A Formal Model of IEEE Floating Point Arithmetic

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Abstract

This development provides a formal model of IEEE-754 floating-point arithmetic. This formalization, including formal specification of the standard and proofs of important properties of floating-point arithmetic, forms the foundation for verifying programs with floating-point computation. There is also a code generation setup for floats so that we can execute programs using this formalization in functional programming languages. The definitions of the IEEE standard in Isabelle is ported from HOL Light [1].

Contents

1 Specification of the IEEE standard

theory *IEEE*
imports
HOL−Library.Float
Word-Lib.Word-Lemmas
begin

typedef (**overloaded**) ('*e*::*len*, '*f*::*len*) *float* = *UNIV*::(*1 word* × '*e word* × '*f word*) *set*
by *auto*

setup-lifting *type-definition-float*

syntax -*float* :: *type* ⇒ *type* ⇒ *type* (‹'(-, -') *float*›)
syntax-types -*float* ⇌ *float*

parse ('*a*, '*b*) *float* as ('a::len, 'b::len) float.

parse-translation ‹
let
fun float t u = *Syntax.const* @{*type-syntax float*} $ *t* $ *u*;
fun len-tr u =
(*case Term-Position.strip-positions u of*
v as Free (*x*, -) =>
if Lexicon.is-tid x then
(*Syntax.const* @{*syntax-const -ofsort*} $ *v* $
Syntax.const @{*class-syntax len*})
else u
| - => *u*)
fun len-float-tr [*t*, *u*] =
float (*len-tr t*) (*len-tr u*)
in
[(@{*syntax-const -float*}, *K len-float-tr*)]
end
›

1.1 Derived parameters for floating point formats

definition *wordlength* :: ('*e*, '*f*) *float itself* ⇒ *nat*
where *wordlength x* = *LENGTH*('*e*) + *LENGTH*('*f*) + *1*

definition *bias* :: (*'e*, *'f*) *float itself* ⇒ *nat*
where *bias x* = *2^(LENGTH('e)* − *1)* − *1*

definition *emax* :: (*'e*, *'f*) *float itself* ⇒ *nat*
where *emax x* = *unat* (− *1*::*'e word*)

abbreviation *fracwidth*::(*'e*, *'f*) *float itself* ⇒ *nat* **where**
fracwidth - ≡ *LENGTH('f)*

1.2 Predicates for the four IEEE formats

definition *is-single* :: (*'e*, *'f*) *float itself* ⇒ *bool*
where *is-single x* ⟷ *LENGTH('e)* = *8* ∧ *wordlength x* = *32*

definition *is-double* :: (*'e*, *'f*) *float itself* ⇒ *bool*
where *is-double x* ⟷ *LENGTH('e)* = *11* ∧ *wordlength x* = *64*

definition *is-single-extended* :: (*'e*, *'f*) *float itself* ⇒ *bool*
where *is-single-extended x* ⟷ *LENGTH('e)* ≥ *11* ∧ *wordlength x* ≥ *43*

definition *is-double-extended* :: (*'e*, *'f*) *float itself* ⇒ *bool*
where *is-double-extended x* ⟷ *LENGTH('e)* ≥ *15* ∧ *wordlength x* ≥ *79*

1.3 Extractors for fields

lift-definition *sign*::(*'e*, *'f*) *float* ⇒ *nat* **is**
λ(*s*::*1 word*, -::*'e word*, -::*'f word*). *unat s* **.**

lift-definition *exponent*::(*'e*, *'f*) *float* ⇒ *nat* **is**
λ(-, *e*::*'e word*, -). *unat e* **.**

lift-definition *fraction*::(*'e*, *'f*) *float* ⇒ *nat* **is**
λ(-, -, *f*::*'f word*). *unat f* **.**

abbreviation *real-of-word x* ≡ *real* (*unat x*)

lift-definition *valof* :: (*'e*, *'f*) *float* ⇒ *real*
is *λ*(*s*, *e*, *f*).
let x = (*TYPE*((*'e*, *'f*) *float*)) *in*
(*if e* = *0*
then (−*1*::*real*)^(*unat s*) ∗ (*2* / (*2^bias x*)) ∗ (*real-of-word f*/*2^*(*LENGTH*(*'f*)))
else (−*1*::*real*)^(*unat s*) ∗ ((*2^*(*unat e*)) / (*2^bias x*)) ∗ (*1* + *real-of-word f*/*2^LENGTH*(*'f*)))
.

1.4 Partition of numbers into disjoint classes

definition *is-nan* :: (*'e*, *'f*) *float* ⇒ *bool*
where *is-nan a* ⟷ *exponent a* = *emax TYPE*((*'e*, *'f*)*float*) ∧ *fraction a* ≠ *0*

definition *is-infinity* :: (*'e*, *'f*) *float* ⇒ *bool*
  where *is-infinity a* ⟷ *exponent a* = *emax TYPE*((*'e*, *'f*)*float*) ∧ *fraction a* = *0*

definition *is-normal* :: (*'e*, *'f*) *float* ⇒ *bool*
  where *is-normal a* ⟷ *0* < *exponent a* ∧ *exponent a* < *emax TYPE*((*'e*, *'f*)*float*)

definition *is-denormal* :: (*'e*, *'f*) *float* ⇒ *bool*
  where *is-denormal a* ⟷ *exponent a* = *0* ∧ *fraction a* ≠ *0*

definition *is-zero* :: (*'e*, *'f*) *float* ⇒ *bool*
  where *is-zero a* ⟷ *exponent a* = *0* ∧ *fraction a* = *0*

definition *is-finite* :: (*'e*, *'f*) *float* ⇒ *bool*
  where *is-finite a* ⟷ (*is-normal a* ∨ *is-denormal a* ∨ *is-zero a*)

1.5 Special values

lift-definition *plus-infinity* :: (*'e*, *'f*) *float* (‹∞›) **is** (*0*, − *1*, *0*) **.**

lift-definition *topfloat* :: (*'e*, *'f*) *float* **is** (*0*, − *2*, *2^LENGTH*(*'f*) − *1*) **.**

instantiation *float*::(*len*, *len*) *zero* **begin**

lift-definition *zero-float* :: (*'e*, *'f*) *float* **is** (*0*, *0*, *0*) **.**

instance proof qed

end

1.6 Negation operation on floating point values

instantiation *float*::(*len*, *len*) *uminus* **begin**
lift-definition *uminus-float* :: (*'e*, *'f*) *float* ⇒ (*'e*, *'f*) *float* **is** λ(*s*, *e*, *f*). (*1* − *s*, *e*, *f*) **.**
instance proof qed
end

abbreviation (*input*) *minus-zero* ≡ − (*0*::(*'e*, *'f*)*float*)
abbreviation (*input*) *minus-infinity* ≡ − ∞
abbreviation (*input*) *bottomfloat* ≡ − *topfloat*

1.7 Real number valuations

The largest value that can be represented in floating point format.

definition *largest* :: (*'e*, *'f*) *float itself* ⇒ *real*
  where *largest x* = (*2^*(*emax x* − *1*) / *2^bias x*) ∗ (*2* − *1*/(*2^fracwidth x*))

Threshold, used for checking overflow.

definition *threshold* :: (*'e*, *'f*) *float itself* ⇒ *real*
where *threshold x* = (*2^(emax x − 1) / 2^bias x*) ∗ (*2 − 1/(2^(Suc(fracwidth x*))))

Unit of least precision.

lift-definition *one-lp*::(*'e* ,*'f*) *float* ⇒ (*'e* ,*'f*) *float* **is** λ(*s*, *e*, *f*). (*0*, *e*::*'e word*, *1*)
.
lift-definition *zero-lp*::(*'e* ,*'f*) *float* ⇒ (*'e* ,*'f*) *float* **is** λ(*s*, *e*, *f*). (*0*, *e*::*'e word*, *0*)
.

definition *ulp* :: (*'e*, *'f*) *float* ⇒ *real* **where** *ulp a* = *valof* (*one-lp a*) − *valof* (*zero-lp a*)

Enumerated type for rounding modes.

datatype *roundmode* = *roundNearestTiesToEven*
| *roundNearestTiesToAway*
| *roundTowardPositive*
| *roundTowardNegative*
| *roundTowardZero*

abbreviation (*input*) *RNE* ≡ *roundNearestTiesToEven*
abbreviation (*input*) *RNA* ≡ *roundNearestTiesToAway*
abbreviation (*input*) *RTP* ≡ *roundTowardPositive*
abbreviation (*input*) *RTN* ≡ *roundTowardNegative*
abbreviation (*input*) *RTZ* ≡ *roundTowardZero*

1.8 Rounding

Characterization of best approximation from a set of abstract values.

definition *is-closest v s x a* ⟷ *a* ∈ *s* ∧ (∀ *b*. *b* ∈ *s* ⟶ |*v a* − *x*| ≤ |*v b* − *x*|)

Best approximation with a deciding preference for multiple possibilities.

definition *closest v p s x* =
(*SOME a*. *is-closest v s x a* ∧ ((∃ *b*. *is-closest v s x b* ∧ *p b*) ⟶ *p a*))

fun *round* :: *roundmode* ⇒ *real* ⇒ (*'e* ,*'f*) *float*
where
round roundNearestTiesToEven y =
(*if y* ≤ − *threshold TYPE*((*'e* ,*'f*) *float*) *then minus-infinity*
else if y ≥ *threshold TYPE*((*'e* ,*'f*) *float*) *then plus-infinity*
else closest (*valof*) (λ*a*. *even* (*fraction a*)) {*a*. *is-finite a*} *y*)
| *round roundNearestTiesToAway y* =
(*if y* ≤ − *threshold TYPE*((*'e* ,*'f*) *float*) *then minus-infinity*
else if y ≥ *threshold TYPE*((*'e* ,*'f*) *float*) *then plus-infinity*
else closest (*valof*) (λ*a*. *True*) {*a*. *is-finite a* ∧ |*valof a*| ≥ |*y*|} *y*)
| *round roundTowardPositive y* =
(*if y* < − *largest TYPE*((*'e* ,*'f*) *float*) *then bottomfloat*
else if y > *largest TYPE*((*'e* ,*'f*) *float*) *then plus-infinity*

```
    else closest (valof) (λa. True) {a. is-finite a ∧ valof a ≥ y} y)
| round roundTowardNegative y =
   (if y < − largest TYPE(('e ,'f) float) then minus-infinity
    else if y > largest TYPE(('e ,'f) float) then topfloat
    else closest (valof) (λa. True) {a. is-finite a ∧ valof a ≤ y} y)
| round roundTowardZero y =
   (if y < − largest TYPE(('e ,'f) float) then bottomfloat
    else if y > largest TYPE(('e ,'f) float) then topfloat
    else closest (valof) (λa. True) {a. is-finite a ∧ |valof a| ≤ |y|} y)
```

Rounding to integer values in floating point format.

```
definition is-integral :: ('e ,'f) float ⇒ bool
  where is-integral a ⟷ is-finite a ∧ (∃ n::nat. |valof a| = real n)

fun intround :: roundmode ⇒ real ⇒ ('e ,'f) float
where
  intround roundNearestTiesToEven y =
    (if y ≤ − threshold TYPE(('e ,'f) float) then minus-infinity
     else if y ≥ threshold TYPE(('e ,'f) float) then plus-infinity
     else closest (valof) (λa. (∃ n::nat. even n ∧ |valof a| = real n)) {a. is-integral
a} y)
| intround roundNearestTiesToAway y =
    (if y ≤ − threshold TYPE(('e ,'f) float) then minus-infinity
     else if y ≥ threshold TYPE(('e ,'f) float) then plus-infinity
     else closest (valof) (λx. True) {a. is-integral a ∧ |valof a| ≥ |y|} y)
| intround roundTowardPositive y =
    (if y < − largest TYPE(('e ,'f) float) then bottomfloat
     else if y > largest TYPE(('e ,'f) float) then plus-infinity
     else closest (valof) (λx. True) {a. is-integral a ∧ valof a ≥ y} y)
| intround roundTowardNegative y =
    (if y < − largest TYPE(('e ,'f) float) then minus-infinity
     else if y > largest TYPE(('e ,'f) float) then topfloat
     else closest (valof) (λx. True) {a. is-integral a ∧ valof a ≥ y} y)
| intround roundTowardZero y =
    (if y < − largest TYPE(('e ,'f) float) then bottomfloat
     else if y > largest TYPE(('e ,'f) float) then topfloat
     else closest (valof) (λx. True) {a. is-integral a ∧ |valof a| ≤ |y|} y)
```

Round, choosing between -0.0 or +0.0

```
definition float-round::roundmode ⇒ bool ⇒ real ⇒ ('e, 'f) float
  where float-round mode toneg r =
      (let x = round mode r in
        if is-zero x
           then if toneg
                  then minus-zero
                else 0
        else x)
```

Non-standard of NaN.

definition *some-nan* :: (*'e* ,*'f*) *float*
where *some-nan* = (*SOME a*. *is-nan a*)

Coercion for signs of zero results.

definition *zerosign* :: *nat* ⇒ (*'e* ,*'f*) *float* ⇒ (*'e* ,*'f*) *float*
where *zerosign s a* =
(*if is-zero a then* (*if s* = *0 then 0 else* − *0*) *else a*)

Remainder operation.

definition *rem* :: *real* ⇒ *real* ⇒ *real*
where *rem x y* =
(*let n* = *closest id* (λ*x*. ∃ *n*::*nat*. *even n* ∧ |*x*| = *real n*) {*x*. ∃ *n* :: *nat*. |*x*| = *real n*} (*x* / *y*)
in x − *n* ∗ *y*)

definition *frem* :: *roundmode* ⇒ (*'e* ,*'f*) *float* ⇒ (*'e* ,*'f*) *float* ⇒ (*'e* ,*'f*) *float*
where *frem m a b* =
(*if is-nan a* ∨ *is-nan b* ∨ *is-infinity a* ∨ *is-zero b then some-nan*
else zerosign (*sign a*) (*round m* (*rem* (*valof a*) (*valof b*))))

1.9 Definitions of the arithmetic operations

definition *fintrnd* :: *roundmode* ⇒ (*'e* ,*'f*) *float* ⇒ (*'e* ,*'f*) *float*
where *fintrnd m a* =
(*if is-nan a then* (*some-nan*)
else if is-infinity a then a
else zerosign (*sign a*) (*intround m* (*valof a*)))

definition *fadd* :: *roundmode* ⇒ (*'e* ,*'f*) *float* ⇒ (*'e* ,*'f*) *float* ⇒ (*'e* ,*'f*) *float*
where *fadd m a b* =
(*if is-nan a* ∨ *is-nan b* ∨ (*is-infinity a* ∧ *is-infinity b* ∧ *sign a* ≠ *sign b*)
then some-nan
else if (*is-infinity a*) *then a*
else if (*is-infinity b*) *then b*
else
zerosign
(*if is-zero a* ∧ *is-zero b* ∧ *sign a* = *sign b then sign a*
else if m = *roundTowardNegative then 1 else 0*)
(*round m* (*valof a* + *valof b*)))

definition *fsub* :: *roundmode* ⇒ (*'e* ,*'f*) *float* ⇒ (*'e* ,*'f*) *float* ⇒ (*'e* ,*'f*) *float*
where *fsub m a b* =
(*if is-nan a* ∨ *is-nan b* ∨ (*is-infinity a* ∧ *is-infinity b* ∧ *sign a* = *sign b*)
then some-nan
else if is-infinity a then a
else if is-infinity b then − *b*
else
zerosign
(*if is-zero a* ∧ *is-zero b* ∧ *sign a* ≠ *sign b then sign a*

```
    else if m = roundTowardNegative then 1 else 0)
   (round m (valof a − valof b)))

definition fmul :: roundmode ⇒ ('e ,'f) float ⇒ ('e ,'f) float ⇒ ('e ,'f) float
  where fmul m a b =
    (if is-nan a ∨ is-nan b ∨ (is-zero a ∧ is-infinity b) ∨ (is-infinity a ∧ is-zero b)
     then some-nan
     else if is-infinity a ∨ is-infinity b
     then (if sign a = sign b then plus-infinity else minus-infinity)
     else zerosign (if sign a = sign b then 0 else 1 ) (round m (valof a ∗ valof b)))

definition fdiv :: roundmode ⇒ ('e ,'f) float ⇒ ('e ,'f) float ⇒ ('e ,'f) float
  where fdiv m a b =
    (if is-nan a ∨ is-nan b ∨ (is-zero a ∧ is-zero b) ∨ (is-infinity a ∧ is-infinity b)
     then some-nan
     else if is-infinity a ∨ is-zero b
     then (if sign a = sign b then plus-infinity else minus-infinity)
     else if is-infinity b
     then (if sign a = sign b then 0 else − 0)
     else zerosign (if sign a = sign b then 0 else 1) (round m (valof a / valof b)))

definition fsqrt :: roundmode ⇒ ('e ,'f) float ⇒ ('e ,'f) float
  where fsqrt m a =
    (if is-nan a then some-nan
     else if is-zero a ∨ is-infinity a ∧ sign a = 0 then a
     else if sign a = 1 then some-nan
     else zerosign (sign a) (round m (sqrt (valof a))))

definition fmul-add :: roundmode ⇒ ('t ,'w) float ⇒ ('t ,'w) float ⇒ ('t ,'w) float
⇒ ('t ,'w) float
  where fmul-add mode x y z = (let
    signP = if sign x = sign y then 0 else 1;
    infP = is-infinity x  ∨ is-infinity y
  in
    if is-nan x ∨ is-nan y ∨ is-nan z then some-nan
    else if is-infinity x ∧ is-zero y ∨
          is-zero x ∧ is-infinity y ∨
          is-infinity z ∧ infP ∧ signP ≠ sign z
      then some-nan
    else if is-infinity z ∧ (sign z = 0) ∨ infP ∧ (signP = 0)
      then plus-infinity
    else if is-infinity z ∧ (sign z = 1) ∨ infP ∧ (signP = 1)
      then minus-infinity
    else let
      r1 = valof x ∗ valof y;
      r2 = valof z;
      r = r1+r2
    in
      if r=0 then ( — Exact Zero Case. Same sign rules as for add apply.
```

if r1=0 ∧ r2=0 ∧ signP=sign z then zerosign signP 0
else if mode = roundTowardNegative then −0
else 0
) *else* (— Not exactly zero: Rounding has sign of exact value, even if rounded val is zero
zerosign (*if r<0 then 1 else 0*) (*round mode r*)
)
)

