ α. Eq α ⇒ α → LIST α → BOOL
val elemBy : ∀ α. (α → α → BOOL) → α → LIST α → BOOL

```

```

let elemBy eq e l = any (eq e) l
let elem = elemBy (=)

```

```

declare hol target_rep function elem = 'MEM'
(* declare ocaml target_rep function elem = 'List.mem' *)
declare isabelle target_rep function elem e l = 'Set.member' e ('set' l)

```

```

assert elem1 : (elem (2 : NAT) [3; 1; 2; 4])
assert elem2 : (elem (3 : NAT) [3; 1; 2; 4])
assert elem3 : (elem (4 : NAT) [3; 1; 2; 4])
assert elem4 : (¬ (elem (5 : NAT) [3; 1; 2; 4]))

```

```

lemma elem_spec : ((∀ e. ¬ (elem e [])) ∧
  (∀ e x xs. (elem e (x :: xs)) = ((e = x) ∨ (elem e xs))))

```

```

(* ----- *)
(* Find *)
(* ----- *)

```

```

val find : ∀ α. (α → BOOL) → LIST α → MAYBE α (* previously not of maybe type *)
let rec find P l = match l with
| [] → Nothing
| x :: xs → if P x then Just x else find P xs
end

```

```

declare termination_argument find = automatic

declare isabelle target_rep function find = 'List.find'
declare {ocaml, hol} rename function find = list_find_opt

assert find1 : ((find (fun n → n > (3 : NAT)) []) = Nothing)
assert find2 : ((find (fun n → n > (3 : NAT)) [2; 1; 3]) = Nothing)
assert find3 : ((find (fun n → n > (3 : NAT)) [2; 1; 5; 4]) = Just 5)
assert find4 : ((find (fun n → n > (3 : NAT)) [2; 1; 4; 5; 4]) = Just 4)

lemma find_in : (∀ P l x. (find P l = Just x) → P x ∧ elem x l)
lemma find_not_in : (∀ P l. (find P l = Nothing) = (¬ (any P l)))

(* ----- *)
(* Lookup in an associative list *)
(* ----- *)
val lookup : ∀ α β. Eq α ⇒ α → LIST (α * β) → MAYBE β
val lookupBy : ∀ α β. (α → α → BOOL) → α → LIST (α * β) → MAYBE β

(* DPM: eta-expansion for Coq backend type-inference. *)
let lookupBy eq k m = Maybe.map (fun x → snd x) (find (fun (k', _) → eq k k') m)
let inline lookup = lookupBy (=)

declare isabelle target_rep function lookup x l = 'Map.map_of' l x
declare {ocaml, hol} rename function lookup = list_assoc_opt

assert lookup1 : (lookup (3 : NAT) ([ (4, (5 : NAT)); (3, 4); (1, 2); (3, 5) ]) = Just 4)
assert lookup2 : (lookup (8 : NAT) ([ (4, (5 : NAT)); (3, 4); (1, 2); (3, 5) ]) = Nothing)
assert lookup3 : (lookup (1 : NAT) ([ (4, (5 : NAT)); (3, 4); (1, 2); (3, 5) ]) = Just 2)

(* ----- *)
(* filter *)
(* ----- *)
val filter : ∀ α. (α → BOOL) → LIST α → LIST α
let rec filter P l = match l with
  | [] → []
  | x :: xs → if (P x) then x :: (filter P xs) else filter P xs
end

declare termination_argument filter = automatic

declare hol target_rep function filter = 'FILTER'
declare ocaml target_rep function filter = 'List.filter'
declare isabelle target_rep function filter = 'List.filter'
declare coq target_rep function filter = 'List.filter'

assert filter0 : (filter (fun x → x > (4 : NAT)) [] = [])
assert filter1 : (filter (fun x → x > (4 : NAT)) [1; 2; 4; 5; 2; 7; 6] = [5; 7; 6])
lemma filter_nil_thm : (∀ P. filter P [] = [])
lemma filter_cons_thm : (∀ P x xs. filter P (x::xs) = (let l' = filter P xs in (if (P x) then x :: l' else l'))))

(* ----- *)
(* partition *)
(* ----- *)
val partition : ∀ α. (α → BOOL) → LIST α → LIST α * LIST α
let partition P l = (filter P l, filter (fun x → ¬ (P x)) l)

```

```

val reversePartition :  $\forall \alpha. (\alpha \rightarrow \text{BOOL}) \rightarrow \text{LIST } \alpha \rightarrow \text{LIST } \alpha * \text{LIST } \alpha$ 
let reversePartition P l = partition P (reverse l)

let inline {hol} partition P l = reversePartition P (reverse l)
declare hol target_rep function reversePartition = 'PARTITION'
declare ocaml target_rep function partition = 'List.partition'
declare isabelle target_rep function partition = 'List.partition'

assert partition0 : (partition (fun x  $\rightarrow$  x > (4 : NAT)) [] = ([], []))
assert partition1 : (partition (fun x  $\rightarrow$  x > (4 : NAT)) [1; 2; 4; 5; 2; 7; 6] = ([5; 7; 6], [1; 2; 4; 2]))
lemma partition_fst : ( $\forall P l$ . fst (partition P l) = filter P l)
lemma partition_snd : ( $\forall P l$ . snd (partition P l) = filter (fun x  $\rightarrow$   $\neg$  (P x)) l)

(* ----- *)
(* delete first element *)
(* with certain property *)
(* ----- *)

val deleteFirst :  $\forall \alpha. (\alpha \rightarrow \text{BOOL}) \rightarrow \text{LIST } \alpha \rightarrow \text{MAYBE (LIST } \alpha)$ 
let rec deleteFirst P l = match l with
| []  $\rightarrow$  Nothing
| x :: xs  $\rightarrow$  if (P x) then Just xs else Maybe.map (fun xs'  $\rightarrow$  x :: xs') (deleteFirst P xs)
end
declare termination_argument deleteFirst = automatic

declare isabelle target_rep function deleteFirst = 'delete_first'
declare {ocaml, hol} rename function deleteFirst = list_delete_first

assert deleteFirst1 : (deleteFirst (fun x  $\rightarrow$  x > (5 : NAT)) [3; 6; 7; 1] = Just [3; 7; 1])
assert deleteFirst2 : (deleteFirst (fun x  $\rightarrow$  x > (15 : NAT)) [3; 6; 7; 1] = Nothing)
assert deleteFirst3 : (deleteFirst (fun x  $\rightarrow$  x > (2 : NAT)) [3; 6; 7; 1] = Just [6; 7; 1])

val delete :  $\forall \alpha. \text{Eq } \alpha \Rightarrow \alpha \rightarrow \text{LIST } \alpha \rightarrow \text{LIST } \alpha$ 
val deleteBy :  $\forall \alpha. (\alpha \rightarrow \alpha \rightarrow \text{BOOL}) \rightarrow \alpha \rightarrow \text{LIST } \alpha \rightarrow \text{LIST } \alpha$ 

let deleteBy eq x l = fromMaybe l (deleteFirst (eq x) l)
let inline delete = deleteBy (=)

declare isabelle target_rep function delete = 'remove'1
declare {ocaml, hol} rename function delete = list_remove1
declare {ocaml, hol} rename function deleteBy = list_delete

assert delete1 : (delete (6 : NAT) [(3 : NAT); 6; 7; 1] = [3; 7; 1])
assert delete2 : (delete (4 : NAT) [(3 : NAT); 6; 7; 1] = [3; 6; 7; 1])
assert delete3 : (delete (3 : NAT) [(3 : NAT); 6; 7; 1] = [6; 7; 1])
assert delete4 : (delete (3 : NAT) [(3 : NAT); 3; 6; 7; 1] = [3; 6; 7; 1])

(* ===== *)
(* Zipping and unzipping lists *)
(* ===== *)

(* ----- *)
(* zip *)
(* ----- *)

```

```

(* zip takes two lists and returns a list of corresponding pairs. If one input list is short, excess elements
val zip :  $\forall \alpha \beta. \text{LIST } \alpha \rightarrow \text{LIST } \beta \rightarrow \text{LIST } (\alpha * \beta)$  (* before combine *)
let rec zip l1 l2 = match (l1, l2) with
| (x :: xs, y :: ys) → (x, y) :: zip xs ys
| _ → []
end
declare termination_argument zip = automatic

declare isabelle target_rep function zip = 'List.zip'
declare {ocaml, hol} rename function zip = list_combine

assert zip1 : (zip [(1 : NAT); 2; 3; 4; 5] [(2 : NAT); 3; 4; 5; 6] = [(1, 2); (2, 3); (3, 4); (4, 5); (5, 6)])

(* this test rules out List.combine for ocaml and ZIP for HOL, but it's needed to make it a total function *)
assert zip2 : (zip [(1 : NAT); 2; 3] [(2 : NAT); 3; 4; 5; 6] = [(1, 2); (2, 3); (3, 4)])

(* ----- *)
(* unzip *)
(* ----- *)

val unzip :  $\forall \alpha \beta. \text{LIST } (\alpha * \beta) \rightarrow (\text{LIST } \alpha * \text{LIST } \beta)$ 
let rec unzip l = match l with
| [] → ([], [])
| (x, y) :: xys → let (xs, ys) = unzip xys in (x :: xs, y :: ys)
end
declare termination_argument unzip = automatic

declare hol target_rep function unzip = 'UNZIP'
declare isabelle target_rep function unzip = 'list_unzip'
declare ocaml target_rep function unzip = 'List.split'

assert unzip1 : (unzip ([] : LIST (NAT * NAT)) = ([], []))
assert unzip2 : (unzip [(1 : NAT), (2 : NAT)]; (2, 3); (3, 4)] = ([1; 2; 3], [2; 3; 4]))

instance  $\forall \alpha. \text{SetType } \alpha \Rightarrow (\text{SetType } (\text{LIST } \alpha))$ 
let setElemCompare = lexicographicCompareBy setElemCompare
end

(* ----- *)
(* distinct elements *)
(* ----- *)

val allDistinct :  $\forall \alpha. \text{Eq } \alpha \Rightarrow \text{LIST } \alpha \rightarrow \text{BOOL}$ 
let rec allDistinct l =
  match l with
  | [] → true
  | (x :: l') →  $\neg (\text{elem } x \ l') \wedge \text{allDistinct } l'$ 
end
declare termination_argument allDistinct = automatic

declare hol target_rep function allDistinct = 'ALL_DISTINCT'

(* some more useful functions *)
val mapMaybe :  $\forall \alpha \beta. (\alpha \rightarrow \text{MAYBE } \beta) \rightarrow \text{LIST } \alpha \rightarrow \text{LIST } \beta$ 
let rec mapMaybe f xs =
  match xs with
  | [] → []

```



```

| x :: xs →
  match f x with
  | Nothing → mapMaybe f xs
  | Just y → y :: (mapMaybe f xs)
  end
end

val mapi : ∀ α β. (NAT → α → β) → LIST α → LIST β
let rec mapiAux f (n : NAT) l = match l with
| [] → []
| x :: xs → (f n x) :: mapiAux f (n + 1) xs
end
let mapi f l = mapiAux f 0 l

val deletes : ∀ α. Eq α ⇒ LIST α → LIST α → LIST α
let deletes xs ys =
  foldl (flip delete) xs ys

(* ===== *)
(* Comments (not clean yet, please ignore the rest of the file) *)
(* ===== *)

(* ----- *)
(* skipped from Haskell Lib*)
(* ----- intersperse :: a -> [a] -> [a]intercalate :: [a] -> [[a]] ----- *)

(* ----- *)
(* skipped from Lem Lib *)
(* ----- val for_all2 : forall 'a 'b. ('a -> 'b -> bool) -> list 'a -> list 'b ----- *)

val catMaybes : ∀ α. LIST (MAYBE α) → LIST α
let rec catMaybes xs =
  match xs with
  | [] → []
  | (Nothing :: xs') →
    catMaybes xs'
  | (Just x :: xs') →
    x :: catMaybes xs'
end

```

## 8 Either

```

(*****
(* A library for sum types *)
(*****)

(* ===== *)
(* Header *)
(* ===== *)

declare {isabelle, hol, coq} rename module = lem_either
declare {ocaml} rename module = Lem_either

open import Bool Basic_classes List Tuple
open import {hol} sumTheory
open import {ocaml} Either

type EITHER  $\alpha$   $\beta$ 
  = LEFT of  $\alpha$ 
  | RIGHT of  $\beta$ 

declare ocaml target_rep type EITHER = 'Either.either'
declare isabelle target_rep type EITHER = 'sum'
declare hol target_rep type EITHER = 'sum'
declare coq target_rep type EITHER = 'sum'

declare isabelle target_rep function Left = 'Inl'
declare isabelle target_rep function Right = 'Inr'
declare ocaml target_rep function Left = 'Either.Left'
declare ocaml target_rep function Right = 'Either.Right'
declare hol target_rep function Left = 'INL'
declare hol target_rep function Right = 'INR'
declare coq target_rep function Left = 'inl'
declare coq target_rep function Right = 'inr'

(* -----
(* Equality. *)
(* -----

val eitherEqual :  $\forall \alpha \beta. Eq \alpha, Eq \beta \Rightarrow (EITHER \alpha \beta) \rightarrow (EITHER \alpha \beta) \rightarrow BOOL$ 
val eitherEqualBy :  $\forall \alpha \beta. (\alpha \rightarrow \alpha \rightarrow BOOL) \rightarrow (\beta \rightarrow \beta \rightarrow BOOL) \rightarrow (EITHER \alpha \beta) \rightarrow (EITHER \alpha \beta) \rightarrow BOOL$ 

let eitherEqualBy eql egr (left : EITHER  $\alpha$   $\beta$ ) (right : EITHER  $\alpha$   $\beta$ ) =
  match (left, right) with
  | (Left l, Left l')  $\rightarrow$  eql l l'
  | (Right r, Right r')  $\rightarrow$  egr r r'
  | _  $\rightarrow$  false
end
let eitherEqual = eitherEqualBy (=) (=)

let inline {hol, isabelle} eitherEqual = unsafe_structural_equality
let inline {ocaml} eitherEqual = eitherEqualBy (=) (=)
declare ocaml target_rep function eitherEqualBy = 'Either.eitherEqualBy'

instance  $\forall \alpha \beta. Eq \alpha, Eq \beta \Rightarrow (Eq (EITHER \alpha \beta))$ 
  let == = eitherEqual

```

```

let <> x y = ¬ (eitherEqual x y)
end

let either_setElemCompare cmpa cmpb x y =
  match (x, y) with
  | (Left x', Left y') → cmpa x' y'
  | (Right x', Right y') → cmpb x' y'
  | (Left _, Right _) → LT
  | (Right _, Left _) → GT
  end

instance ∀ α β. SetType α, SetType β ⇒ (SetType (EITHER α β))
  let setElemCompare x y = either_setElemCompare setElemCompare setElemCompare x y
  end

assert either_equal1 : (((Left false) : EITHER BOOL BOOL) = Left false)
assert either_equal2 : (((Left true) : EITHER BOOL BOOL) ≠ Left false)
assert either_equal3 : (((Left true) : EITHER BOOL BOOL) = Left true)
assert either_equal4 : (((Right false) : EITHER BOOL BOOL) = Right false)
assert either_equal5 : (((Right false) : EITHER BOOL BOOL) ≠ Right true)
assert either_equal6 : (((Right true) : EITHER BOOL BOOL) ≠ Left true)
assert either_equal7 : (((Left true) : EITHER BOOL BOOL) ≠ Right true)

assert either_pattern1 : (match (Left true) with Left x → x | Right y → ¬ y end)
assert either_pattern2 : (match (Right false) with Left x → x | Right y → ¬ y end)
assert either_pattern3 : (¬ (match (Left false) with Left x → x | Right y → ¬ y end))
assert either_pattern4 : (¬ (match (Right true) with Left x → x | Right y → ¬ y end))

(* -----
(* Utility functions.
(* -----

val isLeft : ∀ α β. EITHER α β → BOOL
let inline isLeft = function
  | Left _ → true
  | Right _ → false
end

declare hol target_rep function isLeft = 'ISL'

assert isLeft1 : (isLeft ((Left true) : EITHER BOOL BOOL))
assert isLeft2 : (¬ (isLeft ((Right true) : EITHER BOOL BOOL)))

val isRight : ∀ α β. EITHER α β → BOOL
let inline isRight = function
  | Right _ → true
  | Left _ → false
end

declare hol target_rep function isRight = 'ISR'

assert isRight1 : (isRight ((Right true) : EITHER BOOL BOOL))
assert isRight2 : (¬ (isRight ((Left true) : EITHER BOOL BOOL)))

val either : ∀ α β γ. (α → γ) → (β → γ) → EITHER α β → γ
let either fa fb x = match x with

```

```

| Left a → fa a
| Right b → fb b
end

```

```

declare ocaml target_rep function either = 'Either.either_case'
declare isabelle target_rep function either = 'case_sum'
declare hol target_rep function either fa fb x = 'sum_CASE' x fa fb

```

```

assert either1 : (either ((fun b → ¬ b)) (fun b → b) (Left true) = false)
assert either2 : (either ((fun b → ¬ b)) (fun b → b) (Left false) = true)
assert either3 : (either ((fun b → ¬ b)) (fun b → b) (Right true) = true)
assert either4 : (either ((fun b → ¬ b)) (fun b → b) (Right false) = false)

```

```

val partitionEither : ∀ α β. LIST (EITHER α β) → (LIST α * LIST β)
let rec partitionEither l = match l with
| [] → ([], [])
| x :: xs → begin
  let (ll, rl) = partitionEither xs in
  match x with
  | Left l → (l::ll, rl)
  | Right r → (ll, r::rl)
  end
end
end
declare termination_argument partitionEither = automatic
declare {hol} rename function partitionEither = SUM.PARTITION

```

```

declare isabelle target_rep function partitionEither = 'sum_partition'
declare ocaml target_rep function partitionEither = 'Either.either_partition'

```

```

assert partitionEither1 : (partitionEither [Left true; Right false; Right false; Left false; Right true] = ([true; false], [false; false; true]))

```

```

val lefts : ∀ α β. LIST (EITHER α β) → LIST α
let inline lefts l = fst (partitionEither l)

```

```

assert lefts1 : ((lefts [Left true; Right false; Right false; Left false; Right true]) = [true; false])

```

```

val rights : ∀ α β. LIST (EITHER α β) → LIST β
let inline rights l = snd (partitionEither l)

```

```

assert rights1 : (rights [Left true; Right false; Right false; Left false; Right true] = [false; false; true])

```

## 9 Set\_helpers

```
(*****
(* Helper functions for sets *)
*****)

(* Usually there is a something.lem file containing the main definitions and a  something_extra.lem one containing
extra lemmas *)

(* ===== *)
(* Header *)
(* ===== *)

open import Bool Basic_classes Maybe Function Num

declare {isabelle, hol, ocaml, coq} rename module = lem_set_helpers

open import {coq} Coq.Lists.List

(* ----- *)
(* fold *)
(* ----- *)

(* fold is suspicious, because if given a function, for which the order, in which the arguments are given, matters,
the result may differ *)

val fold :  $\forall \alpha \beta. (\alpha \rightarrow \beta \rightarrow \beta) \rightarrow \text{SET } \alpha \rightarrow \beta \rightarrow \beta$ 
declare compile_message fold = "fold is non-deterministic because the order of the iteration is unclear. Its result may differ"

declare hol target_rep function fold = 'ITSET'
declare isabelle target_rep function fold f A q = 'Finite_Set.fold' f q A
declare ocaml target_rep function fold = 'Pset.fold'
declare coq target_rep function fold = 'set_fold'
```

## 10 Set

```

(*****
(* A library for sets *)
(*
(* It mainly follows the Haskell Set – library *)
(*****

(* Sets in Lem are a bit tricky. On the one hand, we want efficiently executable sets. OCaml and Haskell both

(* ===== *)
(* Header *)
(* ===== *)

open import Bool Basic_classes Maybe Function Num List Set_helpers

declare {isabelle, hol, ocaml, coq} rename module = lem_set

(* DPM: sets currently implemented as lists due to mismatch between Coq type * class hierarchy and the hier
open import {coq} Coq.Lists.List
open import {hol} lemTheory
open import {isabelle} $LIB_DIR/Lem

(* Type of sets and set comprehensions are hard – coded *)

declare ocaml target_rep type SET = 'Pset.set'

(* ----- *)
(* Equality check *)
(* ----- *)

val setEqualBy : ∀ α. (α → α → ORDERING) → SET α → SET α → BOOL
declare coq target_rep function setEqualBy = 'set_equal_by'

val setEqual : ∀ α. SetType α ⇒ SET α → SET α → BOOL
let inline {hol, isabelle} setEqual = unsafe_structural_equality
let inline {coq} setEqual = setEqualBy setElemCompare
declare ocaml target_rep function setEqual = 'Pset.equal'

instance ∀ α. SetType α ⇒ (Eq (SET α))
  let = = setEqual
  let <> s1 s2 = ¬ (setEqual s1 s2)
end

(* ----- *)
(* Empty set *)
(* ----- *)

val empty : ∀ α. SetType α ⇒ SET α
val emptyBy : ∀ α. (α → α → ORDERING) → SET α

declare ocaml target_rep function emptyBy = 'Pset.empty'
let inline {ocaml} empty = emptyBy setElemCompare

declare coq target_rep function empty = 'set_empty'
declare hol target_rep function empty = 'EMPTY'
declare isabelle target_rep function empty = '{}'
```

```

declare html target_rep function empty = '&empty;';
declare tex target_rep function empty = '$\emptyset$';

assert empty0 : (∅ : SET BOOL) = {}
assert empty1 : (∅ : SET NAT) = {}
assert empty2 : (∅ : SET (LIST NAT)) = {}
assert empty3 : (∅ : SET (SET NAT)) = {}

(* ----- *)
(* any / all      *)
(* ----- *)

val any : ∀ α. SetType α ⇒ (α → BOOL) → SET α → BOOL
let inline any P s = (∃ e ∈ s. P e)

declare coq target_rep function any = 'set_any'
declare hol target_rep function any P s = 'EXISTS' P ('SET_TO_LIST' s)
declare isabelle target_rep function any P s = 'Set.Bex' s P
declare ocaml target_rep function any = 'Pset.exists'

assert any0 : any (fun (x : NAT) → x > 5) {3, 4, 6}
assert any1 : ¬ (any (fun (x : NAT) → x > 10) {3, 4, 6})

val all : ∀ α. SetType α ⇒ (α → BOOL) → SET α → BOOL
let inline all P s = (∀ e ∈ s. P e)

declare coq target_rep function all = 'set_for_all'
declare hol target_rep function all P s = 'EVERY' P ('SET_TO_LIST' s)
declare isabelle target_rep function all P s = 'Set.Ball' s P
declare ocaml target_rep function all = 'Pset.for_all'

assert all0 : all (fun (x : NAT) → x > 2) {3, 4, 6}
assert all1 : ¬ (all (fun (x : NAT) → x > 2) {3, 4, 6, 1})

(* ----- *)
(* (IN)          *)
(* ----- *)

val IN [member] : ∀ α. SetType α ⇒ α → SET α → BOOL
val memberBy : ∀ α. (α → α → ORDERING) → α → SET α → BOOL

declare coq target_rep function memberBy = 'set_member_by'
let inline {coq} member = memberBy setElemCompare
declare ocaml target_rep function member = 'Pset.mem'
declare isabelle target_rep function member = infix '<in>'
declare hol target_rep function member = infix 'IN'
declare html target_rep function member = infix '&isin;';
declare tex target_rep function member = infix '$\in$'

assert in1 : ((1 : NAT) ∈ {(2 : NAT), 3, 1})
assert in2 : (¬ ((1 : NAT) ∈ {2, 3, 4}))
assert in3 : (¬ ((1 : NAT) ∈ {}))
assert in4 : ((1 : NAT) ∈ {1, 2, 1, 3, 1, 4})

(* ----- *)
(* not (IN)      *)
(* ----- *)

```

```

val NIN [notMember] :  $\forall \alpha. \text{SetType } \alpha \Rightarrow \alpha \rightarrow \text{SET } \alpha \rightarrow \text{BOOL}$ 
let inline notMember e s =  $\neg (e \in s)$ 
declare html target_rep function notMember = infix '&notin; '
declare isabelle target_rep function notMember = infix '\<notin>'
declare tex target_rep function notMember = infix '$\not\in$'

assert nin1 :  $\neg ((1 : \text{NAT}) \notin \{2, 3, 1\})$ 
assert nin2 :  $((1 : \text{NAT}) \notin \{2, 3, 4\})$ 
assert nin3 :  $((1 : \text{NAT}) \notin \{\})$ 
assert nin4 :  $\neg ((1 : \text{NAT}) \notin \{1, 2, 1, 3, 1, 4\})$ 

(* ----- *)
(* Emptyness check *)
(* ----- *)

val null :  $\forall \alpha. \text{SetType } \alpha \Rightarrow \text{SET } \alpha \rightarrow \text{BOOL}$  (* before is_empty *)
let inline null s = (s = {})

declare ocaml target_rep function null = 'Pset.is_empty'
declare coq target_rep function null = 'set_is_empty'

assert null1 : (null {} : SET NAT)
assert null2 : ( $\neg$  (null {(1 : NAT)}))

(* ----- *)
(* singleton *)
(* ----- *)

val singletonBy :  $\forall \alpha. (\alpha \rightarrow \alpha \rightarrow \text{ORDERING}) \rightarrow \alpha \rightarrow \text{SET } \alpha$ 
val singleton :  $\forall \alpha. \text{SetType } \alpha \Rightarrow \alpha \rightarrow \text{SET } \alpha$ 

declare ocaml target_rep function singletonBy = 'Pset.singleton'
declare coq target_rep function singleton = 'set_singleton'

let inline {ocaml} singleton = singletonBy setElemCompare
let inline ~{ocaml, coq} singleton x = {x}

assert singleton1 : singleton (2 : NAT) = {2}
assert singleton2 :  $\neg$  (null (singleton (2 : NAT)))
assert singleton3 : 2  $\in$  (singleton (2 : NAT))
assert singleton4 : 3  $\notin$  (singleton (2 : NAT))

(* ----- *)
(* size *)
(* ----- *)

val size :  $\forall \alpha. \text{SetType } \alpha \Rightarrow \text{SET } \alpha \rightarrow \text{NAT}$ 

declare ocaml target_rep function size = 'Pset.cardinal'
declare coq target_rep function size = 'set_cardinal'
declare hol target_rep function size = 'CARD'
declare isabelle target_rep function size = 'card'

```



```

assert size1 : (size ({}) : SET NAT) = 0)
assert size2 : (size {(2 : NAT)} = 1)
assert size3 : (size {(1 : NAT), 1} = 1)
assert size4 : (size {(2 : NAT), 1, 3} = 3)
assert size5 : (size {(2 : NAT), 1, 3, 9} = 4)

```

```

lemma null_size : (∀ s. (null s) → (size s = 0))
lemma null_singleton : (∀ x. (size (singleton x) = 1))

```

```

(* ----- *)
(* setting up pattern matching *)
(* ----- *)

```

```

val set_case : ∀ α β. SetType α ⇒ SET α → β → (α → β) → β → β

```

```

(* please provide target bindings, since choose is defined only in extra and not the right thing to use here

```

```

declare hol target_rep function set_case = 'set_CASE'
declare isabelle target_rep function set_case = 'set_case'
declare coq target_rep function set_case = 'set_case'
declare ocaml target_rep function set_case = 'Pset.set_case'

```

```

declare pattern_match inexhaustive SET α = [ empty; singleton ] set_case

```

```

assert set_patterns0 : (
  match ({}) : SET NAT) with
  | ∅ → true
  | _ → false
end
)

```

```

assert set_patterns1 : ¬ (
  match {(2 : NAT)} with
  | ∅ → true
  | _ → false
end
)

```

```

assert set_patterns2 : ¬ (
  match {(3 : NAT), 4} with
  | ∅ → true
  | _ → false
end
)

```

```

assert set_patterns3 : (
  match ({2} : SET NAT) with
  | ∅ → 0
  | singleton x → x
  | _ → 1
end
) = 2

```

```

assert set_patterns4 : (
  match ({}) : SET NAT) with
  | ∅ → 0
  | singleton x → x

```

```

    | _ → 1
  end
) = 0

assert set_patterns5 : (
  match ({3, 4, 5} : SET NAT) with
  | ∅ → 0
  | singleton x → x
  | _ → 1
  end
) = 1

assert set_patterns6 : (
  match ({3, 3, 3} : SET NAT) with
  | ∅ → 0
  | singleton x → x
  | _ → 1
  end
) = 3

assert set_patterns7 : (
  match ({3, 4, 5} : SET NAT) with
  | ∅ → 0
  | singleton _ → 1
  | s → size s
  end
) = 3

assert set_patterns8 : (
  match (({3, 4, 5} : SET NAT), false) with
  | (∅, true) → 0
  | (singleton _, _) → 1
  | (s, true) → size s
  | _ → 5
  end
) = 5

assert set_patterns9 : (
  match ({5} : SET NAT) with
  | ∅ → 0
  | singleton 2 → 0
  | singleton (x + 3) → x
  | _ → 1
  end
) = 2

assert set_patterns10 : (
  match ({2} : SET NAT) with
  | ∅ → 0
  | singleton 2 → 0
  | singleton (x + 3) → x
  | _ → 1
  end
) = 0

(* ----- *)
(* union *)

```

```

(* ----- *)

val unionBy : ∀ α. (α → α → ORDERING) → SET α → SET α → SET α
val union : ∀ α. SetType α ⇒ SET α → SET α → SET α
declare ocaml target_rep function union = 'Pset.union'
declare hol target_rep function union = infix 'UNION'
declare isabelle target_rep function union = infix '\<union>'
declare coq target_rep function unionBy = 'set.union_by'
declare tex target_rep function union = infix '$\cup$'
let inline {coq} union = unionBy setElemCompare

```

```

assert union1 : (({1 : NAT}, 2, 3} ∪ {3, 2, 4} = {1, 2, 3, 4})
lemma union_in : (∀ e s1 s2. e ∈ (s1 ∪ s2) ↔ (e ∈ s1 ∨ e ∈ s2))

```

```

(* ----- *)
(* insert *)
(* ----- *)

```

```

val insert : ∀ α. SetType α ⇒ α → SET α → SET α (* before add *)

```

```

declare ocaml target_rep function insert = 'Pset.add'
declare coq target_rep function insert = 'set.add'
declare hol target_rep function insert = infix 'INSERT'
declare isabelle target_rep function insert = 'Set.insert'

```

```

assert insert1 : ((insert (2 : NAT) {3, 4}) = {2, 3, 4})
assert insert2 : ((insert (3 : NAT) {3, 4}) = {3, 4})
assert insert3 : ((insert (3 : NAT) {}) = {3})

```

```

(* ----- *)
(* filter *)
(* ----- *)

```

```

val filter : ∀ α. SetType α ⇒ (α → BOOL) → SET α → SET α
let filter P s = {e | ∀ e ∈ s | P e}

```

```

declare ocaml target_rep function filter = 'Pset.filter'
declare isabelle target_rep function filter = 'set.filter'
declare hol target_rep function filter = 'SET_FILTER'

```

```

assert filter1 : (filter (fun n → (n > 2)) ({1 : NAT}, 2, 3, 4} = {3, 4})
assert filter2 : (filter (fun n → n > (2 : NAT)) {} = {})
lemma filter_emp : (∀ P. (filter P {}) = {})
lemma filter_insert : (∀ e s P. (filter P (insert e s)) =
  (if (P e) then insert e (filter P s) else (filter P s)))

```

```

(* ----- *)
(* partition *)
(* ----- *)

```

```

val partition : ∀ α. SetType α ⇒ (α → BOOL) → SET α → SET α * SET α
let partition P s = (filter P s, filter (fun e → ¬ (P e)) s)
declare {hol} rename function partition = SET_PARTITION

```

```

(* ----- *)

```

```

(* split *)
(* ----- *)

val split :  $\forall \alpha. \text{SetType } \alpha, \text{Ord } \alpha \Rightarrow \alpha \rightarrow \text{SET } \alpha \rightarrow \text{SET } \alpha * \text{SET } \alpha$ 
let split p s = (filter ((>) p) s, filter ((<) p) s)
declare {hol} rename function split = SET_SPLIT

val splitMember :  $\forall \alpha. \text{SetType } \alpha, \text{Ord } \alpha \Rightarrow \alpha \rightarrow \text{SET } \alpha \rightarrow \text{SET } \alpha * \text{BOOL} * \text{SET } \alpha$ 
let splitMember p s = (filter ((<) p) s, p  $\in$  s, filter ((>) p) s)

assert split_simple : split
  (3, 0)
  ({(1, 0), (2, 0), (3, 0), (4, 0), (5, 0), (6, 0)} : SET ( $\mathbb{N}$  *  $\mathbb{N}$ ))
  = ({(1, 0), (2, 0)}, {(4, 0), (5, 0), (6, 0)})

