A Formal CHERI-C Memory Model

Seung Hoon Park

May 26, 2024

Abstract

In this work, we present a formal memory model that provides a memory semantics for CHERI-C programs with uncompressed capabilities in a 'purecap' environment. We present a CHERI-C memory model theory with properties suitable for verification and potentially other types of analyses. Our theory generates an OCaml executable instance of the memory model, which is then used to instantiate the parametric *Gillian* program analysis framework, enabling concrete execution of CHERI-C programs. The tool can run a CHERI-C test suite, demonstrating the correctness of our tool, and catch a good class of safety violations that the CHERI hardware might miss.

The proof is accompanied by a paper [6] that explains the Gillian framework instantiation that uses the OCaml code generated by this work.

Contents

Acknowledgements

The author was funded by the UKRI programme on Digital Security by Design (Ref. EP/V000225/1, SCorCH).

theory *Preliminary-Library*
imports *Main HOL−Library.Word Word-Lib.Word-Lib-Sumo HOL−Library.Countable*
begin

1 Preliminary Theories

In this subsection, we provide the type and value system used by the CHERI-C Memory Model. We also provide proofs for the conversion between large words (i.e. bits) and a list of bytes. For primitive bytes that are not $U8_\tau$ or $S8_\tau$, we need to be able to convert between their normal representation and list of bytes so that storing values work as intended. The high-level detail is given in the paper [6].

1.1 Types and Values

We first formalise the capability type. We first define *memory capabilities* as a record, then we define *tagged capabilities* by extending the record. We state the class comp_countable for future work, but countable is sufficient for the block_id type. For the permissions, we present only those used by the memory model.

class *comp-countable* = *countable* + *zero* + *ord*

record ('*a* :: *comp-countable*) *mem-capability* =
  block-id :: '*a*
  offset :: *int*
  base :: *nat*
  len :: *nat*
  perm-load :: *bool*
  perm-cap-load :: *bool*
  perm-store :: *bool*
  perm-cap-store :: *bool*
  perm-cap-store-local :: *bool*
  perm-global :: *bool*

record ('*a* :: *comp-countable*) *capability* = '*a mem-capability* +
  tag :: *bool*

cctype corresponds to τ in the paper [6], where τ is the type system.

datatype *cctype* =
  Uint8
  | *Sint8*
  | *Uint16*
  | *Sint16*
  | *Uint32*
  | *Sint32*
  | *Uint64*

```
| Sint64
| Cap
```

'a ccval corresponds to $\mathcal{V}_{\mathcal{C}}$ in the paper [6]. *'a* in this instance must be countable.

```
datatype 'a ccval =
  Uint8-v       8 word
  | Sint8-v     8 sword
  | Uint16-v    16 word
  | Sint16-v    16 sword
  | Uint32-v    32 word
  | Sint32-v    32 sword
  | Uint64-v    64 word
  | Sint64-v    64 sword
  | Cap-v       'a capability
  | Cap-v-frag 'a capability nat
  | Undef
```

memval_type infers the type of a value.

```
fun memval-type :: 'a ccval ⇒ cctype
  where
  memval-type v = (case v of
     Uint8-v  - ⇒ Uint8
   | Sint8-v  - ⇒ Sint8
   | Uint16-v - ⇒ Uint16
   | Sint16-v - ⇒ Sint16
   | Uint32-v - ⇒ Uint32
   | Sint32-v - ⇒ Sint32
   | Uint64-v - ⇒ Uint64
   | Sint64-v - ⇒ Sint64
   | Cap-v    - ⇒ Cap
   | Cap-v-frag - - ⇒ Uint8)
```

1.2 Primitive Value Conversion and Cast Proof

In this subsection, we provide proofs for the conversion between words and list of words. We also provide proofs that casting primitive values is correct. These will be used by the `load` and `store` operations in the memory model.

```
abbreviation encode-u8 :: nat ⇒ 8 word
  where
  encode-u8 x ≡ word-of-nat x

abbreviation decode-u8 :: 8 word ⇒ nat
  where
  decode-u8 b ≡ unat b

abbreviation encode-u8-list :: 8 word ⇒ 8 word list
  where
```

encode-u8-list $w \equiv [w]$

abbreviation *decode-u8-list* :: *8 word list* ⇒ *8 word*
where
decode-u8-list ls ≡ *hd ls*

lemma *encode-decode-u8-list*:
$ls = [b] \Longrightarrow ls =$ *encode-u8-list* (*decode-u8-list ls*)
by *simp*

lemma *decode-encode-u8-list*:
$w =$ *decode-u8-list* (*encode-u8-list w*)
by *simp*

lemma *encode-decode-u8*:
$w =$ *encode-u8* (*decode-u8 w*)
by *simp*

lemma *decode-encode-u8*:
assumes $i \leq 2 \hat{} LENGTH(8) - 1$
shows $i =$ *decode-u8* (*encode-u8 i*)
by (*metis assms le-unat-uoi unat-minus-one-word*)

abbreviation *u64-split* :: *64 word* ⇒ *32 word list*
where
u64-split x ≡ (*word-rsplit* :: *64 word* ⇒ *32 word list*) *x*

abbreviation *u32-split* :: *32 word* ⇒ *16 word list*
where
u32-split x ≡ (*word-rsplit* :: *32 word* ⇒ *16 word list*) *x*

abbreviation *u16-split* :: *16 word* ⇒ *8 word list*
where
u16-split x ≡ (*word-rsplit* :: *16 word* ⇒ *8 word list*) *x*

abbreviation *cat-u16* :: *8 word list* ⇒ *16 word*
where
cat-u16 x ≡ (*word-rcat* :: *8 word list* ⇒ *16 word*) *x*

abbreviation *encode-u16* :: *nat* ⇒ *8 word list*
where
encode-u16 x ≡ *u16-split* (*word-of-nat x*)

abbreviation *decode-u16* :: *8 word list* ⇒ *nat*
where
decode-u16 x ≡ *unat* (*cat-u16 x*)

lemma *flatten-u16-length*:
length (*u16-split vs*) = *2*

by (*simp add*: *length-word-rsplit-even-size wsst-TYs*(*3*))

lemma *rsplit-rcat-eq*:
assumes *LENGTH*((*'b*::*len*)) *mod LENGTH*((*'a*::*len*)) = *0*
and *length w* = *LENGTH*(*'b*) *div LENGTH*(*'a*)
shows (*word-rsplit* :: *'b word* ⇒ *'a word list*) ((*word-rcat* :: *'a word list* ⇒ *'b word*) *w*) = *w*
by (*simp add*: *assms mod-0-imp-dvd size-word.rep-eq word-rsplit-rcat-size*)

lemma *rsplit-rcat-u16-eq*:
assumes *w* = [*a1*, *a2*]
shows (*word-rsplit* :: *16 word* ⇒ *8 word list*) ((*word-rcat* :: *8 word list* ⇒ *16 word*) *w*) = *w*
proof −
have *l1*: *length w* ∗ *8* = *16*
using *assms* **by** *clarsimp*
moreover have *l2*: *size* ((*word-rcat* :: *8 word list* ⇒ *16 word*) *w*) = *16*
using *assms*
by (*simp add*: *size-word.rep-eq*)
from *l1 l2* **have** *length w* ∗ *8* = *size* ((*word-rcat* :: *8 word list* ⇒ *16 word*) *w*)
by *argo*
thus *?thesis*
by (*metis l1 l2 len8 word-rsplit-rcat-size*)
qed

lemma *encode-decode-u16*:
assumes *w* = [*a*, *b*]
shows *w* = *encode-u16* (*decode-u16 w*)
by (*simp add*: *assms rsplit-rcat-eq*)

lemma *cat-flatten-u16-eq*:
cat-u16 (*u16-split w*) = *w*
by (*simp add*: *word-rcat-rsplit*)

lemma *decode-encode-u16*:
assumes *i* ≤ *2* ^ *LENGTH*(*16*) − *1*
shows *i* = *decode-u16* (*encode-u16 i*)
by (*metis assms cat-flatten-u16-eq le-unat-uoi unat-minus-one-word*)

abbreviation *flatten-u32* :: *32 word* ⇒ *8 word list*
where
flatten-u32 x ≡ (*word-rsplit* :: *32 word* ⇒ *8 word list*) *x*

abbreviation *cat-u32* :: *8 word list* ⇒ *32 word*
where
cat-u32 x ≡ (*word-rcat* :: *8 word list* ⇒ *32 word*) *x*

abbreviation *encode-u32* :: *nat* ⇒ *8 word list*

where
encode-u32 x ≡ *flatten-u32* (*word-of-nat x*)

abbreviation *decode-u32* :: *8 word list* ⇒ *nat*
where
decode-u32 i ≡ *unat* (*cat-u32 i*)

lemma *flatten-u32-length*:
length (*flatten-u32 vs*) = *4*
by (*simp add*: *length-word-rsplit-even-size wsst-TYs*(*3*))

lemma *rsplit-rcat-u32-eq*:
assumes *w* = [*a1*, *a2*, *b1*, *b2*]
shows (*word-rsplit* :: *32 word* ⇒ *8 word list*) ((*word-rcat* :: *8 word list* ⇒ *32 word*) *w*) = *w*
using *rsplit-rcat-eq assms*
by *force*

lemma *encode-decode-u32*:
assumes *w* = [*a1*, *a2*, *b1*, *b2*]
shows *w* = *encode-u32* (*decode-u32 w*)
using *assms*
by (*simp add*: *rsplit-rcat-u32-eq*)

lemma *cat-flatten-u32-eq*:
cat-u32 (*flatten-u32 w*) = *w*
by (*simp add*: *word-rcat-rsplit*)

lemma *decode-encode-u32*:
assumes *i* ≤ *2* ^ *LENGTH*(*32*) − *1*
shows *i* = *decode-u32* (*encode-u32 i*)
by (*metis assms le-unat-uoi unat-minus-one-word word-rcat-rsplit*)

abbreviation *flatten-u64* :: *64 word* ⇒ *8 word list*
where
flatten-u64 x ≡ (*word-rsplit* :: *64 word* ⇒ *8 word list*) *x*

abbreviation *cat-u64* :: *8 word list* ⇒ *64 word*
where
cat-u64 x ≡ *word-rcat x*

abbreviation *encode-u64* :: *nat* ⇒ *8 word list*
where
encode-u64 x ≡ *flatten-u64* (*word-of-nat x*)

abbreviation *decode-u64* :: *8 word list* ⇒ *nat*
where
decode-u64 x ≡ *unat* (*cat-u64 x*)

lemma *flatten-u64-length*:
length (*flatten-u64 vs*) = *8*
by (*simp add*: *length-word-rsplit-even-size wsst-TYs*(*3*))

lemma *encode-decode-u64*:
assumes *w* = [*a1*, *a2*, *b1*, *b2*, *c1*, *c2*, *d1*, *d2*]
shows *w* = *encode-u64* (*decode-u64 w*)
using *assms*
by (*simp add*: *rsplit-rcat-eq*)

lemma *cat-flatten-u64-eq*:
cat-u64 (*flatten-u64 w*) = *w*
by (*simp add*: *word-rcat-rsplit*)

lemma *decode-encode-u64*:
assumes *i* ≤ *2* ^ *LENGTH*(*64*) − *1*
shows *i* = *decode-u64* (*encode-u64 i*)
by (*metis assms le-unat-uoi unat-minus-one-word word-rcat-rsplit*)

abbreviation *encode-s8* :: *int* ⇒ *8 sword*
where
encode-s8 x ≡ *word-of-int x*

abbreviation *decode-s8* :: *8 sword* ⇒ *int*
where
decode-s8 b ≡ *sint b*

abbreviation *encode-s8-list* :: *8 sword* ⇒ *8 word list*
where
encode-s8-list w ≡ [*SCAST*(*8 signed* → *8*) *w*]

abbreviation *decode-s8-list* :: *8 word list* ⇒ *8 sword*
where
decode-s8-list ls ≡ *UCAST*(*8* → *8 signed*) (*hd ls*)

lemma *encode-decode-s8-list*:
ls = [*b*] ⟹ *ls* = *encode-s8-list* (*decode-s8-list ls*)
by *simp*

lemma *decode-encode-s8-list*:
w = *decode-s8-list* (*encode-s8-list w*)
by *simp*

lemma *encode-decode-s8*:
w = *encode-s8* (*decode-s8 w*)
by *simp*

lemma *decode-encode-s8*:
assumes − (*2* ^ (*LENGTH*(*8*) − *1*)) ≤ *i*

and $i < 2 \hat{} (LENGTH(8) - 1)$
shows $i = decode\text{-}s8\ (encode\text{-}s8\ i)$
by (*metis assms More-Word.sint-of-int-eq len-signed*)

abbreviation *s64-split* :: *64 sword* ⇒ *32 word list*
where
s64-split x ≡ (*word-rsplit* :: *64 sword* ⇒ *32 word list*) *x*

abbreviation *s32-split* :: *32 sword* ⇒ *16 word list*
where
s32-split x ≡ (*word-rsplit* :: *32 sword* ⇒ *16 word list*) *x*

abbreviation *s16-split* :: *16 sword* ⇒ *8 word list*
where
s16-split x ≡ (*word-rsplit* :: *16 sword* ⇒ *8 word list*) *x*

abbreviation *cat-s16* :: *8 word list* ⇒ *16 sword*
where
cat-s16 x ≡ (*word-rcat* :: *8 word list* ⇒ *16 sword*) *x*

abbreviation *encode-s16* :: *int* ⇒ *8 word list*
where
encode-s16 x ≡ *s16-split* (*word-of-int x*)

abbreviation *decode-s16* :: *8 word list* ⇒ *int*
where
decode-s16 x ≡ *sint* (*cat-s16 x*)

lemma *flatten-s16-length*:
length (*s16-split vs*) = *2*
by (*simp add*: *length-word-rsplit-even-size wsst-TYs*(*3*))

lemma *rsplit-rcat-s16-eq*:
assumes *w* = [*a1*, *a2*]
shows (*word-rsplit* :: *16 sword* ⇒ *8 word list*) ((*word-rcat* :: *8 word list* ⇒ *16 sword*) *w*) = *w*
proof −
have *l1*: *length w* ∗ *8* = *16*
using *assms* **by** *clarsimp*
moreover have *l2*: *size* ((*word-rcat* :: *8 word list* ⇒ *16 sword*) *w*) = *16*
using *assms*
by (*simp add*: *size-word.rep-eq*)
from *l1 l2* **have** *length w* ∗ *8* = *size* ((*word-rcat* :: *8 word list* ⇒ *16 sword*) *w*)
by *argo*
thus *?thesis*
by (*simp add*: *word-rsplit-rcat-size*)
qed

lemma *encode-decode-s16*:
assumes $w = [a, b]$
shows w = *encode-s16* (*decode-s16* w)
by (*simp add*: *assms rsplit-rcat-eq*)

lemma *cat-flatten-s16-eq*:
cat-s16 (*s16-split* w) = w
by (*simp add*: *word-rcat-rsplit*)

lemma *decode-encode-s16*:
assumes $-(2\ \hat{}\ (LENGTH(16) - 1)) \leq i$
and $i < 2\ \hat{}\ (LENGTH(16) - 1)$
shows i = *decode-s16* (*encode-s16* i)
by (*metis assms cat-flatten-s16-eq len-signed sint-of-int-eq*)

abbreviation *flatten-s32* :: *32 sword* ⇒ *8 word list*
where
flatten-s32 $x \equiv$ (*word-rsplit* :: *32 sword* ⇒ *8 word list*) x

abbreviation *cat-s32* :: *8 word list* ⇒ *32 sword*
where
cat-s32 $x \equiv$ (*word-rcat* :: *8 word list* ⇒ *32 sword*) x

abbreviation *encode-s32* :: *int* ⇒ *8 word list*
where
encode-s32 $x \equiv$ *flatten-s32* (*word-of-int* x)

abbreviation *decode-s32* :: *8 word list* ⇒ *int*
where
decode-s32 $i \equiv$ *sint* (*cat-s32* i)

lemma *flatten-s32-length*:
length (*flatten-s32* vs) = *4*
by (*simp add*: *length-word-rsplit-even-size wsst-TYs*(*3*))

lemma *rsplit-rcat-s32-eq*:
assumes $w = [a1, a2, b1, b2]$
shows (*word-rsplit* :: *32 sword* ⇒ *8 word list*) ((*word-rcat* :: *8 word list* ⇒ *32 sword*) w) = w
using *rsplit-rcat-eq assms*
by *force*

lemma *encode-decode-s32*:
assumes $w = [a1, a2, b1, b2]$
shows w = *encode-s32* (*decode-s32* w)
using *assms*
by (*simp add*: *rsplit-rcat-s32-eq*)

lemma *decode-encode-s32*:

assumes $-(2\ \hat{}\ (LENGTH(32)\ -\ 1)) \leq i$
and $i < 2\ \hat{}\ (LENGTH(32)\ -\ 1)$
shows $i = decode\text{-}s32\ (encode\text{-}s32\ i)$
by (*metis assms len-signed sint-of-int-eq word-rcat-rsplit*)

abbreviation *flatten-s64* :: *64 sword* ⇒ *8 word list*
where
flatten-s64 x ≡ (*word-rsplit* :: *64 sword* ⇒ *8 word list*) *x*

lemma *flatten-s64-length*:
length (*flatten-s64 vs*) = *8*
by (*simp add*: *length-word-rsplit-even-size wsst-TYs*(*3*))

abbreviation *cat-s64* :: *8 word list* ⇒ *64 sword*
where
cat-s64 x ≡ *word-rcat x*

abbreviation *encode-s64* :: *int* ⇒ *8 word list*
where
encode-s64 x ≡ *flatten-s64* (*word-of-int x*)

abbreviation *decode-s64* :: *8 word list* ⇒ *int*
where
decode-s64 x ≡ *sint* (*cat-s64 x*)

lemma *encode-decode-s64*:
assumes $w = [a1,\ a2,\ b1,\ b2,\ c1,\ c2,\ d1,\ d2]$
shows $w = encode\text{-}s64\ (decode\text{-}s64\ w)$
using *assms*
by (*simp add*: *rsplit-rcat-eq*)

lemma *decode-encode-s64*:
assumes $-(2\ \hat{}\ (LENGTH(64)\ -\ 1)) \leq i$
and $i < 2\ \hat{}\ (LENGTH(64)\ -\ 1)$
shows $i = decode\text{-}s64\ (encode\text{-}s64\ i)$
by (*metis assms len-signed sint-of-int-eq word-rcat-rsplit*)

definition *word-of-integer* :: *integer* ⇒ *'a*::*len word*
where
word-of-integer x ≡ *word-of-int* (*int-of-integer x*)

definition *sword-of-integer* :: *integer* ⇒ *'a*::*len sword*
where
sword-of-integer x ≡ *word-of-int* (*int-of-integer x*)

definition *integer-of-word* :: *'a*::*len word* ⇒ *integer*
where
integer-of-word x ≡ *integer-of-int* (*uint x*)

definition *integer-of-sword* :: *'a::len sword* ⇒ *integer*
where
integer-of-sword x ≡ *integer-of-int* (*sint x*)

lemma *word-integer-eq*:
word-of-integer (*integer-of-word w*) = *w*
unfolding *word-of-integer-def integer-of-word-def*
by (*metis int-of-integer-of-int integer-of-int-eq-of-int word-uint.Rep-inverse'*)

lemma *sword-integer-eq*:
sword-of-integer (*integer-of-sword w*) = *w*
unfolding *sword-of-integer-def integer-of-sword-def*
by (*metis int-of-integer-of-int integer-of-int-eq-of-int word-sint.Rep-inverse'*)

lemma *integer-word-bounded-eq*:
assumes *0* ≤ *i*
assumes *i* ≤ *2* ^ *LENGTH*('*a*::*len*) − *1*
shows *integer-of-word* ((*word-of-integer* :: *integer* ⇒ '*a word*) *i*) = *i*
unfolding *integer-of-word-def word-of-integer-def*
using *assms*
by (*metis integer-less-eq-iff integer-of-int-eq-of-int minus-integer.rep-eq of-int-0-le-iff of-int-eq-1-iff of-int-eq-numeral-power-cancel-iff of-int-integer-of word-of-int-inverse zle-diff1-eq*)

lemma *integer-sword-bounded-eq*:
assumes − (*2* ^ (*LENGTH*('*a*::*len*) − *1*)) ≤ *i*
and *i* < *2* ^ (*LENGTH*('*a*) − *1*)
shows *integer-of-sword* ((*sword-of-integer* :: *integer* ⇒ '*a sword*) *i*) = *i*
unfolding *integer-of-sword-def sword-of-integer-def*
using *signed-take-bit-int-eq-self assms*
by (*smt* (*verit*) *diff-numeral-special*(*11*) *int-of-integer-numeral integer-less-eq-iff integer-of-int-eq-of-int len-signed minus-integer.rep-eq numeral-power-eq-of-int-cancel-iff of-int-integer-of of-int-power-less-of-int-cancel-iff one-integer.rep-eq sint-of-int-eq uminus-integer.rep-eq*)

definition *word8-of-integer* :: *integer* ⇒ *8 word*
where
word8-of-integer ≡ *word-of-integer*

definition *word16-of-integer* :: *integer* ⇒ *16 word*
where
word16-of-integer ≡ *word-of-integer*

definition *word32-of-integer* :: *integer* ⇒ *32 word*
where
word32-of-integer ≡ *word-of-integer*

definition *word64-of-integer* :: *integer* ⇒ *64 word*
where

word64-of-integer ≡ *word-of-integer*

definition *integer-of-word8* :: *8 word* ⇒ *integer*
where
integer-of-word8 ≡ *integer-of-word*

definition *integer-of-word16* :: *16 word* ⇒ *integer*
where
integer-of-word16 ≡ *integer-of-word*

definition *integer-of-word32* :: *32 word* ⇒ *integer*
where
integer-of-word32 ≡ *integer-of-word*

definition *integer-of-word64* :: *64 word* ⇒ *integer*
where
integer-of-word64 ≡ *integer-of-word*

lemma *word8-integer-eq*:
word8-of-integer (*integer-of-word8 w*) = *w*
unfolding *word8-of-integer-def integer-of-word8-def*
using *word-integer-eq*
by *blast*

lemma *word16-integer-eq*:
word16-of-integer (*integer-of-word16 w*) = *w*
unfolding *word16-of-integer-def integer-of-word16-def*
using *word-integer-eq*
by *blast*

lemma *word32-integer-eq*:
word32-of-integer (*integer-of-word32 w*) = *w*
unfolding *word32-of-integer-def integer-of-word32-def*
using *word-integer-eq*
by *blast*

lemma *word64-integer-eq*:
word64-of-integer (*integer-of-word64 w*) = *w*
unfolding *word64-of-integer-def integer-of-word64-def*
using *word-integer-eq*
by *blast*