1.10 Comparison operations

datatype *ccode* = *Gt* | *Lt* | *Eq* | *Und*

definition *fcompare* :: ('*e* ,'*f*) *float* ⇒ ('*e* ,'*f*) *float* ⇒ *ccode*
where *fcompare a b* =
(*if is-nan a* ∨ *is-nan b then Und*
else if is-infinity a ∧ *sign a* = *1*
then (*if is-infinity b* ∧ *sign b* = *1 then Eq else Lt*)
else if is-infinity a ∧ *sign a* = *0*
then (*if is-infinity b* ∧ *sign b* = *0 then Eq else Gt*)
else if is-infinity b ∧ *sign b* = *1 then Gt*
else if is-infinity b ∧ *sign b* = *0 then Lt*
else if valof a < *valof b then Lt*
else if valof a = *valof b then Eq*
else Gt)

definition *flt* :: ('*e* ,'*f*) *float* ⇒ ('*e* ,'*f*) *float* ⇒ *bool*
where *flt a b* ⟷ *fcompare a b* = *Lt*

definition *fle* :: ('*e* ,'*f*) *float* ⇒ ('*e* ,'*f*) *float* ⇒ *bool*
where *fle a b* ⟷ *fcompare a b* = *Lt* ∨ *fcompare a b* = *Eq*

definition *fgt* :: ('*e* ,'*f*) *float* ⇒ ('*e* ,'*f*) *float* ⇒ *bool*
where *fgt a b* ⟷ *fcompare a b* = *Gt*

definition *fge* :: ('*e* ,'*f*) *float* ⇒ ('*e* ,'*f*) *float* ⇒ *bool*
where *fge a b* ⟷ *fcompare a b* = *Gt* ∨ *fcompare a b* = *Eq*

definition *feq* :: ('*e* ,'*f*) *float* ⇒ ('*e* ,'*f*) *float* ⇒ *bool*
where *feq a b* ⟷ *fcompare a b* = *Eq*

2 Specify float to be double precision and round to even

instantiation *float* :: (*len*, *len*) *plus*
begin

definition *plus-float* :: ('*a*, '*b*) *float* ⇒ ('*a*, '*b*) *float* ⇒ ('*a*, '*b*) *float*

where $a + b = fadd\ RNE\ a\ b$

instance ..

end

instantiation *float* :: (*len*, *len*) *minus*
begin

definition *minus-float* :: ('*a*, '*b*) *float* ⇒ ('*a*, '*b*) *float* ⇒ ('*a*, '*b*) *float*
where $a - b = fsub\ RNE\ a\ b$

instance ..

end

instantiation *float* :: (*len*, *len*) *times*
begin

definition *times-float* :: ('*a*, '*b*) *float* ⇒ ('*a*, '*b*) *float* ⇒ ('*a*, '*b*) *float*
where $a * b = fmul\ RNE\ a\ b$

instance ..

end

instantiation *float* :: (*len*, *len*) *one*
begin

lift-definition *one-float* :: ('*a*, '*b*) *float* **is** $(0, 2\hat{}(LENGTH('a) - 1) - 1, 0)$ **.**

instance ..

end

instantiation *float* :: (*len*, *len*) *inverse*
begin

definition *divide-float* :: ('*a*, '*b*) *float* ⇒ ('*a*, '*b*) *float* ⇒ ('*a*, '*b*) *float*
where $a\ div\ b = fdiv\ RNE\ a\ b$

definition *inverse-float* :: ('*a*, '*b*) *float* ⇒ ('*a*, '*b*) *float*
where $inverse\text{-}float\ a = fdiv\ RNE\ 1\ a$

instance ..

end

definition *float-rem* :: ('*a*, '*b*) *float* ⇒ ('*a*, '*b*) *float* ⇒ ('*a*, '*b*) *float*

where *float-rem a b* = *frem RNE a b*

definition *float-sqrt* :: (*'a*, *'b*) *float* ⇒ (*'a*, *'b*) *float*
where *float-sqrt a* = *fsqrt RNE a*

definition *ROUNDFLOAT* ::(*'a*, *'b*) *float* ⇒ (*'a*, *'b*) *float*
where *ROUNDFLOAT a* = *fintrnd RNE a*

instantiation *float* :: (*len*, *len*) *ord*
begin

definition *less-float* :: (*'a*, *'b*) *float* ⇒ (*'a*, *'b*) *float* ⇒ *bool*
where *a* < *b* ⟷ *flt a b*

definition *less-eq-float* :: (*'a*, *'b*) *float* ⇒ (*'a*, *'b*) *float* ⇒ *bool*
where *a* ≤ *b* ⟷ *fle a b*

instance ..

end

definition *float-eq* :: (*'a*, *'b*) *float* ⇒ (*'a*, *'b*) *float* ⇒ *bool* (**infixl** ‹≐› *70*)
where *float-eq a b* = *feq a b*

instantiation *float* :: (*len*, *len*) *abs*
begin

definition *abs-float* :: (*'a*, *'b*) *float* ⇒ (*'a*, *'b*) *float*
where *abs-float a* = (*if sign a* = *0 then a else* − *a*)

instance ..
end

The *1* + ε property.

definition *normalizes* :: - *itself* ⇒ *real* ⇒ *bool*
where *normalizes float-format x* =
(*1*/ (*2*::*real*)^(*bias float-format* − *1*) ≤ |*x*| ∧ |*x*| < *threshold float-format*)

end

3 Proofs of Properties about Floating Point Arithmetic

theory *IEEE-Properties*
imports *IEEE*
begin

3.1 Theorems derived from definitions

lemma *valof-eq*:
valof x =
(*if exponent x* = *0*
then (− *1*) ^ *sign x* ∗ (*2* / *2* ^ *bias TYPE*((*'a*, *'b*) *float*)) ∗
(*real* (*fraction x*) / *2* ^ *LENGTH*(*'b*))
else (− *1*) ^ *sign x* ∗ (*2* ^ *exponent x* / *2* ^ *bias TYPE*((*'a*, *'b*) *float*)) ∗
(*1* + *real* (*fraction x*) / *2* ^ *LENGTH*(*'b*)))
for *x*::(*'a*, *'b*) *float*
unfolding *Let-def*
by *transfer* (*auto simp*: *bias-def divide-simps unat-eq-0*)

lemma *exponent-le* [*simp*]:
‹*exponent a* ≤ *mask LENGTH*(*'a*)› **for** *a* :: ‹(*'a*, -) *float*›
by *transfer* (*auto simp add*: *of-nat-mask-eq intro*: *word-unat-less-le split*: *prod.split*)

lemma *exponent-not-less* [*simp*]:
‹¬ *mask LENGTH*(*'a*) < *IEEE.exponent a*› **for** *a* :: ‹(*'a*, -) *float*›
by (*simp add*: *not-less*)

lemma *infinity-simps*:
sign (*plus-infinity*::(*'e*, *'f*)*float*) = *0*
sign (*minus-infinity*::(*'e*, *'f*)*float*) = *1*
exponent (*plus-infinity*::(*'e*, *'f*)*float*) = *emax TYPE*((*'e*, *'f*)*float*)
exponent (*minus-infinity*::(*'e*, *'f*)*float*) = *emax TYPE*((*'e*, *'f*)*float*)
fraction (*plus-infinity*::(*'e*, *'f*)*float*) = *0*
fraction (*minus-infinity*::(*'e*, *'f*)*float*) = *0*
subgoal by *transfer auto*
subgoal by *transfer auto*
subgoal by *transfer* (*simp add*: *emax-def mask-eq-exp-minus-1*)
subgoal by *transfer* (*simp add*: *emax-def mask-eq-exp-minus-1*)
subgoal by *transfer auto*
subgoal by *transfer auto*
done

lemma *zero-simps*:
sign (*0*::(*'e*, *'f*)*float*) = *0*
sign (− *0*::(*'e*, *'f*)*float*) = *1*
exponent (*0*::(*'e*, *'f*)*float*) = *0*
exponent (− *0*::(*'e*, *'f*)*float*) = *0*
fraction (*0*::(*'e*, *'f*)*float*) = *0*
fraction (− *0*::(*'e*, *'f*)*float*) = *0*
subgoal by *transfer auto*
subgoal by *transfer auto*
subgoal by *transfer auto*
subgoal by *transfer auto*
subgoal by *transfer auto*
subgoal by *transfer auto*
done

lemma *emax-eq*: *emax x = 2 ^ LENGTH('e) − 1*
for *x*::('*e*, '*f*)*float itself*
by (*simp add*: *emax-def unsigned-minus-1-eq-mask mask-eq-exp-minus-1*)

lemma *topfloat-simps*:
sign (*topfloat*::('*e*, '*f*)*float*) = *0*
exponent (*topfloat*::('*e*, '*f*)*float*) = *emax TYPE*(('*e*, '*f*)*float*) − *1*
fraction (*topfloat*::('*e*, '*f*)*float*) = *2 ^* (*fracwidth TYPE*(('*e*, '*f*)*float*)) − *1*
and *bottomfloat-simps*:
sign (*bottomfloat*::('*e*, '*f*)*float*) = *1*
exponent (*bottomfloat*::('*e*, '*f*)*float*) = *emax TYPE*(('*e*, '*f*)*float*) − *1*
fraction (*bottomfloat*::('*e*, '*f*)*float*) = *2 ^* (*fracwidth TYPE*(('*e*, '*f*)*float*)) − *1*
subgoal by *transfer simp*
subgoal by *transfer* (*simp add*: *emax-eq take-bit-minus-small-eq nat-diff-distrib nat-power-eq*)
subgoal by *transfer* (*simp add*: *unsigned-minus-1-eq-mask mask-eq-exp-minus-1*)
subgoal by *transfer simp*
subgoal by *transfer* (*simp add*: *emax-eq take-bit-minus-small-eq nat-diff-distrib nat-power-eq*)
subgoal by *transfer* (*simp add*: *unsigned-minus-1-eq-mask mask-eq-exp-minus-1*)
done

lemmas *float-defs* =
is-finite-def is-infinity-def is-zero-def is-nan-def
is-normal-def is-denormal-def valof-eq
less-eq-float-def less-float-def
flt-def fgt-def fle-def fge-def feq-def
fcompare-def
infinity-simps
zero-simps
topfloat-simps
bottomfloat-simps
float-eq-def

lemma *float-cases*: *is-nan a* ∨ *is-infinity a* ∨ *is-normal a* ∨ *is-denormal a* ∨ *is-zero a*
by (*auto simp add*: *float-defs not-less le-less emax-def unsigned-minus-1-eq-mask*)

lemma *float-cases-finite*: *is-nan a* ∨ *is-infinity a* ∨ *is-finite a*
by (*simp add*: *float-cases is-finite-def*)

lemma *float-zero1* [*simp*]: *is-zero 0*
unfolding *float-defs*
by *transfer auto*

lemma *float-zero2* [*simp*]: *is-zero* (− *x*) ⟷ *is-zero x*
unfolding *float-defs*
by *transfer auto*

lemma *emax-pos* [*simp*]: *0 < emax x emax x ≠ 0*
by (*auto simp*: *emax-def*)

The types of floating-point numbers are mutually distinct.

lemma *float-distinct*:
¬ (*is-nan a* ∧ *is-infinity a*)
¬ (*is-nan a* ∧ *is-normal a*)
¬ (*is-nan a* ∧ *is-denormal a*)
¬ (*is-nan a* ∧ *is-zero a*)
¬ (*is-infinity a* ∧ *is-normal a*)
¬ (*is-infinity a* ∧ *is-denormal a*)
¬ (*is-infinity a* ∧ *is-zero a*)
¬ (*is-normal a* ∧ *is-denormal a*)
¬ (*is-denormal a* ∧ *is-zero a*)
by (*auto simp*: *float-defs*)

lemma *denormal-imp-not-zero*: *is-denormal f* ⟹ ¬*is-zero f*
by (*simp add*: *is-denormal-def is-zero-def*)

lemma *normal-imp-not-zero*: *is-normal f* ⟹ ¬*is-zero f*
by (*simp add*: *is-normal-def is-zero-def*)

lemma *normal-imp-not-denormal*: *is-normal f* ⟹ ¬*is-denormal f*
by (*simp add*: *is-normal-def is-denormal-def*)

lemma *denormal-zero* [*simp*]: ¬*is-denormal 0* ¬*is-denormal minus-zero*
using *denormal-imp-not-zero float-zero1 float-zero2* **by** *blast+*

lemma *normal-zero* [*simp*]: ¬*is-normal 0* ¬*is-normal minus-zero*
using *normal-imp-not-zero float-zero1 float-zero2* **by** *blast+*

lemma *float-distinct-finite*: ¬ (*is-nan a* ∧ *is-finite a*) ¬(*is-infinity a* ∧ *is-finite a*)
by (*auto simp*: *float-defs*)

lemma *finite-infinity*: *is-finite a* ⟹ ¬ *is-infinity a*
by (*auto simp*: *float-defs*)

lemma *finite-nan*: *is-finite a* ⟹ ¬ *is-nan a*
by (*auto simp*: *float-defs*)

For every real number, the floating-point numbers closest to it always exists.

