

GraalVM Stamp Theory

July 6, 2021

Abstract

The GraalVM compiler uses stamps to track type and range information during program analysis. Type information is recorded by using distinct subclasses of the abstract base class **Stamp**, i.e. **IntegerStamp** is used to represent an integer type. Each subclass introduces facilities for tracking range information. Every subclass of the **Stamp** class forms a lattice, together with an arbitrary top and bottom element each sublattice forms a lattice of all stamps. This Isabelle/HOL theory models stamps as instantiations of a lattice.

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1 Stamps: Type and Range Information

```
theory Stamp4
imports
  Values2
  HOL.Lattices
begin
```

1.1 Void Stamp

The VoidStamp represents a type with no associated values. The VoidStamp lattice is therefore a simple single element lattice.

```
datatype void =
  VoidStamp
```

```
instantiation void :: order
begin
```

```
definition less-eq-void :: void  $\Rightarrow$  void  $\Rightarrow$  bool where
  less-eq-void a b = True
```

```
definition less-void :: void  $\Rightarrow$  void  $\Rightarrow$  bool where
  less-void a b = False
```

```
instance
  apply standard
    apply (simp add: less-eq-void-def less-void-def)
    apply (simp add: less-eq-void-def)
    apply (simp add: less-eq-void-def)
  by (metis (full-types) void.exhaust)

end
```

```
instantiation void :: semilattice-inf
begin
```

```
definition inf-void :: void  $\Rightarrow$  void  $\Rightarrow$  void where
  inf-void a b = VoidStamp
```

```
instance
  apply standard
    apply (simp add: less-eq-void-def)
    apply (simp add: less-eq-void-def)
  by (metis (mono-tags) void.exhaust)

end
```

```
instantiation void :: semilattice-sup
begin
```

definition *sup-void* :: *void* \Rightarrow *void* \Rightarrow *void* **where**
sup-void *a b* = *VoidStamp*

instance
apply *standard*
apply (*simp add: less-eq-void-def*)
apply (*simp add: less-eq-void-def*)
by (*metis (mono-tags) void.exhaust*)

end

instantiation *void* :: *bounded-lattice*
begin

definition *bot-void* :: *void* **where**
bot-void = *VoidStamp*

definition *top-void* :: *void* **where**
top-void = *VoidStamp*

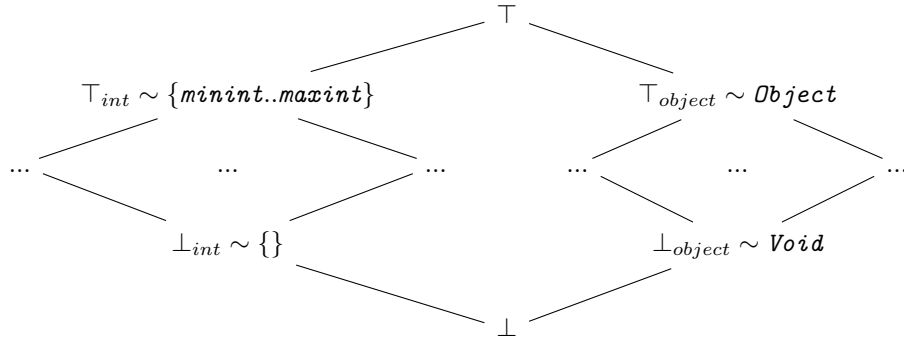
instance
apply *standard*
apply (*simp add: less-eq-void-def*)
by (*simp add: less-eq-void-def*)

end

Definition of the stamp type

datatype *stamp* =
intstamp int64 int64 — Type: Integer; Range: Lower Bound & Upper Bound

1.2 Stamp Lattice



1.2.1 Stamp Order

Defines an ordering on the stamp type.

One stamp is less than another if the valid values for the stamp are a strict subset of the other stamp.

instantiation *stamp* :: *order*
begin

fun *less-eq-stamp* :: *stamp* \Rightarrow *stamp* \Rightarrow *bool* **where**
 less-eq-stamp (*intstamp* *l1* *u1*) (*intstamp* *l2* *u2*) = ($\{l1..u1\} \subseteq \{l2..u2\}$)

fun *less-stamp* :: *stamp* \Rightarrow *stamp* \Rightarrow *bool* **where**
 less-stamp (*intstamp* *l1* *u1*) (*intstamp* *l2* *u2*) = ($\{l1..u1\} \subset \{l2..u2\}$)

lemma *less-le-not-le*:
 fixes *x y* :: *stamp*
 shows $(x < y) = (x \leq y \wedge \neg y \leq x)$
 using *less-eq-stamp.simps less-stamp.simps*
 using *stamp.exhaust subset-not-subset-eq* **by** *metis*

lemma *order-refl*:
 fixes *x* :: *stamp*
 shows $x \leq x$
 using *less-eq-stamp.simps less-stamp.simps*
 using *dual-order.refl stamp.exhaust* **by** *metis*

lemma *order-trans*:
 fixes *x y z* :: *stamp*
 shows $x \leq y \Longrightarrow y \leq z \Longrightarrow x \leq z$

