Isabelle/HOLCF-Prelude

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Abstract

The Isabelle/HOLCF-Prelude is a formalization of a large part of Haskell's standard prelude [2] in Isabelle/HOLCF. We use it to

- prove the correctness of the Eratosthenes' Sieve, in its self-referential implementation commonly used to showcase Haskell's laziness,
- prove correctness of GHC's "fold/build" rule and related rewrite rules, and
- certify a number of hints suggested by `HLint`.

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Contents

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1 Initial Setup for HOLCF-Prelude

theory *HOLCF-Main*

imports
HOLCF
HOLCF−Library.Int-Discrete
HOL−Library.Adhoc-Overloading
begin

All theories from the Isabelle distribution which are used anywhere in the HOLCF-Prelude library must be imported via this file. This way, we only have to hide constant names and syntax in one place.

hide-type (**open**) *list*

hide-const (**open**)
List.append List.concat List.Cons List.distinct List.filter List.last
List.foldr List.foldl List.length List.lists List.map List.Nil List.nth
List.partition List.replicate List.set List.take List.upto List.zip
Orderings.less Product-Type.fst Product-Type.snd

no-notation *Map.map-add* (**infixl** ++ *100*)

no-notation *List.upto* ((*1*[-../-]))

no-notation
Rings.divide (**infixl** *div 70*) **and**
Rings.modulo (**infixl** *mod 70*)

no-notation
Set.member ((:)) **and**
Set.member ((-/ : -) [*51*, *51*] *50*)

no-translations
[*x*, *xs*] == *x* # [*xs*]
[*x*] == *x* # []

no-syntax
-*list* :: *args* ⇒ *'a List.list* ([(-)])

no-notation
List.Nil ([])

no-syntax -*bracket* :: *types* ⇒ *type* ⇒ *type* (([-]/ => -) [*0*, *0*] *0*)
no-syntax -*bracket* :: *types* ⇒ *type* ⇒ *type* (([-]/ ⇒ -) [*0*, *0*] *0*)

no-translations
[*x*<−*xs* . *P*] == *CONST List.filter* (%*x*. *P*) *xs*

no-syntax (*ASCII*)
-*filter* :: *pttrn* ⇒ *'a List.list* ⇒ *bool* ⇒ *'a List.list* ((*1*[-<−-./ -]))

no-syntax

-filter :: *pttrn* ⇒ *'a List.list* ⇒ *bool* ⇒ *'a List.list* ((*1*[-←- ./ -]))

Declarations that belong in HOLCF/Tr.thy:

declare *trE* [*cases type*: *tr*]
declare *tr-induct* [*induct type*: *tr*]

end

2 Type Classes

theory *Type-Classes*
imports *HOLCF-Main*
begin

2.1 Eq class

class *Eq* =
fixes *eq* :: *'a* → *'a* → *tr*

The Haskell type class does allow /= to be specified separately. For now, we assume that all modeled type classes use the default implementation, or an equivalent.

fixrec *neq* :: *'a*::*Eq* → *'a* → *tr* **where**
neq·*x*·*y* = *neg*·(*eq*·*x*·*y*)

class *Eq-strict* = *Eq* +
assumes *eq-strict* [*simp*]:
eq·*x*·⊥ = ⊥
eq·⊥·*y* = ⊥

class *Eq-sym* = *Eq-strict* +
assumes *eq-sym*: *eq*·*x*·*y* = *eq*·*y*·*x*

class *Eq-equiv* = *Eq-sym* +
assumes *eq-self-neq-FF* [*simp*]: *eq*·*x*·*x* ≠ *FF*
and *eq-trans*: *eq*·*x*·*y* = *TT* ⟹ *eq*·*y*·*z* = *TT* ⟹ *eq*·*x*·*z* = *TT*
begin

lemma *eq-refl*: *eq*·*x*·*x* ≠ ⊥ ⟹ *eq*·*x*·*x* = *TT*
⟨*proof*⟩

end

class *Eq-eq* = *Eq-sym* +
assumes *eq-self-neq-FF'*: *eq*·*x*·*x* ≠ *FF*
and *eq-TT-dest*: *eq*·*x*·*y* = *TT* ⟹ *x* = *y*
begin

subclass *Eq-equiv*
⟨*proof*⟩

lemma *eqD* [*dest*]:
$eq{\cdot}x{\cdot}y = TT \Longrightarrow x = y$
$eq{\cdot}x{\cdot}y = FF \Longrightarrow x \neq y$
⟨*proof*⟩

end

2.1.1 Class instances

instantiation *lift* :: (*countable*) *Eq-eq*
begin

definition $eq \equiv (\Lambda(Def\ x)\ (Def\ y).\ Def\ (x = y))$

instance
⟨*proof*⟩

end

lemma *eq-ONE-ONE* [*simp*]: $eq{\cdot}ONE{\cdot}ONE = TT$
⟨*proof*⟩

2.2 Ord class

domain $Ordering = LT \mid EQ \mid GT$

definition *oppOrdering* :: $Ordering \to Ordering$ **where**
$oppOrdering = (\Lambda\ x.\ case\ x\ of\ LT \Rightarrow GT \mid EQ \Rightarrow EQ \mid GT \Rightarrow LT)$

lemma *oppOrdering-simps* [*simp*]:
$oppOrdering{\cdot}LT = GT$
$oppOrdering{\cdot}EQ = EQ$
$oppOrdering{\cdot}GT = LT$
$oppOrdering{\cdot}\bot = \bot$
⟨*proof*⟩

class $Ord = Eq +$
fixes *compare* :: $'a \to 'a \to Ordering$
begin

definition $lt :: 'a \to 'a \to tr$ **where**
$lt = (\Lambda\ x\ y.\ case\ compare{\cdot}x{\cdot}y\ of\ LT \Rightarrow TT \mid EQ \Rightarrow FF \mid GT \Rightarrow FF)$

definition $le :: 'a \to 'a \to tr$ **where**
$le = (\Lambda\ x\ y.\ case\ compare{\cdot}x{\cdot}y\ of\ LT \Rightarrow TT \mid EQ \Rightarrow TT \mid GT \Rightarrow FF)$

lemma *lt-eq-TT-iff*: $lt{\cdot}x{\cdot}y = TT \longleftrightarrow compare{\cdot}x{\cdot}y = LT$

⟨*proof*⟩

end

class *Ord-strict* = *Ord* +
  assumes *compare-strict* [*simp*]:
    compare·⊥·*y* = ⊥
    compare·*x*·⊥ = ⊥
begin

lemma *lt-strict* [*simp*]:
  shows *lt*·⊥·*x* = ⊥
    and *lt*·*x*·⊥ = ⊥
  ⟨*proof*⟩

lemma *le-strict* [*simp*]:
  shows *le*·⊥·*x* = ⊥
    and *le*·*x*·⊥ = ⊥
  ⟨*proof*⟩

end

TODO: It might make sense to have a class for preorders too, analogous to class *eq-equiv*.

class *Ord-linear* = *Ord-strict* +
  assumes *eq-conv-compare*: *eq*·*x*·*y* = *is-EQ*·(*compare*·*x*·*y*)
    and *oppOrdering-compare* [*simp*]:
    oppOrdering·(*compare*·*x*·*y*) = *compare*·*y*·*x*
    and *compare-EQ-dest*: *compare*·*x*·*y* = *EQ* ⟹ *x* = *y*
    and *compare-self-below-EQ*: *compare*·*x*·*x* ⊑ *EQ*
    and *compare-LT-trans*:
    compare·*x*·*y* = *LT* ⟹ *compare*·*y*·*z* = *LT* ⟹ *compare*·*x*·*z* = *LT*

begin

lemma *eq-TT-dest*: *eq*·*x*·*y* = *TT* ⟹ *x* = *y*
  ⟨*proof*⟩

lemma *le-iff-lt-or-eq*:
  le·*x*·*y* = *TT* ⟷ *lt*·*x*·*y* = *TT* ∨ *eq*·*x*·*y* = *TT*
  ⟨*proof*⟩

lemma *compare-sym*:
  compare·*x*·*y* = (*case compare*·*y*·*x of LT* ⇒ *GT* | *EQ* ⇒ *EQ* | *GT* ⇒ *LT*)
  ⟨*proof*⟩

lemma *compare-self-neq-LT* [*simp*]: *compare*·*x*·*x* ≠ *LT*
  ⟨*proof*⟩

lemma *compare-self-neq-GT* [*simp*]: $compare{\cdot}x{\cdot}x \neq GT$
⟨*proof*⟩

declare *compare-self-below-EQ* [*simp*]

lemma *lt-trans*: $lt{\cdot}x{\cdot}y = TT \Longrightarrow lt{\cdot}y{\cdot}z = TT \Longrightarrow lt{\cdot}x{\cdot}z = TT$
⟨*proof*⟩

lemma *compare-GT-iff-LT*: $compare{\cdot}x{\cdot}y = GT \longleftrightarrow compare{\cdot}y{\cdot}x = LT$
⟨*proof*⟩

lemma *compare-GT-trans*:
$compare{\cdot}x{\cdot}y = GT \Longrightarrow compare{\cdot}y{\cdot}z = GT \Longrightarrow compare{\cdot}x{\cdot}z = GT$
⟨*proof*⟩

lemma *compare-EQ-iff-eq-TT*:
$compare{\cdot}x{\cdot}y = EQ \longleftrightarrow eq{\cdot}x{\cdot}y = TT$
⟨*proof*⟩

lemma *compare-EQ-trans*:
$compare{\cdot}x{\cdot}y = EQ \Longrightarrow compare{\cdot}y{\cdot}z = EQ \Longrightarrow compare{\cdot}x{\cdot}z = EQ$
⟨*proof*⟩

lemma *le-trans*:
$le{\cdot}x{\cdot}y = TT \Longrightarrow le{\cdot}y{\cdot}z = TT \Longrightarrow le{\cdot}x{\cdot}z = TT$
⟨*proof*⟩

lemma *neg-lt*: $neg{\cdot}(lt{\cdot}x{\cdot}y) = le{\cdot}y{\cdot}x$
⟨*proof*⟩

lemma *neg-le*: $neg{\cdot}(le{\cdot}x{\cdot}y) = lt{\cdot}y{\cdot}x$
⟨*proof*⟩

subclass *Eq-eq*
⟨*proof*⟩

end

A combinator for defining Ord instances for datatypes.

definition *thenOrdering* :: *Ordering* → *Ordering* → *Ordering* **where**
$thenOrdering = (\Lambda\ x\ y.\ case\ x\ of\ LT \Rightarrow LT \mid EQ \Rightarrow y \mid GT \Rightarrow GT)$

lemma *thenOrdering-simps* [*simp*]:
$thenOrdering{\cdot}LT{\cdot}y = LT$
$thenOrdering{\cdot}EQ{\cdot}y = y$
$thenOrdering{\cdot}GT{\cdot}y = GT$
$thenOrdering{\cdot}\bot{\cdot}y = \bot$
⟨*proof*⟩

lemma *thenOrdering-LT-iff* [*simp*]:
thenOrdering·*x*·*y* = *LT* ⟷ *x* = *LT* ∨ *x* = *EQ* ∧ *y* = *LT*
⟨*proof*⟩

lemma *thenOrdering-EQ-iff* [*simp*]:
thenOrdering·*x*·*y* = *EQ* ⟷ *x* = *EQ* ∧ *y* = *EQ*
⟨*proof*⟩

lemma *thenOrdering-GT-iff* [*simp*]:
thenOrdering·*x*·*y* = *GT* ⟷ *x* = *GT* ∨ *x* = *EQ* ∧ *y* = *GT*
⟨*proof*⟩

lemma *thenOrdering-below-EQ-iff* [*simp*]:
thenOrdering·*x*·*y* ⊑ *EQ* ⟷ *x* ⊑ *EQ* ∧ (*x* = ⊥ ∨ *y* ⊑ *EQ*)
⟨*proof*⟩

lemma *is-EQ-thenOrdering* [*simp*]:
is-EQ·(*thenOrdering*·*x*·*y*) = (*is-EQ*·*x andalso is-EQ*·*y*)
⟨*proof*⟩

lemma *oppOrdering-thenOrdering*:
oppOrdering·(*thenOrdering*·*x*·*y*) =
thenOrdering·(*oppOrdering*·*x*)·(*oppOrdering*·*y*)
⟨*proof*⟩

instantiation *lift* :: ({*linorder*,*countable*}) *Ord-linear*
begin

definition
compare ≡ (Λ (*Def x*) (*Def y*).
if x < *y then LT else if x* > *y then GT else EQ*)

instance ⟨*proof*⟩

end

lemma *lt-le*:
lt·(*x*::′*a*::*Ord-linear*)·*y* = (*le*·*x*·*y andalso neq*·*x*·*y*)
⟨*proof*⟩

end

3 Cpo for Numerals

theory *Numeral-Cpo*
imports *HOLCF-Main*
begin

class *plus-cpo* = *plus* + *cpo* +
  assumes *cont-plus1*: *cont* ($\lambda x{::}'a{::}\{plus,cpo\}.\ x + y$)
  assumes *cont-plus2*: *cont* ($\lambda y{::}'a{::}\{plus,cpo\}.\ x + y$)
begin

abbreviation *plus-section* :: $'a \to 'a \to 'a$ ($'(+')$) **where**
  $(+) \equiv \Lambda\ x\ y.\ x + y$

abbreviation *plus-section-left* :: $'a \Rightarrow 'a \to 'a$ ($'(\text{-}+')$) **where**
  $(x+) \equiv \Lambda\ y.\ x + y$

abbreviation *plus-section-right* :: $'a \Rightarrow 'a \to 'a$ ($'(+\text{-}')$) **where**
  $(+y) \equiv \Lambda\ x.\ x + y$

end

class *minus-cpo* = *minus* + *cpo* +
  assumes *cont-minus1*: *cont* ($\lambda x{::}'a{::}\{minus,cpo\}.\ x - y$)
  assumes *cont-minus2*: *cont* ($\lambda y{::}'a{::}\{minus,cpo\}.\ x - y$)
begin

abbreviation *minus-section* :: $'a \to 'a \to 'a$ ($'(-')$) **where**
  $(-) \equiv \Lambda\ x\ y.\ x - y$

abbreviation *minus-section-left* :: $'a \Rightarrow 'a \to 'a$ ($'(\text{--}')$) **where**
  $(x-) \equiv \Lambda\ y.\ x - y$

abbreviation *minus-section-right* :: $'a \Rightarrow 'a \to 'a$ ($'(-\text{-}')$) **where**
  $(-y) \equiv \Lambda\ x.\ x - y$

end

class *times-cpo* = *times* + *cpo* +
  assumes *cont-times1*: *cont* ($\lambda x{::}'a{::}\{times,cpo\}.\ x * y$)
  assumes *cont-times2*: *cont* ($\lambda y{::}'a{::}\{times,cpo\}.\ x * y$)
begin

end

lemma *cont2cont-plus* [*simp*, *cont2cont*]:
  assumes *cont* ($\lambda x.\ f\ x$) **and** *cont* ($\lambda x.\ g\ x$)
  shows *cont* ($\lambda x.\ f\ x + g\ x :: 'a{::}plus\text{-}cpo$)
  ⟨*proof*⟩

lemma *cont2cont-minus* [*simp*, *cont2cont*]:
  assumes *cont* ($\lambda x.\ f\ x$) **and** *cont* ($\lambda x.\ g\ x$)
  shows *cont* ($\lambda x.\ f\ x - g\ x :: 'a{::}minus\text{-}cpo$)

⟨*proof*⟩

lemma *cont2cont-times* [*simp*, *cont2cont*]:
assumes *cont* (λ*x*. *f x*) **and** *cont* (λ*x*. *g x*)
shows *cont* (λ*x*. *f x* ∗ *g x* :: *'a*::*times-cpo*)
⟨*proof*⟩

instantiation *u* :: ({*zero*,*cpo*}) *zero*
begin
definition *zero-u* = *up*·(*0*::*'a*)
instance ⟨*proof*⟩
end

instantiation *u* :: ({*one*,*cpo*}) *one*
begin
definition *one-u* = *up*·(*1*::*'a*)
instance ⟨*proof*⟩
end

instantiation *u* :: (*plus-cpo*) *plus*
begin
definition *plus-u x y* = (Λ(*up*·*a*) (*up*·*b*). *up*·(*a* + *b*))·*x*·*y* **for** *x y* :: *'a*$_\perp$
instance ⟨*proof*⟩
end

instantiation *u* :: (*minus-cpo*) *minus*
begin
definition *minus-u x y* = (Λ(*up*·*a*) (*up*·*b*). *up*·(*a* − *b*))·*x*·*y* **for** *x y* :: *'a*$_\perp$
instance ⟨*proof*⟩
end

instantiation *u* :: (*times-cpo*) *times*
begin
definition *times-u x y* = (Λ(*up*·*a*) (*up*·*b*). *up*·(*a* ∗ *b*))·*x*·*y* **for** *x y* :: *'a*$_\perp$
instance ⟨*proof*⟩
end

lemma *plus-u-strict* [*simp*]:
fixes *x* :: - *u* **shows** *x* + ⊥ = ⊥ **and** ⊥ + *x* = ⊥
⟨*proof*⟩

lemma *minus-u-strict* [*simp*]:
fixes *x* :: - *u* **shows** *x* − ⊥ = ⊥ **and** ⊥ − *x* = ⊥
⟨*proof*⟩

lemma *times-u-strict* [*simp*]:
fixes *x* :: - *u* **shows** *x* ∗ ⊥ = ⊥ **and** ⊥ ∗ *x* = ⊥
⟨*proof*⟩

lemma *plus-up-up* [*simp*]: $up{\cdot}x + up{\cdot}y = up{\cdot}(x + y)$
⟨*proof*⟩

lemma *minus-up-up* [*simp*]: $up{\cdot}x - up{\cdot}y = up{\cdot}(x - y)$
⟨*proof*⟩

lemma *times-up-up* [*simp*]: $up{\cdot}x * up{\cdot}y = up{\cdot}(x * y)$
⟨*proof*⟩