lemma *is-closest-exists*:
fixes *v* :: (*'e*, *'f*)*float* ⇒ *real*
and *s* :: (*'e*, *'f*)*float set*
assumes *finite*: *finite s*
and *non-empty*: *s ≠* {}
shows ∃ *a*. *is-closest v s x a*
using *finite non-empty*

```
proof (induct s rule: finite-induct)
  case empty
  then show ?case by simp
next
  case (insert z s)
  show ?case
  proof (cases s = {})
    case True
    then have is-closest v (insert z s) x z
      by (auto simp: is-closest-def)
    then show ?thesis by metis
  next
    case False
    then obtain a where a: is-closest v s x a
      using insert by metis
    then show ?thesis
    proof (cases |v a − x| |v z − x| rule: le-cases)
      case le
      then show ?thesis
        by (metis insert-iff a is-closest-def)
    next
      case ge
      have ∀ b. b ∈ s ⟶ |v a − x| ≤ |v b − x|
        by (metis a is-closest-def)
      then have ∀ b. b ∈ insert z s ⟶ |v z − x| ≤ |v b − x|
        by (metis eq-iff ge insert-iff order.trans)
      then show ?thesis using is-closest-def a
        by (metis insertI1)
    qed
  qed
qed

lemma closest-is-everything:
  fixes v :: ('e, 'f)float ⇒ real
    and s :: ('e, 'f)float set
  assumes finite: finite s
    and non-empty: s ≠ {}
  shows is-closest v s x (closest v p s x) ∧
    ((∃ b. is-closest v s x b ∧ p b) ⟶ p (closest v p s x))
  unfolding closest-def
  by (rule someI-ex) (metis assms is-closest-exists [of s v x])

lemma closest-in-set:
  fixes v :: ('e, 'f)float ⇒ real
  assumes finite s and s ≠ {}
  shows closest v p s x ∈ s
  by (metis assms closest-is-everything is-closest-def)

lemma closest-is-closest-finite:
```

fixes $v :: ('e, 'f)float \Rightarrow real$
assumes *finite s* **and** $s \neq \{\}$
shows *is-closest v s x* (*closest v p s x*)
by (*metis closest-is-everything assms*)

instance *float*::(*len*, *len*) *finite* **proof qed** (*transfer*, *simp*)

lemma *is-finite-nonempty*: $\{a.\ is\text{-}finite\ a\} \neq \{\}$
proof −
have $0 \in \{a.\ is\text{-}finite\ a\}$
unfolding *float-defs*
by *transfer auto*
then show *?thesis* **by** (*metis empty-iff*)
qed

lemma *closest-is-closest*:
fixes $v :: ('e, 'f)float \Rightarrow real$
assumes $s \neq \{\}$
shows *is-closest v s x* (*closest v p s x*)
by (*rule closest-is-closest-finite*) (*auto simp*: *assms*)

3.2 Properties about ordering and bounding

Lifting of non-exceptional comparisons.

lemma *float-lt* [*simp*]:
assumes *is-finite a is-finite b*
shows $a < b \longleftrightarrow valof\ a < valof\ b$
proof
assume $valof\ a < valof\ b$
moreover have ¬ *is-nan a* **and** ¬ *is-nan b* **and** ¬ *is-infinity a* **and** ¬ *is-infinity b*
using *assms* **by** (*auto simp*: *finite-nan finite-infinity*)
ultimately have *fcompare a b* = *Lt*
by (*auto simp add*: *is-infinity-def is-nan-def valof-def fcompare-def*)
then show $a < b$ **by** (*auto simp*: *float-defs*)
next
assume $a < b$
then have *lt*: *fcompare a b* = *Lt*
by (*simp add*: *float-defs*)
have ¬ *is-nan a* **and** ¬ *is-nan b* **and** ¬ *is-infinity a* **and** ¬ *is-infinity b*
using *assms* **by** (*auto simp*: *finite-nan finite-infinity*)
then show $valof\ a < valof\ b$
using *lt assms*
by (*simp add*: *fcompare-def is-nan-def is-infinity-def valof-def split*: *if-split-asm*)
qed

lemma *float-eq* [*simp*]:
assumes *is-finite a is-finite b*
shows $a \doteq b \longleftrightarrow valof\ a = valof\ b$

proof
  assume ∗: *valof a = valof b*
  have ¬ *is-nan a* **and** ¬ *is-nan b* **and** ¬ *is-infinity a* **and** ¬ *is-infinity b*
    using *assms float-distinct-finite* **by** *auto*
  with ∗ **have** *fcompare a b = Eq*
    by (*auto simp add*: *is-infinity-def is-nan-def valof-def fcompare-def*)
  then show *a* ≐ *b* **by** (*auto simp*: *float-defs*)
next
  assume *a* ≐ *b*
  then have *eq*: *fcompare a b = Eq*
    by (*simp add*: *float-defs*)
  have ¬ *is-nan a* **and** ¬ *is-nan b* **and** ¬ *is-infinity a* **and** ¬ *is-infinity b*
    using *assms float-distinct-finite* **by** *auto*
  then show *valof a = valof b*
    using *eq assms*
   by (*simp add*: *fcompare-def is-nan-def is-infinity-def valof-def split*: *if-split-asm*)
qed

lemma *float-le* [*simp*]:
  assumes *is-finite a is-finite b*
  shows *a* ≤ *b* ⟷ *valof a* ≤ *valof b*
proof −
  have *a* ≤ *b* ⟷ *a* < *b* ∨ *a* ≐ *b*
    by (*auto simp add*: *float-defs*)
  then show *?thesis*
    by (*auto simp add*: *assms*)
qed

Reflexivity of equality for non-NaNs.

lemma *float-eq-refl* [*simp*]: *a* ≐ *a* ⟷ ¬ *is-nan a*
  by (*auto simp*: *float-defs*)

Properties about ordering.

lemma *float-lt-trans*: *is-finite a* ⟹ *is-finite b* ⟹ *is-finite c* ⟹ *a* < *b* ⟹ *b* < *c* ⟹ *a* < *c*
  by (*auto simp*: *le-trans*)

lemma *float-le-less-trans*: *is-finite a* ⟹ *is-finite b* ⟹ *is-finite c* ⟹ *a* ≤ *b* ⟹ *b* < *c* ⟹ *a* < *c*
  by (*auto simp*: *le-trans*)

lemma *float-le-trans*: *is-finite a* ⟹ *is-finite b* ⟹ *is-finite c* ⟹ *a* ≤ *b* ⟹ *b* ≤ *c* ⟹ *a* ≤ *c*
  by (*auto simp*: *le-trans*)

lemma *float-le-neg*: *is-finite a* ⟹ *is-finite b* ⟹ ¬ *a* < *b* ⟷ *b* ≤ *a*
  by *auto*

Properties about bounding.

lemma *float-le-plus-infinity* [*simp*]: ¬ *is-nan a* ⟹ *a* ≤ *plus-infinity*
unfolding *float-defs*
by *auto*

lemma *minus-infinity-le-float* [*simp*]: ¬ *is-nan a* ⟹ *minus-infinity* ≤ *a*
unfolding *float-defs*
by *auto*

lemma *zero-le-topfloat* [*simp*]: *0* ≤ *topfloat* − *0* ≤ *topfloat*
by (*auto simp*: *float-defs field-simps power-gt1-lemma of-nat-diff mask-eq-exp-minus-1*)

lemma *LENGTH-contr*:
Suc 0 < *LENGTH*('*e*) ⟹ *2* ^ *LENGTH*('*e*::*len*) ≤ *Suc* (*Suc 0*) ⟹ *False*
by (*metis le-antisym len-gt-0 n-less-equal-power-2 not-less-eq numeral-2-eq-2 one-le-numeral self-le-power*)

lemma *valof-topfloat*: *valof* (*topfloat*::('*e*, '*f*)*float*) = *largest TYPE*(('*e*, '*f*)*float*)
if *LENGTH*('*e*) > *1*
using *that LENGTH-contr*
by (*auto simp add*: *emax-eq largest-def divide-simps float-defs of-nat-diff mask-eq-exp-minus-1*)

lemma *float-frac-le*: *fraction a* ≤ *2^LENGTH*('*f*) − *1*
for *a*::('*e*, '*f*)*float*
unfolding *float-defs*
using *less-Suc-eq-le*
by *transfer fastforce*

lemma *float-exp-le*: *is-finite a* ⟹ *exponent a* ≤ *emax TYPE*(('*e*, '*f*)*float*) − *1*
for *a*::('*e*, '*f*)*float*
unfolding *float-defs*
by *auto*

lemma *float-sign-le*: (−*1*::*real*)^(*sign a*) = *1* ∨ (−*1*::*real*)^(*sign a*) = −*1*
by (*metis neg-one-even-power neg-one-odd-power*)

lemma *exp-less*: *a* ≤ *b* ⟹ (*2*::*real*)^*a* ≤ *2^b* **for** *a b* :: *nat*
by *auto*

lemma *div-less*: *a* ≤ *b* ∧ *c* > *0* ⟹ *a*/*c* ≤ *b*/*c* **for** *a b c* :: '*a*::*linordered-field*
by (*metis divide-le-cancel less-asym*)

lemma *finite-topfloat*: *is-finite topfloat*
unfolding *float-defs*
by *auto*

lemmas *float-leI* = *float-le*[*THEN iffD2*]

lemma *factor-minus*: *x* ∗ *a* − *x* = *x* ∗ (*a* − *1*)
for *x a*::'*a*::*comm-semiring-1-cancel*

by (*simp add*: *algebra-simps*)

lemma *real-le-power-numeral-diff*: *real a* ≤ *numeral b* ^ *n* − *1* ⟷ *a* ≤ *numeral b* ^ *n* − *1*
by (*metis* (*mono-tags*, *lifting*) *of-nat-1 of-nat-diff of-nat-le-iff of-nat-numeral one-le-numeral one-le-power semiring-1-class.of-nat-power*)

definition *denormal-exponent*::('*e*, '*f*)*float itself* ⇒ *int* **where**
denormal-exponent x = *1* − (*int* (*LENGTH*('*f*)) + *int* (*bias TYPE*(('*e*, '*f*)*float*)))

definition *normal-exponent*::('*e*, '*f*)*float* ⇒ *int* **where**
normal-exponent x = *int* (*exponent x*) − *int* (*bias TYPE*(('*e*, '*f*)*float*)) − *int* (*LENGTH*('*f*))

definition *denormal-mantissa*::('*e*, '*f*)*float* ⇒ *int* **where**
denormal-mantissa x = (−*1*::*int*)^*sign x* ∗ *int* (*fraction x*)

definition *normal-mantissa*::('*e*, '*f*)*float* ⇒ *int* **where**
normal-mantissa x = (−*1*::*int*)^*sign x* ∗ (*2*^*LENGTH*('*f*) + *int* (*fraction x*))

lemma *unat-one-word-le*: *unat a* ≤ *Suc 0* **for** *a*::*1 word*
using *unat-lt2p*[*of a*]
by *auto*

lemma *one-word-le*: *a* ≤ *1* **for** *a*::*1 word*
by (*auto simp*: *word-le-nat-alt unat-one-word-le*)

lemma *sign-cases*[*case-names pos neg*]:
obtains *sign x* = *0* | *sign x* = *1*
proof *cases*
assume *sign x* = *0*
then show *?thesis* ..
next
assume *sign x* ≠ *0*
have *sign x* ≤ *1*
by *transfer* (*auto simp*: *unat-one-word-le*)
then have *sign x* = *1* **using** ‹*sign x* ≠ *0*›
by *auto*
then show *?thesis* ..
qed

lemma *is-infinity-cases*:
assumes *is-infinity x*
obtains *x* = *plus-infinity* | *x* = *minus-infinity*
proof (*cases rule*: *sign-cases*[*of x*])
assume *sign x* = *0*
then have *x* = *plus-infinity* **using** *assms*
apply (*unfold float-defs*)
apply *transfer*

```
    apply (auto simp add: unat-eq-of-nat emax-def of-nat-mask-eq)
    done
  then show ?thesis ..
next
  assume sign x = 1
  then have x = minus-infinity using assms
    apply (unfold float-defs)
    apply transfer
    apply (auto simp add: unat-eq-of-nat emax-def of-nat-mask-eq)
    done
  then show ?thesis ..
qed

lemma is-zero-cases:
  assumes is-zero x
  obtains x = 0 | x = - 0
proof (cases rule: sign-cases[of x])
  assume sign x = 0
  then have x = 0 using assms
    unfolding float-defs
    by transfer (auto simp: emax-def unat-eq-0)
  then show ?thesis ..
next
  assume sign x = 1
  then have x = minus-zero using assms
    unfolding float-defs
    by transfer (auto simp: emax-def unat-eq-of-nat)
  then show ?thesis ..
qed

lemma minus-minus-float [simp]: - (-f) = f for f::('e, 'f)float
  by transfer auto

lemma sign-minus-float: sign (-f) = (1 - sign f) for f::('e, 'f)float
  by transfer (auto simp: unat-eq-1 one-word-le unat-sub)

lemma exponent-uminus [simp]: exponent (- f) = exponent f by transfer auto
lemma fraction-uminus [simp]: fraction (- f) = fraction f by transfer auto

lemma is-normal-minus-float [simp]: is-normal (-f) = is-normal f for f::('e,
'f)float
  by (auto simp: is-normal-def)

lemma is-denormal-minus-float [simp]: is-denormal (-f) = is-denormal f for
f::('e, 'f)float
  by (auto simp: is-denormal-def)

lemma bitlen-normal-mantissa:
  bitlen (abs (normal-mantissa x)) = Suc LENGTH('f) for x::('e, 'f)float
```

proof −
have *fraction x* < *2* ^ *LENGTH('f)*
using *float-frac-le*[*of x*]
by (*metis One-nat-def Suc-pred le-imp-less-Suc pos2 zero-less-power*)
moreover have − *int* (*fraction x*) ≤ *2* ^ *LENGTH('f)*
using *negative-zle-0 order-trans zero-le-numeral zero-le-power* **by** *blast*
ultimately show *?thesis*
by (*cases x rule*: *sign-cases*)
(*auto simp*: *bitlen-le-iff-power bitlen-ge-iff-power nat-add-distrib*
normal-mantissa-def intro!: *antisym*)
qed

lemma *less-int-natI*: *x* < *y* **if** *0* ≤ *x nat x* < *nat y*
using *that* **by** *arith*

lemma *normal-exponent-bounds-int*:
2 − *2* ^ (*LENGTH('e)* − *1*) − *int LENGTH('f)* ≤ *normal-exponent x*
normal-exponent x ≤ *2* ^ (*LENGTH('e)* − *1*) − *int LENGTH('f)* − *1*
if *is-normal x*
for *x*::(*'e*, *'f*)*float*
using *that*
apply (*auto simp add*: *normal-exponent-def is-normal-def emax-eq bias-def diff-le-eq diff-less-eq*
mask-eq-exp-minus-1 of-nat-diff simp flip: *zless-nat-eq-int-zless power-Suc*)
apply (*simp flip*: *power-Suc mask-eq-exp-minus-1 add*: *nat-mask-eq*)
apply (*simp add*: *mask-eq-exp-minus-1*)
done

lemmas *of-int-leI* = *of-int-le-iff*[*THEN iffD2*]

lemma *normal-exponent-bounds-real*:
2 − *2* ^ (*LENGTH('e)* − *1*) − *real LENGTH('f)* ≤ *normal-exponent x*
normal-exponent x ≤ *2* ^ (*LENGTH('e)* − *1*) − *real LENGTH('f)* − *1*
if *is-normal x*
for *x*::(*'e*, *'f*)*float*
subgoal by (*rule order-trans*[*OF - of-int-leI*[*OF normal-exponent-bounds-int*(*1*)[*OF that*]]]) *auto*
subgoal by (*rule order-trans*[*OF of-int-leI*[*OF normal-exponent-bounds-int*(*2*)[*OF that*]]]) *auto*
done

lemma *float-eqI*:
x = *y* **if** *sign x* = *sign y fraction x* = *fraction y exponent x* = *exponent y*
using *that* **by** *transfer* (*auto simp add*: *word-unat-eq-iff*)

lemma *float-induct*[*induct type*:*float*, *case-names normal denormal neg zero infinity nan*]:
fixes *a*::(*'e*, *'f*)*float*
assumes *normal*:

```
    ⋀x. is-normal x ⟹ valof x = normal-mantissa x * 2 powr normal-exponent x
⟹ P x
  assumes denormal:
    ⋀x. is-denormal x ⟹
     valof x = denormal-mantissa x * 2 powr denormal-exponent TYPE(('e, 'f)float)
⟹
      P x
  assumes zero: P 0 P minus-zero
  assumes infty: P plus-infinity P minus-infinity
  assumes nan: ⋀x. is-nan x ⟹ P x
  shows P a
proof −
  from float-cases[of a]
  consider is-nan a | is-infinity a | is-normal a | is-denormal a | is-zero a by blast
  then show ?thesis
  proof cases
    case 1
    then show ?thesis by (rule nan)
  next
    case 2
   then consider a = plus-infinity | a = minus-infinity by (rule is-infinity-cases)
    then show ?thesis
      by cases (auto intro: infty)
  next
    case hyps: 3
    from hyps have valof a = normal-mantissa a * 2 powr normal-exponent a
      by (cases a rule: sign-cases)
       (auto simp: valof-eq normal-mantissa-def normal-exponent-def is-normal-def
          powr-realpow[symmetric] powr-diff powr-add field-simps)
    from hyps this show ?thesis
      by (rule normal)
  next
    case hyps: 4
    from hyps have valof a = denormal-mantissa a * 2 powr denormal-exponent
TYPE(('e, 'f)float)
      by (cases a rule: sign-cases)
      (auto simp: valof-eq denormal-mantissa-def denormal-exponent-def is-denormal-def
          powr-realpow[symmetric] powr-diff powr-add field-simps)
    from hyps this show ?thesis
      by (rule denormal)
  next
    case 5
    then consider a = 0 | a = minus-zero by (rule is-zero-cases)
    then show ?thesis
      by cases (auto intro: zero)
  qed
qed

lemma infinite-infinity [simp]: ¬ is-finite plus-infinity ¬ is-finite minus-infinity
```