proof –
 fix *x* :: *stamp* **and** *y* :: *stamp* **and** *z* :: *stamp*
 assume $x \leq y$
 assume $y \leq z$
 obtain *l1 u1* **where** *xdef*: $x = \text{intstamp } l1 \ u1$
 using *stamp.exhaust*
 by *blast*
 obtain *l2 u2* **where** *ydef*: $y = \text{intstamp } l2 \ u2$
 using *stamp.exhaust*
 by *blast*
 obtain *l3 u3* **where** *zdef*: $z = \text{intstamp } l3 \ u3$
 using *stamp.exhaust*
 by *blast*
 have *s1*: $\{l1..u1\} \subseteq \{l2..u2\}$
 using $\langle x \leq y \rangle$ *less-eq-stamp.simps xdef ydef* **by** *blast*
 have *s2*: $\{l2..u2\} \subseteq \{l3..u3\}$
 using $\langle y \leq z \rangle$ *less-eq-stamp.simps ydef zdef* **by** *blast*
 from *s1 s2* **have** $\{l1..u1\} \subseteq \{l3..u3\}$
 by (*meson dual-order.trans*)
 then show $x \leq z$

```

    using less-eq-stamp.simps
    using xdef zdef by presburger
qed

lemma antisym:
  fixes x y :: stamp
  shows  $x \leq y \implies y \leq x \implies x = y$ 
proof -
  fix x :: stamp
  fix y :: stamp
  assume xlessy:  $x \leq y$ 
  assume ylessx:  $y \leq x$ 
  obtain l1 u1 where xdef:  $x = \text{intstamp } l1 \ u1$ 
    using stamp.exhaust by blast
  obtain l2 u2 where ydef:  $y = \text{intstamp } l2 \ u2$ 
    using stamp.exhaust by blast

  from xlessy have s1:  $\{l1..u1\} \subseteq \{l2..u2\}$ 
    using less-eq-stamp.simps
    using xdef ydef by blast
  from ylessx have s2:  $\{l2..u2\} \subseteq \{l1..u1\}$ 
    using less-eq-stamp.simps
    using xdef ydef by blast
  have  $\{l1..u1\} \subseteq \{l2..u2\} \implies \{l2..u2\} \subseteq \{l1..u1\} \implies \{l1..u1\} = \{l2..u2\}$ 
    by fastforce
  then have s3:  $\{l1..u1\} = \{l2..u2\} \implies (l1 = l2) \wedge (u1 = u2)$ 

  sorry
  then have  $(l1 = l2) \wedge (u1 = u2) \implies x = y$ 
    using xdef ydef by fastforce
  then show  $x = y$ 
    using s1 s2 s3 by fastforce
qed

instance
  apply standard
  using less-le-not-le apply simp
  using order-refl apply simp
  using order-trans apply simp
  using antisym by simp
end

```

1.2.2 Stamp Join

Defines the *join* operation for stamps.

For any two stamps, the *join* is defined as the intersection of the valid values for the stamp.

```

instantiation stamp :: semilattice-inf
begin

notation inf (infix  $\sqcap$  65)

fun inf-stamp :: stamp  $\Rightarrow$  stamp  $\Rightarrow$  stamp where
  inf-stamp (intstamp l1 u1) (intstamp l2 u2) = intstamp (max l1 l2) (min u1 u2)

lemma inf-le1:
  fixes x y :: stamp
  shows (x  $\sqcap$  y)  $\leq$  x
proof –
  fix x :: stamp
  fix y :: stamp
  obtain l1 u1 where xdef: x = intstamp l1 u1
    using stamp.exhaust by blast
  obtain l2 u2 where ydef: y = intstamp l2 u2
    using stamp.exhaust by blast
  have joindef: x  $\sqcap$  y = intstamp (max l1 l2) (min u1 u2)
    (is ?join = intstamp ?l3 ?u3)
    using inf-stamp.simps xdef ydef
    by force
  have leq: {?l3..?u3}  $\subseteq$  {l1..u1}
    by force
  have (x  $\sqcap$  y)  $\leq$  x = ({?l3..?u3}  $\subseteq$  {l1..u1})
    using xdef joindef inf-stamp.simps
    by force
  then show (x  $\sqcap$  y)  $\leq$  x
    using leq
    by fastforce
qed

lemma inf-le2:
  fixes x y :: stamp
  shows (x  $\sqcap$  y)  $\leq$  y
proof –
  fix x :: stamp
  fix y :: stamp
  obtain l1 u1 where xdef: x = intstamp l1 u1
    using stamp.exhaust by blast
  obtain l2 u2 where ydef: y = intstamp l2 u2
    using stamp.exhaust by blast
  have joindef: x  $\sqcap$  y = intstamp (max l1 l2) (min u1 u2)
    (is ?join = intstamp ?l3 ?u3)
    using inf-stamp.simps xdef ydef
    by force
  have leq: {?l3..?u3}  $\subseteq$  {l2..u2}
    by force
  have (x  $\sqcap$  y)  $\leq$  y = ({?l3..?u3}  $\subseteq$  {l2..u2})

```

```

    using ydef joindef
    by force
  then show  $(x \sqcap y) \leq y$ 
    using leq
    by fastforce
qed

```

```

lemma inf-greatest:
  fixes  $x\ y\ z :: \text{stamp}$ 
  shows  $x \leq y \implies x \leq z \implies x \leq (y \sqcap z)$ 
proof -
  fix  $x\ y\ z :: \text{stamp}$ 
  assume xlessy:  $x \leq y$ 
  assume xlessz:  $x \leq z$ 
  obtain  $l1\ u1$  where xdef:  $x = \text{intstamp } l1\ u1$ 
    using stamp.exhaust by blast
  obtain  $l2\ u2$  where ydef:  $y = \text{intstamp } l2\ u2$ 
    using stamp.exhaust by blast
  obtain  $l3\ u3$  where zdef:  $z = \text{intstamp } l3\ u3$ 
    using stamp.exhaust by blast
  obtain  $l4\ u4$  where yzdef:  $y \sqcap z = \text{intstamp } l4\ u4$ 
    by (meson inf-stamp.elims)
  have max4:  $l4 = \max\ l2\ l3$ 
    using yzdef ydef zdef inf-stamp.simps by simp
  have min4:  $u4 = \min\ u2\ u3$ 
    using yzdef ydef zdef inf-stamp.simps by simp
  have  $\{l1..u1\} \subseteq \{l2..u2\}$ 
    using xlessy xdef ydef
    using less-eq-stamp.simps by blast
  have  $\{l1..u1\} \subseteq \{l3..u3\}$ 
    using xlessz xdef zdef
    using less-eq-stamp.simps by blast
  have leq:  $\{l1..u1\} \subseteq \{l4..u4\}$ 
    using  $\{l1..u1\} \subseteq \{l2..u2\}$   $\{l1..u1\} \subseteq \{l3..u3\}$  max4 min4 by auto
  have  $x \leq (y \sqcap z) = (\{l1..u1\} \subseteq \{l4..u4\})$ 
    by (simp add: xdef yzdef)
  then show  $x \leq (y \sqcap z)$ 
    using leq
    by fastforce
qed

```

```

instance
  apply standard
  using inf-le1 apply simp
  using inf-le2 apply simp
  using inf-greatest by simp
end

```


1.2.3 Stamp Meet

Defines the *meet* operation for stamps.