instance u :: (*plus-cpo*) *plus-cpo*
⟨*proof*⟩

instance u :: (*minus-cpo*) *minus-cpo*
⟨*proof*⟩

instance u :: (*times-cpo*) *times-cpo*
⟨*proof*⟩

instance u :: ({*semigroup-add*,*plus-cpo*}) *semigroup-add*
⟨*proof*⟩

instance u :: ({*ab-semigroup-add*,*plus-cpo*}) *ab-semigroup-add*
⟨*proof*⟩

instance u :: ({*monoid-add*,*plus-cpo*}) *monoid-add*
⟨*proof*⟩

instance u :: ({*comm-monoid-add*,*plus-cpo*}) *comm-monoid-add*
⟨*proof*⟩

instance u :: ({*numeral*, *plus-cpo*}) *numeral* ⟨*proof*⟩

instance *int* :: *plus-cpo*
⟨*proof*⟩

instance *int* :: *minus-cpo*
⟨*proof*⟩

end

4 Data: Functions

theory *Data-Function*
imports *HOLCF-Main*
begin

fixrec *flip* :: $('a \to 'b \to 'c) \to 'b \to 'a \to 'c$ **where**
$flip{\cdot}f{\cdot}x{\cdot}y = f{\cdot}y{\cdot}x$

fixrec *const* :: $'a \to 'b \to 'a$ **where**
  $const{\cdot}x{\cdot}\text{-} = x$

fixrec *dollar* :: $('a \mathrel{->} 'b) \mathrel{->} 'a \mathrel{->} 'b$ **where**
  $dollar{\cdot}f{\cdot}x = f{\cdot}x$

fixrec *dollarBang* :: $('a \mathrel{->} 'b) \mathrel{->} 'a \mathrel{->} 'b$ **where**
  $dollarBang{\cdot}f{\cdot}x = seq{\cdot}x{\cdot}(f{\cdot}x)$

fixrec *on* :: $('b \mathrel{->} 'b \mathrel{->} 'c) \mathrel{->} ('a \mathrel{->} 'b) \mathrel{->} 'a \mathrel{->} 'a \mathrel{->} 'c$ **where**
  $on{\cdot}g{\cdot}f{\cdot}x{\cdot}y = g{\cdot}(f{\cdot}x){\cdot}(f{\cdot}y)$

end

5 Data: Bool

theory *Data-Bool*
  imports *Type-Classes*
begin

5.1 Class instances

Eq

lemma *eq-eqI*[*case-names bottomLTR bottomRTL LTR RTL*]:
  $(x = \bot \Longrightarrow y = \bot) \Longrightarrow (y = \bot \Longrightarrow x = \bot) \Longrightarrow (x = TT \Longrightarrow y = TT) \Longrightarrow (y = TT \Longrightarrow x = TT) \Longrightarrow x = y$
⟨*proof*⟩

lemma *eq-tr-simps* [*simp*]:
  shows $eq{\cdot}TT{\cdot}TT = TT$ **and** $eq{\cdot}TT{\cdot}FF = FF$
    and $eq{\cdot}FF{\cdot}TT = FF$ **and** $eq{\cdot}FF{\cdot}FF = TT$
  ⟨*proof*⟩

Ord

lemma *compare-tr-simps* [*simp*]:
  $compare{\cdot}FF{\cdot}FF = EQ$
  $compare{\cdot}FF{\cdot}TT = LT$
  $compare{\cdot}TT{\cdot}FF = GT$
  $compare{\cdot}TT{\cdot}TT = EQ$
  ⟨*proof*⟩

5.2 Lemmas

lemma *andalso-eq-TT-iff* [*simp*]:
  $(x\ andalso\ y) = TT \longleftrightarrow x = TT \wedge y = TT$
  ⟨*proof*⟩

lemma *andalso-eq-FF-iff* [*simp*]:

$(x\ andalso\ y) = FF \longleftrightarrow x = FF \vee (x = TT \wedge y = FF)$
⟨*proof*⟩

lemma *andalso-eq-bottom-iff* [*simp*]:
$(x\ andalso\ y) = \bot \longleftrightarrow x = \bot \vee (x = TT \wedge y = \bot)$
⟨*proof*⟩

lemma *orelse-eq-FF-iff* [*simp*]:
$(x\ orelse\ y) = FF \longleftrightarrow x = FF \wedge y = FF$
⟨*proof*⟩

lemma *orelse-assoc* [*simp*]:
$((x\ orelse\ y)\ orelse\ z) = (x\ orelse\ y\ orelse\ z)$
⟨*proof*⟩

lemma *andalso-assoc* [*simp*]:
$((x\ andalso\ y)\ andalso\ z) = (x\ andalso\ y\ andalso\ z)$
⟨*proof*⟩

lemma *neg-orelse* [*simp*]:
$neg{\cdot}(x\ orelse\ y) = (neg{\cdot}x\ andalso\ neg{\cdot}y)$
⟨*proof*⟩

lemma *neg-andalso* [*simp*]:
$neg{\cdot}(x\ andalso\ y) = (neg{\cdot}x\ orelse\ neg{\cdot}y)$
⟨*proof*⟩

Not suitable as default simp rules, because they cause the simplifier to loop:

lemma *neg-eq-simps*:
$neg{\cdot}x = TT \Longrightarrow x = FF$
$neg{\cdot}x = FF \Longrightarrow x = TT$
$neg{\cdot}x = \bot \Longrightarrow x = \bot$
⟨*proof*⟩

lemma *neg-eq-TT-iff* [*simp*]: $neg{\cdot}x = TT \longleftrightarrow x = FF$
⟨*proof*⟩

lemma *neg-eq-FF-iff* [*simp*]: $neg{\cdot}x = FF \longleftrightarrow x = TT$
⟨*proof*⟩

lemma *neg-eq-bottom-iff* [*simp*]: $neg{\cdot}x = \bot \longleftrightarrow x = \bot$
⟨*proof*⟩

lemma *neg-eq* [*simp*]:
$neg{\cdot}x = neg{\cdot}y \longleftrightarrow x = y$
⟨*proof*⟩

lemma *neg-neg* [*simp*]:
neg·(*neg*·*x*) = *x*
⟨*proof*⟩

lemma *neg-comp-neg* [*simp*]:
neg oo neg = *ID*
⟨*proof*⟩

end

6 Data: Tuple

theory *Data-Tuple*
imports
Type-Classes
Data-Bool
begin

6.1 Datatype definitions

domain *Unit* (⟨⟩) = *Unit* (⟨⟩)

domain ('*a*, '*b*) *Tuple2* (⟨-, -⟩) =
Tuple2 (**lazy** *fst* :: '*a*) (**lazy** *snd* :: '*b*) (⟨-, -⟩)

notation *Tuple2* (⟨,⟩)

fixrec *uncurry* :: ('*a* → '*b* → '*c*) → ⟨'*a*, '*b*⟩ → '*c*
where *uncurry*·*f*·*p* = *f*·(*fst*·*p*)·(*snd*·*p*)

fixrec *curry* :: (⟨'*a*, '*b*⟩ → '*c*) → '*a* → '*b* → '*c*
where *curry*·*f*·*a*·*b* = *f*·⟨*a*, *b*⟩

domain ('*a*, '*b*, '*c*) *Tuple3* (⟨-, -, -⟩) =
Tuple3 (**lazy** '*a*) (**lazy** '*b*) (**lazy** '*c*) (⟨-, -, -⟩)

notation *Tuple3* (⟨,,⟩)

6.2 Type class instances

instantiation *Unit* :: *Ord-linear*
begin

definition
eq = (Λ ⟨⟩ ⟨⟩. *TT*)

definition
compare = (Λ ⟨⟩ ⟨⟩. *EQ*)

instance
⟨*proof*⟩

end

instantiation *Tuple2* :: (*Eq*, *Eq*) *Eq-strict*
begin

definition
eq = (Λ ⟨*x1*, *y1*⟩ ⟨*x2*, *y2*⟩. *eq*·*x1*·*x2 andalso eq*·*y1*·*y2*)

instance ⟨*proof*⟩

end

lemma *eq-Tuple2-simps* [*simp*]:
eq·⟨*x1*, *y1*⟩·⟨*x2*, *y2*⟩ = (*eq*·*x1*·*x2 andalso eq*·*y1*·*y2*)
⟨*proof*⟩

instance *Tuple2* :: (*Eq-sym*, *Eq-sym*) *Eq-sym*
⟨*proof*⟩

instance *Tuple2* :: (*Eq-equiv*, *Eq-equiv*) *Eq-equiv*
⟨*proof*⟩

instance *Tuple2* :: (*Eq-eq*, *Eq-eq*) *Eq-eq*
⟨*proof*⟩

instantiation *Tuple2* :: (*Ord*, *Ord*) *Ord-strict*
begin

definition
compare = (Λ ⟨*x1*, *y1*⟩ ⟨*x2*, *y2*⟩.
thenOrdering·(*compare*·*x1*·*x2*)·(*compare*·*y1*·*y2*))

instance
⟨*proof*⟩

end

lemma *compare-Tuple2-simps* [*simp*]:
compare·⟨*x1*, *y1*⟩·⟨*x2*, *y2*⟩ = *thenOrdering*·(*compare*·*x1*·*x2*)·(*compare*·*y1*·*y2*)
⟨*proof*⟩

instance *Tuple2* :: (*Ord-linear*, *Ord-linear*) *Ord-linear*
⟨*proof*⟩

instantiation *Tuple3* :: (*Eq*, *Eq*, *Eq*) *Eq-strict*
begin

definition
eq = (Λ ⟨*x1*, *y1*, *z1*⟩ ⟨*x2*, *y2*, *z2*⟩.
eq·*x1*·*x2 andalso eq*·*y1*·*y2 andalso eq*·*z1*·*z2*)

instance ⟨*proof*⟩

end

lemma *eq-Tuple3-simps* [*simp*]:
eq·⟨*x1*, *y1*, *z1*⟩·⟨*x2*, *y2*, *z2*⟩ = (*eq*·*x1*·*x2 andalso eq*·*y1*·*y2 andalso eq*·*z1*·*z2*)
⟨*proof*⟩

instance *Tuple3* :: (*Eq-sym*, *Eq-sym*, *Eq-sym*) *Eq-sym*
⟨*proof*⟩

instance *Tuple3* :: (*Eq-equiv*, *Eq-equiv*, *Eq-equiv*) *Eq-equiv*
⟨*proof*⟩

instance *Tuple3* :: (*Eq-eq*, *Eq-eq*, *Eq-eq*) *Eq-eq*
⟨*proof*⟩

instantiation *Tuple3* :: (*Ord*, *Ord*, *Ord*) *Ord-strict*
begin

definition
compare = (Λ ⟨*x1*, *y1*, *z1*⟩ ⟨*x2*, *y2*, *z2*⟩.
thenOrdering·(*compare*·*x1*·*x2*)·(*thenOrdering*·(*compare*·*y1*·*y2*)·(*compare*·*z1*·*z2*)))

instance
⟨*proof*⟩

end

lemma *compare-Tuple3-simps* [*simp*]:
compare·⟨*x1*, *y1*, *z1*⟩·⟨*x2*, *y2*, *z2*⟩ =
thenOrdering·(*compare*·*x1*·*x2*)·
(*thenOrdering*·(*compare*·*y1*·*y2*)·(*compare*·*z1*·*z2*))
⟨*proof*⟩

instance *Tuple3* :: (*Ord-linear*, *Ord-linear*, *Ord-linear*) *Ord-linear*
⟨*proof*⟩

end

7 Data: Integers

theory *Data-Integer*
imports

Numeral-Cpo
Data-Bool
begin

domain *Integer* = *MkI* (**lazy** *int*)

instance *Integer* :: *flat*
⟨*proof*⟩

instantiation *Integer* :: {*plus*,*times*,*minus*,*uminus*,*zero*,*one*}
begin

definition *0* = *MkI*·*0*
definition *1* = *MkI*·*1*
definition $a + b = (\Lambda\ (MkI{\cdot}x)\ (MkI{\cdot}y).\ MkI{\cdot}(x + y)){\cdot}a{\cdot}b$
definition $a - b = (\Lambda\ (MkI{\cdot}x)\ (MkI{\cdot}y).\ MkI{\cdot}(x - y)){\cdot}a{\cdot}b$
definition $a * b = (\Lambda\ (MkI{\cdot}x)\ (MkI{\cdot}y).\ MkI{\cdot}(x * y)){\cdot}a{\cdot}b$
definition $- a = (\Lambda\ (MkI{\cdot}x).\ MkI{\cdot}(uminus\ x)){\cdot}a$

instance ⟨*proof*⟩

end

lemma *Integer-arith-strict* [*simp*]:
fixes x :: *Integer*
shows $\bot + x = \bot$ **and** $x + \bot = \bot$
and $\bot * x = \bot$ **and** $x * \bot = \bot$
and $\bot - x = \bot$ **and** $x - \bot = \bot$
and $- \bot = (\bot{::}Integer)$
⟨*proof*⟩

lemma *Integer-arith-simps* [*simp*]:
$MkI{\cdot}a + MkI{\cdot}b = MkI{\cdot}(a + b)$
$MkI{\cdot}a * MkI{\cdot}b = MkI{\cdot}(a * b)$
$MkI{\cdot}a - MkI{\cdot}b = MkI{\cdot}(a - b)$
$- MkI{\cdot}a = MkI{\cdot}(uminus\ a)$
⟨*proof*⟩

lemma *plus-MkI-MkI*:
$MkI{\cdot}x + MkI{\cdot}y = MkI{\cdot}(x + y)$
⟨*proof*⟩

instance *Integer* :: {*plus-cpo*,*minus-cpo*,*times-cpo*}
⟨*proof*⟩

instance *Integer* :: *comm-monoid-add*
⟨*proof*⟩

instance *Integer* :: *comm-monoid-mult*

⟨*proof*⟩

instance *Integer* :: *comm-semiring*
⟨*proof*⟩

instance *Integer* :: *semiring-numeral* ⟨*proof*⟩

lemma *Integer-add-diff-cancel* [*simp*]:
$b \neq \bot \Longrightarrow (a::Integer) + b - b = a$
⟨*proof*⟩

lemma *zero-Integer-neq-bottom* [*simp*]: $(0::Integer) \neq \bot$
⟨*proof*⟩

lemma *one-Integer-neq-bottom* [*simp*]: $(1::Integer) \neq \bot$
⟨*proof*⟩

lemma *plus-Integer-eq-bottom-iff* [*simp*]:
fixes $x\ y :: Integer$ **shows** $x + y = \bot \longleftrightarrow x = \bot \vee y = \bot$
⟨*proof*⟩

lemma *diff-Integer-eq-bottom-iff* [*simp*]:
fixes $x\ y :: Integer$ **shows** $x - y = \bot \longleftrightarrow x = \bot \vee y = \bot$
⟨*proof*⟩

lemma *mult-Integer-eq-bottom-iff* [*simp*]:
fixes $x\ y :: Integer$ **shows** $x * y = \bot \longleftrightarrow x = \bot \vee y = \bot$
⟨*proof*⟩

lemma *minus-Integer-eq-bottom-iff* [*simp*]:
fixes $x :: Integer$ **shows** $- x = \bot \longleftrightarrow x = \bot$
⟨*proof*⟩

lemma *numeral-Integer-eq*: $numeral\ k = MkI{\cdot}(numeral\ k)$
⟨*proof*⟩

lemma *numeral-Integer-neq-bottom* [*simp*]: $(numeral\ k::Integer) \neq \bot$
⟨*proof*⟩

Symmetric versions are also needed, because the reorient simproc does not apply to these comparisons.

lemma *bottom-neq-zero-Integer* [*simp*]: $(\bot::Integer) \neq 0$
⟨*proof*⟩

lemma *bottom-neq-one-Integer* [*simp*]: $(\bot::Integer) \neq 1$
⟨*proof*⟩

lemma *bottom-neq-numeral-Integer* [*simp*]: $(\bot::Integer) \neq numeral\ k$
⟨*proof*⟩

instantiation *Integer* :: *Ord-linear*
begin

definition
eq = (Λ (*MkI*·*x*) (*MkI*·*y*). *if x* = *y then TT else FF*)

definition
compare = (Λ (*MkI*·*x*) (*MkI*·*y*).
if x < *y then LT else if x* > *y then GT else EQ*)

instance ⟨*proof*⟩

end

lemma *eq-MkI-MkI* [*simp*]:
eq·(*MkI*·*m*)·(*MkI*·*n*) = (*if m* = *n then TT else FF*)
⟨*proof*⟩

lemma *compare-MkI-MkI* [*simp*]:
compare·(*MkI*·*x*)·(*MkI*·*y*) = (*if x* < *y then LT else if x* > *y then GT else EQ*)
⟨*proof*⟩

lemma *lt-MkI-MkI* [*simp*]:
lt·(*MkI*·*x*)·(*MkI*·*y*) = (*if x* < *y then TT else FF*)
⟨*proof*⟩

lemma *le-MkI-MkI* [*simp*]:
le·(*MkI*·*x*)·(*MkI*·*y*) = (*if x* ≤ *y then TT else FF*)
⟨*proof*⟩

lemma *eq-Integer-bottom-iff* [*simp*]:
fixes *x y* :: *Integer* **shows** *eq*·*x*·*y* = ⊥ ⟷ *x* = ⊥ ∨ *y* = ⊥
⟨*proof*⟩

lemma *compare-Integer-bottom-iff* [*simp*]:
fixes *x y* :: *Integer* **shows** *compare*·*x*·*y* = ⊥ ⟷ *x* = ⊥ ∨ *y* = ⊥
⟨*proof*⟩

lemma *lt-Integer-bottom-iff* [*simp*]:
fixes *x y* :: *Integer* **shows** *lt*·*x*·*y* = ⊥ ⟷ *x* = ⊥ ∨ *y* = ⊥
⟨*proof*⟩

lemma *le-Integer-bottom-iff* [*simp*]:
fixes *x y* :: *Integer* **shows** *le*·*x*·*y* = ⊥ ⟷ *x* = ⊥ ∨ *y* = ⊥
⟨*proof*⟩

lemma *compare-refl-Integer* [*simp*]:
(*x*::*Integer*) ≠ ⊥ ⟹ *compare*·*x*·*x* = *EQ*