by (*auto simp*: *is-finite-def is-normal-def infinity-simps is-denormal-def is-zero-def*)

lemma *nan-not-finite* [*simp*]: *is-nan x* $\Longrightarrow$ $\neg$ *is-finite x*
using *float-distinct-finite*(*1*) **by** *blast*

lemma *valof-nonneg*:
valof x $\geq$ *0* **if** *sign x* = *0* **for** *x*::('*e*, '*f*)*float*
by (*auto simp*: *valof-eq that*)

lemma *valof-nonpos*:
valof x $\leq$ *0* **if** *sign x* = *1* **for** *x*::('*e*, '*f*)*float*
using *that*
by (*auto simp*: *valof-eq is-finite-def*)

lemma *real-le-intI*: *x* $\leq$ *y* **if** *floor x* $\leq$ *floor y x* $\in$ $\mathbb{Z}$ **for** *x y*::*real*
using *that*(*2*,*1*)
by (*induction rule*: *Ints-induct*) (*auto elim*!: *Ints-induct simp*: *le-floor-iff*)

lemma *real-of-int-le-2-powr-bitlenI*:
real-of-int x $\leq$ *2 powr n* $-$ *1* **if** *bitlen* (*abs x*) $\leq$ *m m* $\leq$ *n*
proof $-$
have *real-of-int x* $\leq$ *abs* (*real-of-int x*) **by** *simp*
also have ... $<$ *2 powr* (*bitlen* (*abs x*))
by (*rule abs-real-le-2-powr-bitlen*)
finally have *real-of-int x* $\leq$ *2 powr* (*bitlen* (*abs x*)) $-$ *1*
by (*auto simp*: *powr-real-of-int bitlen-nonneg intro*!: *real-le-intI*)
also have ... $\leq$ *2 powr m* $-$ *1*
by (*simp add*: *that*)
also have ... $\leq$ *2 powr n* $-$ *1*
by (*simp add*: *that*)
finally show *?thesis* **.**
qed

lemma *largest-eq*:
largest TYPE(('*e*, '*f*)*float*) =
(*2* $\hat{}$(*LENGTH*('*f*) + *1*) $-$ *1*) $*$ *2 powr real-of-int* (*2* $\hat{}$(*LENGTH*('*e*) $-$ *1*) $-$
int LENGTH('*f*) $-$ *1*)
proof $-$
have *2* $\hat{}$ *LENGTH*('*e*) $-$ *1* $-$ *1* = (*2*::*nat*) $\hat{}$ *LENGTH*('*e*) $-$ *2*
by *arith*
then have *largest TYPE*(('*e*, '*f*)*float*) =
(*2* $\hat{}$(*LENGTH*('*f*) + *1*) $-$ *1*) $*$
2 powr (*real* (*2* $\hat{}$ *LENGTH*('*e*) $-$ *2*) + *1* $-$ *real* (*2* $\hat{}$(*LENGTH*('*e*) $-$ *1*)) $-$
LENGTH('*f*))
by (*auto simp add*: *largest-def emax-eq bias-def powr-minus field-simps powr-diff*
powr-add of-nat-diff
mask-eq-exp-minus-1 simp flip: *powr-realpow*)
also
have *2* $\hat{}$ *LENGTH*('*e*) $\geq$ (*2*::*nat*)

```
    by (simp add: self-le-power)
  then have (real (2 ^ LENGTH('e) - 2) + 1 - real (2 ^ (LENGTH('e) - 1))
- LENGTH('f)) =
    (real (2 ^ LENGTH('e)) - 2 ^ (LENGTH('e) - 1) - LENGTH('f)) - 1
    by (auto simp add: of-nat-diff)
  also have real (2 ^ LENGTH('e)) = 2 ^ LENGTH('e) by auto
  also have (2 ^ LENGTH('e) - 2 ^ (LENGTH('e) - 1) - real LENGTH('f) -
1) =
    real-of-int ((2 ^ (LENGTH('e) - 1) - int (LENGTH('f)) - 1))
    by (simp, subst power-Suc[symmetric], simp)
  finally show ?thesis by simp
qed

lemma bitlen-denormal-mantissa:
  bitlen (abs (denormal-mantissa x)) ≤ LENGTH('f) for x::('e, 'f)float
proof -
  have fraction x < 2 ^ LENGTH('f)
    using float-frac-le[of x]
    by (metis One-nat-def Suc-pred le-imp-less-Suc pos2 zero-less-power)
  moreover have - int (fraction x) ≤ 2 ^ LENGTH('f)
    using negative-zle-0 order-trans zero-le-numeral zero-le-power by blast
  ultimately show ?thesis
    by (cases x rule: sign-cases)
      (auto simp: bitlen-le-iff-power denormal-mantissa-def intro!: antisym)
qed

lemma float-le-topfloat:
  fixes a::('e, 'f)float
  assumes is-finite a LENGTH('e) > 1
  shows a ≤ topfloat
  using assms(1)
proof (induction a rule: float-induct)
  case (normal x)
  note normal(2)
  also have real-of-int (normal-mantissa x) * 2 powr real-of-int (normal-exponent
x) ≤
    (2 powr (LENGTH('f) + 1) - 1) * 2 powr (2 ^ (LENGTH('e) - 1) - int
LENGTH('f) - 1)
    using normal-exponent-bounds-real(2)[OF ‹is-normal x›]
    by (auto intro!: mult-mono real-of-int-le-2-powr-bitlenI
        simp: bitlen-normal-mantissa powr-realpow[symmetric] ge-one-powr-ge-zero)
  also have ... = largest TYPE(('e, 'f) IEEE.float)
    unfolding largest-eq
    by (auto simp: powr-realpow powr-add)
  also have ... = valof (topfloat::('e, 'f) float)
    using assms
    by (simp add: valof-topfloat)
  finally show ?case
    by (intro float-leI normal finite-topfloat)
```

```
next
  case (denormal x)
  note denormal(2)
  also
  have 3 ≤ 2 powr (1 + real (LENGTH('e) − Suc 0))
  proof −
    have 3 ≤ 2 powr (2::real) by simp
    also have ... ≤ 2 powr (1 + real (LENGTH('e) − Suc 0))
      using assms
      by (subst powr-le-cancel-iff) auto
    finally show ?thesis .
  qed
 then have real-of-int (denormal-mantissa x) * 2 powr real-of-int (denormal-exponent
TYPE(('e, 'f)float)) ≤
    (2 powr (LENGTH('f) + 1) − 1) * 2 powr (2 ^ (LENGTH('e) − 1) − int
LENGTH('f) − 1)
    using bitlen-denormal-mantissa[of x]
    by (auto intro!: mult-mono real-of-int-le-2-powr-bitlenI
        simp: bitlen-normal-mantissa powr-realpow[symmetric] ge-one-powr-ge-zero
mask-eq-exp-minus-1
        denormal-exponent-def bias-def powr-mult-base of-nat-diff)
  also have ... ≤ largest TYPE(('e, 'f) IEEE.float)
    unfolding largest-eq
    by (rule mult-mono)
     (auto simp: powr-realpow powr-add power-Suc[symmetric] simp del: power-Suc)
  also have ... = valof (topfloat::('e, 'f) float)
    using assms
    by (simp add: valof-topfloat)
  finally show ?case
    by (intro float-leI denormal finite-topfloat)
qed auto

lemma float-val-le-largest:
  valof a ≤ largest TYPE(('e, 'f)float)
  if is-finite a LENGTH('e) > 1
  for a::('e, 'f)float
  by (metis that finite-topfloat float-le float-le-topfloat valof-topfloat)

lemma float-val-lt-threshold:
  valof a < threshold TYPE(('e, 'f)float)
  if is-finite a LENGTH('e) > 1
  for a::('e, 'f)float
proof −
  have valof a ≤ largest TYPE(('e, 'f)float)
    by (rule float-val-le-largest [OF that])
  also have ... < threshold TYPE(('e, 'f)float)
    by (auto simp: largest-def threshold-def divide-simps)
  finally show ?thesis .
qed
```

3.3 Algebraic properties about basic arithmetic

Commutativity of addition.

lemma
  assumes *is-finite a is-finite b*
  shows *float-plus-comm-eq*: $a + b = b + a$
    and *float-plus-comm*: *is-finite* $(a + b) \Longrightarrow (a + b) \doteq (b + a)$
proof −
  have ¬ *is-nan a* **and** ¬ *is-nan b* **and** ¬ *is-infinity a* **and** ¬ *is-infinity b*
    using *assms* **by** (*auto simp*: *finite-nan finite-infinity*)
  then show $a + b = b + a$
    by (*simp add*: *float-defs fadd-def plus-float-def add.commute*)
  then show *is-finite* $(a + b) \Longrightarrow (a + b) \doteq (b + a)$
    by (*metis float-eq*)
qed

The floating-point number a falls into the same category as the negation of a.

lemma *is-zero-uminus* [*simp*]: *is-zero* $(-\ a) \longleftrightarrow$ *is-zero a*
  by (*simp add*: *is-zero-def*)

lemma *is-infinity-uminus* [*simp*]: *is-infinity* $(-\ a) =$ *is-infinity a*
  by (*simp add*: *is-infinity-def*)

lemma *is-finite-uminus* [*simp*]: *is-finite* $(-\ a) \longleftrightarrow$ *is-finite a*
  by (*simp add*: *is-finite-def*)

lemma *is-nan-uminus* [*simp*]: *is-nan* $(-\ a) \longleftrightarrow$ *is-nan a*
  by (*simp add*: *is-nan-def*)

The sign of a and the sign of a's negation are different.

lemma *float-neg-sign*: *sign a* $\neq$ *sign* $(-\ a)$
  by (*cases a rule*: *sign-cases*) (*auto simp*: *sign-minus-float*)

lemma *float-neg-sign1*: *sign a* $=$ *sign* $(-\ b) \longleftrightarrow$ *sign a* $\neq$ *sign b*
  by (*metis float-neg-sign sign-cases*)

lemma *valof-uminus*:
  assumes *is-finite a*
  shows *valof* $(-\ a) = -$ *valof a*
  by (*cases a rule*: *sign-cases*) (*auto simp*: *valof-eq sign-minus-float*)

Showing $a + (-\ b) \doteq a - b$.

lemma *float-plus-minus*:
  assumes *is-finite a is-finite b is-finite* $(a - b)$
  shows $(a + -\ b) \doteq (a - b)$
proof −
  have *nab*: ¬ *is-nan a* ¬ *is-nan* $(-\ b)$ ¬ *is-infinity a* ¬ *is-infinity* $(-\ \ b)$

```
    using assms by (auto simp: finite-nan finite-infinity)
  have a − b = (zerosign
        (if is-zero a ∧ is-zero b ∧ sign a ≠ sign b then (sign a) else 0)
        (round RNE (valof a − valof b)))
    using nab
    by (auto simp: minus-float-def fsub-def)
  also have ... =
    (zerosign
        (if is-zero a ∧ is-zero (− b) ∧ sign a = sign (− b) then sign a else 0)
        (round RNE (valof a + valof (− b))))
    using assms
    by (simp add: float-neg-sign1 valof-uminus)
  also have ... = a + − b
    using nab by (auto simp: float-defs fadd-def plus-float-def)
  finally show ?thesis
    using assms by (metis float-eq)
qed

lemma finite-bottomfloat: is-finite bottomfloat
  by (simp add: finite-topfloat)

lemma bottomfloat-eq-m-largest: valof (bottomfloat::('e, 'f)float) = − largest TYPE(('e,
'f)float)
  if LENGTH('e) > 1
  using that
  by (auto simp: valof-topfloat valof-uminus finite-topfloat)

lemma float-val-ge-bottomfloat: valof a ≥ valof (bottomfloat::('e, 'f)float)
  if LENGTH('e) > 1 is-finite a
  for a::('e,'f)float
proof −
  have − a ≤ topfloat
    using that
    by (auto intro: float-le-topfloat)
  then show ?thesis
    using that
    by (auto simp: valof-uminus finite-topfloat)
qed

lemma float-ge-bottomfloat: is-finite a ⟹ a ≥ bottomfloat
  if LENGTH('e) > 1 is-finite a
  for a::('e,'f)float
  by (metis finite-bottomfloat float-le float-val-ge-bottomfloat that)

lemma float-val-ge-largest:
  fixes a::('e,'f)float
  assumes LENGTH('e) > 1 is-finite a
  shows valof a ≥ − largest TYPE(('e,'f)float)
proof −
```

have $-$ *largest TYPE*(('*e*,'*f*)*float*) = *valof* (*bottomfloat*::('*e*,'*f*)*float*)
using *assms*
by (*simp add*: *bottomfloat-eq-m-largest*)
also have ... $\leq$ *valof a*
using *assms* **by** (*simp add*: *float-val-ge-bottomfloat*)
finally show *?thesis* **.**
qed

lemma *float-val-gt-threshold*:
fixes *a*::('*e*,'*f*)*float*
assumes *LENGTH*('*e*) > *1 is-finite a*
shows *valof a* > $-$ *threshold TYPE*(('*e*,'*f*)*float*)
proof $-$
have *largest*: *valof a* $\geq$ $-$*largest TYPE*(('*e*,'*f*)*float*)
using *assms* **by** (*metis float-val-ge-largest*)
then have $-$*largest TYPE*(('*e*,'*f*)*float*) > $-$ *threshold TYPE*(('*e*,'*f*)*float*)
by (*auto simp*: *bias-def threshold-def largest-def divide-simps*)
then show *?thesis*
by (*metis largest less-le-trans*)
qed

Showing *abs* ($-$ *a*) = *abs a*.

lemma *float-abs* [*simp*]: $\neg$ *is-nan a* $\Longrightarrow$ *abs* ($-$ *a*) = *abs a*
by (*metis IEEE.abs-float-def float-neg-sign1 minus-minus-float zero-simps*(*1*))

lemma *neg-zerosign*: $-$ (*zerosign s a*) = *zerosign* (*1* $-$ *s*) ($-$ *a*)
by (*auto simp*: *zerosign-def*)