lemma *integer-word8-bounded-eq*:
assumes *0* ≤ *i*
and *i* ≤ *2* ^ *LENGTH*(*8*) − *1*
shows *integer-of-word8* (*word8-of-integer i*) = *i*
unfolding *word8-of-integer-def integer-of-word8-def*
using *integer-word-bounded-eq assms*
by *blast*

lemma *integer-word16-bounded-eq*:
  assumes *0* ≤ *i*
   and *i* ≤ *2* ^ *LENGTH*(*16*) − *1*
  shows *integer-of-word16* (*word16-of-integer i*) = *i*
  unfolding *word16-of-integer-def integer-of-word16-def*
  using *integer-word-bounded-eq assms*
  by *blast*

lemma *integer-word32-bounded-eq*:
  assumes *0* ≤ *i*
   and *i* ≤ *2* ^ *LENGTH*(*32*) − *1*
  shows *integer-of-word32* (*word32-of-integer i*) = *i*
  unfolding *word32-of-integer-def integer-of-word32-def*
  using *integer-word-bounded-eq assms*
  by *blast*

lemma *integer-word64-bounded-eq*:
  assumes *0* ≤ *i*
   and *i* ≤ *2* ^ *LENGTH*(*64*) − *1*
  shows *integer-of-word64* (*word64-of-integer i*) = *i*
  unfolding *word64-of-integer-def integer-of-word64-def*
  using *integer-word-bounded-eq assms*
  by *blast*

definition *sword8-of-integer* :: *integer* ⇒ *8 sword*
  where
  sword8-of-integer ≡ *sword-of-integer*

definition *sword16-of-integer* :: *integer* ⇒ *16 sword*
  where
  sword16-of-integer ≡ *sword-of-integer*

definition *sword32-of-integer* :: *integer* ⇒ *32 sword*
  where
  sword32-of-integer ≡ *sword-of-integer*

definition *sword64-of-integer* :: *integer* ⇒ *64 sword*
  where
  sword64-of-integer ≡ *sword-of-integer*

definition *integer-of-sword8* :: *8 sword* ⇒ *integer*
  where
  integer-of-sword8 ≡ *integer-of-sword*

definition *integer-of-sword16* :: *16 sword* ⇒ *integer*
  where
  integer-of-sword16 ≡ *integer-of-sword*

definition *integer-of-sword32* :: *32 sword* ⇒ *integer*
where
integer-of-sword32 ≡ *integer-of-sword*

definition *integer-of-sword64* :: *64 sword* ⇒ *integer*
where
integer-of-sword64 ≡ *integer-of-sword*

lemma *sword8-integer-eq*:
sword8-of-integer (*integer-of-sword8 w*) = *w*
unfolding *sword8-of-integer-def integer-of-sword8-def*
using *sword-integer-eq*
by *blast*

lemma *sword16-integer-eq*:
sword16-of-integer (*integer-of-sword16 w*) = *w*
unfolding *sword16-of-integer-def integer-of-sword16-def*
using *sword-integer-eq*
by *blast*

lemma *sword32-integer-eq*:
sword32-of-integer (*integer-of-sword32 w*) = *w*
unfolding *sword32-of-integer-def integer-of-sword32-def*
using *sword-integer-eq*
by *blast*

lemma *sword64-integer-eq*:
sword64-of-integer (*integer-of-sword64 w*) = *w*
unfolding *sword64-of-integer-def integer-of-sword64-def*
using *sword-integer-eq*
by *blast*

lemma *integer-sword8-bounded-eq*:
assumes − (*2* ^ (*LENGTH*(*8*) − *1*)) ≤ *i*
and *i* < *2* ^ (*LENGTH*(*8*) − *1*)
shows *integer-of-sword8* (*sword8-of-integer i*) = *i*
unfolding *sword8-of-integer-def integer-of-sword8-def*
using *integer-sword-bounded-eq assms*
by *metis*

lemma *integer-sword16-bounded-eq*:
assumes − (*2* ^ (*LENGTH*(*16*) − *1*)) ≤ *i*
and *i* < *2* ^ (*LENGTH*(*16*) − *1*)
shows *integer-of-sword16* (*sword16-of-integer i*) = *i*
unfolding *sword16-of-integer-def integer-of-sword16-def*
using *integer-sword-bounded-eq assms*
by *metis*

lemma *integer-sword32-bounded-eq*:

assumes $-(2\ \hat{}\ (LENGTH(32) - 1)) \leq i$
and $i < 2\ \hat{}\ (LENGTH(32) - 1)$
shows *integer-of-sword32* (*sword32-of-integer i*) = *i*
unfolding *sword32-of-integer-def integer-of-sword32-def*
using *integer-sword-bounded-eq assms*
by *metis*

lemma *integer-sword64-bounded-eq*:
assumes $-(2\ \hat{}\ (LENGTH(64) - 1)) \leq i$
and $i < 2\ \hat{}\ (LENGTH(64) - 1)$
shows *integer-of-sword64* (*sword64-of-integer i*) = *i*
unfolding *sword64-of-integer-def integer-of-sword64-def*
using *integer-sword-bounded-eq assms*
by *metis*

lemmas *flatten-types-length* = *flatten-u16-length flatten-s16-length flatten-u32-length flatten-s32-length flatten-u64-length flatten-s64-length*

cast_val is an executable code that ensures easy casting of values. This value cast function is used within the Gillian framework [7, 5, 4, 1].

definition *cast-val* :: *String.literal* ⇒ *integer* ⇒ *integer*
where
cast-val s i ≡
if s = *STR ''uint8''* *then integer-of-word8* (*word8-of-integer i*)
else if s = *STR ''int8''* *then integer-of-sword8* (*sword8-of-integer i*)
else if s = *STR ''uint16''* *then integer-of-word16* (*word16-of-integer i*)
else if s = *STR ''int16''* *then integer-of-sword16* (*sword16-of-integer i*)
else if s = *STR ''uint32''* *then integer-of-word32* (*word32-of-integer i*)
else if s = *STR ''int32''* *then integer-of-sword32* (*sword32-of-integer i*)
else if s = *STR ''uint64''* *then integer-of-word64* (*word64-of-integer i*)
else if s = *STR ''int64''* *then integer-of-sword64* (*sword64-of-integer i*)
else i

end
theory *CHERI-C-Concrete-Memory-Model*
imports *Preliminary-Library*
Separation-Algebra.Separation-Algebra
Containers.Containers
HOL−Library.Mapping
HOL−Library.Code-Target-Numeral
begin

2 CHERI-C Error System

In this section, we formalise the error system used by the memory model.

Below are coprocessor 2 excessptions thrown by the hardware. BadAddressViolation is not a coprocessor 2 exception but remains one given by

the hardware. This corresponds to CapErr in the paper [6].

datatype *c2errtype* =
  TagViolation
  | *PermitLoadViolation*
  | *PermitStoreViolation*
  | *PermitStoreCapViolation*
  | *PermitStoreLocalCapViolation*
  | *LengthViolation*
  | *BadAddressViolation*

These are logical errors produced by the language. In practice, Some of these errors would never be caught due to the inherent spatial safety guarantees given by capabilities. This corresponds to LogicErr in the paper [6].
NOTE: Unhandled corresponds to a custom error not mentioned in *logicerrtype*. One can provide the custom error as a string, but here, for custom errors, we leave it empty to simplify the proof. Ultimately, the important point is that the memory model can still catch custom errors.

datatype *logicerrtype* =
  UseAfterFree
  | *BufferOverrun*
  | *MissingResource*
  | *WrongMemVal*
  | *MemoryNotFreed*
  | *Unhandled String.literal*

We make the distinction between the error types. This corresponds to Err in the paper [6].

datatype *errtype* =
  C2Err c2errtype
  | *LogicErr logicerrtype*

Finally, we have the 'return' type $\mathcal{R}\ \rho$ in the paper [6].

datatype *'a result* =
  Success (*res*: *'a*)
  | *Error* (*err*: *errtype*)

In this theory, we concretise the notion of blocks

type-synonym *block* = *integer*
type-synonym *memcap* = *block mem-capability*
type-synonym *cap* = *block capability*

Because `sizeof` depends on the architecture, it shall be given via the memory model. We also use uncompressed capabilities.

definition *sizeof* :: *cctype* ⇒ *nat* ($|\text{-}|_\tau$)
  where
  sizeof τ ≡ *case* τ *of*
    Uint8 ⇒ *1*

```
| Sint8  ⇒ 1
| Uint16 ⇒ 2
| Sint16 ⇒ 2
| Uint32 ⇒ 4
| Sint32 ⇒ 4
| Uint64 ⇒ 8
| Sint64 ⇒ 8
| Cap ⇒ 32
```

We provide some helper lemmas

```
lemma size-type-align:
  assumes |t|_τ = x
  shows ∃ n. 2 ^ n = x
proof (cases t)
  case Uint8
  then show ?thesis
    using assms
    unfolding sizeof-def
    by fastforce
next
  case Sint8
  then show ?thesis
    using assms
    unfolding sizeof-def
    by fastforce
next
  case Uint16
  then show ?thesis
    using assms
    unfolding sizeof-def
    by (rule-tac x=1 in exI) fastforce
next
  case Sint16
  then show ?thesis
    using assms
    unfolding sizeof-def
    by (rule-tac x=1 in exI) fastforce
next
  case Uint32
  then show ?thesis
    using assms
    unfolding sizeof-def
    by (rule-tac x=2 in exI) fastforce
next
  case Sint32
  then show ?thesis
    using assms
    unfolding sizeof-def
    by (rule-tac x=2 in exI) fastforce
```

next
  case *Uint64*
  then show *?thesis*
    using *assms*
    unfolding *sizeof-def*
    by (*rule-tac x=3* **in** *exI*) *fastforce*
next
  case *Sint64*
  then show *?thesis*
    using *assms*
    unfolding *sizeof-def*
    by (*rule-tac x=3* **in** *exI*) *fastforce*
next
  case *Cap*
  then show *?thesis*
    using *assms*
    unfolding *sizeof-def*
    by (*rule-tac x=5* **in** *exI*) *fastforce*
qed

lemma *memval-size-u8*:
  $|$*memval-type* (*Uint8-v v*)$|_\tau$ = *1*
  unfolding *sizeof-def*
  by *fastforce*

lemma *memval-size-s8*:
  $|$*memval-type* (*Sint8-v v*)$|_\tau$ = *1*
  unfolding *sizeof-def*
  by *fastforce*

lemma *memval-size-u16*:
  $|$*memval-type* (*Uint16-v v*)$|_\tau$ = *2*
  unfolding *sizeof-def*
  by *fastforce*

lemma *memval-size-s16*:
  $|$*memval-type* (*Sint16-v v*)$|_\tau$ = *2*
  unfolding *sizeof-def*
  by *fastforce*

lemma *memval-size-u32*:
  $|$*memval-type* (*Uint32-v v*)$|_\tau$ = *4*
  unfolding *sizeof-def*
  by *fastforce*

lemma *memval-size-s32*:
  $|$*memval-type* (*Sint32-v v*)$|_\tau$ = *4*
  unfolding *sizeof-def*
  by *fastforce*

lemma *memval-size-u64*:
|memval-type (Uint64-v v)|$_\tau$ = 8
unfolding *sizeof-def*
by *fastforce*

lemma *memval-size-s64*:
|memval-type (Sint64-v v)|$_\tau$ = 8
unfolding *sizeof-def*
by *fastforce*

lemma *memval-size-cap*:
|memval-type (Cap-v v)|$_\tau$ = 32
unfolding *sizeof-def*
by *fastforce*

lemmas *memval-size-types = memval-size-u8 memval-size-s8 memval-size-u16 memval-size-s16 memval-size-u32 memval-size-s32 memval-size-u64 memval-size-s64 memval-size-cap*

corollary *memval-size-u16-eq-word-split-len*:
assumes *val = Uint16-v v*
shows *|memval-type val|$_\tau$ = length (u16-split v)*
using *assms memval-size-u16 flatten-u16-length*
by *force*

corollary *memval-size-s16-eq-word-split-len*:
assumes *val = Sint16-v v*
shows *|memval-type val|$_\tau$ = length (s16-split v)*
using *assms memval-size-s16 flatten-s16-length*
by *force*

corollary *memval-size-u32-eq-word-split-len*:
assumes *val = Uint32-v v*
shows *|memval-type val|$_\tau$ = length (flatten-u32 v)*
using *assms memval-size-u32 flatten-u32-length*
by *force*

corollary *memval-size-s32-eq-word-split-len*:
assumes *val = Sint32-v v*
shows *|memval-type val|$_\tau$ = length (flatten-s32 v)*
using *assms memval-size-s32 flatten-s32-length*
by *force*

corollary *memval-size-u64-eq-word-split-len*:
assumes *val = Uint64-v v*
shows *|memval-type val|$_\tau$ = length (flatten-u64 v)*
using *assms memval-size-u64 flatten-u64-length*
by *force*

corollary *memval-size-s64-eq-word-split-len*:
assumes *val* = *Sint64-v v*
shows $|$*memval-type val*$|_\tau$ = *length* (*flatten-s64 v*)
using *assms memval-size-s64 flatten-s64-length*
by *force*

lemma *sizeof-nonzero*:
$|t|_\tau > 0$
by (*simp add*: *sizeof-def split*: *cctype.split*)

We prove that integer is a countable type.

instance *int* :: *comp-countable* **..**

lemma *integer-encode-eq*: (*int-encode* ∘ *int-of-integer*) *x* = (*int-encode* ∘ *int-of-integer*) *y* ⟷ *x* = *y*
using *int-encode-eq integer-eq-iff*
by *auto*

instance *integer* :: *countable*
by (*rule countable-classI*[*of int-encode* ∘ *int-of-integer*]) (*simp only*: *integer-encode-eq*)

instance *integer* :: *comp-countable* **..**

3 Memory

In this section, we formalise the heap and prove some initial properties.

3.1 Definitions

First, we provide $\mathcal{V}_\mathcal{M}$—refer to [6] for the definition. We note that this representation allows us to make the distinction between what is a capability and what is a primitive value stored in memory. We can define a tag-preserving `memcpy` by checking ahead whether there are valid capabilities stored in memory or whether there are simply bytes. The downside to this approach is that overwriting primitive values to where capabilities were stored—and vice versa—will lead to an undefined load operation. However, this tends not to be a big problem, as (1) overwritten capabilities are tag-invalidated anyway, so the capabilities cannot be dereferenced even if the user obtained the capability somehow, and (2) for legacy C programs that do not have access to CHERI library functions, there is no way to access the metadata of the invalidated capabilities. For compatibility purposes, this imposes hardly any problems.

datatype *memval* =
Byte (*of-byte*: *8 word*)
| *ACap* (*of-cap*: *memcap*) (*of-nth*: *nat*)

In general, the bound is irrelevant, as capability bound ensures spatial safety. We add bounds in the heap so that we can incorporate *hybrid* CHERI C programs in the future, where pointers and capabilities co-exist, but strictly speaking, this is not required in *purecap* CHERI C programs, which is what this memory model is based on. Ultimately, this is the pair of mapping defined in the paper [6].

record *object* =
  bounds :: *nat* × *nat*
  content :: (*nat*, *memval*) *mapping*
  tags :: (*nat*, *bool*) *mapping*

t is the datatype that allows us to make the distinction between blocks that are freed and blocks that are valid.

datatype *t* =
  Freed
  | *Map* (*the-map*: *object*)

heap_map in heap is essentially $\mathcal{H}$ defined in the paper [6]. We extend the structure and keep track of the next block for the allocator for efficiency—much like how CompCert's C memory model does this [3].

record *heap* =
  next-block :: *block*
  heap-map :: (*block*, *t*) *mapping*

definition *memval-is-byte* :: *memval* ⇒ *bool*
  where
  memval-is-byte m ≡ *case m of Byte - ⇒ True* | *ACap - - ⇒ False*

abbreviation *memval-is-cap* :: *memval* ⇒ *bool*
  where
  memval-is-cap m ≡ ¬ *memval-is-byte m*

lemma *memval-byte*:
  memval-is-byte m ⟹ ∃ *b*. *m* = *Byte b*
  by (*simp add*: *memval-is-byte-def split*: *memval.split-asm*)

lemma *memval-byte-not-memcap*:
  memval-is-byte m ⟹ *m* ≠ *ACap c n*
  by (*simp add*: *memval-is-byte-def split*: *memval.split-asm*)

lemma *memval-memcap*:
  memval-is-cap m ⟹ ∃ *c n*. *m* = *ACap c n*
  by (*simp add*: *memval-is-byte-def split*: *memval.split-asm*)

lemma *memval-memcap-not-byte*:
  memval-is-cap m ⟹ *m* ≠ *Byte b*
  by (*simp add*: *memval-is-byte-def split*: *memval.split-asm*)

3.2 Properties

We prove that the heap is an instance of separation algebra.

instantiation *unit* :: *cancellative-sep-algebra*
begin
definition *0* ≡ ()
definition *u1* + *u2* = ()
definition (*u1*::*unit*) ## *u2* ≡ *True*
instance
by (*standard*; (*blast* | *simp add*: *sep-disj-unit-def*))
end

instantiation *nat* :: *cancellative-sep-algebra*
begin
definition (*n1*::*nat*) ## *n2* ≡ *True*
instance
by (*standard*; (*blast* | *simp add*: *sep-disj-nat-def*))
end

This proof ultimately shows that heap_map forms a separation algebra.

instantiation *mapping* :: (*type*, *type*) *cancellative-sep-algebra*
begin

definition *zero-map-def*: *0* ≡ *Mapping.empty*
definition *plus-map-def*: *m1* + *m2* ≡ *Mapping* ((*Mapping.lookup m1*) ++ (*Mapping.lookup m2*))
definition *sep-disj-map-def*: *m1* ## *m2* ≡ *Mapping.keys m1* ∩ *Mapping.keys m2* = {}

instance
proof
show ⋀*x* :: ('*a*, '*b*) *mapping*. *x* ## *0*
by (*simp add*: *sep-disj-map-def zero-map-def*)
next
show ⋀*x* :: ('*a*, '*b*) *mapping*. *x* + *0* = *x*
by (*simp add*: *sep-disj-map-def Mapping.keys-def zero-map-def plus-map-def Mapping.empty.abs-eq Mapping.lookup.abs-eq mapping-eqI*)
next
show ⋀*x y* :: ('*a*, '*b*) *mapping*. *x* ## *y* ⟹ *y* ## *x*
using *sep-disj-map-def*
by *auto*
next
show ⋀*x y* :: ('*a*, '*b*) *mapping*. *x* ## *y* ⟹ *x* + *y* = *y* + *x*
using *map-add-comm*
by (*fastforce simp add*: *sep-disj-map-def Mapping.keys-def zero-map-def plus-map-def Mapping.lookup-def*)
next
show ⋀*x y z* :: ('*a*, '*b*) *mapping*. ⟦*x* ## *y*; *y* ## *z*; *x* ## *z*⟧ ⟹ *x* + *y* + *z* = *x* + (*y* + *z*)

by (*simp add*: *sep-disj-map-def Mapping.keys-def zero-map-def plus-map-def Mapping.lookup-def Mapping-inverse*)
next
show $\bigwedge x\ y\ z :: ('a, 'b)\ mapping.\ [\![x\ \#\#\ y + z;\ y\ \#\#\ z]\!] \Longrightarrow x\ \#\#\ y$
by (*simp add*: *sep-disj-map-def Mapping.keys-def zero-map-def plus-map-def Mapping.lookup-def map-add-comm*)
(*metis* (*no-types*, *opaque-lifting*) *Mapping.keys.abs-eq Mapping.keys.rep-eq disjoint-iff domIff map-add-dom-app-simps*(*3*))
next
show $\bigwedge x\ y\ z :: ('a, 'b)\ mapping.\ [\![x\ \#\#\ y + z;\ y\ \#\#\ z]\!] \Longrightarrow x + y\ \#\#\ z$
by (*simp add*: *sep-disj-map-def Mapping.keys-def zero-map-def plus-map-def Mapping.lookup-def map-add-comm Mapping-inverse inf-commute inf-sup-distrib1*)
next
show $\bigwedge x\ z\ y :: ('a, 'b)\ mapping.\ [\![x + z = y + z;\ x\ \#\#\ z;\ y\ \#\#\ z]\!] \Longrightarrow x = y$
by (*simp add*: *plus-map-def sep-disj-map-def*)
(*metis* (*mono-tags*, *opaque-lifting*) *Mapping.keys.abs-eq Mapping.lookup.abs-eq disjoint-iff domIff map-add-dom-app-simps*(*3*) *mapping-eqI*)
qed
end

instantiation *heap-ext* :: (*cancellative-sep-algebra*) *cancellative-sep-algebra*
begin
definition *0* :: *'a heap-scheme* ≡ (| *next-block* = *0*, *heap-map* = *Mapping.empty*, ... = *0* |)
definition (*m1* :: *'a heap-scheme*) + (*m2* :: *'a heap-scheme*) ≡
(| *next-block* = *next-block m1* + *next-block m2*,
heap-map = *Mapping* ((*Mapping.lookup* (*heap-map m1*)) ++ (*Mapping.lookup* (*heap-map m2*))),
... = *heap.more m1* + *heap.more m2* |)
definition (*m1* :: *'a heap-scheme*) ## (*m2* :: *'a heap-scheme*) ≡
Mapping.keys (*heap-map m1*) ∩ *Mapping.keys* (*heap-map m2*) = {}
∧ *heap.more m1* ## *heap.more m2*
instance
proof
show $\bigwedge x :: 'a\ heap\text{-}scheme.\ x\ \#\#\ 0$
by (*simp add*: *plus-heap-ext-def sep-disj-heap-ext-def zero-heap-ext-def*)
next
show $\bigwedge x\ y :: 'a\ heap\text{-}scheme.\ x\ \#\#\ y \Longrightarrow y\ \#\#\ x$
by (*simp add*: *plus-heap-ext-def sep-disj-heap-ext-def zero-heap-ext-def inf-commute sep-disj-commute*)
next
show $\bigwedge x :: 'a\ heap\text{-}scheme.\ x + 0 = x$
by (*simp add*: *plus-heap-ext-def sep-disj-heap-ext-def zero-heap-ext-def inf-commute sep-disj-commute Mapping.empty-def Mapping.lookup.abs-eq*)
(*simp add*: *Mapping.lookup.rep-eq rep-inverse*)
next
show $\bigwedge x\ y :: 'a\ heap\text{-}scheme.\ x\ \#\#\ y \Longrightarrow x + y = y + x$
by (*simp add*: *plus-heap-ext-def sep-disj-heap-ext-def zero-heap-ext-def*)
(*metis keys-dom-lookup map-add-comm sep-add-commute*)

next
show $\bigwedge x\ y\ z :: 'a\ heap\text{-}scheme.\ [\![x\ \#\#\ y;\ y\ \#\#\ z;\ x\ \#\#\ z]\!] \Longrightarrow x + y + z = x + (y + z)$
by (*simp add*: *plus-heap-ext-def sep-disj-heap-ext-def zero-heap-ext-def Mapping.lookup.abs-eq sep-add-assoc*)
next
show $\bigwedge x\ y\ z :: 'a\ heap\text{-}scheme.\ [\![x\ \#\#\ y + z;\ y\ \#\#\ z]\!] \Longrightarrow x\ \#\#\ y$
by (*simp add*: *plus-heap-ext-def sep-disj-heap-ext-def zero-heap-ext-def*)
(*metis plus-map-def sep-disj-addD sep-disj-map-def*)
next
show $\bigwedge x\ y\ z :: 'a\ heap\text{-}scheme.\ [\![x\ \#\#\ y + z;\ y\ \#\#\ z]\!] \Longrightarrow x + y\ \#\#\ z$
by (*simp add*: *plus-heap-ext-def sep-disj-heap-ext-def zero-heap-ext-def Mapping.lookup.abs-eq disjoint-iff keys-dom-lookup sep-disj-addI1*)
next
show $\bigwedge x\ z\ y :: 'a\ heap\text{-}scheme.\ [\![x + z = y + z;\ x\ \#\#\ z;\ y\ \#\#\ z]\!] \Longrightarrow x = y$
by (*simp add*: *plus-heap-ext-def sep-disj-heap-ext-def zero-heap-ext-def*)
(*metis heap.equality plus-map-def sep-add-cancel sep-disj-map-def*)
qed
end

instantiation *mem-capability-ext* :: (*comp-countable*, *zero*) *zero*
begin
definition *0* :: ('*a*, '*b*) *mem-capability-scheme* ≡
(| *block-id* = *0*,
offset = *0*,
base = *0*,
len = *0*,
perm-load = *False*,
perm-cap-load = *False*,
perm-store = *False*,
perm-cap-store = *False*,
perm-cap-store-local = *False*,
perm-global = *False*,
... = *0* |)
instance ..
end

subclass (**in** *comp-countable*) *zero* **.**

instantiation *capability-ext* :: (*zero*) *zero*
begin
definition *0* ≡ (| *tag* = *False*, ... = *0* |)
instance ..
end