(* ----- *)
(* subset and proper subset *)
(* ----- *)

val isSubsetOfBy :  $\forall \alpha. (\alpha \rightarrow \alpha \rightarrow \text{ORDERING}) \rightarrow \text{SET } \alpha \rightarrow \text{SET } \alpha \rightarrow \text{BOOL}$ 
val isProperSubsetOfBy :  $\forall \alpha. (\alpha \rightarrow \alpha \rightarrow \text{ORDERING}) \rightarrow \text{SET } \alpha \rightarrow \text{SET } \alpha \rightarrow \text{BOOL}$ 

val isSubsetOf :  $\forall \alpha. \text{SetType } \alpha \Rightarrow \text{SET } \alpha \rightarrow \text{SET } \alpha \rightarrow \text{BOOL}$ 
val isProperSubsetOf :  $\forall \alpha. \text{SetType } \alpha \Rightarrow \text{SET } \alpha \rightarrow \text{SET } \alpha \rightarrow \text{BOOL}$ 

declare ocaml target_rep function isSubsetOf = 'Pset.subset'
declare hol target_rep function isSubsetOf = infix 'SUBSET'
declare isabelle target_rep function isSubsetOf = infix '\<subsepeq>'
declare html target_rep function isSubsetOf = infix '&sube;'
declare tex target_rep function isSubsetOf = infix '$\subsepeq$'
declare coq target_rep function isSubsetOfBy = 'set_subset_by'
let inline {coq} isSubsetOf = isSubsetOfBy setElemCompare

declare ocaml target_rep function isProperSubsetOf = 'Pset.subset_proper'
declare hol target_rep function isProperSubsetOf = infix 'PSUBSET'
declare isabelle target_rep function isProperSubsetOf = infix '\<subset>'
declare html target_rep function isProperSubsetOf = infix '&sub;'
declare tex target_rep function isProperSubsetOf = infix '$\subset$'
declare coq target_rep function isProperSubsetOfBy = 'set_proper_subset_by'
let inline {coq} isProperSubsetOf = isProperSubsetOfBy setElemCompare

let inline subset = ( $\subseteq$ )
declare tex target_rep function subset = infix '$\subsepeq$'

assert isSubsetOf1 : (({ } : SET NAT)  $\subseteq$  { })
assert isSubsetOf2 : ({(1 : NAT), 2, 3}  $\subseteq$  {1, 2, 3})
assert isSubsetOf3 : ({(1 : NAT), 2}  $\subseteq$  {3, 2, 1})
lemma isSubsetOf_refl : ( $\forall s. s \subseteq s$ )
lemma isSubsetOf_def : ( $\forall s_1 s_2. s_1 \subseteq s_2 = (\forall e. e \in s_1 \longrightarrow e \in s_2)$ )
lemma isSubsetOf_eq : ( $\forall s_1 s_2. (s_1 = s_2) \longleftrightarrow ((s_1 \subseteq s_2) \wedge (s_2 \subseteq s_1))$ )

assert isProperSubsetOf1 : ( $\neg (({ } : \text{SET NAT}) \subset \{ })$ )
assert isProperSubsetOf2 : ( $\neg ({(1 : \text{NAT}), 2, 3} \subset \{1, 2, 3\})$ )
assert isProperSubsetOf3 : ({(1 : NAT), 2}  $\subset$  {3, 2, 1})
lemma isProperSubsetOf_irrefl : ( $\forall s. \neg (s \subset s)$ )
lemma isProperSubsetOf_def : ( $\forall s_1 s_2. s_1 \subset s_2 \longleftrightarrow ((s_1 \subseteq s_2) \wedge \neg (s_2 \subseteq s_1))$ )

```

```
(* ----- *)
(* delete *)
(* ----- *)
```

```
val delete : ∀ α. SetType α, Eq α ⇒ α → SET α → SET α
val deleteBy : ∀ α. SetType α ⇒ (α → α → BOOL) → α → SET α → SET α
```

```
let inline deleteBy eq e s = filter (fun e2 → ¬ (eq e e2)) s
let inline delete e s = deleteBy (=) e s
```

```
(* ----- *)
(* bigunion *)
(* ----- *)
```

```
val bigunion : ∀ α. SetType α ⇒ SET (SET α) → SET α
val bigunionBy : ∀ α. (α → α → ORDERING) → SET (SET α) → SET α
```

```
let bigunion bs = {x | ∀ s ∈ bs x ∈ s | true}
```

```
declare ocaml target_rep function bigunionBy = 'Pset.bigunion'
let inline {ocaml} bigunion = bigunionBy setElemCompare
declare hol target_rep function bigunion = 'BIGUNION'
declare isabelle target_rep function bigunion = '\<Union>'
declare tex target_rep function bigunion = '$\bigcup$'
```

```
assert bigunion0 : (⋃ {{(1 : NAT)}}) = {1}
assert bigunion1 : (⋃ {{(1 : NAT), 2, 3}, {3, 2, 4}}) = {1, 2, 3, 4}
assert bigunion2 : (⋃ {{(1 : NAT), 2, 3}, {3, 2, 4}, {}}) = {1, 2, 3, 4}
assert bigunion3 : (⋃ {{(1 : NAT), 2, 3}, {3, 2, 4}, {5}}) = {1, 2, 3, 4, 5}
lemma bigunion_in : (∀ e bs. e ∈ ⋃ bs ⇔ (∃ s. s ∈ bs ∧ e ∈ s))
```

```
(* ----- *)
(* big intersection *)
(* ----- *)
```

(\* Shaked's addition, for which he is now forever responsible as a de facto \* Lem maintainer... \*)

```
val bigintersection : ∀ α. SetType α ⇒ SET (SET α) → SET α
let bigintersection bs = {x | ∀ x ∈ (⋃ bs) | ∀ s ∈ bs. x ∈ s}
```

```
(* ----- *)
(* difference *)
(* ----- *)
```

```
val differenceBy : ∀ α. (α → α → ORDERING) → SET α → SET α → SET α
val difference : ∀ α. SetType α ⇒ SET α → SET α → SET α
declare ocaml target_rep function difference = 'Pset.diff'
declare hol target_rep function difference = infix 'DIFF'
declare isabelle target_rep function difference = infix '-'
declare tex target_rep function difference = infix '$\setminus$'
declare coq target_rep function differenceBy = 'set_diff_by'
let inline {coq} difference = differenceBy setElemCompare
```

```
let inline \ = (\)
```

```
assert difference1 : ({(1 : NAT), 2, 3} \ {3, 2, 4}) = {1}
```

lemma *difference\_in* :  $(\forall e \ s_1 \ s_2. e \in (s_1 \setminus s_2) \longleftrightarrow (e \in s_1 \wedge \neg (e \in s_2)))$

(\* ----- \*)  
 (\* intersection \*)  
 (\* ----- \*)

val *intersection* :  $\forall \alpha. \text{SetType } \alpha \Rightarrow \text{SET } \alpha \rightarrow \text{SET } \alpha \rightarrow \text{SET } \alpha$   
 val *intersectionBy* :  $\forall \alpha. (\alpha \rightarrow \alpha \rightarrow \text{ORDERING}) \rightarrow \text{SET } \alpha \rightarrow \text{SET } \alpha \rightarrow \text{SET } \alpha$

declare *ocaml* target\_rep function *intersection* = 'Pset.inter'  
 declare *hol* target\_rep function *intersection* = infix 'INTER'  
 declare *isabelle* target\_rep function *intersection* = infix '<inter>'  
 declare *coq* target\_rep function *intersectionBy* = 'set\_inter\_by'  
 declare *tex* target\_rep function *intersection* = infix '\$\cap\$'  
 let inline {*coq*} *intersection* = intersectionBy setElemCompare  
 let inline *inter* =  $(\cap)$   
 declare *tex* target\_rep function *inter* = infix '\$\cap\$'

assert *intersection\_1* :  $(\{1, 2, 3\} \cap \{(3 : \text{NAT}), 2, 4\} = \{2, 3\})$   
 lemma *intersection\_in* :  $(\forall e \ s_1 \ s_2. e \in (s_1 \cap s_2) \longleftrightarrow (e \in s_1 \wedge e \in s_2))$

(\* ----- \*)  
 (\* map \*)  
 (\* ----- \*)

val *map* :  $\forall \alpha \ \beta. \text{SetType } \alpha, \text{SetType } \beta \Rightarrow (\alpha \rightarrow \beta) \rightarrow \text{SET } \alpha \rightarrow \text{SET } \beta$  (\* before image \*)  
 let *map f s* = { *f e* |  $\forall e \in s \mid \text{true}$  }

val *mapBy* :  $\forall \alpha \ \beta. (\beta \rightarrow \beta \rightarrow \text{ORDERING}) \rightarrow (\alpha \rightarrow \beta) \rightarrow \text{SET } \alpha \rightarrow \text{SET } \beta$

declare *ocaml* target\_rep function *mapBy* = 'Pset.map'

let inline {*ocaml*} *map* = mapBy setElemCompare  
 declare *hol* target\_rep function *map* = 'IMAGE'  
 declare *isabelle* target\_rep function *map* = 'Set.image'

assert *map\_1* :  $(\text{map succ } \{(2 : \text{NAT}), 3, 4\} = \{5, 4, 3\})$   
 assert *map\_2* :  $(\text{map } (\text{fun } n \rightarrow n * 3) \{(2 : \text{NAT}), 3, 4\} = \{6, 9, 12\})$

(\* ----- \*)  
 (\* bigunionMap \*)  
 (\* ----- \*)

(\* In order to avoid providing an comparison function for sets of sets, it might be better to combine biguni

val *bigunionMap* :  $\forall \alpha \ \beta. \text{SetType } \alpha, \text{SetType } \beta \Rightarrow (\alpha \rightarrow \text{SET } \beta) \rightarrow \text{SET } \alpha \rightarrow \text{SET } \beta$   
 val *bigunionMapBy* :  $\forall \alpha \ \beta. (\beta \rightarrow \beta \rightarrow \text{ORDERING}) \rightarrow (\alpha \rightarrow \text{SET } \beta) \rightarrow \text{SET } \alpha \rightarrow \text{SET } \beta$

let inline *bigunionMap f bs* =  $\bigcup (\text{map } f \text{ } bs)$

declare *ocaml* target\_rep function *bigunionMapBy* = 'Pset.map\_union'  
 let inline {*ocaml*} *bigunionMap* = bigunionMapBy setElemCompare

assert *bigunionmap\_0* :  $(\text{bigunionMap } (\text{fun } n \rightarrow \{n, 2 * n, 3 * n\}) \{(1 : \text{NAT})\} = \{1, 2, 3\})$   
 assert *bigunionmap\_1* :  $(\text{bigunionMap } (\text{fun } n \rightarrow \{n, 2 * n, 3 * n\}) \{(2 : \text{NAT}), 8\} = \{2, 4, 6, 8, 16, 24\})$

```

(* ----- *)
(* mapMaybe and fromMaybe *)
(* ----- *)

(* If the mapping function returns Just x, x is added to the result set. If it returns Nothing, no element is
val mapMaybe : ∀ α β. SetType α, SetType β ⇒ (α → MAYBE β) → SET α → SET β
let setMapMaybe f s =
  bigunionMap (fun x → match f x with
    | Just y → singleton y
    | Nothing → ∅
  end)
    s

(* The name mapMaybe is already being used in the list.lem *)
declare rename function mapMaybe = setMapMaybe

val removeMaybe : ∀ α. SetType α ⇒ SET (MAYBE α) → SET α
let removeMaybe s = setMapMaybe (fun x → x) s

(* ----- *)
(* min and max *)
(* ----- *)

val findMin : ∀ α. SetType α, Eq α ⇒ SET α → MAYBE α
val findMax : ∀ α. SetType α, Eq α ⇒ SET α → MAYBE α

(* Informal, since THE is not supported by all backends
val findMinBy : forall 'a. ('a -> 'a -> bool) -> (
declare ocaml target_rep function findMin = 'Pset.min_elt_opt'
declare ocaml target_rep function findMax = 'Pset.max_elt_opt'

(* XXX: move into Lem libraries... *)
declare isabelle target_rep function findMin = 'Elf.Types.Local.find_min_element'
declare isabelle target_rep function findMax = 'Elf.Types.Local.find_max_element'

declare hol target_rep function findMin = 'ARB'
declare hol target_rep function findMax = 'ARB'

(* ----- *)
(* fromList *)
(* ----- *)

val fromList : ∀ α. SetType α ⇒ LIST α → SET α (* before from_list *)
val fromListBy : ∀ α. (α → α → ORDERING) → LIST α → SET α

declare ocaml target_rep function fromListBy = 'Pset.from_list'
let inline {ocaml} fromList = fromListBy setElemCompare
declare hol target_rep function fromList = 'LIST_TO_SET'
declare isabelle target_rep function fromList = 'List.set'
declare coq target_rep function fromListBy = 'set_from_list_by'
let inline {coq} fromList = fromListBy setElemCompare

assert fromList1 : (fromList [(2 : NAT); 4; 3] = {2, 3, 4})
assert fromList2 : (fromList [(2 : NAT); 2; 3; 2; 4] = {2, 3, 4})
assert fromList3 : (fromList ([] : LIST NAT) = {})

```

```

(* ----- *)
(* Sigma *)
(* ----- *)

val sigma : ∀ α β. SetType α, SetType β ⇒ SET α → (α → SET β) → SET (α * β)
val sigmaBy : ∀ α β. ((α * β) → (α * β) → ORDERING) → SET α → (α → SET β) → SET (α * β)

declare ocaml target_rep function sigmaBy = 'Pset.sigma'

let sigma sa sb = { (a, b) | ∀ a ∈ sa b ∈ sb a | true }
let inline {ocaml} sigma = sigmaBy setElemCompare

declare isabelle target_rep function sigma = 'Sigma'
declare coq target_rep function sigmaBy = 'set_sigma_by'
let inline {coq} sigma = sigmaBy setElemCompare
declare hol target_rep function sigma = 'SET.SIGMA'

assert Sigma1 : (sigma {(2 : NAT), 3} (fun n → {n*2, n * 3}) = {(2, 4), (2, 6), (3, 6), (3, 9)})
lemma Sigma2 : (∀ sa sb a b. ((a, b) ∈ sigma sa sb) ↔ ((a ∈ sa) ∧ (b ∈ sb a)))

(* ----- *)
(* cross product *)
(* ----- *)

val cross : ∀ α β. SetType α, SetType β ⇒ SET α → SET β → SET (α * β)
val crossBy : ∀ α β. ((α * β) → (α * β) → ORDERING) → SET α → SET β → SET (α * β)

declare ocaml target_rep function crossBy = 'Pset.cross'

let cross s1 s2 = { (e1, e2) | ∀ e1 ∈ s1 e2 ∈ s2 | true }

declare isabelle target_rep function cross = infix '\<times>'
declare hol target_rep function cross = infix 'CROSS'
declare tex target_rep function cross = infix '$\times$'
let inline {ocaml} cross = crossBy setElemCompare

lemma cross_by_sigma : ∀ s1 s2. s1 × s2 = sigma s1 (const s2)
assert cross1 : ({(2 : NAT), 3} × {true, false} = {(2, true), (3, true), (2, false), (3, false)})

(* ----- *)
(* finite *)
(* ----- *)

val finite : ∀ α. SetType α ⇒ SET α → BOOL

let inline {ocaml, coq} finite _s = true
declare hol target_rep function finite = 'FINITE'
declare isabelle target_rep function finite = 'finite'

(* ----- *)
(* fixed point *)
(* ----- *)

val leastFixedPoint : ∀ α. SetType α

```



```

⇒ NAT → (SET α → SET α) → SET α → SET α
let rec leastFixedPoint bound f x =
  match bound with
  | 0 → x
  | bound' + 1 → let fx = f x in
    if fx ⊆ x then x
    else leastFixedPoint bound' f (fx ∪ x)
end

declare {isabelle} termination_argument leastFixedPoint = automatic

assert lfp_empty0 : leastFixedPoint 0 (map (fun x → x)) ({ } : SET NAT) = { }
assert lfp_empty1 : leastFixedPoint 1 (map (fun x → x)) ({ } : SET NAT) = { }
assert lfp_saturate_neg1 : leastFixedPoint 1 (map (fun x → -x)) ({1, 2, 3} : SET INT) = {-3, -2, -1, 1, 2, 3}

assert lfp_saturate_neg2 : leastFixedPoint 2 (map (fun x → -x)) ({1, 2, 3} : SET INT) = {-3, -2, -1, 1, 2, 3}

assert lfp_saturate_mod3 : leastFixedPoint 3 (map (fun x → (2*x) mod 5)) ({1} : SET NAT) = {1, 2, 3, 4}

assert lfp_saturate_mod4 : leastFixedPoint 4 (map (fun x → (2*x) mod 5)) ({1} : SET NAT) = {1, 2, 3, 4}

assert lfp_saturate_mod5 : leastFixedPoint 5 (map (fun x → (2*x) mod 5)) ({1} : SET NAT) = {1, 2, 3, 4}

assert lfp_termination : {1, 3, 5, 7, 9} ⊆ leastFixedPoint 5 (map (fun x → 2+x)) {(1 :  $\mathbb{N}$ )}
```

## 11 Map

```

(*****
(* A library for finite maps *)
(*****)

(* ===== *)
(* Header *)
(* ===== *)

declare {isabelle, ocaml, hol, coq} rename module = lem_map

open import Bool Basic_classes Function Maybe List Tuple Set Num
open import {hol} finite_mapTheory finite_mapLib

type MAP 'k 'v
declare ocaml target_rep type MAP = 'Pmap.map'
declare isabelle target_rep type MAP = 'Map.map'
declare hol target_rep type MAP = 'fmap'
declare coq target_rep type MAP = 'fmap'

(* ----- *)
(* Map equality. *)
(* ----- *)

val mapEqual : ∀ 'k 'v. Eq 'k, Eq 'v ⇒ MAP 'k 'v → MAP 'k 'v → BOOL
val mapEqualBy : ∀ 'k 'v. ('k → 'k → BOOL) → ('v → 'v → BOOL) → MAP 'k 'v → MAP 'k 'v → BOOL

declare ocaml target_rep function mapEqualBy eq_k eq_v = 'Pmap.equal' eq_v
declare coq target_rep function mapEqualBy = 'fmap.equal.by'
let inline ~{hol, isabelle} mapEqual = mapEqualBy (=) (=)
let inline {hol, isabelle} mapEqual = unsafe_structural_equality

instance ∀ 'k 'v. Eq 'k, Eq 'v ⇒ (Eq (MAP 'k 'v))
  let == mapEqual
  let <> m1 m2 = ¬ (mapEqual m1 m2)
end

(* ----- *)
(* Map type class *)
(* ----- *)

class ( MapKeyType α )
  val {ocaml, coq} mapKeyCompare : α → α → ORDERING
end

default_instance ∀ α. SetType α ⇒ ( MapKeyType α )
  let mapKeyCompare = setElemCompare
end

(* ----- *)
(* Empty maps *)
(* ----- *)

```

```

val empty :  $\forall 'k 'v. \text{MapKeyType } 'k \Rightarrow \text{MAP } 'k 'v$ 
val emptyBy :  $\forall 'k 'v. ('k \rightarrow 'k \rightarrow \text{ORDERING}) \rightarrow \text{MAP } 'k 'v$ 

```

```

declare ocaml target_rep function emptyBy = 'Pmap.empty'

```

```

let inline {ocaml} empty = emptyBy mapKeyCompare
declare coq target_rep function empty = 'fmap.empty'
declare hol target_rep function empty = 'FEMPTY'
declare isabelle target_rep function empty = 'Map.empty'

```

```

(* -----
(* Insertion *)
(* -----

```

```

val insert :  $\forall 'k 'v. \text{MapKeyType } 'k \Rightarrow 'k \rightarrow 'v \rightarrow \text{MAP } 'k 'v \rightarrow \text{MAP } 'k 'v$ 

```

```

declare coq target_rep function insert = 'fmap.add'
declare ocaml target_rep function insert = 'Pmap.add'
(* declare hol      target_rep function insert k v m = 'FUPDATE' m (k, v) *)
declare hol target_rep function insert k v m = special "%e |+ (%e, %e)" m k v
declare isabelle target_rep function insert = 'map.update'

```

```

(* -----
(* Singleton *)
(* -----

```

```

val singleton :  $\forall 'k 'v. \text{MapKeyType } 'k \Rightarrow 'k \rightarrow 'v \rightarrow \text{MAP } 'k 'v$ 
let inline singleton k v = insert k v empty

```

```

assert insert_equal_singleton : (mapEqual (insert (42 : NAT) false empty)
                                     (singleton 42 false))
assert commutative_insert1 : (mapEqual
    (insert (8 : NAT) true (insert 5 false empty))
    (insert 5 false (insert 8 true empty)))
assert commutative_insert2 : ( $\neg$  (mapEqual
    (insert (8 : NAT) true (insert 8 false empty))
    (insert 8 false (insert 8 true empty))))

```

```

(* -----
(* Emptiness check *)
(* -----

```

```

val null :  $\forall 'k 'v. \text{MapKeyType } 'k, \text{Eq } 'k, \text{Eq } 'v \Rightarrow \text{MAP } 'k 'v \rightarrow \text{BOOL}$ 
let inline null m = (m = empty)

```

```

declare coq target_rep function null = 'fmap.is_empty'
declare ocaml target_rep function null = 'Pmap.is_empty'

```

```

assert empty_null : (null (empty : MAP NAT BOOL))

```

```

(* -----
(* lookup *)
(* -----

```

```

(* -----

val lookupBy : ∀ 'k 'v. ('k → 'k → ORDERING) → 'k → MAP 'k 'v → MAYBE 'v
declare coq target_rep function lookupBy = 'fmap_lookup_by'

val lookup : ∀ 'k 'v. MapKeyType 'k ⇒ 'k → MAP 'k 'v → MAYBE 'v
let inline {coq} lookup = lookupBy mapKeyCompare
declare isabelle target_rep function lookup k m = ''m k
declare hol target_rep function lookup k m = 'FLOOKUP' m k
declare ocaml target_rep function lookup = 'Pmap.lookup'

assert lookup_insert1 : (lookup 16 (insert (16 : NAT) true empty) = Just true)
assert lookup_insert2 : (lookup 16 (insert 36 false (insert (16 : NAT) true empty)) = Just true )
assert lookup_insert3 : (lookup 36 (insert 36 false (insert (16 : NAT) true empty)) = Just false )

assert lookup_empty0 : (lookup 25 (empty : MAP NAT BOOL) = Nothing)
assert find_insert0 : (lookup 16 (insert (16 : NAT) true empty) = Just true)

lemma lookup_empty : (∀ k. lookup k empty = Nothing)
lemma lookup_insert : (∀ k k' v m. lookup k (insert k' v m) = (if (k = k') then Just v else lookup k m))

(* -----
(* findWithDefault
*)
(* -----

val findWithDefault : ∀ 'k 'v. MapKeyType 'k ⇒ 'k → 'v → MAP 'k 'v → 'v
let inline findWithDefault k v m = fromMaybe v (lookup k m)

(* -----
(* from lists
*)
(* -----

val fromList : ∀ 'k 'v. MapKeyType 'k ⇒ LIST ('k * 'v) → MAP 'k 'v
let fromList l = foldl (fun m (k, v) → insert k v m) empty l

declare isabelle target_rep function fromList l = 'Map.map_of' (reverse l)
declare hol target_rep function fromList l = 'FUPDATE_LIST' 'FEMPTY' l

assert fromList0 : (fromList [((2 : NAT), true);((3 : NAT), true);((4 : NAT), false)] =
  fromList [((4 : NAT), false);((3 : NAT), true);((2 : NAT), true)])
(* later entries have priority *)
assert fromList1 : (fromList [((2 : NAT), true);((2 : NAT), false);((3 : NAT), true);((4 : NAT), false)] =
  fromList [((4 : NAT), false);((3 : NAT), true);((2 : NAT), false)])

(* -----
(* to sets / domain / range
*)
(* -----

val toSet : ∀ 'k 'v. MapKeyType 'k, SetType 'k, SetType 'v ⇒ MAP 'k 'v → SET ('k * 'v)
val toSetBy : ∀ 'k 'v. (('k * 'v) → ('k * 'v) → ORDERING) → MAP 'k 'v → SET ('k * 'v)

declare ocaml target_rep function toSetBy = 'Pmap.bindings'
let inline {ocaml} toSet = toSetBy setElemCompare
declare isabelle target_rep function toSet = 'map_to_set'
declare hol target_rep function toSet = 'FMAP_TO_SET'
declare coq target_rep function toSet = 'id'

```

```

assert toSet0 : (toSet (empty : MAP NAT BOOL) = {})
assert toSet1 : (toSet (fromList [(2 : NAT), true]; (3, true); (4, false))) =
  {(2, true), (3, true), (4, false)}
assert toSet2 : (toSet (fromList [(2 : NAT), true]; (3, true); (2, false); (4, false))) =
  {(2, false), (3, true), (4, false)}

```

```

val domainBy : ∀ 'k 'v. ('k → 'k → ORDERING) → MAP 'k 'v → SET 'k
val domain : ∀ 'k 'v. MapKeyType 'k, SetType 'k ⇒ MAP 'k 'v → SET 'k
declare ocaml target_rep function domain = 'Pmap.domain'
declare isabelle target_rep function domain = 'Map.dom'
declare hol target_rep function domain = 'FDOM'
declare coq target_rep function domainBy = 'fmap_domain_by'
let inline {coq} domain = domainBy setElemCompare

```

```

assert domain0 : (domain (empty : MAP NAT BOOL) = {})
assert domain1 : (domain (fromList [(2 : NAT), true]; (3, true); (4, false))) =
  {2, 3, 4}
assert domain2 : (domain (fromList [(2 : NAT), true]; (3, true); (2, false); (4, false))) =
  {2, 3, 4}

```

```

val range : ∀ 'k 'v. MapKeyType 'k, SetType 'v ⇒ MAP 'k 'v → SET 'v
val rangeBy : ∀ 'k 'v. ('v → 'v → ORDERING) → MAP 'k 'v → SET 'v

```

```

declare ocaml target_rep function rangeBy = 'Pmap.range'
declare hol target_rep function range = 'FRANGE'
declare isabelle target_rep function range = 'Map.ran'
declare coq target_rep function rangeBy = 'fmap_range_by'
let inline {ocaml, coq} range = rangeBy setElemCompare

```

```

assert range0 : (range (empty : MAP NAT BOOL) = {})
assert range1 : (range (fromList [(2 : NAT), true]; (3, true); (4, false))) =
  {true, false}
assert range2 : (range (fromList [(2 : NAT), true]; (3, true); (4, true))) = {true}

```

```

(* ----- *)
(* member *)
(* ----- *)

```

```

val member : ∀ 'k 'v. MapKeyType 'k, SetType 'k, Eq 'k ⇒ 'k → MAP 'k 'v → BOOL
let inline member k m = k ∈ domain m
declare ocaml target_rep function member = 'Pmap.mem'

```

```

val notMember : ∀ 'k 'v. MapKeyType 'k, SetType 'k, Eq 'k ⇒ 'k → MAP 'k 'v → BOOL
let inline notMember k m = ¬ (member k m)

```

```

assert member_insert1 : (member 16 (insert (16 : NAT) true empty))
assert member_insert2 : (¬ (member 25 (insert (16 : NAT) true empty)))
assert member_insert3 : (member 16 (insert 36 false (insert (16 : NAT) true empty)))

```

```

lemma member_empty : (∀ k. ¬ (member k empty))
lemma member_insert : (∀ k k' v m. member k (insert k' v m) = ((k = k') ∨ member k m))

```

```

(* ----- *)
(* Quantification *)

```

```

(* -----

val any :  $\forall 'k 'v. \text{MapKeyType } 'k, \text{Eq } 'v \Rightarrow ('k \rightarrow 'v \rightarrow \text{BOOL}) \rightarrow \text{MAP } 'k 'v \rightarrow \text{BOOL}$ 
val all :  $\forall 'k 'v. \text{MapKeyType } 'k, \text{Eq } 'v \Rightarrow ('k \rightarrow 'v \rightarrow \text{BOOL}) \rightarrow \text{MAP } 'k 'v \rightarrow \text{BOOL}$ 

let all P m = ( $\forall k v. (P k v \wedge (\text{lookup } k m = \text{Just } v))$ )
let inline any P m =  $\neg (\text{all } (\text{fun } k v \rightarrow \neg (P k v)) m)$ 

declare ocaml target_rep function any = 'Pmap.exist'
declare ocaml target_rep function all = 'Pmap.for_all'
declare coq target_rep function all = 'fmap_all'
declare isabelle target_rep function any = 'map_any'
declare isabelle target_rep function all = 'map_all'
declare hol target_rep function all P = 'FEVERY' (uncurry P)

assert any0 : (any (fun _k v  $\rightarrow v$ ) (insert 36 false (insert (16 : NAT) true empty)))
assert any1 : ( $\neg$  (any (fun _k v  $\rightarrow v$ ) (insert 36 false (insert (16 : NAT) false empty))))
assert any2 : (any (fun _k v  $\rightarrow \neg v$ ) (insert 36 false (insert (16 : NAT) true empty)))
assert any3 : ( $\neg$  (any (fun _k v  $\rightarrow \neg v$ ) (insert 36 true (insert (16 : NAT) true empty))))

assert all0 : (all (fun _k v  $\rightarrow v$ ) (insert 36 true (insert (16 : NAT) true empty)))
assert all1 : ( $\neg$  (all (fun _k v  $\rightarrow v$ ) (insert 36 true (insert (16 : NAT) false empty))))
assert all2 : (all (fun _k v  $\rightarrow \neg v$ ) (insert 36 false (insert (16 : NAT) false empty)))
assert all3 : ( $\neg$  (all (fun _k v  $\rightarrow \neg v$ ) (insert 36 false (insert (16 : NAT) true empty))))

(* -----
(* Set-like operations. *)
(* -----

val deleteBy :  $\forall 'k 'v. ('k \rightarrow 'k \rightarrow \text{ORDERING}) \rightarrow 'k \rightarrow \text{MAP } 'k 'v \rightarrow \text{MAP } 'k 'v$ 
val delete :  $\forall 'k 'v. \text{MapKeyType } 'k \Rightarrow 'k \rightarrow \text{MAP } 'k 'v \rightarrow \text{MAP } 'k 'v$ 
val deleteSwap :  $\forall 'k 'v. \text{MapKeyType } 'k \Rightarrow \text{MAP } 'k 'v \rightarrow 'k \rightarrow \text{MAP } 'k 'v$ 

declare coq target_rep function deleteBy = 'fmap.delete.by'
declare ocaml target_rep function delete = 'Pmap.remove'
declare isabelle target_rep function delete = 'map_remove'
declare hol target_rep function deleteSwap = infix '\\\
let inline {hol} delete k m = deleteSwap m k
let inline {coq} delete = deleteBy mapKeyCompare
let inline {coq} deleteSwap m k = delete k m

assert delete_insert1 : ( $\neg$  (member (5 : NAT) (delete 5 (insert 5 true empty))))
assert delete_insert2 : (member (7 : NAT) (delete 5 (insert 7 true empty)))
assert delete_delete : (null (delete (5 : NAT) (delete (5 : NAT) (insert 5 true empty))))

val union :  $\forall 'k 'v. \text{MapKeyType } 'k \Rightarrow \text{MAP } 'k 'v \rightarrow \text{MAP } 'k 'v \rightarrow \text{MAP } 'k 'v$ 
declare coq target_rep function union = ('@' 'List.app' '_')
declare ocaml target_rep function union = 'Pmap.union'
declare isabelle target_rep function union = infix '++'
declare hol target_rep function union = 'FUNION'

val unions :  $\forall 'k 'v. \text{MapKeyType } 'k \Rightarrow \text{LIST } (\text{MAP } 'k 'v) \rightarrow \text{MAP } 'k 'v$ 
let inline unions = foldr (union) empty

(* -----
(* Maps (in the functor sense). *)
(* -----

```

```

val map : ∀ 'k 'v 'w. MapKeyType 'k ⇒ ('v → 'w) → MAP 'k 'v → MAP 'k 'w

declare hol target_rep function map = infix 'o_f'
declare coq target_rep function map = 'fmap_map'
declare ocaml target_rep function map = 'Pmap.map'
declare isabelle target_rep function map = 'map_image'

assert map0 : (map (fun b → ¬ b) (insert (2 : NAT) true (insert (3 : NAT) false empty))) =
  insert (2 : NAT) false (insert (3 : NAT) true empty))

val mapi : ∀ 'k 'v 'w. MapKeyType 'k ⇒ ('k → 'v → 'w) → MAP 'k 'v → MAP 'k 'w

(* TODO: add Coq *)
declare ocaml target_rep function mapi = 'Pmap.mapi'
declare isabelle target_rep function mapi = 'map_domain_image'
declare compile_message mapi = "Map.mapi is only defined for the ocaml backend"

(* ----- *)
(* Cardinality *)
(* ----- *)
val size : ∀ 'k 'v. MapKeyType 'k, SetType 'k ⇒ MAP 'k 'v → NAT
let inline size m = Set.size (domain m)

declare ocaml target_rep function size = 'Pmap.cardinal'
declare hol target_rep function size = 'FCARD'

assert empty_size : (size (empty : MAP NAT BOOL) = 0)
assert singleton_size : (size (singleton (2 : NAT) (3 : NAT)) = 1)

(* instance of SetType *)
let map_setElemCompare cmp x y =
  cmp (toSet x) (toSet y)

instance ∀ α β. SetType α, SetType β, MapKeyType α ⇒ (SetType (MAP α β))
  let setElemCompare x y = map_setElemCompare setElemCompare x y
end

```

## 12 Relation

```

(*****
(* A library for binary relations *)
(*****)