For any two stamps, the *meet* is defined as the union of the valid values for the stamp.

instantiation *stamp* :: *semilattice-sup*
begin

notation *sup* (**infix** \sqcup 65)

fun *sup-stamp* :: *stamp* \Rightarrow *stamp* \Rightarrow *stamp* **where**
sup-stamp (*intstamp* *l1* *u1*) (*intstamp* *l2* *u2*) = *intstamp* (*min* *l1* *l2*) (*max* *u1* *u2*)

lemma *sup-ge1*:

fixes *x y* :: *stamp*
shows $x \leq x \sqcup y$

proof –

fix *x* :: *stamp*

fix *y* :: *stamp*

obtain *l1 u1* **where** *xdef*: $x = \text{intstamp } l1 \ u1$

using *stamp.exhaust* **by** *blast*

obtain *l2 u2* **where** *ydef*: $y = \text{intstamp } l2 \ u2$

using *stamp.exhaust* **by** *blast*

have *joindef*: $x \sqcup y = \text{intstamp } (\text{min } l1 \ l2) \ (\text{max } u1 \ u2)$

(**is** *?join* = *intstamp* *?l3* *?u3*)

using *inf-stamp.simps* *xdef* *ydef*

by *force*

have *leq*: $\{l1..u1\} \subseteq \{?l3..?u3\}$

by *simp*

have $x \leq x \sqcup y = (\{l1..u1\} \subseteq \{?l3..?u3\})$

using *xdef* *joindef* *inf-stamp.simps*

by *force*

then show $x \leq x \sqcup y$

using *leq*

by *fastforce*

qed

lemma *sup-ge2*:

fixes *x y* :: *stamp*

shows $y \leq x \sqcup y$

proof –

fix *x* :: *stamp*

fix *y* :: *stamp*

obtain *l1 u1* **where** *xdef*: $x = \text{intstamp } l1 \ u1$

using *stamp.exhaust* **by** *blast*

obtain *l2 u2* **where** *ydef*: $y = \text{intstamp } l2 \ u2$

using *stamp.exhaust* **by** *blast*

have *joindef*: $x \sqcup y = \text{intstamp } (\text{min } l1 \ l2) \ (\text{max } u1 \ u2)$

(**is** *?join* = *intstamp* *?l3* *?u3*)

```

    using inf-stamp.simps xdef ydef
  by force
have leq:  $\{l2..u2\} \subseteq \{?l3..?u3\}$  (is ?subset-thesis)
  by simp
have ?thesis = (?subset-thesis)
  using ydef joindef sup-stamp.simps less-eq-stamp.simps
  by (metis Stamp4.sup-ge1 max.commute min.commute sup-stamp.elims)
then show ?thesis
  using leq
  by fastforce
qed

```

lemma sup-least:

```

  fixes x y z :: stamp
  shows  $y \leq x \implies z \leq x \implies ((y \sqcup z) \leq x)$ 
proof -
  fix x y z :: stamp
  assume xlessy:  $y \leq x$ 
  assume xlessz:  $z \leq x$ 
  obtain l1 u1 where xdef:  $x = \text{intstamp } l1 \ u1$ 
    using stamp.exhaust by blast
  obtain l2 u2 where ydef:  $y = \text{intstamp } l2 \ u2$ 
    using stamp.exhaust by blast
  obtain l3 u3 where zdef:  $z = \text{intstamp } l3 \ u3$ 
    using stamp.exhaust by blast
  have yzdef:  $y \sqcup z = \text{intstamp } (\min l2 \ l3) \ (\max u2 \ u3)$ 
    (is ?meet =  $\text{intstamp } ?l4 \ ?u4$ )
    using sup-stamp.simps
    by (simp add: ydef zdef)
  have s1:  $\{l2..u2\} \subseteq \{l1..u1\}$ 
    using xlessy xdef ydef
    using less-eq-stamp.simps by blast
  have s2:  $\{l3..u3\} \subseteq \{l1..u1\}$ 
    using xlessz xdef zdef
    using less-eq-stamp.simps by blast
  have leq:  $\{?l4..?u4\} \subseteq \{l1..u1\}$  (is ?subset-thesis)
    using s1 s2 unfolding atLeastatMost-subset-iff

```

```

    by (metis (no-types, hide-lams) inf.orderE inf-stamp.simps max.bounded-iff
max.cobounded2 min.bounded-iff min.cobounded2 stamp.inject xdef xlessy xlessz ydef
zdef)

```

```

  have  $(y \sqcup z \leq x) = ?subset-thesis$ 
    using yzdef xdef less-eq-stamp.simps
    by simp
  then show  $(y \sqcup z \leq x)$ 
    using leq by fastforce
qed

```

instance

```

apply standard
using sup-ge1 apply simp
using sup-ge2 apply simp
using sup-least by simp
end

```

1.2.4 Stamp Bounds

Defines the top and bottom elements of the stamp lattice.

This poses an interesting question as our stamp type is a union of the various *Stamp* subclasses, e.g. *IntegerStamp*, *ObjectStamp*, etc.