3.4 Properties about Rounding Errors

definition *error* :: ('*e*, '*f*)*float itself* $\Rightarrow$ *real* $\Rightarrow$ *real*
where *error* - *x* = *valof* (*round RNE x*::('*e*, '*f*)*float*) $-$ *x*

lemma *bound-at-worst-lemma*:
fixes *a*::('*e*, '*f*)*float*
assumes *threshold*: |*x*| < *threshold TYPE*(('*e*, '*f*)*float*)
assumes *finite*: *is-finite a*
shows |*valof* (*round RNE x*::('*e*, '*f*)*float*) $-$ *x*| $\leq$ |*valof a* $-$ *x*|
proof $-$
have $*$: (*round RNE x*::('*e*,'*f*)*float*) =
closest valof (λ*a*. *even* (*fraction a*)) {*a*. *is-finite a*} *x*
using *threshold finite*
by *auto*
have *is-closest* (*valof*) {*a*. *is-finite a*} *x* (*round RNE x*::('*e*,'*f*)*float*)
using *is-finite-nonempty*
unfolding $*$
by (*intro closest-is-closest*) *auto*
then show *?thesis*
using *finite is-closest-def* **by** (*metis mem-Collect-eq*)

qed

lemma *error-at-worst-lemma*:
fixes *a*::('*e*, '*f*)*float*
assumes *threshold*: |*x*| < *threshold TYPE*(('*e*, '*f*)*float*)
and *is-finite a*
shows |*error TYPE*(('*e*, '*f*)*float*) *x*| ≤ |*valof a* − *x*|
unfolding *error-def*
by (*rule bound-at-worst-lemma*; *fact*)

lemma *error-is-zero* [*simp*]:
fixes *a*::('*e*, '*f*)*float*
assumes *is-finite a* 1 < *LENGTH*('*e*)
shows *error TYPE*(('*e*, '*f*)*float*) (*valof a*) = *0*
proof −
have |*valof a*| < *threshold TYPE*(('*e*, '*f*)*float*)
by (*metis abs-less-iff minus-less-iff float-val-gt-threshold float-val-lt-threshold assms*)
then show *?thesis*
by (*metis abs-le-zero-iff abs-zero diff-self error-at-worst-lemma assms*(*1*))
qed

lemma *is-finite-zerosign* [*simp*]: *is-finite* (*zerosign s a*) ⟷ *is-finite a*
by (*auto simp*: *zerosign-def is-finite-def*)

lemma *is-finite-closest*: *is-finite* (*closest* (*v*::-⇒*real*) *p* {*a*. *is-finite a*} *x*)
using *closest-is-closest*[*OF is-finite-nonempty*, *of v x p*]
by (*auto simp*: *is-closest-def*)

lemma *defloat-float-zerosign-round-finite*:
assumes *threshold*: |*x*| < *threshold TYPE*(('*e*, '*f*)*float*)
shows *is-finite* (*zerosign s* (*round RNE x*::('*e*, '*f*)*float*))
proof −
have (*round RNE x*::('*e*, '*f*)*float*) =
(*closest valof* (λ*a*. *even* (*fraction a*)) {*a*. *is-finite a*} *x*)
using *threshold* **by** (*metis* (*full-types*) *abs-less-iff leD le-minus-iff round.simps*(*1*))
then have *is-finite* (*round RNE x*::('*e*, '*f*)*float*)
by (*metis is-finite-closest*)
then show *?thesis*
using *is-finite-zerosign* **by** *auto*
qed

lemma *valof-zero* [*simp*]: *valof 0* = *0 valof minus-zero* = *0*
by (*auto simp add*: *zerosign-def valof-eq zero-simps*)

lemma *signzero-zero*:
is-zero a ⟹ *valof* (*zerosign s a*) = *0*
by (*auto simp add*: *zerosign-def*)

lemma *val-zero*: *is-zero a* $\Longrightarrow$ *valof a = 0*
by (*cases a rule*: *is-zero-cases*) *auto*

lemma *float-add*:
fixes *a b*::(*'e*, *'f*)*float*
assumes *is-finite a*
and *is-finite b*
and *threshold*: |*valof a* + *valof b*| < *threshold TYPE*((*'e*, *'f*)*float*)
shows *finite-float-add*: *is-finite* (*a* + *b*)
and *error-float-add*: *valof* (*a* + *b*) = *valof a* + *valof b* + *error TYPE*((*'e*, *'f*)*float*) (*valof a* + *valof b*)
proof −
have ¬ *is-nan a* **and** ¬ *is-nan b* **and** ¬ *is-infinity a* **and** ¬ *is-infinity b*
using *assms float-distinct-finite* **by** *auto*
then have *ab*: (*a* + *b*) =
(*zerosign*
(*if is-zero a* ∧ *is-zero b* ∧ *sign a* = *sign b then* (*sign a*) *else 0*)
(*round RNE* (*valof a* + *valof b*)))
using *assms* **by** (*auto simp add*: *float-defs fadd-def plus-float-def*)
then show *is-finite* ((*a* + *b*))
by (*metis threshold defloat-float-zerosign-round-finite*)
have *val-ab*: *valof* (*a* + *b*) =
valof (*zerosign*
(*if is-zero a* ∧ *is-zero b* ∧ *sign a* = *sign b then* (*sign a*) *else 0*)
(*round RNE* (*valof a* + *valof b*)::(*'e*, *'f*)*float*))
by (*auto simp*: *ab is-infinity-def is-nan-def valof-def*)
show *valof* (*a* + *b*) = *valof a* + *valof b* + *error TYPE*((*'e*, *'f*)*float*) (*valof a* + *valof b*)
proof (*cases is-zero* (*round RNE* (*valof a* + *valof b*)::(*'e*, *'f*)*float*))
case *True*
have *valof a* + *valof b* + *error TYPE*((*'e*, *'f*)*float*) (*valof a* + *valof b*) =
valof (*round RNE* (*valof a* + *valof b*)::(*'e*, *'f*)*float*)
unfolding *error-def*
by *simp*
then show *?thesis*
by (*metis True signzero-zero val-zero val-ab*)
next
case *False*
then show *?thesis*
by (*metis ab add.commute eq-diff-eq' error-def zerosign-def*)
qed
qed

lemma *float-sub*:
fixes *a b*::(*'e*, *'f*)*float*
assumes *is-finite a*
and *is-finite b*
and *threshold*: |*valof a* − *valof b*| < *threshold TYPE*((*'e*, *'f*)*float*)
shows *finite-float-sub*: *is-finite* (*a* − *b*)

```
    and error-float-sub: valof (a − b) = valof a − valof b + error TYPE(('e, 'f)float) (valof a − valof b)
proof −
  have ¬ is-nan a and ¬ is-nan b and ¬ is-infinity a and ¬ is-infinity b
    using assms by (auto simp: finite-nan finite-infinity)
  then have ab: a − b =
    (zerosign
      (if is-zero a ∧ is-zero b ∧ sign a ≠ sign b then sign a else 0)
      (round RNE (valof a − valof b)))
    using assms by (auto simp add: float-defs fsub-def minus-float-def)
  then show is-finite (a − b)
   by (metis threshold defloat-float-zerosign-round-finite)
  have val-ab: valof (a − b) =
    valof (zerosign
      (if is-zero a ∧ is-zero b ∧ sign a ≠ sign b then sign a else 0)
      (round RNE (valof a − valof b)::('e, 'f)float))
    by (auto simp: ab is-infinity-def is-nan-def valof-def)
  show valof (a − b) = valof a − valof b + error TYPE(('e, 'f)float) (valof a − valof b)
  proof (cases is-zero (round RNE (valof a − valof b)::('e, 'f)float))
    case True
    have valof a − valof b + error TYPE(('e, 'f)float) (valof a − valof b) =
        valof (round RNE (valof a − valof b)::('e, 'f)float)
      unfolding error-def by simp
    then show ?thesis
      by (metis True signzero-zero val-zero val-ab)
  next
    case False
    then show ?thesis
      by (metis ab add.commute eq-diff-eq' error-def zerosign-def)
  qed
qed

lemma float-mul:
  fixes a b::('e, 'f)float
  assumes is-finite a
    and is-finite b
    and threshold: |valof a ∗ valof b| < threshold TYPE(('e, 'f)float)
  shows finite-float-mul: is-finite (a ∗ b)
   and error-float-mul: valof (a ∗ b) = valof a ∗ valof b + error TYPE(('e, 'f)float) (valof a ∗ valof b)
proof −
  have non: ¬ is-nan a ¬ is-nan b ¬ is-infinity a ¬ is-infinity b
    using assms float-distinct-finite by auto
  then have ab: a ∗ b =
    (zerosign (of-bool (sign a ≠ sign b))
      (round RNE (valof a ∗ valof b)::('e, 'f)float))
    using assms by (auto simp: float-defs fmul-def times-float-def)
  then show is-finite (a ∗ b)
```

```
    by (metis threshold defloat-float-zerosign-round-finite)
  have val-ab: valof (a * b) =
      valof (zerosign (of-bool (sign a ≠ sign b))
        (round RNE (valof a * valof b)::('e, 'f)float))
    by (auto simp: ab float-defs of-bool-def)
  show valof (a * b) = valof a * valof b + error TYPE(('e, 'f)float) (valof a *
valof b)
  proof (cases is-zero (round RNE (valof a * valof b)::('e, 'f)float))
    case True
    have valof a * valof b + error TYPE(('e, 'f)float) (valof a * valof b) =
        valof (round RNE (valof a * valof b)::('e, 'f)float)
      unfolding error-def
      by simp
    then show ?thesis
      by (metis True signzero-zero val-zero val-ab)
  next
    case False then show ?thesis
      by (metis ab add.commute eq-diff-eq' error-def zerosign-def)
  qed
qed

lemma float-div:
  fixes a b::('e, 'f)float
  assumes is-finite a
    and is-finite b
    and not-zero: ¬ is-zero b
    and threshold: |valof a / valof b| < threshold TYPE(('e, 'f)float)
  shows finite-float-div: is-finite (a / b)
   and error-float-div: valof (a / b) = valof a / valof b + error TYPE(('e, 'f)float)
(valof a / valof b)
proof −
  have ab: a / b =
    (zerosign (of-bool (sign a ≠ sign b))
      (round RNE (valof a / valof b)))
     using assms
    by (simp add: divide-float-def fdiv-def finite-infinity finite-nan not-zero float-defs
[symmetric])
  then show is-finite (a / b)
    by (metis threshold defloat-float-zerosign-round-finite)
  have val-ab: valof (a / b) =
      valof (zerosign (of-bool (sign a ≠ sign b))
        (round RNE (valof a / valof b))::('e, 'f)float)
    by (auto simp: ab float-defs of-bool-def)
  show valof (a / b) = valof a / valof b + error TYPE(('e, 'f)float) (valof a /
valof b)
  proof (cases is-zero (round RNE (valof a / valof b)::('e, 'f)float))
    case True
    have valof a / valof b + error TYPE(('e, 'f)float) (valof a / valof b) =
        valof (round RNE (valof a / valof b)::('e, 'f)float)
```

unfolding *error-def*
by *simp*
then show *?thesis*
by (*metis True signzero-zero val-zero val-ab*)
next
case *False* **then show** *?thesis*
by (*metis ab add.commute eq-diff-eq′ error-def zerosign-def*)
qed
qed

lemma *valof-one* [*simp*]: *valof* (*1* :: (*′e*, *′f*) *float*) = *of-bool* (*LENGTH*(*′e*) > *1*)
apply *transfer*
apply (*auto simp add*: *bias-def unat-mask-eq simp flip*: *mask-eq-exp-minus-1*)
apply (*simp add*: *mask-eq-exp-minus-1*)
done

end
theory *FP64*
imports
IEEE
Word-Lib.Word-64
begin

4 Concrete encodings

Floating point operations defined as operations on words. Called "fixed precision" (fp) word in HOL4.

type-synonym *float64* = (*11*,*52*)*float*
type-synonym *fp64* = *64 word*

lift-definition *fp64-of-float* :: *float64* ⇒ *fp64* **is**
λ(*s*::*1 word*, *e*::*11 word*, *f*::*52 word*). *word-cat s* (*word-cat e f*::*63 word*) .

lift-definition *float-of-fp64* :: *fp64* ⇒ *float64* **is**
λ*x*. *apsnd word-split* (*word-split x*::*1 word* ∗ *63 word*) .

definition *rel-fp64* ≡ (λ*x* (*y*::*word64*). *x* = *float-of-fp64 y*)

definition *eq-fp64*::*float64* ⇒ *float64* ⇒ *bool* **where** [*simp*]: *eq-fp64* ≡ (=)

lemma *float-of-fp64-inverse*[*simp*]: *fp64-of-float* (*float-of-fp64 a*) = *a*
by (*auto*
simp: *fp64-of-float-def float-of-fp64-def Abs-float-inverse apsnd-def map-prod-def word-size*
dest!: *word-cat-split-alt*[*rotated*]
split: *prod.splits*)

lemma *float-of-fp64-inj-iff*[*simp*]: *fp64-of-float r* = *fp64-of-float s* ⟷ *r* = *s*

using *Rep-float-inject*
by (*force simp*: *fp64-of-float-def word-cat-inj word-size split*: *prod.splits*)

lemma *fp64-of-float-inverse*[*simp*]: *float-of-fp64* (*fp64-of-float a*) = *a*
using *float-of-fp64-inj-iff float-of-fp64-inverse* **by** *blast*

lemma *Quotientfp*: *Quotient eq-fp64 fp64-of-float float-of-fp64 rel-fp64*
— *eq-fp64* is a workaround to prevent a (failing – TODO: why?) code setup in *setup-lifting*.
by (*force intro*!: *QuotientI simp*: *rel-fp64-def*)

setup-lifting *Quotientfp*

lift-definition *fp64-lessThan*::*fp64* ⇒ *fp64* ⇒ *bool* **is**
flt::*float64*⇒*float64*⇒*bool* **by** *simp*

lift-definition *fp64-lessEqual*::*fp64* ⇒ *fp64* ⇒ *bool* **is**
fle::*float64*⇒*float64*⇒*bool* **by** *simp*

lift-definition *fp64-greaterThan*::*fp64* ⇒ *fp64* ⇒ *bool* **is**
fgt::*float64*⇒*float64*⇒*bool* **by** *simp*

lift-definition *fp64-greaterEqual*::*fp64* ⇒ *fp64* ⇒ *bool* **is**
fge::*float64*⇒*float64*⇒*bool* **by** *simp*

lift-definition *fp64-equal*::*fp64* ⇒ *fp64* ⇒ *bool* **is**
feq::*float64*⇒*float64*⇒*bool* **by** *simp*

lift-definition *fp64-abs*::*fp64* ⇒ *fp64* **is**
abs::*float64*⇒*float64* **by** *simp*

lift-definition *fp64-negate*::*fp64* ⇒ *fp64* **is**
uminus::*float64*⇒*float64* **by** *simp*

lift-definition *fp64-sqrt*::*roundmode* ⇒ *fp64* ⇒ *fp64* **is**
fsqrt::*roundmode*⇒*float64*⇒*float64* **by** *simp*

lift-definition *fp64-add*::*roundmode* ⇒ *fp64* ⇒ *fp64* ⇒ *fp64* **is**
fadd::*roundmode*⇒*float64*⇒*float64*⇒*float64* **by** *simp*

lift-definition *fp64-sub*::*roundmode* ⇒ *fp64* ⇒ *fp64* ⇒ *fp64* **is**
fsub::*roundmode*⇒*float64*⇒*float64*⇒*float64* **by** *simp*

lift-definition *fp64-mul*::*roundmode* ⇒ *fp64* ⇒ *fp64* ⇒ *fp64* **is**
fmul::*roundmode*⇒*float64*⇒*float64*⇒*float64* **by** *simp*

lift-definition *fp64-div*::*roundmode* ⇒ *fp64* ⇒ *fp64* ⇒ *fp64* **is**
fdiv::*roundmode*⇒*float64*⇒*float64*⇒*float64* **by** *simp*

lift-definition *fp64-mul-add*::*roundmode* ⇒ *fp64* ⇒ *fp64* ⇒ *fp64* ⇒ *fp64* **is**
fmul-add::*roundmode*⇒*float64*⇒*float64*⇒*float64*⇒*float64* **by** *simp*

end

theory *Conversion-IEEE-Float*
imports
HOL−Library.Float
IEEE-Properties
HOL−Library.Code-Target-Numeral
begin

definition *of-finite* (*x*::('*e*, '*f*)*float*) =
(*if is-normal x then* (*Float* (*normal-mantissa x*) (*normal-exponent x*))
else if is-denormal x then (*Float* (*denormal-mantissa x*) (*denormal-exponent*
TYPE(('*e*, '*f*)*float*)))
else 0)

lemma *float-val-of-finite*: *is-finite x* ⟹ *of-finite x* = *valof x*
by (*induction x*) (*auto simp*: *normal-imp-not-denormal of-finite-def*)

definition *is-normal-Float*::('*e*, '*f*)*float itself* ⇒ *Float.float* ⇒ *bool* **where**
is-normal-Float x f ⟷
mantissa f ≠ *0* ∧
bitlen |*mantissa f*| ≤ *fracwidth x* + *1* ∧
− *int* (*bias x*) − *bitlen* |*mantissa f*| + *1* < *Float.exponent f* ∧
Float.exponent f < *2*^(*LENGTH*('*e*)) − *bitlen* |*mantissa f*| − *bias x*