(* ===== *)
(* Header *)
(* ===== *)

declare {isabelle, ocaml, hol, coq} rename module = lem_relation

open import Bool Basic_classes Tuple Set Num
open import {hol} set_relationTheory

(* ===== *)
(* The type of relations *)
(* ===== *)

type REL_PRED  $\alpha$   $\beta$  =  $\alpha \rightarrow \beta \rightarrow \text{BOOL}$ 
type REL_SET  $\alpha$   $\beta$  = SET ( $\alpha * \beta$ )

(* Binary relations are usually represented as either sets of pairs (rel_set) or as curried functions (rel_p) *)

type REL  $\alpha$   $\beta$  = REL_SET  $\alpha$   $\beta$ 

val relToSet :  $\forall \alpha \beta. \text{SetType } \alpha, \text{SetType } \beta \Rightarrow \text{REL } \alpha \beta \rightarrow \text{REL\_SET } \alpha \beta$ 
val relFromSet :  $\forall \alpha \beta. \text{SetType } \alpha, \text{SetType } \beta \Rightarrow \text{REL\_SET } \alpha \beta \rightarrow \text{REL } \alpha \beta$ 

let inline relToSet s = s
let inline relFromSet r = r

declare tex target_rep function relFromSet r = r

val relEq :  $\forall \alpha \beta. \text{SetType } \alpha, \text{SetType } \beta \Rightarrow \text{REL } \alpha \beta \rightarrow \text{REL } \alpha \beta \rightarrow \text{BOOL}$ 
let relEq  $r_1$   $r_2$  = (relToSet  $r_1$  = relToSet  $r_2$ )

(*instance forall 'a 'b. SetType 'a, SetType 'b => (Eq (rel 'a 'b)) let (=) = relEqend*)

lemma relToSet_inv : ( $\forall r. (\text{relToSet } r) = r$ )

val relToPred :  $\forall \alpha \beta. \text{SetType } \alpha, \text{SetType } \beta, \text{Eq } \alpha, \text{Eq } \beta \Rightarrow \text{REL } \alpha \beta \rightarrow \text{REL\_PRED } \alpha \beta$ 
val relFromPred :  $\forall \alpha \beta. \text{SetType } \alpha, \text{SetType } \beta, \text{Eq } \alpha, \text{Eq } \beta \Rightarrow \text{SET } \alpha \rightarrow \text{SET } \beta \rightarrow \text{REL\_PRED } \alpha \beta \rightarrow \text{REL } \alpha \beta$ 

let relToPred r = (fun x y  $\rightarrow (x, y) \in \text{relToSet } r$ )
let relFromPred xs ys p = Set.filter (fun (x, y)  $\rightarrow p$  x y) (xs  $\times$  ys)

let inline {hol} relToPred r x y = (x, y)  $\in$  relToSet r
declare {hol} rename function relToPred = rel_to_pred

assert rel_basic_0 : {((2 : NAT), (3 : NAT)), (3, 4)} = relFromPred {2, 3} {1, 2, 3, 4, 5, 6} (fun x y  $\rightarrow y = x + 1$ )
assert rel_basic_1 : relToSet ({((2 : NAT), (3 : NAT)), (3, 4)}) = {(2, 3), (3, 4)}
assert rel_basic_2 : relToPred ({((2 : NAT), (3 : NAT)), (3, 4)}) 2 3

(* ===== *)

```



```

(* Basic Operations *)
(* ===== *)

(* ----- *)
(* membership test *)
(* ----- *)

val inRel :  $\forall \alpha \beta. \text{SetType } \alpha, \text{SetType } \beta, \text{Eq } \alpha, \text{Eq } \beta \Rightarrow \alpha \rightarrow \beta \rightarrow \text{REL } \alpha \beta \rightarrow \text{BOOL}$ 
let inline inRel a b rel = (a, b)  $\in$  relToSet rel

lemma inRel_set : ( $\forall s a b. \text{inRel } a b (s) = ((a, b) \in s)$ )
lemma inRel_pred : ( $\forall p a b sa sb. \text{inRel } a b (\text{relFromPred } sa sb p) = p a b \wedge a \in sa \wedge b \in sb$ )

assert in_rel0 : (inRel 2 3 {((2 : NAT), (3 : NAT)), (4, 5)})
assert in_rel1 : (inRel 4 5 {((2 : NAT), (3 : NAT)), (4, 5)})
assert in_rel2 :  $\neg$  (inRel 3 2 {((2 : NAT), (3 : NAT)), (4, 5)})
assert in_rel3 :  $\neg$  (inRel 7 4 {((2 : NAT), (3 : NAT)), (4, 5)})

(* ----- *)
(* empty relation *)
(* ----- *)

val relEmpty :  $\forall \alpha \beta. \text{SetType } \alpha, \text{SetType } \beta \Rightarrow \text{REL } \alpha \beta$ 
let inline relEmpty = {}
declare tex target_rep function relEmpty = '$\emptyset$'

assert relEmpty0 : relToSet  $\emptyset$  = ({ } : SET (NAT * NAT))
assert relEmpty1 :  $\neg$  (inRel true (2 : NAT)  $\emptyset$ )

(* ----- *)
(* Insertion *)
(* ----- *)

val relAdd :  $\forall \alpha \beta. \text{SetType } \alpha, \text{SetType } \beta \Rightarrow \alpha \rightarrow \beta \rightarrow \text{REL } \alpha \beta \rightarrow \text{REL } \alpha \beta$ 
let inline relAdd a b r = (insert (a, b) (relToSet r))

assert relAdd0 : inRel (2 : NAT) (3 : NAT) (relAdd 2 3  $\emptyset$ )
assert relAdd1 : inRel (4 : NAT) (5 : NAT) (relAdd 2 3 (relAdd 4 5  $\emptyset$ ))
assert relAdd2 :  $\neg$  (inRel (2 : NAT) (5 : NAT) (relAdd 2 3 (relAdd 4 5  $\emptyset$ )))
assert relAdd3 :  $\neg$  (inRel (4 : NAT) (9 : NAT) (relAdd 2 3 (relAdd 4 5  $\emptyset$ )))

lemma in_relAdd : ( $\forall a b a' b' r. \text{inRel } a b (\text{relAdd } a' b' r) =$ 
  ( $((a = a') \wedge (b = b')) \vee \text{inRel } a b r$ )

(* ----- *)
(* Identity relation *)
(* ----- *)

val relIdOn :  $\forall \alpha. \text{SetType } \alpha, \text{Eq } \alpha \Rightarrow \text{SET } \alpha \rightarrow \text{REL } \alpha \alpha$ 
let relIdOn s = relFromPred s s (=)

val relId :  $\forall \alpha. \text{SetType } \alpha, \text{Eq } \alpha \Rightarrow \text{REL } \alpha \alpha$ 
let  $\sim \{coq, ocaml, isabelle\}$  relId = {(x, x) |  $\forall x$  | true}

declare isabelle target_rep function relId = 'Id'

```

```

lemma relId_spec : (∀ x y s. (inRel x y (relIdOn s) ↔ (x ∈ s ∧ (x = y))))

assert rel_id0 : inRel (0 : NAT) 0 (relIdOn {0, 1, 2, 3})
assert rel_id1 : inRel (2 : NAT) 2 (relIdOn {0, 1, 2, 3})
assert rel_id2 : ¬ (inRel (5 : NAT) 5 (relIdOn {0, 1, 2, 3}))
assert rel_id3 : ¬ (inRel (0 : NAT) 2 (relIdOn {0, 1, 2, 3}))

(* ----- *)
(* relation union      *)
(* ----- *)

val relUnion : ∀ α β. SetType α, SetType β ⇒ REL α β → REL α β → REL α β
let inline relUnion r1 r2 = ((relToSet r1) ∪ (relToSet r2))
declare tex target_rep function relUnion = infix '$\cup$'

lemma in_rel_union : (∀ a b r1 r2. inRel a b (r1 ∪ r2) = inRel a b r1 ∨ inRel a b r2)
assert rel_union0 : (relAdd (2 : NAT) true ∅) ∪ (relAdd 5 false ∅) =
  {(5, false), (2, true)}

(* ----- *)
(* relation intersection *)
(* ----- *)

val relIntersection : ∀ α β. SetType α, SetType β, Eq α, Eq β ⇒ REL α β → REL α β → REL α β
let inline relIntersection r1 r2 = ((relToSet r1) ∩ (relToSet r2))
declare tex target_rep function relIntersection = infix '$\cap$'

lemma in_rel_inter : (∀ a b r1 r2. inRel a b (r1 ∩ r2) = inRel a b r1 ∧ inRel a b r2)
assert rel_inter0 : (relAdd (2 : NAT) true (relAdd 7 false ∅)) ∩
  (relAdd 7 false (relAdd 2 false ∅)) =
  {(7, false)}

(* ----- *)
(* Relation Composition *)
(* ----- *)

val relComp : ∀ α β γ. SetType α, SetType β, SetType γ, Eq α, Eq β ⇒ REL α β → REL β γ → REL α γ

let relComp r1 r2 = {(e1, e3) | ∀ (e1, e2) ∈ (relToSet r1) (e2', e3) ∈ (relToSet r2) | e2 = e2'}

declare hol target_rep function relComp = 'rcomp'
declare isabelle target_rep function relComp = infix 'o'

lemma rel_comp1 : (∀ r1 r2 e1 e2 e3. (inRel e1 e2 r1 ∧ inRel e2 e3 r2) → inRel e1 e3 (relComp r1 r2))
lemma ~{coq, ocaml} rel_comp2 : (∀ r. (relComp r relId = r) ∧ (relComp relId r = r))
lemma rel_comp3 : (∀ r. (relComp r ∅ = ∅) ∧ (relComp ∅ r = ∅))

assert rel_comp0 : (relComp ({((2 : NAT), (4 : NAT)), (2, 8)}) ({(4, (3 : NAT)), (2, 8)}) =
  {(2, 3)})

(* ----- *)
(* restrict            *)
(* ----- *)

val relRestrict : ∀ α. SetType α, Eq α ⇒ REL α α → SET α → REL α α
let relRestrict r s = {(a, b) | ∀ a ∈ s b ∈ s | inRel a b r}

declare hol target_rep function relRestrict = 'rrestrict'

```

```
assert rel_restrict0 : (relRestrict ({((2 : NAT), (4 : NAT)), (2, 2), (2, 8)}) {2, 8} =
  {(2, 8), (2, 2)})
```

```
lemma rel_restrict_empty : (∀ r. relRestrict r {} = ∅)
lemma rel_restrict_rel_empty : (∀ s. relRestrict ∅ s = ∅)
lemma rel_restrict_rel_add : (∀ r x y s. relRestrict (relAdd x y r) s =
  if ((x ∈ s) ∧ (y ∈ s)) then relAdd x y (relRestrict r s) else relRestrict r s)
```

```
(* ----- *)
(* Converse      *)
(* ----- *)
```

```
val relConverse : ∀ α β. SetType α, SetType β ⇒ REL α β → REL β α
let relConverse r = (Set.map swap (relToSet r))
```

```
declare {hol} rename function relConverse = lem_converse
declare isabelle target_rep function relConverse = 'converse'
```

```
assert rel_converse0 : relConverse ({((2 : NAT), (3 : NAT)), (3, 4), (4, 5)}) =
  {(3, 2), (4, 3), (5, 4)}
lemma rel_converse_empty : relConverse ∅ = ∅
lemma rel_converse_add : ∀ x y r. relConverse (relAdd x y r) = relAdd y x (relConverse r)
lemma rel_converse_converse : ∀ r. relConverse (relConverse r) = r
```

```
(* ----- *)
(* domain        *)
(* ----- *)
```

```
val relDomain : ∀ α β. SetType α, SetType β ⇒ REL α β → SET α
let relDomain r = Set.map (fun x → fst x) (relToSet r)
```

```
declare tex target_rep function relDomain = 'dom'
declare hol target_rep function relDomain = 'domain'
declare isabelle target_rep function relDomain = 'Domain'
```

```
assert rel_domain0 : dom ({((2 : NAT), (3 : NAT)), (3, 4), (4, 5)}) = {2, 3, 4}
assert rel_domain1 : dom ({((5 : NAT), (3 : NAT)), (3, 4), (4, 5)}) = {3, 4, 5}
assert rel_domain2 : dom ({((3 : NAT), (3 : NAT)), (3, 4), (4, 5)}) = {3, 4}
```

```
(* ----- *)
(* range          *)
(* ----- *)
```

```
val relRange : ∀ α β. SetType α, SetType β ⇒ REL α β → SET β
let relRange r = Set.map (fun x → snd x) (relToSet r)
```

```
declare tex target_rep function relRange = 'rng'
declare hol target_rep function relRange = 'range'
declare isabelle target_rep function relRange = 'Range'
```

```
assert rel_range0 : rng ({((2 : NAT), (3 : NAT)), (3, 4), (4, 5)}) = {3, 4, 5}
assert rel_range1 : rng ({((5 : NAT), (6 : NAT)), (3, 4), (4, 5)}) = {4, 5, 6}
assert rel_range2 : rng ({((3 : NAT), (5 : NAT)), (3, 4), (4, 5)}) = {4, 5}
```

```

(* ----- *)
(* field / definedOn      *)
(* ----- *)
(* avoid the keyword field *)
(* ----- *)

```

```

val relDefinedOn :  $\forall \alpha. \text{SetType } \alpha \Rightarrow \text{REL } \alpha \ \alpha \rightarrow \text{SET } \alpha$ 
let inline relDefinedOn r = ((dom r)  $\cup$  (rng r))

```

```

declare {hol} rename function relDefinedOn = rdefined_on

```

```

assert rel_field0 : relDefinedOn ({((2 : NAT), (3 : NAT)), (3, 4), (4, 5)}) = {2, 3, 4, 5}
assert rel_field1 : relDefinedOn ({((5 : NAT), (6 : NAT)), (3, 4), (4, 5)}) = {3, 4, 5, 6}
assert rel_field2 : relDefinedOn ({((3 : NAT), (5 : NAT)), (3, 4), (4, 5)}) = {3, 4, 5}

```

```

(* ----- *)
(* relOver                *)
(* ----- *)
(* avoid the keyword field *)
(* ----- *)

```

```

val relOver :  $\forall \alpha. \text{SetType } \alpha \Rightarrow \text{REL } \alpha \ \alpha \rightarrow \text{SET } \alpha \rightarrow \text{BOOL}$ 
let relOver r s = ((relDefinedOn r)  $\subseteq$  s)

```

```

declare {hol} rename function relOver = rel_over

```

```

assert rel_over0 : relOver ({((2 : NAT), (3 : NAT)), (3, 4), (4, 5)}) {2, 3, 4, 5}
assert rel_over1 :  $\neg$  (relOver ({((2 : NAT), (3 : NAT)), (3, 4), (4, 5)}) {3, 4, 5})

```

```

lemma rel_over_empty :  $\forall s. \text{relOver } \emptyset \ s$ 
lemma rel_over_add :  $\forall x \ y \ s \ r. \text{relOver } (\text{relAdd } x \ y \ r) \ s = (x \in s \wedge y \in s \wedge \text{relOver } r \ s)$ 

```

```

(* ----- *)
(* apply a relation       *)
(* ----- *)

```

(\* Given a relation r and a set s, relApply r s applies s to r, i.e. it returns the set of all value reachable

```

val relApply :  $\forall \alpha \ \beta. \text{SetType } \alpha, \text{SetType } \beta, \text{Eq } \alpha \Rightarrow \text{REL } \alpha \ \beta \rightarrow \text{SET } \alpha \rightarrow \text{SET } \beta$ 
let relApply r s = { y |  $\forall (x, y) \in (\text{relToSet } r) \mid x \in s$  }
declare {hol} rename function relApply = rapply
declare isabelle target_rep function relApply = 'Image'

```

```

assert rel_apply0 : relApply ({((2 : NAT), (3 : NAT)), (3, 4), (4, 5)}) {2, 3} = {3, 4}
assert rel_apply1 : relApply ({((2 : NAT), (3 : NAT)), (3, 7), (3, 5)}) {2, 3} = {3, 5, 7}

```

```

lemma rel_apply_empty_set :  $\forall r. \text{relApply } r \ \{\} = \{\}$ 
lemma rel_apply_empty :  $\forall s. \text{relApply } \emptyset \ s = \{\}$ 
lemma rel_apply_add :  $\forall x \ y \ s \ r. \text{relApply } (\text{relAdd } x \ y \ r) \ s = (\text{if } (x \in s) \text{ then } (\text{insert } y \ (\text{relApply } r \ s)) \text{ else } \text{relApply } r \ s)$ 

```

```

(* ===== *)
(* Properties                                *)
(* ===== *)

```

```

(* ----- *)
(* subrel      *)
(* ----- *)

val isSubrel :  $\forall \alpha \beta. \text{SetType } \alpha, \text{SetType } \beta, \text{Eq } \alpha, \text{Eq } \beta \Rightarrow \text{REL } \alpha \beta \rightarrow \text{REL } \alpha \beta \rightarrow \text{BOOL}$ 
let inline isSubrel  $r_1 r_2 = (\text{relToSet } r_1) \subseteq (\text{relToSet } r_2)$ 

declare {tex} target_rep function isSubrel = infix '$\subseteq$'

lemma is_subrel_empty :  $\forall r. \emptyset \subseteq r$ 
lemma is_subrel_empty2 :  $\forall r. r \subseteq \emptyset = (r = \emptyset)$ 
lemma is_subrel_add :  $\forall x y r_1 r_2. (\text{relAdd } x y r_1) \subseteq r_2 = (\text{inRel } x y r_2 \wedge r_1 \subseteq r_2)$ 

assert is_subrel_0 :  $\emptyset \subseteq \{((2 : \text{NAT}), (3 : \text{NAT})), (3, 4), (4, 5)\}$ 
assert is_subrel_1 :  $\{((2 : \text{NAT}), (3 : \text{NAT})), (3, 4), (4, 5)\} \subseteq \{(2, 3), (3, 4), (4, 5)\}$ 
assert is_subrel_2 :  $\{((2 : \text{NAT}), (3 : \text{NAT})), (4, 5)\} \subseteq \{(2, 3), (3, 4), (4, 5)\}$ 
assert is_subrel_3 :  $\neg (\{((2 : \text{NAT}), (3 : \text{NAT})), (3, 4), (4, 5)\} \subseteq \{(2, 3), (4, 5)\})$ 

(* ----- *)
(* reflexivity  *)
(* ----- *)

val isReflexiveOn :  $\forall \alpha. \text{SetType } \alpha, \text{Eq } \alpha \Rightarrow \text{REL } \alpha \alpha \rightarrow \text{SET } \alpha \rightarrow \text{BOOL}$ 
let isReflexiveOn  $r s = (\forall e \in s. \text{inRel } e e r)$ 

declare {hol} rename function isReflexiveOn = lem_is_reflexive_on

val isReflexive :  $\forall \alpha. \text{SetType } \alpha, \text{Eq } \alpha \Rightarrow \text{REL } \alpha \alpha \rightarrow \text{BOOL}$ 
let  $\sim\{ocaml, coq\}$  isReflexive  $r = (\forall e. \text{inRel } e e r)$ 

declare {hol} rename function isReflexive = lem_is_reflexive
declare isabelle target_rep function isReflexive = 'refl'

assert is_reflexive_on_0 : isReflexiveOn  $(\{((2 : \text{NAT}), (2 : \text{NAT})), (3, 3), (3, 4), (4, 5)\}) \{2, 3\}$ 
assert is_reflexive_on_1 :  $\neg (\text{isReflexiveOn } (\{((2 : \text{NAT}), (2 : \text{NAT})), (3, 3), (3, 4), (4, 5)\}) \{2, 4, 3\})$ 
assert is_reflexive_on_2 :  $\neg (\text{isReflexiveOn } (\{((2 : \text{NAT}), (2 : \text{NAT})), (3, 3), (3, 4), (4, 5)\}) \{5, 2\})$ 

(* ----- *)
(* irreflexivity *)
(* ----- *)

val isIrreflexiveOn :  $\forall \alpha. \text{SetType } \alpha, \text{Eq } \alpha \Rightarrow \text{REL } \alpha \alpha \rightarrow \text{SET } \alpha \rightarrow \text{BOOL}$ 
let isIrreflexiveOn  $r s = (\forall e \in s. \neg (\text{inRel } e e r))$ 

declare {hol} target_rep function isIrreflexiveOn = 'irreflexive'

val isIrreflexive :  $\forall \alpha. \text{SetType } \alpha, \text{Eq } \alpha \Rightarrow \text{REL } \alpha \alpha \rightarrow \text{BOOL}$ 
let isIrreflexive  $r = (\forall (e_1, e_2) \in (\text{relToSet } r). \neg (e_1 = e_2))$ 

declare {hol} rename function isIrreflexive = lem_is_irreflexive
declare isabelle target_rep function isIrreflexive = 'irrefl'

assert is_irreflexive_on_0 : isIrreflexiveOn  $(\{((2 : \text{NAT}), (2 : \text{NAT})), (3, 3), (3, 4), (4, 5)\}) \{4\}$ 
assert is_irreflexive_on_1 :  $\neg (\text{isIrreflexiveOn } (\{((2 : \text{NAT}), (2 : \text{NAT})), (3, 3), (3, 4), (4, 5)\}) \{2, 4\})$ 
assert is_irreflexive_on_2 :  $\neg (\text{isIrreflexiveOn } (\{((2 : \text{NAT}), (2 : \text{NAT})), (3, 3), (3, 4), (4, 5)\}) \{5, 2\})$ 
assert is_irreflexive_on_3 : isIrreflexiveOn  $(\{((2 : \text{NAT}), (2 : \text{NAT})), (3, 3), (3, 4), (4, 5)\}) \{5, 4\}$ 

```

```

assert is_irreflexive_0 : ¬ (isIrreflexive ({((2 : NAT), (2 : NAT)), (3, 3), (3, 4), (4, 5)}))
assert is_irreflexive_1 : isIrreflexive ({((2 : NAT), (3 : NAT)), (3, 4), (4, 5)})

```

```

(* ----- *)
(* symmetry      *)
(* ----- *)

```

```

val isSymmetricOn : ∀ α. SetType α, Eq α ⇒ REL α α → SET α → BOOL
let isSymmetricOn r s = (∀ e₁ ∈ s e₂ ∈ s. (inRel e₁ e₂ r) → (inRel e₂ e₁ r))

```

```

declare {hol} rename function isSymmetricOn = lem_is_symmetric_on

```

```

val isSymmetric : ∀ α. SetType α, Eq α ⇒ REL α α → BOOL
let isSymmetric r = (∀ (e₁, e₂) ∈ relToSet r. inRel e₂ e₁ r)

```

```

declare {hol} rename function isSymmetric = lem_is_symmetric
declare isabelle target_rep function isSymmetric = 'sym'

```

```

assert is_symmetric_on_0 : isSymmetricOn ({((2 : NAT), (2 : NAT)), (3, 3), (3, 4), (4, 5), (5, 4)}) {4}
assert is_symmetric_on_1 : isSymmetricOn ({((2 : NAT), (2 : NAT)), (3, 3), (3, 4), (4, 5), (5, 4)}) {3}
assert is_symmetric_on_2 : ¬ (isSymmetricOn ({((2 : NAT), (2 : NAT)), (3, 3), (3, 4), (4, 5), (5, 4)}) {3, 4})

```

```

assert is_symmetric_0 : ¬ (isSymmetric ({((2 : NAT), (2 : NAT)), (3, 3), (3, 4), (4, 5)}))
assert is_symmetric_1 : isSymmetric ({((2 : NAT), (3 : NAT)), (3, 2), (4, 5), (5, 4)})

```

```

lemma is_symmetric_empty : ∀ r. isSymmetricOn r {}
lemma is_symmetric_sing : ∀ r x. isSymmetricOn r {x}

```

```

(* ----- *)
(* antisymmetry      *)
(* ----- *)

```

```

val isAntisymmetricOn : ∀ α. SetType α, Eq α ⇒ REL α α → SET α → BOOL
let isAntisymmetricOn r s = (∀ e₁ ∈ s e₂ ∈ s. (inRel e₁ e₂ r) → (inRel e₂ e₁ r) → (e₁ = e₂))

```

```

declare {hol} rename function isAntisymmetricOn = lem_is_antisymmetric_on

```

```

val isAntisymmetric : ∀ α. SetType α, Eq α ⇒ REL α α → BOOL
let isAntisymmetric r = (∀ (e₁, e₂) ∈ relToSet r. (inRel e₂ e₁ r) → (e₁ = e₂))

```

```

declare hol target_rep function isAntisymmetric = 'antisym'
declare isabelle target_rep function isAntisymmetric = 'antisym'

```

```

assert is_antisymmetric_on_0 : isAntisymmetricOn ({((2 : NAT), (2 : NAT)), (3, 3), (3, 4), (4, 5), (5, 4)}) {3, 4}

```

```

assert is_antisymmetric_on_1 : ¬ (isAntisymmetricOn ({((2 : NAT), (2 : NAT)), (3, 3), (3, 4), (4, 5), (5, 4)}) {4, 5})

```

```

assert is_antisymmetric_0 : isAntisymmetric ({((2 : NAT), (2 : NAT)), (3, 3), (3, 4), (4, 5)})
assert is_antisymmetric_1 : ¬ (isAntisymmetric ({((2 : NAT), (3 : NAT)), (3, 2), (4, 5), (2, 4)}))

```

```

lemma is_antisymmetric_empty : ∀ r. isAntisymmetricOn r {}
lemma is_antisymmetric_sing : ∀ r x. isAntisymmetricOn r {x}

```

```

(* ----- *)
(* transitivity *)
(* ----- *)

val isTransitiveOn : ∀ α. SetType α, Eq α ⇒ REL α α → SET α → BOOL
let isTransitiveOn r s = (∀ e1 ∈ s e2 ∈ s e3 ∈ s. (inRel e1 e2 r) → (inRel e2 e3 r) → (inRel e1 e3 r))

declare {hol} rename function isTransitiveOn = lem_transitive_on

val isTransitive : ∀ α. SetType α, Eq α ⇒ REL α α → BOOL
let isTransitive r = (∀ (e1, e2) ∈ relToSet r e3 ∈ relApply r {e2}. inRel e1 e3 r)

declare hol target_rep function isTransitive = 'transitive'
declare isabelle target_rep function isTransitive = 'trans'

assert is_transitive_on0 : isTransitiveOn ({((2 : NAT), (3 : NAT)), (3, 4), (2, 4), (4, 5), (5, 4)}) {2, 3, 4}
assert is_transitive_on1 : ¬ (isTransitiveOn ({((2 : NAT), (3 : NAT)), (3, 4), (2, 4), (4, 5), (5, 4)}) {2, 3, 4, 5})

assert is_transitive0 : ¬ (isTransitive ({((2 : NAT), (2 : NAT)), (3, 3), (3, 4), (4, 5)}))
assert is_transitive1 : isTransitive ({((2 : NAT), (3 : NAT)), (3, 4), (2, 4)})

(* ----- *)
(* total *)
(* ----- *)

val isTotalOn : ∀ α. SetType α, Eq α ⇒ REL α α → SET α → BOOL
let isTotalOn r s = (∀ e1 ∈ s e2 ∈ s. (inRel e1 e2 r) ∨ (inRel e2 e1 r))

declare {hol} rename function isTotalOn = lem_is_total_on

val isTotal : ∀ α. SetType α, Eq α ⇒ REL α α → BOOL
let ~{ocaml, coq} isTotal r = (∀ e1 e2. (inRel e1 e2 r) ∨ (inRel e2 e1 r))
declare {hol} rename function isTotal = lem_is_total
declare isabelle target_rep function isTotal = 'total'

val isTrichotomousOn : ∀ α. SetType α, Eq α ⇒ REL α α → SET α → BOOL
let isTrichotomousOn r s = (∀ e1 ∈ s e2 ∈ s. (inRel e1 e2 r) ∨ (e1 = e2) ∨ (inRel e2 e1 r))

declare {hol} rename function isTrichotomousOn = lem_is_trichotomous_on

val isTrichotomous : ∀ α. SetType α, Eq α ⇒ REL α α → BOOL
let ~{ocaml, coq} isTrichotomous r = (∀ e1 e2. (inRel e1 e2 r) ∨ (e1 = e2) ∨ (inRel e2 e1 r))

declare {hol} rename function isTrichotomous = lem_is_trichotomous

assert is_total_on0 : isTotalOn ({((2 : NAT), (3 : NAT)), (3, 4), (3, 3), (4, 4)}) {3, 4}
assert is_total_on1 : ¬ (isTotalOn ({((2 : NAT), (3 : NAT)), (3, 4), (3, 3), (4, 4)}) {2, 4})

assert is_trichotomous_on0 : isTrichotomousOn ({((2 : NAT), (3 : NAT)), (3, 4)}) {3, 4}
assert is_trichotomous_on1 : ¬ (isTrichotomousOn ({((2 : NAT), (3 : NAT)), (3, 4)}) {2, 3, 4})

(* ----- *)
(* is_single_valued *)
(* ----- *)

```

```

val isSingleValued :  $\forall \alpha \beta. \text{SetType } \alpha, \text{SetType } \beta, \text{Eq } \alpha, \text{Eq } \beta \Rightarrow \text{REL } \alpha \beta \rightarrow \text{BOOL}$ 
let isSingleValued r = ( $\forall (e_1, e2a) \in \text{relToSet } r \ e2b \in \text{relApply } r \{e_1\}. e2a = e2b$ )

```

```

declare {hol} rename function isSingleValued = lem_is_single_valued

```

```

assert is_single_valued0 : isSingleValued ({((2 : NAT), (3 : NAT)), (3, 4)})
assert is_single_valued1 :  $\neg$  (isSingleValued ({((2 : NAT), (3 : NAT)), (2, 4), (3, 4)}))

```

```

(* ----- *)
(* equivalence relation *)
(* ----- *)

```

```

val isEquivalenceOn :  $\forall \alpha. \text{SetType } \alpha, \text{Eq } \alpha \Rightarrow \text{REL } \alpha \alpha \rightarrow \text{SET } \alpha \rightarrow \text{BOOL}$ 
let isEquivalenceOn r s = isReflexiveOn r s  $\wedge$  isSymmetricOn r s  $\wedge$  isTransitiveOn r s

```

```

declare {hol} rename function isEquivalenceOn = lem_is_equivalence_on

```

```

val isEquivalence :  $\forall \alpha. \text{SetType } \alpha, \text{Eq } \alpha \Rightarrow \text{REL } \alpha \alpha \rightarrow \text{BOOL}$ 
let  $\sim$ {ocaml, coq} isEquivalence r = isReflexive r  $\wedge$  isSymmetric r  $\wedge$  isTransitive r

```

```

declare {hol} rename function isEquivalence = lem_is_equivalence

```

```

assert is_equivalence0 : isEquivalenceOn ({((2 : NAT), (3 : NAT)), (3, 2), (2, 2), (3, 3), (4, 4)}) {2, 3, 4}
assert is_equivalence1 :  $\neg$  (isEquivalenceOn ({((2 : NAT), (3 : NAT)), (3, 2), (2, 4), (2, 2), (3, 3), (4, 4)}) {2, 3, 4})
assert is_equivalence2 :  $\neg$  (isEquivalenceOn ({((2 : NAT), (3 : NAT)), (3, 2), (2, 2), (3, 3), }) {2, 3, 4})

```

```

(* ----- *)
(* well founded *)
(* ----- *)

```

```

val isWellFounded :  $\forall \alpha. \text{SetType } \alpha, \text{Eq } \alpha \Rightarrow \text{REL } \alpha \alpha \rightarrow \text{BOOL}$ 
let  $\sim$ {ocaml, coq} isWellFounded r = ( $\forall P. (\forall x. (\forall y. \text{inRel } y \ x \ r \longrightarrow P \ x) \longrightarrow P \ x) \longrightarrow (\forall x. P \ x)$ )

```

```

declare hol target_rep function isWellFounded r = 'WF' ('reln_to_rel' r)

```

```

(* ===== *)
(* Orders *)
(* ===== *)

```

```

(* ----- *)
(* pre - or quasiorders *)
(* ----- *)

```

```

val isPreorderOn :  $\forall \alpha. \text{SetType } \alpha, \text{Eq } \alpha \Rightarrow \text{REL } \alpha \alpha \rightarrow \text{SET } \alpha \rightarrow \text{BOOL}$ 
let isPreorderOn r s = isReflexiveOn r s  $\wedge$  isTransitiveOn r s

```

```

declare {hol} rename function isPreorderOn = lem_is_preorder_on

```

```

val isPreorder :  $\forall \alpha. \text{SetType } \alpha, \text{Eq } \alpha \Rightarrow \text{REL } \alpha \alpha \rightarrow \text{BOOL}$ 

```



```

let ~{ocaml, coq} isPreorder r = isReflexive r ∧ isTransitive r

declare {hol} rename function isPreorder = lem_is_preorder

assert is_preorder_0 : isPreorderOn ({((2 : NAT), (3 : NAT)), (3, 2), (2, 2), (3, 3), (4, 4)}) {2, 3, 4}
assert is_preorder_1 : ¬ (isPreorderOn ({((2 : NAT), (3 : NAT)), (2, 2), (3, 3)}) {2, 3, 4})
assert is_preorder_2 : ¬ (isPreorderOn ({((2 : NAT), (3 : NAT)), (3, 4), (2, 2), (3, 3), (4, 4)}) {2, 3, 4})