⟨*proof*⟩

lemma *eq-refl-Integer* [*simp*]:
(*x*::*Integer*) ≠ ⊥ ⟹ *eq*·*x*·*x* = *TT*
⟨*proof*⟩

lemma *lt-refl-Integer* [*simp*]:
(*x*::*Integer*) ≠ ⊥ ⟹ *lt*·*x*·*x* = *FF*
⟨*proof*⟩

lemma *le-refl-Integer* [*simp*]:
(*x*::*Integer*) ≠ ⊥ ⟹ *le*·*x*·*x* = *TT*
⟨*proof*⟩

lemma *eq-Integer-numeral-simps* [*simp*]:
eq·(*0*::*Integer*)·*0* = *TT*
eq·(*0*::*Integer*)·*1* = *FF*
eq·(*1*::*Integer*)·*0* = *FF*
eq·(*1*::*Integer*)·*1* = *TT*
eq·(*0*::*Integer*)·(*numeral k*) = *FF*
eq·(*numeral k*)·(*0*::*Integer*) = *FF*
k ≠ *Num.One* ⟹ *eq*·(*1*::*Integer*)·(*numeral k*) = *FF*
k ≠ *Num.One* ⟹ *eq*·(*numeral k*)·(*1*::*Integer*) = *FF*
eq·(*numeral k*::*Integer*)·(*numeral l*) = (*if k* = *l then TT else FF*)
⟨*proof*⟩

lemma *compare-Integer-numeral-simps* [*simp*]:
compare·(*0*::*Integer*)·*0* = *EQ*
compare·(*0*::*Integer*)·*1* = *LT*
compare·(*1*::*Integer*)·*0* = *GT*
compare·(*1*::*Integer*)·*1* = *EQ*
compare·(*0*::*Integer*)·(*numeral k*) = *LT*
compare·(*numeral k*)·(*0*::*Integer*) = *GT*
Num.One < *k* ⟹ *compare*·(*1*::*Integer*)·(*numeral k*) = *LT*
Num.One < *k* ⟹ *compare*·(*numeral k*)·(*1*::*Integer*) = *GT*
compare·(*numeral k*::*Integer*)·(*numeral l*) =
(*if k* < *l then LT else if k* > *l then GT else EQ*)
⟨*proof*⟩

lemma *lt-Integer-numeral-simps* [*simp*]:
lt·(*0*::*Integer*)·*0* = *FF*
lt·(*0*::*Integer*)·*1* = *TT*
lt·(*1*::*Integer*)·*0* = *FF*
lt·(*1*::*Integer*)·*1* = *FF*
lt·(*0*::*Integer*)·(*numeral k*) = *TT*
lt·(*numeral k*)·(*0*::*Integer*) = *FF*
Num.One < *k* ⟹ *lt*·(*1*::*Integer*)·(*numeral k*) = *TT*
lt·(*numeral k*)·(*1*::*Integer*) = *FF*
lt·(*numeral k*::*Integer*)·(*numeral l*) = (*if k* < *l then TT else FF*)

⟨*proof*⟩

lemma *le-Integer-numeral-simps* [*simp*]:
le·(0::Integer)·0 = TT
le·(0::Integer)·1 = TT
le·(1::Integer)·0 = FF
le·(1::Integer)·1 = TT
le·(0::Integer)·(numeral k) = TT
le·(numeral k)·(0::Integer) = FF
le·(1::Integer)·(numeral k) = TT
Num.One < k ⟹ le·(numeral k)·(1::Integer) = FF
le·(numeral k::Integer)·(numeral l) = (if k ≤ l then TT else FF)
⟨*proof*⟩

lemma *MkI-eq-0-iff* [*simp*]: *MkI·n = 0 ⟷ n = 0*
⟨*proof*⟩

lemma *MkI-eq-1-iff* [*simp*]: *MkI·n = 1 ⟷ n = 1*
⟨*proof*⟩

lemma *MkI-eq-numeral-iff* [*simp*]: *MkI·n = numeral k ⟷ n = numeral k*
⟨*proof*⟩

lemma *MkI-0*: *MkI·0 = 0*
⟨*proof*⟩

lemma *MkI-1*: *MkI·1 = 1*
⟨*proof*⟩

lemma *le-plus-1*:
fixes *m* :: *Integer*
assumes *le·m·n = TT*
shows *le·m·(n + 1) = TT*
⟨*proof*⟩

7.1 Induction rules that do not break the abstraction

lemma *nonneg-Integer-induct* [*consumes 1*, *case-names 0 step*]:
fixes *i* :: *Integer*
assumes *i-nonneg*: *le·0·i = TT*
and *zero*: *P 0*
and *step*: ⋀*i*. *le·1·i = TT ⟹ P (i − 1) ⟹ P i*
shows *P i*
⟨*proof*⟩

end

8 Data: List

theory *Data-List*
  imports
    Type-Classes
    Data-Function
    Data-Bool
    Data-Tuple
    Data-Integer
    Numeral-Cpo
begin

no-notation (*ASCII*)
  Set.member (′(:′)) **and**
  Set.member ((-/ : -) [*51*, *51*] *50*)

8.1 Datatype definition

domain ′*a list* ([-]) =
  Nil ([]) |
  Cons (**lazy** *head* :: ′*a*) (**lazy** *tail* :: [′*a*]) (**infixr** : *65*)

8.1.1 Section syntax for *Cons*

syntax
  -*Cons-section* :: ′*a* → [′*a*] → [′*a*] (′(:′))
  -*Cons-section-left* :: ′*a* ⇒ [′*a*] → [′*a*] (′(-:′))
translations
  (*x*:) == (*CONST Rep-cfun*) (*CONST Cons*) *x*

abbreviation *Cons-section-right* :: [′*a*] ⇒ ′*a* → [′*a*] (′(:-′)) **where**
  (:*xs*) ≡ Λ *x*. *x*:*xs*

syntax
  -*lazy-list* :: *args* ⇒ [′*a*] ([(-)])
translations
  [*x*, *xs*] == *x* : [*xs*]
  [*x*] == *x* : []

abbreviation *null* :: [′*a*] → *tr* **where** *null* ≡ *is-Nil*

8.2 Haskell function definitions

instantiation *list* :: (*Eq*) *Eq-strict*
begin

fixrec *eq-list* :: [′*a*] → [′*a*] → *tr* **where**
  eq-list·[]·[] = *TT* |
  eq-list·(*x* : *xs*)·[] = *FF* |
  eq-list·[]·(*y* : *ys*) = *FF* |

```
  eq-list·(x : xs)·(y : ys) = (eq·x·y andalso eq-list·xs·ys)

instance ⟨proof⟩

end

instance list :: (Eq-sym) Eq-sym
⟨proof⟩

instance list :: (Eq-equiv) Eq-equiv
⟨proof⟩

instance list :: (Eq-eq) Eq-eq
⟨proof⟩

instantiation list :: (Ord) Ord-strict
begin

fixrec compare-list :: ['a] → ['a] → Ordering where
  compare-list·[]·[] = EQ |
  compare-list·(x : xs)·[] = GT |
  compare-list·[]·(y : ys) = LT |
  compare-list·(x : xs)·(y : ys) =
    thenOrdering·(compare·x·y)·(compare-list·xs·ys)

instance
  ⟨proof⟩

end

instance list :: (Ord-linear) Ord-linear
⟨proof⟩

fixrec zipWith :: ('a → 'b → 'c) → ['a] → ['b] → ['c] where
  zipWith·f·(x : xs)·(y : ys) = f·x·y : zipWith·f·xs·ys |
  zipWith·f·(x : xs)·[] = [] |
  zipWith·f·[]·ys = []

definition zip :: ['a] → ['b] → [⟨'a, 'b⟩] where
  zip = zipWith·⟨,⟩

fixrec zipWith3 :: ('a → 'b → 'c → 'd) → ['a] → ['b] → ['c] → ['d] where
  zipWith3·f·(x : xs)·(y : ys)·(z : zs) = f·x·y·z : zipWith3·f·xs·ys·zs |
  (unchecked) zipWith3·f·xs·ys·zs = []

definition zip3 :: ['a] → ['b] → ['c] → [⟨'a, 'b, 'c⟩] where
  zip3 = zipWith3·⟨,,⟩

fixrec map :: ('a → 'b) → ['a] → ['b] where
```

```
  map·f·[] = [] |
  map·f·(x : xs) = f·x : map·f·xs

fixrec filter :: ('a → tr) → ['a] → ['a] where
  filter·P·[] = [] |
  filter·P·(x : xs) =
    If (P·x) then x : filter·P·xs else filter·P·xs

fixrec repeat :: 'a → ['a] where
  [simp del]: repeat·x = x : repeat·x

fixrec takeWhile :: ('a → tr) → ['a] → ['a] where
 takeWhile·p·[]     =  [] |
 takeWhile·p·(x:xs) = If p·x then x : takeWhile·p·xs else  []

fixrec dropWhile :: ('a → tr) → ['a] → ['a] where
 dropWhile·p·[]     =  [] |
 dropWhile·p·(x:xs) = If p·x then dropWhile·p·xs else (x:xs)

fixrec span :: ('a -> tr) -> ['a] -> ⟨['a],['a]⟩ where
 span·p·[]     = ⟨[],[]⟩ |
 span·p·(x:xs) = If p·x then (case span·p·xs of ⟨ys, zs⟩ ⇒ ⟨x:ys,zs⟩) else ⟨[], x:xs⟩

fixrec break :: ('a -> tr) -> ['a] -> ⟨['a],['a]⟩ where
 break·p = span·(neg oo p)

fixrec nth :: ['a] → Integer → 'a where
  nth·[]·n = ⊥ |
  nth-Cons [simp del]:
  nth·(x : xs)·n = If eq·n·0 then x else nth·xs·(n − 1)


abbreviation nth-syn :: ['a] ⇒ Integer ⇒ 'a (infixl !! 100) where
  xs !! n ≡ nth·xs·n

definition partition :: ('a → tr) → ['a] → ⟨['a], ['a]⟩ where
  partition = (Λ P xs. ⟨filter·P·xs, filter·(neg oo P)·xs⟩)

fixrec iterate :: ('a → 'a) → 'a → ['a] where
  iterate·f·x = x : iterate·f·(f·x)

fixrec foldl ::  ('a -> 'b -> 'a) -> 'a -> ['b] -> 'a where
  foldl·f·z·[]     = z |
  foldl·f·z·(x:xs) = foldl·f·(f·z·x)·xs

fixrec foldl1 ::  ('a -> 'a -> 'a) -> ['a] -> 'a where
  foldl1·f·[]     = ⊥ |
  foldl1·f·(x:xs) = foldl·f·x·xs
```

fixrec *foldr* :: $('a \to 'b \to 'b) \to 'b \to ['a] \to 'b$ **where**
  $foldr{\cdot}f{\cdot}d{\cdot}[] = d$ |
  $foldr{\cdot}f{\cdot}d{\cdot}(x : xs) = f{\cdot}x{\cdot}(foldr{\cdot}f{\cdot}d{\cdot}xs)$

fixrec *foldr1* :: $('a \to 'a \to 'a) \to ['a] \to 'a$ **where**
  $foldr1{\cdot}f{\cdot}[] = \bot$ |
  $foldr1{\cdot}f{\cdot}[x] = x$ |
  $foldr1{\cdot}f{\cdot}(x : (x'{:}xs)) = f{\cdot}x{\cdot}(foldr1{\cdot}f{\cdot}(x'{:}xs))$

fixrec *elem* :: $'a{::}Eq \to ['a] \to tr$ **where**
  $elem{\cdot}x{\cdot}[] = FF$ |
  $elem{\cdot}x{\cdot}(y : ys) = (eq{\cdot}y{\cdot}x\ orelse\ elem{\cdot}x{\cdot}ys)$

fixrec *notElem* :: $'a{::}Eq \to ['a] \to tr$ **where**
  $notElem{\cdot}x{\cdot}[] = TT$ |
  $notElem{\cdot}x{\cdot}(y : ys) = (neq{\cdot}y{\cdot}x\ andalso\ notElem{\cdot}x{\cdot}ys)$

fixrec *append* :: $['a] \to ['a] \to ['a]$ **where**
  $append{\cdot}[]{\cdot}ys = ys$ |
  $append{\cdot}(x : xs){\cdot}ys = x : append{\cdot}xs{\cdot}ys$

abbreviation *append-syn* :: $['a] \Rightarrow ['a] \Rightarrow ['a]$ (**infixr** $++$ *65*) **where**
  $xs ++ ys \equiv append{\cdot}xs{\cdot}ys$

definition *concat* :: $[['a]] \to ['a]$ **where**
  $concat = foldr{\cdot}append{\cdot}[]$

definition *concatMap* :: $('a \to ['b]) \to ['a] \to ['b]$ **where**
  $concatMap = (\Lambda\ f.\ concat\ oo\ map{\cdot}f)$

fixrec *last* :: $['a] \mathrel{-\!\!>} 'a$ **where**
  $last{\cdot}[x] = x$ |
  $last{\cdot}(\text{-}{:}(x{:}xs)) = last{\cdot}(x{:}xs)$

fixrec *init* :: $['a] \mathrel{-\!\!>} ['a]$ **where**
  $init{\cdot}[x] = []$ |
  $init{\cdot}(x{:}(y{:}xs)) = x{:}(init{\cdot}(y{:}xs))$

fixrec *reverse* :: $['a] \mathrel{-\!\!>} ['a]$ **where**
  $[simp\ del]{:}reverse = foldl{\cdot}(flip{\cdot}(:)){\cdot}[]$

fixrec *the-and* :: $[tr] \to tr$ **where**
  $the\text{-}and = foldr{\cdot}trand{\cdot}TT$

fixrec *the-or* :: $[tr] \to tr$ **where**
  $the\text{-}or = foldr{\cdot}tror{\cdot}FF$

fixrec *all* :: $('a \to tr) \to ['a] \to tr$ **where**
  $all{\cdot}P = the\text{-}and\ oo\ (map{\cdot}P)$

```
fixrec any :: ('a → tr) → ['a] → tr where
  any·P = the-or oo (map·P)

fixrec tails :: ['a] → [['a]] where
  tails·[] = [[]] |
  tails·(x : xs) = (x : xs) : tails·xs

fixrec inits :: ['a] → [['a]] where
  inits·[] = [[]] |
  inits·(x : xs) = [[]] ++ map·(x:)·(inits·xs)

fixrec scanr :: ('a → 'b → 'b) → 'b → ['a] → ['b]
where
  scanr·f·q0·[] = [q0] |
  scanr·f·q0·(x : xs) = (
    let qs = scanr·f·q0·xs in
    (case qs of
      [] ⇒ ⊥
    | q : qs' ⇒ f·x·q : qs))

fixrec scanr1 :: ('a → 'a → 'a) → ['a] → ['a]
where
  scanr1·f·[] = [] |
  scanr1·f·(x : xs) =
    (case xs of
      [] ⇒ [x]
    | x' : xs' ⇒ (
      let qs = scanr1·f·xs in
      (case qs of
        [] ⇒ ⊥
      | q : qs' ⇒ f·x·q : qs)))

fixrec scanl :: ('a → 'b → 'a) → 'a → ['b] → ['a] where
  scanl·f·q·ls = q : (case ls of
    [] ⇒ []
  | x : xs ⇒ scanl·f·(f·q·x)·xs)

definition scanl1 :: ('a → 'a → 'a) → ['a] → ['a] where
  scanl1 = (Λ f ls. (case ls of
    [] ⇒ []
  | x : xs ⇒ scanl·f·x·xs))
```

8.2.1 Arithmetic Sequences

```
fixrec upto :: Integer → Integer → [Integer] where
  [simp del]: upto·x·y = If le·x·y then x : upto·(x+1)·y else []

fixrec intsFrom :: Integer → [Integer] where
```

```
  [simp del]: intsFrom·x = seq·x·(x : intsFrom·(x+1))

class Enum =
  fixes toEnum :: Integer → 'a
    and fromEnum :: 'a → Integer
begin

definition succ :: 'a → 'a where
  succ = toEnum oo (+1) oo fromEnum

definition pred :: 'a → 'a where
  pred = toEnum oo (−1) oo fromEnum

definition enumFrom :: 'a → ['a] where
  enumFrom = (Λ x. map·toEnum·(intsFrom·(fromEnum·x)))

definition enumFromTo :: 'a → 'a → ['a] where
  enumFromTo = (Λ x y. map·toEnum·(upto·(fromEnum·x)·(fromEnum·y)))

end

abbreviation enumFrom-To-syn :: 'a::Enum ⇒ 'a ⇒ ['a] ((1[-../-])) where
  [m..n] ≡ enumFromTo·m·n

abbreviation enumFrom-syn :: 'a::Enum ⇒ ['a] ((1[-..])) where
  [n..] ≡ enumFrom·n

instantiation Integer :: Enum
begin
definition [simp]: toEnum = ID
definition [simp]: fromEnum = ID
instance ⟨proof⟩
end

fixrec take :: Integer → ['a] → ['a] where
  [simp del]: take·n·xs = If le·n·0 then [] else
    (case xs of [] ⇒ [] | y : ys ⇒ y : take·(n − 1)·ys)

fixrec drop :: Integer → ['a] → ['a] where
  [simp del]: drop·n·xs = If le·n·0 then xs else
    (case xs of [] ⇒ [] | y : ys ⇒ drop·(n − 1)·ys)

fixrec isPrefixOf :: ['a::Eq] → ['a] → tr where
  isPrefixOf·[]·- = TT |
  isPrefixOf·(x:xs)·[] = FF |
  isPrefixOf·(x:xs)·(y:ys) = (eq·x·y andalso isPrefixOf·xs·ys)

fixrec isSuffixOf :: ['a::Eq] → ['a] → tr where
  isSuffixOf·x·y = isPrefixOf·(reverse·x)·(reverse·y)
```

fixrec *intersperse* :: $'a \to ['a] \to ['a]$ **where**
  $intersperse{\cdot}sep{\cdot}[] = [] \mid$
  $intersperse{\cdot}sep{\cdot}[x] = [x] \mid$
  $intersperse{\cdot}sep{\cdot}(x{:}y{:}xs) = x{:}sep{:}intersperse{\cdot}sep{\cdot}(y{:}xs)$

fixrec *intercalate* :: $['a] \to [['a]] \to ['a]$ **where**
  $intercalate{\cdot}xs{\cdot}xss = concat{\cdot}(intersperse{\cdot}xs{\cdot}xss)$

definition *replicate* :: $Integer \to 'a \to ['a]$ **where**
  $replicate = (\Lambda\ n\ x.\ take{\cdot}n{\cdot}(repeat{\cdot}x))$

definition *findIndices* :: $('a \to tr) \to ['a] \to [Integer]$ **where**
  $findIndices = (\Lambda\ P\ xs.$
    $map{\cdot}snd{\cdot}(filter{\cdot}(\Lambda\ \langle x,\ i\rangle.\ P{\cdot}x){\cdot}(zip{\cdot}xs{\cdot}[0..])))$

fixrec *length* :: $['a] \to Integer$ **where**
  $length{\cdot}[] = 0 \mid$
  $length{\cdot}(x : xs) = length{\cdot}xs + 1$

fixrec *delete* :: $'a{::}Eq \to ['a] \to ['a]$ **where**
  $delete{\cdot}x{\cdot}[] = [] \mid$
  $delete{\cdot}x{\cdot}(y : ys) = If\ eq{\cdot}x{\cdot}y\ then\ ys\ else\ y : delete{\cdot}x{\cdot}ys$

fixrec *diff* :: $['a{::}Eq] \to ['a] \to ['a]$ **where**
  $diff{\cdot}xs{\cdot}[] = xs \mid$
  $diff{\cdot}xs{\cdot}(y : ys) = diff{\cdot}(delete{\cdot}y{\cdot}xs){\cdot}ys$

abbreviation *diff-syn* :: $['a{::}Eq] \Rightarrow ['a] \Rightarrow ['a]$ (**infixl** $\backslash\backslash$ *70*) **where**
  $xs \setminus\setminus ys \equiv diff{\cdot}xs{\cdot}ys$