Section 4.5 of CHERI C/C++ Programming Guide defines what a `NULL` capability is [8].

definition *null-capability* :: *cap* (*NULL*)
where

NULL ≡ *0*

context
notes *null-capability-def*[*simp*]
begin

lemma *null-capability-block-id*[*simp*]:
block-id NULL = *0*
by (*simp add*: *zero-mem-capability-ext-def*)

lemma *null-capability-offset*[*simp*]:
offset NULL = *0*
by (*simp add*: *zero-mem-capability-ext-def*)

lemma *null-capability-base*[*simp*]:
base NULL = *0*
by (*simp add*: *zero-mem-capability-ext-def*)

lemma *null-capability-len*[*simp*]:
len NULL = *0*
by (*simp add*: *zero-mem-capability-ext-def*)

lemma *null-capability-perm-load*[*simp*]:
perm-load NULL = *False*
by (*simp add*: *zero-mem-capability-ext-def*)

lemma *null-capability-perm-cap-load*[*simp*]:
perm-cap-load NULL = *False*
by (*simp add*: *zero-mem-capability-ext-def*)

lemma *null-capability-perm-store*[*simp*]:
perm-store NULL = *False*
by (*simp add*: *zero-mem-capability-ext-def*)

lemma *null-capability-perm-cap-store*[*simp*]:
perm-cap-store NULL = *False*
by (*simp add*: *zero-mem-capability-ext-def*)

lemma *null-capability-perm-cap-store-local*[*simp*]:
perm-cap-store-local NULL = *False*
by (*simp add*: *zero-mem-capability-ext-def*)

lemma *null-capability-tag*[*simp*]:
tag NULL = *False*
by (*simp add*: *zero-capability-ext-def zero-mem-capability-ext-def*)

end

Here, we define the initial heap.

definition *init-heap* :: *heap*
where
init-heap ≡ *0* ⦇ *next-block* := *1* ⦈

abbreviation *cap-offset* :: *nat* ⇒ *nat*
where
cap-offset p ≡ *if p mod* $|Cap|_\tau$ = *0 then p else p* − *p mod* $|Cap|_\tau$

We state the well-formedness property $\mathcal{W}_f^{\mathcal{C}}$ stated in the paper [6].

definition *wellformed* :: (*block*, *t*) *mapping* ⇒ *bool* ($\mathcal{W}_{\mathfrak{f}}$/(-/))
where
$\mathcal{W}_{\mathfrak{f}}$(*h*) ≡
∀ *b obj*. *Mapping.lookup h b* = *Some* (*Map obj*)
⟶ *Set.filter* (λ*x*. *x mod* $|Cap|_\tau$ ≠ *0*) (*Mapping.keys* (*tags obj*)) = {}

lemma *init-heap-empty*:
Mapping.keys (*heap-map init-heap*) = {}
unfolding *init-heap-def zero-heap-ext-def*
by *simp*

Below shows $\mathcal{W}_f^{\mathcal{C}}(\mu_0)$

lemma *init-wellformed*:
$\mathcal{W}_{\mathfrak{f}}$(*heap-map init-heap*)
unfolding *init-heap-def wellformed-def zero-heap-ext-def*
by *simp*

lemma *mapping-lookup-disj1*:
m1 ## *m2* ⟹ *Mapping.lookup m1 n* = *Some x* ⟹ *Mapping.lookup* (*m1* + *m2*) *n* = *Some x*
by (*metis Mapping.keys.rep-eq Mapping.lookup.abs-eq Mapping.lookup.rep-eq disjoint-iff is-none-simps*(*2*) *keys-is-none-rep map-add-dom-app-simps*(*3*) *plus-map-def sep-disj-map-def*)

lemma *mapping-lookup-disj2*:
m1 ## *m2* ⟹ *Mapping.lookup m2 n* = *Some x* ⟹ *Mapping.lookup* (*m1* + *m2*) *n* = *Some x*
by (*metis Mapping.keys.rep-eq Mapping.lookup.abs-eq Mapping.lookup.rep-eq disjoint-iff is-none-simps*(*2*) *keys-is-none-rep map-add-dom-app-simps*(*2*) *plus-map-def sep-disj-map-def*)

Below shows that well-formedness is composition-compatible

lemma *heap-map h1* ## *heap-map h2* ⟹ $\mathcal{W}_{\mathfrak{f}}$(*heap-map h1* + *heap-map h2*)
⟹ $\mathcal{W}_{\mathfrak{f}}$(*heap-map h1*) ∧ $\mathcal{W}_{\mathfrak{f}}$(*heap-map h2*)
unfolding *wellformed-def*
by (*safe*, *erule-tac x*=*b* **in** *allE*, *erule-tac x*=*obj* **in** *allE*)
(*fastforce intro*: *mapping-lookup-disj1 mapping-lookup-disj2*)+

4 Helper functions and lemmas

primrec *is-memval-defined* :: (*nat*, *memval*) *mapping* ⇒ *nat* ⇒ *nat* ⇒ *bool*
where
is-memval-defined - - 0 = True
| *is-memval-defined m off* (*Suc siz*) = ((*off* ∈ *Mapping.keys m*) ∧ *is-memval-defined m* (*Suc off*) *siz*)

primrec *is-contiguous-bytes* :: (*nat*, *memval*) *mapping* ⇒ *nat* ⇒ *nat* ⇒ *bool*
where
is-contiguous-bytes - - 0 = True
| *is-contiguous-bytes m off* (*Suc siz*) = ((*off* ∈ *Mapping.keys m*)
∧ *memval-is-byte* (*the* (*Mapping.lookup m off*))
∧ *is-contiguous-bytes m* (*Suc off*) *siz*)

definition *get-cap* :: (*nat*, *memval*) *mapping* ⇒ *nat* ⇒ *memcap*
where
get-cap m off = of-cap (*the* (*Mapping.lookup m off*))

fun *is-cap* :: (*nat*, *memval*) *mapping* ⇒ *nat* ⇒ *bool*
where
is-cap m off = (*off* ∈ *Mapping.keys m* ∧ *memval-is-cap* (*the* (*Mapping.lookup m off*)))

primrec *is-contiguous-cap* :: (*nat*, *memval*) *mapping* ⇒ *memcap* ⇒ *nat* ⇒ *nat* ⇒ *bool*
where
is-contiguous-cap - - - 0 = True
| *is-contiguous-cap m c off* (*Suc siz*) = ((*off* ∈ *Mapping.keys m*)
∧ *memval-is-cap* (*the* (*Mapping.lookup m off*))
∧ *of-cap* (*the* (*Mapping.lookup m off*)) = *c*
∧ *of-nth* (*the* (*Mapping.lookup m off*)) = *siz*
∧ *is-contiguous-cap m c* (*Suc off*) *siz*)

primrec *is-contiguous-zeros-prim* :: (*nat*, *memval*) *mapping* ⇒ *nat* ⇒ *nat* ⇒ *bool*
where
is-contiguous-zeros-prim - - 0 = True
| *is-contiguous-zeros-prim m off* (*Suc siz*) = (*Mapping.lookup m off* = *Some* (*Byte 0*)
∧ *is-contiguous-zeros-prim m* (*Suc off*) *siz*)

definition *is-contiguous-zeros* :: (*nat*, *memval*) *mapping* ⇒ *nat* ⇒ *nat* ⇒ *bool*
where
is-contiguous-zeros m off siz ≡ ∀ *ofs* ≥ *off*. *ofs* < *off* + *siz* ⟶ *Mapping.lookup m ofs* = *Some* (*Byte 0*)

lemma *is-contiguous-zeros-code*[*code*]:
is-contiguous-zeros m off siz = is-contiguous-zeros-prim m off siz
proof *safe*

show *is-contiguous-zeros m off siz* ⟹ *is-contiguous-zeros-prim m off siz*
unfolding *is-contiguous-zeros-def*
proof (*induct siz arbitrary*: *off*)
case *0*
thus *?case* **by** *simp*
next
case (*Suc siz*)
thus *?case*
by *fastforce*
qed
next
show *is-contiguous-zeros-prim m off siz* ⟹ *is-contiguous-zeros m off siz*
unfolding *is-contiguous-zeros-def*
proof (*induct siz arbitrary*: *off*)
case *0*
thus *?case*
by *auto*
next
case (*Suc siz*)
have *alt*: *is-contiguous-zeros-prim m* (*Suc off*) *siz*
using *Suc*(*2*) *is-contiguous-zeros-prim.simps*(*2*)[**where** *?m*=*m* **and** *?off*=*off* **and** *?siz*=*siz*]
by *blast*
have *add-simp*: *Suc off* + *siz* = *off* + *Suc siz*
by *simp*
show *?case*
using *Suc*(*1*)[**where** *?off*=*Suc off*, *OF alt*, *simplified add-simp le-eq-less-or-eq Suc-le-eq*]
Suc(*2*) *Suc-le-eq le-eq-less-or-eq*
by *auto*
qed
qed

primrec *retrieve-bytes* :: (*nat*, *memval*) *mapping* ⇒ *nat* ⇒ *nat* ⇒ *8 word list*
where
retrieve-bytes m - 0 = []
| *retrieve-bytes m off* (*Suc siz*) = *of-byte* (*the* (*Mapping.lookup m off*)) # *retrieve-bytes m* (*Suc off*) *siz*

primrec *is-same-cap* :: (*nat*, *memval*) *mapping* ⇒ *memcap* ⇒ *nat* ⇒ *nat* ⇒ *bool*
where
is-same-cap - - - 0 = *True*
| *is-same-cap m c off* (*Suc siz*) = (*of-cap* (*the* (*Mapping.lookup m off*)) = *c* ∧ *is-same-cap m c* (*Suc off*) *siz*)

definition *retrieve-tval* :: *object* ⇒ *nat* ⇒ *cctype* ⇒ *bool* ⇒ *block ccval*

where
retrieve-tval obj off typ pcl ≡
if is-contiguous-bytes (*content obj*) *off* |*typ*|$_\tau$ *then*
(*case typ of*
Uint8 ⇒ *Uint8-v* (*decode-u8-list* (*retrieve-bytes* (*content obj*) *off* |*typ*|$_\tau$))
| *Sint8* ⇒ *Sint8-v* (*decode-s8-list* (*retrieve-bytes* (*content obj*) *off* |*typ*|$_\tau$))
| *Uint16* ⇒ *Uint16-v* (*cat-u16* (*retrieve-bytes* (*content obj*) *off* |*typ*|$_\tau$))
| *Sint16* ⇒ *Sint16-v* (*cat-s16* (*retrieve-bytes* (*content obj*) *off* |*typ*|$_\tau$))
| *Uint32* ⇒ *Uint32-v* (*cat-u32* (*retrieve-bytes* (*content obj*) *off* |*typ*|$_\tau$))
| *Sint32* ⇒ *Sint32-v* (*cat-s32* (*retrieve-bytes* (*content obj*) *off* |*typ*|$_\tau$))
| *Uint64* ⇒ *Uint64-v* (*cat-u64* (*retrieve-bytes* (*content obj*) *off* |*typ*|$_\tau$))
| *Sint64* ⇒ *Sint64-v* (*cat-s64* (*retrieve-bytes* (*content obj*) *off* |*typ*|$_\tau$))
| *Cap* ⇒ *if is-contiguous-zeros* (*content obj*) *off* |*typ*|$_\tau$ *then Cap-v NULL*
else Undef)
else if is-cap (*content obj*) *off then*
let cap = *get-cap* (*content obj*) *off in*
let tv = *the* (*Mapping.lookup* (*tags obj*) (*cap-offset off*)) *in*
let t = (*case pcl of False* ⇒ *False* | *True* ⇒ *tv*) *in*
let cv = *mem-capability.extend cap* ⦇ *tag* = *t* ⦈ *in*
let nth-frag = *of-nth* (*the* (*Mapping.lookup* (*content obj*) *off*)) *in*
(*case typ of*
Uint8 ⇒ *Cap-v-frag* (*mem-capability.extend cap* ⦇ *tag* = *False* ⦈) *nth-frag*
| *Sint8* ⇒ *Cap-v-frag* (*mem-capability.extend cap* ⦇ *tag* = *False* ⦈) *nth-frag*
| *Cap* ⇒ *if is-contiguous-cap* (*content obj*) *cap off* |*typ*|$_\tau$ *then Cap-v cv else*
Undef
| - ⇒ *Undef*)
else Undef

primrec *store-bytes* :: (*nat*, *memval*) *mapping* ⇒ *nat* ⇒ *8 word list* ⇒ (*nat*, *memval*) *mapping*
where
store-bytes obj - [] = *obj*
| *store-bytes obj off* (*v* # *vs*) = *store-bytes* (*Mapping.update off* (*Byte v*) *obj*) (*Suc off*) *vs*

primrec *store-cap* :: (*nat*, *memval*) *mapping* ⇒ *nat* ⇒ *cap* ⇒ *nat* ⇒ (*nat*, *memval*) *mapping*
where
store-cap obj - - *0* = *obj*
| *store-cap obj off cap* (*Suc n*) = *store-cap* (*Mapping.update off* (*ACap* (*mem-capability.truncate cap*) *n*) *obj*) (*Suc off*) *cap n*

abbreviation *store-tag* :: (*nat*, *bool*) *mapping* ⇒ *nat* ⇒ *bool* ⇒ (*nat*, *bool*) *mapping*
where
store-tag obj off tg ≡ *Mapping.update off tg obj*

definition *store-tval* :: *object* ⇒ *nat* ⇒ *block ccval* ⇒ *object*
where

store-tval obj off val ≡
case val of Uint8-v v ⇒ *obj* (| *content* := *store-bytes* (*content obj*) *off* (*encode-u8-list v*),
tags := *store-tag* (*tags obj*) (*cap-offset off*) *False* |)
| *Sint8-v v* ⇒ *obj* (| *content* := *store-bytes* (*content obj*) *off* (*encode-s8-list v*),
tags := *store-tag* (*tags obj*) (*cap-offset off*) *False* |)
| *Uint16-v v* ⇒ *obj* (| *content* := *store-bytes* (*content obj*) *off* (*u16-split v*),
tags := *store-tag* (*tags obj*) (*cap-offset off*) *False* |)
| *Sint16-v v* ⇒ *obj* (| *content* := *store-bytes* (*content obj*) *off* (*s16-split v*),
tags := *store-tag* (*tags obj*) (*cap-offset off*) *False* |)
| *Uint32-v v* ⇒ *obj* (| *content* := *store-bytes* (*content obj*) *off* (*flatten-u32 v*),
tags := *store-tag* (*tags obj*) (*cap-offset off*) *False* |)
| *Sint32-v v* ⇒ *obj* (| *content* := *store-bytes* (*content obj*) *off* (*flatten-s32 v*),
tags := *store-tag* (*tags obj*) (*cap-offset off*) *False* |)
| *Uint64-v v* ⇒ *obj* (| *content* := *store-bytes* (*content obj*) *off* (*flatten-u64 v*),
tags := *store-tag* (*tags obj*) (*cap-offset off*) *False* |)
| *Sint64-v v* ⇒ *obj* (| *content* := *store-bytes* (*content obj*) *off* (*flatten-s64 v*),
tags := *store-tag* (*tags obj*) (*cap-offset off*) *False* |)
| *Cap-v c* ⇒ *obj* (| *content* := *store-cap* (*content obj*) *off c* $|Cap|_\tau$,
tags := *store-tag* (*tags obj*) (*cap-offset off*) (*tag c*) |)
| *Cap-v-frag c n* ⇒ *obj* (| *content* := *Mapping.update off* (*ACap* (*mem-capability.truncate c*) *n*) (*content obj*),
tags := *store-tag* (*tags obj*) (*cap-offset off*) *False*|)

lemma *stored-bytes-prev*:
assumes $x < off$
shows *Mapping.lookup* (*store-bytes obj off vs*) *x* = *Mapping.lookup obj x*
using *assms*
by (*induct vs arbitrary*: *obj off*) *fastforce+*

lemma *stored-tags-prev*:
assumes $x < off$
shows *Mapping.lookup* (*store-tag obj off vs*) *x* = *Mapping.lookup obj x*
using *assms*
by *force*

lemma *stored-cap-prev*:
assumes $x < off$
shows *Mapping.lookup* (*store-cap obj off cap siz*) *x* = *Mapping.lookup obj x*
using *assms*
by (*induct siz arbitrary*: *obj off*) *fastforce+*

lemma *stored-bytes-instant-correctness*:
Mapping.lookup (*store-bytes obj off* (*v # vs*)) *off* = *Some* (*Byte v*)
proof (*induct vs arbitrary*: *obj off*)
case *Nil*
thus *?case* **by** *force*
next
case (*Cons a vs*)
thus *?case* **using** *stored-bytes-prev Suc-eq-plus1 lessI store-bytes.simps*(*2*)
by *metis*
qed

lemma *stored-cap-instant-correctness*:
Mapping.lookup (*store-cap obj off cap* (*Suc siz*)) *off* = *Some* (*ACap* (*mem-capability.truncate cap*) *siz*)
proof (*induct siz arbitrary*: *obj off*)
case *0*
thus *?case* **by** *force*
next
case (*Suc siz*)
thus *?case* **using** *stored-cap-prev Suc-eq-plus1 lessI store-cap.simps*(*2*) *lookup-update*
by *metis*
qed

lemma *numeral-4-eq-4*: *4* = *Suc* (*Suc* (*Suc* (*Suc 0*)))
by (*simp add*: *eval-nat-numeral*)

lemma *numeral-5-eq-5*: *5* = *Suc* (*Suc* (*Suc* (*Suc* (*Suc 0*))))
by (*simp add*: *eval-nat-numeral*)

lemma *numeral-6-eq-6*: *6* = *Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc 0*)))))
by (*simp add*: *eval-nat-numeral*)

lemma *numeral-7-eq-7*: *7* = *Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc 0*))))))
by (*simp add*: *eval-nat-numeral*)

lemma *numeral-8-eq-8*: *8* = *Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc 0*)))))))
by (*simp add*: *eval-nat-numeral*)

lemma *list-length-2-realise*:
length ls = *2* ⟹ ∃ *n0 n1*. *ls* = [*n0*, *n1*]
by (*metis One-nat-def Suc-length-conv add-diff-cancel-right' len-gt-0 len-of-finite-2-def*

list.size(*4*) *list-exhaust-size-eq0 list-exhaust-size-gt0 one-add-one*)

lemma *list-length-4-realise*:
length ls = *4* ⟹ ∃ *n0 n1 n2 n3*. *ls* = [*n0*, *n1*, *n2*, *n3*]
by (*metis list-exhaust-size-eq0 list-exhaust-size-gt0 numeral-4-eq-4 size-Cons-lem-eq zero-less-Suc*)

lemma *list-length-8-realise*:
length ls = 8 ⟹ ∃ n0 n1 n2 n3 n4 n5 n6 n7. ls = [n0, n1, n2, n3, n4, n5, n6, n7]
using *list-exhaust-size-eq0 list-exhaust-size-gt0 numeral-8-eq-8 size-Cons-lem-eq zero-less-Suc*
by *smt*

lemma *u16-split-realise*:
∃ b0 b1. u16-split v = [b0, b1]
using *list-length-2-realise*[**where** *?ls=u16-split v*, *OF flatten-u16-length*[**where** *?vs=v*]]
by *assumption*

lemma *s16-split-realise*:
∃ b0 b1. s16-split v = [b0, b1]
using *list-length-2-realise*[**where** *?ls=s16-split v*, *OF flatten-s16-length*[**where** *?vs=v*]]
by *assumption*

lemma *u32-split-realise*:
∃ b0 b1 b2 b3. flatten-u32 v = [b0, b1, b2, b3]
using *list-length-4-realise*[**where** *?ls=flatten-u32 v*, *OF flatten-u32-length*[**where** *?vs=v*]]
by *assumption*

lemma *s32-split-realise*:
∃ b0 b1 b2 b3. flatten-s32 v = [b0, b1, b2, b3]
using *list-length-4-realise*[**where** *?ls=flatten-s32 v*, *OF flatten-s32-length*[**where** *?vs=v*]]
by *assumption*

lemma *u64-split-realise*:
∃ b0 b1 b2 b3 b4 b5 b6 b7. flatten-u64 v = [b0, b1, b2, b3, b4, b5, b6, b7]
using *list-length-8-realise*[**where** *?ls=flatten-u64 v*, *OF flatten-u64-length*[**where** *?vs=v*]]
by *assumption*

lemma *s64-split-realise*:
∃ b0 b1 b2 b3 b4 b5 b6 b7. flatten-s64 v = [b0, b1, b2, b3, b4, b5, b6, b7]
using *list-length-8-realise*[**where** *?ls=flatten-s64 v*, *OF flatten-s64-length*[**where** *?vs=v*]]
by *assumption*

lemma *store-bytes-u16*:
shows *off ∈ Mapping.keys (store-bytes m off (u16-split v))*
and *Suc off ∈ Mapping.keys (store-bytes m off (u16-split v))*
and *∃ b0. Mapping.lookup (store-bytes m off (u16-split v)) off = Some (Byte b0)*
and *∃ b1. Mapping.lookup (store-bytes m off (u16-split v)) (Suc off) = Some*