Each subclass should preferably have its own unique top and bottom element, i.e. An *IntegerStamp* would have the top element of the full range of integers allowed by the bit width and a bottom of a range with no integers. While the *ObjectStamp* should have *Object* as the top and *Void* as the bottom element.

```

instantiation stamp :: bounded-lattice
begin

```

```

notation bot ( $\perp$  50)

```

```

notation top ( $\top$  50)

```

```

definition width-min :: nat  $\Rightarrow$  int64 where
  width-min bits =  $-(2^{\wedge}(bits-1))$ 

```

```

definition width-max :: nat  $\Rightarrow$  int64 where
  width-max bits =  $(2^{\wedge}(bits-1)) - 1$ 

```

```

value (sint (width-min 64), sint (width-max 64))

```

```

value max-word::int64

```

```

lemma

```

```

  assumes x = width-min 64

```

```

  assumes y = width-max 64

```

```

  shows sint x < sint y

```

```

  using assms unfolding width-min-def width-max-def by simp

```

Note that this definition is valid for unsigned integers only.

The bottom and top element for signed integers would be (- 9223372036854775808, 9223372036854775807).

For unsigned we have (0, 18446744073709551615).

For Java we are likely to be more concerned with signed integers. To use the appropriate bottom and top for signed integers we would need to change our definition of *less_eq* from *l1..u1* <= *l2..u2* to *sint* *l1*..*sint* *u1* <= *sint* *l2*..*sint* *u2*

We may still find an unsigned integer stamp useful. I plan to investigate

the Java code to see if this is useful and then apply the changes to switch to signed integers.

definition *bot-stamp* = *intstamp max-word 0*

definition *top-stamp* = *intstamp 0 max-word*

lemma *bot-least*:

fixes *a :: stamp*

shows $(\perp) \leq a$

proof –

obtain *min max* **where** *bot-def*: \perp = *intstamp max min*

using *bot-stamp-def*

by *force*

have *min* < *max*

using *bot-def*

unfolding *bot-stamp-def width-min-def width-max-def*

using *word-gt-0* **by** *fastforce*

then have $\{max..min\} = \{\}$

using *bot-def*

unfolding *bot-stamp-def width-min-def width-max-def*

by *auto*

then show *?thesis*

unfolding *bot-stamp-def*

using *less-eq-stamp.simps*

by (*simp add: stamp.induct*)

qed

lemma *top-greatest*:

fixes *a :: stamp*

shows $a \leq (\top)$

proof –

obtain *min max* **where** *top-def*: \top = *intstamp min max*

using *top-stamp-def*

by *force*

have *max-is-max*: $\neg(\exists n. n > max)$

by (*metis stamp.inject top-def top-stamp-def word-order.extremum-strict*)

have *min-is-min*: $\neg(\exists n. n < min)$

by (*metis not-less-iff-gr-or-eq stamp.inject top-def top-stamp-def word-coorder.not-eq-extremum*)

have $\neg(\exists l u. \{min..max\} < \{l..u\})$

using *max-is-max min-is-min*

by (*metis atLeastatMost-psubset-iff not-less*)

then show *?thesis*

unfolding *top-stamp-def*

using *less-eq-stamp.simps*

using *less-eq-stamp.elims(3)* **by** *fastforce*

qed

instance

apply *standard*

using *bot-least* **apply** *simp*

```

    using top-greatest by simp
end

```

1.3 Java Stamp Methods

The following are methods from the Java Stamp class, they are the methods primarily used for optimizations.

definition *is-unrestricted* :: stamp \Rightarrow bool **where**
is-unrestricted $s = (\top = s)$

fun *is-empty* :: stamp \Rightarrow bool **where**
is-empty $s = (\perp = s)$

fun *as-constant* :: stamp \Rightarrow Value option **where**
as-constant (intstamp $l\ u$) = (if (card { $l..u$ }) = 1
 then Some (IntVal64 (SOME x . $x \in \{l..u\}$))
 else None)

definition *always-distinct* :: stamp \Rightarrow stamp \Rightarrow bool **where**
always-distinct stamp1 stamp2 = ($\perp = (\text{stamp1} \sqcap \text{stamp2})$)

definition *never-distinct* :: stamp \Rightarrow stamp \Rightarrow bool **where**
never-distinct stamp1 stamp2 =
 (*as-constant* stamp1 = *as-constant* stamp2 \wedge *as-constant* stamp1 \neq None)

1.4 Mapping to Values

fun *valid-value* :: stamp \Rightarrow Value \Rightarrow bool **where**
valid-value (intstamp $l\ u$) (IntVal64 v) = ($v \in \{l..u\}$) |
valid-value (intstamp $l\ u$) - = False

The *valid-value* function is used to map a stamp instance to the values that are allowed by the stamp.

It would be nice if there was a slightly more integrated way to perform this mapping as it requires some infrastructure to prove some fairly simple properties.

lemma *bottom-range-empty*:
 $\neg(\text{valid-value } (\perp) v)$
unfolding *bot-stamp-def*
using *valid-value.elims(2)* **by** *fastforce*

lemma *join-values*:
assumes *joined* = *x-stamp* \sqcap *y-stamp*
shows *valid-value* *joined* $x \longleftrightarrow (\text{valid-value } x\text{-stamp } x \wedge \text{valid-value } y\text{-stamp } x)$
proof (cases x)
case *UndefVal*
then show *?thesis*
using *valid-value.elims(2)* **by** *blast*

```

next
  case (IntVal32 x2)
  then show ?thesis
    using valid-value.elims(2) by blast
next
  case (IntVal64 x3)
  obtain lx ux where xdef: x-stamp = intstamp lx ux
    using stamp.exhaust by blast
  obtain ly uy where ydef: y-stamp = intstamp ly uy
    using stamp.exhaust by blast
  obtain v where x = IntVal64 v
    using IntVal64 by blast
  have joined = intstamp (max lx ly) (min ux uy)
    (is joined = intstamp ?lj ?uj)
    by (simp add: xdef ydef assms)
  then have valid-value joined (IntVal64 v) = (v ∈ {?lj..?uj})
    by simp
  then show ?thesis
    using ⟨x = IntVal64 v⟩ xdef ydef by force
next
  case (FloatVal x4)
  then show ?thesis
    using valid-value.elims(2) by blast
next
  case (ObjRef x5)
  then show ?thesis
    using valid-value.elims(2) by blast
next
  case (ObjStr x6)
  then show ?thesis
    using valid-value.elims(2) by blast
qed