(* ----- *)
(* partial orders      *)
(* ----- *)

val isPartialOrderOn : ∀ α. SetType α, Eq α ⇒ REL α α → SET α → BOOL
let isPartialOrderOn r s = isReflexiveOn r s ∧ isTransitiveOn r s ∧ isAntisymmetricOn r s

declare {hol} rename function isPartialOrderOn = lem_is_partial_order_on

assert is_partialorder_0 : isPartialOrderOn ({((2 : NAT), (3 : NAT)), (2, 2), (3, 3), (4, 4)}) {2, 3, 4}
assert is_partialorder_1 : ¬ (isPartialOrderOn ({((2 : NAT), (3 : NAT)), (3, 2), (2, 2), (3, 3), (4, 4)}) {2, 3, 4})

assert is_partialorder_2 : ¬ (isPartialOrderOn ({((2 : NAT), (3 : NAT)), (2, 2), (3, 3)}) {2, 3, 4})
assert is_partialorder_3 : ¬ (isPartialOrderOn ({((2 : NAT), (3 : NAT)), (3, 4), (2, 2), (3, 3), (4, 4)}) {2, 3, 4})

val isStrictPartialOrderOn : ∀ α. SetType α, Eq α ⇒ REL α α → SET α → BOOL
let isStrictPartialOrderOn r s = isIrreflexiveOn r s ∧ isTransitiveOn r s

declare {hol} rename function isStrictPartialOrderOn = lem_is_strict_partial_order_on

lemma isStrictPartialOrderOn_antisym : (∀ r s. isStrictPartialOrderOn r s → isAntisymmetricOn r s)

assert is_strict_partialorder_on_0 : isStrictPartialOrderOn ({((2 : NAT), (3 : NAT))}) {2, 3, 4}
assert is_strict_partialorder_on_1 : isStrictPartialOrderOn ({((2 : NAT), (3 : NAT)), (3, 4), (2, 4)}) {2, 3, 4}

assert is_strict_partialorder_on_2 : ¬ (isStrictPartialOrderOn ({((2 : NAT), (3 : NAT)), (3, 4)}) {2, 3, 4})
assert is_strict_partialorder_on_3 : ¬ (isStrictPartialOrderOn ({((2 : NAT), (3 : NAT)), (3, 2)}) {2, 3, 4})
assert is_strict_partialorder_on_4 : ¬ (isStrictPartialOrderOn ({((2 : NAT), (3 : NAT)), (2, 2)}) {2, 3, 4})

val isStrictPartialOrder : ∀ α. SetType α, Eq α ⇒ REL α α → BOOL
let isStrictPartialOrder r = isIrreflexive r ∧ isTransitive r

declare {hol} rename function isStrictPartialOrder = lem_is_strict_partial_order

assert is_strict_partialorder_0 : isStrictPartialOrder ({((2 : NAT), (3 : NAT))})
assert is_strict_partialorder_1 : isStrictPartialOrder ({((2 : NAT), (3 : NAT)), (3, 4), (2, 4)})
assert is_strict_partialorder_2 : ¬ (isStrictPartialOrder ({((2 : NAT), (3 : NAT)), (3, 4)}))
assert is_strict_partialorder_3 : ¬ (isStrictPartialOrder ({((2 : NAT), (3 : NAT)), (3, 2)}))
assert is_strict_partialorder_4 : ¬ (isStrictPartialOrder ({((2 : NAT), (3 : NAT)), (2, 2)}))

val isPartialOrder : ∀ α. SetType α, Eq α ⇒ REL α α → BOOL
let ~{ocaml, coq} isPartialOrder r = isReflexive r ∧ isTransitive r ∧ isAntisymmetric r

declare {hol} rename function isPartialOrder = lem_is_partial_order

(* ----- *)

```

```

(* total / linear orders *)
(* ----- *)

val isTotalOrderOn : ∀ α. SetType α, Eq α ⇒ REL α α → SET α → BOOL
let isTotalOrderOn r s = isPartialOrderOn r s ∧ isTotalOn r s

declare {hol} rename function isTotalOrderOn = lem_is_total_order_on

val isStrictTotalOrderOn : ∀ α. SetType α, Eq α ⇒ REL α α → SET α → BOOL
let isStrictTotalOrderOn r s = isStrictPartialOrderOn r s ∧ isTrichotomousOn r s

declare {hol} rename function isStrictTotalOrderOn = lem_is_strict_total_order_on

val isTotalOrder : ∀ α. SetType α, Eq α ⇒ REL α α → BOOL
let ~{ocaml, coq} isTotalOrder r = isPartialOrder r ∧ isTotal r

declare {hol} rename function isTotalOrder = lem_is_total_order

val isStrictTotalOrder : ∀ α. SetType α, Eq α ⇒ REL α α → BOOL
let ~{ocaml, coq} isStrictTotalOrder r = isStrictPartialOrder r ∧ isTrichotomous r

declare {hol} rename function isStrictTotalOrder = lem_is_strict_total_order

assert is_totalorder_on0 : isTotalOrderOn ({((2 : NAT), (3 : NAT)), (2, 2), (3, 3), (4, 4)}) {2, 3}
assert is_totalorder_on1 : ¬ (isTotalOrderOn ({((2 : NAT), (3 : NAT)), (2, 2), (3, 3), (4, 4)}) {2, 3, 4})
assert is_totalorder_on2 : ¬ (isTotalOrderOn ({((2 : NAT), (3 : NAT)))} {2, 3})

assert is_strict_totalorder_on0 : isStrictTotalOrderOn ({((2 : NAT), (3 : NAT)))} {2, 3}
assert is_strict_totalorder_on1 : ¬ (isStrictTotalOrderOn ({((2 : NAT), (3 : NAT)))} {2, 3, 4})

(* ===== *)
(* closures *)
(* ===== *)

(* ----- *)
(* transitive closure *)
(* ----- *)

val transitiveClosure : ∀ α. SetType α, Eq α ⇒ REL α α → REL α α
val transitiveClosureByEq : ∀ α. (α → α → BOOL) → REL α α → REL α α
val transitiveClosureByCmp : ∀ α. (α * α → α * α → ORDERING) → REL α α → REL α α

declare ocaml target_rep function transitiveClosureByCmp = 'Pset.tc'
declare hol target_rep function transitiveClosure = 'tc'
declare isabelle target_rep function transitiveClosure = 'trancl'
declare coq target_rep function transitiveClosureByEq = 'set_tc'

let inline {coq} transitiveClosure = transitiveClosureByEq (=)
let inline {ocaml} transitiveClosure = transitiveClosureByCmp setElemCompare

lemma transitiveClosure_spec1 : (∀ r. r ⊆ (transitiveClosure r))
lemma transitiveClosure_spec2 : (∀ r. isTransitive (transitiveClosure r))
lemma transitiveClosure_spec3 : (∀ r1 r2. ((isTransitive r2) ∧ (r1 ⊆ r2)) → (transitiveClosure r1) ⊆ r2)
lemma transitiveClosure_spec4 : (∀ r. isTransitive r → (transitiveClosure r = r))

```

```

assert transitive_closure0 : (transitiveClosure ({((2 : NAT), (3 : NAT)), (3, 4)})) =
    {(2, 3), (2, 4), (3, 4)}
assert transitive_closure1 : (transitiveClosure ({((2 : NAT), (3 : NAT)), (3, 4), (4, 5), (7, 9)})) =
    {(2, 3), (2, 4), (2, 5), (3, 4), (3, 5), (4, 5), (7, 9)}

(* ----- *)
(* transitive closure step *)
(* ----- *)

val transitiveClosureAdd : ∀ α. SetType α, Eq α ⇒ α → α → REL α α → REL α α

let transitiveClosureAdd x y r =
    ((relAdd x y r) ∪ ({(x, z) | ∀ z ∈ rng r | inRel y z r}) ∪
    {(z, y) | ∀ z ∈ dom r | inRel z x r}))

declare {hol} rename function transitiveClosureAdd = tc_insert

lemma transitive_closure_add_thm : ∀ x y r. isTransitive r → (transitiveClosureAdd x y r = transitiveClosure (relAdd x y r))

assert transitive_closure_add0 : transitiveClosureAdd (2 : NAT) (3 : NAT) {} = {(2, 3)}
assert transitive_closure_add1 : transitiveClosureAdd (3 : NAT) (4 : NAT) {(2, 3)} = {(2, 3), (3, 4), (2, 4)}
assert transitive_closure_add2 : transitiveClosureAdd (4 : NAT) (5 : NAT) {(2, 3), (3, 4), (2, 4)} =
    {(2, 3), (3, 4), (2, 4), (4, 5), (2, 5), (3, 5)}

(* ===== *)
(* reflexive closure *)
(* ===== *)

val reflexiveTransitiveClosureOn : ∀ α. SetType α, Eq α ⇒ REL α α → SET α → REL α α
let reflexiveTransitiveClosureOn r s = transitiveClosure (r ∪ (relIdOn s))
declare {hol} rename function reflexiveTransitiveClosureOn = reflexive_transitive_closure_on

assert reflexive_transitive_closure0 : (reflexiveTransitiveClosureOn ({((2 : NAT), (3 : NAT)), (3, 4)}) {2, 3, 4}) =
    {(2, 3), (2, 4), (3, 4), (2, 2), (3, 3), (4, 4)}

val reflexiveTransitiveClosure : ∀ α. SetType α, Eq α ⇒ REL α α → REL α α
let ~{ocaml, cog} reflexiveTransitiveClosure r = transitiveClosure (r ∪ relId)

(* ===== *)
(* inverse of closures *)
(* ===== *)

(* ----- *)
(* without transitive edges *)
(* ----- *)

val withoutTransitiveEdges : ∀ α. SetType α, Eq α ⇒ REL α α → REL α α
let withoutTransitiveEdges r =
    let tc = transitiveClosure r in
    {(a, c) | ∀ (a, c) ∈ r
    | ∀ b ∈ rng r. a ≠ b ∧ b ≠ c → ¬ ((a, b) ∈ tc ∧ (b, c) ∈ tc)}

```

```

declare isabelle target_rep function withoutTransitiveEdges = 'LemExtraDefs.without_trans_edges'

lemma transcl_withoutTransitiveEdges_thm :  $\forall r. \text{finite } r \longrightarrow$ 
    transitiveClosure (withoutTransitiveEdges r) = transitiveClosure r

assert withoutTransitiveEdges0 : withoutTransitiveEdges  $\{((0 : \text{NAT}), 1)\} = \{((0 : \text{NAT}), 1)\}$ 
assert withoutTransitiveEdges1 : withoutTransitiveEdges  $\{((0 : \text{NAT}), 1), (1, 2), (0, 2)\} =$ 
     $\{((0 : \text{NAT}), 1), (1, 2)\}$ 
assert withoutTransitiveEdges2 : withoutTransitiveEdges  $\{((0 : \text{NAT}), 1), (1, 2), (2, 3), (0, 3)\} =$ 
     $\{((0 : \text{NAT}), 1), (1, 2), (2, 3)\}$ 
assert withoutTransitiveEdges3 : withoutTransitiveEdges  $\{((0 : \text{NAT}), 0), (0, 1)\} =$ 
     $\{((0 : \text{NAT}), 0), (0, 1)\}$ 

```

## 13 Sorting

```

(*****
(* A library for sorting lists *)
(*
(* It mainly follows the Haskell List – library *)
(*****)

(* ===== *)
(* Header *)
(* ===== *)

declare {isabelle, hol, ocaml, coq} rename module = lem_sorting

open import Bool Basic_classes Maybe List Num

open import {isabelle} HOL – Library.Permutation
open import {coq} Coq.Lists.List
open import {hol} sortingTheory permLib
open import {isabelle} $LIB_DIR/Lem

(* ----- *)
(* permutations *)
(* ----- *)

val isPermutation : ∀ α. Eq α ⇒ LIST α → LIST α → BOOL
val isPermutationBy : ∀ α. (α → α → BOOL) → LIST α → LIST α → BOOL

let rec isPermutationBy eq l1 l2 = match l1 with
| [] → null l2
| (x :: xs) → begin
  match deleteFirst (eq x) l2 with
  | Nothing → false
  | Just ys → isPermutationBy eq xs ys
  end
end
end
declare termination_argument isPermutationBy = automatic
declare {hol} rename function isPermutationBy = PERM_BY

let inline isPermutation = isPermutationBy (=)

declare isabelle target_rep function isPermutation = infix '<~~>'
declare hol target_rep function isPermutation = 'PERM'

assert perm1 : (isPermutation ([] : LIST NAT) [])
assert perm2 : (¬ (isPermutation [(2 : NAT)] []))
assert perm3 : (isPermutation [(2 : NAT); 1; 3; 5; 4] [1; 2; 3; 4; 5])
assert perm4 : (¬ (isPermutation [(2 : NAT); 3; 3; 5; 4] [1; 2; 3; 4; 5]))
assert perm5 : (¬ (isPermutation [(2 : NAT); 1; 3; 5; 4; 3] [1; 2; 3; 4; 5]))
assert perm6 : (isPermutation [(2 : NAT); 1; 3; 5; 4; 3] [1; 2; 3; 3; 4; 5])

lemma isPermutation1 : (∀ l. isPermutation l l)
lemma isPermutation2 : (∀ l1 l2. isPermutation l1 l2 ⇔ isPermutation l2 l1)
lemma isPermutation3 : (∀ l1 l2 l3. isPermutation l1 l2 → isPermutation l2 l3 → isPermutation l1 l3)
lemma isPermutation4 : (∀ l1 l2. isPermutation l1 l2 → (length l1 = length l2))

```

lemma *isPermutation*<sub>5</sub> :  $(\forall l_1 l_2. \text{isPermutation } l_1 l_2 \longrightarrow (\forall x. \text{elem } x l_1 = \text{elem } x l_2))$

```
(* ----- *)
(* isSorted      *)
(* ----- *)
```

(\* isSortedBy R l checks, whether the list l is sorted by ordering R. R should represent an order, i.e. it sh

```
val isSorted :  $\forall \alpha. \text{Ord } \alpha \Rightarrow \text{LIST } \alpha \rightarrow \text{BOOL}$ 
val isSortedBy :  $\forall \alpha. (\alpha \rightarrow \alpha \rightarrow \text{BOOL}) \rightarrow \text{LIST } \alpha \rightarrow \text{BOOL}$ 
```

(\* DPM: rejigged the definition with a nested match to get past Coq's termination checker. \*)

```
let rec isSortedBy cmp l = match l with
| [] → true
| x1 :: xs →
  match xs with
  | [] → true
  | x2 :: _ → (cmp x1 x2 ∧ isSortedBy cmp xs)
end
end
declare termination_argument isSortedBy = automatic
```

let inline *isSorted* = isSortedBy ( $\leq$ )

```
declare isabelle target_rep function isSortedBy = 'sorted_by'
declare hol target_rep function isSortedBy = 'SORTED'
```

```
assert isSorted1 : (isSorted ([] : LIST NAT))
assert isSorted2 : (isSorted [(2 : NAT)])
assert isSorted3 : (isSorted [(2 : NAT); 4; 5])
assert isSorted4 : (isSorted [(1 : NAT); 2; 2; 4; 4; 8])
assert isSorted5 : ( $\neg$  (isSorted [(3 : NAT); 2]))
assert isSorted6 : ( $\neg$  (isSorted [(1 : NAT); 2; 3; 2; 3; 4; 5]))
```

```
(* ----- *)
(* insertion sort      *)
(* ----- *)
```

```
val insert :  $\forall \alpha. \text{Ord } \alpha \Rightarrow \alpha \rightarrow \text{LIST } \alpha \rightarrow \text{LIST } \alpha$ 
val insertBy :  $\forall \alpha. (\alpha \rightarrow \alpha \rightarrow \text{BOOL}) \rightarrow \alpha \rightarrow \text{LIST } \alpha \rightarrow \text{LIST } \alpha$ 
```

```
val insertSort :  $\forall \alpha. \text{Ord } \alpha \Rightarrow \text{LIST } \alpha \rightarrow \text{LIST } \alpha$ 
val insertSortBy :  $\forall \alpha. (\alpha \rightarrow \alpha \rightarrow \text{BOOL}) \rightarrow \text{LIST } \alpha \rightarrow \text{LIST } \alpha$ 
```

```
let rec insertBy cmp e l = match l with
| [] → [e]
| x :: xs → if cmp x e then x :: (insertBy cmp e xs) else (e :: x :: xs)
end
declare termination_argument insertBy = automatic
```

let inline *insert* = insertBy ( $\leq$ )

```
let insertSortBy cmp l = List.foldl (fun l e → insertBy cmp e l) [] l
let inline insertSort = insertSortBy ( $\leq$ )
```

```

declare isabelle target_rep function insertBy = 'insert_sort_insert_by'
declare isabelle target_rep function insertSortBy = 'insert_sort_by'

```

```

declare {hol} rename function insertBy = INSERT_SORT_INSERT
declare {hol} rename function insertSortBy = INSERT_SORT

```

```

lemma insertBy1 : (∀ l e cmp. ((∀ x y z. cmp x y ∧ cmp y z ⟶ cmp x z) ∧ isSortedBy cmp l) ⟶ isSortedBy cmp (insertBy

```

```

lemma insertBy2 : (∀ l e cmp. length (insertBy cmp e l) = length l + 1)

```

```

lemma insertBy3 : (∀ l e1 e2 cmp. elem e1 (insertBy cmp e2 l) = ((e1 = e2) ∨ elem e1 l))

```

```

lemma insertSort1 : (∀ l cmp. isPermutation (insertSort l) l)

```

```

lemma insertSort2 : (∀ l cmp. isSorted (insertSort l))

```

```

(* ----- *)
(* general sorting      *)
(* ----- *)

```

```

val sort : ∀ α. Ord α ⟹ LIST α → LIST α

```

```

val sortBy : ∀ α. (α → α → BOOL) → LIST α → LIST α

```

```

val sortByOrd : ∀ α. (α → α → ORDERING) → LIST α → LIST α

```

```

val predicate_of_ord : ∀ α. (α → α → ORDERING) → α → α → BOOL

```

```

let predicate_of_ord f x y =

```

```

  match f x y with

```

```

  | LT → true

```

```

  | EQ → true

```

```

  | GT → false

```

```

end

```

```

let inline sortBy = insertSortBy

```

```

declare isabelle target_rep function sortBy = 'sort_by'

```

```

declare hol target_rep function sortBy = 'QSORT'

```

```

declare ocaml target_rep function sortByOrd = 'List.sort'

```

```

let inline {isabelle, hol} sortByOrd f xs = sortBy (predicate_of_ord f) xs

```

```

declare coq target_rep function sortByOrd = 'sort_by_ordering'

```

```

let inline ~{ocaml} sort = sortBy (≤)

```

```

let inline {ocaml} sort = sortByOrd compare

```

```

assert sort1 : (sort ([] : LIST NAT) = [])

```

```

assert sort2 : (sort ([6; 4; 3; 8; 1; 2] : LIST NAT) = [1; 2; 3; 4; 6; 8])

```

```

assert sort3 : (sort ([5; 4; 5; 2; 4] : LIST NAT) = [2; 4; 4; 5; 5])

```

```

lemma sort4 : (∀ l cmp. isPermutation (sort l) l)

```

```

lemma sort5 : (∀ l cmp. isSorted (sort l))

```

## 14 Function\_extra

```

declare {isabelle, hol, ocaml, coq} rename module = lem_function_extra

open import Maybe Bool Basic_classes Num Function

open import {hol} lemTheory
open import {isabelle} $LIB_DIR/Lem

(* ----- *)
(* Tests for function      *)
(* ----- *)

(* These tests are not written in function itself, because the nat type  is not available there, yet *)

assert id0 : id (2 : NAT) = 2
assert id1 : id (5 : NAT) = 5
assert id2 : id (2 : NAT) = 2

assert const0 : (const (2 : NAT)) true = 2
assert const1 : (const (5 : NAT)) false = 5
assert const2 : (const (2 : NAT)) (3 : NAT) = 2

assert comb0 : (comb (fun (x : NAT) → 3 * x) succ 2 = 9)
assert comb1 : (comb succ (fun (x : NAT) → 3 * x) 2 = 7)

assert apply0 : ($) (fun (x : NAT) → 3 * x) 2 = 6
assert apply1 : (fun (x : NAT) → 3 * x) $ 2 = 6

assert flip0 : flip (fun (x : NAT) y → x - y) 3 5 = 2
assert flip1 : flip (fun (x : NAT) y → x - y) 5 3 = 0

(* ----- *)
(* getting a unique value *)
(* ----- *)

val THE : ∀ α. (α → BOOL) → MAYBE α
declare hol target_rep function THE = '$THE'
declare ocaml target_rep function THE = 'THE'
declare isabelle target_rep function THE = 'The_opt'

lemma ~{coq} THE_spec : (∀ p x. (THE p = Just x) ↔ ((p x) ∧ (∀ y. p y → (x = y))))

```



## 15 Assert\_extra

```
(* ----- *)
(* impure functions for signalling *)
(* catastrophic failure, or function *)
(* preconditions. *)
(* ----- *)

declare {isabelle, ocaml, hol, coq} rename module = lem_assert_extra
open import {ocaml} Xstring
open import {hol} stringTheory lemTheory
open import {coq} Coq.Strings.Ascii Coq.Strings.String
open import {isabelle} $LIB_DIR/Lem

(* ----- *)
(* failing with a proper error message *)
(* ----- *)

val failwith :  $\forall \alpha. \text{STRING} \rightarrow \alpha$ 
declare ocaml target_rep function failwith = 'failwith'
declare hol target_rep function failwith = 'failwith'
declare isabelle target_rep function failwith = 'failwith'
declare coq target_rep function failwith s = 'DAEMON'

(* ----- *)
(* failing without an error message *)
(* ----- *)

val fail :  $\forall \alpha. \alpha$ 
let fail = failwith "fail"
declare ocaml target_rep function fail = 'assert' 'false'

(* ----- *)
(* assertions *)
(* ----- *)

val ensure :  $\text{BOOL} \rightarrow \text{STRING} \rightarrow \text{UNIT}$ 
let ensure test msg =
  if test then
    ()
  else
    failwith msg
```

## 16 List\_extra

```

(*****
(* A library for lists — the non — pure part *)
(*
(* It mainly follows the Haskell List — library *)
(*****

(* ===== *)
(* Header *)
(* ===== *)

(* rename module to clash with existing list modules of targets  problem: renaming from inside the module i

declare {isabelle, hol, ocaml, coq} rename module = lem_list_extra

open import Bool Maybe Basic_classes Tuple Num List Assert_extra

(* ----- *)
(* head of non — empty list *)
(* ----- *)
val head :  $\forall \alpha. \text{LIST } \alpha \rightarrow \alpha$ 
let head l = match l with | x :: xs  $\rightarrow$  x | []  $\rightarrow$  failwith “List_extra.head of empty list” end

declare compile_message head = “head is only defined on non-empty list and should therefore be avoided. Use maching ins

declare hol target_rep function head = 'HD'
declare ocaml target_rep function head = 'List.hd'
declare isabelle target_rep function head = 'List.hd'

assert head_simple1 : (head [3;1] = (3 : NAT))
assert head_simple2 : (head [5;4] = (5 : NAT))

(* ----- *)
(* tail of non — empty list *)
(* ----- *)
val tail :  $\forall \alpha. \text{LIST } \alpha \rightarrow \text{LIST } \alpha$ 
let tail l = match l with | x :: xs  $\rightarrow$  xs | []  $\rightarrow$  failwith “List_extra.tail of empty list” end

declare compile_message tail = “tail is only defined on non-empty list and should therefore be avoided. Use maching instea

declare hol target_rep function tail = 'TL'
declare ocaml target_rep function tail = 'List.tl'
declare isabelle target_rep function tail = 'List.tl'

assert tail_simple1 : (tail [(3 : NAT);1] = [1])
assert tail_simple2 : (tail [(5 : NAT)] = [])
assert tail_simple3 : (tail [(5 : NAT);4;3;2] = [4;3;2])

lemma head_tail_cons : ( $\forall l. \text{length } l > 0 \longrightarrow (l = (\text{head } l)::(\text{tail } l))$ )

(* ----- *)

```

```

(* last *)
(* ----- *)
val last :  $\forall \alpha. \text{LIST } \alpha \rightarrow \alpha$ 
let rec last l = match l with | [x]  $\rightarrow$  x |  $x_1 :: x_2 :: xs \rightarrow$  last ( $x_2 :: xs$ ) | []  $\rightarrow$  failwith "List_extra.last of empty list" end

declare compile_message last = "last is only defined on non-empty list and should therefore be avoided. Use maching instead"

declare hol target_rep function last = 'LAST'
declare isabelle target_rep function last = 'List.last'

assert last_simple1 : (last [(3 : NAT); 1] = 1)
assert last_simple2 : (last [(5 : NAT); 4] = 4)

(* ----- *)
(* init *)
(* ----- *)

(* All elements of a non – empty list except the last one. *)
val init :  $\forall \alpha. \text{LIST } \alpha \rightarrow \text{LIST } \alpha$ 
let rec init l = match l with | [x]  $\rightarrow$  [] |  $x_1 :: x_2 :: xs \rightarrow$   $x_1 :: (\text{init } (x_2 :: xs))$  | []  $\rightarrow$  failwith "List_extra.init of empty list" end

declare compile_message init = "init is only defined on non-empty list and should therefore be avoided. Use maching instead"

declare hol target_rep function init = 'FRONT'
declare isabelle target_rep function init = 'List.butlast'

assert init_simple1 : (init [(3 : NAT); 1] = [3])
assert init_simple2 : (init [(5 : NAT)] = [])
assert init_simple3 : (init [(5 : NAT); 4; 3; 2] = [5; 4; 3])

lemma init_last_append : ( $\forall l. \text{length } l > 0 \rightarrow (l = (\text{init } l) ++ [\text{last } l])$ )
lemma init_last_dest : ( $\forall l. \text{length } l > 0 \rightarrow (\text{dest.init } l = \text{Just } (\text{init } l, \text{last } l))$ )

(* ----- *)
(* foldl1 / foldr1 *)
(* ----- *)

(* folding functions for non – empty lists, which don't take the base case *)
val foldl1 :  $\forall \alpha. (\alpha \rightarrow \alpha \rightarrow \alpha) \rightarrow \text{LIST } \alpha \rightarrow \alpha$ 
let foldl1 f x xs = match x xs with | (x :: xs)  $\rightarrow$  foldl f x xs | []  $\rightarrow$  failwith "List_extra.foldl1 of empty list" end

declare compile_message foldl1 = "foldl1 is only defined on non-empty lists. Better use foldl or explicit pattern matching."

val foldr1 :  $\forall \alpha. (\alpha \rightarrow \alpha \rightarrow \alpha) \rightarrow \text{LIST } \alpha \rightarrow \alpha$ 
let foldr1 f x xs = match x xs with | (x :: xs)  $\rightarrow$  foldr f x xs | []  $\rightarrow$  failwith "List_extra.foldr1 of empty list" end

declare compile_message foldr1 = "foldr1 is only defined on non-empty lists. Better use foldr or explicit pattern matching."

(* ----- *)

```

```

(* nth element *)
(* ----- *)

(* get the nth element of a list *)
val nth : ∀ α. LIST α → NAT → α
let nth l n = match index l n with Just e → e | Nothing → failwith "List_extra.nth" end
declare compile_message foldl1 = "nth is undefined for too large indices, use carefully"

declare hol target_rep function nth l n = 'EL' n l
declare ocaml target_rep function nth = 'List.nth'
declare isabelle target_rep function nth = 'List.nth'
declare coq target_rep function nth l n = 'List.nth' n l

assert nth_0 : (nth [0; 1; 2; 3; 4; 5] 0 = (0 : NAT))
assert nth_1 : (nth [0; 1; 2; 3; 4; 5] 1 = (1 : NAT))
assert nth_2 : (nth [0; 1; 2; 3; 4; 5] 2 = (2 : NAT))
assert nth_3 : (nth [0; 1; 2; 3; 4; 5] 3 = (3 : NAT))
assert nth_4 : (nth [0; 1; 2; 3; 4; 5] 4 = (4 : NAT))
assert nth_5 : (nth [0; 1; 2; 3; 4; 5] 5 = (5 : NAT))

lemma nth_index : (∀ l n e. n < length l → index l n = Just (nth l n))

(* ----- *)
(* Find_non_pure *)
(* ----- *)
val findNonPure : ∀ α. (α → BOOL) → LIST α → α
let findNonPure P l = match (find P l) with
| Just e → e
| Nothing → failwith "List_extra.findNonPure"
end

declare compile_message findNonPure = "findNonPure is undefined if no element with the property is in the list. Better use"

(* ----- *)
(* zip same length *)
(* ----- *)

val zipSameLength : ∀ α β. LIST α → LIST β → LIST (α * β)
let rec zipSameLength l1 l2 = match (l1, l2) with
| (x :: xs, y :: ys) → (x, y) :: zipSameLength xs ys
| ([], []) → []
| _ → failwith "List_extra.zipSameLength of different length lists"

end

declare termination_argument zipSameLength = automatic

declare compile_message zipSameLength = "zipSameLength is undefined if the two lists have different lengths"

declare hol target_rep function zipSameLength l1 l2 = 'ZIP' (l1, l2)
declare ocaml target_rep function zipSameLength = 'List.combine'

assert zipSameLength_1 : (zipSameLength [(1 : NAT); 2; 3; 4; 5] [(2 : NAT); 3; 4; 5; 6] = [(1, 2); (2, 3); (3, 4); (4, 5); (5, 6)])

val unfoldr : ∀ α β. (α → MAYBE (β * α)) → α → LIST β

```

```

let rec unfoldr f x =
  match f x with
  | Just (y, x') →
    y :: unfoldr f x'
  | Nothing →
    []
end

```

## 17 String

```

(*****
(* A library for strings *)
(*****

(* ===== *)
(* Header *)
(* ===== *)

declare {ocaml, isabelle, hol, coq} rename module = lem_string

open import Bool Basic_classes List
open import {ocaml} Xstring
open import {hol} lemTheory stringTheory
open import {coq} Coq.Strings.Ascii Coq.Strings.String

(* ----- *)
(* basic instantiations *)
(* ----- *)

(* set up the string and char types correctly for the backends and make sure that parsing and equality check

declare ocaml target_rep type CHAR = 'char'
declare hol target_rep type CHAR = 'char'
declare isabelle target_rep type CHAR = 'char'
declare coq target_rep type CHAR = 'ascii'

declare ocaml target_rep type STRING = 'string'
declare hol target_rep type STRING = 'string'
declare isabelle target_rep type STRING = 'string'
declare coq target_rep type STRING = 'string'

assert char_simple_0 : ¬ (#'0' = ((#'1') : CHAR))
assert char_simple_1 : ¬ (#'X' = #'Y')
assert char_simple_2 : ¬ (#'\xAF' = #'\x00')
assert char_simple_3 : ¬ (#' ' = #'@')
assert char_simple_4 : ¬ (#'\' = #'\n')
assert char_simple_5 : (#'\x20 = #' ')
assert char_simple_6 : ¬ ([#\x20; #' '; #'\x60; #'\x27; #'~'; #'\'] = [])

assert string_simple_0 : ¬ ("Hello" = ("Goodby" : STRING))
assert string_simple_1 : ¬ ("Hello\nWorld" = "Goodby\x20!")
assert string_simple_2 : ¬ ("123_\\t-+!X_@ = "!"")
assert string_simple_3 : ("Hello World" = ("Hello\x20World" : STRING))

(* ----- *)
(* translations between strings and char lists *)
(* ----- *)

val toCharList : STRING → LIST CHAR
declare ocaml target_rep function toCharList = 'Xstring.explode'
declare hol target_rep function toCharList = 'EXPLODE'
declare isabelle target_rep function toCharList s = ''s
declare coq target_rep function toCharList = 'string_to_char_list' (* TODO: check *)

assert toCharList_0 : (toCharList "Hello" = [#'H'; #'e'; #'l'; #'l'; #'o'])
assert toCharList_1 : (toCharList "H\nA" = [#'H'; #'\n'; #'A'])

```

```

val toString : LIST CHAR → STRING
declare ocaml target_rep function toString = 'Xstring.implode'
declare hol target_rep function toString = 'IMPLODE'
declare isabelle target_rep function toString s = ''s
declare coq target_rep function toString = 'string_from_char_list' (* TODO: check *)

assert toString0 : (toString [#'H'; #'e'; #'l'; #'l'; #'o'] = "Hello")
assert toString1 : (toString [#'H'; #'\\n'; #'A'] = "H\\nA")

(* ----- *)
(* generating strings *)
(* ----- *)

val makeString : NAT → CHAR → STRING
let makeString len c = toString (replicate len c)
declare ocaml target_rep function makeString = 'String.make'
declare isabelle target_rep function makeString = 'List.replicate'
declare hol target_rep function makeString = 'REPLICATE'
declare coq target_rep function makeString = 'string.make_string'

assert makeString0 : (makeString 0 #'a' = "")
assert makeString1 : (makeString 5 #'a' = "aaaaa")
assert makeString2 : (makeString 3 #'c' = "ccc")

(* ----- *)
(* length *)
(* ----- *)

val stringLength : STRING → NAT
declare hol target_rep function stringLength = 'STRLEN'
declare ocaml target_rep function stringLength = 'String.length'
declare isabelle target_rep function stringLength = 'List.length'
declare coq target_rep function stringLength = 'String.length' (* TODO: check *)

assert stringLength0 : (stringLength "" = 0)
assert stringLength1 : (stringLength "abc" = 3)
assert stringLength2 : (stringLength "123456" = 6)

(* ----- *)
(* string concatenation *)
(* ----- *)

val ^ [stringAppend] : STRING → STRING → STRING
let inline stringAppend x y = (toString ((toCharList x) ++ (toCharList y)))
declare ocaml target_rep function stringAppend = infix '^'
declare hol target_rep function stringAppend = 'STRCAT'
declare isabelle target_rep function stringAppend = infix '@'
declare coq target_rep function stringAppend = 'String.append'

assert stringAppend0 : (^ "Hello" ^ " " "World!" = "Hello World!")