definition *is-denormal-Float*::('*e*, '*f*)*float itself* ⇒ *Float.float* ⇒ *bool* **where**
is-denormal-Float x f ⟷
mantissa f ≠ *0* ∧
bitlen |*mantissa f*| ≤ *1* − *Float.exponent f* − *int* (*bias x*) ∧
1 − *2*^(*LENGTH*('*e*) − *1*) − *int LENGTH*('*f*) < *Float.exponent f*

lemmas *is-denormal-FloatD* =
is-denormal-Float-def[*THEN iffD1*, *THEN conjunct1*]
is-denormal-Float-def[*THEN iffD1*, *THEN conjunct2*]

definition *is-finite-Float*::('*e*, '*f*)*float itself* ⇒ *Float.float* ⇒ *bool* **where**
is-finite-Float x f ⟷ *is-normal-Float x f* ∨ *is-denormal-Float x f* ∨ *f* = *0*

lemma *is-finite-Float-eq*:
is-finite-Float TYPE(('*e*, '*f*)*float*) *f* ⟷
(*let e* = *Float.exponent f*; *bm* = *bitlen* (*abs* (*mantissa f*))
in bm ≤ *Suc LENGTH*('*f*) ∧
bm ≤ *2* ^ (*LENGTH*('*e*) − *1*) − *e* ∧
1 − *2* ^ (*LENGTH*('*e*) − *1*) − *int LENGTH*('*f*) < *e*)
proof −
have ∗: (*2*::*int*) ^ (*LENGTH*('*e*) − *Suc 0*) − *1* < *2* ^ *LENGTH*('*e*)

```
    by (metis Suc-1 diff-le-self lessI linorder-not-less one-less-numeral-iff
        power-strict-increasing-iff zle-diff1-eq)
  have **: 1 - 2 ^ (LENGTH('e) - Suc 0) < int LENGTH('f)
    by (smt (verit) len-gt-0 of-nat-0-less-iff zero-less-power)
  have ***: 2 ^ (LENGTH('e) - 1) + 1 =
    2 ^ LENGTH('e) - int (bias TYPE(('e, 'f) IEEE.float))
    by (simp add: bias-def power-Suc[symmetric] of-nat-diff mask-eq-exp-minus-1)
  have rewr: x ≤ 2 ^ n - e ⟷ x + e < 2 ^ n + 1 for x::int and n e
    by auto
  show ?thesis
    unfolding *** rewr
    using * **
    unfolding is-finite-Float-def is-normal-Float-def is-denormal-Float-def
   by (auto simp: Let-def bias-def mantissa-eq-zero-iff of-nat-diff mask-eq-exp-minus-1
        intro: le-less-trans[OF add-right-mono])
qed

lift-definition normal-of-Float :: Float.float ⇒ ('e, 'f)float
  is λx. let m = mantissa x; e = Float.exponent x in
    (if m > 0 then 0 else 1,
      word-of-int (e + int (bias TYPE(('e, 'f)float)) + bitlen |m| - 1),
     word-of-int (|m| * 2 ^ (Suc LENGTH('f) - nat (bitlen |m|)) - 2 ^ (LENGTH('f))))
  .

lemma sign-normal-of-Float:sign (normal-of-Float x) = (if x > 0 then 0 else 1)
  by transfer (auto simp: Let-def mantissa-pos-iff)

lemma uint-word-of-int-bitlen-eq:
  uint (word-of-int x::'a::len word) = x if bitlen x ≤ LENGTH('a) x ≥ 0
  using that by (simp add: bitlen-le-iff-power take-bit-int-eq-self unsigned-of-int)

lemma fraction-normal-of-Float:fraction (normal-of-Float x::('e, 'f)float) =
  (nat |mantissa x| * 2 ^ (Suc LENGTH('f) - nat (bitlen |mantissa x|)) - 2 ^
LENGTH('f))
  if is-normal-Float TYPE(('e, 'f)float) x
proof -
  from that have bmp: bitlen |mantissa x| > 0
   by (metis abs-of-nonneg bitlen-bounds bitlen-def is-normal-Float-def nat-code(2)
of-nat-0-le-iff
        power.simps(1) zabs-less-one-iff zero-less-abs-iff)
  have mless: |mantissa x| < 2 ^ nat (bitlen |mantissa x|)
    using bitlen-bounds by force
  have lem: 2 ^ nat (bitlen |mantissa x| - 1) ≤ |mantissa x|
    using bitlen-bounds is-normal-Float-def that zero-less-abs-iff by blast
  from that have nble: nat (bitlen |mantissa x|) ≤ Suc LENGTH('f)
    using bitlen-bounds by (auto simp: is-normal-Float-def)
  have nn: 0 ≤ |mantissa x| * 2 ^ (Suc LENGTH('f) - nat (bitlen |mantissa x|))
- 2 ^ LENGTH('f)
    apply (rule add-le-imp-le-diff)
```

```
    apply (rule order-trans[rotated])
     apply (rule mult-right-mono)
      apply (rule lem, force)
    unfolding power-add[symmetric]
    using nble bmp
    by (auto)
  have |mantissa x| * 2 ^(Suc LENGTH('f) - nat (bitlen |mantissa x|)) < 2 * 2
^ LENGTH('f)
    apply (rule less-le-trans)
     apply (rule mult-strict-right-mono)
      apply (rule mless)
     apply force
    unfolding power-add[symmetric] power-Suc[symmetric]
    apply (rule power-increasing)
    using nble
    by auto
  then have bitlen (|mantissa x| * 2 ^(Suc LENGTH('f) - nat (bitlen |mantissa
x|)) - 2 ^ LENGTH('f))
    ≤ int LENGTH('f)
    unfolding bitlen-le-iff-power
    by simp
  then show ?thesis
    apply (transfer fixing: x)
   unfolding Let-def split-beta' fst-conv snd-conv uint-nat [symmetric] nat-uint-eq
[symmetric]
    using nn
    apply (subst uint-word-of-int-bitlen-eq)
      apply (auto simp: nat-mult-distrib nat-diff-distrib nat-power-eq)
    done
qed

lemma exponent-normal-of-Float:exponent (normal-of-Float x::('e, 'f)float) =
  nat (Float.exponent x + (bias TYPE(('e, 'f)float)) + bitlen |mantissa x| - 1)
  if is-normal-Float TYPE(('e, 'f)float) x
  using that
  apply (transfer fixing: x)
  apply (simp flip: uint-nat nat-uint-eq add: Let-def)
 apply (auto simp: is-normal-Float-def bitlen-le-iff-power uint-word-of-int-bitlen-eq
Let-def)
  apply transfer
  apply (simp add: nat-take-bit-eq take-bit-int-eq-self)
  done

lift-definition denormal-of-Float :: Float.float ⇒ ('e, 'f)float
  is λx. let m = mantissa x; e = Float.exponent x in
  (if m ≥ 0 then 0 else 1, 0,
   word-of-int (|m| * 2 ^nat (e + bias TYPE(('e, 'f)float) + fracwidth TYPE(('e,
'f)float) - 1)))
  .
```

lemma *sign-denormal-of-Float*:*sign* (*denormal-of-Float x*) = (*if x* ≥ *0 then 0 else 1*)
by *transfer* (*auto simp*: *Let-def mantissa-nonneg-iff*)

lemma *exponent-denormal-of-Float*:*exponent* (*denormal-of-Float x*::('*e*, '*f*)*float*) = *0*
by (*transfer fixing*: *x*) (*auto simp*: *Let-def*)

lemma *fraction-denormal-of-Float*:*fraction* (*denormal-of-Float x*::('*e*, '*f*)*float*) =
(*nat* |*mantissa x*| ∗ *2* ^ *nat* (*Float.exponent x* + *bias TYPE*(('*e*, '*f*)*float*) + *LENGTH*('*f*) − *1*))
if *is-denormal-Float TYPE*(('*e*, '*f*)*float*) *x*
proof −
have *mless*: |*mantissa x*| < *2* ^ *nat* (*bitlen* |*mantissa x*|)
using *bitlen-bounds* **by** *force*
have ∗: *nat* (*bitlen* |*mantissa x*|) +
nat (*Float.exponent x* + (*2* ^ (*LENGTH*('*e*) − *Suc 0*) + *int LENGTH*('*f*)) − *2*)
≤ *LENGTH*('*f*)
using *that*
by (*auto simp*: *is-denormal-Float-def nat-diff-distrib' le-diff-conv mask-eq-exp-minus-1 bitlen-nonneg nat-le-iff bias-def nat-add-distrib*[*symmetric*] *of-nat-diff*)
have |*mantissa x*| ∗ *2* ^ *nat* (*Float.exponent x* + *int* (*bias TYPE*(('*e*, '*f*)*float*)) +
LENGTH('*f*) − *1*) < *2* ^ *LENGTH*('*f*)
apply (*rule less-le-trans*)
apply (*rule mult-strict-right-mono*)
apply (*rule mless*, *force*)
unfolding *power-add*[*symmetric*] *power-Suc*[*symmetric*]
apply (*rule power-increasing*)
apply (*auto simp*: *bias-def*)
using *that* ∗
by (*auto simp*: *is-denormal-Float-def algebra-simps of-nat-diff mask-eq-exp-minus-1*)
then show *?thesis*
apply (*transfer fixing*: *x*)
apply *transfer*
apply (*simp add*: *Let-def nat-eq-iff take-bit-eq-mod*)
done
qed

definition *of-finite-Float* :: *Float.float* ⇒ ('*e*, '*f*) *float* **where**
of-finite-Float x = (*if is-normal-Float TYPE*(('*e*, '*f*)*float*) *x then normal-of-Float x*
else if is-denormal-Float TYPE(('*e*, '*f*)*float*) *x then denormal-of-Float x*
else 0)

lemma *valof-normal-of-Float*: *valof* (*normal-of-Float x*::('*e*, '*f*)*float*) = *x*
if *is-normal-Float TYPE*(('*e*, '*f*)*float*) *x*

proof −
have *valof* (*normal-of-Float x*::(*'e*, *'f*)*float*) =
(− *1*) ^ *sign* (*normal-of-Float x*::(*'e*, *'f*)*float*) ∗
((*1* + *real* (*nat* |*mantissa x*| ∗ *2* ^ (*Suc LENGTH*(*'f*) − *nat* (*bitlen* |*mantissa x*|)) − *2* ^ *LENGTH*(*'f*)) / *2* ^ *LENGTH*(*'f*)) ∗
2 powr (*bitlen* |*mantissa x*| − *1*)) ∗
2 powr Float.exponent x
(**is** - = *?s* ∗ *?m* ∗ *?e*)
using *that*
by (*auto simp*: *is-normal-Float-def valof-eq fraction-normal-of-Float powr-realpow*[*symmetric*] *exponent-normal-of-Float powr-diff powr-add*)
also
have |*mantissa x*| > *0*
using *that*
by (*auto simp*: *is-normal-Float-def*)
have *bound*: *2* ^ *LENGTH*(*'f*) ≤ *nat* |*mantissa x*| ∗ *2* ^ (*Suc LENGTH*(*'f*) − *nat* (*bitlen* |*mantissa x*|))
proof −
have (*2*::*nat*) ^ *LENGTH*(*'f*) ≤ *2* ^ *nat* (*bitlen* |*mantissa x*| − *1*) ∗ *2* ^ (*Suc LENGTH*(*'f*) − *nat* (*bitlen* |*mantissa x*|))
by (*simp add*: *power-add*[*symmetric*])
also have ... ≤ *nat* |*mantissa x*| ∗ *2* ^ (*Suc LENGTH*(*'f*) − *nat* (*bitlen* |*mantissa x*|))
using *bitlen-bounds*[*of* |*mantissa x*|] *that*
by (*auto simp*: *is-normal-Float-def*)
finally show *?thesis* **.**
qed
have *?m* = *abs* (*mantissa x*)
apply (*subst of-nat-diff*)
subgoal using *bound* **by** *auto*
subgoal
using *that*
by (*auto simp*: *powr-realpow*[*symmetric*] *powr-add*[*symmetric*] *is-normal-Float-def bitlen-nonneg of-nat-diff divide-simps*)
done
finally show *?thesis*
by (*auto simp*: *mantissa-exponent sign-normal-of-Float abs-real-def zero-less-mult-iff*)
qed

lemma *valof-denormal-of-Float*: *valof* (*denormal-of-Float x*::(*'e*, *'f*)*float*) = *x*
if *is-denormal-Float TYPE*((*'e*, *'f*)*float*) *x*
proof −
have *less*: *0* < *Float.exponent x* + (*int* (*bias TYPE*((*'e*, *'f*) *IEEE.float*)) + *int LENGTH*(*'f*))
using *that*
by (*auto simp*: *is-denormal-Float-def bias-def of-nat-diff mask-eq-exp-minus-1*)
have *valof* (*denormal-of-Float x*::(*'e*, *'f*)*float*) =
((− *1*) ^ *sign* (*denormal-of-Float x*::(*'e*, *'f*)*float*) ∗ |*real-of-int* (*mantissa x*)|) ∗
(*2 powr real* (*nat* (*Float.exponent x* + *int* (*bias TYPE*((*'e*, *'f*) *IEEE.float*)) +

int LENGTH('f) − 1)) /
(2 powr real (bias TYPE(('e, 'f) IEEE.float)) ∗ 2 powr LENGTH('f)) ∗ 2)
(is - = ?m ∗ ?e)
by (*auto simp*: *valof-eq exponent-denormal-of-Float fraction-denormal-of-Float that*
mantissa-exponent powr-realpow[*symmetric*])
also have *?m = mantissa x*
by (*auto simp*: *sign-denormal-of-Float abs-real-def mantissa-neg-iff*)
also have *?e = 2 powr Float.exponent x*
by (*auto simp*: *powr-add*[*symmetric*] *divide-simps powr-mult-base less ac-simps*)
finally show *?thesis* **by** (*simp add*: *mantissa-exponent*)
qed

lemma *valof-of-finite-Float*:
is-finite-Float (TYPE(('e, 'f) IEEE.float)) x ⟹ valof (of-finite-Float x::('e, 'f)float) = x
by (*auto simp*: *of-finite-Float-def is-finite-Float-def valof-denormal-of-Float valof-normal-of-Float*)

lemma *is-normal-normal-of-Float*:
is-normal (normal-of-Float x::('e, 'f)float) **if** *is-normal-Float TYPE(('e, 'f)float) x*
using *that*
by (*auto simp*: *is-normal-def exponent-normal-of-Float that is-normal-Float-def*
emax-eq nat-less-iff of-nat-diff)

lemma *is-denormal-denormal-of-Float*: *is-denormal (denormal-of-Float x::('e, 'f)float)*
if *is-denormal-Float TYPE(('e, 'f)float) x*
using *that*
by (*auto simp*: *is-denormal-def exponent-denormal-of-Float that is-denormal-Float-def*
emax-eq fraction-denormal-of-Float le-nat-iff bias-def)

lemma *is-finite-of-finite-Float*: *is-finite (of-finite-Float x)*
by (*auto simp*: *is-finite-def of-finite-Float-def is-normal-normal-of-Float*
is-denormal-denormal-of-Float)

lemma *Float-eq-zero-iff*: *Float m e = 0 ⟷ m = 0*
by (*metis Float.compute-is-float-zero Float-0-eq-0*)

lemma *bitlen-mantissa-Float*:
shows *bitlen |mantissa (Float m e)| = (if m = 0 then 0 else bitlen |m| + e) − Float.exponent (Float m e)*
using *bitlen-Float*[*of m e*] **by** *auto*

lemma *exponent-Float*:
shows *Float.exponent (Float m e) = (if m = 0 then 0 else bitlen |m| + e) − bitlen |mantissa (Float m e)|*
using *bitlen-Float*[*of m e*] **by** *auto*

lemma *is-normal-Float-normal*:

```
  is-normal-Float TYPE(('e, 'f)float) (Float (normal-mantissa x) (normal-exponent
x))
  if is-normal x for x::('e, 'f)float
proof −
  define f where f = Float (normal-mantissa x) (normal-exponent x)
  from that have f ≠ 0
    by (auto simp: f-def is-normal-def zero-float-def[symmetric]
        Float-eq-zero-iff normal-mantissa-def add-nonneg-eq-0-iff)
  from denormalize-shift[OF f-def this] obtain i where
    i: normal-mantissa x = mantissa f * 2 ^ i normal-exponent x = Float.exponent
f − int i
    by auto
  have mantissa f ≠ 0
    by (auto simp: ‹f ≠ 0› i mantissa-eq-zero-iff Float-eq-zero-iff)
  moreover
  have normal-exponent x ≤ Float.exponent f unfolding i by simp
  then have  bitlen |mantissa f| ≤ 1 + int LENGTH('f)
    unfolding bitlen-mantissa-Float bitlen-normal-mantissa f-def
    by auto
  moreover
 have − int (bias TYPE(('e, 'f)float)) − bitlen |mantissa f| + 1 < Float.exponent
f
    unfolding bitlen-mantissa-Float bitlen-normal-mantissa f-def
    using that
    by (auto simp: mantissa-eq-zero-iff abs-mult bias-def normal-mantissa-def nor-
mal-exponent-def
        is-normal-def emax-eq less-diff-conv add-nonneg-eq-0-iff)
  moreover
  have 2 ^(LENGTH('e) − Suc 0) + − (1::int) * 2 ^ LENGTH('e) ≤ 0
    by simp
  then have (2::int) ^(LENGTH('e) − Suc 0) < 1 + 2 ^ LENGTH('e) by arith
  then have Float.exponent f <
      2 ^ LENGTH('e) − bitlen |mantissa f| − int (bias TYPE(('e, 'f)float))
    using normal-exponent-bounds-int[OF that]
    unfolding bitlen-mantissa-Float bitlen-normal-mantissa f-def
   by (auto simp: bias-def algebra-simps power-Suc[symmetric] of-nat-diff mask-eq-exp-minus-1
      intro: le-less-trans[OF add-right-mono] normal-exponent-bounds-int[OF that])
  ultimately
  show ?thesis
    by (auto simp: is-normal-Float-def f-def)
qed


lemma is-denormal-Float-denormal:
  is-denormal-Float TYPE(('e, 'f)float)
    (Float (denormal-mantissa x) (denormal-exponent TYPE(('e, 'f)float)))
  if is-denormal x for x::('e, 'f)float
proof −
 define f where f = Float (denormal-mantissa x) (denormal-exponent TYPE(('e,
```