```

```

lemma disjoint-empty:
  fixes x-stamp y-stamp :: stamp
  assumes  $\perp = x\text{-stamp} \sqcap y\text{-stamp}$ 
  shows  $\neg(\text{valid-value } x\text{-stamp } x \wedge \text{valid-value } y\text{-stamp } x)$ 
  using assms bottom-range-empty join-values
  by blast

```

experiment begin

A possible equivalent alternative to the definition of less_eq

```

fun less-eq-alt :: 'a::ord × 'a ⇒ 'a × 'a ⇒ bool where
  less-eq-alt (l1, u1) (l2, u2) = ((¬ l1 ≤ u1) ∨ l2 ≤ l1 ∧ u1 ≤ u2)

```

Proof equivalence

lemma

```

fixes  $l1\ l2\ u1\ u2 :: int$ 
assumes  $l1 \leq u1 \wedge l2 \leq u2$ 
shows  $\{l1..u1\} \subseteq \{l2..u2\} = ((l1 \geq l2) \wedge (u1 \leq u2))$ 
by (simp add: assms)

lemma
  fixes  $l1\ l2\ u1\ u2 :: int$ 
  shows  $\{l1..u1\} \subseteq \{l2..u2\} = less-eq-alt\ (l1, u1)\ (l2, u2)$ 
  by simp
end

```

1.5 Generic Integer Stamp

Experimental definition of integer stamps generically, restricting the datatype to only allow valid ranges and the bottom integer element (`max_int..min_int`).

```

lemma
  assumes  $(x::int) > 0$ 
  shows  $(2^x)/2 = (2^{x-1})$ 
  sorry

definition max-signed-int :: 'a::len word where
  max-signed-int =  $(2^{(LENGTH('a) - 1)} - 1)$ 

definition min-signed-int :: 'a::len word where
  min-signed-int =  $-(2^{(LENGTH('a) - 1)})$ 

definition int-bottom :: 'a::len word  $\times$  'a word where
  int-bottom = (max-signed-int, min-signed-int)

definition int-top :: 'a::len word  $\times$  'a word where
  int-top = (min-signed-int, max-signed-int)

```

```

lemma
  fixes  $x :: 'a::len word$ 
  shows  $sint\ x \leq sint\ (((2^{(LENGTH('a) - 1)} - 1))::'a\ word)$ 
  using sint-greater-eq sorry

```

```

value sint ( $0::1\ word$ )
value sint ( $1::1\ word$ )
value sint ( $((2^0) - 1)::1\ word$ )

value sint ( $((2^{31}) - 1)::32\ word$ )

```

```

lemma max-signed:
  fixes  $a :: 'a::len word$ 
  shows  $sint\ a \leq sint\ (max-signed-int::'a\ word)$ 

```

```

proof (cases sint a = sint (max-signed-int::'a word))
  case True
    then show ?thesis by simp
next
  case False
    have sint a < sint (max-signed-int::'a word)
      using False unfolding max-signed-int-def sorry
    then show ?thesis by simp
qed

lemma min-signed:
  fixes a :: 'a::len word
  shows sint a ≥ sint (min-signed-int::'a word)
  sorry

value max-signed-int :: 32 word
value int-bottom::(32 word × 32 word)
value sint (2147483647::32 word)
value sint (2147483648::32 word)

typedef (overloaded) ('a::len) intstamp =
  {bounds :: ('a word, 'a word) prod . ((fst bounds) ≤s (snd bounds) ∨ bounds =
  int-bottom)}
proof –
  show ?thesis
    by (smt (z3) mem-Collect-eq prod.sel(1) prod.sel(2) signed-minus-1 sint-0)
qed

setup-lifting type-definition-intstamp

lift-definition lower :: ('a::len) intstamp ⇒ 'a word
  is prod.fst ∘ Rep-intstamp .

lift-definition upper :: ('a::len) intstamp ⇒ 'a word
  is prod.snd ∘ Rep-intstamp .

lift-definition lower-int :: ('a::len) intstamp ⇒ int
  is sint ∘ prod.fst .

lift-definition upper-int :: ('a::len) intstamp ⇒ int
  is sint ∘ prod.snd .

lift-definition range :: ('a::len) intstamp ⇒ int set
  is λ (l, u). {sint l..sint u} .

lift-definition bounds :: ('a::len) intstamp ⇒ ('a word × 'a word)
  is Rep-intstamp .

```


lift-definition *is-bottom* :: ('a::len) intstamp \Rightarrow bool
is $\lambda x. x = \text{int-bottom}$.

lift-definition *from-bounds* :: ('a::len word \times 'a word) \Rightarrow 'a intstamp
is *Abs-intstamp* .

instantiation *intstamp* :: (len) order
begin

definition *less-eq-intstamp* :: 'a intstamp \Rightarrow 'a intstamp \Rightarrow bool **where**
less-eq-intstamp s1 s2 = (range s1 \subseteq range s2)

definition *less-intstamp* :: 'a intstamp \Rightarrow 'a intstamp \Rightarrow bool **where**
less-intstamp s1 s2 = (range s1 \subset range s2)

value *int-bottom*::(1 word \times 1 word)
value *sint* (0::1 word)
value *sint* (1::1 word)

value *int-bottom*::(2 word \times 2 word)
value *sint* (1::2 word)
value *sint* (2::2 word)
value *sint* ((2^{LENGTH(32)} - 1) - 1)::32 word) > *sint* ((- (2^{LENGTH(32)} - 1))::32 word)

lemma *bottom-is-bottom*:

assumes *is-bottom* s
shows $s \leq a$

proof -

have *boundsdef*: *bounds* s = *int-bottom*
by (metis *assms* *bounds.transfer* *is-bottom.rep-eq*)
obtain *min max* **where** *bounds* s = (*max*, *min*)
by *fastforce*
then have *max* \neq *min*
by (metis *boundsdef* *dual-order.eq-iff* *fst-conv* *int-bottom-def* *less-minus-one-simps*(1)
max-signed *min-signed* *not-less* *sint-0* *sint-n1* *snd-conv*)
then have *sint* *min* < *sint* *max*
unfolding *boundsdef* *int-bottom-def*
using *max-signed*
by (metis (*bounds* s = (*max*, *min*)) *boundsdef* *int-bottom-def* *order.not-eq-order-implies-strict*
prod.sel(1) *signed-word-eqI*)
then have range s = {}
unfolding *range-def* *bounds-def*
by (*simp* *add*: (*bounds* s = (*max*, *min*)) *bounds.transfer*)
then show ?thesis
by (*simp* *add*: *Stamp4.less-eq-intstamp-def*)

qed

lemma *bounds-has-value*:
 fixes $x\ y :: \text{int}$
 assumes $x < y$
 shows $\text{card } \{x..y\} > 0$
 using *assms* by *auto*

lemma *bounds-has-no-value*:
 fixes $x\ y :: \text{int}$
 assumes $x < y$
 shows $\text{card } \{y..x\} = 0$
 using *assms* by *auto*

lemma *bottom-unique*:
 fixes $a\ s :: 'a\ \text{intstamp}$
 assumes *is-bottom* s
 shows $a \leq s \longleftrightarrow \text{is-bottom } a$

proof –

have $\forall x. \text{sint } (\text{fst } (\text{bounds } x)) \leq \text{sint } (\text{snd } (\text{bounds } x)) \vee \text{is-bottom } x$
 unfolding *bounds-def* *is-bottom-def*
 using *Rep-intstamp*
 using *word-sle-eq* by *auto*
 then have $\forall x. (\text{card } (\text{range } x)) > 0 \vee \text{is-bottom } x$
 unfolding *range-def* using *bounds-has-value*
 by (*simp* add: *bounds.transfer* *case-prod-beta*)
 obtain $\text{min } \text{max}$ where *boundsdef*: $\text{bounds } s = (\text{max}, \text{min})$
 by *fastforce*
 have *nooverlap*: $\text{sint } \text{min} < \text{sint } \text{max}$
 using *max-signed*
 by (*metis* *assms* *bounds.transfer* *boundsdef* *fst-conv* *int-bottom-def* *is-bottom.rep-eq* *min-signed* *order.not-eq-order-implies-strict* *signed-word-eqI* *sint-0* *snd-conv* *verit-la-disequality* *zero-neq-one*)
 have $\text{range } s = \{\text{sint } \text{max}.. \text{sint } \text{min}\}$
 by (*simp* add: *bounds.transfer* *boundsdef* *range.rep-eq*)
 then have $\text{card } (\text{range } s) = 0$
 using *nooverlap* *bounds-has-no-value* by *simp*
 then have $\forall x. (\text{card } (\text{range } x)) > 0 \longrightarrow s < x$
 using $\langle \text{Stamp4.range } s = \{\text{sint } \text{max}.. \text{sint } \text{min}\} \rangle$ *atLeastatMost-empty* *less-intstamp-def*
 by *auto*
 then show *?thesis*
 by (*meson* $\langle \forall x. 0 < \text{card } (\text{Stamp4.range } x) \vee \text{is-bottom } x \rangle$ *bottom-is-bottom* *leD* *less-eq-intstamp-def* *less-intstamp-def*)
 qed

lemma *bottom-antisym*:
 assumes *is-bottom* x
 shows $x \leq y \implies y \leq x \implies x = y$

```

    using assms proof (cases is-bottom y)
  case True
    then show ?thesis
      by (metis Rep-intstamp-inverse assms is-bottom.rep-eq)
  next
    case False
    assume  $y \leq x$ 
    have  $\neg(y \leq x)$ 
      using bottom-unique False assms
      by simp
    then show ?thesis
      using  $\langle y \leq x \rangle$  by auto
qed

lemma int-antisym:
  fixes  $x y :: 'a \text{ intstamp}$ 
  shows  $x \leq y \implies y \leq x \implies x = y$ 
proof -
  fix  $x :: 'a \text{ intstamp}$ 
  fix  $y :: 'a \text{ intstamp}$ 
  assume  $xlessy: x \leq y$ 
  assume  $ylessx: y \leq x$ 
  obtain  $l1\ u1$  where  $xdef: \text{bounds } x = (l1, u1)$ 
    by fastforce
  obtain  $l2\ u2$  where  $ydef: \text{bounds } y = (l2, u2)$ 
    by fastforce

  from  $xlessy$  have  $s1: \{sint\ l1..sint\ u1\} \subseteq \{sint\ l2..sint\ u2\}$  (is ? $xlessy$ )
    using  $xdef\ ydef$  unfolding bounds-def range-def less-eq-intstamp-def
    by simp
  from  $ylessx$  have  $s2: \{sint\ l2..sint\ u2\} \subseteq \{sint\ l1..sint\ u1\}$  (is ? $ylessx$ )
    using  $xdef\ ydef$  unfolding bounds-def range-def less-eq-intstamp-def
    by simp
  show  $x = y$  proof (cases is-bottom x)
    case True
      then show ?thesis using bottom-antisym  $xlessy\ ylessx$ 
        by simp
    next
      case False
      then show ?thesis sorry
  qed
qed

instance
  apply standard
  apply (simp add: less-eq-intstamp-def less-intstamp-def less-le-not-le)
  apply blast
  using less-eq-intstamp-def apply force
  using less-eq-intstamp-def apply force