(* ----- *)
(* setting up pattern matching *)
(* ----- *)

```

```

val string_case :  $\forall \alpha. \text{STRING} \rightarrow \alpha \rightarrow (\text{CHAR} \rightarrow \text{STRING} \rightarrow \alpha) \rightarrow \alpha$ 

let string_case s c_empty c_cons =
  match (toCharList s) with
  | []  $\rightarrow$  c_empty
  | c :: cs  $\rightarrow$  c_cons c (toString cs)
end
declare ocaml target_rep function string_case = 'Xstring.string_case'
declare hol target_rep function string_case = 'list_CASE'
declare isabelle target_rep function string_case s c_e c_c = 'case_list' c_e c_c s

val empty_string : STRING
let inline empty_string = ""

assert empty_string0 : (empty_string = "")
assert empty_string1 :  $\neg$  (empty_string = "xxx")

val cons_string : CHAR  $\rightarrow$  STRING  $\rightarrow$  STRING
let inline cons_string c s = toString (c :: toCharList s)

assert string_cons0 : (cons_string #'a' empty_string = "a")
assert string_cons1 : (cons_string #'x' "yz" = "xyz")

declare ocaml target_rep function cons_string = 'Xstring.cons_string'
declare hol target_rep function cons_string = 'STRING'
declare isabelle target_rep function cons_string = infix ' #'

declare pattern_match exhaustive STRING = [ empty_string; cons_string ] string_case

assert string_patterns0 : (
  match "" with
  | empty_string  $\rightarrow$  true
  | _  $\rightarrow$  false
end
)

assert string_patterns1 : (
  match "abc" with
  | empty_string  $\rightarrow$  ""
  | cons_string c s  $\rightarrow$  (^ makeString 5 c s)
  end = "aaaaabc"
)

val concat : STRING  $\rightarrow$  LIST STRING  $\rightarrow$  STRING
let rec concat sep ss =
  match ss with
  | []  $\rightarrow$  ""
  | s :: ss'  $\rightarrow$ 
    match ss' with
    | []  $\rightarrow$  s
    | _  $\rightarrow$  ^ s ^ sep concat sep ss'
  end
end

```



## 18 Num\_extra

```
(* *****)
(*
(* A library of additional functions on numbers *)
(*
(* *****)
```

```
open import Basic_classes
open import Num
open import String
open import Assert_extra
```

```
open import {hol} ASCIInumbersTheory
```

```
declare {hol, isabelle, ocaml, coq} rename module = lem_num_extra
```

```
val naturalOfString : STRING →  $\mathbb{N}$ 
```

```
declare compile_message naturalOfString = "naturalOfString can fail, potentially with an exception, if the string cannot be"
```

```
declare ocaml target_rep function naturalOfString = 'Nat_big_num.of_string_nat'
declare hol target_rep function naturalOfString = 'toNum'
```

```
val integerOfString : STRING →  $\mathbb{Z}$ 
```

```
declare compile_message integerOfString = "integerOfString can fail, potentially with an exception, if the string cannot be"
```

```
declare ocaml target_rep function integerOfString = 'Nat_big_num.of_string'
```

```
val integerOfChar : CHAR →  $\mathbb{Z}$ 
```

```
let integerOfChar = function
| #'0' → 0
| #'1' → 1
| #'2' → 2
| #'3' → 3
| #'4' → 4
| #'5' → 5
| #'6' → 6
| #'7' → 7
| #'8' → 8
| #'9' → 9
| _ → failwith "integerOfChar: unexpected character"
end
```

```
val integerOfStringHelper : LIST CHAR →  $\mathbb{Z}$ 
```

```
let rec integerOfStringHelper s = match s with
| d :: ds → integerOfChar d + (10 * integerOfStringHelper ds)
| [] → 0
end
```

```
declare {isabelle} termination_argument integerOfStringHelper = automatic
```

```
let ~{ocaml, hol} integerOfString s = match String.toCharList s with
| #'-' :: ds → integerNegate (integerOfStringHelper (List.reverse ds))
| ds → integerOfStringHelper (List.reverse ds)
```

end

```
let {hol} integerOfString s = match s with
| cons_string #' - ' s' → integerNegate (integerFromNatural (naturalOfString s'))
| _ → integerFromNatural (naturalOfString s)
end
```

```
assert {ocaml, hol, isabelle} integerOfString_test1 : (integerOfString "4096" = 4096)
assert {ocaml, hol, isabelle} integerOfString_test2 : (integerOfString "-4096" = -4096)
```

```
(* Truncation integer division (round toward zero) *)
val integerDiv_t :  $\mathbb{Z} \rightarrow \mathbb{Z} \rightarrow \mathbb{Z}$ 
declare ocaml target_rep function integerDiv_t = 'Nat_big_num.integerDiv_t'
declare hol target_rep function integerDiv_t = '$/'
```

```
(* Truncation modulo *)
val integerRem_t :  $\mathbb{Z} \rightarrow \mathbb{Z} \rightarrow \mathbb{Z}$ 
declare ocaml target_rep function integerRem_t = 'Nat_big_num.integerRem_t'
declare hol target_rep function integerRem_t = '$%'
```

```
(* Flooring modulo *)
val integerRem_f :  $\mathbb{Z} \rightarrow \mathbb{Z} \rightarrow \mathbb{Z}$ 
declare ocaml target_rep function integerRem_f = 'Nat_big_num.integerRem_f'
declare hol target_rep function integerRem_f = '$%'
```

## 19 Map\_extra

```
(*****
(* A library for finite maps *)
(*****)

(* ===== *)
(* Header *)
(* ===== *)

declare {isabelle, hol, ocaml, coq} rename module = lem_map_extra

open import Bool Basic_classes Function Assert_extra Maybe List Num Set Map

(* ----- *)
(* find *)
(* ----- *)

val find : ∀ 'k 'v. MapKeyType 'k ⇒ 'k → MAP 'k 'v → 'v
let find k m = match (lookup k m) with Just x → x | Nothing → failwith "Map_extra.find" end

declare ocaml target_rep function find = 'Pmap.find'
declare isabelle target_rep function find = 'map_find'
declare hol target_rep function find k m = 'FAPPLY' m k

declare compile_message find = "find is only defined if the key is found. Use lookup instead and handle the not-found case"

assert find_insert1 : (find 16 (insert (16 : NAT) true empty) = true)
assert find_insert2 : (find 36 (insert 36 false (insert (16 : NAT) true empty)) = false )

(* ----- *)
(* from sets / domain / range *)
(* ----- *)

val fromSet : ∀ 'k 'v. MapKeyType 'k ⇒ ('k → 'v) → SET 'k → MAP 'k 'v
let fromSet f s = Set_helpers.fold (fun k m → Map.insert k (f k) m) s Map.empty

declare compile_message fromSet = "fromSet only works for finite sets, use carefully."

declare ocaml target_rep function fromSet = 'Pmap.from_set'
declare hol target_rep function fromSet = 'FUN_FMAP'

(*assert fromSet_0 : (fromSet succ (Set.empty : set nat) = Map.empty)assert fromSet_1 : (fromSet succ {(2 : nat)})

(* ----- *)
(* fold *)
(* ----- *)

val fold : ∀ 'k 'v 'r. MapKeyType 'k, SetType 'k, SetType 'v ⇒ ('k → 'v → 'r → 'r) → MAP 'k 'v → 'r → 'r
let fold f m v = Set_helpers.fold (fun (k, v) r → f k v r) (Map.toSet m) v

declare ocaml target_rep function fold = 'Pmap.fold'

declare compile_message fold = "Map_extra.fold iterates over the elements of the map in a unspecified order"
```

```

(*assert fold_1 : (fold (fun k v a -> (a + k)) (Map.fromList [(2 : nat), (3 : nat)]; (3, 4); (4, 5))] 0 = 9)assert fold_1

val toList : ∀ 'k 'v. MapKeyType 'k ⇒ MAP 'k 'v → LIST ('k * 'v)

declare ocaml target_rep function toList = 'Pmap.bindings_list'
declare coq target_rep function toList = 'fmap_elements' (* TODO *)
declare hol target_rep function toList = 'MAP_TO_LIST'
declare isabelle target_rep function toList m = 'list_of_set' ('LemExtraDefs.map_to_set' m)
(* declare compile_message toList = "Map.extra.toList is only defined for the ocaml, isabelle and coq backend" *)

(* more 'map' functions *)

(* TODO : this function is in map_extra rather than map just for implementation reasons *)
val mapMaybe : ∀ α β γ. MapKeyType α ⇒ (α → β → MAYBE γ) → MAP α β → MAP α γ
(* OLD : TODO : mapMaybe depends on toList that is not defined for hol and isabelle *)
let mapMaybe f m =
  List.foldl
    (fun m' (k, v) →
      match f k v with
      | Nothing → m'
      | Just v' → Map.insert k v' m')
    Map.empty
    (toList m)

declare {ocaml, hol, isabelle} rename function mapMaybe = option_map
declare compile_message toList = "Map.extra.mapMaybe is only defined for the ocaml and coq backend"

```

## 20 Set\_extra

```

(*****
(* A library for sets *)
(*
(* It mainly follows the Haskell Set – library *)
(*****

(* ===== *)
(* Header *)
(* ===== *)

open import Bool Basic_classes Maybe Function Num List Sorting Set

declare {hol, isabelle, ocaml, coq} rename module = lem_set_extra

(* ----- *)
(* set choose (be careful !) *)
(* ----- *)

val choose : ∀ α. SetType α ⇒ SET α → α
declare compile_message choose = “choose is non-deterministic and only defined for non-empty sets. Its result may differ t

declare hol target_rep function choose = 'CHOICE'
declare isabelle target_rep function choose = 'set_choose'
declare ocaml target_rep function choose = 'Pset.choose'

lemma ~{coq} choose_sing : (∀ x. choose {x} = x)
lemma ~{coq} choose_in : (∀ s. ¬ (null s) → ((choose s) ∈ s))

assert ~{coq} choose_0 : choose {(2 : NAT)} = 2
assert ~{coq} choose_1 : choose {(5 : NAT)} = 5
assert ~{coq} choose_2 : choose {(6 : NAT)} = 6
assert ~{coq} choose_3 : choose {(6 : NAT), 1, 2} ∈ {6, 1, 2}

(* ----- *)
(* chooseAndSplit *)
(* ----- *)
(* The idea here is to provide a simple primitive that Lem code can use * to perform its own custom searches
val chooseAndSplit : ∀ α. SetType α, Ord α ⇒ SET α → MAYBE (SET α * α * SET α)
let ~{coq} chooseAndSplit s =
  if s = ∅ then
    Nothing
  else
    let element = choose s in
    let (lt, gt) = Set.split element s in
    Just (lt, element, gt)

declare ocaml target_rep function chooseAndSplit = 'Pset.choose_and_split'
declare coq target_rep function chooseAndSplit = 'choose_and_split'

(* ----- *)
(* universal set *)
(* ----- *)

val universal : ∀ α. SetType α ⇒ SET α

```

declare compile\_message universal = “universal sets are usually infinite and only available in HOL and Isabelle”

declare hol target\_rep function universal = 'UNIV'  
 declare isabelle target\_rep function universal = 'UNIV'

assert {hol} in\_univ<sub>0</sub> : true ∈ universal  
 assert {hol} in\_univ<sub>1</sub> : (1 : NAT) ∈ universal  
 lemma {hol} in\_univ\_thm : ∀ x. x ∈ universal

(\* ----- \*)  
 (\* toList \*)  
 (\* ----- \*)

val toList : ∀ α. SetType α ⇒ SET α → LIST α  
 declare compile\_message toList = “toList is only defined on finite sets and the order of the resulting list is unspecified and

declare ocaml target\_rep function toList = 'Pset.elements'  
 declare isabelle target\_rep function toList = 'list\_of\_set'  
 declare hol target\_rep function toList = 'SET\_TO\_LIST'  
 declare coq target\_rep function toList = 'set\_to\_list'

assert toList<sub>0</sub> : toList ({ } : SET NAT) = []  
 assert toList<sub>1</sub> : toList {(6 : NAT), 1, 2} ∈ {[1;2;6], [1;6;2], [2;1;6], [2;6;1], [6;1;2], [6;2;1]}  
 assert toList<sub>2</sub> : toList {(2 : NAT)} : SET NAT = [2]

(\* ----- \*)  
 (\* toOrderedList \*)  
 (\* ----- \*)

(\* "toOrderedList" returns a sorted list. Therefore the result is (given a suitable order) deterministic. Th

val toOrderedListBy : ∀ α. (α → α → BOOL) → SET α → LIST α  
 declare isabelle target\_rep function toOrderedListBy = 'ordered\_list\_of\_set'  
 declare hol target\_rep function toOrderedListBy = 'ARB'

val toOrderedList : ∀ α. SetType α, Ord α ⇒ SET α → LIST α  
 let inline ~{isabelle, ocaml} toOrderedList l = sort (toList l)  
 let inline {isabelle} toOrderedList = toOrderedListBy (≤)  
 declare ocaml target\_rep function toOrderedList = 'Pset.elements'

declare compile\_message toOrderedList = “toOrderedList is only defined on finite sets.”

assert toOrderedList<sub>0</sub> : toOrderedList ({ } : SET NAT) = []  
 assert toOrderedList<sub>1</sub> : toOrderedList {(6 : NAT), 1, 2} = [1;2;6]  
 assert toOrderedList<sub>2</sub> : toOrderedList {(2 : NAT)} : SET NAT = [2]

(\* ----- \*)  
 (\* compare \*)  
 (\* ----- \*)

val setCompareBy : ∀ α. (α → α → ORDERING) → SET α → SET α → ORDERING  
 let {isabelle, hol} setCompareBy cmp ss ts =  
 let ss' = toOrderedListBy (fun x y → cmp x y = LT) ss in

```

let ts' = toOrderedListBy (fun x y → cmp x y = LT) ts in
  lexicographicCompareBy cmp ss' ts'

declare coq target_rep function setCompareBy = 'set_compare_by'
declare ocaml target_rep function setCompareBy = 'Pset.compare_by'

val setCompare : ∀ α. SetType α, Ord α ⇒ SET α → SET α → ORDERING
let setCompare = setCompareBy compare

instance ∀ α. SetType α ⇒ (SetType (SET α))
  let setElemCompare = setCompareBy setElemCompare
end

(* ----- *)
(* unbounded fixed point *)
(* ----- *)

(* Is NOT supported by the coq backend! *)
val leastFixedPointUnbounded : ∀ α. SetType α ⇒ (SET α → SET α) → SET α → SET α
let rec leastFixedPointUnbounded f x =
  let fx = f x in
  if fx ⊆ x then x
  else leastFixedPointUnbounded f (fx ∪ x)

declare isabelle target_rep function leastFixedPointUnbounded f s = 'LemExtraDefs.unbounded_lfp' s f

declare compile_message toOrderedList = "leastFixedPointUnbounded is deprecated as it is not supported by all backends ("

assert lfp_empty : leastFixedPointUnbounded (map (fun x → x)) ({ } : SET NAT) = { }
assert lfp_saturate_neg : leastFixedPointUnbounded (map (fun x → -x)) ({1, 2, 3} : SET INT) = {-3, -2, -1, 1, 2, 3}

assert lfp_saturate_mod : leastFixedPointUnbounded (map (fun x → (2*x) mod 5)) ({1} : SET NAT) = {1, 2, 3, 4}

```

## 21 Maybe\_extra

```

(*****
(* extra functions for maybe / option *)
(*
*)
*****)

declare {isabelle, hol, ocaml, coq} rename module = lem_maybe_extra

open import Basic_classes Maybe Assert_extra

(* ----- *)
(* fromJust *)
(* ----- *)

val fromJust :  $\forall \alpha. \text{MAYBE } \alpha \rightarrow \alpha$ 
let fromJust op = match op with | Just v  $\rightarrow$  v | Nothing  $\rightarrow$  failwith “fromJust of Nothing” end
declare termination_argument fromJust = automatic
declare compile_message fromJust = “fromJust is only defined on Just. Better use ‘fromMaybe’ or use explicit matching to

declare hol target_rep function fromJust = 'THE'
declare isabelle target_rep function fromJust = 'Option.the'

```



## 22 String\_extra

```

(* ***** *)
(* String functions *)
(* ***** *)

open import Basic_classes
open import Num
open import List
open import String
open import List_extra
open import {hol} stringLib
open import {hol} ASCIInumbersTheory

declare {isabelle, ocaml, hol, coq} rename module = lem_string_extra

(* ***** *)
(* Character's to numbers *)
(* ***** *)

val ord : CHAR → NAT
declare hol target_rep function ord = 'ORD'
declare ocaml target_rep function ord = 'Char.code'
(* TODO: The Isabelle and Coq representations are taken from a quick Google search, they might not be the b
declare isabelle target_rep function ord = 'of_char'
declare coq target_rep function ord = 'nat_of_ascii'

val chr : NAT → CHAR
declare hol target_rep function chr = 'CHR'
declare ocaml target_rep function chr = 'Char.chr'
(* TODO: The Isabelle and Coq representations are taken from a quick Google search, they might not be the b
declare isabelle target_rep function chr = '(%n. char_of (n::nat))'
declare coq target_rep function chr = 'ascii_of_nat'

(* ***** *)
(* Converting to strings *)
(* ***** *)

val stringFromNatHelper : NAT → LIST CHAR → LIST CHAR
let rec stringFromNatHelper n acc =
  if n = 0 then
    acc
  else
    stringFromNatHelper (n / 10) (chr (n mod 10 + 48) :: acc)

declare {isabelle} termination_argument stringFromNatHelper = automatic

val stringFromNat : NAT → STRING
let ~{ocaml, hol} stringFromNat n =
  if n = 0 then "0" else toString (stringFromNatHelper n [])

declare ocaml target_rep function stringFromNat = 'string_of_int'
declare hol target_rep function stringFromNat = 'num_to_dec_string'

assert stringFromNat_0 : stringFromNat 0 = "0"
assert stringFromNat_1 : stringFromNat 1 = "1"
assert stringFromNat_2 : stringFromNat 42 = "42"

```

```

val stringFromNaturalHelper :  $\mathbb{N}$  → LIST CHAR → LIST CHAR
let rec stringFromNaturalHelper n acc =
  if n = 0 then
    acc
  else
    stringFromNaturalHelper (n / 10) (chr (natFromNatural (n mod 10 + 48)) :: acc)

declare {isabelle} termination_argument stringFromNaturalHelper = automatic

val stringFromNatural :  $\mathbb{N}$  → STRING
let ~{ocaml, hol} stringFromNatural n =
  if n = 0 then "0" else toString (stringFromNaturalHelper n [])

declare hol target_rep function stringFromNatural = 'num_to_dec_string'
declare ocaml target_rep function stringFromNatural = 'Nat_big_num.to_string'

assert stringFromNatural0 : stringFromNatural 0 = "0"
assert stringFromNatural1 : stringFromNatural 1 = "1"
assert stringFromNatural2 : stringFromNatural 42 = "42"

val stringFromInt : INT → STRING
let ~{ocaml} stringFromInt i =
  if i < 0 then
    ~ "-" stringFromNat (natFromInt i)
  else
    stringFromNat (natFromInt i)

declare ocaml target_rep function stringFromInt = 'string_of_int'

assert stringFromInt0 : stringFromInt 0 = "0"
assert stringFromInt1 : stringFromInt 1 = "1"
assert stringFromInt2 : stringFromInt 42 = "42"
assert stringFromInt3 : stringFromInt (-1) = "-1"

val stringFromInteger :  $\mathbb{Z}$  → STRING
let ~{ocaml} stringFromInteger i =
  if i < 0 then
    ~ "-" stringFromNatural (naturalFromInteger i)
  else
    stringFromNatural (naturalFromInteger i)

declare ocaml target_rep function stringFromInteger = 'Nat_big_num.to_string'

assert stringFromInteger0 : stringFromInteger 0 = "0"
assert stringFromInteger1 : stringFromInteger 1 = "1"
assert stringFromInteger2 : stringFromInteger 42 = "42"
assert stringFromInteger3 : stringFromInteger (-1) = "-1"

(*****
(* List – like operations *)
*****)

val nth : STRING → NAT → CHAR
let nth s n = List.extra.nth (toCharList s) n

declare hol target_rep function nth l n = 'SUB' (l, n)

```

```

declare ocaml target_rep function nth = 'String.get'

val stringConcat : LIST STRING → STRING
let stringConcat s =
  List.foldr ~ ^ "" s

declare hol target_rep function stringConcat = 'CONCAT'
declare ocaml target_rep function stringConcat s = 'String.concat' ^ "" s

(*****
(* String comparison
*)
*****)

val stringCompare : STRING → STRING → ORDERING

(* TODO : *)
let inline stringCompare x y = EQ (* XXX : broken *)
let inline {ocaml} stringCompare = defaultCompare

declare compile_message stringCompare = "It is highly unclear, what string comparison should do. Do we have  $abc < ABC$ "

let stringLess x y = orderingIsLess (stringCompare x y)
let stringLessEq x y = orderingIsLessEqual (stringCompare x y)
let stringGreater x y = stringLess y x
let stringGreaterEq x y = stringLessEq y x

instance (Ord STRING)
  let compare = stringCompare
  let < = stringLess
  let <= = stringLessEq
  let > = stringGreater
  let >= = stringGreaterEq
end

assert {ocaml} string_compare1 : "abc" < "bbc"
assert {ocaml} string_compare2 : "abc" ≤ "abc"
assert {ocaml} string_compare3 : "abc" > "ab"

```

## 23 Word

```

(* *****
(* A generic library for machine words.
(* *****

declare {isabelle, coq, hol, ocaml} rename module = Lem_word

open import Bool Maybe Num Basic_classes List

open import {isabelle} HOL – Word.Word
open import {hol} wordsTheory wordsLib

(* ===== *)
(* Define general purpose word, i.e. sequences of bits of arbitrary length *)
(* ===== *)

type BITSEQUENCE = BITSEQ of
  MAYBE NAT * (* length of the sequence, Nothing means infinite length *)
  BOOL * (* sign of the word, used to fill up after concrete value is exhausted *)
  LIST BOOL (* the initial part of the sequence, least significant bit first *)

val bitSeqEq : BITSEQUENCE → BITSEQUENCE → BOOL
let inline bitSeqEq = unsafe_structural_equality
instance (Eq BITSEQUENCE)
  let == bitSeqEq
  let <> n1 n2 = ¬ (bitSeqEq n1 n2)
end

val boolListFrombitSeq : NAT → BITSEQUENCE → LIST BOOL

let rec boolListFrombitSeqAux n s bl =
  if n = 0 then [] else
  match bl with
  | [] → replicate n s
  | b :: bl' → b :: (boolListFrombitSeqAux (n-1) s bl')
end
declare termination_argument boolListFrombitSeqAux = automatic

let boolListFrombitSeq n (BitSeq _ s bl) = boolListFrombitSeqAux n s bl

assert boolListFrombitSeq0 : boolListFrombitSeq 5 (BitSeq Nothing false [true; false; true]) = [true; false; true; false; false]
assert boolListFrombitSeq1 : boolListFrombitSeq 5 (BitSeq Nothing true [true; false; true]) = [true; false; true; true; true]
assert boolListFrombitSeq2 : boolListFrombitSeq 2 (BitSeq Nothing true [true; false; true]) = [true; false]

lemma boolListFrombitSeq_len : ∀ n bs. (List.length (boolListFrombitSeq n bs) = n)

val bitSeqFromBoolList : LIST BOOL → MAYBE BITSEQUENCE
let bitSeqFromBoolList bl =
  match dest_init bl with
  | Nothing → Nothing
  | Just (bl', s) → Just (BitSeq (Just (List.length bl)) s bl')
end

```

```

assert bitSeqFromBoolList0 : bitSeqFromBoolList [] = Nothing
assert bitSeqFromBoolList1 : bitSeqFromBoolList [true; false; false] = Just (BitSeq (Just 3) false [true; false])
assert bitSeqFromBoolList2 : bitSeqFromBoolList [true; false; true] = Just (BitSeq (Just 3) true [true; false])

```

```

lemma bitSeqFromBoolList_nothing :  $\forall bl. (\text{isNothing } (\text{bitSeqFromBoolList } bl) \longleftrightarrow \text{List.null } bl)$ 

```

```

(* cleans up the representation of a bitSequence without changing its semantics *)

```

```

val cleanBitSeq : BITSEQUENCE → BITSEQUENCE

```

```

let cleanBitSeq (BitSeq len s bl) = match len with
| Nothing → (BitSeq len s (List.reverse (dropWhile ((=) s) (List.reverse bl))))
| Just n → (BitSeq len s (List.reverse (dropWhile ((=) s) (List.reverse (List.take (n-1) bl))))))
end

```

```

assert cleanBitSeq0 : cleanBitSeq (BitSeq Nothing false [true; false; true; false; false]) = (BitSeq Nothing false [true; false; true])

```

```

assert cleanBitSeq1 : cleanBitSeq (BitSeq Nothing true [true; false; true; false; false]) = (BitSeq Nothing true [true; false; true; false])

```

```

assert cleanBitSeq2 : cleanBitSeq (BitSeq (Just 4) true [true; false; true; false; false]) = (BitSeq (Just 4) true [true; false])

```

```

val bitSeqTestBit : BITSEQUENCE → NAT → MAYBE BOOL

```

```

let bitSeqTestBit (BitSeq len s bl) pos =
  match len with
  | Nothing → if pos < length bl then index bl pos else Just s
  | Just l → if (pos ≥ l) then Nothing else
    if (pos = (l - 1) ∨ pos ≥ length bl) then Just s else
    index bl pos
end

```

```

val bitSeqSetBit : BITSEQUENCE → NAT → BOOL → BITSEQUENCE

```

```

let bitSeqSetBit (BitSeq len s bl) pos v =
  let bl' = if (pos < length bl) then bl else bl ++ replicate pos s in
  let bl'' = List.update bl' pos v in
  let bs' = BitSeq len s bl'' in
  cleanBitSeq bs'

```

```

val resizeBitSeq : MAYBE NAT → BITSEQUENCE → BITSEQUENCE

```

```

let resizeBitSeq new_len bs =
  let (BitSeq len s bl) = cleanBitSeq bs in
  let shorten_opt = match (new_len, len) with
  | (Nothing, _) → Nothing
  | (Just l1, Nothing) → Just l1
  | (Just l1, Just l2) → if (l1 < l2) then Just l1 else Nothing
  end in
  match shorten_opt with
  | Nothing → BitSeq new_len s bl
  | Just l1 → (
    let bl' = List.take l1 (bl ++ [s]) in
    match dest_init bl' with
    | Nothing → (BitSeq len s bl) (* do nothing if size 0 is requested *)
    | Just (bl'', s') → cleanBitSeq (BitSeq new_len s' bl'')
  )
end)
end

```

```

assert resizeBitSeq0 : (resizeBitSeq Nothing (BitSeq (Just 5) true [false; false]) = (BitSeq Nothing true [false; false]))

```

```

assert resizeBitSeq1 : (resizeBitSeq (Just 3) (BitSeq Nothing true [false; true; false; false])) = (BitSeq (Just 3) false [false; true]))
assert resizeBitSeq2 : (resizeBitSeq (Just 3) (BitSeq Nothing false [false; true; true; false])) = (BitSeq (Just 3) true [false]))
assert resizeBitSeq3 : (resizeBitSeq (Just 3) (BitSeq (Just 10) false [false; true; true; false])) = (BitSeq (Just 3) true [false]))
assert resizeBitSeq4 : (resizeBitSeq (Just 10) (BitSeq (Just 3) false [false; true; true; false])) = (BitSeq (Just 10) false [false; true]))

val bitSeqNot : BITSEQUENCE → BITSEQUENCE
let bitSeqNot (BitSeq len s bl) = BitSeq len (¬ s) (List.map (fun b → ¬ b) bl)

assert bitSeqNot0 : (bitSeqNot (BitSeq (Just 2) true [false; true])) = BitSeq (Just 2) false [true; false]

val bitSeqBinop : (BOOL → BOOL → BOOL) → BITSEQUENCE → BITSEQUENCE → BITSEQUENCE

val bitSeqBinopAux : (BOOL → BOOL → BOOL) → BOOL → LIST BOOL → BOOL → LIST BOOL →
LIST BOOL
let rec bitSeqBinopAux binop s1 bl1 s2 bl2 =
  match (bl1, bl2) with
  | ([], []) → []
  | (b1 :: bl1', []) → (binop b1 s2) :: bitSeqBinopAux binop s1 bl1' s2 []
  | ([], b2 :: bl2') → (binop s1 b2) :: bitSeqBinopAux binop s1 [] s2 bl2'
  | (b1 :: bl1', b2 :: bl2') → (binop b1 b2) :: bitSeqBinopAux binop s1 bl1' s2 bl2'
  end
declare termination_argument bitSeqBinopAux = automatic
declare coq target_rep function bitSeqBinopAux = 'bitSeqBinopAux'

let bitSeqBinop binop bs1 bs2 = (
  let (BitSeq len1 s1 bl1) = cleanBitSeq bs1 in
  let (BitSeq len2 s2 bl2) = cleanBitSeq bs2 in

  let len = match (len1, len2) with
  | (Just l1, Just l2) → Just (max l1 l2)
  | _ → Nothing
  end in
  let s = binop s1 s2 in
  let bl = bitSeqBinopAux binop s1 bl1 s2 bl2 in
  cleanBitSeq (BitSeq len s bl)
)

let bitSeqAnd = bitSeqBinop (∧)
let bitSeqOr = bitSeqBinop (∨)
let bitSeqXor = bitSeqBinop xor

val bitSeqShiftLeft : BITSEQUENCE → NAT → BITSEQUENCE
let bitSeqShiftLeft (BitSeq len s bl) n = cleanBitSeq (BitSeq len s (replicate n false ++ bl))

val bitSeqArithmeticShiftRight : BITSEQUENCE → NAT → BITSEQUENCE
let bitSeqArithmeticShiftRight bs n =
  let (BitSeq len s bl) = cleanBitSeq bs in
  cleanBitSeq (BitSeq len s (drop n bl))

val bitSeqLogicalShiftRight : BITSEQUENCE → NAT → BITSEQUENCE
let bitSeqLogicalShiftRight bs n =
  if (n = 0) then cleanBitSeq bs else
  let (BitSeq len s bl) = cleanBitSeq bs in

```

```

match len with
| Nothing → cleanBitSeq (BitSeq len s (drop n bl))
| Just l → cleanBitSeq (BitSeq len false ((drop n bl) ++ replicate l s))
end

(* integerFromBoolList sign bl creates an integer from a list of bits (least significant bit first) and an e
val integerFromBoolList : (BOOL * LIST BOOL) →  $\mathbb{Z}$ 

let rec integerFromBoolListAux (acc :  $\mathbb{Z}$ ) (bl : LIST BOOL) =
  match bl with
  | [] → acc
  | (true :: bl') → integerFromBoolListAux ((acc * 2) + 1) bl'
  | (false :: bl') → integerFromBoolListAux (acc * 2) bl'
end
declare termination_argument integerFromBoolListAux = automatic

let integerFromBoolList (sign, bl) =
  if sign then
    -(integerFromBoolListAux 0 (List.reverseMap (fun b → ¬ b) bl) + 1)
  else integerFromBoolListAux 0 (List.reverse bl)

assert integerFromBoolList0 : integerFromBoolList (false, [false; true; false]) = 2
assert integerFromBoolList1 : integerFromBoolList (false, [false; true; false; true]) = 10
assert integerFromBoolList2 : integerFromBoolList (true, [false; true; false; true]) = -6
assert integerFromBoolList3 : integerFromBoolList (true, [false; true]) = -2
assert integerFromBoolList4 : integerFromBoolList (true, [true; false]) = -3

(* [boolListFromInteger i] creates a sign bit and a list of booleans from an integer. The len_opt tells it when
val boolListFromInteger :  $\mathbb{Z}$  → BOOL * LIST BOOL

let rec boolListFromNatural acc (remainder :  $\mathbb{N}$ ) =
  if (remainder > 0) then
    (boolListFromNatural (((remainder mod 2) = 1) :: acc)
     (remainder / 2))
  else
    List.reverse acc
declare termination_argument boolListFromNatural = automatic
declare coq target_rep function boolListFromNatural = 'boolListFromNatural'

let boolListFromInteger (i :  $\mathbb{Z}$ ) =
  if (i < 0) then
    (true, List.map (fun b → ¬ b) (boolListFromNatural [] (naturalFromInteger (-(i + 1)))))
  else
    (false, boolListFromNatural [] (naturalFromInteger i))

assert boolListFromInteger0 : boolListFromInteger 2 = (false, [false; true])
assert boolListFromInteger1 : boolListFromInteger 10 = (false, [false; true; false; true])
assert boolListFromInteger2 : boolListFromInteger (-6) = (true, [false; true; false])
assert boolListFromInteger3 : boolListFromInteger (-2) = (true, [false])
assert boolListFromInteger4 : boolListFromInteger (-3) = (true, [true; false])

lemma boolListFromInteger_inverse1 : (∀ i. integerFromBoolList (boolListFromInteger i) = i)
lemma boolListFromInteger_inverse2 : (∀ s bl i. boolListFromInteger (integerFromBoolList (s, bl)) =
  (s, List.reverse (dropWhile ((=) s) (List.reverse bl))))