(*Byte b1*)
proof −
show *off* ∈ *Mapping.keys* (*store-bytes m off* (*u16-split v*))
by (*metis* (*no-types*, *opaque-lifting*) *domIff u16-split-realise handy-if-lemma keys-dom-lookup*
stored-bytes-instant-correctness)
next
show *Suc off* ∈ *Mapping.keys* (*store-bytes m off* (*u16-split v*))
by (*metis* (*mono-tags*, *opaque-lifting*) *domIff u16-split-realise handy-if-lemma keys-dom-lookup*
store-bytes.simps(*2*) *stored-bytes-instant-correctness*)
next
show ∃ *b0*. *Mapping.lookup* (*store-bytes m off* (*u16-split v*)) *off* = *Some* (*Byte b0*)
by (*metis u16-split-realise stored-bytes-instant-correctness*)
next
show ∃ *b1*. *Mapping.lookup* (*store-bytes m off* (*u16-split v*)) (*Suc off*) = *Some* (*Byte b1*)
by (*metis u16-split-realise store-bytes.simps*(*2*) *stored-bytes-instant-correctness*)
qed

lemma *store-bytes-s16*:
shows *off* ∈ *Mapping.keys* (*store-bytes m off* (*s16-split v*))
and *Suc off* ∈ *Mapping.keys* (*store-bytes m off* (*s16-split v*))
and ∃ *b0*. *Mapping.lookup* (*store-bytes m off* (*s16-split v*)) *off* = *Some* (*Byte b0*)
and ∃ *b1*. *Mapping.lookup* (*store-bytes m off* (*s16-split v*)) (*Suc off*) = *Some* (*Byte b1*)
proof −
show *off* ∈ *Mapping.keys* (*store-bytes m off* (*s16-split v*))
by (*metis* (*no-types*, *opaque-lifting*) *domIff s16-split-realise handy-if-lemma keys-dom-lookup*
stored-bytes-instant-correctness)
next
show *Suc off* ∈ *Mapping.keys* (*store-bytes m off* (*s16-split v*))
by (*metis* (*mono-tags*, *opaque-lifting*) *domIff s16-split-realise handy-if-lemma keys-dom-lookup*
store-bytes.simps(*2*) *stored-bytes-instant-correctness*)
next
show ∃ *b0*. *Mapping.lookup* (*store-bytes m off* (*s16-split v*)) *off* = *Some* (*Byte b0*)
by (*metis s16-split-realise stored-bytes-instant-correctness*)
next
show ∃ *b1*. *Mapping.lookup* (*store-bytes m off* (*s16-split v*)) (*Suc off*) = *Some* (*Byte b1*)
by (*metis s16-split-realise store-bytes.simps*(*2*) *stored-bytes-instant-correctness*)
qed

lemma *store-bytes-u32*:

shows *off* ∈ *Mapping.keys* (*store-bytes m off* (*flatten-u32 v*))
and *Suc off* ∈ *Mapping.keys* (*store-bytes m off* (*flatten-u32 v*))
and *Suc* (*Suc off*) ∈ *Mapping.keys* (*store-bytes m off* (*flatten-u32 v*))
and *Suc* (*Suc* (*Suc off*)) ∈ *Mapping.keys* (*store-bytes m off* (*flatten-u32 v*))
and ∃ *b0*. *Mapping.lookup* (*store-bytes m off* (*flatten-u32 v*)) *off* = *Some* (*Byte b0*)
and ∃ *b1*. *Mapping.lookup* (*store-bytes m off* (*flatten-u32 v*)) (*Suc off*) = *Some* (*Byte b1*)
and ∃ *b2*. *Mapping.lookup* (*store-bytes m off* (*flatten-u32 v*)) (*Suc* (*Suc off*)) = *Some* (*Byte b2*)
and ∃ *b3*. *Mapping.lookup* (*store-bytes m off* (*flatten-u32 v*)) (*Suc* (*Suc* (*Suc off*))) = *Some* (*Byte b3*)
proof −
show *off* ∈ *Mapping.keys* (*store-bytes m off* (*flatten-u32 v*))
by (*metis* (*no-types*, *opaque-lifting*) *domIff handy-if-lemma keys-dom-lookup stored-bytes-instant-correctness u32-split-realise*)
next
show *Suc off* ∈ *Mapping.keys* (*store-bytes m off* (*flatten-u32 v*))
by (*metis* (*mono-tags*, *opaque-lifting*) *domIff u32-split-realise handy-if-lemma keys-dom-lookup store-bytes.simps*(*2*) *stored-bytes-instant-correctness*)
next
show *Suc* (*Suc off*) ∈ *Mapping.keys* (*store-bytes m off* (*flatten-u32 v*))
by (*metis* (*mono-tags*, *opaque-lifting*) *domIff u32-split-realise handy-if-lemma keys-dom-lookup store-bytes.simps*(*2*) *stored-bytes-instant-correctness*)
next
show *Suc* (*Suc* (*Suc off*)) ∈ *Mapping.keys* (*store-bytes m off* (*flatten-u32 v*))
by (*metis* (*mono-tags*, *opaque-lifting*) *domIff u32-split-realise handy-if-lemma keys-dom-lookup store-bytes.simps*(*2*) *stored-bytes-instant-correctness*)
next
show ∃ *b0*. *Mapping.lookup* (*store-bytes m off* (*flatten-u32 v*)) *off* = *Some* (*Byte b0*)
by (*metis u32-split-realise stored-bytes-instant-correctness*)
next
show ∃ *b1*. *Mapping.lookup* (*store-bytes m off* (*flatten-u32 v*)) (*Suc off*) = *Some* (*Byte b1*)
by (*metis u32-split-realise store-bytes.simps*(*2*) *stored-bytes-instant-correctness*)
next
show ∃ *b2*. *Mapping.lookup* (*store-bytes m off* (*flatten-u32 v*)) (*Suc* (*Suc off*)) = *Some* (*Byte b2*)
by (*metis u32-split-realise store-bytes.simps*(*2*) *stored-bytes-instant-correctness*)
next
show ∃ *b3*. *Mapping.lookup* (*store-bytes m off* (*flatten-u32 v*)) (*Suc* (*Suc* (*Suc off*))) = *Some* (*Byte b3*)
by (*metis u32-split-realise store-bytes.simps*(*2*) *stored-bytes-instant-correctness*)
qed

lemma *store-bytes-s32*:
shows *off* ∈ *Mapping.keys* (*store-bytes m off* (*flatten-s32 v*))
and *Suc off* ∈ *Mapping.keys* (*store-bytes m off* (*flatten-s32 v*))
and *Suc* (*Suc off*) ∈ *Mapping.keys* (*store-bytes m off* (*flatten-s32 v*))
and *Suc* (*Suc* (*Suc off*)) ∈ *Mapping.keys* (*store-bytes m off* (*flatten-s32 v*))
and ∃ *b0*. *Mapping.lookup* (*store-bytes m off* (*flatten-s32 v*)) *off* = *Some* (*Byte b0*)
and ∃ *b1*. *Mapping.lookup* (*store-bytes m off* (*flatten-s32 v*)) (*Suc off*) = *Some* (*Byte b1*)
and ∃ *b2*. *Mapping.lookup* (*store-bytes m off* (*flatten-s32 v*)) (*Suc* (*Suc off*)) = *Some* (*Byte b2*)
and ∃ *b3*. *Mapping.lookup* (*store-bytes m off* (*flatten-s32 v*)) (*Suc* (*Suc* (*Suc off*))) = *Some* (*Byte b3*)
proof −
show *off* ∈ *Mapping.keys* (*store-bytes m off* (*flatten-s32 v*))
by (*metis* (*no-types*, *opaque-lifting*) *domIff handy-if-lemma keys-dom-lookup stored-bytes-instant-correctness s32-split-realise*)
next
show *Suc off* ∈ *Mapping.keys* (*store-bytes m off* (*flatten-s32 v*))
by (*metis* (*mono-tags*, *opaque-lifting*) *domIff s32-split-realise handy-if-lemma keys-dom-lookup store-bytes.simps*(*2*) *stored-bytes-instant-correctness*)
next
show *Suc* (*Suc off*) ∈ *Mapping.keys* (*store-bytes m off* (*flatten-s32 v*))
by (*metis* (*mono-tags*, *opaque-lifting*) *domIff s32-split-realise handy-if-lemma keys-dom-lookup store-bytes.simps*(*2*) *stored-bytes-instant-correctness*)
next
show *Suc* (*Suc* (*Suc off*)) ∈ *Mapping.keys* (*store-bytes m off* (*flatten-s32 v*))
by (*metis* (*mono-tags*, *opaque-lifting*) *domIff s32-split-realise handy-if-lemma keys-dom-lookup store-bytes.simps*(*2*) *stored-bytes-instant-correctness*)
next
show ∃ *b0*. *Mapping.lookup* (*store-bytes m off* (*flatten-s32 v*)) *off* = *Some* (*Byte b0*)
by (*metis s32-split-realise stored-bytes-instant-correctness*)
next
show ∃ *b1*. *Mapping.lookup* (*store-bytes m off* (*flatten-s32 v*)) (*Suc off*) = *Some* (*Byte b1*)
by (*metis s32-split-realise store-bytes.simps*(*2*) *stored-bytes-instant-correctness*)
next
show ∃ *b2*. *Mapping.lookup* (*store-bytes m off* (*flatten-s32 v*)) (*Suc* (*Suc off*)) = *Some* (*Byte b2*)
by (*metis s32-split-realise store-bytes.simps*(*2*) *stored-bytes-instant-correctness*)
next
show ∃ *b3*. *Mapping.lookup* (*store-bytes m off* (*flatten-s32 v*)) (*Suc* (*Suc* (*Suc off*))) = *Some* (*Byte b3*)
by (*metis s32-split-realise store-bytes.simps*(*2*) *stored-bytes-instant-correctness*)
qed

lemma *store-bytes-u64*:
shows *off* ∈ *Mapping.keys* (*store-bytes m off* (*flatten-u64 v*))
and *Suc off* ∈ *Mapping.keys* (*store-bytes m off* (*flatten-u64 v*))
and *Suc* (*Suc off*) ∈ *Mapping.keys* (*store-bytes m off* (*flatten-u64 v*))
and *Suc* (*Suc* (*Suc off*)) ∈ *Mapping.keys* (*store-bytes m off* (*flatten-u64 v*))
and *Suc* (*Suc* (*Suc* (*Suc off*))) ∈ *Mapping.keys* (*store-bytes m off* (*flatten-u64 v*))
and *Suc* (*Suc* (*Suc* (*Suc* (*Suc off*)))) ∈ *Mapping.keys* (*store-bytes m off* (*flatten-u64 v*))
and *Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc off*))))) ∈ *Mapping.keys* (*store-bytes m off* (*flatten-u64 v*))
and *Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc off*)))))) ∈ *Mapping.keys* (*store-bytes m off* (*flatten-u64 v*))
and ∃ *b0*. *Mapping.lookup* (*store-bytes m off* (*flatten-u64 v*)) *off* = *Some* (*Byte b0*)
and ∃ *b1*. *Mapping.lookup* (*store-bytes m off* (*flatten-u64 v*)) (*Suc off*) = *Some* (*Byte b1*)
and ∃ *b2*. *Mapping.lookup* (*store-bytes m off* (*flatten-u64 v*)) (*Suc* (*Suc off*)) = *Some* (*Byte b2*)
and ∃ *b3*. *Mapping.lookup* (*store-bytes m off* (*flatten-u64 v*)) (*Suc* (*Suc* (*Suc off*))) = *Some* (*Byte b3*)
and ∃ *b0*. *Mapping.lookup* (*store-bytes m off* (*flatten-u64 v*)) (*Suc* (*Suc* (*Suc* (*Suc off*)))) = *Some* (*Byte b0*)
and ∃ *b1*. *Mapping.lookup* (*store-bytes m off* (*flatten-u64 v*)) (*Suc* (*Suc* (*Suc* (*Suc* (*Suc off*))))) = *Some* (*Byte b1*)
and ∃ *b2*. *Mapping.lookup* (*store-bytes m off* (*flatten-u64 v*)) (*Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc off*)))))) = *Some* (*Byte b2*)
and ∃ *b3*. *Mapping.lookup* (*store-bytes m off* (*flatten-u64 v*)) (*Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc off*))))))) = *Some* (*Byte b3*)
proof −
show *off* ∈ *Mapping.keys* (*store-bytes m off* (*flatten-u64 v*))
by (*metis* (*no-types*, *opaque-lifting*) *domIff handy-if-lemma keys-dom-lookup*
stored-bytes-instant-correctness u64-split-realise)
next
show *Suc off* ∈ *Mapping.keys* (*store-bytes m off* (*flatten-u64 v*))
by (*metis* (*mono-tags*, *opaque-lifting*) *domIff u64-split-realise handy-if-lemma keys-dom-lookup*
store-bytes.simps(*2*) *stored-bytes-instant-correctness*)
next
show *Suc* (*Suc off*) ∈ *Mapping.keys* (*store-bytes m off* (*flatten-u64 v*))
by (*metis* (*mono-tags*, *opaque-lifting*) *domIff u64-split-realise handy-if-lemma keys-dom-lookup*
store-bytes.simps(*2*) *stored-bytes-instant-correctness*)
next
show *Suc* (*Suc* (*Suc off*)) ∈ *Mapping.keys* (*store-bytes m off* (*flatten-u64 v*))
by (*metis* (*mono-tags*, *opaque-lifting*) *domIff u64-split-realise handy-if-lemma keys-dom-lookup*
store-bytes.simps(*2*) *stored-bytes-instant-correctness*)

next
show *Suc* (*Suc* (*Suc* (*Suc off*))) ∈ *Mapping.keys* (*store-bytes m off* (*flatten-u64 v*))
by (*metis* (*mono-tags*, *opaque-lifting*) *domIff u64-split-realise handy-if-lemma keys-dom-lookup*
store-bytes.simps(2) *stored-bytes-instant-correctness*)
next
show *Suc* (*Suc* (*Suc* (*Suc* (*Suc off*)))) ∈ *Mapping.keys* (*store-bytes m off* (*flatten-u64 v*))
by (*metis* (*mono-tags*, *opaque-lifting*) *domIff u64-split-realise handy-if-lemma keys-dom-lookup*
store-bytes.simps(2) *stored-bytes-instant-correctness*)
next
show *Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc off*))))) ∈ *Mapping.keys* (*store-bytes m off* (*flatten-u64 v*))
by (*metis* (*mono-tags*, *opaque-lifting*) *domIff u64-split-realise handy-if-lemma keys-dom-lookup*
store-bytes.simps(2) *stored-bytes-instant-correctness*)
next
show *Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc off*)))))) ∈ *Mapping.keys* (*store-bytes m off* (*flatten-u64 v*))
by (*metis* (*mono-tags*, *opaque-lifting*) *domIff u64-split-realise handy-if-lemma keys-dom-lookup*
store-bytes.simps(2) *stored-bytes-instant-correctness*)
next
show ∃ *b0*. *Mapping.lookup* (*store-bytes m off* (*flatten-u64 v*)) *off* = *Some* (*Byte b0*)
by (*metis u64-split-realise stored-bytes-instant-correctness*)
next
show ∃ *b1*. *Mapping.lookup* (*store-bytes m off* (*flatten-u64 v*)) (*Suc off*) = *Some* (*Byte b1*)
by (*metis u64-split-realise store-bytes.simps*(2) *stored-bytes-instant-correctness*)
next
show ∃ *b2*. *Mapping.lookup* (*store-bytes m off* (*flatten-u64 v*)) (*Suc* (*Suc off*)) = *Some* (*Byte b2*)
by (*metis u64-split-realise store-bytes.simps*(2) *stored-bytes-instant-correctness*)
next
show ∃ *b3*. *Mapping.lookup* (*store-bytes m off* (*flatten-u64 v*)) (*Suc* (*Suc* (*Suc off*))) = *Some* (*Byte b3*)
by (*metis u64-split-realise store-bytes.simps*(2) *stored-bytes-instant-correctness*)
next
show ∃ *b0*. *Mapping.lookup* (*store-bytes m off* (*flatten-u64 v*)) (*Suc* (*Suc* (*Suc* (*Suc off*)))) = *Some* (*Byte b0*)
by (*metis u64-split-realise store-bytes.simps*(2) *stored-bytes-instant-correctness*)
next
show∃ *b1*. *Mapping.lookup* (*store-bytes m off* (*flatten-u64 v*)) (*Suc* (*Suc* (*Suc* (*Suc* (*Suc off*))))) = *Some* (*Byte b1*)
by (*metis u64-split-realise store-bytes.simps*(2) *stored-bytes-instant-correctness*)
next

show $\exists$ *b2*. *Mapping.lookup* (*store-bytes m off* (*flatten-u64 v*)) (*Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc off*)))))) = *Some* (*Byte b2*)
by (*metis u64-split-realise store-bytes.simps*(2) *stored-bytes-instant-correctness*)
next
show $\exists$ *b3*. *Mapping.lookup* (*store-bytes m off* (*flatten-u64 v*)) (*Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc off*))))))) = *Some* (*Byte b3*)
by (*metis u64-split-realise store-bytes.simps*(2) *stored-bytes-instant-correctness*)
qed

lemma *store-bytes-s64*:
shows *off* $\in$ *Mapping.keys* (*store-bytes m off* (*flatten-s64 v*))
and *Suc off* $\in$ *Mapping.keys* (*store-bytes m off* (*flatten-s64 v*))
and *Suc* (*Suc off*) $\in$ *Mapping.keys* (*store-bytes m off* (*flatten-s64 v*))
and *Suc* (*Suc* (*Suc off*)) $\in$ *Mapping.keys* (*store-bytes m off* (*flatten-s64 v*))
and *Suc* (*Suc* (*Suc* (*Suc off*))) $\in$ *Mapping.keys* (*store-bytes m off* (*flatten-s64 v*))
and *Suc* (*Suc* (*Suc* (*Suc* (*Suc off*)))) $\in$ *Mapping.keys* (*store-bytes m off* (*flatten-s64 v*))
and *Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc off*))))) $\in$ *Mapping.keys* (*store-bytes m off* (*flatten-s64 v*))
and *Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc off*)))))) $\in$ *Mapping.keys* (*store-bytes m off* (*flatten-s64 v*))
and $\exists$ *b0*. *Mapping.lookup* (*store-bytes m off* (*flatten-s64 v*)) *off* = *Some* (*Byte b0*)
and $\exists$ *b1*. *Mapping.lookup* (*store-bytes m off* (*flatten-s64 v*)) (*Suc off*) = *Some* (*Byte b1*)
and $\exists$ *b2*. *Mapping.lookup* (*store-bytes m off* (*flatten-s64 v*)) (*Suc* (*Suc off*)) = *Some* (*Byte b2*)
and $\exists$ *b3*. *Mapping.lookup* (*store-bytes m off* (*flatten-s64 v*)) (*Suc* (*Suc* (*Suc off*))) = *Some* (*Byte b3*)
and $\exists$ *b0*. *Mapping.lookup* (*store-bytes m off* (*flatten-s64 v*)) (*Suc* (*Suc* (*Suc* (*Suc off*)))) = *Some* (*Byte b0*)
and $\exists$ *b1*. *Mapping.lookup* (*store-bytes m off* (*flatten-s64 v*)) (*Suc* (*Suc* (*Suc* (*Suc* (*Suc off*))))) = *Some* (*Byte b1*)
and $\exists$ *b2*. *Mapping.lookup* (*store-bytes m off* (*flatten-s64 v*)) (*Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc off*)))))) = *Some* (*Byte b2*)
and $\exists$ *b3*. *Mapping.lookup* (*store-bytes m off* (*flatten-s64 v*)) (*Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc off*))))))) = *Some* (*Byte b3*)
proof −
show *off* $\in$ *Mapping.keys* (*store-bytes m off* (*flatten-s64 v*))
by (*metis* (*no-types*, *opaque-lifting*) *domIff handy-if-lemma keys-dom-lookup stored-bytes-instant-correctness s64-split-realise*)
next
show *Suc off* $\in$ *Mapping.keys* (*store-bytes m off* (*flatten-s64 v*))
by (*metis* (*mono-tags*, *opaque-lifting*) *domIff s64-split-realise handy-if-lemma keys-dom-lookup store-bytes.simps*(2) *stored-bytes-instant-correctness*)
next
show *Suc* (*Suc off*) $\in$ *Mapping.keys* (*store-bytes m off* (*flatten-s64 v*))

by (*metis* (*mono-tags*, *opaque-lifting*) *domIff s64-split-realise handy-if-lemma keys-dom-lookup*
store-bytes.simps(2) *stored-bytes-instant-correctness*)
next
show *Suc* (*Suc* (*Suc off*)) ∈ *Mapping.keys* (*store-bytes m off* (*flatten-s64 v*))
by (*metis* (*mono-tags*, *opaque-lifting*) *domIff s64-split-realise handy-if-lemma keys-dom-lookup*
store-bytes.simps(2) *stored-bytes-instant-correctness*)
next
show *Suc* (*Suc* (*Suc* (*Suc off*))) ∈ *Mapping.keys* (*store-bytes m off* (*flatten-s64 v*))
by (*metis* (*mono-tags*, *opaque-lifting*) *domIff s64-split-realise handy-if-lemma keys-dom-lookup*
store-bytes.simps(2) *stored-bytes-instant-correctness*)
next
show *Suc* (*Suc* (*Suc* (*Suc* (*Suc off*)))) ∈ *Mapping.keys* (*store-bytes m off* (*flatten-s64 v*))
by (*metis* (*mono-tags*, *opaque-lifting*) *domIff s64-split-realise handy-if-lemma keys-dom-lookup*
store-bytes.simps(2) *stored-bytes-instant-correctness*)
next
show *Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc off*))))) ∈ *Mapping.keys* (*store-bytes m off* (*flatten-s64 v*))
by (*metis* (*mono-tags*, *opaque-lifting*) *domIff s64-split-realise handy-if-lemma keys-dom-lookup*
store-bytes.simps(2) *stored-bytes-instant-correctness*)
next
show *Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc off*)))))) ∈ *Mapping.keys* (*store-bytes m off* (*flatten-s64 v*))
by (*metis* (*mono-tags*, *opaque-lifting*) *domIff s64-split-realise handy-if-lemma keys-dom-lookup*
store-bytes.simps(2) *stored-bytes-instant-correctness*)
next
show ∃ *b0*. *Mapping.lookup* (*store-bytes m off* (*flatten-s64 v*)) *off* = *Some* (*Byte b0*)
by (*metis s64-split-realise stored-bytes-instant-correctness*)
next
show ∃ *b1*. *Mapping.lookup* (*store-bytes m off* (*flatten-s64 v*)) (*Suc off*) = *Some* (*Byte b1*)
by (*metis s64-split-realise store-bytes.simps*(2) *stored-bytes-instant-correctness*)
next
show ∃ *b2*. *Mapping.lookup* (*store-bytes m off* (*flatten-s64 v*)) (*Suc* (*Suc off*)) = *Some* (*Byte b2*)
by (*metis s64-split-realise store-bytes.simps*(2) *stored-bytes-instant-correctness*)
next
show ∃ *b3*. *Mapping.lookup* (*store-bytes m off* (*flatten-s64 v*)) (*Suc* (*Suc* (*Suc off*))) = *Some* (*Byte b3*)
by (*metis s64-split-realise store-bytes.simps*(2) *stored-bytes-instant-correctness*)
next