'f)float))
  from *that* **have** *f* ≠ *0*
    by (*auto simp*: *f-def is-denormal-def zero-float-def*[*symmetric*]
        Float-eq-zero-iff denormal-mantissa-def add-nonneg-eq-0-iff)
  from *denormalize-shift*[*OF f-def this*] **obtain** *i* **where**
     i: *denormal-mantissa x* = *mantissa f* ∗ *2* ^ *i denormal-exponent TYPE*(('*e*,
'*f*)*float*) = *Float.exponent f* − *int i*
    by *auto*
  have *mantissa f* ≠ *0*
    by (*auto simp*: ‹*f* ≠ *0*› *i mantissa-eq-zero-iff Float-eq-zero-iff*)
  moreover
   have *bitlen* |*mantissa f*| ≤ *1* − *Float.exponent f* − *int* (*bias TYPE*(('*e*, '*f*)
IEEE.float))
    using ‹*mantissa f* ≠ *0*›
    unfolding *f-def bitlen-mantissa-Float*
    using *bitlen-denormal-mantissa*[*of x*]
    by (*auto simp*: *denormal-exponent-def*)
  moreover
  have *2* − *2* ^ (*LENGTH*('*e*) − *Suc 0*) − *int LENGTH*('*f*) ≤ *Float.exponent f*
    (**is** *?l* ≤ -)
  proof −
    have *?l* ≤ *denormal-exponent TYPE*(('*e*, '*f*)*float*) + *i*
      using *that*
        by (*auto simp*: *is-denormal-def bias-def denormal-exponent-def of-nat-diff*
mask-eq-exp-minus-1)
    also have ... = *Float.exponent f* **unfolding** *i* **by** *auto*
    finally show *?thesis* **.**
  qed
  ultimately
  show *?thesis*
    unfolding *is-denormal-Float-def exponent-Float f-def*[*symmetric*]
    by *auto*
qed

lemma *is-finite-Float-of-finite*: *is-finite-Float TYPE*(('*e*, '*f*)*float*) (*of-finite x*) **for**
x::('*e*, '*f*)*float*
  by (*auto simp*: *is-finite-Float-def of-finite-def is-normal-Float-normal*
      is-denormal-Float-denormal)

end

5 Code Generation Setup for Floats

theory *Double*
  imports
    Conversion-IEEE-Float
    HOL−*Library.Monad-Syntax*
    HOL−*Library.Code-Target-Numeral*
begin

A type for code generation to SML/OCaml

typedef *double* = *UNIV*::(*11*, *52*) *float set* **..**

setup-lifting *type-definition-double*

instantiation *double* :: {*uminus*,*plus*,*times*,*minus*,*zero*,*one*,*abs*,*ord*,*inverse*} **begin**
lift-definition *uminus-double*::*double* ⇒ *double* **is** *uminus* **.**
lift-definition *plus-double*::*double* ⇒ *double* ⇒ *double* **is** *plus* **.**
lift-definition *times-double*::*double* ⇒ *double* ⇒ *double* **is** *times* **.**
lift-definition *divide-double*::*double* ⇒ *double* ⇒ *double* **is** *divide* **.**
lift-definition *inverse-double*::*double* ⇒ *double* **is** *inverse* **.**
lift-definition *minus-double*::*double* ⇒ *double* ⇒ *double* **is** *minus* **.**
lift-definition *zero-double*::*double* **is** *0* **.**
lift-definition *one-double*::*double* **is** *1* **.**
lift-definition *less-eq-double*::*double* ⇒ *double* ⇒ *bool* **is** (≤) **.**
lift-definition *less-double*::*double* ⇒ *double* ⇒ *bool* **is** (<) **.**
instance proof qed
end

lift-definition *eq-double*::*double*⇒*double*⇒*bool* **is** *float-eq* **.**

lift-definition *sqrt-double*::*double*⇒*double* **is** *float-sqrt* **.**

no-notation *plus-infinity* (‹∞›)

lift-definition *infinity-double*::*double* (‹∞›) **is** *plus-infinity* **.**

lift-definition *is-normal*::*double* ⇒ *bool* **is** *IEEE.is-normal* **.**
lift-definition *is-zero*::*double* ⇒ *bool* **is** *IEEE.is-zero* **.**
lift-definition *is-finite*::*double* ⇒ *bool* **is** *IEEE.is-finite* **.**
lift-definition *is-nan*::*double* ⇒ *bool* **is** *IEEE.is-nan* **.**

code-printing type-constructor *double* ⇀
(*SML*) *real* **and** (*OCaml*) *float*

code-printing constant *0* :: *double* ⇀
(*SML*) *0.0* **and** (*OCaml*) *0.0*
declare *zero-double.abs-eq*[*code del*]

code-printing constant *1* :: *double* ⇀
(*SML*) *1.0* **and** (*OCaml*) *1.0*
declare *one-double.abs-eq*[*code del*]

code-printing constant *eq-double* :: *double* ⇒ *double* ⇒ *bool* ⇀
(*SML*) *Real.*== ((-:*real*), (-)) **and** (*OCaml*) *Pervasives.*(=)
declare *eq-double.abs-eq*[*code del*]

code-printing constant *Orderings.less-eq* :: *double* ⇒ *double* ⇒ *bool* ⇀
(*SML*) *Real.*<= ((-), (-)) **and** (*OCaml*) *Pervasives.*(<=)

declare *less-double-def* [*code del*]

code-printing constant *Orderings.less* :: *double* ⇒ *double* ⇒ *bool* ⇀
(*SML*) *Real.<* ((-), (-)) **and** (*OCaml*) *Pervasives.*(<)
declare *less-eq-double-def*[*code del*]

code-printing constant (+) :: *double* ⇒ *double* ⇒ *double* ⇀
(*SML*) *Real.+* ((-), (-)) **and** (*OCaml*) *Pervasives.*(+.)
declare *plus-double-def*[*code del*]

code-printing constant (∗) :: *double* ⇒ *double* ⇒ *double* ⇀
(*SML*) *Real.∗* ((-), (-)) **and** (*OCaml*) *Pervasives.*(∗.)
declare *times-double-def* [*code del*]

code-printing constant (−) :: *double* ⇒ *double* ⇒ *double* ⇀
(*SML*) *Real.−* ((-), (-)) **and** (*OCaml*) *Pervasives.*(−.)
declare *minus-double-def* [*code del*]

code-printing constant *uminus* :: *double* ⇒ *double* ⇀
(*SML*) *Real.~* **and** (*OCaml*) *Pervasives.*(~−.)

code-printing constant (/) :: *double* ⇒ *double* ⇒ *double* ⇀
(*SML*) *Real.'/* ((-), (-)) **and** (*OCaml*) *Pervasives.*('/.)
declare *divide-double-def* [*code del*]

code-printing constant *sqrt-double* :: *double* ⇒ *double* ⇀
(*SML*) *Math.sqrt* **and** (*OCaml*) *Pervasives.sqrt*
declare *sqrt-def*[*code del*]

code-printing constant *infinity-double* :: *double* ⇀
(*SML*) *Real.posInf*
declare *infinity-double.abs-eq*[*code del*]

code-printing constant *is-normal* :: *double* ⇒ *bool* ⇀
(*SML*) *Real.isNormal*
declare [[*code drop*: *is-normal*]]

code-printing constant *is-finite* :: *double* ⇒ *bool* ⇀
(*SML*) *Real.isFinite*
declare [[*code drop*: *is-finite*]]

code-printing constant *is-nan* :: *double* ⇒ *bool* ⇀
(*SML*) *Real.isNan*
declare [[*code drop*: *is-nan*]]

Mapping natural numbers to doubles.

fun *float-of* :: *nat* ⇒ *double*
where
float-of 0 = *0*

| *float-of* (*Suc n*) = *float-of n* + *1*

lemma *float-of 2* < *float-of 3* + *float-of 4*
by *eval*

export-code *float-of* **in** *SML*

5.1 Conversion from int

lift-definition *double-of-int*::*int* ⇒ *double* **is** λ*i*. *round RNE* (*real-of-int i*) **.**

context includes *integer.lifting* **begin**
lift-definition *double-of-integer*::*integer* ⇒ *double* **is** *double-of-int* **.**
end

lemma *float-of-int*[*code*]:
double-of-int i = *double-of-integer* (*integer-of-int i*)
by (*auto simp*: *double-of-integer-def*)

code-printing
constant *double-of-integer* :: *integer* ⇒ *double* ⇀ (*SML*) *Real.fromLargeInt*
declare [[*code drop*: *double-of-integer*]]

5.2 Conversion to and from software floats, extracting information

Need to trust a lot of code here...

lemma *is-finite-double-eq*:
is-finite-Float TYPE((*11*, *52*)*float*) *f* ⟷
(*let e* = *Float.exponent f*; *bm* = *bitlen* (*abs* (*mantissa f*))
in (*bm* ≤ *53* ∧ *e* + *bm* < *1025* ∧ − *1075* < *e*))
unfolding *is-finite-Float-eq*
by (*auto simp*: *Let-def*)

code-printing
code-module *IEEE-Mantissa-Exponent* ⇀ (*SML*)
‹
structure IEEE-Mantissa-Exponent =
struct
fun to-man-exp-double x =
if Real.isFinite x
then case Real.toManExp x of {*man* = *m*, *exp* = *e*} =>
SOME (*Real.floor* (*Real.*∗ (*m*, *Math.pow* (*2.0*, *53.0*))), *IntInf.*− (*e*, *53*))
else NONE
fun normfloat (*m*, *e*) =
(*if m mod 2* = *0 andalso m* <> *0 then normfloat* (*m div 2*, *e* + *1*)
else if m = *0 then* (*0*, *0*) *else* (*m*, *e*))
fun bitlen x = (*if 0* < *x then bitlen* (*x div 2*) + *1 else 0*)
fun is-finite-double-eq m e =

```
  let
    val (m, e) = normfloat (m, e)
    val bm = bitlen (abs m)
  in bm <= 53 andalso e + bm < 1025 andalso e > ~1075 end
fun from-man-exp-double m e =
  if is-finite-double-eq m e
  then SOME (Real.fromManExp {man = Real.fromLargeInt m, exp = e})
  else NONE
end
›

lift-definition of-finite::double ⇒ Float.float is Conversion-IEEE-Float.of-finite .

definition man-exp-of-double::double ⇒ (integer * integer)option where
  man-exp-of-double d = (if is-finite d then let f = of-finite d in
    Some (integer-of-int (mantissa f), integer-of-int (Float.exponent f)) else None)

lift-definition of-finite-Float::Float.float ⇒ double is Conversion-IEEE-Float.of-finite-Float
.

definition double-of-man-exp::integer ⇒ integer ⇒ double option where
  double-of-man-exp m e = (let f = Float (int-of-integer m) (int-of-integer e) in
    if is-finite-Float TYPE((11, 52)float) f
    then Some (of-finite-Float f)
    else None)

code-printing
  constant man-exp-of-double :: double ⇒ (integer * integer) option ⇀
    (SML) IEEE'-Mantissa'-Exponent.to'-man'-exp'-double |
  constant double-of-man-exp :: integer ⇒ integer ⇒ double option ⇀
    (SML) IEEE'-Mantissa'-Exponent.from'-man'-exp'-double
declare [[code drop: man-exp-of-double]]
declare [[code drop: double-of-man-exp]]

lift-definition Float-of-double::double ⇒ Float.float option is
  λx. if is-finite x then Some (of-finite x) else None .

lift-definition double-of-Float::Float.float ⇒ double option is
  λx. if is-finite-Float TYPE((11, 52)float) x then Some (of-finite-Float x) else
None .

lemma compute-Float-of-double[code]:
  Float-of-double x =
   map-option (λ(m, e). Float (int-of-integer m) (int-of-integer e)) (man-exp-of-double
x)
  apply (rule sym)
 by transfer (auto simp: man-exp-of-double-def Let-def mantissa-exponent[symmetric]
      Float-mantissa-exponent)
```

lemma *compute-double-of-Float*[*code*]:
double-of-Float f = *double-of-man-exp* (*integer-of-int* (*mantissa f*)) (*integer-of-int* (*Float.exponent f*))
unfolding *double-of-man-exp-def Let-def Float-mantissa-exponent int-of-integer-integer-of-int*
apply *auto*
subgoal by *transfer auto*
subgoal by *transfer auto*
done

definition *check-conversion m e* =
(*let f* = *Float* (*int-of-integer m*) (*int-of-integer e*) *in*
do {
d ← *double-of-Float f*;
Float-of-double d
} = (*if is-finite-Float TYPE*((*11*, *52*)*float*) *f then Some f else None*))

primrec *check-all*::*nat* ⇒ (*nat* ⇒ *bool*) ⇒ *bool* **where**
check-all 0 P ⟷ *True*
| *check-all* (*Suc i*) *P* ⟷ *P i* ∧ *check-all i P*

definition *check-conversions dm de* =
check-all (*nat* (*2* ∗ *de*)) (λ*e*. *check-all* (*nat* (*2* ∗ *dm*)) (λ*m*.
check-conversion (*integer-of-int* (*int m* − *dm*)) (*integer-of-int* (*int e* − *de*))))

lemma *check-conversions 100 100*
by *eval*

end

6 Specification of the IEEE standard with a single NaN value

theory *IEEE-Single-NaN*
imports
IEEE-Properties
begin

This theory defines a type of floating-point numbers that contains a single NaN value, much like specification level 2 of IEEE-754 (which does not distinguish between a quiet and a signaling NaN, nor between different bit representations of NaN).

In contrast, the type (′*e*, ′*f*) *IEEE.float* defined in `IEEE.thy` may contain several distinct (bit) representations of NaN, much like specification level 4 of IEEE-754.

One aim of this theory is to define a floating-point type (along with arithmetic operations) whose semantics agrees with the semantics of the SMT-LIB floating-point theory at https://smtlib.cs.uiowa.edu/theories-FloatingPoint.

shtml. The following development therefore deviates from `IEEE.thy` in some places to ensure alignment with the SMT-LIB theory.