8.3 Logical predicates on lists

inductive *finite-list* :: $['a] \Rightarrow bool$ **where**
  Nil [*intro*!, *simp*]: *finite-list* [] $\mid$
  Cons [*intro*!, *simp*]: $\bigwedge x\ xs.\ finite\text{-}list\ xs \Longrightarrow finite\text{-}list\ (x : xs)$

inductive-cases *finite-listE* [*elim*!]: *finite-list* $(x : xs)$

lemma *finite-list-upwards*:
  assumes *finite-list xs* **and** $xs \sqsubseteq ys$
  shows *finite-list ys*
⟨*proof*⟩

lemma *adm-finite-list* [*simp*]: *adm finite-list*
  ⟨*proof*⟩

lemma *bot-not-finite-list* [*simp*]:
  finite-list $\bot$ = *False*

⟨*proof*⟩

inductive *listmem* :: *'a* ⇒ [*'a*] ⇒ *bool* **where**
listmem x (*x* : *xs*) |
listmem x xs ⟹ *listmem x* (*y* : *xs*)

lemma *listmem-simps* [*simp*]:
shows ¬ *listmem x* ⊥ **and** ¬ *listmem x* []
and *listmem x* (*y* : *ys*) ⟷ *x* = *y* ∨ *listmem x ys*
⟨*proof*⟩

definition *set* :: [*'a*] ⇒ *'a set* **where**
set xs = {*x*. *listmem x xs*}

lemma *set-simps* [*simp*]:
shows *set* ⊥ = {} **and** *set* [] = {}
and *set* (*x* : *xs*) = *insert x* (*set xs*)
⟨*proof*⟩

inductive *distinct* :: [*'a*] ⇒ *bool* **where**
Nil [*intro*!, *simp*]: *distinct* [] |
Cons [*intro*!, *simp*]: ⋀*x xs*. *distinct xs* ⟹ *x* ∉ *set xs* ⟹ *distinct* (*x* : *xs*)

8.4 Properties

lemma *map-strict* [*simp*]:
map·*P*·⊥ = ⊥
⟨*proof*⟩

lemma *map-ID* [*simp*]:
map·*ID*·*xs* = *xs*
⟨*proof*⟩

lemma *enumFrom-intsFrom-conv* [*simp*]:
enumFrom = *intsFrom*
⟨*proof*⟩

lemma *enumFromTo-upto-conv* [*simp*]:
enumFromTo = *upto*
⟨*proof*⟩

lemma *zipWith-strict* [*simp*]:
zipWith·*f*·⊥·*ys* = ⊥
zipWith·*f*·(*x* : *xs*)·⊥ = ⊥
⟨*proof*⟩

lemma *zip-simps* [*simp*]:
zip·(*x* : *xs*)·(*y* : *ys*) = ⟨*x*, *y*⟩ : *zip*·*xs*·*ys*
zip·(*x* : *xs*)·[] = []

$zip{\cdot}(x : xs){\cdot}\bot = \bot$
$zip{\cdot}[]{\cdot}ys = []$
$zip{\cdot}\bot{\cdot}ys = \bot$
⟨*proof*⟩

lemma *zip-Nil2* [*simp*]:
$xs \neq \bot \Longrightarrow zip{\cdot}xs{\cdot}[] = []$
⟨*proof*⟩

lemma *nth-strict* [*simp*]:
$nth{\cdot}\bot{\cdot}n = \bot$
$nth{\cdot}xs{\cdot}\bot = \bot$
⟨*proof*⟩

lemma *upto-strict* [*simp*]:
$upto{\cdot}\bot{\cdot}y = \bot$
$upto{\cdot}x{\cdot}\bot = \bot$
⟨*proof*⟩

lemma *upto-simps* [*simp*]:
$n < m \Longrightarrow upto{\cdot}(MkI{\cdot}m){\cdot}(MkI{\cdot}n) = []$
$m \leq n \Longrightarrow upto{\cdot}(MkI{\cdot}m){\cdot}(MkI{\cdot}n) = MkI{\cdot}m : [MkI{\cdot}m{+}1..MkI{\cdot}n]$
⟨*proof*⟩

lemma *filter-strict* [*simp*]:
$filter{\cdot}P{\cdot}\bot = \bot$
⟨*proof*⟩

lemma *nth-Cons-simp* [*simp*]:
$eq{\cdot}n{\cdot}0 = TT \Longrightarrow nth{\cdot}(x : xs){\cdot}n = x$
$eq{\cdot}n{\cdot}0 = FF \Longrightarrow nth{\cdot}(x : xs){\cdot}n = nth{\cdot}xs{\cdot}(n - 1)$
⟨*proof*⟩

lemma *nth-Cons-split*:
$P\ (nth{\cdot}(x : xs){\cdot}n) = ((eq{\cdot}n{\cdot}0 = FF \longrightarrow P\ (nth{\cdot}(x : xs){\cdot}n)) \wedge$
$(eq{\cdot}n{\cdot}0 = TT \longrightarrow P\ (nth{\cdot}(x : xs){\cdot}n)) \wedge$
$(n = \bot \longrightarrow P\ (nth{\cdot}(x : xs){\cdot}n)))$

⟨*proof*⟩

lemma *nth-Cons-numeral* [*simp*]:
$(x : xs)\ !!\ 0 = x$
$(x : xs)\ !!\ 1 = xs\ !!\ 0$
$(x : xs)\ !!\ numeral\ (Num.Bit0\ k) = xs\ !!\ numeral\ (Num.BitM\ k)$
$(x : xs)\ !!\ numeral\ (Num.Bit1\ k) = xs\ !!\ numeral\ (Num.Bit0\ k)$
⟨*proof*⟩

lemma *take-strict* [*simp*]:
$take{\cdot}\bot{\cdot}xs = \bot$
⟨*proof*⟩

lemma *take-strict-2* [*simp*]:
$le{\cdot}1{\cdot}i = TT \Longrightarrow take{\cdot}i{\cdot}\bot = \bot$
⟨*proof*⟩

lemma *drop-strict* [*simp*]:
$drop{\cdot}\bot{\cdot}xs = \bot$
⟨*proof*⟩

lemma *isPrefixOf-strict* [*simp*]:
$isPrefixOf{\cdot}\bot{\cdot}xs = \bot$
$isPrefixOf{\cdot}(x{:}xs){\cdot}\bot = \bot$
⟨*proof*⟩

lemma *last-strict*[*simp*]:
$last{\cdot}\bot = \bot$
$last{\cdot}(x{:}\bot) = \bot$
⟨*proof*⟩

lemma *last-nil* [*simp*]:
$last{\cdot}[] = \bot$
⟨*proof*⟩

lemma *last-spine-strict*: $\neg$ *finite-list xs* $\Longrightarrow last{\cdot}xs = \bot$
⟨*proof*⟩

lemma *init-strict* [*simp*]:
$init{\cdot}\bot = \bot$
$init{\cdot}(x{:}\bot) = \bot$
⟨*proof*⟩

lemma *init-nil* [*simp*]:
$init{\cdot}[] = \bot$
⟨*proof*⟩

lemma *strict-foldr-strict2* [*simp*]:
$(\bigwedge x.\ f{\cdot}x{\cdot}\bot = \bot) \Longrightarrow foldr{\cdot}f{\cdot}\bot{\cdot}xs = \bot$
⟨*proof*⟩

lemma *foldr-strict* [*simp*]:
$foldr{\cdot}f{\cdot}d{\cdot}\bot = \bot$
$foldr{\cdot}f{\cdot}\bot{\cdot}[] = \bot$
$foldr{\cdot}\bot{\cdot}d{\cdot}(x : xs) = \bot$
⟨*proof*⟩

lemma *foldr-Cons-Nil* [*simp*]:

$foldr{\cdot}(:){\cdot}[]{\cdot}xs = xs$
⟨*proof*⟩

lemma *append-strict1* [*simp*]:
$\bot \mathbin{+\!\!+} ys = \bot$
⟨*proof*⟩

lemma *foldr-append* [*simp*]:
$foldr{\cdot}f{\cdot}a{\cdot}(xs \mathbin{+\!\!+} ys) = foldr{\cdot}f{\cdot}(foldr{\cdot}f{\cdot}a{\cdot}ys){\cdot}xs$
⟨*proof*⟩

lemma *foldl-strict* [*simp*]:
$foldl{\cdot}f{\cdot}d{\cdot}\bot = \bot$
$foldl{\cdot}f{\cdot}\bot{\cdot}[] = \bot$
⟨*proof*⟩

lemma *foldr1-strict* [*simp*]:
$foldr1{\cdot}f{\cdot}\bot = \bot$
$foldr1{\cdot}f{\cdot}(x{:}\bot) = \bot$
⟨*proof*⟩

lemma *foldl1-strict* [*simp*]:
$foldl1{\cdot}f{\cdot}\bot = \bot$
⟨*proof*⟩

lemma *foldl-spine-strict*:
$\neg$ *finite-list xs* $\Longrightarrow foldl{\cdot}f{\cdot}x{\cdot}xs = \bot$
⟨*proof*⟩

lemma *foldl-assoc-foldr*:
assumes *finite-list xs*
and *assoc*: $\bigwedge x\ y\ z.\ f{\cdot}(f{\cdot}x{\cdot}y){\cdot}z = f{\cdot}x{\cdot}(f{\cdot}y{\cdot}z)$
and *neutr1*: $\bigwedge x.\ f{\cdot}z{\cdot}x = x$
and *neutr2*: $\bigwedge x.\ f{\cdot}x{\cdot}z = x$
shows $foldl{\cdot}f{\cdot}z{\cdot}xs = foldr{\cdot}f{\cdot}z{\cdot}xs$
⟨*proof*⟩

lemma *elem-strict* [*simp*]:
$elem{\cdot}x{\cdot}\bot = \bot$
⟨*proof*⟩

lemma *notElem-strict* [*simp*]:
$notElem{\cdot}x{\cdot}\bot = \bot$
⟨*proof*⟩

lemma *list-eq-nil*[*simp*]:
$eq{\cdot}l{\cdot}[] = TT \longleftrightarrow l = []$
$eq{\cdot}[]{\cdot}l = TT \longleftrightarrow l = []$
⟨*proof*⟩

lemma *take-Nil* [*simp*]:
$n \neq \bot \Longrightarrow take{\cdot}n{\cdot}[] = []$
⟨*proof*⟩

lemma *take-0* [*simp*]:
$take{\cdot}0{\cdot}xs = []$
$take{\cdot}(MkI{\cdot}0){\cdot}xs = []$
⟨*proof*⟩

lemma *take-Cons* [*simp*]:
$le{\cdot}1{\cdot}i = TT \Longrightarrow take{\cdot}i{\cdot}(x{:}xs) = x : take{\cdot}(i - 1){\cdot}xs$
⟨*proof*⟩

lemma *take-MkI-Cons* [*simp*]:
$0 < n \Longrightarrow take{\cdot}(MkI{\cdot}n){\cdot}(x : xs) = x : take{\cdot}(MkI{\cdot}(n - 1)){\cdot}xs$
⟨*proof*⟩

lemma *take-numeral-Cons* [*simp*]:
$take{\cdot}1{\cdot}(x : xs) = [x]$
$take{\cdot}(numeral\ (Num.Bit0\ k)){\cdot}(x : xs) = x : take{\cdot}(numeral\ (Num.BitM\ k)){\cdot}xs$
$take{\cdot}(numeral\ (Num.Bit1\ k)){\cdot}(x : xs) = x : take{\cdot}(numeral\ (Num.Bit0\ k)){\cdot}xs$
⟨*proof*⟩

lemma *drop-0* [*simp*]:
$drop{\cdot}0{\cdot}xs = xs$
$drop{\cdot}(MkI{\cdot}0){\cdot}xs = xs$
⟨*proof*⟩

lemma *drop-pos* [*simp*]:
$le{\cdot}n{\cdot}0 = FF \Longrightarrow drop{\cdot}n{\cdot}xs = (case\ xs\ of\ [] \Rightarrow [] \mid y : ys \Rightarrow drop{\cdot}(n - 1){\cdot}ys)$
⟨*proof*⟩

lemma *drop-numeral-Cons* [*simp*]:
$drop{\cdot}1{\cdot}(x : xs) = xs$
$drop{\cdot}(numeral\ (Num.Bit0\ k)){\cdot}(x : xs) = drop{\cdot}(numeral\ (Num.BitM\ k)){\cdot}xs$
$drop{\cdot}(numeral\ (Num.Bit1\ k)){\cdot}(x : xs) = drop{\cdot}(numeral\ (Num.Bit0\ k)){\cdot}xs$
⟨*proof*⟩

lemma *take-drop-append*:
$take{\cdot}(MkI{\cdot}i){\cdot}xs +\!\!+ drop{\cdot}(MkI{\cdot}i){\cdot}xs = xs$
⟨*proof*⟩

lemma *take-intsFrom-enumFrom* [*simp*]:
$take{\cdot}(MkI{\cdot}n){\cdot}[MkI{\cdot}i..] = [MkI{\cdot}i..MkI{\cdot}(n{+}i) - 1]$
⟨*proof*⟩

lemma *drop-intsFrom-enumFrom* [*simp*]:
assumes $n \geq 0$

shows *drop*·(*MkI*·*n*)·[*MkI*·*i*..] = [*MkI*·(*n*+*i*)..]
⟨*proof*⟩

lemma *last-append-singleton*:
finite-list xs ⟹ *last*·(*xs* ++ [*x*]) = *x*
⟨*proof*⟩

lemma *init-append-singleton*:
finite-list xs ⟹ *init*·(*xs* ++ [*x*]) = *xs*
⟨*proof*⟩

lemma *append-Nil2* [*simp*]:
xs ++ [] = *xs*
⟨*proof*⟩

lemma *append-assoc* [*simp*]:
(*xs* ++ *ys*) ++ *zs* = *xs* ++ *ys* ++ *zs*
⟨*proof*⟩

lemma *concat-simps* [*simp*]:
concat·[] = []
concat·(*xs* : *xss*) = *xs* ++ *concat*·*xss*
concat·⊥ = ⊥
⟨*proof*⟩

lemma *concatMap-simps* [*simp*]:
concatMap·*f*·[] = []
concatMap·*f*·(*x* : *xs*) = *f*·*x* ++ *concatMap*·*f*·*xs*
concatMap·*f*·⊥ = ⊥
⟨*proof*⟩

lemma *filter-append* [*simp*]:
filter·*P*·(*xs* ++ *ys*) = *filter*·*P*·*xs* ++ *filter*·*P*·*ys*
⟨*proof*⟩

lemma *elem-append* [*simp*]:
elem·*x*·(*xs* ++ *ys*) = (*elem*·*x*·*xs* *orelse* *elem*·*x*·*ys*)
⟨*proof*⟩

lemma *filter-filter* [*simp*]:
filter·*P*·(*filter*·*Q*·*xs*) = *filter*·(Λ *x*. *Q*·*x* *andalso* *P*·*x*)·*xs*
⟨*proof*⟩

lemma *filter-const-TT* [*simp*]:
filter·(Λ -. *TT*)·*xs* = *xs*
⟨*proof*⟩

lemma *tails-strict* [*simp*]:
tails·⊥ = ⊥

⟨*proof*⟩

lemma *inits-strict* [*simp*]:
inits·⊥ = ⊥
⟨*proof*⟩

lemma *the-and-strict* [*simp*]:
the-and·⊥ = ⊥
⟨*proof*⟩

lemma *the-or-strict* [*simp*]:
the-or·⊥ = ⊥
⟨*proof*⟩

lemma *all-strict* [*simp*]:
all·*P*·⊥ = ⊥
⟨*proof*⟩

lemma *any-strict* [*simp*]:
any·*P*·⊥ = ⊥
⟨*proof*⟩

lemma *tails-neq-Nil* [*simp*]:
tails·*xs* ≠ []
⟨*proof*⟩

lemma *inits-neq-Nil* [*simp*]:
inits·*xs* ≠ []
⟨*proof*⟩

lemma *Nil-neq-tails* [*simp*]:
[] ≠ *tails*·*xs*
⟨*proof*⟩

lemma *Nil-neq-inits* [*simp*]:
[] ≠ *inits*·*xs*
⟨*proof*⟩

lemma *finite-list-not-bottom* [*simp*]:
assumes *finite-list xs* **shows** *xs* ≠ ⊥
⟨*proof*⟩

lemma *head-append* [*simp*]:
head·(*xs* ++ *ys*) = *If null*·*xs then head*·*ys else head*·*xs*
⟨*proof*⟩

lemma *filter-cong*:
∀ *x*∈*set xs*. *p*·*x* = *q*·*x* ⟹ *filter*·*p*·*xs* = *filter*·*q*·*xs*
⟨*proof*⟩

lemma *filter-TT* [*simp*]:
assumes $\forall\, x{\in}set\ xs.\ P{\cdot}x = TT$
shows $filter{\cdot}P{\cdot}xs = xs$
⟨*proof*⟩

lemma *filter-FF* [*simp*]:
assumes *finite-list xs*
and $\forall\, x{\in}set\ xs.\ P{\cdot}x = FF$
shows $filter{\cdot}P{\cdot}xs = []$
⟨*proof*⟩

lemma *map-cong*:
$\forall\, x{\in}set\ xs.\ p{\cdot}x = q{\cdot}x \Longrightarrow map{\cdot}p{\cdot}xs = map{\cdot}q{\cdot}xs$
⟨*proof*⟩

lemma *finite-list-upto*:
finite-list $(upto{\cdot}(MkI{\cdot}m){\cdot}(MkI{\cdot}n))$ (**is** *?P m n*)
⟨*proof*⟩

lemma *filter-commute*:
assumes $\forall\, x{\in}set\ xs.\ (Q{\cdot}x\ andalso\ P{\cdot}x) = (P{\cdot}x\ andalso\ Q{\cdot}x)$
shows $filter{\cdot}P{\cdot}(filter{\cdot}Q{\cdot}xs) = filter{\cdot}Q{\cdot}(filter{\cdot}P{\cdot}xs)$
⟨*proof*⟩

lemma *upto-append-intsFrom* [*simp*]:
assumes $m \le n$
shows $upto{\cdot}(MkI{\cdot}m){\cdot}(MkI{\cdot}n) +\!\!+ intsFrom{\cdot}(MkI{\cdot}n{+}1) = intsFrom{\cdot}(MkI{\cdot}m)$
(**is** *?u m n ++ - = ?i m*)
⟨*proof*⟩

lemma *set-upto* [*simp*]:
$set\ (upto{\cdot}(MkI{\cdot}m){\cdot}(MkI{\cdot}n)) = \{MkI{\cdot}i \mid i.\ m \le i \wedge i \le n\}$
(**is** *set (?u m n) = ?R m n*)
⟨*proof*⟩

lemma *Nil-append-iff* [*iff*]:
$xs +\!\!+ ys = [] \longleftrightarrow xs = [] \wedge ys = []$
⟨*proof*⟩

This version of definedness rule for Nil is made necessary by the reorient simproc.

lemma *bottom-neq-Nil* [*simp*]: $\bot \neq []$
⟨*proof*⟩

Simproc to rewrite $[] = x$ to $x = []$.