show $\exists$ *b0*. *Mapping.lookup* (*store-bytes m off* (*flatten-s64 v*)) (*Suc* (*Suc* (*Suc* (*Suc off*)))) = *Some* (*Byte b0*)
by (*metis s64-split-realise store-bytes.simps*(*2*) *stored-bytes-instant-correctness*)
next
show$\exists$ *b1*. *Mapping.lookup* (*store-bytes m off* (*flatten-s64 v*)) (*Suc* (*Suc* (*Suc* (*Suc* (*Suc off*))))) = *Some* (*Byte b1*)
by (*metis s64-split-realise store-bytes.simps*(*2*) *stored-bytes-instant-correctness*)
next
show $\exists$ *b2*. *Mapping.lookup* (*store-bytes m off* (*flatten-s64 v*)) (*Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc off*)))))) = *Some* (*Byte b2*)
by (*metis s64-split-realise store-bytes.simps*(*2*) *stored-bytes-instant-correctness*)
next
show $\exists$ *b3*. *Mapping.lookup* (*store-bytes m off* (*flatten-s64 v*)) (*Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc off*))))))) = *Some* (*Byte b3*)
by (*metis s64-split-realise store-bytes.simps*(*2*) *stored-bytes-instant-correctness*)
qed

corollary *u16-store-bytes-imp-is-contiguous-bytes*:
is-contiguous-bytes (*store-bytes m off* (*u16-split v*)) *off 2*
by (*metis One-nat-def Suc-1 is-contiguous-bytes.simps*(*1*) *is-contiguous-bytes.simps*(*2*) *memval-memcap-not-byte option.sel store-bytes-u16*)

corollary *s16-store-bytes-imp-is-contiguous-bytes*:
is-contiguous-bytes (*store-bytes m off* (*s16-split v*)) *off 2*
by (*metis One-nat-def Suc-1 is-contiguous-bytes.simps*(*1*) *is-contiguous-bytes.simps*(*2*) *memval-memcap-not-byte option.sel store-bytes-s16*)

corollary *u32-store-bytes-imp-is-contiguous-bytes*:
is-contiguous-bytes (*store-bytes m off* (*flatten-u32 v*)) *off 4*
by(*simp add*: *numeral-4-eq-4*, *safe*)
(*simp add*: *store-bytes-u32*, *metis memval-memcap-not-byte option.sel store-bytes-u32*)+

corollary *s32-store-bytes-imp-is-contiguous-bytes*:
is-contiguous-bytes (*store-bytes m off* (*flatten-s32 v*)) *off 4*
by(*simp add*: *numeral-4-eq-4*, *safe*)
(*simp add*: *store-bytes-s32*, *metis memval-memcap-not-byte option.sel store-bytes-s32*)+

corollary *u64-store-bytes-imp-is-contiguous-bytes*:
is-contiguous-bytes (*store-bytes m off* (*flatten-u64 v*)) *off 8*
by(*simp add*: *numeral-8-eq-8*, *safe*)
(*simp add*: *store-bytes-u64*, *metis memval-memcap-not-byte option.sel store-bytes-u64*)+

corollary *s64-store-bytes-imp-is-contiguous-bytes*:
is-contiguous-bytes (*store-bytes m off* (*flatten-s64 v*)) *off 8*
by(*simp add*: *numeral-8-eq-8*, *safe*)
(*simp add*: *store-bytes-s64*, *metis memval-memcap-not-byte option.sel store-bytes-s64*)+

lemma *stored-tval-contiguous-bytes*:
assumes *val* ≠ *Undef*
and ∀ *v*. *val* ≠ *Cap-v v*
and ∀ *v n*. *val* ≠ *Cap-v-frag v n*
shows *is-contiguous-bytes* (*content* (*store-tval obj off val*)) *off* $|memval\text{-}type\ val|_\tau$
unfolding *sizeof-def*
by (*simp add*: *assms store-tval-def memval-is-byte-def split*: *ccval.split*) (*presburger add*: *s16-store-bytes-imp-is-contiguous-bytes s32-store-bytes-imp-is-contiguous-bytes s64-store-bytes-imp-is-contiguous-bytes u16-store-bytes-imp-is-contiguous-bytes u32-store-bytes-imp-is-contiguo u64-store-bytes-imp-is-contiguous-bytes*)

lemma *suc-of-32*:
32 = *Suc 31*
by *simp*

lemma *store-cap-correct-dom*:
shows *off* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *1* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *2* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *3* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *4* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *5* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *6* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *7* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *8* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *9* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *10* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *11* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *12* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *13* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *14* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *15* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *16* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *17* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *18* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *19* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *20* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *21* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *22* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *23* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *24* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *25* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *26* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *27* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *28* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *29* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *30* ∈ *Mapping.keys* (*store-cap m off cap 32*)
and *off* + *31* ∈ *Mapping.keys* (*store-cap m off cap 32*)

proof − **qed** (*simp add*: *suc-of-32 domIff eval-nat-numeral*(*3*) *numeral-Bit0*)+

lemma *store-cap-correct-val*:
shows *Mapping.lookup* (*store-cap m off cap 32*) *off* =
Some (*ACap* (*mem-capability.truncate cap*) *31*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *1*) =
Some (*ACap* (*mem-capability.truncate cap*) *30*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *2*) =
Some (*ACap* (*mem-capability.truncate cap*) *29*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *3*) =
Some (*ACap* (*mem-capability.truncate cap*) *28*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *4*) =
Some (*ACap* (*mem-capability.truncate cap*) *27*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *5*) =
Some (*ACap* (*mem-capability.truncate cap*) *26*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *6*) =
Some (*ACap* (*mem-capability.truncate cap*) *25*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *7*) =
Some (*ACap* (*mem-capability.truncate cap*) *24*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *8*) =
Some (*ACap* (*mem-capability.truncate cap*) *23*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *9*) =
Some (*ACap* (*mem-capability.truncate cap*) *22*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *10*) =
Some (*ACap* (*mem-capability.truncate cap*) *21*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *11*) =
Some (*ACap* (*mem-capability.truncate cap*) *20*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *12*) =
Some (*ACap* (*mem-capability.truncate cap*) *19*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *13*) =
Some (*ACap* (*mem-capability.truncate cap*) *18*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *14*) =
Some (*ACap* (*mem-capability.truncate cap*) *17*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *15*) =
Some (*ACap* (*mem-capability.truncate cap*) *16*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *16*) =
Some (*ACap* (*mem-capability.truncate cap*) *15*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *17*) =
Some (*ACap* (*mem-capability.truncate cap*) *14*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *18*) =
Some (*ACap* (*mem-capability.truncate cap*) *13*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *19*) =
Some (*ACap* (*mem-capability.truncate cap*) *12*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *20*) =
Some (*ACap* (*mem-capability.truncate cap*) *11*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *21*) =
Some (*ACap* (*mem-capability.truncate cap*) *10*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *22*) =
Some (*ACap* (*mem-capability.truncate cap*) *9*)

and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *23*) =
Some (*ACap* (*mem-capability.truncate cap*) *8*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *24*) =
Some (*ACap* (*mem-capability.truncate cap*) *7*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *25*) =
Some (*ACap* (*mem-capability.truncate cap*) *6*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *26*) =
Some (*ACap* (*mem-capability.truncate cap*) *5*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *27*) =
Some (*ACap* (*mem-capability.truncate cap*) *4*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *28*) =
Some (*ACap* (*mem-capability.truncate cap*) *3*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *29*) =
Some (*ACap* (*mem-capability.truncate cap*) *2*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *30*) =
Some (*ACap* (*mem-capability.truncate cap*) *1*)
and *Mapping.lookup* (*store-cap m off cap 32*) (*off* + *31*) =
Some (*ACap* (*mem-capability.truncate cap*) *0*)
proof − **qed** (*simp add*: *stored-cap-instant-correctness suc-of-32 eval-nat-numeral*(*3*) *numeral-Bit0*)+

corollary *store-cap-imp-is-contiguous-cap*:
is-contiguous-cap (*store-cap m off cap 32*) (*mem-capability.truncate cap*) *off 32*
using *memval-byte-not-memcap*
by (*simp add*: *eval-nat-numeral*(*3*) *numeral-Bit0*, *blast*)

lemma *stored-tval-is-cap*:
assumes *val* = *Cap-v v*
shows *is-cap* (*content* (*store-tval obj off val*)) *off*
using *memval-byte-not-memcap sizeof-def store-cap-correct-val*(*1*)
by (*auto simp add*: *assms store-tval-def conjI sizeof-def store-cap-correct-dom*(*1*) *split*: *ccval.split*)

lemma *stored-tval-contiguous-cap*:
assumes *val* = *Cap-v cap*
shows *is-contiguous-cap* (*content* (*store-tval obj off val*)) (*mem-capability.truncate cap*) *off* |*memval-type val*|$_\tau$
using *assms store-tval-def*
by (*simp add*: *sizeof-def store-cap-imp-is-contiguous-cap*)

lemma *decode-encoded-u16-in-mem*:
cat-u16 (*retrieve-bytes* (*content* (*store-tval obj off* (*Uint16-v x*))) *off* |*Uint16*|$_\tau$) = *x*
proof −
have *of-byte* (*the* (*Mapping.lookup* (*store-bytes* (*content obj*) *off* (*u16-split x*)) *off*)) = *u16-split x* ! *0*
by (*smt* (*verit*, *best*) *Some-to-the length-nth-simps*(*3*) *memval.sel*(*1*) *stored-bytes-instant-correctness u16-split-realise*)
also have *of-byte* (*the* (*Mapping.lookup* (*store-bytes* (*content obj*) *off* (*u16-split*

x)) (*Suc off*))) = (*u16-split x*) ! *1*
by (*metis One-nat-def length-nth-simps*(*3*) *memval.sel*(*1*) *nth-Cons-Suc option.sel store-bytes.simps*(*2*) *stored-bytes-instant-correctness u16-split-realise*)
ultimately show *?thesis*
by (*clarsimp simp add*: *sizeof-def store-tval-def eval-nat-numeral*(*3*), *simp add*: *numeral-Bit0*)
(*metis cat-flatten-u16-eq length-nth-simps*(*3*) *nth-Cons-Suc u16-split-realise*)
qed

lemma *decode-encoded-s16-in-mem*:
cat-s16 (*retrieve-bytes* (*content* (*store-tval obj off* (*Sint16-v x*))) *off* |*Sint16*|$_\tau$) = *x*
proof −
have *of-byte* (*the* (*Mapping.lookup* (*store-bytes* (*content obj*) *off* (*s16-split x*)) *off*)) = *s16-split x* ! *0*
by (*smt* (*verit*, *best*) *Some-to-the length-nth-simps*(*3*) *memval.sel*(*1*) *stored-bytes-instant-correctness s16-split-realise*)
also have *of-byte* (*the* (*Mapping.lookup* (*store-bytes* (*content obj*) *off* (*s16-split x*)) (*Suc off*))) = (*s16-split x*) ! *1*
by (*metis One-nat-def length-nth-simps*(*3*) *memval.sel*(*1*) *nth-Cons-Suc option.sel store-bytes.simps*(*2*) *stored-bytes-instant-correctness s16-split-realise*)
ultimately show *?thesis*
by (*clarsimp simp add*: *sizeof-def store-tval-def eval-nat-numeral*(*3*), *simp add*: *numeral-Bit0*)
(*metis cat-flatten-s16-eq length-nth-simps*(*3*) *nth-Cons-Suc s16-split-realise*)
qed

lemma *decode-encoded-u32-in-mem*:
cat-u32 (*retrieve-bytes* (*content* (*store-tval obj off* (*Uint32-v x*))) *off* |*Uint32*|$_\tau$) = *x*
proof −
have *fst*: *of-byte* (*the* (*Mapping.lookup* (*store-bytes* (*content obj*) *off* (*flatten-u32 x*)) *off*)) = *flatten-u32 x* ! *0*
by (*metis length-nth-simps*(*3*) *memval.sel*(*1*) *option.sel stored-bytes-instant-correctness u32-split-realise*)
have *snd*: *of-byte* (*the* (*Mapping.lookup* (*store-bytes* (*content obj*) *off* (*flatten-u32 x*)) (*Suc off*))) = *flatten-u32 x* ! *1*
by (*metis One-nat-def length-nth-simps*(*3*) *length-nth-simps*(*4*) *memval.sel*(*1*) *option.sel store-bytes.simps*(*2*) *stored-bytes-instant-correctness u32-split-realise*)
have *trd*: *of-byte* (*the* (*Mapping.lookup* (*store-bytes* (*content obj*) *off* (*flatten-u32 x*)) (*Suc* (*Suc off*)))) = *flatten-u32 x* ! *2*
by (*metis One-nat-def Suc-1 length-nth-simps*(*3*) *length-nth-simps*(*4*) *memval.sel*(*1*) *option.sel store-bytes.simps*(*2*) *stored-bytes-instant-correctness u32-split-realise*)
have *fth*: *of-byte* (*the* (*Mapping.lookup* (*store-bytes* (*content obj*) *off* (*flatten-u32 x*)) (*Suc* (*Suc* (*Suc off*))))) = *flatten-u32 x* ! *3*
by (*metis Some-to-the length-nth-simps*(*3*) *length-nth-simps*(*4*) *memval.sel*(*1*) *numeral-3-eq-3 store-bytes.simps*(*2*) *stored-bytes-instant-correctness u32-split-realise*)
show *?thesis*
by (*clarsimp simp add*: *sizeof-def store-tval-def eval-nat-numeral*(*3*), *simp add*:

numeral-Bit0)
(*smt* (*verit*, *del-insts*) *fst snd trd fth One-nat-def Suc-1 eval-nat-numeral*(*3*) *length-nth-simps*(*3*) *length-nth-simps*(*4*) *u32-split-realise word-rcat-rsplit*)
qed

lemma *decode-encoded-s32-in-mem*:
cat-s32 (*retrieve-bytes* (*content* (*store-tval obj off* (*Sint32-v x*))) *off* |*Sint32*|$_\tau$) = *x*
proof −
have *fst*: *of-byte* (*the* (*Mapping.lookup* (*store-bytes* (*content obj*) *off* (*flatten-s32 x*)) *off*)) = *flatten-s32 x* ! *0*
by (*metis length-nth-simps*(*3*) *memval.sel*(*1*) *option.sel stored-bytes-instant-correctness s32-split-realise*)
have *snd*: *of-byte* (*the* (*Mapping.lookup* (*store-bytes* (*content obj*) *off* (*flatten-s32 x*)) (*Suc off*))) = *flatten-s32 x* ! *1*
by (*metis One-nat-def length-nth-simps*(*3*) *length-nth-simps*(*4*) *memval.sel*(*1*) *option.sel store-bytes.simps*(*2*) *stored-bytes-instant-correctness s32-split-realise*)
have *trd*: *of-byte* (*the* (*Mapping.lookup* (*store-bytes* (*content obj*) *off* (*flatten-s32 x*)) (*Suc* (*Suc off*)))) = *flatten-s32 x* ! *2*
by (*metis One-nat-def Suc-1 length-nth-simps*(*3*) *length-nth-simps*(*4*) *memval.sel*(*1*) *option.sel store-bytes.simps*(*2*) *stored-bytes-instant-correctness s32-split-realise*)
have *fth*: *of-byte* (*the* (*Mapping.lookup* (*store-bytes* (*content obj*) *off* (*flatten-s32 x*)) (*Suc* (*Suc* (*Suc off*))))) = *flatten-s32 x* ! *3*
by (*metis Some-to-the length-nth-simps*(*3*) *length-nth-simps*(*4*) *memval.sel*(*1*) *numeral-3-eq-3 store-bytes.simps*(*2*) *stored-bytes-instant-correctness s32-split-realise*)
show *?thesis*
by (*clarsimp simp add*: *sizeof-def store-tval-def eval-nat-numeral*(*3*), *simp add*: *numeral-Bit0*)
(*smt* (*verit*, *del-insts*) *fst snd trd fth One-nat-def Suc-1 eval-nat-numeral*(*3*) *length-nth-simps*(*3*) *length-nth-simps*(*4*) *s32-split-realise word-rcat-rsplit*)
qed

lemma *cat-flatten-u64-contents-eq*:
cat-u64 [*flatten-u64 vs* ! *0*, *flatten-u64 vs* ! *1*, *flatten-u64 vs* ! *2*, *flatten-u64 vs* ! *3*, *flatten-u64 vs* ! *4*, *flatten-u64 vs* ! *5*, *flatten-u64 vs* ! *6*, *flatten-u64 vs* ! *7*] = *vs*
using *u64-split-realise*[**where** *?v*=*vs*]
by *clarsimp* (*metis cat-flatten-u64-eq*)

lemma *cat-flatten-s64-contents-eq*:
cat-s64 [*flatten-s64 vs* ! *0*, *flatten-s64 vs* ! *1*, *flatten-s64 vs* ! *2*, *flatten-s64 vs* ! *3*, *flatten-s64 vs* ! *4*, *flatten-s64 vs* ! *5*, *flatten-s64 vs* ! *6*, *flatten-s64 vs* ! *7*] = *vs*
using *s64-split-realise*[**where** *?v*=*vs*]
by *clarsimp* (*metis word-rcat-rsplit*)

lemma *decode-encoded-u64-in-mem*:
cat-u64 (*retrieve-bytes* (*content* (*store-tval obj off* (*Uint64-v x*))) *off* |*Uint64*|$_\tau$) = *x*
proof −
have *all-bytes*: *of-byte* (*the* (*Mapping.lookup* (*store-bytes* (*content obj*) *off* (*flatten-u64*

x)) *off*)) = *flatten-u64 x* ! *0* ∧
of-byte (*the* (*Mapping.lookup* (*store-bytes* (*content obj*) *off* (*flatten-u64 x*)) (*Suc off*))) = *flatten-u64 x* ! *1* ∧
of-byte (*the* (*Mapping.lookup* (*store-bytes* (*content obj*) *off* (*flatten-u64 x*)) (*Suc* (*Suc off*)))) = *flatten-u64 x* ! *2* ∧
of-byte (*the* (*Mapping.lookup* (*store-bytes* (*content obj*) *off* (*flatten-u64 x*)) (*Suc* (*Suc* (*Suc off*))))) = *flatten-u64 x* ! *3* ∧
of-byte (*the* (*Mapping.lookup* (*store-bytes* (*content obj*) *off* (*flatten-u64 x*)) (*Suc* (*Suc* (*Suc* (*Suc off*)))))) = *flatten-u64 x* ! *4* ∧
of-byte (*the* (*Mapping.lookup* (*store-bytes* (*content obj*) *off* (*flatten-u64 x*)) (*Suc* (*Suc* (*Suc* (*Suc* (*Suc off*))))))) = *flatten-u64 x* ! *5* ∧
of-byte (*the* (*Mapping.lookup* (*store-bytes* (*content obj*) *off* (*flatten-u64 x*)) (*Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc off*)))))))) = *flatten-u64 x* ! *6* ∧
of-byte (*the* (*Mapping.lookup* (*store-bytes* (*content obj*) *off* (*flatten-u64 x*)) (*Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc off*))))))))) = *flatten-u64 x* ! *7*
by (*smt* (*verit*, *best*) *length-nth-simps*(*3*) *length-nth-simps*(*4*) *memval.sel*(*1*) *option.sel One-nat-def numeral-2-eq-2 numeral-3-eq-3 numeral-4-eq-4 numeral-5-eq-5 numeral-6-eq-6 numeral-7-eq-7 store-bytes.simps*(*2*) *stored-bytes-instant-correctness u64-split-realise*)
show *?thesis*
by (*clarsimp simp add*: *sizeof-def store-tval-def eval-nat-numeral*(*3*), *simp add*: *numeral-Bit0*)
(*presburger add*: *all-bytes cat-flatten-u64-contents-eq*)
qed

lemma *decode-encoded-s64-in-mem*:
cat-s64 (*retrieve-bytes* (*content* (*store-tval obj off* (*Sint64-v x*))) *off* |*Sint64*|$_\tau$) = *x*
proof −
have *all-bytes*: *of-byte* (*the* (*Mapping.lookup* (*store-bytes* (*content obj*) *off* (*flatten-s64 x*)) *off*)) = *flatten-s64 x* ! *0* ∧
of-byte (*the* (*Mapping.lookup* (*store-bytes* (*content obj*) *off* (*flatten-s64 x*)) (*Suc off*))) = *flatten-s64 x* ! *1* ∧
of-byte (*the* (*Mapping.lookup* (*store-bytes* (*content obj*) *off* (*flatten-s64 x*)) (*Suc* (*Suc off*)))) = *flatten-s64 x* ! *2* ∧
of-byte (*the* (*Mapping.lookup* (*store-bytes* (*content obj*) *off* (*flatten-s64 x*)) (*Suc* (*Suc* (*Suc off*))))) = *flatten-s64 x* ! *3* ∧
of-byte (*the* (*Mapping.lookup* (*store-bytes* (*content obj*) *off* (*flatten-s64 x*)) (*Suc* (*Suc* (*Suc* (*Suc off*)))))) = *flatten-s64 x* ! *4* ∧
of-byte (*the* (*Mapping.lookup* (*store-bytes* (*content obj*) *off* (*flatten-s64 x*)) (*Suc* (*Suc* (*Suc* (*Suc* (*Suc off*))))))) = *flatten-s64 x* ! *5* ∧
of-byte (*the* (*Mapping.lookup* (*store-bytes* (*content obj*) *off* (*flatten-s64 x*)) (*Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc off*)))))))) = *flatten-s64 x* ! *6* ∧
of-byte (*the* (*Mapping.lookup* (*store-bytes* (*content obj*) *off* (*flatten-s64 x*)) (*Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc* (*Suc off*))))))))) = *flatten-s64 x* ! *7*
by (*smt* (*verit*, *best*) *length-nth-simps*(*3*) *length-nth-simps*(*4*) *memval.sel*(*1*) *option.sel One-nat-def numeral-2-eq-2 numeral-3-eq-3 numeral-4-eq-4 numeral-5-eq-5 numeral-6-eq-6 numeral-7-eq-7 store-bytes.simps*(*2*) *stored-bytes-instant-correctness s64-split-realise*)