(* [bitSeqFromInteger len_opt i] encodes [i] as a bitsequence with [len_opt] bits. If there are not enough bits

```

```

val bitSeqFromInteger : MAYBE NAT →  $\mathbb{Z}$  → BITSEQUENCE
let bitSeqFromInteger len_opt i =
  let (s, bl) = boolListFromInteger i in
  resizeBitSeq len_opt (BitSeq Nothing s bl)

assert bitSeqFromInteger0 : (bitSeqFromInteger Nothing 5 = BitSeq Nothing false [true; false; true])
assert bitSeqFromInteger1 : (bitSeqFromInteger (Just 2) 5 = BitSeq (Just 2) false [true])
assert bitSeqFromInteger2 : (bitSeqFromInteger Nothing (-5) = BitSeq Nothing true [true; true; false])
assert bitSeqFromInteger3 : (bitSeqFromInteger (Just 3) (-5) = BitSeq (Just 3) false [true; true])
assert bitSeqFromInteger4 : (bitSeqFromInteger (Just 2) (-5) = BitSeq (Just 2) true [])
assert bitSeqFromInteger5 : (bitSeqFromInteger (Just 5) (-5) = BitSeq (Just 5) true [true; true; false])

val integerFromBitSeq : BITSEQUENCE →  $\mathbb{Z}$ 
let integerFromBitSeq bs =
  let (BitSeq len s bl) = cleanBitSeq bs in
  integerFromBoolList (s, bl)

assert integerFromBitSeq0 : (integerFromBitSeq (BitSeq Nothing false [true; false; true]) = 5)
assert integerFromBitSeq1 : (integerFromBitSeq (BitSeq (Just 2) false [true]) = 1)
assert integerFromBitSeq2 : (integerFromBitSeq (BitSeq Nothing true [true; true; false]) = (-5))
assert integerFromBitSeq3 : (integerFromBitSeq (BitSeq (Just 2) true [true; true; false]) = (-1))

lemma integerFromBitSeq_inv : (∀ i. integerFromBitSeq (bitSeqFromInteger Nothing i) = i)
assert integerFromBitSeq_inv0 : (integerFromBitSeq (bitSeqFromInteger Nothing 10)) = 10
assert integerFromBitSeq_inv1 : (integerFromBitSeq (bitSeqFromInteger Nothing (-1932))) = (-1932)
assert integerFromBitSeq_inv2 : (integerFromBitSeq (bitSeqFromInteger Nothing 343)) = 343

(* Now we can via translation to integers map arithmetic operations to bitSequences *)

val bitSeqArithUnaryOp : ( $\mathbb{Z}$  →  $\mathbb{Z}$ ) → BITSEQUENCE → BITSEQUENCE
let bitSeqArithUnaryOp uop bs =
  let (BitSeq len _) = bs in
  bitSeqFromInteger len (uop (integerFromBitSeq bs))

val bitSeqArithBinOp : ( $\mathbb{Z}$  →  $\mathbb{Z}$  →  $\mathbb{Z}$ ) → BITSEQUENCE →
BITSEQUENCE → BITSEQUENCE
let bitSeqArithBinOp binop bs1 bs2 =
  let (BitSeq len1 _) = bs1 in
  let (BitSeq len2 _) = bs2 in
  let len = match (len1, len2) with
    | (Just l1, Just l2) → Just (max l1 l2)
    | _ → Nothing
  in
  bitSeqFromInteger len (binop (integerFromBitSeq bs1) (integerFromBitSeq bs2))

val bitSeqArithBinTest : ∀ α. ( $\mathbb{Z}$  →  $\mathbb{Z}$  → α) → BITSEQUENCE →
BITSEQUENCE → α
let bitSeqArithBinTest binop bs1 bs2 = binop (integerFromBitSeq bs1) (integerFromBitSeq bs2)

(* now instantiate the number interface for bit - sequences *)

val bitSeqFromNumeral : NUMERAL → BITSEQUENCE
let inline bitSeqFromNumeral n = bitSeqFromInteger Nothing (integerFromNumeral n)

```



```

instance (Numeral BITSEQUENCE)
  let fromNumeral n = bitSeqFromNumeral n
end

val bitSeqLess : BITSEQUENCE → BITSEQUENCE → BOOL
let bitSeqLess bs1 bs2 = bitSeqArithBinTest (<) bs1 bs2

val bitSeqLessEqual : BITSEQUENCE → BITSEQUENCE → BOOL
let bitSeqLessEqual bs1 bs2 = bitSeqArithBinTest (≤) bs1 bs2

val bitSeqGreater : BITSEQUENCE → BITSEQUENCE → BOOL
let bitSeqGreater bs1 bs2 = bitSeqArithBinTest (>) bs1 bs2

val bitSeqGreaterEqual : BITSEQUENCE → BITSEQUENCE → BOOL
let bitSeqGreaterEqual bs1 bs2 = bitSeqArithBinTest (≥) bs1 bs2

val bitSeqCompare : BITSEQUENCE → BITSEQUENCE → ORDERING
let bitSeqCompare bs1 bs2 = bitSeqArithBinTest compare bs1 bs2

instance (Ord BITSEQUENCE)
  let compare = bitSeqCompare
  let < = bitSeqLess
  let <= = bitSeqLessEqual
  let > = bitSeqGreater
  let >= = bitSeqGreaterEqual
end

instance (SetType BITSEQUENCE)
  let setElemCompare = bitSeqCompare
end

(* arithmetic negation, don't mix up with bitwise negation *)
val bitSeqNegate : BITSEQUENCE → BITSEQUENCE
let bitSeqNegate bs = bitSeqArithUnaryOp integerNegate bs

instance (NumNegate BITSEQUENCE)
  let ~ = bitSeqNegate
end

val bitSeqAdd : BITSEQUENCE → BITSEQUENCE → BITSEQUENCE
let bitSeqAdd bs1 bs2 = bitSeqArithBinOp (+) bs1 bs2

instance (NumAdd BITSEQUENCE)
  let + = bitSeqAdd
end

val bitSeqMinus : BITSEQUENCE → BITSEQUENCE → BITSEQUENCE
let bitSeqMinus bs1 bs2 = bitSeqArithBinOp (−) bs1 bs2

instance (NumMinus BITSEQUENCE)
  let − = bitSeqMinus
end

val bitSeqSucc : BITSEQUENCE → BITSEQUENCE
let bitSeqSucc bs = bitSeqArithUnaryOp succ bs

instance (NumSucc BITSEQUENCE)

```

```

    let succ = bitSeqSucc
end

val bitSeqPred : BITSEQUENCE → BITSEQUENCE
let bitSeqPred bs = bitSeqArithUnaryOp pred bs

instance (NumPred BITSEQUENCE)
  let pred = bitSeqPred
end

val bitSeqMult : BITSEQUENCE → BITSEQUENCE → BITSEQUENCE
let bitSeqMult bs1 bs2 = bitSeqArithBinOp integerMult bs1 bs2

instance (NumMult BITSEQUENCE)
  let * = bitSeqMult
end

val bitSeqPow : BITSEQUENCE → NAT → BITSEQUENCE
let bitSeqPow bs n = bitSeqArithUnaryOp (fun i → integerPow i n) bs

instance ( NumPow BITSEQUENCE )
  let ** = bitSeqPow
end

val bitSeqDiv : BITSEQUENCE → BITSEQUENCE → BITSEQUENCE
let bitSeqDiv bs1 bs2 = bitSeqArithBinOp integerDiv bs1 bs2

instance ( NumIntegerDivision BITSEQUENCE )
  let div = bitSeqDiv
end

instance ( NumDivision BITSEQUENCE )
  let / = bitSeqDiv
end

val bitSeqMod : BITSEQUENCE → BITSEQUENCE → BITSEQUENCE
let bitSeqMod bs1 bs2 = bitSeqArithBinOp integerMod bs1 bs2

instance ( NumRemainder BITSEQUENCE )
  let mod = bitSeqMod
end

val bitSeqMin : BITSEQUENCE → BITSEQUENCE → BITSEQUENCE
let bitSeqMin bs1 bs2 = bitSeqArithBinOp integerMin bs1 bs2

val bitSeqMax : BITSEQUENCE → BITSEQUENCE → BITSEQUENCE
let bitSeqMax bs1 bs2 = bitSeqArithBinOp integerMax bs1 bs2

instance ( OrdMaxMin BITSEQUENCE )
  let max = bitSeqMax
  let min = bitSeqMin
end

assert bitSequence_test1 : (2 + (5 : BITSEQUENCE) = 7)
assert bitSequence_test2 : (8 - (7 : BITSEQUENCE) = 1)
assert bitSequence_test3 : (7 - (8 : BITSEQUENCE) = -1)
assert bitSequence_test4 : (7 * (8 : BITSEQUENCE) = 56)

```

```

assert bitSequence_test5 : ((7 : BITSEQUENCE)2 = 49)
assert bitSequence_test6 : (div 11 (4 : BITSEQUENCE) = 2)
assert bitSequence_test6a : (div (- 11) (4 : BITSEQUENCE) = -3)
assert bitSequence_test7 : (11 / (4 : BITSEQUENCE) = 2)
assert bitSequence_test7a : (-11 / (4 : BITSEQUENCE) = -3)
assert bitSequence_test8 : (11 mod (4 : BITSEQUENCE) = 3)
assert bitSequence_test8a : (-11 mod (4 : BITSEQUENCE) = 1)
assert bitSequence_test9 : (11 < (12 : BITSEQUENCE))
assert bitSequence_test10 : (11 ≤ (12 : BITSEQUENCE))
assert bitSequence_test11 : (12 ≤ (12 : BITSEQUENCE))
assert bitSequence_test12 : (¬ (12 < (12 : BITSEQUENCE)))
assert bitSequence_test13 : (12 > (11 : BITSEQUENCE))
assert bitSequence_test14 : (12 ≥ (11 : BITSEQUENCE))
assert bitSequence_test15 : (12 ≥ (12 : BITSEQUENCE))
assert bitSequence_test16 : (¬ (12 > (12 : BITSEQUENCE)))
assert bitSequence_test17 : (min 12 (12 : BITSEQUENCE) = 12)
assert bitSequence_test18 : (min 10 (12 : BITSEQUENCE) = 10)
assert bitSequence_test19 : (min 12 (10 : BITSEQUENCE) = 10)
assert bitSequence_test20 : (max 12 (12 : BITSEQUENCE) = 12)
assert bitSequence_test21 : (max 10 (12 : BITSEQUENCE) = 12)
assert bitSequence_test22 : (max 12 (10 : BITSEQUENCE) = 12)
assert bitSequence_test23 : (succ 12 = (13 : BITSEQUENCE))
assert bitSequence_test24 : (succ 0 = (1 : BITSEQUENCE))
assert bitSequence_test25 : (pred 12 = (11 : BITSEQUENCE))
assert bitSequence_test26 : (pred 0 = -(1 : BITSEQUENCE))

```

```

(* ===== *)
(* Interface for bitoperations *)
(* ===== *)

```

```

class ( WordNot α )
  val lnot : α → α
end

```

```

class ( WordAnd α )
  val land [conjunction] : α → α → α
end

```

```

class ( WordOr α )
  val lor [inclusive_or] : α → α → α
end

```

```

class ( WordXor α )
  val lxor [exclusive_or] : α → α → α
end

```

```

class ( WordLsl α )
  val lsl [left_shift] : α → NAT → α
end

```

```

class ( WordLsr α )
  val lsr [logical_right_shift] : α → NAT → α
end

```

```

class ( WordAsr  $\alpha$  )
  val asr [arithmetic_right_shift] :  $\alpha \rightarrow \text{NAT} \rightarrow \alpha$ 
end

(* ----- *)
(* bitSequence *)
(* ----- *)

instance ( WordNot BITSEQUENCE )
  let lnot = bitSeqNot
end

instance ( WordAnd BITSEQUENCE )
  let land = bitSeqAnd
end

instance ( WordOr BITSEQUENCE )
  let lor = bitSeqOr
end

instance ( WordXor BITSEQUENCE )
  let lxor = bitSeqXor
end

instance ( WordLsl BITSEQUENCE )
  let lsl = bitSeqShiftLeft
end

instance ( WordLsr BITSEQUENCE )
  let lsr = bitSeqLogicalShiftRight
end

instance ( WordAsr BITSEQUENCE )
  let asr = bitSeqArithmeticShiftRight
end

assert bitSequence_bittest1 : ((6 : BITSEQUENCE) land 5 = 4)
assert bitSequence_bittest2 : ((6 : BITSEQUENCE) lor 5 = 7)
assert bitSequence_bittest3 : ((6 : BITSEQUENCE) lxor 5 = 3)
assert bitSequence_bittest4 : ((12 : BITSEQUENCE) land 9 = 8)
assert bitSequence_bittest5 : ((12 : BITSEQUENCE) lor 9 = 13)
assert bitSequence_bittest6 : ((12 : BITSEQUENCE) lxor 9 = 5)

assert bitSequence_bittest7 : (lnot (12 : BITSEQUENCE) = -13)
assert bitSequence_bittest8 : (lnot (27 : BITSEQUENCE) = -28)
assert bitSequence_bittest9 : ((27 : BITSEQUENCE) lsl 0 = 27)
assert bitSequence_bittest10 : ((27 : BITSEQUENCE) lsl 1 = 54)
assert bitSequence_bittest11 : ((27 : BITSEQUENCE) lsl 2 = 108)
assert bitSequence_bittest12 : ((27 : BITSEQUENCE) lsl 3 = 216)
assert bitSequence_bittest13 : ((27 : BITSEQUENCE) lsr 0 = 27)
assert bitSequence_bittest14 : ((27 : BITSEQUENCE) lsr 1 = 13)
assert bitSequence_bittest15 : ((27 : BITSEQUENCE) lsr 2 = 6)
assert bitSequence_bittest16 : ((27 : BITSEQUENCE) lsr 3 = 3)
assert bitSequence_bittest17 : ((27 : BITSEQUENCE) asr 0 = 27)
assert bitSequence_bittest18 : ((27 : BITSEQUENCE) asr 1 = 13)
assert bitSequence_bittest19 : ((27 : BITSEQUENCE) asr 2 = 6)
assert bitSequence_bittest20 : ((27 : BITSEQUENCE) asr 3 = 3)
assert bitSequence_bittest21 : ((-(27 : BITSEQUENCE)) lsr 0 = -(27))

```

```

assert bitSequence_bittest22 : ((-(27 : BITSEQUENCE) asr 0) = -(27))
assert bitSequence_bittest23 : ((-(27 : BITSEQUENCE)) lsr 1 = -(14))
assert bitSequence_bittest24 : ((-(27 : BITSEQUENCE)) asr 1 = -(14))

```

```

(* ----- *)
(* int32      *)
(* ----- *)

```

```

val int32Lnot : INT32 → INT32
declare ocaml target_rep function int32Lnot = 'Int32.lognot'
declare hol target_rep function int32Lnot w = ('~' w)
declare isabelle target_rep function int32Lnot w = ('NOT' w)
declare coq target_rep function int32Lnot w = w (* XXX: fix *)

```

```

instance ( WordNot INT32 )
  let lnot = int32Lnot
end

```

```

val int32Lor : INT32 → INT32 → INT32
declare ocaml target_rep function int32Lor = 'Int32.logor'
declare hol target_rep function int32Lor = 'word_or'
declare isabelle target_rep function int32Lor = infix 'OR'
declare coq target_rep function int32Lor q w = w (* XXX: fix *)

```

```

instance ( WordOr INT32 )
  let lor = int32Lor
end

```

```

val int32Lxor : INT32 → INT32 → INT32
declare ocaml target_rep function int32Lxor = 'Int32.logxor'
declare hol target_rep function int32Lxor = 'word_xor'
declare isabelle target_rep function int32Lxor = infix 'XOR'
declare coq target_rep function int32Lxor q w = w (* XXX: fix *)

```

```

instance ( WordXor INT32 )
  let lxor = int32Lxor
end

```

```

val int32Land : INT32 → INT32 → INT32
declare ocaml target_rep function int32Land = 'Int32.logand'
declare hol target_rep function int32Land = 'word_and'
declare isabelle target_rep function int32Land = infix 'AND'
declare coq target_rep function int32Land q w = w (* XXX: fix *)

```

```

instance ( WordAnd INT32 )
  let land = int32Land
end

```

```

val int32Lsl : INT32 → NAT → INT32
declare ocaml target_rep function int32Lsl = 'Int32.shift_left'
declare hol target_rep function int32Lsl = 'word_lsl'
declare isabelle target_rep function int32Lsl = infix '<<'
declare coq target_rep function int32Lsl q w = q (* XXX: fix *)

```

```

instance ( WordLsl INT32 )
  let lsl = int32Lsl

```

end

```
val int32Lsr : INT32 → NAT → INT32
declare ocaml target_rep function int32Lsr = 'Int32.shift_right_logical'
declare hol target_rep function int32Lsr = 'word_lsr'
declare isabelle target_rep function int32Lsr = infix '>>'
declare coq target_rep function int32Lsr q w = q (* XXX : fix *)
```

```
instance (WordLsr INT32)
  let lsr = int32Lsr
end
```

```
val int32Asr : INT32 → NAT → INT32
declare ocaml target_rep function int32Asr = 'Int32.shift_right'
declare hol target_rep function int32Asr = 'word_asr'
declare isabelle target_rep function int32Asr = infix '>>>'
declare coq target_rep function int32Asr q w = q (* XXX : fix *)
```

```
instance (WordAsr INT32)
  let asr = int32Asr
end
```

```
assert int32_bittest1 : ((6 : INT32) land 5 = 4)
assert int32_bittest2 : ((6 : INT32) lor 5 = 7)
assert int32_bittest3 : ((6 : INT32) lxor 5 = 3)
assert int32_bittest4 : ((12 : INT32) land 9 = 8)
assert int32_bittest5 : ((12 : INT32) lor 9 = 13)
assert int32_bittest6 : ((12 : INT32) lxor 9 = 5)

assert int32_bittest7 : (lnot (12 : INT32) = -13)
assert int32_bittest8 : (lnot (27 : INT32) = -28)
assert int32_bittest9 : ((27 : INT32) lsl 0 = 27)
assert int32_bittest10 : ((27 : INT32) lsl 1 = 54)
assert int32_bittest11 : ((27 : INT32) lsl 2 = 108)
assert int32_bittest12 : ((27 : INT32) lsl 3 = 216)
assert int32_bittest13 : ((27 : INT32) lsr 0 = 27)
assert int32_bittest14 : ((27 : INT32) lsr 1 = 13)
assert int32_bittest15 : ((27 : INT32) lsr 2 = 6)
assert int32_bittest16 : ((27 : INT32) lsr 3 = 3)
assert int32_bittest17 : ((27 : INT32) asr 0 = 27)
assert int32_bittest18 : ((27 : INT32) asr 1 = 13)
assert int32_bittest19 : ((27 : INT32) asr 2 = 6)
assert int32_bittest20 : ((27 : INT32) asr 3 = 3)
assert int32_bittest21 : ((-(27 : INT32)) lsr 0 = -(27))
assert int32_bittest22 : ((-(27 : INT32) asr 0) = -(27))
assert int32_bittest23 : ((-(27 : INT32)) lsr 2 = 1073741817)
assert int32_bittest24 : ((-(27 : INT32)) asr 2 = -(7))
```

```
(* ----- *)
(* int64          *)
(* ----- *)
```

```
val int64Lnot : INT64 → INT64
declare ocaml target_rep function int64Lnot = 'Int64.lognot'
declare hol target_rep function int64Lnot w = (~, w)
```

```

declare isabelle target_rep function int64Lnot  $w = ('NOT' w)$ 
declare coq target_rep function int64Lnot  $w = w (* XXX : fix *)$ 

instance ( WordNot INT64)
  let lnot = int64Lnot
end

val int64Lor : INT64 → INT64 → INT64
declare ocaml target_rep function int64Lor = 'Int64.logor'
declare hol target_rep function int64Lor = 'word_or'
declare isabelle target_rep function int64Lor = infix 'OR'
declare coq target_rep function int64Lor  $q w = w (* XXX : fix *)$ 

instance ( WordOr INT64)
  let lor = int64Lor
end

val int64Lxor : INT64 → INT64 → INT64
declare ocaml target_rep function int64Lxor = 'Int64.logxor'
declare hol target_rep function int64Lxor = 'word_xor'
declare isabelle target_rep function int64Lxor = infix 'XOR'
declare coq target_rep function int64Lxor  $q w = w (* XXX : fix *)$ 

instance ( WordXor INT64)
  let lxor = int64Lxor
end

val int64Land : INT64 → INT64 → INT64
declare ocaml target_rep function int64Land = 'Int64.logand'
declare hol target_rep function int64Land = 'word_and'
declare isabelle target_rep function int64Land = infix 'AND'
declare coq target_rep function int64Land  $q w = w (* XXX : fix *)$ 

instance ( WordAnd INT64)
  let land = int64Land
end

val int64Lsl : INT64 → NAT → INT64
declare ocaml target_rep function int64Lsl = 'Int64.shift_left'
declare hol target_rep function int64Lsl = 'word_lsl'
declare isabelle target_rep function int64Lsl = infix '<<'
declare coq target_rep function int64Lsl  $q w = q (* XXX : fix *)$ 

instance ( WordLsl INT64)
  let lsl = int64Lsl
end

val int64Lsr : INT64 → NAT → INT64
declare ocaml target_rep function int64Lsr = 'Int64.shift_right_logical'
declare hol target_rep function int64Lsr = 'word_lsr'
declare isabelle target_rep function int64Lsr = infix '>>'
declare coq target_rep function int64Lsr  $q w = q (* XXX : fix *)$ 

instance ( WordLsr INT64)
  let lsr = int64Lsr
end

val int64Asr : INT64 → NAT → INT64

```

```

declare ocaml target_rep function int64Asr = 'Int64.shift_right'
declare hol target_rep function int64Asr = 'word_asr'
declare isabelle target_rep function int64Asr = infix '>>>'
declare coq target_rep function int64Asr q w = q (* XXX : fix *)

```

```

instance (WordAsr INT64)
  let asr = int64Asr
end

```

```

assert int64_bittest1 : ((6 : INT64) land 5 = 4)
assert int64_bittest2 : ((6 : INT64) lor 5 = 7)
assert int64_bittest3 : ((6 : INT64) lxor 5 = 3)
assert int64_bittest4 : ((12 : INT64) land 9 = 8)
assert int64_bittest5 : ((12 : INT64) lor 9 = 13)
assert int64_bittest6 : ((12 : INT64) lxor 9 = 5)

assert int64_bittest7 : (lnot (12 : INT64) = -13)
assert int64_bittest8 : (lnot (27 : INT64) = -28)
assert int64_bittest9 : ((27 : INT64) lsl 0 = 27)
assert int64_bittest10 : ((27 : INT64) lsl 1 = 54)
assert int64_bittest11 : ((27 : INT64) lsl 2 = 108)
assert int64_bittest12 : ((27 : INT64) lsl 3 = 216)
assert int64_bittest13 : ((27 : INT64) lsr 0 = 27)
assert int64_bittest14 : ((27 : INT64) lsr 1 = 13)
assert int64_bittest15 : ((27 : INT64) lsr 2 = 6)
assert int64_bittest16 : ((27 : INT64) lsr 3 = 3)
assert int64_bittest17 : ((27 : INT64) asr 0 = 27)
assert int64_bittest18 : ((27 : INT64) asr 1 = 13)
assert int64_bittest19 : ((27 : INT64) asr 2 = 6)
assert int64_bittest20 : ((27 : INT64) asr 3 = 3)
assert int64_bittest21 : ((-(27 : INT64)) lsr 0 = -(27))
assert int64_bittest22 : ((-(27 : INT64) asr 0) = -(27))
assert int64_bittest23 : ((-(27 : INT64)) lsr 34 = 1073741823)
assert int64_bittest24 : ((-(27 : INT64)) asr 2 = -(7))

```

```

(* ----- *)
(* Words via bit sequences *)
(* ----- *)

```

```

val defaultLnot : ∀ α. (BITSEQUENCE → α) → (α → BITSEQUENCE) → α → α
let defaultLnot fromBitSeq toBitSeq x = fromBitSeq (bitSeqNegate (toBitSeq x))

```

```

val defaultLand : ∀ α. (BITSEQUENCE → α) → (α → BITSEQUENCE) → α → α → α
let defaultLand fromBitSeq toBitSeq x1 x2 = fromBitSeq (bitSeqAnd (toBitSeq x1) (toBitSeq x2))

```

```

val defaultLor : ∀ α. (BITSEQUENCE → α) → (α → BITSEQUENCE) → α → α → α
let defaultLor fromBitSeq toBitSeq x1 x2 = fromBitSeq (bitSeqOr (toBitSeq x1) (toBitSeq x2))

```

```

val defaultLxor : ∀ α. (BITSEQUENCE → α) → (α → BITSEQUENCE) → α → α → α
let defaultLxor fromBitSeq toBitSeq x1 x2 = fromBitSeq (bitSeqXor (toBitSeq x1) (toBitSeq x2))

```

```

val defaultLsl : ∀ α. (BITSEQUENCE → α) → (α → BITSEQUENCE) → α → NAT → α
let defaultLsl fromBitSeq toBitSeq x n = fromBitSeq (bitSeqShiftLeft (toBitSeq x) n)

```

```

val defaultLsr : ∀ α. (BITSEQUENCE → α) → (α → BITSEQUENCE) → α → NAT → α
let defaultLsr fromBitSeq toBitSeq x n = fromBitSeq (bitSeqLogicalShiftRight (toBitSeq x) n)

```



```

val defaultAsr :  $\forall \alpha. (\text{BITSEQUENCE} \rightarrow \alpha) \rightarrow (\alpha \rightarrow \text{BITSEQUENCE}) \rightarrow \alpha \rightarrow \text{NAT} \rightarrow \alpha$ 
let defaultAsr fromBitSeq toBitSeq x n = fromBitSeq (bitSeqArithmeticShiftRight (toBitSeq x) n)

```

```

(* ----- *)
(* integer      *)
(* ----- *)

```

```

val integerLnot :  $\mathbb{Z} \rightarrow \mathbb{Z}$ 
let integerLnot i =  $-(i + 1)$ 

```

```

instance ( WordNot  $\mathbb{Z}$  )
  let lnot = integerLnot
end

```

```

val integerLor :  $\mathbb{Z} \rightarrow \mathbb{Z} \rightarrow \mathbb{Z}$ 
let integerLor i1 i2 = defaultLor integerFromBitSeq (bitSeqFromInteger Nothing) i1 i2
declare ocaml target_rep function integerLor = 'Nat_big_num.bitwise_or'

```

```

instance ( WordOr  $\mathbb{Z}$  )
  let lor = integerLor
end

```

```

val integerLxor :  $\mathbb{Z} \rightarrow \mathbb{Z} \rightarrow \mathbb{Z}$ 
let integerLxor i1 i2 = defaultLxor integerFromBitSeq (bitSeqFromInteger Nothing) i1 i2
declare ocaml target_rep function integerLxor = 'Nat_big_num.bitwise_xor'

```

```

instance ( WordXor  $\mathbb{Z}$  )
  let lxor = integerLxor
end

```

```

val integerLand :  $\mathbb{Z} \rightarrow \mathbb{Z} \rightarrow \mathbb{Z}$ 
let integerLand i1 i2 = defaultLand integerFromBitSeq (bitSeqFromInteger Nothing) i1 i2
declare ocaml target_rep function integerLand = 'Nat_big_num.bitwise_and'

```

```

instance ( WordAnd  $\mathbb{Z}$  )
  let land = integerLand
end

```

```

val integerLsl :  $\mathbb{Z} \rightarrow \text{NAT} \rightarrow \mathbb{Z}$ 
let integerLsl i n = defaultLsl integerFromBitSeq (bitSeqFromInteger Nothing) i n
declare ocaml target_rep function integerLsl = 'Nat_big_num.shift_left'

```

```

instance ( WordLsl  $\mathbb{Z}$  )
  let lsl = integerLsl
end

```

```

val integerAsr :  $\mathbb{Z} \rightarrow \text{NAT} \rightarrow \mathbb{Z}$ 
let integerAsr i n = defaultAsr integerFromBitSeq (bitSeqFromInteger Nothing) i n
declare ocaml target_rep function integerAsr = 'Nat_big_num.shift_right'

```

```

instance ( WordLsr  $\mathbb{Z}$  )
  let lsr = integerAsr
end

```

```

instance ( WordAsr  $\mathbb{Z}$  )
  let asr = integerAsr

```

end

```

assert integer_bittest1 : ((6 :  $\mathbb{Z}$ ) land 5 = 4)
assert integer_bittest2 : ((6 :  $\mathbb{Z}$ ) lor 5 = 7)
assert integer_bittest3 : ((6 :  $\mathbb{Z}$ ) lxor 5 = 3)
assert integer_bittest4 : ((12 :  $\mathbb{Z}$ ) land 9 = 8)
assert integer_bittest5 : ((12 :  $\mathbb{Z}$ ) lor 9 = 13)
assert integer_bittest6 : ((12 :  $\mathbb{Z}$ ) lxor 9 = 5)

assert integer_bittest7 : (lnot (12 :  $\mathbb{Z}$ ) = -13)
assert integer_bittest8 : (lnot (27 :  $\mathbb{Z}$ ) = -28)
assert integer_bittest9 : ((27 :  $\mathbb{Z}$ ) lsl 0 = 27)
assert integer_bittest10 : ((27 :  $\mathbb{Z}$ ) lsl 1 = 54)
assert integer_bittest11 : ((27 :  $\mathbb{Z}$ ) lsl 2 = 108)
assert integer_bittest12 : ((27 :  $\mathbb{Z}$ ) lsl 3 = 216)
assert integer_bittest13 : ((27 :  $\mathbb{Z}$ ) lsr 0 = 27)
assert integer_bittest14 : ((27 :  $\mathbb{Z}$ ) lsr 1 = 13)
assert integer_bittest15 : ((27 :  $\mathbb{Z}$ ) lsr 2 = 6)
assert integer_bittest16 : ((27 :  $\mathbb{Z}$ ) lsr 3 = 3)
assert integer_bittest17 : ((27 :  $\mathbb{Z}$ ) asr 0 = 27)
assert integer_bittest18 : ((27 :  $\mathbb{Z}$ ) asr 1 = 13)
assert integer_bittest19 : ((27 :  $\mathbb{Z}$ ) asr 2 = 6)
assert integer_bittest20 : ((27 :  $\mathbb{Z}$ ) asr 3 = 3)
assert integer_bittest22 : ((-(27 :  $\mathbb{Z}$ ) asr 0) = -(27))
assert integer_bittest24 : ((-(27 :  $\mathbb{Z}$ ) asr 2) = -(7))

```

```

(* ----- *)
(* int          *)
(* ----- *)

```

(\* sometimes it is convenient to be able to perform bit – operations on ints. However, since int is not well

```

val intFromBitSeq : BITSEQUENCE → INT
let intFromBitSeq bs = intFromInteger (integerFromBitSeq (resizeBitSeq (Just 31) bs))

```

```

val bitSeqFromInt : INT → BITSEQUENCE
let bitSeqFromInt i = bitSeqFromInteger (Just 31) (integerFromInt i)

```

```

val intLnot : INT → INT
let intLnot i = -(i + 1)
declare ocaml target_rep function intLnot = 'lnot'

```

```

instance ( WordNot INT)
  let lnot = intLnot
end

```

```

val intLor : INT → INT → INT
let intLor i1 i2 = defaultLor intFromBitSeq bitSeqFromInt i1 i2
declare ocaml target_rep function intLor = infix 'lor'

```

```

instance ( WordOr INT)
  let lor = intLor
end

```

```

val intLxor : INT → INT → INT
let intLxor i1 i2 = defaultLxor intFromBitSeq bitSeqFromInt i1 i2
declare ocaml target_rep function intLxor = infix 'lxor'

```

```

instance (WordXor INT)
  let lxor = intLxor
end

```

```

val intLand : INT → INT → INT
let intLand i1 i2 = defaultLand intFromBitSeq bitSeqFromInt i1 i2
declare ocaml target_rep function intLand = infix 'land'

```

```

instance (WordAnd INT)
  let land = intLand
end

```

```

val intLsl : INT → NAT → INT
let intLsl i n = defaultLsl intFromBitSeq bitSeqFromInt i n
declare ocaml target_rep function intLsl = infix 'lsl'

```

```

instance (WordLsl INT)
  let lsl = intLsl
end

```

```

val intAsr : INT → NAT → INT
let intAsr i n = defaultAsr intFromBitSeq bitSeqFromInt i n
declare ocaml target_rep function intAsr = infix 'asr'

```