⟨*ML*⟩

lemma *set-append* [*simp*]:
assumes *finite-list xs*
shows *set* (*xs* ++ *ys*) = *set xs* ∪ *set ys*
⟨*proof*⟩

lemma *distinct-Cons* [*simp*]:
distinct (*x* : *xs*) ⟷ *distinct xs* ∧ *x* ∉ *set xs*
(**is** *?l* = *?r*)
⟨*proof*⟩

lemma *finite-list-append* [*iff*]:
finite-list (*xs* ++ *ys*) ⟷ *finite-list xs* ∧ *finite-list ys*
(**is** *?l* = *?r*)
⟨*proof*⟩

lemma *distinct-append* [*simp*]:
assumes *finite-list* (*xs* ++ *ys*)
shows *distinct* (*xs* ++ *ys*) ⟷ *distinct xs* ∧ *distinct ys* ∧ *set xs* ∩ *set ys* = {}
(**is** *?P xs ys*)
⟨*proof*⟩

lemma *finite-set* [*simp*]:
assumes *distinct xs*
shows *finite* (*set xs*)
⟨*proof*⟩

lemma *distinct-card*:
assumes *distinct xs*
shows *MkI*·(*int* (*card* (*set xs*))) = *length*·*xs*
⟨*proof*⟩

lemma *set-delete* [*simp*]:
fixes *xs* :: ['*a*::*Eq-eq*]
assumes *distinct xs*
and ∀ *x*∈*set xs*. *eq*·*a*·*x* ≠ ⊥
shows *set* (*delete*·*a*·*xs*) = *set xs* − {*a*}
⟨*proof*⟩

lemma *distinct-delete* [*simp*]:
fixes *xs* :: ['*a*::*Eq-eq*]
assumes *distinct xs*
and ∀ *x*∈*set xs*. *eq*·*a*·*x* ≠ ⊥
shows *distinct* (*delete*·*a*·*xs*)
⟨*proof*⟩

lemma *set-diff* [*simp*]:
fixes *xs ys* :: ['*a*::*Eq-eq*]
assumes *distinct ys* **and** *distinct xs*
and ∀ *a*∈*set ys*. ∀ *x*∈*set xs*. *eq*·*a*·*x* ≠ ⊥

shows *set* (*xs* \\ *ys*) = *set xs* − *set ys*
⟨*proof*⟩

lemma *distinct-delete-filter*:
fixes *xs* :: ['*a*::*Eq-eq*]
assumes *distinct xs*
and ∀ *x*∈*set xs*. *eq*·*a*·*x* ≠ ⊥
shows *delete*·*a*·*xs* = *filter*·(Λ *x*. *neq*·*a*·*x*)·*xs*
⟨*proof*⟩

lemma *distinct-diff-filter*:
fixes *xs ys* :: ['*a*::*Eq-eq*]
assumes *finite-list ys*
and *distinct xs*
and ∀ *a*∈*set ys*. ∀ *x*∈*set xs*. *eq*·*a*·*x* ≠ ⊥
shows *xs* \\ *ys* = *filter*·(Λ *x*. *neg*·(*elem*·*x*·*ys*))·*xs*
⟨*proof*⟩

lemma *distinct-upto* [*intro*, *simp*]:
distinct [*MkI*·*m*..*MkI*·*n*]
⟨*proof*⟩

lemma *set-intsFrom* [*simp*]:
set (*intsFrom*·(*MkI*·*m*)) = {*MkI*·*n* | *n*. *m* ≤ *n*}
(**is** *set* (*?i m*) = *?I*)
⟨*proof*⟩

lemma *If-eq-bottom-iff* [*simp*]:
(*If b then x else y* = ⊥) ⟷ *b* = ⊥ ∨ *b* = *TT* ∧ *x* = ⊥ ∨ *b* = *FF* ∧ *y* = ⊥
⟨*proof*⟩

lemma *upto-eq-bottom-iff* [*simp*]:
upto·*m*·*n* = ⊥ ⟷ *m* = ⊥ ∨ *n* = ⊥
⟨*proof*⟩

lemma *seq-eq-bottom-iff* [*simp*]:
seq·*x*·*y* = ⊥ ⟷ *x* = ⊥ ∨ *y* = ⊥
⟨*proof*⟩

lemma *intsFrom-eq-bottom-iff* [*simp*]:
intsFrom·*m* = ⊥ ⟷ *m* = ⊥
⟨*proof*⟩

lemma *intsFrom-split*:
assumes *m* ≥ *n*
shows [*MkI*·*n*..] = [*MkI*·*n* .. *MkI*·(*m* − *1*)] ++ [*MkI*·*m*..]
⟨*proof*⟩

lemma *filter-fast-forward*:

assumes $n{+}1 \leq n'$
and $\forall k \,.\, n < k \longrightarrow k < n' \longrightarrow \neg\, P\ k$
shows *filter*·(Λ (*MkI*·*i*) . *Def* (*P i*))·[*MkI*·(*n*+*1*)..] = *filter*·(Λ (*MkI*·*i*) . *Def* (*P i*))·[*MkI*·*n'*..]
⟨*proof*⟩

lemma *null-eq-TT-iff* [*simp*]:
null·*xs* = *TT* ⟷ *xs* = []
⟨*proof*⟩

lemma *null-set-empty-conv*:
xs ≠ ⊥ ⟹ *null*·*xs* = *TT* ⟷ *set xs* = {}
⟨*proof*⟩

lemma *elem-TT* [*simp*]:
fixes *x* :: 'a::*Eq-eq* **shows** *elem*·*x*·*xs* = *TT* ⟹ *x* ∈ *set xs*
⟨*proof*⟩

lemma *elem-FF* [*simp*]:
fixes *x* :: 'a::*Eq-equiv* **shows** *elem*·*x*·*xs* = *FF* ⟹ *x* ∉ *set xs*
⟨*proof*⟩

lemma *length-strict* [*simp*]:
length·⊥ = ⊥
⟨*proof*⟩

lemma *repeat-neq-bottom* [*simp*]:
repeat·*x* ≠ ⊥
⟨*proof*⟩

lemma *list-case-repeat* [*simp*]:
list-case·*a*·*f*·(*repeat*·*x*) = *f*·*x*·(*repeat*·*x*)
⟨*proof*⟩

lemma *length-append* [*simp*]:
length·(*xs* ++ *ys*) = *length*·*xs* + *length*·*ys*
⟨*proof*⟩

lemma *replicate-strict* [*simp*]:
replicate·⊥·*x* = ⊥
⟨*proof*⟩

lemma *replicate-0* [*simp*]:
replicate·*0*·*x* = []
replicate·(*MkI*·*0*)·*xs* = []
⟨*proof*⟩

lemma *Integer-add-0* [*simp*]: *MkI*·*0* + *n* = *n*
⟨*proof*⟩

lemma *replicate-MkI-plus-1* [*simp*]:
$0 \leq n \Longrightarrow replicate{\cdot}(MkI{\cdot}(n{+}1)){\cdot}x = x : replicate{\cdot}(MkI{\cdot}n){\cdot}x$
$0 \leq n \Longrightarrow replicate{\cdot}(MkI{\cdot}(1{+}n)){\cdot}x = x : replicate{\cdot}(MkI{\cdot}n){\cdot}x$
⟨*proof*⟩

lemma *replicate-append-plus-conv*:
assumes $0 \leq m$ **and** $0 \leq n$
shows $replicate{\cdot}(MkI{\cdot}m){\cdot}x \mathbin{++} replicate{\cdot}(MkI{\cdot}n){\cdot}x$
$= replicate{\cdot}(MkI{\cdot}m + MkI{\cdot}n){\cdot}x$
⟨*proof*⟩

lemma *replicate-MkI-1* [*simp*]:
$replicate{\cdot}(MkI{\cdot}1){\cdot}x = x : []$
⟨*proof*⟩

lemma *length-replicate* [*simp*]:
assumes $0 \leq n$
shows $length{\cdot}(replicate{\cdot}(MkI{\cdot}n){\cdot}x) = MkI{\cdot}n$
⟨*proof*⟩

lemma *map-oo* [*simp*]:
$map{\cdot}f{\cdot}(map{\cdot}g{\cdot}xs) = map{\cdot}(f \mathbin{oo} g){\cdot}xs$
⟨*proof*⟩

lemma *nth-Cons-MkI* [*simp*]:
$0 < i \Longrightarrow (a : xs) \mathbin{!!} (MkI{\cdot}i) = xs \mathbin{!!} (MkI{\cdot}(i - 1))$
⟨*proof*⟩

lemma *map-plus-intsFrom*:
$map{\cdot}(+\ MkI{\cdot}n){\cdot}(intsFrom{\cdot}(MkI{\cdot}m)) = intsFrom{\cdot}(MkI{\cdot}(m{+}n))$ (**is** $?l = ?r$)
⟨*proof*⟩

lemma *plus-eq-MkI-conv*:
$l + n = MkI{\cdot}m \longleftrightarrow (\exists\, l'\ n'.\ l = MkI{\cdot}l' \wedge n = MkI{\cdot}n' \wedge m = l' + n')$
⟨*proof*⟩

lemma *length-ge-0*:
$length{\cdot}xs = MkI{\cdot}n \Longrightarrow n \geq 0$
⟨*proof*⟩

lemma *length-0-conv* [*simp*]:
$length{\cdot}xs = MkI{\cdot}0 \longleftrightarrow xs = []$
⟨*proof*⟩

lemma *length-ge-1* [*simp*]:
$length{\cdot}xs = MkI{\cdot}(1 + int\ n)$
$\longleftrightarrow (\exists\, u\ us.\ xs = u : us \wedge length{\cdot}us = MkI{\cdot}(int\ n))$
(**is** $?l = ?r$)

⟨*proof*⟩

lemma *finite-list-length-conv*:
finite-list xs ⟷ (∃ *n*. *length*·*xs* = *MkI*·(*int n*)) (**is** *?l* = *?r*)
⟨*proof*⟩

lemma *nth-append*:
assumes *length*·*xs* = *MkI*·*n* **and** *n* ≤ *m*
shows (*xs* ++ *ys*) !! *MkI*·*m* = *ys* !! *MkI*·(*m* − *n*)
⟨*proof*⟩

lemma *replicate-nth* [*simp*]:
assumes *0* ≤ *n*
shows (*replicate*·(*MkI*·*n*)·*x* ++ *xs*) !! *MkI*·*n* = *xs* !! *MkI*·*0*
⟨*proof*⟩

lemma *map2-zip*:
map·(Λ⟨*x*, *y*⟩. ⟨*x*, *f*·*y*⟩)·(*zip*·*xs*·*ys*) = *zip*·*xs*·(*map*·*f*·*ys*)
⟨*proof*⟩

lemma *map2-filter*:
map·(Λ⟨*x*, *y*⟩. ⟨*x*, *f*·*y*⟩)·(*filter*·(Λ⟨*x*, *y*⟩. *P*·*x*)·*xs*)
= *filter*·(Λ⟨*x*, *y*⟩. *P*·*x*)·(*map*·(Λ⟨*x*, *y*⟩. ⟨*x*, *f*·*y*⟩)·*xs*)
⟨*proof*⟩

lemma *map-map-snd*:
f·⊥ = ⊥ ⟹ *map*·*f*·(*map*·*snd*·*xs*)
= *map*·*snd*·(*map*·(Λ⟨*x*, *y*⟩. ⟨*x*, *f*·*y*⟩)·*xs*)
⟨*proof*⟩

lemma *findIndices-Cons* [*simp*]:
findIndices·*P*·(*a* : *xs*) =
If P·*a then 0* : *map*·(+*1*)·(*findIndices*·*P*·*xs*)
else map·(+*1*)·(*findIndices*·*P*·*xs*)
⟨*proof*⟩

lemma *filter-alt-def*:
fixes *xs* :: ['*a*]
shows *filter*·*P*·*xs* = *map*·(*nth*·*xs*)·(*findIndices*·*P*·*xs*)
⟨*proof*⟩

abbreviation *cfun-image* :: ('*a* → '*b*) ⇒ '*a set* ⇒ '*b set* (**infixr** ‘· *90*) **where**
f ‘· *A* ≡ *Rep-cfun f* ‘ *A*

lemma *set-map*:
set (*map*·*f*·*xs*) = *f* ‘· *set xs* (**is** *?l* = *?r*)
⟨*proof*⟩

8.5 *reverse* and *reverse* induction

Alternative simplification rules for *reverse* (easier to use for equational reasoning):

lemma *reverse-Nil* [*simp*]:
reverse·[] = []
⟨*proof*⟩

lemma *reverse-singleton* [*simp*]:
reverse·[*x*] = [*x*]
⟨*proof*⟩

lemma *reverse-strict* [*simp*]:
reverse·⊥ = ⊥
⟨*proof*⟩

lemma *foldl-flip-Cons-append*:
foldl·(*flip*·(:))·*ys*·*xs* = *foldl*·(*flip*·(:))·[]·*xs* ++ *ys*
⟨*proof*⟩

lemma *reverse-Cons* [*simp*]:
reverse·(*x*:*xs*) = *reverse*·*xs* ++ [*x*]
⟨*proof*⟩

lemma *reverse-append-below*:
reverse·(*xs* ++ *ys*) ⊑ *reverse*·*ys* ++ *reverse*·*xs*
⟨*proof*⟩

lemma *reverse-reverse-below*:
reverse·(*reverse*·*xs*) ⊑ *xs*
⟨*proof*⟩

lemma *reverse-append* [*simp*]:
assumes *finite-list xs*
shows *reverse*·(*xs* ++ *ys*) = *reverse*·*ys* ++ *reverse*·*xs*
⟨*proof*⟩

lemma *reverse-spine-strict*:
¬ *finite-list xs* ⟹ *reverse*·*xs* = ⊥
⟨*proof*⟩

lemma *reverse-finite* [*simp*]:
assumes *finite-list xs* **shows** *finite-list* (*reverse*·*xs*)
⟨*proof*⟩

lemma *reverse-reverse* [*simp*]:
assumes *finite-list xs* **shows** *reverse*·(*reverse*·*xs*) = *xs*
⟨*proof*⟩

lemma *reverse-induct* [*consumes 1*, *case-names Nil snoc*]:
⟦finite-list xs; *P []*; *⋀x xs . finite-list xs ⟹ P xs ⟹ P (xs ++ [x])⟧ ⟹ P xs*
⟨*proof*⟩

lemma *length-plus-not-0*:
le·1·n = TT ⟹ le·(length·xs + n)·0 = TT ⟹ False
⟨*proof*⟩

lemma *take-length-plus-1*:
length·xs ≠ ⊥ ⟹ take·(length·xs + 1)·(y:ys) = y : take·(length·xs)·ys
⟨*proof*⟩

lemma *le-length-plus*:
length·xs ≠ ⊥ ⟹ n ≠ ⊥ ⟹ le·n·(length·xs + n) = TT
⟨*proof*⟩

lemma *eq-take-length-isPrefixOf*:
eq·xs·(take·(length·xs)·ys) ⊑ isPrefixOf·xs·ys
⟨*proof*⟩

end

9 Data: Maybe

theory *Data-Maybe*
imports
Type-Classes
Data-Function
Data-List
Data-Bool
begin

domain *'a Maybe = Nothing | Just* (**lazy** *'a*)

abbreviation *maybe* :: *'b → ('a → 'b) → 'a Maybe → 'b* **where**
maybe ≡ Maybe-case

fixrec *isJust* :: *'a Maybe → tr* **where**
isJust·(Just·a) = TT |
isJust·Nothing = FF

fixrec *isNothing* :: *'a Maybe → tr* **where**
isNothing = neg oo isJust

fixrec *fromJust* :: *'a Maybe → 'a* **where**
fromJust·(Just·a) = a |
fromJust·Nothing = ⊥

fixrec *fromMaybe* :: *'a → 'a Maybe → 'a* **where**

```
  fromMaybe·d·Nothing = d |
  fromMaybe·d·(Just·a) = a

fixrec maybeToList :: 'a Maybe → ['a] where
  maybeToList·Nothing = [] |
  maybeToList·(Just·a) = [a]

fixrec listToMaybe :: ['a] → 'a Maybe where
  listToMaybe·[] = Nothing |
  listToMaybe·(a:-) = Just·a


fixrec catMaybes :: ['a Maybe] → ['a] where
  catMaybes = concatMap·maybeToList

fixrec mapMaybe :: ('a → 'b Maybe) → ['a] → ['b] where
  mapMaybe·f = catMaybes oo map·f

instantiation Maybe :: (Eq) Eq-strict
begin

definition
  eq = maybe·(maybe·TT·(Λ y. FF))·(Λ x. maybe·FF·(Λ y. eq·x·y))

instance ⟨proof⟩

end

lemma eq-Maybe-simps [simp]:
  eq·Nothing·Nothing = TT
  eq·Nothing·(Just·y) = FF
  eq·(Just·x)·Nothing = FF
  eq·(Just·x)·(Just·y) = eq·x·y
  ⟨proof⟩

instance Maybe :: (Eq-sym) Eq-sym
⟨proof⟩

instance Maybe :: (Eq-equiv) Eq-equiv
⟨proof⟩

instance Maybe :: (Eq-eq) Eq-eq
⟨proof⟩

instantiation Maybe :: (Ord) Ord-strict
begin

definition
  compare = maybe·(maybe·EQ·(Λ y. LT))·(Λ x. maybe·GT·(Λ y. compare·x·y))
```

instance ⟨*proof*⟩

end

lemma *compare-Maybe-simps* [*simp*]:
  compare·*Nothing*·*Nothing* = *EQ*
  compare·*Nothing*·(*Just*·*y*) = *LT*
  compare·(*Just*·*x*)·*Nothing* = *GT*
  compare·(*Just*·*x*)·(*Just*·*y*) = *compare*·*x*·*y*
  ⟨*proof*⟩

instance *Maybe* :: (*Ord-linear*) *Ord-linear*
⟨*proof*⟩

lemma *isJust-strict* [*simp*]: *isJust*·⊥ = ⊥ ⟨*proof*⟩
lemma *fromMaybe-strict* [*simp*]: *fromMaybe*·*x*·⊥ = ⊥ ⟨*proof*⟩
lemma *maybeToList-strict* [*simp*]: *maybeToList*·⊥ = ⊥ ⟨*proof*⟩

end

10 Definedness

theory *Definedness*
  imports
    Data-List
begin

This is an attempt for a setup for better handling bottom, by a better simp setup, and less breaking the abstractions.