show *?thesis*
by (*clarsimp simp add*: *sizeof-def store-tval-def eval-nat-numeral*(*3*), *simp add*: *numeral-Bit0*)
(*presburger add*: *all-bytes cat-flatten-s64-contents-eq*)
qed

lemma *retrieve-stored-tval-cap*:
assumes *val* = *Cap-v v*
shows *retrieve-tval* (*store-tval obj off val*) *off* (*memval-type val*) *True* = *val*
apply (*clarsimp simp add*: *assms*)
unfolding *retrieve-tval-def*
apply (*clarsimp simp add*: *stored-tval-contiguous-cap*; *safe*)
apply (*metis is-contiguous-bytes.simps*(*2*) *less-numeral-extra*(*3*) *not0-implies-Suc sizeof-nonzero*)
subgoal
apply (*subgoal-tac is-contiguous-cap* (*content* (*store-tval obj off* (*Cap-v v*))) (*get-cap* (*content* (*store-tval obj off* (*Cap-v v*))) *off*) *off* |*Cap*|$_\tau$)
apply *clarsimp*
apply (*simp only*: *store-tval-def get-cap-def sizeof-def*)
apply *clarsimp*
apply (*subst suc-of-32*)
apply (*simp only*: *stored-cap-instant-correctness*)
apply *simp*
apply (*simp add*: *mem-capability.extend-def mem-capability.truncate-def*)
apply (*metis cctype.simps*(*81*) *get-cap-def is-contiguous-cap.simps*(*2*) *mem-val-size-cap sizeof-def stored-tval-contiguous-cap suc-of-32*)
done
subgoal
using *stored-tval-is-cap* **by** *auto*
subgoal
using *stored-tval-is-cap* **by** *auto*
subgoal
using *stored-tval-is-cap* **by** *auto*
subgoal
using *stored-tval-is-cap* **by** *auto*
subgoal
apply (*metis is-contiguous-bytes.simps*(*2*) *less-numeral-extra*(*3*) *not0-implies-Suc sizeof-nonzero*)
done
subgoal
apply (*subgoal-tac is-contiguous-cap* (*content* (*store-tval obj off* (*Cap-v v*))) (*get-cap* (*content* (*store-tval obj off* (*Cap-v v*))) *off*) *off* |*Cap*|$_\tau$)
apply *clarsimp*
apply (*simp only*: *store-tval-def get-cap-def sizeof-def*)
apply *clarsimp*
apply (*subst suc-of-32*)
apply (*simp only*: *stored-cap-instant-correctness*)
apply *simp*
apply (*simp add*: *mem-capability.extend-def mem-capability.truncate-def*)

apply (*metis cctype.simps*(*81*) *get-cap-def is-contiguous-cap.simps*(*2*) *mem-val-size-cap sizeof-def stored-tval-contiguous-cap suc-of-32*)
done
subgoal
using *stored-tval-is-cap* **by** *auto*
subgoal
using *stored-tval-is-cap* **by** *auto*
subgoal
apply (*metis cctype.simps*(*81*) *is-contiguous-bytes.simps*(*2*) *sizeof-def suc-of-32*)
done
subgoal
apply (*subgoal-tac is-contiguous-cap* (*content* (*store-tval obj off* (*Cap-v v*))) (*get-cap* (*content* (*store-tval obj off* (*Cap-v v*))) *off*) *off* $|Cap|_\tau$)
apply *clarsimp*
apply (*simp only*: *store-tval-def get-cap-def sizeof-def*)
apply *clarsimp*
apply (*metis is-contiguous-zeros-def le-eq-less-or-eq less-add-same-cancel1 mem-val-memcap-not-byte option.sel suc-of-32 zero-less-Suc*)
apply (*metis cctype.simps*(*81*) *get-cap-def is-contiguous-cap.simps*(*2*) *mem-val-size-cap sizeof-def stored-tval-contiguous-cap suc-of-32*)
done
subgoal
using *stored-tval-is-cap* **by** *auto*
subgoal
using *stored-tval-is-cap* **by** *auto*
subgoal
using *stored-tval-is-cap* **by** *auto*
subgoal
using *stored-tval-is-cap* **by** *auto*
subgoal
apply (*metis gr-implies-not-zero is-contiguous-bytes.simps*(*2*) *old.nat.exhaust sizeof-nonzero*)
done
subgoal
apply (*subgoal-tac is-contiguous-cap* (*content* (*store-tval obj off* (*Cap-v v*))) (*get-cap* (*content* (*store-tval obj off* (*Cap-v v*))) *off*) *off* $|Cap|_\tau$)
apply *clarsimp*
apply (*simp only*: *store-tval-def get-cap-def sizeof-def*)
apply *clarsimp*
apply (*subst suc-of-32*)
apply (*simp only*: *stored-cap-instant-correctness*)
apply *simp*
apply (*simp add*: *mem-capability.extend-def mem-capability.truncate-def*)
apply (*metis cctype.simps*(*81*) *get-cap-def is-contiguous-cap.simps*(*2*) *mem-val-size-cap sizeof-def stored-tval-contiguous-cap suc-of-32*)
done
subgoal
using *stored-tval-is-cap* **by** *auto*
subgoal

using *stored-tval-is-cap* **by** *auto*
done

lemma *retrieve-stored-tval-cap-no-perm-cap-load*:
assumes *val* = *Cap-v v*
shows *retrieve-tval* (*store-tval obj off val*) *off* (*memval-type val*) *False* = (*Cap-v* (*v* (‖ *tag* := *False* ‖)))
apply (*clarsimp simp add*: *assms*)
unfolding *retrieve-tval-def*
apply (*clarsimp simp add*: *stored-tval-contiguous-cap*; *safe*)
subgoal
apply (*metis is-contiguous-bytes.simps*(*2*) *less-numeral-extra*(*3*) *not0-implies-Suc sizeof-nonzero*)
done
subgoal
apply (*subgoal-tac is-contiguous-cap* (*content* (*store-tval obj off* (*Cap-v v*))) (*get-cap* (*content* (*store-tval obj off* (*Cap-v v*))) *off*) *off* $|Cap|_\tau$)
apply *clarsimp*
apply (*simp only*: *store-tval-def get-cap-def sizeof-def*)
apply *clarsimp*
apply (*metis is-contiguous-zeros-def le-eq-less-or-eq less-add-same-cancel1 memval-memcap-not-byte option.sel suc-of-32 zero-less-Suc*)
apply (*metis cctype.simps*(*81*) *get-cap-def is-contiguous-cap.simps*(*2*) *memval-size-cap sizeof-def stored-tval-contiguous-cap suc-of-32*)
done
subgoal
using *stored-tval-is-cap* **by** *auto*
subgoal
using *stored-tval-is-cap* **by** *auto*
subgoal
using *stored-tval-is-cap* **by** *auto*
subgoal
using *stored-tval-is-cap* **by** *auto*
subgoal
apply (*metis is-contiguous-bytes.simps*(*2*) *less-numeral-extra*(*3*) *not0-implies-Suc sizeof-nonzero*)
done
subgoal
apply (*subgoal-tac is-contiguous-cap* (*content* (*store-tval obj off* (*Cap-v v*))) (*get-cap* (*content* (*store-tval obj off* (*Cap-v v*))) *off*) *off* $|Cap|_\tau$)
apply *clarsimp*
apply (*simp only*: *store-tval-def get-cap-def sizeof-def*)
apply *clarsimp*
apply (*subst suc-of-32*)
apply (*simp only*: *stored-cap-instant-correctness*)
apply *simp*
apply (*simp add*: *mem-capability.extend-def mem-capability.truncate-def*)
apply (*metis cctype.simps*(*81*) *get-cap-def is-contiguous-cap.simps*(*2*) *memval-size-cap sizeof-def stored-tval-contiguous-cap suc-of-32*)

done
subgoal
using *stored-tval-is-cap* **by** *auto*
subgoal
using *stored-tval-is-cap* **by** *auto*
done

lemma *retrieve-stored-tval-u8*:
assumes *val* = *Uint8-v v*
shows *retrieve-tval* (*store-tval obj off val*) *off* (*memval-type val*) *b* = *val*
unfolding *retrieve-tval-def*
proof (*clarsimp simp add*: *assms stored-tval-contiguous-bytes*; *safe*)
show ⟦*off* ∈ *Mapping.keys* (*content* (*store-tval obj off* (*Uint8-v v*))); *memval-is-cap* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Uint8-v v*))) *off*)); *is-contiguous-bytes* (*content* (*store-tval obj off* (*Uint8-v v*))) *off* |*Uint8*|$_\tau$⟧ ⟹ *decode-u8-list* (*retrieve-bytes* (*content* (*store-tval obj off* (*Uint8-v v*))) *off* |*Uint8*|$_\tau$) = *v*
by (*simp add*: *sizeof-def*)
next
show ⟦*off* ∈ *Mapping.keys* (*content* (*store-tval obj off* (*Uint8-v v*))); *memval-is-cap* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Uint8-v v*))) *off*))⟧ ⟹ *is-contiguous-bytes* (*content* (*store-tval obj off* (*Uint8-v v*))) *off* |*Uint8*|$_\tau$
by (*metis One-nat-def ccval.distinct*(*15*) *ccval.distinct*(*17*) *ccval.distinct*(*19*) *is-contiguous-bytes.simps*(*2*) *memval-size-u8 stored-tval-contiguous-bytes*)
next
show ⟦*off* ∉ *Mapping.keys* (*content* (*store-tval obj off* (*Uint8-v v*))); *is-contiguous-bytes* (*content* (*store-tval obj off* (*Uint8-v v*))) *off* |*Uint8*|$_\tau$⟧ ⟹ *decode-u8-list* (*retrieve-bytes* (*content* (*store-tval obj off* (*Uint8-v v*))) *off* |*Uint8*|$_\tau$) = *v*
by (*simp add*: *sizeof-def*)
next
show *off* ∉ *Mapping.keys* (*content* (*store-tval obj off* (*Uint8-v v*))) ⟹ *is-contiguous-bytes* (*content* (*store-tval obj off* (*Uint8-v v*))) *off* |*Uint8*|$_\tau$
by (*metis cctype.simps*(*73*) *ccval.distinct*(*15*) *ccval.distinct*(*17*) *ccval.distinct*(*19*) *memval-size-u8 sizeof-def stored-tval-contiguous-bytes*)
next
show ⟦*memval-is-byte* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Uint8-v v*))) *off*)); *is-contiguous-bytes* (*content* (*store-tval obj off* (*Uint8-v v*))) *off* |*Uint8*|$_\tau$⟧ ⟹ *decode-u8-list* (*retrieve-bytes* (*content* (*store-tval obj off* (*Uint8-v v*))) *off* |*Uint8*|$_\tau$) = *v*
by (*clarsimp simp add*: *sizeof-def store-tval-def*)
next
show *memval-is-byte* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Uint8-v v*))) *off*)) ⟹ *is-contiguous-bytes* (*content* (*store-tval obj off* (*Uint8-v v*))) *off* |*Uint8*|$_\tau$
by (*metis cctype.simps*(*73*) *ccval.distinct*(*15*) *ccval.distinct*(*17*) *ccval.distinct*(*19*) *memval-size-u8 sizeof-def stored-tval-contiguous-bytes*)
qed

lemma *retrieve-stored-tval-s8*:
assumes *val* = *Sint8-v v*
shows *retrieve-tval* (*store-tval obj off val*) *off* (*memval-type val*) *b* = *val*
unfolding *retrieve-tval-def*
proof (*clarsimp simp add*: *assms stored-tval-contiguous-bytes*; *safe*)
show ⟦*off* ∈ *Mapping.keys* (*content* (*store-tval obj off* (*Sint8-v v*))); *memval-is-cap* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Sint8-v v*))) *off*));
is-contiguous-bytes (*content* (*store-tval obj off* (*Sint8-v v*))) *off* |*Sint8*|$_\tau$⟧
⟹ *decode-u8-list* (*retrieve-bytes* (*content* (*store-tval obj off* (*Sint8-v v*))) *off* |*Sint8*|$_\tau$) = *SCAST*(*8 signed* → *8*) *v*
by (*simp add*: *sizeof-def*)
next
show ⟦*off* ∈ *Mapping.keys* (*content* (*store-tval obj off* (*Sint8-v v*))); *memval-is-cap* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Sint8-v v*))) *off*))⟧
⟹ *is-contiguous-bytes* (*content* (*store-tval obj off* (*Sint8-v v*))) *off* |*Sint8*|$_\tau$
by (*metis One-nat-def ccval.distinct*(*33*) *ccval.distinct*(*35*) *ccval.distinct*(*37*) *is-contiguous-bytes.simps*(*2*) *memval-size-s8 stored-tval-contiguous-bytes*)
next
show ⟦*off* ∉ *Mapping.keys* (*content* (*store-tval obj off* (*Sint8-v v*))); *is-contiguous-bytes* (*content* (*store-tval obj off* (*Sint8-v v*))) *off* |*Sint8*|$_\tau$⟧
⟹ *decode-u8-list* (*retrieve-bytes* (*content* (*store-tval obj off* (*Sint8-v v*))) *off* |*Sint8*|$_\tau$) = *SCAST*(*8 signed* → *8*) *v*
by (*simp add*: *sizeof-def*)
next
show *off* ∉ *Mapping.keys* (*content* (*store-tval obj off* (*Sint8-v v*))) ⟹ *is-contiguous-bytes* (*content* (*store-tval obj off* (*Sint8-v v*))) *off* |*Sint8*|$_\tau$
by (*metis cctype.simps*(*74*) *ccval.distinct*(*33*) *ccval.distinct*(*35*) *ccval.distinct*(*37*) *memval-size-s8 sizeof-def stored-tval-contiguous-bytes*)
next
show ⟦*memval-is-byte* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Sint8-v v*))) *off*)); *is-contiguous-bytes* (*content* (*store-tval obj off* (*Sint8-v v*))) *off* |*Sint8*|$_\tau$⟧
⟹ *decode-u8-list* (*retrieve-bytes* (*content* (*store-tval obj off* (*Sint8-v v*))) *off* |*Sint8*|$_\tau$) = *SCAST*(*8 signed* → *8*) *v*
by (*clarsimp simp add*: *sizeof-def store-tval-def*)
next
show *memval-is-byte* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Sint8-v v*))) *off*)) ⟹ *is-contiguous-bytes* (*content* (*store-tval obj off* (*Sint8-v v*))) *off* |*Sint8*|$_\tau$
by (*metis cctype.simps*(*74*) *ccval.distinct*(*33*) *ccval.distinct*(*35*) *ccval.distinct*(*37*) *memval-size-s8 sizeof-def stored-tval-contiguous-bytes*)
qed

lemma *retrieve-stored-tval-u16*:
assumes *val* = *Uint16-v v*
shows *retrieve-tval* (*store-tval obj off val*) *off* (*memval-type val*) *b* = *val*
unfolding *retrieve-tval-def*
proof (*clarsimp simp add*: *assms stored-tval-contiguous-bytes*; *safe*)
show ⟦*off* ∈ *Mapping.keys* (*content* (*store-tval obj off* (*Uint16-v v*))); *memval-is-cap* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Uint16-v v*))) *off*));
is-contiguous-bytes (*content* (*store-tval obj off* (*Uint16-v v*))) *off* |*Uint16*|$_\tau$⟧

$\Longrightarrow$ *cat-u16* (*retrieve-bytes* (*content* (*store-tval obj off* (*Uint16-v v*))) *off* $|Uint16|_\tau$)
= *v*
by (*presburger add*: *decode-encoded-u16-in-mem*)
next
show ⟦*off* ∈ *Mapping.keys* (*content* (*store-tval obj off* (*Uint16-v v*))); *memval-is-cap* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Uint16-v v*))) *off*))⟧
$\Longrightarrow$ *is-contiguous-bytes* (*content* (*store-tval obj off* (*Uint16-v v*))) *off* $|Uint16|_\tau$
by (*metis ccval.distinct*(*49*) *ccval.distinct*(*51*) *ccval.distinct*(*53*) *is-contiguous-bytes.simps*(*2*) *memval-size-u16 numeral-2-eq-2 stored-tval-contiguous-bytes*)
next
show ⟦*off* ∉ *Mapping.keys* (*content* (*store-tval obj off* (*Uint16-v v*))); *is-contiguous-bytes* (*content* (*store-tval obj off* (*Uint16-v v*))) *off* $|Uint16|_\tau$⟧
$\Longrightarrow$ *cat-u16* (*retrieve-bytes* (*content* (*store-tval obj off* (*Uint16-v v*))) *off* $|Uint16|_\tau$)
= *v*
by (*presburger add*: *decode-encoded-u16-in-mem*)
next
show *off* ∉ *Mapping.keys* (*content* (*store-tval obj off* (*Uint16-v v*))) $\Longrightarrow$ *is-contiguous-bytes* (*content* (*store-tval obj off* (*Uint16-v v*))) *off* $|Uint16|_\tau$
by (*metis Suc-1 ccval.distinct*(*49*) *ccval.distinct*(*51*) *ccval.distinct*(*53*) *is-contiguous-bytes.simps*(*2*) *memval-size-u16 stored-tval-contiguous-bytes*)
next
show ⟦*memval-is-byte* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Uint16-v v*))) *off*)); *is-contiguous-bytes* (*content* (*store-tval obj off* (*Uint16-v v*))) *off* $|Uint16|_\tau$⟧
$\Longrightarrow$ *cat-u16* (*retrieve-bytes* (*content* (*store-tval obj off* (*Uint16-v v*))) *off* $|Uint16|_\tau$)
= *v*
by (*presburger add*: *decode-encoded-u16-in-mem*)
next
show *memval-is-byte* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Uint16-v v*))) *off*)) $\Longrightarrow$ *is-contiguous-bytes* (*content* (*store-tval obj off* (*Uint16-v v*))) *off* $|Uint16|_\tau$
by (*metis cctype.simps*(*75*) *ccval.distinct*(*49*) *ccval.distinct*(*51*) *ccval.distinct*(*53*) *memval-size-u16 sizeof-def stored-tval-contiguous-bytes*)
qed

lemma *retrieve-stored-tval-s16*:
assumes *val* = *Sint16-v v*
shows *retrieve-tval* (*store-tval obj off val*) *off* (*memval-type val*) *b* = *val*
unfolding *retrieve-tval-def*
proof (*clarsimp simp add*: *assms stored-tval-contiguous-bytes*; *safe*)
show ⟦*off* ∈ *Mapping.keys* (*content* (*store-tval obj off* (*Sint16-v v*))); *memval-is-cap* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Sint16-v v*))) *off*)); *is-contiguous-bytes* (*content* (*store-tval obj off* (*Sint16-v v*))) *off* $|Sint16|_\tau$⟧
$\Longrightarrow$ *cat-s16* (*retrieve-bytes* (*content* (*store-tval obj off* (*Sint16-v v*))) *off* $|Sint16|_\tau$)
= *v*
by (*presburger add*: *decode-encoded-s16-in-mem*)
next
show ⟦*off* ∈ *Mapping.keys* (*content* (*store-tval obj off* (*Sint16-v v*))); *memval-is-cap* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Sint16-v v*))) *off*))⟧
$\Longrightarrow$ *is-contiguous-bytes* (*content* (*store-tval obj off* (*Sint16-v v*))) *off* $|Sint16|_\tau$

by (*metis ccval.distinct*(*63*) *ccval.distinct*(*65*) *ccval.distinct*(*67*) *is-contiguous-bytes.simps*(*2*) *memval-size-s16 numeral-2-eq-2 stored-tval-contiguous-bytes*)
next
show ⟦*off* ∉ *Mapping.keys* (*content* (*store-tval obj off* (*Sint16-v v*))); *is-contiguous-bytes* (*content* (*store-tval obj off* (*Sint16-v v*))) *off* |*Sint16*|$_\tau$⟧
⟹ *cat-s16* (*retrieve-bytes* (*content* (*store-tval obj off* (*Sint16-v v*))) *off* |*Sint16*|$_\tau$)
= *v*
by (*presburger add*: *decode-encoded-s16-in-mem*)
next
show *off* ∉ *Mapping.keys* (*content* (*store-tval obj off* (*Sint16-v v*))) ⟹ *is-contiguous-bytes* (*content* (*store-tval obj off* (*Sint16-v v*))) *off* |*Sint16*|$_\tau$
by (*metis Suc-1 ccval.distinct*(*63*) *ccval.distinct*(*65*) *ccval.distinct*(*67*) *is-contiguous-bytes.simps*(*2*) *memval-size-s16 stored-tval-contiguous-bytes*)
next
show ⟦*memval-is-byte* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Sint16-v v*))) *off*)); *is-contiguous-bytes* (*content* (*store-tval obj off* (*Sint16-v v*))) *off* |*Sint16*|$_\tau$⟧
⟹ *cat-s16* (*retrieve-bytes* (*content* (*store-tval obj off* (*Sint16-v v*))) *off* |*Sint16*|$_\tau$)
= *v*
by (*presburger add*: *decode-encoded-s16-in-mem*)
next
show *memval-is-byte* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Sint16-v v*))) *off*)) ⟹ *is-contiguous-bytes* (*content* (*store-tval obj off* (*Sint16-v v*))) *off* |*Sint16*|$_\tau$
by (*metis cctype.simps*(*76*) *ccval.distinct*(*63*) *ccval.distinct*(*65*) *ccval.distinct*(*67*) *memval-size-s16 sizeof-def stored-tval-contiguous-bytes*)
qed