```

instance (WordAsr INT)
  let asr = intAsr
end

```

```

assert int_bittest1 : ((6 : INT) land 5 = 4)
assert int_bittest2 : ((6 : INT) lor 5 = 7)
assert int_bittest3 : ((6 : INT) lxor 5 = 3)
assert int_bittest4 : ((12 : INT) land 9 = 8)
assert int_bittest5 : ((12 : INT) lor 9 = 13)
assert int_bittest6 : ((12 : INT) lxor 9 = 5)

```

```

assert int_bittest7 : (lnot (12 : INT) = -13)
assert int_bittest8 : (lnot (27 : INT) = -28)
assert int_bittest9 : ((27 : INT) lsl 0 = 27)
assert int_bittest10 : ((27 : INT) lsl 1 = 54)
assert int_bittest11 : ((27 : INT) lsl 2 = 108)
assert int_bittest12 : ((27 : INT) lsl 3 = 216)
assert int_bittest17 : ((27 : INT) asr 0 = 27)
assert int_bittest18 : ((27 : INT) asr 1 = 13)
assert int_bittest19 : ((27 : INT) asr 2 = 6)
assert int_bittest20 : ((27 : INT) asr 3 = 3)
assert int_bittest22 : ((-(27 : INT) asr 0) = -(27))
assert int_bittest24 : ((-(27 : INT)) asr 2 = -(7))

```

(\* ----- \*)

```

(* natural *)
(* ----- *)

(* some operations work also on positive numbers *)

val naturalFromBitSeq : BITSEQUENCE →  $\mathbb{N}$ 
let naturalFromBitSeq bs = naturalFromInteger (integerFromBitSeq bs)

val bitSeqFromNatural : MAYBE NAT →  $\mathbb{N}$  → BITSEQUENCE
let bitSeqFromNatural len n = bitSeqFromInteger len (integerFromNatural n)

val naturalLor :  $\mathbb{N}$  →  $\mathbb{N}$  →  $\mathbb{N}$ 
let naturalLor i1 i2 = defaultLor naturalFromBitSeq (bitSeqFromNatural Nothing) i1 i2
declare ocaml target_rep function naturalLor = 'Nat_big_num.bitwise_or'

instance (WordOr  $\mathbb{N}$ )
  let lor = naturalLor
end

val naturalLxor :  $\mathbb{N}$  →  $\mathbb{N}$  →  $\mathbb{N}$ 
let naturalLxor i1 i2 = defaultLxor naturalFromBitSeq (bitSeqFromNatural Nothing) i1 i2
declare ocaml target_rep function naturalLxor = 'Nat_big_num.bitwise_xor'

instance (WordXor  $\mathbb{N}$ )
  let lxor = naturalLxor
end

val naturalLand :  $\mathbb{N}$  →  $\mathbb{N}$  →  $\mathbb{N}$ 
let naturalLand i1 i2 = defaultLand naturalFromBitSeq (bitSeqFromNatural Nothing) i1 i2
declare ocaml target_rep function naturalLand = 'Nat_big_num.bitwise_and'

instance (WordAnd  $\mathbb{N}$ )
  let land = naturalLand
end

val naturalLsl :  $\mathbb{N}$  → NAT →  $\mathbb{N}$ 
let naturalLsl i n = defaultLsl naturalFromBitSeq (bitSeqFromNatural Nothing) i n
declare ocaml target_rep function naturalLsl = 'Nat_big_num.shift_left'

instance (WordLsl  $\mathbb{N}$ )
  let lsl = naturalLsl
end

val naturalAsr :  $\mathbb{N}$  → NAT →  $\mathbb{N}$ 
let naturalAsr i n = defaultAsr naturalFromBitSeq (bitSeqFromNatural Nothing) i n
declare ocaml target_rep function naturalAsr = 'Nat_big_num.shift_right'

instance (WordLsr  $\mathbb{N}$ )
  let lsr = naturalAsr
end

instance (WordAsr  $\mathbb{N}$ )
  let asr = naturalAsr
end

assert natural_bittest1 : ((6 :  $\mathbb{N}$ ) land 5 = 4)

```

```

assert natural_bittest2 : ((6 :  $\mathbb{N}$ ) lor 5 = 7)
assert natural_bittest3 : ((6 :  $\mathbb{N}$ ) lxor 5 = 3)
assert natural_bittest4 : ((12 :  $\mathbb{N}$ ) land 9 = 8)
assert natural_bittest5 : ((12 :  $\mathbb{N}$ ) lor 9 = 13)
assert natural_bittest6 : ((12 :  $\mathbb{N}$ ) lxor 9 = 5)

```

```

assert natural_bittest9 : ((27 :  $\mathbb{N}$ ) lsl 0 = 27)
assert natural_bittest10 : ((27 :  $\mathbb{N}$ ) lsl 1 = 54)
assert natural_bittest11 : ((27 :  $\mathbb{N}$ ) lsl 2 = 108)
assert natural_bittest12 : ((27 :  $\mathbb{N}$ ) lsl 3 = 216)
assert natural_bittest13 : ((27 :  $\mathbb{N}$ ) lsr 0 = 27)
assert natural_bittest14 : ((27 :  $\mathbb{N}$ ) lsr 1 = 13)
assert natural_bittest15 : ((27 :  $\mathbb{N}$ ) lsr 2 = 6)
assert natural_bittest16 : ((27 :  $\mathbb{N}$ ) lsr 3 = 3)
assert natural_bittest17 : ((27 :  $\mathbb{N}$ ) asr 0 = 27)
assert natural_bittest18 : ((27 :  $\mathbb{N}$ ) asr 1 = 13)
assert natural_bittest19 : ((27 :  $\mathbb{N}$ ) asr 2 = 6)
assert natural_bittest20 : ((27 :  $\mathbb{N}$ ) asr 3 = 3)

```

```

(* ----- *)
(* nat      *)
(* ----- *)

```

(\* sometimes it is convenient to be able to perform bit – operations on nats. However, since nat is not well

```

val natFromBitSeq : BITSEQUENCE → NAT
let natFromBitSeq bs = natFromNatural (naturalFromBitSeq (resizeBitSeq (Just 31) bs))

```

```

val bitSeqFromNat : NAT → BITSEQUENCE
let bitSeqFromNat i = bitSeqFromNatural (Just 31) (naturalFromNat i)

```

```

val natLor : NAT → NAT → NAT
let natLor i1 i2 = defaultLor natFromBitSeq bitSeqFromNat i1 i2
declare ocaml target_rep function natLor = infix 'lor'

```

```

instance (WordOr NAT)
  let lor = natLor
end

```

```

val natLxor : NAT → NAT → NAT
let natLxor i1 i2 = defaultLxor natFromBitSeq bitSeqFromNat i1 i2
declare ocaml target_rep function natLxor = infix 'lxor'

```

```

instance (WordXor NAT)
  let lxor = natLxor
end

```

```

val natLand : NAT → NAT → NAT
let natLand i1 i2 = defaultLand natFromBitSeq bitSeqFromNat i1 i2
declare ocaml target_rep function natLand = infix 'land'

```

```

instance (WordAnd NAT)
  let land = natLand
end

```

```

val natLsl : NAT → NAT → NAT
let natLsl i n = defaultLsl natFromBitSeq bitSeqFromNat i n
declare ocaml target_rep function natLsl = infix 'lsl'

instance (WordLsl NAT)
  let lsl = natLsl
end

val natAsr : NAT → NAT → NAT
let natAsr i n = defaultAsr natFromBitSeq bitSeqFromNat i n
declare ocaml target_rep function natAsr = infix 'asr'

instance (WordAsr NAT)
  let asr = natAsr
end

assert nat_bittest1 : ((6 : NAT) land 5 = 4)
assert nat_bittest2 : ((6 : NAT) lor 5 = 7)
assert nat_bittest3 : ((6 : NAT) lxor 5 = 3)
assert nat_bittest4 : ((12 : NAT) land 9 = 8)
assert nat_bittest5 : ((12 : NAT) lor 9 = 13)
assert nat_bittest6 : ((12 : NAT) lxor 9 = 5)

assert nat_bittest9 : ((27 : NAT) lsl 0 = 27)
assert nat_bittest10 : ((27 : NAT) lsl 1 = 54)
assert nat_bittest11 : ((27 : NAT) lsl 2 = 108)
assert nat_bittest12 : ((27 : NAT) lsl 3 = 216)
assert nat_bittest17 : ((27 : NAT) asr 0 = 27)
assert nat_bittest18 : ((27 : NAT) asr 1 = 13)
assert nat_bittest19 : ((27 : NAT) asr 2 = 6)
assert nat_bittest20 : ((27 : NAT) asr 3 = 3)

```

## 24 Show

```

declare {isabelle, hol, ocaml, coq} rename module = lem_show

open import String Maybe Num Basic_classes

open import {hol} lemTheory

class (Show  $\alpha$ )
  val show :  $\alpha \rightarrow \text{STRING}$ 
end

instance (Show STRING)
  let show s = ~ "\ " ~ s ~ "\ "
end

val stringFromMaybe :  $\forall \alpha. (\alpha \rightarrow \text{STRING}) \rightarrow \text{MAYBE } \alpha \rightarrow \text{STRING}$ 
let stringFromMaybe showX x =
  match x with
  | Just x  $\rightarrow$  ~ "Just (" ~ showX x ~ ")"
  | Nothing  $\rightarrow$  "Nothing"
end

instance  $\forall \alpha. \text{Show } \alpha \Rightarrow (\text{Show } (\text{MAYBE } \alpha))$ 
  let show x_opt = stringFromMaybe show x_opt
end

val stringFromListAux :  $\forall \alpha. (\alpha \rightarrow \text{STRING}) \rightarrow \text{LIST } \alpha \rightarrow \text{STRING}$ 
let rec stringFromListAux showX x =
  match x with
  | []  $\rightarrow$  ""
  | x :: xs'  $\rightarrow$ 
    match xs' with
    | []  $\rightarrow$  showX x
    | _  $\rightarrow$  ~ showX x ~ "; " ~ stringFromListAux showX xs'
    end
  end
end

val stringFromList :  $\forall \alpha. (\alpha \rightarrow \text{STRING}) \rightarrow \text{LIST } \alpha \rightarrow \text{STRING}$ 
let stringFromList showX xs =
  ~ "[" ~ stringFromListAux showX xs ~ "]"

instance  $\forall \alpha. \text{Show } \alpha \Rightarrow (\text{Show } (\text{LIST } \alpha))$ 
  let show xs = stringFromList show xs
end

val stringFromPair :  $\forall \alpha \beta. (\alpha \rightarrow \text{STRING}) \rightarrow (\beta \rightarrow \text{STRING}) \rightarrow (\alpha * \beta) \rightarrow \text{STRING}$ 
let stringFromPair showX showY (x, y) =
  ~ "(" ~ showX x ~ ", " ~ showY y ~ ")"

instance  $\forall \alpha \beta. \text{Show } \alpha, \text{Show } \beta \Rightarrow (\text{Show } (\alpha * \beta))$ 
  let show = stringFromPair show show
end

instance (Show BOOL)
  let show b = if b then "true" else "false"
end

```

## 25 Show\_extra

```
declare {isabelle, hol, ocaml, coq} rename module = lem_show_extra
```

```
open import String Maybe Num Basic_classes Set Relation Show
import Set_extra String_extra
```

```
instance (Show NAT)
  let show = String_extra.stringFromNat
end
```

```
instance (Show  $\mathbb{N}$ )
  let show = String_extra.stringFromNatural
end
```

```
instance (Show INT)
  let show = String_extra.stringFromInt
end
```

```
instance (Show  $\mathbb{Z}$ )
  let show = String_extra.stringFromInteger
end
```

```
let stringFromSet showX xs =
  ~ "{ " ^ Show.stringFromListAux showX (Set_extra.toList xs) " }
```

(\* Abbreviates the representation if the relation is transitive. \*)

```
let stringFromRelation showX rel1 =
  if isTransitive rel1 then
    let pruned_rel = withoutTransitiveEdges rel1 in
    if (∀ e ∈ rel1. (e ∈ pruned_rel)) then
      (* The relations are the same (there are no transitive edges),
        stringFromSet showX rel1
      else
        ~ "transcl of " stringFromSet showX pruned_rel
    else
      stringFromSet showX rel1
```

so we can just as well print the origin

```
instance ∀ α. Show α, SetType α ⇒ (Show (SET α))
  let show xs = stringFromSet show xs
end
```



## 26 Machine\_word

```
(*****)
(* A new machine word library, suitable for targetting from Sail, *)
(* and a thin wrapper around the HOL and Isabelle word libraries. *)
(*****)

declare {isabelle, coq, hol, ocaml} rename module = Lem_machine_word

open import Bool Num Basic_classes Show Function

open import {isabelle} HOL – Word.Word
open import {hol} wordsTheory wordsLib bitstringTheory integer_wordTheory

type MWORD  $\alpha$ 
declare isabelle target_sorts MWORD = len

class (Size  $\alpha$ )
  val size : NAT
end

declare isabelle target_rep type MWORD  $\alpha$  = 'Word.word'  $\alpha$ 
declare hol target_rep type MWORD  $\alpha$  = 'words$word'  $\alpha$ 
declare ocaml target_rep type MWORD  $\alpha$  = 'Lem.mword'

val native_size :  $\forall \alpha$ . NAT
declare hol target_rep function native_size = 'dimindex' ('the_value' : 'itself'  $\alpha$ )
declare isabelle target_rep function native_size = 'len_of' ('TYPE(_)' : 'itself'  $\alpha$ )

let inline {isabelle, hol} size = native_size

val ocaml_inject :  $\forall \alpha$ . NAT *  $\mathbb{N} \rightarrow$  MWORD  $\alpha$ 
declare ocaml target_rep function ocaml_inject = 'Lem.machine_word_inject'

(* A singleton type family that can be used to carry a size as the type parameter *)

type ITSELF  $\alpha$ 
declare isabelle target_sorts ITSELF = len
declare hol target_rep type ITSELF  $\alpha$  = 'itself'  $\alpha$ 
declare isabelle target_rep type ITSELF  $\alpha$  = 'itself'  $\alpha$ 
declare ocaml target_rep type ITSELF  $\alpha$  = 'unit'

val the_value :  $\forall \alpha$ . ITSELF  $\alpha$ 
declare hol target_rep function the_value = 'the_value'
declare isabelle target_rep function the_value = 'TYPE(_)'
declare ocaml target_rep function the_value = '()'

val size_itself :  $\forall \alpha$ . Size  $\alpha \Rightarrow$  ITSELF  $\alpha \rightarrow$  NAT
let size_itself x = size

(*****)
(* Fixed bitwidths extracted from Anthony's models. *)
(* *)
(* If you need a size N that is not included here, put the lines *)
(* *)
(* type tyN *)
(* instance (Size tyN) let size = N end *)
(* declare isabelle target_rep type tyN = 'N' *)
```

```

(* declare hol target_rep type tyN = 'N' *)
(* *)
(* in your project, replacing N in each line. *)
(*****)

```

```

type TY1
type TY2
type TY3
type TY4
type TY5
type TY6
type TY7
type TY8
type TY9
type TY10
type TY11
type TY12
type TY13
type TY14
type TY15
type TY16
type TY17
type TY18
type TY19
type TY20
type TY21
type TY22
type TY23
type TY24
type TY25
type TY26
type TY27
type TY28
type TY29
type TY30
type TY31
type TY32
type TY33
type TY34
type TY35
type TY36
type TY37
type TY38
type TY39
type TY40
type TY41
type TY42
type TY43
type TY44
type TY45
type TY46
type TY47
type TY48
type TY49
type TY50
type TY51
type TY52
type TY53

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type TY<sub>54</sub>  
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type TY253
type TY254
type TY255
type TY256
type TY257

```

```

instance (Size TY1) let size = 1 end
instance (Size TY2) let size = 2 end
instance (Size TY3) let size = 3 end
instance (Size TY4) let size = 4 end
instance (Size TY5) let size = 5 end
instance (Size TY6) let size = 6 end
instance (Size TY7) let size = 7 end
instance (Size TY8) let size = 8 end
instance (Size TY9) let size = 9 end
instance (Size TY10) let size = 10 end
instance (Size TY11) let size = 11 end
instance (Size TY12) let size = 12 end
instance (Size TY13) let size = 13 end
instance (Size TY14) let size = 14 end
instance (Size TY15) let size = 15 end
instance (Size TY16) let size = 16 end
instance (Size TY17) let size = 17 end
instance (Size TY18) let size = 18 end
instance (Size TY19) let size = 19 end
instance (Size TY20) let size = 20 end
instance (Size TY21) let size = 21 end
instance (Size TY22) let size = 22 end
instance (Size TY23) let size = 23 end
instance (Size TY24) let size = 24 end
instance (Size TY25) let size = 25 end
instance (Size TY26) let size = 26 end
instance (Size TY27) let size = 27 end

```

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instance (Size TY28) let size = 28 end
instance (Size TY29) let size = 29 end
instance (Size TY30) let size = 30 end
instance (Size TY31) let size = 31 end
instance (Size TY32) let size = 32 end
instance (Size TY33) let size = 33 end
instance (Size TY34) let size = 34 end
instance (Size TY35) let size = 35 end
instance (Size TY36) let size = 36 end
instance (Size TY37) let size = 37 end
instance (Size TY38) let size = 38 end
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instance (Size TY40) let size = 40 end
instance (Size TY41) let size = 41 end
instance (Size TY42) let size = 42 end
instance (Size TY43) let size = 43 end
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instance (Size TY46) let size = 46 end
instance (Size TY47) let size = 47 end
instance (Size TY48) let size = 48 end
instance (Size TY49) let size = 49 end
instance (Size TY50) let size = 50 end
instance (Size TY51) let size = 51 end
instance (Size TY52) let size = 52 end
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instance (Size TY60) let size = 60 end
instance (Size TY61) let size = 61 end
instance (Size TY62) let size = 62 end
instance (Size TY63) let size = 63 end
instance (Size TY64) let size = 64 end
instance (Size TY65) let size = 65 end
instance (Size TY66) let size = 66 end
instance (Size TY67) let size = 67 end
instance (Size TY68) let size = 68 end
instance (Size TY69) let size = 69 end
instance (Size TY70) let size = 70 end
instance (Size TY71) let size = 71 end
instance (Size TY72) let size = 72 end
instance (Size TY73) let size = 73 end
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instance (Size TY75) let size = 75 end
instance (Size TY76) let size = 76 end
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instance (Size TY78) let size = 78 end
instance (Size TY79) let size = 79 end
instance (Size TY80) let size = 80 end
instance (Size TY81) let size = 81 end
instance (Size TY82) let size = 82 end
instance (Size TY83) let size = 83 end
instance (Size TY84) let size = 84 end
instance (Size TY85) let size = 85 end

```

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instance (Size TY86) let size = 86 end
instance (Size TY87) let size = 87 end
instance (Size TY88) let size = 88 end
instance (Size TY89) let size = 89 end
instance (Size TY90) let size = 90 end
instance (Size TY91) let size = 91 end
instance (Size TY92) let size = 92 end
instance (Size TY93) let size = 93 end
instance (Size TY94) let size = 94 end
instance (Size TY95) let size = 95 end
instance (Size TY96) let size = 96 end
instance (Size TY97) let size = 97 end
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instance (Size TY99) let size = 99 end
instance (Size TY100) let size = 100 end
instance (Size TY101) let size = 101 end
instance (Size TY102) let size = 102 end
instance (Size TY103) let size = 103 end
instance (Size TY104) let size = 104 end
instance (Size TY105) let size = 105 end
instance (Size TY106) let size = 106 end
instance (Size TY107) let size = 107 end
instance (Size TY108) let size = 108 end
instance (Size TY109) let size = 109 end
instance (Size TY110) let size = 110 end
instance (Size TY111) let size = 111 end
instance (Size TY112) let size = 112 end
instance (Size TY113) let size = 113 end
instance (Size TY114) let size = 114 end
instance (Size TY115) let size = 115 end
instance (Size TY116) let size = 116 end
instance (Size TY117) let size = 117 end
instance (Size TY118) let size = 118 end
instance (Size TY119) let size = 119 end
instance (Size TY120) let size = 120 end
instance (Size TY121) let size = 121 end
instance (Size TY122) let size = 122 end
instance (Size TY123) let size = 123 end
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instance (Size TY126) let size = 126 end
instance (Size TY127) let size = 127 end
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instance (Size TY130) let size = 130 end
instance (Size TY131) let size = 131 end
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instance (Size TY137) let size = 137 end
instance (Size TY138) let size = 138 end
instance (Size TY139) let size = 139 end
instance (Size TY140) let size = 140 end
instance (Size TY141) let size = 141 end
instance (Size TY142) let size = 142 end
instance (Size TY143) let size = 143 end

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instance (Size TY144) let size = 144 end
instance (Size TY145) let size = 145 end
instance (Size TY146) let size = 146 end
instance (Size TY147) let size = 147 end
instance (Size TY148) let size = 148 end
instance (Size TY149) let size = 149 end
instance (Size TY150) let size = 150 end
instance (Size TY151) let size = 151 end
instance (Size TY152) let size = 152 end
instance (Size TY153) let size = 153 end
instance (Size TY154) let size = 154 end
instance (Size TY155) let size = 155 end
instance (Size TY156) let size = 156 end
instance (Size TY157) let size = 157 end
instance (Size TY158) let size = 158 end
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instance (Size TY161) let size = 161 end
instance (Size TY162) let size = 162 end
instance (Size TY163) let size = 163 end
instance (Size TY164) let size = 164 end
instance (Size TY165) let size = 165 end
instance (Size TY166) let size = 166 end
instance (Size TY167) let size = 167 end
instance (Size TY168) let size = 168 end
instance (Size TY169) let size = 169 end
instance (Size TY170) let size = 170 end
instance (Size TY171) let size = 171 end
instance (Size TY172) let size = 172 end
instance (Size TY173) let size = 173 end
instance (Size TY174) let size = 174 end
instance (Size TY175) let size = 175 end
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instance (Size TY179) let size = 179 end
instance (Size TY180) let size = 180 end
instance (Size TY181) let size = 181 end
instance (Size TY182) let size = 182 end
instance (Size TY183) let size = 183 end
instance (Size TY184) let size = 184 end
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instance (Size TY188) let size = 188 end
instance (Size TY189) let size = 189 end
instance (Size TY190) let size = 190 end
instance (Size TY191) let size = 191 end
instance (Size TY192) let size = 192 end
instance (Size TY193) let size = 193 end
instance (Size TY194) let size = 194 end
instance (Size TY195) let size = 195 end
instance (Size TY196) let size = 196 end
instance (Size TY197) let size = 197 end
instance (Size TY198) let size = 198 end
instance (Size TY199) let size = 199 end
instance (Size TY200) let size = 200 end
instance (Size TY201) let size = 201 end

```

```

instance (Size TY202) let size = 202 end
instance (Size TY203) let size = 203 end
instance (Size TY204) let size = 204 end
instance (Size TY205) let size = 205 end
instance (Size TY206) let size = 206 end
instance (Size TY207) let size = 207 end
instance (Size TY208) let size = 208 end
instance (Size TY209) let size = 209 end
instance (Size TY210) let size = 210 end
instance (Size TY211) let size = 211 end
instance (Size TY212) let size = 212 end
instance (Size TY213) let size = 213 end
instance (Size TY214) let size = 214 end
instance (Size TY215) let size = 215 end
instance (Size TY216) let size = 216 end
instance (Size TY217) let size = 217 end
instance (Size TY218) let size = 218 end
instance (Size TY219) let size = 219 end
instance (Size TY220) let size = 220 end
instance (Size TY221) let size = 221 end
instance (Size TY222) let size = 222 end
instance (Size TY223) let size = 223 end
instance (Size TY224) let size = 224 end
instance (Size TY225) let size = 225 end
instance (Size TY226) let size = 226 end
instance (Size TY227) let size = 227 end
instance (Size TY228) let size = 228 end
instance (Size TY229) let size = 229 end
instance (Size TY230) let size = 230 end
instance (Size TY231) let size = 231 end
instance (Size TY232) let size = 232 end
instance (Size TY233) let size = 233 end
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instance (Size TY235) let size = 235 end
instance (Size TY236) let size = 236 end
instance (Size TY237) let size = 237 end
instance (Size TY238) let size = 238 end
instance (Size TY239) let size = 239 end
instance (Size TY240) let size = 240 end
instance (Size TY241) let size = 241 end
instance (Size TY242) let size = 242 end
instance (Size TY243) let size = 243 end
instance (Size TY244) let size = 244 end
instance (Size TY245) let size = 245 end
instance (Size TY246) let size = 246 end
instance (Size TY247) let size = 247 end
instance (Size TY248) let size = 248 end
instance (Size TY249) let size = 249 end
instance (Size TY250) let size = 250 end
instance (Size TY251) let size = 251 end
instance (Size TY252) let size = 252 end
instance (Size TY253) let size = 253 end
instance (Size TY254) let size = 254 end
instance (Size TY255) let size = 255 end
instance (Size TY256) let size = 256 end
instance (Size TY257) let size = 257 end

```

```

declare isabelle target_rep type TY1 = '1'

```

```

declare isabelle target_rep type TY2 = '2'
declare isabelle target_rep type TY3 = '3'
declare isabelle target_rep type TY4 = '4'
declare isabelle target_rep type TY5 = '5'
declare isabelle target_rep type TY6 = '6'
declare isabelle target_rep type TY7 = '7'
declare isabelle target_rep type TY8 = '8'
declare isabelle target_rep type TY9 = '9'
declare isabelle target_rep type TY10 = '10'
declare isabelle target_rep type TY11 = '11'
declare isabelle target_rep type TY12 = '12'
declare isabelle target_rep type TY13 = '13'
declare isabelle target_rep type TY14 = '14'
declare isabelle target_rep type TY15 = '15'
declare isabelle target_rep type TY16 = '16'
declare isabelle target_rep type TY17 = '17'
declare isabelle target_rep type TY18 = '18'
declare isabelle target_rep type TY19 = '19'
declare isabelle target_rep type TY20 = '20'
declare isabelle target_rep type TY21 = '21'
declare isabelle target_rep type TY22 = '22'
declare isabelle target_rep type TY23 = '23'
declare isabelle target_rep type TY24 = '24'
declare isabelle target_rep type TY25 = '25'
declare isabelle target_rep type TY26 = '26'
declare isabelle target_rep type TY27 = '27'
declare isabelle target_rep type TY28 = '28'
declare isabelle target_rep type TY29 = '29'
declare isabelle target_rep type TY30 = '30'
declare isabelle target_rep type TY31 = '31'
declare isabelle target_rep type TY32 = '32'
declare isabelle target_rep type TY33 = '33'
declare isabelle target_rep type TY34 = '34'
declare isabelle target_rep type TY35 = '35'
declare isabelle target_rep type TY36 = '36'
declare isabelle target_rep type TY37 = '37'
declare isabelle target_rep type TY38 = '38'
declare isabelle target_rep type TY39 = '39'
declare isabelle target_rep type TY40 = '40'
declare isabelle target_rep type TY41 = '41'
declare isabelle target_rep type TY42 = '42'
declare isabelle target_rep type TY43 = '43'
declare isabelle target_rep type TY44 = '44'
declare isabelle target_rep type TY45 = '45'
declare isabelle target_rep type TY46 = '46'
declare isabelle target_rep type TY47 = '47'
declare isabelle target_rep type TY48 = '48'
declare isabelle target_rep type TY49 = '49'
declare isabelle target_rep type TY50 = '50'
declare isabelle target_rep type TY51 = '51'
declare isabelle target_rep type TY52 = '52'
declare isabelle target_rep type TY53 = '53'
declare isabelle target_rep type TY54 = '54'
declare isabelle target_rep type TY55 = '55'
declare isabelle target_rep type TY56 = '56'
declare isabelle target_rep type TY57 = '57'
declare isabelle target_rep type TY58 = '58'
declare isabelle target_rep type TY59 = '59'

```

```

declare isabelle target_rep type TY60 = '60'
declare isabelle target_rep type TY61 = '61'
declare isabelle target_rep type TY62 = '62'
declare isabelle target_rep type TY63 = '63'
declare isabelle target_rep type TY64 = '64'
declare isabelle target_rep type TY65 = '65'
declare isabelle target_rep type TY66 = '66'
declare isabelle target_rep type TY67 = '67'
declare isabelle target_rep type TY68 = '68'
declare isabelle target_rep type TY69 = '69'
declare isabelle target_rep type TY70 = '70'
declare isabelle target_rep type TY71 = '71'
declare isabelle target_rep type TY72 = '72'
declare isabelle target_rep type TY73 = '73'
declare isabelle target_rep type TY74 = '74'
declare isabelle target_rep type TY75 = '75'
declare isabelle target_rep type TY76 = '76'
declare isabelle target_rep type TY77 = '77'
declare isabelle target_rep type TY78 = '78'
declare isabelle target_rep type TY79 = '79'
declare isabelle target_rep type TY80 = '80'
declare isabelle target_rep type TY81 = '81'
declare isabelle target_rep type TY82 = '82'
declare isabelle target_rep type TY83 = '83'
declare isabelle target_rep type TY84 = '84'
declare isabelle target_rep type TY85 = '85'
declare isabelle target_rep type TY86 = '86'
declare isabelle target_rep type TY87 = '87'
declare isabelle target_rep type TY88 = '88'
declare isabelle target_rep type TY89 = '89'
declare isabelle target_rep type TY90 = '90'
declare isabelle target_rep type TY91 = '91'
declare isabelle target_rep type TY92 = '92'
declare isabelle target_rep type TY93 = '93'
declare isabelle target_rep type TY94 = '94'
declare isabelle target_rep type TY95 = '95'
declare isabelle target_rep type TY96 = '96'
declare isabelle target_rep type TY97 = '97'
declare isabelle target_rep type TY98 = '98'
declare isabelle target_rep type TY99 = '99'
declare isabelle target_rep type TY100 = '100'
declare isabelle target_rep type TY101 = '101'
declare isabelle target_rep type TY102 = '102'
declare isabelle target_rep type TY103 = '103'
declare isabelle target_rep type TY104 = '104'
declare isabelle target_rep type TY105 = '105'
declare isabelle target_rep type TY106 = '106'
declare isabelle target_rep type TY107 = '107'
declare isabelle target_rep type TY108 = '108'
declare isabelle target_rep type TY109 = '109'
declare isabelle target_rep type TY110 = '110'
declare isabelle target_rep type TY111 = '111'
declare isabelle target_rep type TY112 = '112'
declare isabelle target_rep type TY113 = '113'
declare isabelle target_rep type TY114 = '114'
declare isabelle target_rep type TY115 = '115'
declare isabelle target_rep type TY116 = '116'
declare isabelle target_rep type TY117 = '117'

```

[illegible]

[illegible]

```

declare isabelle target_rep type TY234 = '234'
declare isabelle target_rep type TY235 = '235'
declare isabelle target_rep type TY236 = '236'
declare isabelle target_rep type TY237 = '237'
declare isabelle target_rep type TY238 = '238'
declare isabelle target_rep type TY239 = '239'
declare isabelle target_rep type TY240 = '240'
declare isabelle target_rep type TY241 = '241'
declare isabelle target_rep type TY242 = '242'
declare isabelle target_rep type TY243 = '243'
declare isabelle target_rep type TY244 = '244'
declare isabelle target_rep type TY245 = '245'
declare isabelle target_rep type TY246 = '246'
declare isabelle target_rep type TY247 = '247'
declare isabelle target_rep type TY248 = '248'
declare isabelle target_rep type TY249 = '249'
declare isabelle target_rep type TY250 = '250'
declare isabelle target_rep type TY251 = '251'
declare isabelle target_rep type TY252 = '252'
declare isabelle target_rep type TY253 = '253'
declare isabelle target_rep type TY254 = '254'
declare isabelle target_rep type TY255 = '255'
declare isabelle target_rep type TY256 = '256'
declare isabelle target_rep type TY257 = '257'

```

```

declare hol target_rep type TY1 = '1'
declare hol target_rep type TY2 = '2'
declare hol target_rep type TY3 = '3'
declare hol target_rep type TY4 = '4'
declare hol target_rep type TY5 = '5'
declare hol target_rep type TY6 = '6'
declare hol target_rep type TY7 = '7'
declare hol target_rep type TY8 = '8'
declare hol target_rep type TY9 = '9'
declare hol target_rep type TY10 = '10'
declare hol target_rep type TY11 = '11'
declare hol target_rep type TY12 = '12'
declare hol target_rep type TY13 = '13'
declare hol target_rep type TY14 = '14'
declare hol target_rep type TY15 = '15'
declare hol target_rep type TY16 = '16'
declare hol target_rep type TY17 = '17'
declare hol target_rep type TY18 = '18'
declare hol target_rep type TY19 = '19'
declare hol target_rep type TY20 = '20'
declare hol target_rep type TY21 = '21'
declare hol target_rep type TY22 = '22'
declare hol target_rep type TY23 = '23'
declare hol target_rep type TY24 = '24'
declare hol target_rep type TY25 = '25'
declare hol target_rep type TY26 = '26'
declare hol target_rep type TY27 = '27'
declare hol target_rep type TY28 = '28'
declare hol target_rep type TY29 = '29'
declare hol target_rep type TY30 = '30'
declare hol target_rep type TY31 = '31'
declare hol target_rep type TY32 = '32'
declare hol target_rep type TY33 = '33'

```