definition *defined* :: *'a* :: *pcpo* ⇒ *bool* **where**
  defined *x* = (*x* ≠ ⊥)

lemma *defined-bottom* [*simp*]: ¬ *defined* ⊥
  ⟨*proof*⟩

lemma *defined-seq* [*simp*]: *defined* *x* ⟹ *seq*·*x*·*y* = *y*
  ⟨*proof*⟩

consts *val* :: *'a*::*type* ⇒ *'b*::*type* (⟦-⟧)

val for booleans

definition *val-Bool* :: *tr* ⇒ *bool* **where**
  val-Bool *i* = (*THE* *j*. *i* = *Def* *j*)

adhoc-overloading
  val *val-Bool*

lemma *defined-Bool-simps* [*simp*]:
defined (*Def i*)
defined TT
defined FF
⟨*proof*⟩

lemma *val-Bool-simp1* [*simp*]:
⟦*Def i*⟧ = *i*
⟨*proof*⟩

lemma *val-Bool-simp2* [*simp*]:
⟦*TT*⟧ = *True*
⟦*FF*⟧ = *False*
⟨*proof*⟩

lemma *IF-simps* [*simp*]:
defined b ⟹ ⟦ *b* ⟧ ⟹ (*If b then x else y*) = *x*
defined b ⟹ ⟦ *b* ⟧ = *False* ⟹ (*If b then x else y*) = *y*
⟨*proof*⟩

lemma *defined-neg* [*simp*]: *defined* (*neg*·*b*) ⟷ *defined b*
⟨*proof*⟩

lemma *val-Bool-neg* [*simp*]: *defined b* ⟹ ⟦ *neg* · *b* ⟧ = (¬ ⟦ *b* ⟧)
⟨*proof*⟩

val for integers

definition *val-Integer* :: *Integer* ⇒ *int* **where**
val-Integer i = (*THE j*. *i* = *MkI*·*j*)

adhoc-overloading
val val-Integer

lemma *defined-Integer-simps* [*simp*]:
defined (*MkI*·*i*)
defined (*0*::*Integer*)
defined (*1*::*Integer*)
⟨*proof*⟩

lemma *defined-numeral* [*simp*]: *defined* (*numeral x* :: *Integer*)
⟨*proof*⟩

lemma *val-Integer-simps* [*simp*]:
⟦*MkI*·*i*⟧ = *i*
⟦*0*⟧ = *0*
⟦*1*⟧ = *1*
⟨*proof*⟩

lemma *val-Integer-numeral* [*simp*]: ⟦ *numeral x* :: *Integer* ⟧ = *numeral x*

⟨*proof*⟩

lemma *val-Integer-to-MkI*:
defined i ⟹ *i* = (*MkI* · ⟦ *i* ⟧)
⟨*proof*⟩

lemma *defined-Integer-minus* [*simp*]: *defined i* ⟹ *defined j* ⟹ *defined* (*i* − (*j*::*Integer*))
⟨*proof*⟩

lemma *val-Integer-minus* [*simp*]: *defined i* ⟹ *defined j* ⟹ ⟦ *i* − *j* ⟧ = ⟦ *i* ⟧ − ⟦ *j* ⟧
⟨*proof*⟩

lemma *defined-Integer-plus* [*simp*]: *defined i* ⟹ *defined j* ⟹ *defined* (*i* + (*j*::*Integer*))
⟨*proof*⟩

lemma *val-Integer-plus* [*simp*]: *defined i* ⟹ *defined j* ⟹ ⟦ *i* + *j* ⟧ = ⟦ *i* ⟧ + ⟦ *j* ⟧
⟨*proof*⟩

lemma *defined-Integer-eq* [*simp*]: *defined* (*eq*·*a*·*b*) ⟷ *defined a* ∧ *defined* (*b*::*Integer*)
⟨*proof*⟩

lemma *val-Integer-eq* [*simp*]: *defined a* ⟹ *defined b* ⟹ ⟦ *eq*·*a*·*b* ⟧ = (⟦ *a* ⟧ = (⟦ *b* ⟧ :: *int*))
⟨*proof*⟩

Full induction for non-negative integers

lemma *nonneg-full-Int-induct* [*consumes 1*, *case-names neg Suc*]:
assumes *defined*: *defined i*
assumes *neg*: ⋀ *i*. *defined i* ⟹ ⟦*i*⟧ < *0* ⟹ *P i*
assumes *step*: ⋀ *i*. *defined i* ⟹ *0* ≤ ⟦*i*⟧ ⟹ (⋀ *j*. *defined j* ⟹ ⟦ *j* ⟧ < ⟦ *i* ⟧ ⟹ *P j*) ⟹ *P i*
shows *P* (*i*::*Integer*)
⟨*proof*⟩

Some list lemmas re-done with the new setup.

lemma *nth-tail*:
defined n ⟹ ⟦ *n* ⟧ ≥ *0* ⟹ *tail*·*xs* !! *n* = *xs* !! (*1* + *n*)
⟨*proof*⟩

lemma *nth-zipWith*:
assumes *f1* [*simp*]: ⋀*y*. *f*·⊥·*y* = ⊥
assumes *f2* [*simp*]: ⋀*x*. *f*·*x*·⊥ = ⊥
shows *zipWith*·*f*·*xs*·*ys* !! *n* = *f*·(*xs* !! *n*)·(*ys* !! *n*)
⟨*proof*⟩

lemma *nth-neg* [*simp*]: *defined n* $\Longrightarrow$ $[\![$ *n* $]\!]$ $<$ *0* $\Longrightarrow$ *nth*·*xs*·*n* = $\bot$
⟨*proof*⟩

lemma *nth-Cons-simp* [*simp*]:
defined n $\Longrightarrow$ $[\![$ *n* $]\!]$ = *0* $\Longrightarrow$ *nth*·(*x* : *xs*)·*n* = *x*
defined n $\Longrightarrow$ $[\![$ *n* $]\!]$ > *0* $\Longrightarrow$ *nth*·(*x* : *xs*)·*n* = *nth*·*xs*·(*n* − *1*)
⟨*proof*⟩

end

11 List Comprehension

theory *List-Comprehension*
imports *Data-List*
begin

no-notation
disj (**infixr** | *30*)

nonterminal *llc-qual* **and** *llc-quals*

syntax
-llc :: *'a* ⇒ *llc-qual* ⇒ *llc-quals* ⇒ [*'a*] ([- | --)
-llc-gen :: *'a* ⇒ [*'a*] ⇒ *llc-qual* (- <− -)
-llc-guard :: *tr* ⇒ *llc-qual* (-)
-llc-let :: *letbinds* ⇒ *llc-qual* (*let* -)
-llc-quals :: *llc-qual* ⇒ *llc-quals* ⇒ *llc-quals* (, --)
-llc-end :: *llc-quals* (])
-llc-abs :: *'a* ⇒ [*'a*] ⇒ [*'a*]

translations
[*e* | *p* <− *xs*] => *CONST concatMap*·(*-llc-abs p* [*e*])·*xs*
-llc e (*-llc-gen p xs*) (*-llc-quals q qs*)
=> *CONST concatMap*·(*-llc-abs p* (*-llc e q qs*))·*xs*
[*e* | *b*] => *If b then* [*e*] *else* []
-llc e (*-llc-guard b*) (*-llc-quals q qs*)
=> *If b then* (*-llc e q qs*) *else* []
-llc e (*-llc-let b*) (*-llc-quals q qs*)
=> *-Let b* (*-llc e q qs*)

⟨*ML*⟩

lemma *concatMap-singleton* [*simp*]:
concatMap·(Λ *x*. [*f*·*x*])·*xs* = *map*·*f*·*xs*
⟨*proof*⟩

lemma *listcompr-filter* [*simp*]:
[*x* | *x* <− *xs*, *P*·*x*] = *filter*·*P*·*xs*
⟨*proof*⟩

lemma $[y \mid \mathit{let}\ y = x{*}2;\ z = y,\ x <- xs] = A$
⟨*proof*⟩

end

12 The Num Class

theory *Num-Class*
imports
Type-Classes
Data-Integer
Data-Tuple
begin

12.1 Num class

class *Num-syn* =
Eq +
plus +
minus +
times +
zero +
one +
fixes *negate* :: $'a \to 'a$
and *abs* :: $'a \to 'a$
and *signum* :: $'a \to 'a$
and *fromInteger* :: *Integer* $\to 'a$

class *Num* = *Num-syn* + *plus-cpo* + *minus-cpo* + *times-cpo*

class *Num-strict* = *Num* +
assumes *plus-strict*[*simp*]:
$x + \bot = (\bot :: 'a :: Num)$
$\bot + x = \bot$
assumes *minus-strict*[*simp*]:
$x - \bot = \bot$
$\bot - x = \bot$
assumes *mult-strict*[*simp*]:
$x * \bot = \bot$
$\bot * x = \bot$
assumes *negate-strict*[*simp*]:
$\mathit{negate}{\cdot}\bot = \bot$
assumes *abs-strict*[*simp*]:
$\mathit{abs}{\cdot}\bot = \bot$
assumes *signum-strict*[*simp*]:
$\mathit{signum}{\cdot}\bot = \bot$
assumes *fromInteger-strict*[*simp*]:

$fromInteger{\cdot}\bot = \bot$

class *Num-faithful* =

Num-syn +

assumes *abs-signum-eq*: $(eq{\cdot}((abs{\cdot}x) * (signum{\cdot}x)){\cdot}(x::'a::\{Num\text{-}syn\})) \sqsubseteq TT$

class *Integral* =
Num +

fixes *div mod* :: $'a \to 'a \to ('a::Num)$
fixes *toInteger* :: $'a \to Integer$
begin

fixrec *divMod* :: $'a \to 'a \to \langle 'a, 'a\rangle$ **where** $divMod{\cdot}x{\cdot}y = \langle div{\cdot}x{\cdot}y,\ mod{\cdot}x{\cdot}y\rangle$

fixrec *even* :: $'a \to tr$ **where** $even{\cdot}x = eq{\cdot}(div{\cdot}x{\cdot}(fromInteger{\cdot}2)){\cdot}0$
fixrec *odd* :: $'a \to tr$ **where** $odd{\cdot}x = neg{\cdot}(even{\cdot}x)$
end

class *Integral-strict* = *Integral* +
assumes *div-strict*[*simp*]:
$div{\cdot}x{\cdot}\bot = (\bot::'a::Integral)$
$div{\cdot}\bot{\cdot}x = \bot$
assumes *mod-strict*[*simp*]:
$mod{\cdot}x{\cdot}\bot = \bot$
$mod{\cdot}\bot{\cdot}x = \bot$
assumes *toInteger-strict*[*simp*]:
$toInteger{\cdot}\bot = \bot$

class *Integral-faithful* =
Integral +
Num-faithful +

assumes $eq{\cdot}y{\cdot}0 = FF \Longrightarrow div{\cdot}x{\cdot}y * y + mod{\cdot}x{\cdot}y = (x::'a::\{Integral\})$

12.2 Instances for Integer

instantiation *Integer* :: *Num-syn*
begin
definition *negate* = $(\Lambda\ (MkI{\cdot}x).\ MkI{\cdot}(uminus\ x))$
definition *abs* = $(\Lambda\ (MkI{\cdot}x)\ .\ MkI{\cdot}(|x|))$

definition *signum* = (Λ (*MkI*·*x*) . *MkI*·(*sgn x*))
definition *fromInteger* = (Λ *x*. *x*)
instance⟨*proof*⟩
end

instance *Integer* :: *Num*
⟨*proof*⟩

instance *Integer* :: *Num-faithful*
⟨*proof*⟩

instance *Integer* :: *Num-strict*
⟨*proof*⟩

instantiation *Integer* :: *Integral*
begin
definition *div* = (Λ (*MkI*·*x*) (*MkI*·*y*). *MkI*·(*Rings.divide x y*))
definition *mod* = (Λ (*MkI*·*x*) (*MkI*·*y*). *MkI*·(*Rings.modulo x y*))
definition *toInteger* = (Λ *x*. *x*)
instance ⟨*proof*⟩
end

instance *Integer* :: *Integral-strict*
⟨*proof*⟩

instance *Integer* :: *Integral-faithful*
⟨*proof*⟩

lemma *Integer-Integral-simps*[*simp*]:
div·(*MkI*·*x*)·(*MkI*·*y*) = *MkI*·(*Rings.divide x y*)
mod·(*MkI*·*x*)·(*MkI*·*y*) = *MkI*·(*Rings.modulo x y*)
fromInteger·*i* = *i*
⟨*proof*⟩

end
theory *HOLCF-Prelude*
imports
HOLCF-Main
Type-Classes
Numeral-Cpo
Data-Function
Data-Bool
Data-Tuple
Data-Integer
Data-List
Data-Maybe
begin
end
theory *Fibs*

imports
../HOLCF-Prelude
../Definedness
begin

13 Fibonacci sequence

In this example, we show that the self-recursive lazy definition of the fibonacci sequence is actually defined and correct.

fixrec *fibs* :: [*Integer*] **where**
[*simp del*]: *fibs* = *0* : *1* : *zipWith*·(+)·*fibs*·(*tail*·*fibs*)

fun *fib* :: *int* ⇒ *int* **where**
fib n = (*if n* ≤ *0 then 0 else if n* = *1 then 1 else fib* (*n* − *1*) + *fib* (*n* − *2*))

declare *fib.simps* [*simp del*]

lemma *fibs-0* [*simp*]:
fibs !! *0* = *0*
⟨*proof*⟩

lemma *fibs-1* [*simp*]:
fibs !! *1* = *1*
⟨*proof*⟩

And the proof that *fibs* !! *i* is defined and the fibs value.

lemma [*simp*]:−*1* + ⟦*i*⟧ = ⟦ *i* ⟧ − *1* ⟨*proof*⟩
lemma [*simp*]:−*2* + ⟦*i*⟧ = ⟦ *i* ⟧ − *2* ⟨*proof*⟩

lemma *nth-fibs*:
assumes *defined i* **and** ⟦ *i* ⟧ ≥ *0* **shows** *defined* (*fibs* !! *i*) **and** ⟦ *fibs* !! *i* ⟧ = *fib* ⟦ *i* ⟧
⟨*proof*⟩

end
theory *Sieve-Primes*
imports
HOL−Computational-Algebra.Primes
../Num-Class
../HOLCF-Prelude

begin

14 The Sieve of Eratosthenes

declare [[*coercion int*]]
declare [[*coercion-enabled*]]

This example proves that the well-known Haskell two-liner that lazily calculates the list of all primes does indeed do so. This proof is using coinduction.

We need to hide some constants again since we imported something from HOL not via *HOLCF−Prelude.HOLCF-Main*.

no-notation
Rings.divide (**infixl** *div 70*) **and**
Rings.modulo (**infixl** *mod 70*)

no-notation
Set.member ((:)) **and**
Set.member ((-/ : -) [*51*, *51*] *50*)

This is the implementation. We also need a modulus operator.

fixrec *sieve* :: [*Integer*] → [*Integer*] **where**
sieve·(*p* : *xs*) = *p* : (*sieve*·(*filter*·(Λ *x*. *neg*·(*eq*·(*mod*·*x*·*p*)·*0*))·*xs*))

fixrec *primes* :: [*Integer*] **where**
primes = *sieve*·[*2*..]