lemma *retrieve-stored-tval-u32*:
assumes *val* = *Uint32-v v*
shows *retrieve-tval* (*store-tval obj off val*) *off* (*memval-type val*) *b* = *val*
unfolding *retrieve-tval-def*
proof (*clarsimp simp add*: *assms stored-tval-contiguous-bytes*; *safe*)
show ⟦*off* ∈ *Mapping.keys* (*content* (*store-tval obj off* (*Uint32-v v*))); *memval-is-cap* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Uint32-v v*))) *off*)); *is-contiguous-bytes* (*content* (*store-tval obj off* (*Uint32-v v*))) *off* |*Uint32*|$_\tau$⟧
⟹ *cat-u32* (*retrieve-bytes* (*content* (*store-tval obj off* (*Uint32-v v*))) *off* |*Uint32*|$_\tau$)
= *v*
by (*presburger add*: *decode-encoded-u32-in-mem*)
next
show ⟦*off* ∈ *Mapping.keys* (*content* (*store-tval obj off* (*Uint32-v v*))); *memval-is-cap* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Uint32-v v*))) *off*))⟧
⟹ *is-contiguous-bytes* (*content* (*store-tval obj off* (*Uint32-v v*))) *off* |*Uint32*|$_\tau$
by (*metis ccval.distinct*(*75*) *ccval.distinct*(*77*) *ccval.distinct*(*79*) *is-contiguous-bytes.simps*(*2*) *memval-size-u32 numeral-4-eq-4 stored-tval-contiguous-bytes*)
next
show ⟦*off* ∉ *Mapping.keys* (*content* (*store-tval obj off* (*Uint32-v v*))); *is-contiguous-bytes* (*content* (*store-tval obj off* (*Uint32-v v*))) *off* |*Uint32*|$_\tau$⟧
⟹ *cat-u32* (*retrieve-bytes* (*content* (*store-tval obj off* (*Uint32-v v*))) *off* |*Uint32*|$_\tau$)
= *v*

by (*presburger add*: *decode-encoded-u32-in-mem*)
next
show *off* ∉ *Mapping.keys* (*content* (*store-tval obj off* (*Uint32-v v*))) ⟹ *is-contiguous-bytes* (*content* (*store-tval obj off* (*Uint32-v v*))) *off* |*Uint32*|$_\tau$
by (*metis ccval.distinct*(*77*) *ccval.distinct*(*79*) *is-cap.elims*(*2*) *is-contiguous-bytes.simps*(*2*) *memval-size-u32 numeral-4-eq-4 stored-tval-contiguous-bytes stored-tval-is-cap*)
next
show ⟦*memval-is-byte* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Uint32-v v*))) *off*)); *is-contiguous-bytes* (*content* (*store-tval obj off* (*Uint32-v v*))) *off* |*Uint32*|$_\tau$⟧ ⟹ *cat-u32* (*retrieve-bytes* (*content* (*store-tval obj off* (*Uint32-v v*))) *off* |*Uint32*|$_\tau$) = *v*
by (*presburger add*: *decode-encoded-u32-in-mem*)
next
show *memval-is-byte* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Uint32-v v*))) *off*)) ⟹ *is-contiguous-bytes* (*content* (*store-tval obj off* (*Uint32-v v*))) *off* |*Uint32*|$_\tau$
by (*metis cctype.simps*(*77*) *ccval.distinct*(*75*) *ccval.distinct*(*77*) *ccval.distinct*(*79*) *memval-size-u32 sizeof-def stored-tval-contiguous-bytes*)
qed

lemma *retrieve-stored-tval-s32*:
assumes *val* = *Sint32-v v*
shows *retrieve-tval* (*store-tval obj off val*) *off* (*memval-type val*) *b* = *val*
unfolding *retrieve-tval-def*
proof (*clarsimp simp add*: *assms stored-tval-contiguous-bytes*; *safe*)
show ⟦*off* ∈ *Mapping.keys* (*content* (*store-tval obj off* (*Sint32-v v*))); *memval-is-cap* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Sint32-v v*))) *off*)); *is-contiguous-bytes* (*content* (*store-tval obj off* (*Sint32-v v*))) *off* |*Sint32*|$_\tau$⟧ ⟹ *cat-s32* (*retrieve-bytes* (*content* (*store-tval obj off* (*Sint32-v v*))) *off* |*Sint32*|$_\tau$) = *v*
by (*presburger add*: *decode-encoded-s32-in-mem*)
next
show ⟦*off* ∈ *Mapping.keys* (*content* (*store-tval obj off* (*Sint32-v v*))); *memval-is-cap* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Sint32-v v*))) *off*))⟧ ⟹ *is-contiguous-bytes* (*content* (*store-tval obj off* (*Sint32-v v*))) *off* |*Sint32*|$_\tau$
by (*metis cctype.simps*(*78*) *ccval.distinct*(*85*) *ccval.distinct*(*87*) *ccval.distinct*(*89*) *flatten-s32-length memval-size-s32-eq-word-split-len sizeof-def stored-tval-contiguous-bytes*)
next
show ⟦*off* ∉ *Mapping.keys* (*content* (*store-tval obj off* (*Sint32-v v*))); *is-contiguous-bytes* (*content* (*store-tval obj off* (*Sint32-v v*))) *off* |*Sint32*|$_\tau$⟧ ⟹ *cat-s32* (*retrieve-bytes* (*content* (*store-tval obj off* (*Sint32-v v*))) *off* |*Sint32*|$_\tau$) = *v*
by (*presburger add*: *decode-encoded-s32-in-mem*)
next
show *off* ∉ *Mapping.keys* (*content* (*store-tval obj off* (*Sint32-v v*))) ⟹ *is-contiguous-bytes* (*content* (*store-tval obj off* (*Sint32-v v*))) *off* |*Sint32*|$_\tau$
by (*metis ccval.distinct*(*85*) *ccval.distinct*(*87*) *ccval.distinct*(*89*) *is-contiguous-bytes.simps*(*2*) *less-numeral-extra*(*3*) *not0-implies-Suc sizeof-nonzero stored-tval-contiguous-bytes*)
next

show ⟦*memval-is-byte* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Sint32-v v*))) *off*)); *is-contiguous-bytes* (*content* (*store-tval obj off* (*Sint32-v v*))) *off* $|Sint32|_\tau$⟧
⟹ *cat-s32* (*retrieve-bytes* (*content* (*store-tval obj off* (*Sint32-v v*))) *off* $|Sint32|_\tau$)
= *v*
by (*presburger add*: *decode-encoded-s32-in-mem*)
next
show *memval-is-byte* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Sint32-v v*))) *off*)) ⟹ *is-contiguous-bytes* (*content* (*store-tval obj off* (*Sint32-v v*))) *off* $|Sint32|_\tau$
by (*metis cctype.simps*(*78*) *ccval.distinct*(*85*) *ccval.distinct*(*87*) *ccval.simps*(*100*) *flatten-s32-length memval-size-s32-eq-word-split-len sizeof-def stored-tval-contiguous-bytes*)
qed

lemma *retrieve-stored-tval-u64*:
assumes *val* = *Uint64-v v*
shows *retrieve-tval* (*store-tval obj off val*) *off* (*memval-type val*) *b* = *val*
unfolding *retrieve-tval-def*
proof (*clarsimp simp add*: *assms stored-tval-contiguous-bytes*; *safe*)
show ⟦*off* ∈ *Mapping.keys* (*content* (*store-tval obj off* (*Uint64-v v*))); *memval-is-cap* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Uint64-v v*))) *off*)); *is-contiguous-bytes* (*content* (*store-tval obj off* (*Uint64-v v*))) *off* $|Uint64|_\tau$⟧
⟹ *cat-u64* (*retrieve-bytes* (*content* (*store-tval obj off* (*Uint64-v v*))) *off* $|Uint64|_\tau$)
= *v*
by (*presburger add*: *decode-encoded-u64-in-mem*)
next
show ⟦*off* ∈ *Mapping.keys* (*content* (*store-tval obj off* (*Uint64-v v*))); *memval-is-cap* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Uint64-v v*))) *off*))⟧
⟹ *is-contiguous-bytes* (*content* (*store-tval obj off* (*Uint64-v v*))) *off* $|Uint64|_\tau$
by (*metis cctype.simps*(*79*) *ccval.distinct*(*93*) *ccval.distinct*(*95*) *ccval.distinct*(*97*) *memval-size-u64 sizeof-def stored-tval-contiguous-bytes*)
next
show ⟦*off* ∉ *Mapping.keys* (*content* (*store-tval obj off* (*Uint64-v v*))); *is-contiguous-bytes* (*content* (*store-tval obj off* (*Uint64-v v*))) *off* $|Uint64|_\tau$⟧
⟹ *cat-u64* (*retrieve-bytes* (*content* (*store-tval obj off* (*Uint64-v v*))) *off* $|Uint64|_\tau$)
= *v*
by (*presburger add*: *decode-encoded-u64-in-mem*)
next
show *off* ∉ *Mapping.keys* (*content* (*store-tval obj off* (*Uint64-v v*))) ⟹ *is-contiguous-bytes* (*content* (*store-tval obj off* (*Uint64-v v*))) *off* $|Uint64|_\tau$
by (*metis cctype.simps*(*79*) *ccval.distinct*(*95*) *ccval.distinct*(*97*) *is-cap.elims*(*1*) *memval-size-u64 sizeof-def stored-tval-contiguous-bytes stored-tval-is-cap*)
next
show ⟦*memval-is-byte* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Uint64-v v*))) *off*)); *is-contiguous-bytes* (*content* (*store-tval obj off* (*Uint64-v v*))) *off* $|Uint64|_\tau$⟧
⟹ *cat-u64* (*retrieve-bytes* (*content* (*store-tval obj off* (*Uint64-v v*))) *off* $|Uint64|_\tau$)
= *v*
by (*presburger add*: *decode-encoded-u64-in-mem*)
next
show *memval-is-byte* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Uint64-v*

v))) *off*)) ⟹ *is-contiguous-bytes* (*content* (*store-tval obj off* (*Uint64-v v*))) *off* |*Uint64*|$_\tau$
by (*metis cctype.simps*(*79*) *ccval.distinct*(*93*) *ccval.distinct*(*95*) *ccval.distinct*(*97*) *memval-size-u64 sizeof-def stored-tval-contiguous-bytes*)
qed

lemma *retrieve-stored-tval-s64*:
assumes *val* = *Sint64-v v*
shows *retrieve-tval* (*store-tval obj off val*) *off* (*memval-type val*) *b* = *val*
unfolding *retrieve-tval-def*
proof (*clarsimp simp add*: *assms stored-tval-contiguous-bytes*; *safe*)
show ⟦*off* ∈ *Mapping.keys* (*content* (*store-tval obj off* (*Sint64-v v*))); *memval-is-cap* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Sint64-v v*))) *off*)); *is-contiguous-bytes* (*content* (*store-tval obj off* (*Sint64-v v*))) *off* |*Sint64*|$_\tau$⟧
⟹ *cat-s64* (*retrieve-bytes* (*content* (*store-tval obj off* (*Sint64-v v*))) *off* |*Sint64*|$_\tau$) = *v*
by (*presburger add*: *decode-encoded-s64-in-mem*)
next
show ⟦*off* ∈ *Mapping.keys* (*content* (*store-tval obj off* (*Sint64-v v*))); *memval-is-cap* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Sint64-v v*))) *off*))⟧
⟹ *is-contiguous-bytes* (*content* (*store-tval obj off* (*Sint64-v v*))) *off* |*Sint64*|$_\tau$
by (*metis cctype.simps*(*80*) *ccval.distinct*(*101*) *ccval.distinct*(*103*) *ccval.distinct*(*99*) *memval-size-s64 sizeof-def stored-tval-contiguous-bytes*)
next
show ⟦*off* ∉ *Mapping.keys* (*content* (*store-tval obj off* (*Sint64-v v*))); *is-contiguous-bytes* (*content* (*store-tval obj off* (*Sint64-v v*))) *off* |*Sint64*|$_\tau$⟧
⟹ *cat-s64* (*retrieve-bytes* (*content* (*store-tval obj off* (*Sint64-v v*))) *off* |*Sint64*|$_\tau$) = *v*
by (*presburger add*: *decode-encoded-s64-in-mem*)
next
show *off* ∉ *Mapping.keys* (*content* (*store-tval obj off* (*Sint64-v v*))) ⟹ *is-contiguous-bytes* (*content* (*store-tval obj off* (*Sint64-v v*))) *off* |*Sint64*|$_\tau$
by (*metis bot-nat-0.not-eq-extremum ccval.distinct*(*101*) *ccval.distinct*(*103*) *ccval.distinct*(*99*) *is-contiguous-bytes.simps*(*2*) *list-decode.cases sizeof-nonzero stored-tval-contiguous-bytes*)

next
show ⟦*memval-is-byte* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Sint64-v v*))) *off*)); *is-contiguous-bytes* (*content* (*store-tval obj off* (*Sint64-v v*))) *off* |*Sint64*|$_\tau$⟧
⟹ *cat-s64* (*retrieve-bytes* (*content* (*store-tval obj off* (*Sint64-v v*))) *off* |*Sint64*|$_\tau$) = *v*
by (*presburger add*: *decode-encoded-s64-in-mem*)
next
show *memval-is-byte* (*the* (*Mapping.lookup* (*content* (*store-tval obj off* (*Sint64-v v*))) *off*)) ⟹ *is-contiguous-bytes* (*content* (*store-tval obj off* (*Sint64-v v*))) *off* |*Sint64*|$_\tau$
by (*metis cctype.simps*(*80*) *ccval.distinct*(*101*) *ccval.distinct*(*103*) *ccval.distinct*(*99*) *memval-size-s64 sizeof-def stored-tval-contiguous-bytes*)
qed

lemma *memcap-truncate-extend-equiv*:
mem-capability.extend (*mem-capability.truncate c*) (| *tag* = *tag c* |) = *c*
by (*simp add*: *mem-capability.extend-def mem-capability.truncate-def*)

corollary *Acap-truncate-extend-equiv*:
mem-capability.extend (*of-cap* (*ACap* (*mem-capability.truncate c*) *n*)) (| *tag* = *tag c* |) = *c*
by *clarsimp* (*blast intro*: *memcap-truncate-extend-equiv*)

lemma *memcap-truncate-extend-gen*:
mem-capability.extend (*mem-capability.truncate c*) (| *tag* = *b* |) = *c* (| *tag* := *b* |)
by (*simp add*: *mem-capability.extend-def mem-capability.truncate-def*)

corollary *Acap-truncate-extend-gen*:
mem-capability.extend (*of-cap* (*ACap* (*mem-capability.truncate c*) *n*)) (| *tag* = *b* |) = *c* (| *tag* := *b* |)
by *clarsimp* (*blast intro*: *memcap-truncate-extend-gen*)

lemma *retrieve-stored-tval-cap-frag*:
assumes *val* = *Cap-v-frag c n*
shows *retrieve-tval* (*store-tval obj off val*) *off* (*memval-type val*) *b* =
Cap-v-frag (*c* (| *tag* := *False* |)) *n*
by (*clarsimp simp add*: *assms retrieve-tval-def store-tval-def sizeof-def get-cap-def memcap-truncate-extend-gen memval-is-byte-def split*: *bool.split*)

lemmas *retrieve-stored-tval-prim* = *retrieve-stored-tval-u8 retrieve-stored-tval-s8*
retrieve-stored-tval-u16 retrieve-stored-tval-s16
retrieve-stored-tval-u32 retrieve-stored-tval-s32
retrieve-stored-tval-u64 retrieve-stored-tval-s64

lemma *retrieve-stored-tval-any-perm*:
assumes *val* ≠ *Undef*
and ∀ *v*. *val* ≠ *Cap-v v*
and ∀ *v n*. *val* ≠ *Cap-v-frag v n*
shows *retrieve-tval* (*store-tval obj off val*) *off* (*memval-type val*) *b* = *val*
using *retrieve-stored-tval-prim*[**where** *?obj*=*obj* **and** *?off*=*off* **and** *?val*=*val* **and** *?b*=*b*]
by (*clarsimp simp add*: *assms split*: *ccval.split*)

lemma *retrieve-stored-tval-with-perm-cap-load*:
assumes *val* ≠ *Undef*
and ∀ *v n*. *val* ≠ *Cap-v-frag v n*
shows *retrieve-tval* (*store-tval obj off val*) *off* (*memval-type val*) *True* = *val*
using *retrieve-stored-tval-prim*[**where** *?obj*=*obj* **and** *?off*=*off* **and** *?val*=*val* **and** *?b*=*True*]
retrieve-stored-tval-cap[**where** *?obj*=*obj* **and** *?off*=*off* **and** *?val*=*val*]
by (*clarsimp simp add*: *assms split*: *ccval.split*)

lemma *store-bytes-domain-1*:

assumes $x + \mathit{length}\ \mathit{vs} \leq n$
shows $\mathit{Mapping.lookup}\ (\mathit{store\text{-}bytes}\ m\ n\ \mathit{vs})\ x = \mathit{Mapping.lookup}\ m\ x$
using *assms*
by (*induct vs arbitrary*: $x\ m\ n$) *simp-all*

lemma *store-bytes-domain-2*:
assumes $n + \mathit{length}\ \mathit{vs} \leq x$
shows $\mathit{Mapping.lookup}\ (\mathit{store\text{-}bytes}\ m\ n\ \mathit{vs})\ x = \mathit{Mapping.lookup}\ m\ x$
using *assms*
by (*induct vs arbitrary*: $x\ m\ n$) *simp-all*

lemma *store-bytes-keys-1*:
$\mathit{Set.filter}\ (\lambda\ x.\ x + \mathit{length}\ \mathit{vs} \leq n)\ (\mathit{Mapping.keys}\ m) =$
$\mathit{Set.filter}\ (\lambda\ x.\ x + \mathit{length}\ \mathit{vs} \leq n)\ (\mathit{Mapping.keys}\ (\mathit{store\text{-}bytes}\ m\ n\ \mathit{vs}))$
by (*induct vs arbitrary*: $m\ n$)
(*simp*, *smt* (*verit*, *best*) *Collect-cong Set.filter-def keys-is-none-rep store-bytes-domain-1*)

lemma *store-bytes-keys-2*:
$\mathit{Set.filter}\ (\lambda\ x.\ n + \mathit{length}\ \mathit{vs} \leq x)\ (\mathit{Mapping.keys}\ m) =$
$\mathit{Set.filter}\ (\lambda\ x.\ n + \mathit{length}\ \mathit{vs} \leq x)\ (\mathit{Mapping.keys}\ (\mathit{store\text{-}bytes}\ m\ n\ \mathit{vs}))$
by (*induct vs arbitrary*: $m\ n$)
(*simp*, *smt* (*verit*, *best*) *Collect-cong Set.filter-def keys-is-none-rep store-bytes-domain-2*)

lemma *store-cap-domain-1*:
assumes $x + n \leq p$
shows $\mathit{Mapping.lookup}\ (\mathit{store\text{-}cap}\ m\ p\ c\ n)\ x = \mathit{Mapping.lookup}\ m\ x$
using *assms*
by (*induct n arbitrary*: $x\ m\ p$) *simp-all*

lemma *store-cap-domain-2*:
assumes $p + n \leq x$
shows $\mathit{Mapping.lookup}\ (\mathit{store\text{-}cap}\ m\ p\ c\ n)\ x = \mathit{Mapping.lookup}\ m\ x$
using *assms*
by (*induct n arbitrary*: $x\ m\ p$) *simp-all*

lemma *store-cap-keys-1*:
$\mathit{Set.filter}\ (\lambda\ x.\ x + n \leq p)\ (\mathit{Mapping.keys}\ m) =$
$\mathit{Set.filter}\ (\lambda\ x.\ x + n \leq p)\ (\mathit{Mapping.keys}\ (\mathit{store\text{-}cap}\ m\ p\ c\ n))$
by (*induct n arbitrary*: $m\ p$)
(*force*, *smt* (*verit*, *best*) *Collect-cong Set.filter-def keys-is-none-rep store-cap-domain-1*)

lemma *store-cap-keys-2*:
$\mathit{Set.filter}\ (\lambda\ x.\ p + n \leq x)\ (\mathit{Mapping.keys}\ m) =$
$\mathit{Set.filter}\ (\lambda\ x.\ p + n \leq x)\ (\mathit{Mapping.keys}\ (\mathit{store\text{-}cap}\ m\ p\ c\ n))$
by (*induct n arbitrary*: $m\ p$)
(*force*, *smt* (*verit*, *best*) *Collect-cong Set.filter-def keys-is-none-rep store-cap-domain-2*)

lemma *store-tags-domain-1*:
assumes $x < n$

shows *Mapping.lookup* (*store-tag m n b*) *x* = *Mapping.lookup m x*
using *assms* **by** *auto*

lemma *store-tags-domain-2*:
assumes *n* < *x*
shows *Mapping.lookup* (*store-tag m n b*) *x* = *Mapping.lookup m x*
using *assms* **by** *auto*

lemma *store-tags-keys-1*:
Set.filter (λ *x*. *x* < *n*) (*Mapping.keys m*) =
Set.filter (λ *x*. *x* < *n*) (*Mapping.keys* (*store-tag m n b*))
by *fastforce*

lemma *store-tags-keys-2*:
Set.filter (λ *x*. *n* < *x*) (*Mapping.keys m*) =
Set.filter (λ *x*. *n* < *x*) (*Mapping.keys* (*store-tag m n b*))
by *fastforce*

lemma *cap-offset-aligned*:
(*cap-offset n*) *mod* $|Cap|_\tau$ = *0*
unfolding *sizeof-def*
by *force*

lemma *store-tags-offset*:
assumes *Set.filter* (λ *x*. *x mod* $|Cap|_\tau$ ≠ *0*) (*Mapping.keys m*) = {}
shows *Set.filter* (λ *x*. *x mod* $|Cap|_\tau$ ≠ *0*) (*Mapping.keys* (*store-tag m* (*cap-offset n*) *b*)) = {}
using *assms*
unfolding *sizeof-def*
by *force*

lemma *store-tval-disjoint-bounds*:
assumes *store-tval obj off val* = *obj'*
and *val* ≠ *Undef*
shows *bounds obj* = *bounds obj'*
using *assms*
unfolding *store-tval-def*
by (*clarsimp split*: *ccval.split-asm*)

lemma *store-tval-disjoint-1-content*:
assumes *store-tval obj off val* = *obj'*
and *val* ≠ *Undef*
and *off'* < *off*
shows *Mapping.lookup* (*content obj*) *off'* = *Mapping.lookup* (*content obj'*) *off'*
using *assms*
by (*clarsimp simp add*: *store-tval-def split*: *ccval.split-asm*)
(*presburger add*: *stored-bytes-prev stored-cap-prev*)+

lemma *store-tval-disjoint-1-content-bytes*:

assumes *store-tval obj off val* = *obj'*
and *val* ≠ *Undef*
and *off'* + *n* ≤ *off*
shows *retrieve-bytes* (*content obj*) *off'* *n* = *retrieve-bytes* (*content obj'*) *off'* *n*
using *assms*

proof (*induct n arbitrary*: *obj obj' off val off'*)
case *0*
then show *?case*
by *force*
next
case (*Suc n*)
then show *?case*
by (*metis* (*no-types*, *lifting*) *Suc-eq-plus1 add.assoc le-eq-less-or-eq less-add-same-cancel1 order-le-less-trans plus-1-eq-Suc retrieve-bytes.simps*(*2*) *store-tval-disjoint-1-content zero-less-Suc*)
qed