```

declare hol target_rep type TY34 = '34'
declare hol target_rep type TY35 = '35'
declare hol target_rep type TY36 = '36'
declare hol target_rep type TY37 = '37'
declare hol target_rep type TY38 = '38'
declare hol target_rep type TY39 = '39'
declare hol target_rep type TY40 = '40'
declare hol target_rep type TY41 = '41'
declare hol target_rep type TY42 = '42'
declare hol target_rep type TY43 = '43'
declare hol target_rep type TY44 = '44'
declare hol target_rep type TY45 = '45'
declare hol target_rep type TY46 = '46'
declare hol target_rep type TY47 = '47'
declare hol target_rep type TY48 = '48'
declare hol target_rep type TY49 = '49'
declare hol target_rep type TY50 = '50'
declare hol target_rep type TY51 = '51'
declare hol target_rep type TY52 = '52'
declare hol target_rep type TY53 = '53'
declare hol target_rep type TY54 = '54'
declare hol target_rep type TY55 = '55'
declare hol target_rep type TY56 = '56'
declare hol target_rep type TY57 = '57'
declare hol target_rep type TY58 = '58'
declare hol target_rep type TY59 = '59'
declare hol target_rep type TY60 = '60'
declare hol target_rep type TY61 = '61'
declare hol target_rep type TY62 = '62'
declare hol target_rep type TY63 = '63'
declare hol target_rep type TY64 = '64'
declare hol target_rep type TY65 = '65'
declare hol target_rep type TY66 = '66'
declare hol target_rep type TY67 = '67'
declare hol target_rep type TY68 = '68'
declare hol target_rep type TY69 = '69'
declare hol target_rep type TY70 = '70'
declare hol target_rep type TY71 = '71'
declare hol target_rep type TY72 = '72'
declare hol target_rep type TY73 = '73'
declare hol target_rep type TY74 = '74'
declare hol target_rep type TY75 = '75'
declare hol target_rep type TY76 = '76'
declare hol target_rep type TY77 = '77'
declare hol target_rep type TY78 = '78'
declare hol target_rep type TY79 = '79'
declare hol target_rep type TY80 = '80'
declare hol target_rep type TY81 = '81'
declare hol target_rep type TY82 = '82'
declare hol target_rep type TY83 = '83'
declare hol target_rep type TY84 = '84'
declare hol target_rep type TY85 = '85'
declare hol target_rep type TY86 = '86'
declare hol target_rep type TY87 = '87'
declare hol target_rep type TY88 = '88'
declare hol target_rep type TY89 = '89'
declare hol target_rep type TY90 = '90'
declare hol target_rep type TY91 = '91'

```



```

declare hol target_rep type TY92 = '92'
declare hol target_rep type TY93 = '93'
declare hol target_rep type TY94 = '94'
declare hol target_rep type TY95 = '95'
declare hol target_rep type TY96 = '96'
declare hol target_rep type TY97 = '97'
declare hol target_rep type TY98 = '98'
declare hol target_rep type TY99 = '99'
declare hol target_rep type TY100 = '100'
declare hol target_rep type TY101 = '101'
declare hol target_rep type TY102 = '102'
declare hol target_rep type TY103 = '103'
declare hol target_rep type TY104 = '104'
declare hol target_rep type TY105 = '105'
declare hol target_rep type TY106 = '106'
declare hol target_rep type TY107 = '107'
declare hol target_rep type TY108 = '108'
declare hol target_rep type TY109 = '109'
declare hol target_rep type TY110 = '110'
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declare hol target_rep type TY112 = '112'
declare hol target_rep type TY113 = '113'
declare hol target_rep type TY114 = '114'
declare hol target_rep type TY115 = '115'
declare hol target_rep type TY116 = '116'
declare hol target_rep type TY117 = '117'
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declare hol target_rep type TY121 = '121'
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declare hol target_rep type TY123 = '123'
declare hol target_rep type TY124 = '124'
declare hol target_rep type TY125 = '125'
declare hol target_rep type TY126 = '126'
declare hol target_rep type TY127 = '127'
declare hol target_rep type TY128 = '128'
declare hol target_rep type TY129 = '129'
declare hol target_rep type TY130 = '130'
declare hol target_rep type TY131 = '131'
declare hol target_rep type TY132 = '132'
declare hol target_rep type TY133 = '133'
declare hol target_rep type TY134 = '134'
declare hol target_rep type TY135 = '135'
declare hol target_rep type TY136 = '136'
declare hol target_rep type TY137 = '137'
declare hol target_rep type TY138 = '138'
declare hol target_rep type TY139 = '139'
declare hol target_rep type TY140 = '140'
declare hol target_rep type TY141 = '141'
declare hol target_rep type TY142 = '142'
declare hol target_rep type TY143 = '143'
declare hol target_rep type TY144 = '144'
declare hol target_rep type TY145 = '145'
declare hol target_rep type TY146 = '146'
declare hol target_rep type TY147 = '147'
declare hol target_rep type TY148 = '148'
declare hol target_rep type TY149 = '149'

```

```

declare hol target_rep type TY150 = '150'
declare hol target_rep type TY151 = '151'
declare hol target_rep type TY152 = '152'
declare hol target_rep type TY153 = '153'
declare hol target_rep type TY154 = '154'
declare hol target_rep type TY155 = '155'
declare hol target_rep type TY156 = '156'
declare hol target_rep type TY157 = '157'
declare hol target_rep type TY158 = '158'
declare hol target_rep type TY159 = '159'
declare hol target_rep type TY160 = '160'
declare hol target_rep type TY161 = '161'
declare hol target_rep type TY162 = '162'
declare hol target_rep type TY163 = '163'
declare hol target_rep type TY164 = '164'
declare hol target_rep type TY165 = '165'
declare hol target_rep type TY166 = '166'
declare hol target_rep type TY167 = '167'
declare hol target_rep type TY168 = '168'
declare hol target_rep type TY169 = '169'
declare hol target_rep type TY170 = '170'
declare hol target_rep type TY171 = '171'
declare hol target_rep type TY172 = '172'
declare hol target_rep type TY173 = '173'
declare hol target_rep type TY174 = '174'
declare hol target_rep type TY175 = '175'
declare hol target_rep type TY176 = '176'
declare hol target_rep type TY177 = '177'
declare hol target_rep type TY178 = '178'
declare hol target_rep type TY179 = '179'
declare hol target_rep type TY180 = '180'
declare hol target_rep type TY181 = '181'
declare hol target_rep type TY182 = '182'
declare hol target_rep type TY183 = '183'
declare hol target_rep type TY184 = '184'
declare hol target_rep type TY185 = '185'
declare hol target_rep type TY186 = '186'
declare hol target_rep type TY187 = '187'
declare hol target_rep type TY188 = '188'
declare hol target_rep type TY189 = '189'
declare hol target_rep type TY190 = '190'
declare hol target_rep type TY191 = '191'
declare hol target_rep type TY192 = '192'
declare hol target_rep type TY193 = '193'
declare hol target_rep type TY194 = '194'
declare hol target_rep type TY195 = '195'
declare hol target_rep type TY196 = '196'
declare hol target_rep type TY197 = '197'
declare hol target_rep type TY198 = '198'
declare hol target_rep type TY199 = '199'
declare hol target_rep type TY200 = '200'
declare hol target_rep type TY201 = '201'
declare hol target_rep type TY202 = '202'
declare hol target_rep type TY203 = '203'
declare hol target_rep type TY204 = '204'
declare hol target_rep type TY205 = '205'
declare hol target_rep type TY206 = '206'
declare hol target_rep type TY207 = '207'

```

```

declare hol target_rep type TY208 = '208'
declare hol target_rep type TY209 = '209'
declare hol target_rep type TY210 = '210'
declare hol target_rep type TY211 = '211'
declare hol target_rep type TY212 = '212'
declare hol target_rep type TY213 = '213'
declare hol target_rep type TY214 = '214'
declare hol target_rep type TY215 = '215'
declare hol target_rep type TY216 = '216'
declare hol target_rep type TY217 = '217'
declare hol target_rep type TY218 = '218'
declare hol target_rep type TY219 = '219'
declare hol target_rep type TY220 = '220'
declare hol target_rep type TY221 = '221'
declare hol target_rep type TY222 = '222'
declare hol target_rep type TY223 = '223'
declare hol target_rep type TY224 = '224'
declare hol target_rep type TY225 = '225'
declare hol target_rep type TY226 = '226'
declare hol target_rep type TY227 = '227'
declare hol target_rep type TY228 = '228'
declare hol target_rep type TY229 = '229'
declare hol target_rep type TY230 = '230'
declare hol target_rep type TY231 = '231'
declare hol target_rep type TY232 = '232'
declare hol target_rep type TY233 = '233'
declare hol target_rep type TY234 = '234'
declare hol target_rep type TY235 = '235'
declare hol target_rep type TY236 = '236'
declare hol target_rep type TY237 = '237'
declare hol target_rep type TY238 = '238'
declare hol target_rep type TY239 = '239'
declare hol target_rep type TY240 = '240'
declare hol target_rep type TY241 = '241'
declare hol target_rep type TY242 = '242'
declare hol target_rep type TY243 = '243'
declare hol target_rep type TY244 = '244'
declare hol target_rep type TY245 = '245'
declare hol target_rep type TY246 = '246'
declare hol target_rep type TY247 = '247'
declare hol target_rep type TY248 = '248'
declare hol target_rep type TY249 = '249'
declare hol target_rep type TY250 = '250'
declare hol target_rep type TY251 = '251'
declare hol target_rep type TY252 = '252'
declare hol target_rep type TY253 = '253'
declare hol target_rep type TY254 = '254'
declare hol target_rep type TY255 = '255'
declare hol target_rep type TY256 = '256'
declare hol target_rep type TY257 = '257'

```

```

val word_length : ∀ α. MWORD α → NAT
declare ocaml target_rep function word_length = 'Lem.word_length'
declare isabelle target_rep function word_length = 'size'
declare hol target_rep function word_length = 'words$word_len'

```

```

(*****
(* Conversions
*)

```

(\*\*\*\*\*)

val *signedIntegerFromWord* :  $\forall \alpha. \text{MWORD } \alpha \rightarrow \mathbb{Z}$

declare *isabelle* target\_rep function *signedIntegerFromWord* = 'Word.sint'

declare *hol* target\_rep function *signedIntegerFromWord* = 'integer\_word\$w2i'

declare *ocaml* target\_rep function *signedIntegerFromWord* = 'Lem.signedIntegerFromWord'

val *unsignedIntegerFromWord* :  $\forall \alpha. \text{MWORD } \alpha \rightarrow \mathbb{Z}$

declare *isabelle* target\_rep function *unsignedIntegerFromWord* = 'Word.uint'

declare *hol* target\_rep function *unsignedIntegerFromWord* = 'lem\$w2ui'

declare *ocaml* target\_rep function *unsignedIntegerFromWord* = 'Lem.naturalFromWord'

(\* Version without typeclass constraint so that we can derive operations in Lem for one of the theorem provers \*)

val *proverWordFromInteger* :  $\forall \alpha. \mathbb{Z} \rightarrow \text{MWORD } \alpha$

declare *isabelle* target\_rep function *proverWordFromInteger* = 'Word.word\_of\_int'

declare *hol* target\_rep function *proverWordFromInteger* = 'integer\_word\$i2w'

val *wordFromInteger* :  $\forall \alpha. \text{Size } \alpha \Rightarrow \mathbb{Z} \rightarrow \text{MWORD } \alpha$

let inline {*isabelle*, *hol*} *wordFromInteger* *i* = *proverWordFromInteger* *i*

(\* The OCaml version is defined after the arithmetic operations, below. \*)

val *naturalFromWord* :  $\forall \alpha. \text{MWORD } \alpha \rightarrow \mathbb{N}$

declare *isabelle* target\_rep function *naturalFromWord* = 'Word.unat'

declare *hol* target\_rep function *naturalFromWord* = 'words\$w2n'

declare *ocaml* target\_rep function *naturalFromWord* = 'Lem.naturalFromWord'

val *wordFromNatural* :  $\forall \alpha. \text{Size } \alpha \Rightarrow \mathbb{N} \rightarrow \text{MWORD } \alpha$

declare *hol* target\_rep function *wordFromNatural* = 'words\$n2w'

let inline {*isabelle*} *wordFromNatural* *n* =  
wordFromInteger (integerFromNatural *n*)

let {*ocaml*} *wordFromNatural* *n* = *ocaml.inject* (size, *n*)

val *wordToHex* :  $\forall \alpha. \text{MWORD } \alpha \rightarrow \text{STRING}$

declare *hol* target\_rep function *wordToHex* = 'words\$word\_to\_hex.string'

(\* Building libraries fails if we don't provide implementations for the type class. \*)

let {*ocaml*, *isabelle*, *coq*} *wordToHex* *w* = "wordToHex not yet implemented"

instance  $\forall \alpha. (\text{Show } (\text{MWORD } \alpha))$

let *show* = *wordToHex*

end

val *wordFromBitlist* :  $\forall \alpha. \text{Size } \alpha \Rightarrow \text{LIST BOOL} \rightarrow \text{MWORD } \alpha$

declare *isabelle* target\_rep function *wordFromBitlist* = 'Word.of\_bl'

declare *hol* target\_rep function *wordFromBitlist* = 'bitstring\$v2w'

declare *ocaml* target\_rep function *wordFromBitlist* = 'Lem.wordFromBitlist'

val *bitlistFromWord* :  $\forall \alpha. \text{MWORD } \alpha \rightarrow \text{LIST BOOL}$

declare *isabelle* target\_rep function *bitlistFromWord* = 'Word.to\_bl'

declare *hol* target\_rep function *bitlistFromWord* = 'bitstring\$w2v'

declare *ocaml* target\_rep function *bitlistFromWord* = 'Lem.bitlistFromWord'

```

val size_test_fn :  $\forall \alpha. \text{Size } \alpha \Rightarrow \text{MWORD } \alpha \rightarrow \text{NAT}$ 
let size_test_fn _ = size

assert {ocaml, isabelle} size_test : size_test_fn ((wordFromNatural 0) : MWORD TY5) = 5

assert {ocaml, isabelle, hol} size_itself_test : size_itself (the_value : ITSELF TY7) = 7

assert {ocaml, hol, isabelle} length_test :
  word_length ((wordFromNatural 0) : MWORD TY13) = 13
assert {ocaml, hol, isabelle} signedIntFromword_test :
  signedIntegerFromWord ((wordFromNatural 130) : MWORD TY8) = -126
assert {ocaml, hol, isabelle} wordFromBitlist_test :
  ((wordFromBitlist [false; false; true; false]) : MWORD TY4) = wordFromNatural 2
assert {ocaml, hol, isabelle} bitlistFromWord_test :
  bitlistFromWord ((wordFromNatural 2) : MWORD TY4) = [false; false; true; false]
assert {ocaml, hol, isabelle} wordFromBitlist_bitListFromWord_test :
  let w : MWORD TY8 = wordFromNatural 33 in
  wordFromBitlist (bitlistFromWord w) = w

(*****
(* Comparisons
*)
*****)

val mwordEq :  $\forall \alpha. \text{MWORD } \alpha \rightarrow \text{MWORD } \alpha \rightarrow \text{BOOL}$ 
declare ocaml target_rep function mwordEq = 'Lem.word_equal'
let inline ~{ocaml} mwordEq = unsafe_structural_equality

instance  $\forall \alpha. (Eq (\text{MWORD } \alpha))$ 
  let == mwordEq
  let <> w1 w2 =  $\neg$  (mwordEq w1 w2)
end

val signedLess :  $\forall \alpha. \text{MWORD } \alpha \rightarrow \text{MWORD } \alpha \rightarrow \text{BOOL}$ 

declare isabelle target_rep function signedLess = 'Word.word_sless'
declare hol target_rep function signedLess = 'words$word_lt'

val signedLessEq :  $\forall \alpha. \text{MWORD } \alpha \rightarrow \text{MWORD } \alpha \rightarrow \text{BOOL}$ 

declare isabelle target_rep function signedLessEq = 'Word.word_sle'
declare hol target_rep function signedLessEq = 'words$word_le'

val unsignedLess :  $\forall \alpha. \text{MWORD } \alpha \rightarrow \text{MWORD } \alpha \rightarrow \text{BOOL}$ 

declare isabelle target_rep function unsignedLess = infix '<'
declare hol target_rep function unsignedLess = 'words$word_lo'
declare ocaml target_rep function unsignedLess = 'Lem.unsignedLess'

val unsignedLessEq :  $\forall \alpha. \text{MWORD } \alpha \rightarrow \text{MWORD } \alpha \rightarrow \text{BOOL}$ 

declare isabelle target_rep function unsignedLessEq = infix '\<le>'
declare hol target_rep function unsignedLessEq = 'words$word_ls'
declare ocaml target_rep function unsignedLessEq = 'Lem.unsignedLessEq'

let {ocaml} signedLess w1 w2 = (signedIntegerFromWord w1) < (signedIntegerFromWord w2)
let {ocaml} signedLessEq w1 w2 = (signedIntegerFromWord w1)  $\leq$  (signedIntegerFromWord w2)

```

```

(* Comparison tests are below, after the definition of wordFromInteger *)

(*****
(* Appending, splitting and probing words *)
*****)

val word_concat :  $\forall \alpha \beta \gamma$ . MWORD  $\alpha \rightarrow$  MWORD  $\beta \rightarrow$  MWORD  $\gamma$ 
declare hol target_rep function word_concat = 'words$word_concat'
declare isabelle target_rep function word_concat = 'Word.word_cat'
declare ocaml target_rep function word_concat = 'Lem.word_concat'

(* Note that we assume the result type has the correct size, especially for Isabelle. *)
val word_extract :  $\forall \alpha \beta$ . NAT  $\rightarrow$  NAT  $\rightarrow$  MWORD  $\alpha \rightarrow$  MWORD  $\beta$ 
declare hol target_rep function word_extract lo hi v = 'words$word_extract' hi lo v
declare isabelle target_rep function word_extract lo hi v = 'Word.slice' lo v
declare ocaml target_rep function word_extract = 'Lem.word_extract'

(* Needs to be in the prover because we'd end up with unknown sizes in the types in Lem. *)
val word_update :  $\forall \alpha \beta$ . MWORD  $\alpha \rightarrow$  NAT  $\rightarrow$  NAT  $\rightarrow$  MWORD  $\beta \rightarrow$  MWORD  $\alpha$ 
declare hol target_rep function word_update v lo hi w = 'words$bit_field_insert' hi lo w v
declare isabelle target_rep function word_update v lo hi w = 'Lem.word_update' v lo hi w
declare ocaml target_rep function word_update = 'Lem.word_update'

val setBit :  $\forall \alpha$ . MWORD  $\alpha \rightarrow$  NAT  $\rightarrow$  BOOL  $\rightarrow$  MWORD  $\alpha$ 

declare isabelle target_rep function setBit = 'Bits.set_bit'
declare hol target_rep function setBit w i b = '$:+' i b w
declare ocaml target_rep function setBit = 'Lem.word_setBit'

val getBit :  $\forall \alpha$ . MWORD  $\alpha \rightarrow$  NAT  $\rightarrow$  BOOL

declare isabelle target_rep function getBit = 'Bits.test_bit'
declare hol target_rep function getBit w b = 'words$word_bit' b w
declare ocaml target_rep function getBit = 'Lem.word_getBit'

val msb :  $\forall \alpha$ . MWORD  $\alpha \rightarrow$  BOOL

declare isabelle target_rep function msb = 'Bits.msb'
declare hol target_rep function msb = 'words$word_msb'
declare ocaml target_rep function msb = 'Lem.word_msb'

val lsb :  $\forall \alpha$ . MWORD  $\alpha \rightarrow$  BOOL

declare isabelle target_rep function lsb = 'Bits.lsb'
declare hol target_rep function lsb = 'words$word_lsb'
declare ocaml target_rep function lsb = 'Lem.word_lsb'

assert {ocaml, hol, isabelle} extract_concat_test :
  let x : MWORD TY16 = wordFromNatural 1234 in
  word_concat ((word_extract 11 15 x) : MWORD TY5)
    ((word_concat ((word_extract 4 10 x) : MWORD TY7)
      ((word_extract 0 3 x) : MWORD TY4)) : MWORD TY11)
    = x
assert {ocaml, hol, isabelle} update_test :
  let x : MWORD TY16 = wordFromNatural 1234 in
  let y : MWORD TY8 = wordFromNatural 41 in
  word_update x 1 8 y = wordFromNatural 1106

```

```

assert {ocaml, hol, isabelle} setBit_test1 : setBit (wordFromNatural 12 : MWORD TY8) 1 true = wordFromNatural 14

assert {ocaml, hol, isabelle} setBit_test2 : setBit (wordFromNatural 14 : MWORD TY8) 1 false = wordFromNatural 12

assert {ocaml, hol, isabelle} setBit_test3 : setBit (wordFromNatural 2 : MWORD TY8) 1 false = wordFromNatural 0

assert {ocaml, hol, isabelle} getBit_test : getBit (wordFromNatural 3 : MWORD TY8) 1 = true

(*****
(* Bitwise operations, shifts, etc.                                     *)
*****)

val shiftLeft : ∀ α. MWORD α → NAT → MWORD α

declare isabelle target_rep function shiftLeft = infix '<<'
declare hol target_rep function shiftLeft = 'words$word_lsl'
declare ocaml target_rep function shiftLeft = 'Lem.word_shiftLeft'

val shiftRight : ∀ α. MWORD α → NAT → MWORD α

declare isabelle target_rep function shiftRight = infix '>>'
declare hol target_rep function shiftRight = 'words$word_lsr'
declare ocaml target_rep function shiftRight = 'Lem.word_shiftRight'

val arithShiftRight : ∀ α. MWORD α → NAT → MWORD α

declare isabelle target_rep function arithShiftRight = infix '>>>'
declare hol target_rep function arithShiftRight = 'words$word_asr'
declare ocaml target_rep function arithShiftRight = 'Lem.word_arithShiftRight'

val lAnd : ∀ α. MWORD α → MWORD α → MWORD α

declare isabelle target_rep function lAnd = 'Bits.bitAND'
declare hol target_rep function lAnd = 'words$word_and'
declare ocaml target_rep function lAnd = 'Lem.word_and'

val lOr : ∀ α. MWORD α → MWORD α → MWORD α

declare isabelle target_rep function lOr = 'Bits.bitOR'
declare hol target_rep function lOr = 'words$word_or'
declare ocaml target_rep function lOr = 'Lem.word_or'

val lXor : ∀ α. MWORD α → MWORD α → MWORD α

declare isabelle target_rep function lXor = 'Bits.bitXOR'
declare hol target_rep function lXor = 'words$word_xor'
declare ocaml target_rep function lXor = 'Lem.word_xor'

val lNot : ∀ α. MWORD α → MWORD α

declare isabelle target_rep function lNot = 'Bits.bitNOT'
declare hol target_rep function lNot = 'words$word_lcomp'
declare ocaml target_rep function lNot = 'Lem.word_not'

val rotateRight : ∀ α. NAT → MWORD α → MWORD α

declare isabelle target_rep function rotateRight = 'Word.word_rotr'
declare hol target_rep function rotateRight i w = 'words$word_ror' w i

```

```

declare ocaml target_rep function rotateRight = 'Lem.word_ror'

val rotateLeft :  $\forall \alpha. \text{NAT} \rightarrow \text{MWORD } \alpha \rightarrow \text{MWORD } \alpha$ 

declare isabelle target_rep function rotateLeft = 'Word.word_rotl'
declare hol target_rep function rotateLeft  $i\ w$  = 'words$word_rol'  $w\ i$ 
declare ocaml target_rep function rotateLeft = 'Lem.word_rotl'

val zeroExtend :  $\forall \alpha\ \beta. \text{Size } \beta \Rightarrow \text{MWORD } \alpha \rightarrow \text{MWORD } \beta$ 

declare isabelle target_rep function zeroExtend = 'Word.ucast'
declare hol target_rep function zeroExtend = 'words$w2w'
let {ocaml} zeroExtend  $x$  = wordFromNatural (naturalFromWord  $x$ )

val signExtend :  $\forall \alpha\ \beta. \text{Size } \beta \Rightarrow \text{MWORD } \alpha \rightarrow \text{MWORD } \beta$ 

declare isabelle target_rep function signExtend = 'Word.scast'
declare hol target_rep function signExtend = 'words$sw2sw'
(* ocaml after definition for wordFromInteger *)

assert {ocaml, hol, isabelle} shift_test1 : shiftLeft (wordFromNatural 5 : MWORD TY8) 2 = wordFromNatural 20
assert {ocaml, hol, isabelle} shift_test2 : shiftRight (wordFromNatural 5 : MWORD TY8) 2 = wordFromNatural 1
assert {ocaml, hol, isabelle} shift_test3 : shiftRight (wordFromNatural 129 : MWORD TY8) 2 = wordFromNatural 32
assert {ocaml, hol, isabelle} shift_test4 : arithShiftRight (wordFromNatural 129 : MWORD TY8) 2 = wordFromNatural 224

assert {ocaml, hol, isabelle} and_test : lAnd (wordFromNatural 5) (wordFromNatural 36) = (wordFromNatural 4 : MWORD TY8)
assert {ocaml, hol, isabelle} or_test : lOr (wordFromNatural 5) (wordFromNatural 36) = (wordFromNatural 37 : MWORD TY8)
assert {ocaml, hol, isabelle} xor_test : lXor (wordFromNatural 5) (wordFromNatural 36) = (wordFromNatural 33 : MWORD TY8)
assert {ocaml, hol, isabelle} not_test : lNot (wordFromNatural 37) = (wordFromNatural 218 : MWORD TY8)

assert {ocaml, hol, isabelle} rotateR_test : rotateRight 3 (wordFromNatural 37) = (wordFromNatural 164 : MWORD TY8)
assert {ocaml, hol, isabelle} rotateL_test : rotateLeft 3 (wordFromNatural 37) = (wordFromNatural 41 : MWORD TY8)
assert {ocaml, hol, isabelle} zext_test0 : zeroExtend (wordFromNatural 130 : MWORD TY8) = (wordFromNatural 130 : MWORD TY16)
assert {ocaml, hol, isabelle} zext_test1 : zeroExtend (wordFromNatural 130 : MWORD TY8) = (wordFromNatural 2 : MWORD TY7)

(* Sign extension tests are below, after the definition of wordFromInteger *)

(*****
(* Arithmetic *)
*****)

val plus :  $\forall \alpha. \text{MWORD } \alpha \rightarrow \text{MWORD } \alpha \rightarrow \text{MWORD } \alpha$ 

declare isabelle target_rep function plus = infix '+'
declare hol target_rep function plus = 'words$word_add'
declare ocaml target_rep function plus = 'Lem.word_plus'

val minus :  $\forall \alpha. \text{MWORD } \alpha \rightarrow \text{MWORD } \alpha \rightarrow \text{MWORD } \alpha$ 

```



```

declare isabelle target_rep function minus = infix '-'
declare hol target_rep function minus = 'words$word_sub'
declare ocaml target_rep function minus = 'Lem.word_minus'

```

```

val uminus :  $\forall \alpha. \text{MWORD } \alpha \rightarrow \text{MWORD } \alpha$ 

```

```

declare isabelle target_rep function uminus w = '-' w
declare hol target_rep function uminus = 'words$word_2comp'
declare ocaml target_rep function uminus = 'Lem.word_uminus'

```

```

val times :  $\forall \alpha. \text{MWORD } \alpha \rightarrow \text{MWORD } \alpha \rightarrow \text{MWORD } \alpha$ 

```

```

declare isabelle target_rep function times = infix '*'
declare hol target_rep function times = 'words$word_mul'
declare ocaml target_rep function times = 'Lem.word_times'

```

```

val unsignedDivide :  $\forall \alpha. \text{MWORD } \alpha \rightarrow \text{MWORD } \alpha \rightarrow \text{MWORD } \alpha$ 
val signedDivide :  $\forall \alpha. \text{MWORD } \alpha \rightarrow \text{MWORD } \alpha \rightarrow \text{MWORD } \alpha$ 

```

```

declare isabelle target_rep function unsignedDivide = infix 'div'
declare hol target_rep function unsignedDivide = 'words$word_div'
declare ocaml target_rep function unsignedDivide = 'Lem.word_udiv'
declare hol target_rep function signedDivide = 'words$word_quot'

```

```

let {isabelle, ocaml} signedDivide x y =
  if msb x then
    if msb y then unsignedDivide (uminus x) (uminus y)
    else uminus (unsignedDivide (uminus x) y)
  else if msb y then uminus (unsignedDivide x (uminus y))
  else unsignedDivide x y

```

```

val modulo :  $\forall \alpha. \text{MWORD } \alpha \rightarrow \text{MWORD } \alpha \rightarrow \text{MWORD } \alpha$ 

```

```

declare isabelle target_rep function modulo = infix 'mod'
declare hol target_rep function modulo = 'words$word_mod'
declare ocaml target_rep function modulo = 'Lem.word_mod'

```

(\* Now we can define wordFromInteger for OCaml \*)

```

let {ocaml} wordFromInteger i =
  if i < 0
  then uminus (wordFromNatural (naturalFromInteger (-i)))
  else wordFromNatural (naturalFromInteger i)

```

```

let {ocaml} signExtend x = wordFromInteger (signedIntegerFromWord x)

```

```

assert {ocaml, hol, isabelle} wordFromInteger_nat_test1 : ((wordFromInteger 42) : MWORD TY8) = wordFromNatural 42

```

```

assert {ocaml, hol, isabelle} wordFromInteger_nat_test2 : ((wordFromInteger (-42)) : MWORD TY8) = uminus (wordFromNatural 42)

```

```

assert {ocaml, hol, isabelle} plus_test : plus (wordFromInteger (-5) : MWORD TY8) (wordFromNatural 2) = wordFromNatural 7

```

```

assert {ocaml, hol, isabelle} minus_test : minus (wordFromInteger (-5) : MWORD TY8) (wordFromNatural 2) = wordFromNatural -7

```

```

assert {ocaml, hol, isabelle} times_test : times (wordFromInteger (-5) : MWORD TY8) (wordFromNatural 2) = wordFromNatural -10

```

```

assert {ocaml, hol, isabelle} udiv_test : unsignedDivide (wordFromInteger (-5) : MWORD TY8) (wordFromNatural 2) = wordFromNatural 2
assert {ocaml, hol, isabelle} sdiv_test : signedDivide (wordFromInteger (-5) : MWORD TY8) (wordFromNatural 2) = wordFromNatural 2

(* Comparison tests, which need wordFromInteger *)

assert {ocaml, hol, isabelle} signedLess_test1 : signedLess (wordFromInteger (-5)) ((wordFromInteger 3) : MWORD TY8)
assert {ocaml, hol, isabelle} signedLess_test2 : signedLess (wordFromInteger 3) ((wordFromInteger 5) : MWORD TY8)
assert {ocaml, hol, isabelle} signedLess_test3 : ¬ (signedLess (wordFromInteger 3) ((wordFromInteger 3) : MWORD TY8))
assert {ocaml, hol, isabelle} signedLessEq_test1 : signedLessEq (wordFromInteger (-5)) ((wordFromInteger 3) : MWORD TY8)
assert {ocaml, hol, isabelle} signedLessEq_test2 : signedLessEq (wordFromInteger 3) ((wordFromInteger 5) : MWORD TY8)
assert {ocaml, hol, isabelle} signedLessEq_test3 : signedLessEq (wordFromInteger 3) ((wordFromInteger 3) : MWORD TY8)
assert {ocaml, hol, isabelle} unsignedLess_test1 : unsignedLess (wordFromInteger 3) ((wordFromInteger 5) : MWORD TY8)
assert {ocaml, hol, isabelle} unsignedLess_test2 : unsignedLess (wordFromInteger 3) ((wordFromInteger 255) : MWORD TY8)
assert {ocaml, hol, isabelle} unsignedLess_test3 : ¬ (unsignedLess (wordFromInteger 255) ((wordFromInteger 255) : MWORD TY8))
assert {ocaml, hol, isabelle} unsignedLessEq_test1 : unsignedLessEq (wordFromInteger 3) ((wordFromInteger 5) : MWORD TY8)
assert {ocaml, hol, isabelle} unsignedLessEq_test2 : unsignedLessEq (wordFromInteger 3) ((wordFromInteger 255) : MWORD TY8)
assert {ocaml, hol, isabelle} unsignedLessEq_test3 : unsignedLessEq (wordFromInteger 255) ((wordFromInteger 255) : MWORD TY8)

(* sign extend tests *)

assert {ocaml, hol, isabelle} sext_test0 : signExtend (wordFromNatural 130 : MWORD TY8) = (wordFromInteger (-126) : MWORD TY16)
assert {ocaml, hol, isabelle} sext_test1 : signExtend (wordFromNatural 130 : MWORD TY8) = (wordFromInteger 2 : MWORD TY7)

```

## 27 Pervasives

```
declare {isabelle, ocaml, hol, coq} rename module = Lem_pervasives
```

```
include import Basic_classes Bool Tuple Maybe Either Function Num Map Set List String Word Show
```

```
import Sorting Relation
```

## 28 Pervasives\_extra

```
declare {isabelle, ocaml, hol, coq} rename module = Lem_pervasives_extra
```

```
include import Pervasives
```

```
include import Function_extra Maybe_extra Map_extra Num_extra Set_extra Set_helpers List_extra String_extra Assert_extra
```