Simplification rules for modI:

definition *MkI′* :: *int* ⇒ *Integer* **where**
MkI′ x = *MkI*·*x*

lemma *MkI′-simps* [*simp*]:
shows *MkI′ 0* = *0* **and** *MkI′ 1* = *1* **and** *MkI′* (*numeral k*) = *numeral k*
⟨*proof*⟩

lemma *modI-numeral-numeral* [*simp*]:
mod·(*numeral i*)·(*numeral j*) = *MkI′* (*Rings.modulo* (*numeral i*) (*numeral j*))
⟨*proof*⟩

Some lemmas demonstrating evaluation of our list:

lemma *primes* !! *0* = *2*
⟨*proof*⟩

lemma *primes* !! *1* = *3*
⟨*proof*⟩

lemma *primes* !! *2* = *5*
⟨*proof*⟩

lemma *primes* !! *3* = *7*
⟨*proof*⟩

Auxiliary lemmas about prime numbers

lemma *find-next-prime-nat*:
fixes *n* :: *nat*

assumes *prime n*
shows $\exists\ n'.\ n' > n \wedge$ *prime* $n' \wedge (\forall k.\ n < k \longrightarrow k < n' \longrightarrow \neg$ *prime* $k)$
⟨*proof*⟩

Simplification for andalso:

lemma *andAlso-Def*[*simp*]: $((Def\ x)$ *andalso* $(Def\ y)) = Def\ (x \wedge y)$
⟨*proof*⟩

This defines the bisimulation and proves it to be a list bisimulation.

definition *prim-bisim*:
prim-bisim x1 x2 = $(\exists\ n\ .$ *prime* $n\ \wedge$
x1 = *sieve*·(*filter*·(Λ (*MkI*·*i*). *Def* $((\forall d.\ d > 1 \longrightarrow d < n \longrightarrow \neg$ (*d dvd i*))))·[*MkI*·*n*..]) ∧
x2 = *filter*·(Λ (*MkI*·*i*). *Def* (*prime* (*nat* |*i*|)))·[*MkI*·*n*..])

lemma *prim-bisim-is-bisim*: *list-bisim prim-bisim*
⟨*proof*⟩

Now we apply coinduction:

lemma *sieve-produces-primes*:
fixes *n* :: *nat*
assumes *prime n*
shows *sieve*·(*filter*·(Λ (*MkI*·*i*). *Def* $((\forall d{::}int.\ d > 1 \longrightarrow d < n \longrightarrow \neg$ (*d dvd i*))))·[*MkI*·*n*..])
= *filter*·(Λ (*MkI*·*i*). *Def* (*prime* (*nat* |*i*|)))·[*MkI*·*n*..]
⟨*proof*⟩

And finally show the correctness of primes.

theorem *primes*:
shows *primes* = *filter*·(Λ (*MkI*·*i*). *Def* (*prime* (*nat* |*i*|)))·[*MkI*·*2*..]
⟨*proof*⟩

end

15 GHC's "fold/build" Rule

theory *GHC-Rewrite-Rules*
imports *../HOLCF-Prelude*
begin

15.1 Approximating the Rewrite Rule

The original rule looks as follows (see also [3]):

```
"fold/build"
  forall k z (g :: forall b. (a -> b -> b) -> b -> b).
  foldr k z (build g) = g k z
```

Since we do not have rank-2 polymorphic types in Isabelle/HOL, we try to imitate a similar statement by introducing a new type that combines possible folds with their argument lists, i.e., f below is a function that, in a way, represents the list xs, but where list constructors are functionally abstracted.

abbreviation (*input*) *abstract-list* **where**
  abstract-list xs ≡ (Λ *c n*. *foldr*·*c*·*n*·*xs*)

cpodef ('*a*, '*b*) *listfun* =
  {(*f* :: ('*a* → '*b* → '*b*) → '*b* → '*b*, *xs*). *f* = *abstract-list xs*}
  ⟨*proof*⟩

definition *listfun* :: ('*a*, '*b*) *listfun* → ('*a* → '*b* → '*b*) → '*b* → '*b* **where**
  listfun = (Λ *g*. *Product-Type.fst* (*Rep-listfun g*))

definition *build* :: ('*a*, '*b*) *listfun* → ['*a*] **where**
  build = (Λ *g*. *Product-Type.snd* (*Rep-listfun g*))

definition *augment* :: ('*a*, '*b*) *listfun* → ['*a*] → ['*a*] **where**
  augment = (Λ *g xs*. *build*·*g* ++ *xs*)

definition *listfun-comp* :: ('*a*, '*b*) *listfun* → ('*a*, '*b*) *listfun* → ('*a*, '*b*) *listfun* **where**
  listfun-comp = (Λ *g h*.
    Abs-listfun (Λ *c n*. *listfun*·*g*·*c*·(*listfun*·*h*·*c*·*n*), *build*·*g* ++ *build*·*h*))

abbreviation
  listfun-comp-infix :: ('*a*, '*b*) *listfun* ⇒ ('*a*, '*b*) *listfun* ⇒ ('*a*, '*b*) *listfun* (**infixl** ∘*lf* *55*)
  where
    g ∘*lf* *h* ≡ *listfun-comp*·*g*·*h*

fixrec *mapFB* :: ('*b* → '*c* → '*c*) → ('*a* → '*b*) → '*a* → '*c* → '*c* **where**
  mapFB·*c*·*f* = (Λ *x ys*. *c*·(*f*·*x*)·*ys*)

15.2 Lemmas

lemma *cont-listfun-body* [*simp*]:
  cont (λ*g*. *Product-Type.fst* (*Rep-listfun g*))
  ⟨*proof*⟩

lemma *cont-build-body* [*simp*]:
  cont (λ*g*. *Product-Type.snd* (*Rep-listfun g*))
  ⟨*proof*⟩

lemma *build-Abs-listfun*:
  assumes *abstract-list xs* = *f*
  shows *build*·(*Abs-listfun* (*f*, *xs*)) = *xs*
  ⟨*proof*⟩

lemma *listfun-Abs-listfun* [*simp*]:
assumes *abstract-list xs* = *f*
shows *listfun*·(*Abs-listfun* (*f*, *xs*)) = *f*
⟨*proof*⟩

lemma *augment-Abs-listfun* [*simp*]:
assumes *abstract-list xs* = *f*
shows *augment*·(*Abs-listfun* (*f*, *xs*))·*ys* = *xs* ++ *ys*
⟨*proof*⟩

lemma *cont-augment-body* [*simp*]:
cont (λ*g*. *Abs-cfun* ((++) (*Product-Type.snd* (*Rep-listfun g*))))
⟨*proof*⟩

lemma *fold*/*build*:
fixes *g* :: ('*a*, '*b*) *listfun*
shows *foldr*·*k*·*z*·(*build*·*g*) = *listfun*·*g*·*k*·*z*
⟨*proof*⟩

lemma *foldr*/*augment*:
fixes *g* :: ('*a*, '*b*) *listfun*
shows *foldr*·*k*·*z*·(*augment*·*g*·*xs*) = *listfun*·*g*·*k*·(*foldr*·*k*·*z*·*xs*)
⟨*proof*⟩

lemma *foldr*/*id*:
foldr·(:)·[] = (Λ *x*. *x*)
⟨*proof*⟩

lemma *foldr*/*app*:
foldr·(:)·*ys* = (Λ *xs*. *xs* ++ *ys*)
⟨*proof*⟩

lemma *foldr*/*cons*: *foldr*·*k*·*z*·(*x*:*xs*) = *k*·*x*·(*foldr*·*k*·*z*·*xs*) ⟨*proof*⟩
lemma *foldr*/*single*: *foldr*·*k*·*z*·[*x*] = *k*·*x*·*z* ⟨*proof*⟩
lemma *foldr*/*nil*: *foldr*·*k*·*z*·[] = *z* ⟨*proof*⟩

lemma *cont-listfun-comp-body1* [*simp*]:
cont (λ*h*. *Abs-listfun* (Λ *c n*. *listfun*·*g*·*c*·(*listfun*·*h*·*c*·*n*), *build*·*g* ++ *build*·*h*))
⟨*proof*⟩

lemma *cont-listfun-comp-body2* [*simp*]:
cont (λ*g*. *Abs-listfun* (Λ *c n*. *listfun*·*g*·*c*·(*listfun*·*h*·*c*·*n*), *build*·*g* ++ *build*·*h*))
⟨*proof*⟩

lemma *cont-listfun-comp-body* [*simp*]:
cont (λ*g*. Λ *h*. *Abs-listfun* (Λ *c n*. *listfun*·*g*·*c*·(*listfun*·*h*·*c*·*n*), *build*·*g* ++ *build*·*h*))
⟨*proof*⟩

lemma *abstract-list-build-append*:

abstract-list (*build*·*g* ++ *build*·*h*) = (Λ *c n*. *listfun*·*g*·*c*·(*listfun*·*h*·*c*·*n*))
⟨*proof*⟩

lemma *augment/build*:
augment·*g*·(*build*·*h*) = *build*·(*g* ∘*lf h*)
⟨*proof*⟩

lemma *augment/nil*:
augment·*g*·[] = *build*·*g*
⟨*proof*⟩

lemma *build-listfun-comp* [*simp*]:
build·(*g* ∘*lf h*) = *build*·*g* ++ *build*·*h*
⟨*proof*⟩

lemma *augment-augment*:
augment·*g*·(*augment*·*h*·*xs*) = *augment*·(*g* ∘*lf h*)·*xs*
⟨*proof*⟩

lemma *abstract-list-map* [*simp*]:
abstract-list (*map*·*f*·*xs*) = (Λ *c n*. *foldr*·(*mapFB*·*c*·*f*)·*n*·*xs*)
⟨*proof*⟩

lemma *map*:
map·*f*·*xs* = *build*·(*Abs-listfun* (Λ *c n*. *foldr*·(*mapFB*·*c*·*f*)·*n*·*xs*, *map*·*f*·*xs*))
⟨*proof*⟩

lemma *mapList*:
foldr·(*mapFB*·(:)·*f*)·[] = *map*·*f*
⟨*proof*⟩

lemma *mapFB*:
mapFB·(*mapFB*·*c*·*f*)·*g* = *mapFB*·*c*·(*f oo g*)
⟨*proof*⟩

lemma ++:
xs ++ *ys* = *augment*·(*Abs-listfun* (*abstract-list xs*, *xs*))·*ys*
⟨*proof*⟩

15.3 Examples

fixrec *sum* :: [*Integer*] → *Integer* **where**
sum·*xs* = *foldr*·(+)·0·*xs*

fixrec *down′* :: *Integer* → (*Integer* → *′a* → *′a*) → *′a* → *′a* **where**
down′·*v*·*c*·*n* = *If le*·1·*v then c*·*v*·(*down′*·(*v* − 1)·*c*·*n*) *else n*
declare *down′.simps* [*simp del*]

lemma *down′-strict* [*simp*]: *down′*·⊥ = ⊥ ⟨*proof*⟩

definition *down* :: *'b itself* ⇒ *Integer* → [*Integer*] **where**
down C-type = (Λ *v*. *build*·(*Abs-listfun* (
(*down'* :: *Integer* → (*Integer* → *'b* → *'b*) → *'b* → *'b*)·*v*,
down'·*v*·(:)·[])))

lemma *abstract-list-down'* [*simp*]:
abstract-list (*down'*·*v*·(:)·[]) = *down'*·*v*
⟨*proof*⟩

lemma *cont-Abs-listfun-down'* [*simp*]:
cont (λ*v*. *Abs-listfun* (*down'*·*v*, *down'*·*v*·(:)·[]))
⟨*proof*⟩

lemma *sum-down*:
sum·((*down TYPE*(*Integer*))·*v*) = *down'*·*v*·(+)·*0*
⟨*proof*⟩

end
theory *HLint*
imports
../HOLCF-Prelude
../List-Comprehension
begin

16 HLint

The tool `hlint` analyses Haskell code and, based on a data base of rewrite rules, suggests stylistic improvements to it. We verify a number of these rules using our implementation of the Haskell standard library.

16.1 Ord

```
x == a || x == b || x == c ==> x `elem` [a,b,c]
```

lemma (*eq*·(*x*::*'a*::*Eq-sym*)·*a orelse eq*·*x*·*b orelse eq*·*x*·*c*) = *elem*·*x*·[*a*, *b*, *c*]
⟨*proof*⟩

```
x /= a && x /= b && x /= c ==> x `notElem` [a,b,c]
```

lemma (*neq*·(*x*::*'a*::*Eq-sym*)·*a andalso neq*·*x*·*b andalso neq*·*x*·*c*) = *notElem*·*x*·[*a*, *b*, *c*]
⟨*proof*⟩

16.2 List

```
concat (map f x) ==> concatMap f x
```

lemma *concat*·(*map*·*f*·*x*) = *concatMap*·*f*·*x*

⟨*proof*⟩

```
concat [a, b] ==> a ++ b
```

lemma *concat*·[*a*, *b*] = *a* ++ *b*
⟨*proof*⟩

```
map f (map g x) ==> map (f . g) x
```

lemma *map*·*f*·(*map*·*g*·*x*) = *map*·(*f oo g*)·*x*
⟨*proof*⟩

```
x !! 0 ==> head x
```

lemma *x* !! *0* = *head*·*x*
⟨*proof*⟩

```
take n (repeat x) ==> replicate n x
```

lemma *take*·*n*·(*repeat*·*x*) = *replicate*·*n*·*x*
⟨*proof*⟩

```
lemma "head\<cdot>(reverse\<cdot>x) = last\<cdot>x"
```

lemma *head*·(*reverse*·*x*) = *last*·*x*
⟨*proof*⟩

```
head (drop n x) ==> x !! n where note = "if the index is non-negative"
```

lemma
assumes *le*·*0*·*n* ≠ *FF*
shows *head*·(*drop*·*n*·*x*) = *x* !! *n*
⟨*proof*⟩

```
reverse (tail (reverse x)) ==> init x
```

lemma *reverse*·(*tail*·(*reverse*·*x*)) ⊑ *init*·*x*
⟨*proof*⟩

```
take (length x - 1) x ==> init x
```

lemma
assumes *x* ≠ []
shows *take*·(*length*·*x* − *1*)·*x* ⊑ *init*·*x*
⟨*proof*⟩

```
foldr (++) [] ==> concat
```

lemma *foldr-append-concat*:*foldr*·*append*·[] = *concat*
⟨*proof*⟩

```
foldl (++) [] ==> concat
```

lemma *foldl*·*append*·[] ⊑ *concat*
⟨*proof*⟩

```
span (not . p) ==> break p
```

lemma $span{\cdot}(neg\ oo\ p) = break{\cdot}p$
⟨*proof*⟩

```
break (not . p) ==> span p
```

lemma $break{\cdot}(neg\ oo\ p) = span{\cdot}p$
⟨*proof*⟩

```
or (map p x) ==> any p x
```

lemma $the\text{-}or{\cdot}(map{\cdot}p{\cdot}x) = any{\cdot}p{\cdot}x$
⟨*proof*⟩

```
and (map p x) ==> all p x
```

lemma $the\text{-}and{\cdot}(map{\cdot}p{\cdot}x) = all{\cdot}p{\cdot}x$
⟨*proof*⟩

```
zipWith (,) ==> zip
```

lemma $zipWith{\cdot}\langle,\rangle = zip$
⟨*proof*⟩

```
zipWith3 (,,) ==> zip3
```

lemma $zipWith3{\cdot}\langle,,\rangle = zip3$
⟨*proof*⟩

```
length x == 0 ==> null x where note = "increases laziness"
```

lemma $eq{\cdot}(length{\cdot}x){\cdot}0 \sqsubseteq null{\cdot}x$
⟨*proof*⟩

```
length x /= 0 ==> not (null x)
```

lemma $neq{\cdot}(length{\cdot}x){\cdot}0 \sqsubseteq neg{\cdot}(null{\cdot}x)$
⟨*proof*⟩

```
map (uncurry f) (zip x y) ==> zipWith f x y
```

lemma $map{\cdot}(uncurry{\cdot}f){\cdot}(zip{\cdot}x{\cdot}y) = zipWith{\cdot}f{\cdot}x{\cdot}y$
⟨*proof*⟩

```
map f (zip x y) ==> zipWith (curry f) x y where _ = isVar f
```

lemma $map{\cdot}f{\cdot}(zip{\cdot}x{\cdot}y) = zipWith{\cdot}(curry{\cdot}f){\cdot}x{\cdot}y$
⟨*proof*⟩

```
not (elem x y) ==> notElem x y
```

lemma $neg{\cdot}(elem{\cdot}x{\cdot}y) = notElem{\cdot}x{\cdot}y$
⟨*proof*⟩

```
foldr f z (map g x) ==> foldr (f . g) z x
```

lemma $foldr{\cdot}f{\cdot}z{\cdot}(map{\cdot}g{\cdot}x) = foldr{\cdot}(f\ oo\ g){\cdot}z{\cdot}x$
⟨*proof*⟩

```
null (filter f x) ==> not (any f x)
```

lemma *null*·(*filter*·*f*·*x*) = *neg*·(*any*·*f*·*x*)
⟨*proof*⟩

```
filter f x == [] ==> not (any f x)
```

lemma *eq*·(*filter*·*f*·*x*)·[] = *neg*·(*any*·*f*·*x*)
⟨*proof*⟩

```
filter f x /= [] ==> any f x
```

lemma *neq*·(*filter*·*f*·*x*)·[] = *any*·*f*·*x*
⟨*proof*⟩

```
any (== a) ==> elem a
```

lemma *any*·(Λ *z*. *eq*·*z*·*a*) = *elem*·*a*
⟨*proof*⟩

```
any ((==) a) ==> elem a
```

lemma *any*·(*eq*·(*a*::'*a*::*Eq-sym*)) = *elem*·*a*
⟨*proof*⟩

```
any (a ==) ==> elem a
```

lemma *any*·(Λ *z*. *eq*·(*a*::'*a*::*Eq-sym*)·*z*) = *elem*·*a*
⟨*proof*⟩

```
all (/= a) ==> notElem a
```

lemma *all*·(Λ *z*. *neq*·*z*·(*a*::'*a*::*Eq-sym*)) = *notElem*·*a*
⟨*proof*⟩

```
all (a /=) ==> notElem a
```

lemma *all*·(Λ *z*. *neq*·(*a*::'*a*::*Eq-sym*)·*z*) = *notElem*·*a*
⟨*proof*⟩

16.3 Folds

```
foldr  (&&) True ==> and
```

lemma *foldr*·*trand*·*TT* = *the-and*
⟨*proof*⟩

```
foldl  (&&) True ==> and
```

lemma *foldl-to-and*:*foldl*·*trand*·*TT* ⊑ *the-and*
⟨*proof*⟩

```
foldr1 (&&)  ==> and
```

lemma *foldr1*·*trand* ⊑ *the-and*
⟨*proof*⟩

```
foldl1 (&&)  ==> and
```

lemma *foldl1·trand* $\sqsubseteq$ *the-and*
⟨*proof*⟩

```
foldr  (||) False ==> or
```

lemma *foldr·tror·FF* = *the-or*
⟨*proof*⟩

```
foldl  (||) False ==> or
```

lemma *foldl-to-or*: *foldl·tror·FF* $\sqsubseteq$ *the-or*
⟨*proof*⟩

```
foldr1 (||)  ==> or
```