```

```

  by (simp add: int-antisym)
end

value take-bit LENGTH(63) 20::int
value take-bit LENGTH(63) ((-20)::int)
value bit (20::int64) (63::nat)
value bit ((-20)::int64) (63::nat)

value ((-20)::int64) < (20::int64)

value take-bit LENGTH(63) ((-20)::int)

lift-definition smax :: 'a::len word  $\Rightarrow$  'a word  $\Rightarrow$  'a word
  is  $\lambda a b. (if (sint a) \leq (sint b) then b else a) .$ 

lift-definition smin :: 'a::len word  $\Rightarrow$  'a word  $\Rightarrow$  'a word
  is  $\lambda a b. (if (sint a) \leq (sint b) then a else b) .$ 

instantiation intstamp :: (len) semilattice-inf
begin

notation inf (infix  $\sqcap$  65)

definition join-bounds :: 'a intstamp  $\Rightarrow$  'a intstamp  $\Rightarrow$  ('a word  $\times$  'a word) where
  join-bounds s1 s2 = (smax (lower s1) (lower s2), smin (upper s1) (upper s2))

definition join-or-bottom :: 'a intstamp  $\Rightarrow$  'a intstamp  $\Rightarrow$  ('a word  $\times$  'a word)
where
  join-or-bottom s1 s2 = (let bound = (join-bounds s1 s2) in
    if sint (fst bound)  $\geq$  sint (snd bound) then int-bottom else bound)

definition inf-intstamp :: 'a intstamp  $\Rightarrow$  'a intstamp  $\Rightarrow$  'a intstamp where
  inf-intstamp s1 s2 = from-bounds (join-or-bottom s1 s2)

lemma always-valid:
  fixes s1 s2 :: 'a intstamp
  shows Rep-intstamp (from-bounds (join-or-bottom s1 s2)) = join-or-bottom s1 s2
  unfolding join-or-bottom-def join-bounds-def from-bounds-def
  using Abs-intstamp-inverse
  by (smt (z3) from-bounds.transfer from-bounds-def mem-Collect-eq word-sle-eq)

lemma invalid-join:
  fixes s1 s2 :: 'a intstamp
  assumes bound = join-bounds s1 s2
  assumes sint (fst bound)  $\geq$  sint (snd bound)
  shows from-bounds int-bottom = s1  $\sqcap$  s2
  using assms(1) assms(2) inf-intstamp-def join-or-bottom-def by presburger

```

```

lemma unfold-bounds:
  bounds  $x = (\text{lower } x, \text{upper } x)$ 
  by (simp add: bounds.transfer lower.rep-eq upper.rep-eq)

lemma int-inf-le1:
  fixes  $x\ y :: 'a\ \text{intstamp}$ 
  shows  $(x \sqcap y) \leq x$ 
proof (cases is-bottom  $(x \sqcap y)$ )
  case True
  then show ?thesis
    by (simp add: bottom-is-bottom)
next
  case False
  then show ?thesis
  using False proof –
    obtain  $l1\ u1$  where  $xdef: \text{lower } x = l1 \wedge \text{upper } x = u1$ 
      by fastforce
    obtain  $l2\ u2$  where  $ydef: \text{lower } y = l2 \wedge \text{upper } y = u2$ 
      by fastforce
    have  $\text{joindef}: x \sqcap y = \text{from-bounds } ((\text{smax } l1\ l2, \text{smmin } u1\ u2))$ 
      (is  $x \sqcap y = \text{from-bounds } (?l3, ?u3)$ )
    using False
    by (smt ( $z3$ ) Stamp4.inf-intstamp-def Stamp4.join-bounds-def always-valid
      is-bottom.rep-eq join-or-bottom-def xdef ydef)
    have  $\text{leq}: \{\text{sint } ?l3.. \text{sint } ?u3\} \subseteq \{\text{sint } l1.. \text{sint } u1\}$ 
      by (smt ( $z3$ ) atLeastatMost-subset-iff smax.transfer smmin.transfer)
    have  $(x \sqcap y) \leq x = (\{\text{sint } ?l3.. \text{sint } ?u3\} \subseteq \{\text{sint } l1.. \text{sint } u1\})$ 
      using  $xdef\ \text{joindef}\ \text{range-def}\ \text{less-eq-intstamp-def}$ 
    by (smt ( $z3$ ) False Stamp4.always-valid Stamp4.join-or-bottom-def bounds.abs-eq
      case-prod-conv inf-intstamp-def is-bottom.rep-eq join-bounds-def range.rep-eq unfold-bounds ydef)
    then show  $(x \sqcap y) \leq x$ 
      using leq
      by fastforce
  qed
qed

lemma int-inf-le2:
  fixes  $x\ y :: 'a\ \text{intstamp}$ 
  shows  $(x \sqcap y) \leq y$ 
proof (cases is-bottom  $(x \sqcap y)$ )
  case True
  then show ?thesis
    by (simp add: bottom-is-bottom)
next
  case False
  then show ?thesis
  using False proof –
    obtain  $l1\ u1$  where  $xdef: \text{lower } x = l1 \wedge \text{upper } x = u1$ 

```

```

    by fastforce
  obtain l2 u2 where ydef: lower y = l2  $\wedge$  upper y = u2
    by fastforce
  have joindef:  $x \sqcap y = \text{from-bounds } ((\text{smax } l1 \ l2, \text{ smin } u1 \ u2))$ 
    (is  $x \sqcap y = \text{from-bounds } (?l3, ?u3)$ )
    using False
    by (smt (z3) Stamp4.inf-intstamp-def Stamp4.join-bounds-def always-valid
is-bottom.rep-eq join-or-bottom-def xdef ydef)
  have leq:  $\{\text{sint } ?l3..\text{sint } ?u3\} \subseteq \{\text{sint } l1..\text{sint } u1\}$ 
    by (smt (z3) atLeastatMost-subset-iff smax.transfer smin.transfer)
  have  $(x \sqcap y) \leq y = (\{\text{sint } ?l3..\text{sint } ?u3\} \subseteq \{\text{sint } l2..\text{sint } u2\})$ 
    using xdef joindef range-def less-eq-intstamp-def
    by (smt (z3) False Stamp4.always-valid Stamp4.join-or-bottom-def bounds.abs-eq
case-prod-conv inf-intstamp-def is-bottom.rep-eq join-bounds-def range.rep-eq un-
fold-bounds ydef)
  then show  $(x \sqcap y) \leq y$ 
    using leq
    by (smt (z3) atLeastatMost-subset-iff smax.transfer smin.transfer)
qed
qed