Note that we are using HOL equality (rather than IEEE-754 floating-point equality) in the following definition. This is because we do not want to identify $+0$ and -0.

definition *is-nan-equivalent* :: (*'e*, *'f*) *float* ⇒ (*'e*, *'f*) *float* ⇒ *bool*
  where *is-nan-equivalent a b* ≡ *a* = *b* ∨ (*is-nan a* ∧ *is-nan b*)

quotient-type (**overloaded**) (*'e*, *'f*) *floatSingleNaN* = (*'e*, *'f*) *float* / *is-nan-equivalent*
  by (*metis equivpI is-nan-equivalent-def reflpI sympI transpI*)

Note that (*'e*, *'f*) *floatSingleNaN* does not count the hidden bit in the significand. For instance, IEEE-754's double-precision binary floating point format `binary64` corresponds to (*11*, *52*) *floatSingleNaN*. The corresponding SMT-LIB sort is `(_ FloatingPoint 11 53)`, where the hidden bit is counted. Since the bit size is encoded as a type argument, and Isabelle/HOL does not permit arithmetic on type expressions, it would be difficult to resolve this difference without completely separating the definition of (*'e*, *'f*) *floatSingleNaN* in this theory from the definition of (*'e*, *'f*) *IEEE.float* in IEEE.thy.

syntax *-floatSingleNaN* :: *type* ⇒ *type* ⇒ *type* (‹*'*(-, -*'*) *floatSingleNaN*›)
syntax-types *-floatSingleNaN* ⇌ *floatSingleNaN*

Parse (*'a*, *'b*) *floatSingleNaN* as (*'a*::*len*, *'b*::*len*) *floatSingleNaN*.

parse-translation ‹
```
let
  fun float t u = Syntax.const @{type-syntax floatSingleNaN} $ t $ u;
  fun len-tr u =
    (case Term-Position.strip-positions u of
      v as Free (x, -) =>
        if Lexicon.is-tid x then
          (Syntax.const @{syntax-const -ofsort} $ v $
            Syntax.const @{class-syntax len})
        else u
    | - => u)
  fun len-float-tr [t, u] =
    float (len-tr t) (len-tr u)
in
  [(@{syntax-const -floatSingleNaN}, K len-float-tr)]
end
```
›

6.1 Value constructors

6.1.1 FP literals as bit string triples, with the leading bit for the significand not represented (hidden bit)

lift-definition *fp* :: *1 word* ⇒ *'e word* ⇒ *'f word* ⇒ (*'e*, *'f*) *floatSingleNaN*
is *λs e f. IEEE.Abs-float* (*s*, *e*, *f*) **.**

6.1.2 Plus and minus infinity

lift-definition *plus-infinity* :: (*'e*, *'f*) *floatSingleNaN* (‹∞›) **is** *IEEE.plus-infinity*
.

lift-definition *minus-infinity* :: (*'e*, *'f*) *floatSingleNaN* **is** *IEEE.minus-infinity* **.**

6.1.3 Plus and minus zero

instantiation *floatSingleNaN* :: (*len*, *len*) *zero* **begin**

lift-definition *zero-floatSingleNaN* :: (*'a*, *'b*) *floatSingleNaN* **is** *0* **.**

instance ..

end

lift-definition *minus-zero* :: (*'e*, *'f*) *floatSingleNaN* **is** *IEEE.minus-zero* **.**

6.1.4 Non-numbers (NaN)

lift-definition *NaN* :: (*'e*, *'f*) *floatSingleNaN* **is** *some-nan* **.**

6.2 Operators

6.2.1 Absolute value

setup ‹*Sign.mandatory-path abs-floatSingleNaN-inst*› — workaround to avoid a duplicate fact declaration `abs_floatSingleNaN_def` in lift_definition below

instantiation *floatSingleNaN* :: (*len*, *len*) *abs*
begin

lift-definition *abs-floatSingleNaN* :: (*'a*, *'b*) *floatSingleNaN* ⇒ (*'a*, *'b*) *floatSingleNaN* **is** *abs*
unfolding *is-nan-equivalent-def* **by** (*metis IEEE.abs-float-def is-nan-uminus*)

instance ..

end

setup ‹*Sign.parent-path*›

6.2.2 Negation (no rounding needed)

instantiation *floatSingleNaN* :: (*len*, *len*) *uminus*
begin

lift-definition *uminus-floatSingleNaN* :: ('*a*, '*b*) *floatSingleNaN* ⇒ ('*a*, '*b*) *floatSingleNaN* **is** *uminus*
unfolding *is-nan-equivalent-def* **by** (*metis is-nan-uminus*)

instance ..

end

6.2.3 Addition

lift-definition *fadd* :: *roundmode* ⇒ ('*e* ,'*f*) *floatSingleNaN* ⇒ ('*e* ,'*f*) *floatSingleNaN* ⇒ ('*e* ,'*f*) *floatSingleNaN* **is** *IEEE.fadd*
unfolding *is-nan-equivalent-def* **by** (*metis IEEE.fadd-def*)

6.2.4 Subtraction

lift-definition *fsub* :: *roundmode* ⇒ ('*e* ,'*f*) *floatSingleNaN* ⇒ ('*e* ,'*f*) *floatSingleNaN* ⇒ ('*e* ,'*f*) *floatSingleNaN* **is** *IEEE.fsub*
unfolding *is-nan-equivalent-def* **by** (*metis IEEE.fsub-def*)

6.2.5 Multiplication

lift-definition *fmul* :: *roundmode* ⇒ ('*e* ,'*f*) *floatSingleNaN* ⇒ ('*e* ,'*f*) *floatSingleNaN* ⇒ ('*e* ,'*f*) *floatSingleNaN* **is** *IEEE.fmul*
unfolding *is-nan-equivalent-def* **by** (*metis IEEE.fmul-def*)

6.2.6 Division

lift-definition *fdiv* :: *roundmode* ⇒ ('*e* ,'*f*) *floatSingleNaN* ⇒ ('*e* ,'*f*) *floatSingleNaN* ⇒ ('*e* ,'*f*) *floatSingleNaN* **is** *IEEE.fdiv*
unfolding *is-nan-equivalent-def* **by** (*metis IEEE.fdiv-def*)

6.2.7 Fused multiplication and addition; $(x \cdot y) + z$

lift-definition *fmul-add* :: *roundmode* ⇒ ('*e* ,'*f*) *floatSingleNaN* ⇒ ('*e* ,'*f*) *floatSingleNaN* ⇒ ('*e* ,'*f*) *floatSingleNaN* ⇒ ('*e* ,'*f*) *floatSingleNaN* **is** *IEEE.fmul-add*
unfolding *is-nan-equivalent-def* **by** (*smt* (*verit*) *IEEE.fmul-add-def*)

6.2.8 Square root

lift-definition *fsqrt* :: *roundmode* ⇒ ('*e* ,'*f*) *floatSingleNaN* ⇒ ('*e* ,'*f*) *floatSingleNaN* **is** *IEEE.fsqrt*
unfolding *is-nan-equivalent-def* **by** (*metis IEEE.fsqrt-def*)

6.2.9 Remainder: $x - y \cdot n$, where $n \in \mathrm{Z}$ is nearest to x/y

lift-definition *frem* :: *roundmode* ⇒ ('*e* ,'*f*) *floatSingleNaN* ⇒ ('*e* ,'*f*) *floatSingleNaN* ⇒ ('*e* ,'*f*) *floatSingleNaN* **is** *IEEE.frem*
unfolding *is-nan-equivalent-def* **by** (*metis IEEE.frem-def*)

lift-definition *float-rem* :: ('*e* ,'*f*) *floatSingleNaN* ⇒ ('*e* ,'*f*) *floatSingleNaN* ⇒ ('*e* ,'*f*) *floatSingleNaN* **is** *IEEE.float-rem*
unfolding *is-nan-equivalent-def* **by** (*metis IEEE.frem-def IEEE.float-rem-def*)

6.2.10 Rounding to integral

lift-definition *fintrnd* :: *roundmode* ⇒ ('*e* ,'*f*) *floatSingleNaN* ⇒ ('*e* ,'*f*) *floatSingleNaN* **is** *IEEE.fintrnd*
unfolding *is-nan-equivalent-def* **by** (*metis IEEE.fintrnd-def*)

6.2.11 Minimum and maximum

In IEEE 754-2019, the minNum and maxNum operations of the 2008 version of the standard have been replaced by minimum, minimumNumber, maximum, maximumNumber (see Section 9.6 of the 2019 standard). These are not (yet) available in SMT-LIB. We currently do not implement any of these operations.

6.2.12 Comparison operators

lift-definition *fle* :: ('*e* ,'*f*) *floatSingleNaN* ⇒ ('*e* ,'*f*) *floatSingleNaN* ⇒ *bool* **is** *IEEE.fle*
unfolding *is-nan-equivalent-def* **by** (*smt* (*verit*) *IEEE.fcompare-def IEEE.fle-def*)

lift-definition *flt* :: ('*e* ,'*f*) *floatSingleNaN* ⇒ ('*e* ,'*f*) *floatSingleNaN* ⇒ *bool* **is** *IEEE.flt*
unfolding *is-nan-equivalent-def* **by** (*smt* (*verit*) *IEEE.fcompare-def IEEE.flt-def*)

lift-definition *fge* :: ('*e* ,'*f*) *floatSingleNaN* ⇒ ('*e* ,'*f*) *floatSingleNaN* ⇒ *bool* **is** *IEEE.fge*
unfolding *is-nan-equivalent-def* **by** (*smt* (*verit*) *IEEE.fcompare-def IEEE.fge-def*)

lift-definition *fgt* :: ('*e* ,'*f*) *floatSingleNaN* ⇒ ('*e* ,'*f*) *floatSingleNaN* ⇒ *bool* **is** *IEEE.fgt*
unfolding *is-nan-equivalent-def* **by** (*smt* (*verit*) *IEEE.fcompare-def IEEE.fgt-def*)

6.2.13 IEEE 754 equality

lift-definition *feq* :: ('*e* ,'*f*) *floatSingleNaN* ⇒ ('*e* ,'*f*) *floatSingleNaN* ⇒ *bool* **is** *IEEE.feq*
unfolding *is-nan-equivalent-def* **by** (*smt* (*verit*) *IEEE.fcompare-def IEEE.feq-def*)

6.2.14 Classification of numbers

lift-definition *is-normal* :: ('e, 'f) *floatSingleNaN* ⇒ *bool* **is** *IEEE.is-normal*
unfolding *is-nan-equivalent-def* **using** *float-distinct* **by** *blast*

lift-definition *is-subnormal* :: ('e, 'f) *floatSingleNaN* ⇒ *bool* **is** *IEEE.is-denormal*
unfolding *is-nan-equivalent-def* **using** *float-distinct* **by** *blast*

lift-definition *is-zero* :: ('e, 'f) *floatSingleNaN* ⇒ *bool* **is** *IEEE.is-zero*
unfolding *is-nan-equivalent-def* **using** *float-distinct* **by** *blast*

lift-definition *is-infinity* :: ('e, 'f) *floatSingleNaN* ⇒ *bool* **is** *IEEE.is-infinity*
unfolding *is-nan-equivalent-def* **using** *float-distinct* **by** *blast*

lift-definition *is-nan* :: ('e, 'f) *floatSingleNaN* ⇒ *bool* **is** *IEEE.is-nan*
unfolding *is-nan-equivalent-def* **by** *blast*

lift-definition *is-finite* :: ('e, 'f) *floatSingleNaN* ⇒ *bool* **is** *IEEE.is-finite*
unfolding *is-nan-equivalent-def* **using** *nan-not-finite* **by** *blast*

definition *is-negative* :: ('e, 'f) *floatSingleNaN* ⇒ *bool*
where *is-negative x* ≡ *x* = *minus-zero* ∨ *flt x minus-zero*

definition *is-positive* :: ('e, 'f) *floatSingleNaN* ⇒ *bool*
where *is-positive x* ≡ *x* = *0* ∨ *flt 0 x*

6.3 Conversions to other sorts

6.3.1 to real

SMT-LIB leaves `fp.to_real` unspecified for $+\infty$, $-\infty$, NaN. In contrast, *valof* is (partially) specified also for those arguments. This means that the SMT-LIB semantics can prove fewer theorems about `fp.to_real` than Isabelle can prove about *valof*.

lift-definition *valof* :: ('e,'f) *floatSingleNaN* ⇒ *real*
is λ*a*. *if IEEE.is-infinity a then undefined a*
else if IEEE.is-nan a then undefined — returning the same value for all floats that satisfy *IEEE.is-nan* is necessary to obtain a function that can be lifted to the quotient type
else IEEE.valof a
unfolding *is-nan-equivalent-def* **using** *float-distinct*(*1*) **by** *fastforce*

6.3.2 to unsigned machine integer, represented as a bit vector

definition *unsigned-word-of-floatSingleNaN* :: *roundmode* ⇒ ('e,'f) *floatSingleNaN* ⇒ 'a::*len word*
where *unsigned-word-of-floatSingleNaN mode a* ≡
if is-infinity a ∨ *is-nan a then undefined mode a*
else (*SOME w*. *valof* (*fintrnd mode a*) = *real-of-word w*)

6.3.3 to signed machine integer, represented as a 2's complement bit vector

definition *signed-word-of-floatSingleNaN* :: *roundmode* ⇒ (*'e*,*'f*) *floatSingleNaN* ⇒ *'a*::*len word*
where *signed-word-of-floatSingleNaN mode a* ≡
if is-infinity a ∨ *is-nan a then undefined mode a*
else (*SOME w*. *valof* (*fintrnd mode a*) = *real-of-int* (*sint w*))

6.4 Conversions from other sorts

6.4.1 from single bitstring representation in IEEE 754 interchange format

The intention is that *LENGTH*(*'a*) = *1* + *LENGTH*(*'e*) + *LENGTH*(*'f*) (recall that *LENGTH*(*'f*) does not include the significand's hidden bit). Of course, the type system of Isabelle/HOL is not strong enough to enforce this.

definition *floatSingleNaN-of-IEEE754-word* :: *'a*::*len word* ⇒ (*'e*,*'f*) *floatSingleNaN*
where *floatSingleNaN-of-IEEE754-word w* ≡
let (*se*, *f*) = *word-split w* :: *'a word* × -; (*s*, *e*) = *word-split se in fp s e f* — using *'a word* ensures that no bits are lost in *se*

6.4.2 from real

lift-definition *round* :: *roundmode* ⇒ *real* ⇒ (*'e*,*'f*) *floatSingleNaN* **is** *IEEE.round*
.

6.4.3 from another floating point sort

definition *floatSingleNaN-of-floatSingleNaN* :: *roundmode* ⇒ (*'a*,*'b*) *floatSingleNaN* ⇒ (*'e*,*'f*) *floatSingleNaN*
where *floatSingleNaN-of-floatSingleNaN mode a* ≡
if a = *plus-infinity then plus-infinity*
else if a = *minus-infinity then minus-infinity*
else if a = *NaN then NaN*
else round mode (*valof a*)

6.4.4 from signed machine integer, represented as a 2's complement bit vector

definition *floatSingleNaN-of-signed-word* :: *roundmode* ⇒ *'a*::*len word* ⇒ (*'e*,*'f*) *floatSingleNaN*
where *floatSingleNaN-of-signed-word mode w* ≡ *round mode* (*real-of-int* (*sint w*))

6.4.5 from unsigned machine integer, represented as bit vector

definition *floatSingleNaN-of-unsigned-word* :: *roundmode* ⇒ *'a*::*len word* ⇒ (*'e*,*'f*) *floatSingleNaN*
  where *floatSingleNaN-of-unsigned-word mode w* ≡ *round mode* (*real-of-word w*)

end

7 Translation of the IEEE model (with a single NaN value) into SMT-LIB's floating point theory

theory *IEEE-Single-NaN-SMTLIB*
  imports
    IEEE-Single-NaN
begin

SMT setup. Note that an interpretation of floating-point arithmetic in SMT-LIB allows external SMT solvers that support the SMT-LIB floating-point theory to find more proofs, but—in the absence of built-in floating-point automation in Isabelle/HOL—significantly *reduces* Sledgehammer's proof reconstruction rate. Until such automation becomes available, you probably want to use the interpreted translation only if you intend to use the external SMT solvers as trusted oracles.

ML-file ‹*smt-float.ML*›

end

References

[1] J. Harrison. *Floating point verification in HOL light: the exponential function.* Springer, 1997.