lemma *foldr1·tror* $\sqsubseteq$ *the-or*
⟨*proof*⟩

```
foldl1 (||)  ==> or
```

lemma *foldl1·tror* $\sqsubseteq$ *the-or*
⟨*proof*⟩

16.4 Function

```
(\x -> x) ==> id
```

lemma (Λ *x*. *x*) = *ID*
⟨*proof*⟩

```
(\x y -> x) ==> const
```

lemma (Λ *x y*. *x*) = *const*
⟨*proof*⟩

```
(\(x,y) -> y) ==> fst where _ = notIn x y
```

lemma (Λ ⟨*x*, *y*⟩. *x*) = *fst*
⟨*proof*⟩

```
(\(x,y) -> y) ==> snd where _ = notIn x y
```

lemma (Λ ⟨*x*, *y*⟩. *y*) = *snd*
⟨*proof*⟩

```
(\x y-> f (x,y)) ==> curry f where _ = notIn [x,y] f
```

lemma (Λ *x y*. *f*·⟨*x*, *y*⟩) = *curry*·*f*
⟨*proof*⟩

```
(\(x,y) -> f x y) ==> uncurry f where _ = notIn [x,y] f
```

lemma (Λ ⟨*x*, *y*⟩. *f*·*x*·*y*) $\sqsubseteq$ *uncurry*·*f*
⟨*proof*⟩

```
(\x -> y) ==> const y where _ = isAtom y && notIn x y
```

lemma $(\Lambda\ x.\ y) = const{\cdot}y$
⟨*proof*⟩

lemma $flip{\cdot}f{\cdot}x{\cdot}y = f{\cdot}y{\cdot}x$ ⟨*proof*⟩

16.5 Bool

```
a == True ==> a
```

lemma $eq\text{-}true{:}eq{\cdot}x{\cdot}TT = x$
⟨*proof*⟩

```
a == False ==> not a
```

lemma $eq\text{-}false{:}eq{\cdot}x{\cdot}FF = neg{\cdot}x$
⟨*proof*⟩

```
(if a then x else x) ==> x where note = "reduces strictness"
```

lemma $if\text{-}equal{:}(If\ a\ then\ x\ else\ x) \sqsubseteq x$
⟨*proof*⟩

```
(if a then True else False) ==> a
```

lemma $(If\ a\ then\ TT\ else\ FF) = a$
⟨*proof*⟩

```
(if a then False else True) ==> not a
```

lemma $(If\ a\ then\ FF\ else\ TT) = neg{\cdot}a$
⟨*proof*⟩

```
(if a then t else (if b then t else f)) ==> if a || b then t else
f
```

lemma $(If\ a\ then\ t\ else\ (If\ b\ then\ t\ else\ f)) = (If\ a\ orelse\ b\ then\ t\ else\ f)$
⟨*proof*⟩

```
(if a then (if b then t else f) else f) ==> if a && b then t else
f
```

lemma $(If\ a\ then\ (If\ b\ then\ t\ else\ f)\ else\ f) = (If\ a\ andalso\ b\ then\ t\ else\ f)$
⟨*proof*⟩

```
(if x then True else y) ==> x || y where _ = notEq y False
```

lemma $(If\ x\ then\ TT\ else\ y) = (x\ orelse\ y)$
⟨*proof*⟩

```
(if x then y else False) ==> x && y where _ = notEq y True
```

lemma $(If\ x\ then\ y\ else\ FF) = (x\ andalso\ y)$
⟨*proof*⟩

```
 (if c then (True, x) else (False, x)) ==> (c, x) where note = "reduces
strictness"
```

lemma (*If c then* $\langle TT, x\rangle$ *else* $\langle FF, x\rangle$) $\sqsubseteq \langle c, x\rangle$
⟨*proof*⟩

```
 (if c then (False, x) else (True, x)) ==> (not c, x) where note
= "reduces strictness"
```

lemma (*If c then* $\langle FF, x\rangle$ *else* $\langle TT, x\rangle$) $\sqsubseteq \langle neg{\cdot}c, x\rangle$
⟨*proof*⟩

```
 or [x,y]  ==> x || y
```

lemma *the-or*$\cdot[x, y] = (x$ *orelse* $y)$
⟨*proof*⟩

```
 or [x,y,z]  ==> x || y || z
```

lemma *the-or*$\cdot[x, y, z] = (x$ *orelse* y *orelse* $z)$
⟨*proof*⟩

```
 and [x,y]  ==> x && y
```

lemma *the-and*$\cdot[x, y] = (x$ *andalso* $y)$
⟨*proof*⟩

```
 and [x,y,z]  ==> x && y && z
```

lemma *the-and*$\cdot[x, y, z] = (x$ *andalso* y *andalso* $z)$
⟨*proof*⟩

16.6 Arrow

```
 (fst x, snd x) ==>  x
```

lemma $x \sqsubseteq \langle fst{\cdot}x, snd{\cdot}x\rangle$
⟨*proof*⟩

16.7 Seq

```
 x `seq` x ==> x
```

lemma $seq{\cdot}x{\cdot}x = x$ ⟨*proof*⟩

16.8 Evaluate

```
 True && x ==> x
```

lemma $(TT$ *andalso* $x) = x$ ⟨*proof*⟩

```
 False && x ==> False
```

lemma $(FF$ *andalso* $x) = FF$ ⟨*proof*⟩

```
True || x ==> True
```

lemma $(TT\ orelse\ x) = TT\ \langle proof \rangle$

```
False || x ==> x
```

lemma $(FF\ orelse\ x) = x\ \langle proof \rangle$

```
not True ==> False
```

lemma $neg{\cdot}TT = FF\ \langle proof \rangle$

```
not False ==> True
```

lemma $neg{\cdot}FF = TT\ \langle proof \rangle$

```
fst (x,y) ==> x
```

lemma $fst{\cdot}\langle x,\ y\rangle = x\ \langle proof \rangle$

```
snd (x,y) ==> y
```

lemma $snd{\cdot}\langle x,\ y\rangle = y\ \langle proof \rangle$

```
f (fst p) (snd p) ==> uncurry f p
```

lemma $f{\cdot}(fst{\cdot}p){\cdot}(snd{\cdot}p) = uncurry{\cdot}f{\cdot}p$
$\langle proof \rangle$

```
init [x] ==> []
```

lemma $init{\cdot}[x] = []\ \langle proof \rangle$

```
null [] ==> True
```

lemma $null{\cdot}[] = TT\ \langle proof \rangle$

```
length [] ==> 0
```

lemma $length{\cdot}[] = 0\ \langle proof \rangle$

```
foldl f z [] ==> z
```

lemma $foldl{\cdot}f{\cdot}z{\cdot}[] = z\ \langle proof \rangle$

```
foldr f z [] ==> z
```

lemma $foldr{\cdot}f{\cdot}z{\cdot}[] = z\ \langle proof \rangle$

```
foldr1 f [x] ==> x
```

lemma $foldr1{\cdot}f{\cdot}[x] = x\ \langle proof \rangle$

```
scanr f z [] ==> [z]
```

lemma $scanr{\cdot}f{\cdot}z{\cdot}[] = [z]\ \langle proof \rangle$

```
scanr1 f [] ==> []
```

lemma $scanr1{\cdot}f{\cdot}[] = []\ \langle proof \rangle$

```
scanr1 f [x] ==> [x]
```

lemma *scanr1*·*f*·[*x*] = [*x*] ⟨*proof*⟩

```
take n [] ==> []
```

lemma *take*·*n*·[] ⊑ [] ⟨*proof*⟩

```
drop n [] ==> []
```

lemma *drop*·*n*·[] ⊑ []
⟨*proof*⟩

```
takeWhile p [] ==> []
```

lemma *takeWhile*·*p*·[] = [] ⟨*proof*⟩

```
dropWhile p [] ==> []
```

lemma *dropWhile*·*p*·[] = [] ⟨*proof*⟩

```
span p [] ==> ([],[])
```

lemma *span*·*p*·[] = ⟨[], []⟩ ⟨*proof*⟩

```
concat [a] ==> a
```

lemma *concat*·[*a*] = *a* ⟨*proof*⟩

```
concat [] ==> []
```

lemma *concat*·[] = [] ⟨*proof*⟩

```
zip [] [] ==> []
```

lemma *zip*·[]·[] = [] ⟨*proof*⟩

```
id x ==> x
```

lemma *ID*·*x* = *x* ⟨*proof*⟩

```
const x y ==> x
```

lemma *const*·*x*·*y* = *x* ⟨*proof*⟩

16.9 Complex hints

```
take (length t) s == t ==> t `Data.List.isPrefixOf` s
```

lemma
fixes *t* :: ['*a*::*Eq-sym*]
shows *eq*·(*take*·(*length*·*t*)·*s*)·*t* ⊑ *isPrefixOf*·*t*·*s*
⟨*proof*⟩

```
(take i s == t) ==> _eval_ ((i >= length t) && (t `Data.List.isPrefixOf`
s))
```

The hint is not true in general, as the following two lemmas show:

lemma
assumes $t = []$ **and** $s = x : xs$ **and** $i = 1$
shows $\neg\ (eq{\cdot}(take{\cdot}i{\cdot}s){\cdot}t \sqsubseteq (le{\cdot}(length{\cdot}t){\cdot}i\ andalso\ isPrefixOf{\cdot}t{\cdot}s))$
⟨*proof*⟩

lemma
assumes $le{\cdot}0{\cdot}i = TT$ **and** $le{\cdot}i{\cdot}0 = FF$
and $s = \bot$ **and** $t = []$
shows $\neg\ ((le{\cdot}(length{\cdot}t){\cdot}i\ andalso\ isPrefixOf{\cdot}t{\cdot}s) \sqsubseteq eq{\cdot}(take{\cdot}i{\cdot}s){\cdot}t)$
⟨*proof*⟩

lemma $neg{\cdot}(eq{\cdot}a{\cdot}b) = neq{\cdot}a{\cdot}b$ ⟨*proof*⟩

```
not (a /= b) ==> a == b
```

lemma $neg{\cdot}(neq{\cdot}a{\cdot}b) = eq{\cdot}a{\cdot}b$ ⟨*proof*⟩

```
map id ==> id
```

lemma *map-id*:$map{\cdot}ID = ID$ ⟨*proof*⟩

```
x == [] ==> null x
```

lemma $eq{\cdot}x{\cdot}[] = null{\cdot}x$ ⟨*proof*⟩

```
any id ==> or
```

lemma $any{\cdot}ID =$ *the-or* ⟨*proof*⟩

```
all id ==> and
```

lemma $all{\cdot}ID =$ *the-and* ⟨*proof*⟩

```
(if x then False else y) ==> (not x && y)
```

lemma (*If* x *then FF else* y) = ($neg{\cdot}x\ andalso\ y$) ⟨*proof*⟩

```
(if x then y else True) ==> (not x || y)
```

lemma (*If* x *then* y *else* TT) = ($neg{\cdot}x\ orelse\ y$) ⟨*proof*⟩

```
not (not x) ==> x
```

lemma $neg{\cdot}(neg{\cdot}x) = x$ ⟨*proof*⟩

```
(if c then f x else f y) ==> f (if c then x else y)
```

lemma (*If* c *then* $f{\cdot}x$ *else* $f{\cdot}y$) $\sqsubseteq f{\cdot}$(*If* c *then* x *else* y) ⟨*proof*⟩

```
(\ x -> [x]) ==> (: [])
```

lemma ($\Lambda\ x.\ [x]$) = ($\Lambda\ z.\ z : []$) ⟨*proof*⟩

`True == a ==> a`

lemma $eq{\cdot}TT{\cdot}a = a\ \langle proof \rangle$

`False == a ==> not a`

lemma $eq{\cdot}FF{\cdot}a = neg{\cdot}a\ \langle proof \rangle$

`a /= True ==> not a`

lemma $neq{\cdot}a{\cdot}TT = neg{\cdot}a\ \langle proof \rangle$

`a /= False ==> a`

lemma $neq{\cdot}a{\cdot}FF = a\ \langle proof \rangle$

`True /= a ==> not a`

lemma $neq{\cdot}TT{\cdot}a = neg{\cdot}a\ \langle proof \rangle$

`False /= a ==> a`

lemma $neq{\cdot}FF{\cdot}a = a\ \langle proof \rangle$

`not (isNothing x) ==> isJust x`

lemma $neg{\cdot}(isNothing{\cdot}x) = isJust{\cdot}x\ \langle proof \rangle$

`not (isJust x) ==> isNothing x`

lemma $neg{\cdot}(isJust{\cdot}x) = isNothing{\cdot}x\ \langle proof \rangle$

`x == Nothing ==> isNothing x`

lemma $eq{\cdot}x{\cdot}Nothing = isNothing{\cdot}x\ \langle proof \rangle$

`Nothing == x ==> isNothing x`

lemma $eq{\cdot}Nothing{\cdot}x = isNothing{\cdot}x\ \langle proof \rangle$

`x /= Nothing ==> Data.Maybe.isJust x`

lemma $neq{\cdot}x{\cdot}Nothing = isJust{\cdot}x\ \langle proof \rangle$

`Nothing /= x ==> Data.Maybe.isJust x`

lemma $neq{\cdot}Nothing{\cdot}x = isJust{\cdot}x\ \langle proof \rangle$

`(if isNothing x then y else fromJust x) ==> fromMaybe y x`

lemma $(If\ isNothing{\cdot}x\ then\ y\ else\ fromJust{\cdot}x) = fromMaybe{\cdot}y{\cdot}x\ \langle proof \rangle$

`(if isJust x then fromJust x else y) ==> fromMaybe y x`

lemma $(If\ isJust{\cdot}x\ then\ fromJust{\cdot}x\ else\ y) = fromMaybe{\cdot}y{\cdot}x\ \langle proof \rangle$

`(isJust x && (fromJust x == y)) ==> x == Just y`

lemma $(isJust{\cdot}x\ andalso\ (eq{\cdot}(fromJust{\cdot}x){\cdot}y)) = eq{\cdot}x{\cdot}(Just{\cdot}y)\ \langle proof \rangle$

```
elem True ==> or
```

lemma $elem{\cdot}TT = the\text{-}or$
$\langle proof \rangle$

```
notElem False ==> and
```

lemma $notElem{\cdot}FF = the\text{-}and$
$\langle proof \rangle$

```
all ((/=) a) ==> notElem a
```

lemma $all{\cdot}(neq{\cdot}(a::'a::Eq\text{-}sym)) = notElem{\cdot}a$
$\langle proof \rangle$

```
maybe x id ==> Data.Maybe.fromMaybe x
```

lemma $maybe{\cdot}x{\cdot}ID = fromMaybe{\cdot}x$
$\langle proof \rangle$

```
maybe False (const True) ==> Data.Maybe.isJust
```

lemma $maybe{\cdot}FF{\cdot}(const{\cdot}TT) = isJust$
$\langle proof \rangle$

```
maybe True (const False) ==> Data.Maybe.isNothing
```

lemma $maybe{\cdot}TT{\cdot}(const{\cdot}FF) = isNothing$
$\langle proof \rangle$

```
maybe [] (: []) ==> maybeToList
```

lemma $maybe{\cdot}[]{\cdot}(\Lambda\ z.\ z : []) = maybeToList$
$\langle proof \rangle$

```
catMaybes (map f x) ==> mapMaybe f x
```

lemma $catMaybes{\cdot}(map{\cdot}f{\cdot}x) = mapMaybe{\cdot}f{\cdot}x\ \langle proof \rangle$

```
(if isNothing x then y else f (fromJust x)) ==> maybe y f x
```

lemma $(If\ isNothing{\cdot}x\ then\ y\ else\ f{\cdot}(fromJust{\cdot}x)) = maybe{\cdot}y{\cdot}f{\cdot}x\ \langle proof \rangle$

```
(if isJust x then f (fromJust x) else y) ==> maybe y f x
```

lemma $(If\ isJust{\cdot}x\ then\ f{\cdot}(fromJust{\cdot}x)\ else\ y) = maybe{\cdot}y{\cdot}f{\cdot}x\ \langle proof \rangle$

```
(map fromJust . filter isJust) ==> Data.Maybe.catMaybes
```

lemma $(map{\cdot}fromJust\ oo\ filter{\cdot}isJust) = catMaybes$
$\langle proof \rangle$

```
concatMap (maybeToList . f) ==> Data.Maybe.mapMaybe f
```

lemma $concatMap{\cdot}(maybeToList\ oo\ f) = mapMaybe{\cdot}f$
$\langle proof \rangle$

```
concatMap maybeToList ==> catMaybes
```

lemma *concatMap·maybeToList = catMaybes* ⟨*proof*⟩

```
mapMaybe f (map g x) ==> mapMaybe (f . g) x
```

lemma *mapMaybe·f·(map·g·x) = mapMaybe·(f oo g)·x* ⟨*proof*⟩

```
(($) . f) ==> f
```

lemma (*dollar oo f*) = *f* ⟨*proof*⟩

```
(f $) ==> f
```

lemma (Λ *z*. *dollar·f·z*) = *f* ⟨*proof*⟩

```
(\ a b -> g (f a) (f b)) ==> g `Data.Function.on` f
```

lemma (Λ *a b*. *g·(f·a)·(f·b)*) = *on·g·f* ⟨*proof*⟩

```
id $! x ==> x
```

lemma *dollarBang·ID·x = x* ⟨*proof*⟩

```
[x | x <- y] ==> y
```

lemma [*x* | *x* <− *y*] = *y* ⟨*proof*⟩

```
isPrefixOf (reverse x) (reverse y) ==> isSuffixOf x y
```

lemma *isPrefixOf·(reverse·x)·(reverse·y) = isSuffixOf·x·y* ⟨*proof*⟩

```
concat (intersperse x y) ==> intercalate x y
```

lemma *concat·(intersperse·x·y) = intercalate·x·y* ⟨*proof*⟩

```
x `seq` y ==> y
```

lemma
assumes *x* ≠ ⊥ **shows** *seq·x·y = y*
⟨*proof*⟩

```
f $! x ==> f x
```

lemma assumes *x* ≠ ⊥ **shows** *dollarBang·f·x = f·x*
⟨*proof*⟩

```
maybe (f x) (f . g) ==> (f . maybe x g)
```

lemma *maybe·(f·x)·(f oo g)* ⊑ (*f oo maybe·x·g*)
⟨*proof*⟩

end

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