```

```

lemma
  assumes  $x \leq y$ 
  assumes is-bottom y
  shows is-bottom x
  using bottom-is-bottom assms
  using bottom-unique by auto

```

```

lemma int-inf-greatest:
  fixes  $x \ y :: 'a \ \text{intstamp}$ 
  shows  $x \leq y \implies x \leq z \implies x \leq y \sqcap z$ 
  sorry

```

```

instance
  apply standard
  apply (simp add: local.int-inf-le1)
  apply (simp add: local.int-inf-le2)
  by (simp add: local.int-inf-greatest)

```

end

```

instantiation intstamp :: (len) semilattice-sup
begin

```

```

notation sup (infix  $\sqcup$  65)

```

```

instance sorry

```

```

end

instantiation intstamp :: (len) bounded-lattice
begin

notation bot ( $\perp$  50)
notation top ( $\top$  50)

definition bot-intstamp = int-bottom
definition top-intstamp = int-top

instance sorry

end

value sint (0::1 word)
value sint (1::1 word)

datatype Stamp =
  BottomStamp |
  TopStamp |
  VoidStamp |

  Int8Stamp 8 intstamp |
  Int16Stamp 16 intstamp |
  Int32Stamp 32 intstamp |
  Int64Stamp 64 intstamp

instantiation Stamp :: order
begin

fun less-eq-Stamp :: Stamp  $\Rightarrow$  Stamp  $\Rightarrow$  bool where
  less-eq-Stamp BottomStamp - = True |
  less-eq-Stamp - TopStamp = True |
  less-eq-Stamp VoidStamp VoidStamp = True |
  less-eq-Stamp (Int8Stamp v1) (Int8Stamp v2) = (v1  $\leq$  v2) |
  less-eq-Stamp (Int16Stamp v1) (Int16Stamp v2) = (v1  $\leq$  v2) |
  less-eq-Stamp (Int32Stamp v1) (Int32Stamp v2) = (v1  $\leq$  v2) |
  less-eq-Stamp (Int64Stamp v1) (Int64Stamp v2) = (v1  $\leq$  v2) |
  less-eq-Stamp - - = False

fun less-Stamp :: Stamp  $\Rightarrow$  Stamp  $\Rightarrow$  bool where
  less-Stamp BottomStamp BottomStamp = False |
  less-Stamp BottomStamp - = True |
  less-Stamp TopStamp TopStamp = False |
  less-Stamp - TopStamp = True |
  less-Stamp VoidStamp VoidStamp = False |
  less-Stamp (Int8Stamp v1) (Int8Stamp v2) = (v1 < v2) |
  less-Stamp (Int16Stamp v1) (Int16Stamp v2) = (v1 < v2) |

```

```

less-Stamp (Int32Stamp v1) (Int32Stamp v2) = (v1 < v2) |
less-Stamp (Int64Stamp v1) (Int64Stamp v2) = (v1 < v2) |
less-Stamp - - = False

instance
  apply standard sorry
end

instantiation Stamp :: semilattice-inf
begin

notation inf (infix  $\sqcap$  65)

fun inf-Stamp :: Stamp  $\Rightarrow$  Stamp  $\Rightarrow$  Stamp where
  inf-Stamp BottomStamp - = BottomStamp |
  inf-Stamp - BottomStamp = BottomStamp |
  inf-Stamp TopStamp - = TopStamp |
  inf-Stamp - TopStamp = TopStamp |
  inf-Stamp VoidStamp VoidStamp = VoidStamp |
  inf-Stamp (Int8Stamp v1) (Int8Stamp v2) = Int8Stamp (v1  $\sqcap$  v2) |
  inf-Stamp (Int16Stamp v1) (Int16Stamp v2) = Int16Stamp (v1  $\sqcap$  v2) |
  inf-Stamp (Int32Stamp v1) (Int32Stamp v2) = Int32Stamp (v1  $\sqcap$  v2) |
  inf-Stamp (Int64Stamp v1) (Int64Stamp v2) = Int64Stamp (v1  $\sqcap$  v2)

instance
  apply standard sorry
end

instantiation Stamp :: semilattice-sup
begin

notation sup (infix  $\sqcup$  65)

fun sup-Stamp :: Stamp  $\Rightarrow$  Stamp  $\Rightarrow$  Stamp where
  sup-Stamp BottomStamp - = BottomStamp |
  sup-Stamp - BottomStamp = BottomStamp |
  sup-Stamp TopStamp - = TopStamp |
  sup-Stamp - TopStamp = TopStamp |
  sup-Stamp VoidStamp VoidStamp = VoidStamp |
  sup-Stamp (Int8Stamp v1) (Int8Stamp v2) = Int8Stamp (v1  $\sqcup$  v2) |
  sup-Stamp (Int16Stamp v1) (Int16Stamp v2) = Int16Stamp (v1  $\sqcup$  v2) |
  sup-Stamp (Int32Stamp v1) (Int32Stamp v2) = Int32Stamp (v1  $\sqcup$  v2) |
  sup-Stamp (Int64Stamp v1) (Int64Stamp v2) = Int64Stamp (v1  $\sqcup$  v2)

instance
  apply standard sorry
end

```



```

instantiation Stamp :: bounded-lattice
begin

notation bot ( $\perp$  50)
notation top ( $\top$  50)

definition top-Stamp :: Stamp where
  top-Stamp = TopStamp
definition bot-Stamp :: Stamp where
  bot-Stamp = BottomStamp

instance
  apply standard sorry
end

lemma [code]: Rep-intstamp (from-bounds (l, u)) = (l, u)
  using Abs-intstamp-inverse from-bounds.rep-eq
  sorry

code-datatype Abs-intstamp

end

```