lemma *store-tval-disjoint-1-content-contiguous-bytes*:
assumes *store-tval obj off val* = *obj'*
and *val* ≠ *Undef*
and *off'* + *n* ≤ *off*
shows *is-contiguous-bytes* (*content obj*) *off'* *n* = *is-contiguous-bytes* (*content obj'*) *off'* *n*
using *assms*
proof (*induct n arbitrary*: *obj obj' off val off'*)
case *0*
then show *?case*
by *force*
next
case (*Suc n*)
then show *?case*
by (*smt* (*verit*, *best*) *add.assoc add.commute domIff is-contiguous-bytes.simps*(*2*) *keys-dom-lookup le-eq-less-or-eq less-add-same-cancel1 order-le-less-trans plus-1-eq-Suc store-tval-disjoint-1-content zero-less-Suc*)
qed

lemma *store-tval-disjoint-1-content-contiguous-caps*:
assumes *store-tval obj off val* = *obj'*
and *val* ≠ *Undef*
and *off'* + *n* ≤ *off*
shows *is-contiguous-cap* (*content obj*) *cap off'* *n* = *is-contiguous-cap* (*content obj'*) *cap off'* *n*
using *assms*
proof (*induct n arbitrary*: *obj obj' off val off'*)
case *0*
then show *?case*
by *force*
next

case (*Suc n*)
then show *?case*
by (*smt* (*verit*, *best*) *add.assoc add.commute domIff is-contiguous-cap.simps*(*2*) *keys-dom-lookup le-eq-less-or-eq less-add-same-cancel1 order-le-less-trans plus-1-eq-Suc store-tval-disjoint-1-content zero-less-Suc*)
qed

lemma *store-tval-disjoint-1-tags*:
assumes *store-tval obj off val* = *obj'*
and *val* ≠ *Undef*
and *off'* + |*Cap*|$_\tau$ ≤ *off*
shows *Mapping.lookup* (*tags obj*) *off'* = *Mapping.lookup* (*tags obj'*) *off'*
using *assms*
by (*clarsimp simp add*: *store-tval-def split*: *ccval.split-asm*)
(*metis Mapping.lookup-update-neq add.commute add-cancel-right-right bot-nat-0.extremum-strict diff-diff-cancel le-add1 le-add-diff-inverse less-diff-conv2 mod-less-divisor mod-less-eq-dividend sizeof-nonzero*)+

lemma *store-tval-disjoint-2-content*:
assumes *store-tval obj off val* = *obj'*
and *val* ≠ *Undef*
and *off* + |*memval-type val*|$_\tau$ ≤ *off'*
shows *Mapping.lookup* (*content obj*) *off'* = *Mapping.lookup* (*content obj'*) *off'*
using *assms*
proof (*clarsimp simp add*: *store-tval-def split*: *ccval.split-asm*)
show ⋀*x*. ⟦*off* + |*Cap*|$_\tau$ ≤ *off'*; *val* = *Cap-v x*; *obj'* = *obj*(|*content* := *store-cap* (*content obj*) *off x* |*Cap*|$_\tau$, *tags* := *store-tag* (*tags obj*) (*cap-offset off*) (*tag x*)|)⟧
⟹ *Mapping.lookup* (*content obj*) *off'* = *Mapping.lookup* (*store-cap* (*content obj*) *off x* |*Cap*|$_\tau$) *off'*
by (*presburger add*: *store-cap-domain-2*)
qed (*force simp add*: *sizeof-def* | *metis assms*(*3*) *store-bytes-domain-2 flatten-types-length memval-size-types*)+

lemma *store-tval-disjoint-2-content-bytes*:
assumes *store-tval obj off val* = *obj'*
and *val* ≠ *Undef*
and *off* + |*memval-type val*|$_\tau$ ≤ *off'*
shows *retrieve-bytes* (*content obj*) *off'* *n* = *retrieve-bytes* (*content obj'*) *off'* *n*
using *assms*
proof (*induct n arbitrary*: *obj obj' off off' val*)
case *0*
then show *?case*
by *force*
next
case (*Suc n*)
then show *?case*
by (*metis less-Suc-eq-le less-or-eq-imp-le retrieve-bytes.simps*(*2*) *store-tval-disjoint-2-content*)

qed

lemma *store-tval-disjoint-2-content-contiguous-bytes*:
assumes *store-tval obj off val* = *obj′*
and *val* ≠ *Undef*
and *off* + |*memval-type val*|$_\tau$ ≤ *off′*
shows *is-contiguous-bytes* (*content obj*) *off′ n* = *is-contiguous-bytes* (*content obj′*) *off′ n*
using *assms*
proof (*induct n arbitrary*: *obj obj′ off val off′*)
case *0*
then show *?case*
by *force*
next
case (*Suc n*)
then show *?case*
by (*smt* (*verit*, *best*) *domIff is-contiguous-bytes.simps*(*2*) *keys-dom-lookup le-eq-less-or-eq lessI order-le-less-trans store-tval-disjoint-2-content*)
qed

lemma *store-tval-disjoint-2-content-contiguous-caps*:
assumes *store-tval obj off val* = *obj′*
and *val* ≠ *Undef*
and *off* + |*memval-type val*|$_\tau$ ≤ *off′*
shows *is-contiguous-cap* (*content obj*) *cap off′ n* = *is-contiguous-cap* (*content obj′*) *cap off′ n*
using *assms*
proof (*induct n arbitrary*: *obj obj′ off val off′*)
case *0*
then show *?case*
by *force*
next
case (*Suc n*)
then show *?case*
by (*smt* (*verit*, *best*) *domIff is-contiguous-cap.simps*(*2*) *keys-dom-lookup le-eq-less-or-eq lessI order-le-less-trans store-tval-disjoint-2-content*)
qed

lemma *store-tval-disjoint-2-tags*:
assumes *store-tval obj off val* = *obj′*
and *val* ≠ *Undef*
and *off* + |*memval-type val*|$_\tau$ ≤ *off′*
shows *Mapping.lookup* (*tags obj*) *off′* = *Mapping.lookup* (*tags obj′*) *off′*
using *assms*
by (*clarsimp simp add*: *store-tval-def split*: *ccval.split-asm*)
(*force simp add*: *assms*(*3*) *sizeof-def*)+

lemma *zero-imp-bytes*:
is-contiguous-zeros obj off n ⟹ ¬ *is-contiguous-bytes obj off n* ⟹ *False*

proof (*simp add*: *is-contiguous-zeros-code*, *induct n arbitrary*: *obj off*)
case *0*
then show *?case*
by *simp*
next
case (*Suc n*)
then show *?case*
using *keys-dom-lookup memval-memcap-not-byte*
by *fastforce*
qed

lemma *retrieve-stored-tval-disjoint-1*:
assumes *store-tval obj off val* = *obj'*
and *val* ≠ *Undef*
and *off'* + |*t*|$_\tau$ ≤ *off*
shows *retrieve-tval obj off' t b* = *retrieve-tval obj' off' t b*
using *assms*
apply (*clarsimp simp add*: *retrieve-tval-def*)
apply (*rule conjI*, *rule impI*, *rule conjI*, *rule impI*, *rule conjI*, *rule impI*, *rule conjI*, *rule impI*, *rule conjI*, *rule impI*, *rule conjI*, *rule impI*, *rule conjI*, *rule impI*)
subgoal
by (*simp split*: *cctype.split*, *safe*; (*force simp add*: *numeral-2-eq-2 numeral-4-eq-4 numeral-8-eq-8 sizeof-def*)+)
subgoal
apply (*simp split*: *cctype.split*, *safe*, (*force simp add*: *sizeof-def numeral-2-eq-2 numeral-4-eq-4 numeral-8-eq-8*)+)
apply (*metis is-contiguous-bytes.simps*(*2*) *less-imp-Suc-add sizeof-nonzero*)
done
subgoal
apply (*intro strip conjI*)
apply (*simp split*: *cctype.split*, *safe*; (*force simp add*: *numeral-2-eq-2 numeral-4-eq-4 numeral-8-eq-8 sizeof-def*)+)
apply (*simp split*: *cctype.split*, *metis is-contiguous-bytes.simps*(*1*) *is-contiguous-bytes.simps*(*2*) *old.nat.exhaust*)
done
subgoal
using *zero-imp-bytes* **by** *presburger*
subgoal
by (*smt* (*z3*) *store-tval-disjoint-1-content-bytes zero-imp-bytes*)
subgoal
by (*simp add*: *is-contiguous-zeros-def*, *metis* (*no-types*, *lifting*) *order-less-le-trans store-tval-disjoint-1-content*)
subgoal
unfolding *is-contiguous-zeros-def*
by (*smt* (*verit*) *cctype.exhaust cctype.simps*(*73*) *cctype.simps*(*74*) *cctype.simps*(*75*) *cctype.simps*(*76*) *cctype.simps*(*77*) *cctype.simps*(*78*) *cctype.simps*(*79*) *cctype.simps*(*80*) *get-cap-def keys-is-none-rep less-add-same-cancel1 order-less-le-trans sizeof-nonzero store-tval-disjoint-1-content store-tval-disjoint-1-content-bytes store-tval-disjoint-1-content-contiguous-bytes store-tval-disjoint-1-content-contiguous-caps store-tval-disjoint-1-tags*)

apply (*rule impI*, *rule conjI*, *rule impI*, *rule conjI*, *rule impI*, *rule conjI*, *rule impI*)
apply (*smt* (*z3*) *store-tval-disjoint-1-content-bytes zero-imp-bytes*)
apply (*smt* (*verit*, *best*) *store-tval-disjoint-1-content-bytes zero-imp-bytes*)
apply (*simp add*: *is-contiguous-zeros-def*, *smt* (*z3*) *le-add-diff-inverse2 store-tval-disjoint-1-content trans-less-add2*)
apply (*rule impI*, *rule conjI*, *rule impI*)
apply (*simp add*: *is-contiguous-zeros-def*)
apply (*smt* (*z3*) *le-add-diff-inverse2 store-tval-disjoint-1-content trans-less-add2*)
subgoal
apply (*rule impI*, *rule conjI*, *rule impI*, *rule conjI*, *rule impI*, *rule conjI*, *rule impI*, *rule conjI*, *rule impI*)
apply (*metis is-contiguous-bytes.simps*(*2*) *less-nat-zero-code old.nat.exhaust sizeof-nonzero*)
using *store-tval-disjoint-1-content-contiguous-bytes*
apply *blast*
apply (*metis is-contiguous-bytes.simps*(*2*) *less-numeral-extra*(*3*) *not0-implies-Suc sizeof-nonzero*)
apply (*rule impI*, *rule conjI*, *rule impI*, *rule conjI*, *rule impI*)
using *store-tval-disjoint-1-content-contiguous-bytes*
apply *blast*
apply (*simp add*: *Let-def split*: *cctype.split*; *clarsimp*, *smt* (*verit*, *best*) *add.commute add-diff-cancel-right' add-le-cancel-left bot-nat-0.not-eq-extremum get-cap-def le-add-diff-inverse2 le-eq-less-or-eq order-less-le-trans sizeof-nonzero store-tval-disjoint-1-content store-tval-disjoint-1-content-contiguous-caps store-tval-disjoint-1-tags zero-less-diff*)
apply (*metis add.right-neutral add-less-cancel-left domIff keys-dom-lookup le-add-diff-inverse2 sizeof-nonzero store-tval-disjoint-1-content trans-less-add2*)
apply (*smt* (*z3*) *keys-is-none-rep less-add-same-cancel1 order-less-le-trans sizeof-nonzero store-tval-disjoint-1-content store-tval-disjoint-1-content-bytes store-tval-disjoint-1-content-conti*
done
done

lemma *retrieve-stored-tval-disjoint-2*:
assumes *store-tval obj off val* = *obj'*
and *val* ≠ *Undef*
and *off* + |*memval-type val*|$_\tau$ ≤ *off'*
and *t* = *Cap* ⟹ *off' mod* |*Cap*|$_\tau$ = *0*
shows *retrieve-tval obj off' t b* = *retrieve-tval obj' off' t b*
using *assms*(*1*) *assms*(*2*) *assms*(*3*)
apply (*clarsimp simp add*: *retrieve-tval-def*)
apply (*rule conjI*, *rule impI*, *rule conjI*, *rule impI*, *rule conjI*, *rule impI*, *rule conjI*, *rule impI*, *rule conjI*, *rule impI*, *rule conjI*, *rule impI*)
subgoal
by (*simp split*: *cctype.split*, *safe*; (*force simp add*: *numeral-2-eq-2 numeral-4-eq-4 numeral-8-eq-8 sizeof-def*)+)
subgoal
apply (*simp split*: *cctype.split*, *safe*, (*force simp add*: *sizeof-def numeral-2-eq-2 numeral-4-eq-4 numeral-8-eq-8*)+)
apply (*metis is-contiguous-bytes.simps*(*2*) *less-imp-Suc-add sizeof-nonzero*)

done
subgoal
apply (*rule impI*, *rule conjI*, *rule impI*)
apply (*simp split*: *cctype.split*, *safe*; (*force simp add*: *numeral-2-eq-2 numeral-4-eq-4 numeral-8-eq-8 sizeof-def*)+)
apply (*simp split*: *cctype.split*, *metis is-contiguous-bytes.simps*(*1*) *is-contiguous-bytes.simps*(*2*) *old.nat.exhaust*)
done
subgoal
using *zero-imp-bytes* **by** *presburger*
subgoal
by (*smt* (*z3*) *memval-type.elims store-tval-disjoint-2-content-bytes zero-imp-bytes*)
subgoal
by (*smt* (*z3*) *is-contiguous-zeros-def le-trans memval-type.elims store-tval-disjoint-2-content*)
subgoal
unfolding *is-contiguous-zeros-def*
by (*smt* (*verit*) *get-cap-def keys-is-none-rep le-trans memval-type.elims store-tval-disjoint-2-content store-tval-disjoint-2-content-bytes store-tval-disjoint-2-content-contiguous-bytes store-tval-disjoint-2-content-co store-tval-disjoint-2-tags*)
subgoal
apply (*rule impI*, *rule conjI*, *rule impI*, *rule conjI*, *rule impI*, *rule conjI*, *rule impI*)
apply (*metis* (*no-types*, *opaque-lifting*) *is-contiguous-bytes.simps*(*2*) *less-numeral-extra*(*3*) *not0-implies-Suc sizeof-nonzero zero-imp-bytes*)
apply (*smt* (*z3*) *assms*(*3*) *store-tval-disjoint-2-content-bytes zero-imp-bytes*)
apply (*simp add*: *is-contiguous-zeros-def*, *metis assms*(*3*) *order-trans store-tval-disjoint-2-content*)
unfolding *is-contiguous-zeros-def*
by (*smt* (*verit*) *assms*(*3*) *assms*(*4*) *cctype.exhaust cctype.simps*(*73*) *cctype.simps*(*74*) *cctype.simps*(*75*) *cctype.simps*(*76*) *cctype.simps*(*77*) *cctype.simps*(*78*) *cctype.simps*(*79*) *cctype.simps*(*80*) *get-cap-def keys-is-none-rep mod-0-imp-dvd mod-greater-zero-iff-not-dvd store-tval-disjoint-2-content store-tval-disjoint-2-content-bytes store-tval-disjoint-2-content-contiguous-bytes*)
done

lemma *type-uniq*:
assumes ∃ *x n*. *ret* = *Cap-v-frag x n*
shows *ret* ≠ *Uint8-v v1 ret* ≠ *Sint8-v v2 ret* ≠ *Uint16-v v3 ret* ≠ *Sint16-v v4*
ret ≠ *Uint32-v v5 ret* ≠ *Sint32-v v6 ret* ≠ *Uint64-v v7 ret* ≠ *Sint64-v v8*
ret ≠ *Cap-v v9*
using *assms*
by *blast*+

5 Memory Actions / Operations

definition *alloc* :: *heap* ⇒ *bool* ⇒ *nat* ⇒ (*heap* × *cap*) *result*
where
alloc h c s ≡
let cap = (| *block-id* = (*next-block h*),
offset = *0*,

```
                base = 0,
                len = s,
                perm-load = True,
                perm-cap-load = c,
                perm-store = True,
                perm-cap-store = c,
                perm-cap-store-local = c,
                perm-global = False,
                tag = True
              |) in
    let h' = h (| next-block := (next-block h) + 1,
                  heap-map := Mapping.update
                                (next-block h)
                                (Map (| bounds = (0, s),
                                        content = Mapping.empty,
                                        tags = Mapping.empty
                                     |)
                                ) (heap-map h)
               |) in
    Success (h', cap)

definition free :: heap ⇒ cap ⇒ (heap × cap) result
  where
  free h c ≡
    if c = NULL then Success (h, c) else
    if tag c = False then Error (C2Err (TagViolation)) else
    if perm-global c = True then Error (LogicErr (Unhandled 0)) else
    let obj = Mapping.lookup (heap-map h) (block-id c) in
    (case obj of None      ⇒ Error (LogicErr (MissingResource))
               | Some cobj ⇒
      (case cobj of Freed ⇒ Error (LogicErr (UseAfterFree))
                  | Map m ⇒
        if offset c ≠ 0 then Error (LogicErr (Unhandled 0))
        else if offset c > base c + len c then Error (LogicErr (Unhandled 0)) else
      let cap-bound = (base c, base c + len c) in
      if cap-bound ≠ bounds m then Error (LogicErr (Unhandled 0)) else
      let h' = h (| heap-map := Mapping.update (block-id c) Freed (heap-map h) |)
in
      let cap = c (| tag := False |) in
      Success (h', cap)))
```

How load works: The hardware would perform a CL[C] operation on the given capability first. An invalid capability for load would be caught by the hardware. Once all the hardware checks are performed, we then proceed to the logical checks.

```
definition load :: heap ⇒ cap ⇒ cctype ⇒ block ccval result
  where
  load h c t ≡
    if tag c = False then
```

```
    Error (C2Err TagViolation)
  else if perm-load c = False then
    Error (C2Err PermitLoadViolation)
  else if offset c + |t|_τ > base c + len c then
    Error (C2Err LengthViolation)
  else if offset c < base c then
    Error (C2Err LengthViolation)
  else if offset c mod |t|_τ ≠ 0 then
    Error (C2Err BadAddressViolation)
  else
    let obj = Mapping.lookup (heap-map h) (block-id c) in
   (case obj of None      ⇒ Error (LogicErr (MissingResource))
              | Some cobj ⇒
     (case cobj of Freed ⇒ Error (LogicErr (UseAfterFree))
                 | Map m ⇒ if offset c < fst (bounds m) ∨ offset c + |t|_τ > snd
(bounds m) then
                           Error (LogicErr BufferOverrun) else
                           Success (retrieve-tval m (nat (offset c)) t (perm-cap-load
c))))

definition store :: heap ⇒ cap ⇒ block ccval ⇒ heap result
  where
  store h c v ≡
    if tag c = False then
      Error (C2Err TagViolation)
    else if perm-store c = False then
      Error (C2Err PermitStoreViolation)
    else if (case v of Cap-v cv ⇒ ¬ perm-cap-store c ∧ tag cv | - ⇒ False) then
      Error (C2Err PermitStoreCapViolation)
   else if (case v of Cap-v cv ⇒ ¬ perm-cap-store-local c ∧ tag cv ∧ ¬ perm-global
cv | - ⇒ False) then
      Error (C2Err PermitStoreLocalCapViolation)
    else if offset c + |memval-type v|_τ > base c + len c then
      Error (C2Err LengthViolation)
    else if offset c < base c then
      Error (C2Err LengthViolation)
    else if offset c mod |memval-type v|_τ ≠ 0 then
      Error (C2Err BadAddressViolation)
    else if v = Undef then
      Error (LogicErr (Unhandled 0))
    else
      let obj = Mapping.lookup (heap-map h) (block-id c) in
     (case obj of None      ⇒ Error (LogicErr (MissingResource))
                | Some cobj ⇒
       (case cobj of Freed ⇒ Error (LogicErr (UseAfterFree))
                   | Map m ⇒ if offset c < fst (bounds m) ∨ offset c + |memval-type
v|_τ > snd (bounds m) then
                             Error (LogicErr BufferOverrun) else
                             Success (h (| heap-map := Mapping.update
```

```
    (block-id c)
  (Map (store-tval m (nat (offset c)) v))
    (heap-map h) |)))
```

5.1 Properties of the operations

Here we provide all the properties the operations satisfy. In general, you may find the following forms of proofs:

- If we have valid input, the operation will succeed
- If we have invalid inputs, the operations will return the appropriate error
- If the operation succeeds, we have a valid input

good variable laws are also proven at the next subsubsection.

5.1.1 Correctness Properties

lemma *alloc-always-success*:
  $\exists!$ *res*. *alloc h c s* = *Success res*
  by (*simp add*: *alloc-def*)

schematic-goal *alloc-updated-heap-and-cap*:
  alloc h c s = *Success* (*?h'*, *?cap*)
  by (*fastforce simp add*: *alloc-def*)

lemma *alloc-never-fails*:
  alloc h c s = *Error e* $\Longrightarrow$ *False*
  by (*simp add*: *alloc-def*)

In practice, malloc may actually return NULL when allocation fails. However, this still complies with The C Standard.

lemma *alloc-no-null-ret*:
  assumes *alloc h c s* = *Success* (*h'*, *cap*)
  shows *cap* $\neq$ *NULL*
proof −
  have *perm-load cap*
    using *assms alloc-def*
    by *force*
  moreover have ¬ *perm-load NULL*
    unfolding *null-capability-def zero-capability-ext-def zero-mem-capability-ext-def*
    by *force*
  ultimately show *?thesis*
    by *blast*
qed

lemma *alloc-correct*:
assumes *alloc h c s* = *Success* (*h'*, *cap*)
shows *next-block h'* = *next-block h* + *1*
and *Mapping.lookup* (*heap-map h'*) (*next-block h*)
= *Some* (*Map* (| *bounds* = (*0*, *s*), *content* = *Mapping.empty*, *tags* = *Mapping.empty*|))
using *assms alloc-def*
by *auto*

Section 7.20.3.2 of The C Standard states free(NULL) results in no action occurring [2].

lemma *free-null*:
free h NULL = *Success* (*h*, *NULL*)
by (*simp add*: *free-def*)

lemma *free-false-tag*:
assumes *c* ≠ *NULL*
and *tag c* = *False*
shows *free h c* = *Error* (*C2Err* (*TagViolation*))
by (*presburger add*: *assms free-def*)

lemma *free-global-cap*:
assumes *c* ≠ *NULL*
and *tag c* = *True*
and *perm-global c* = *True*
shows *free h c* = *Error* (*LogicErr* (*Unhandled 0*))
by (*presburger add*: *assms free-def*)

lemma *free-nonexistant-obj*:
assumes *c* ≠ *NULL*
and *tag c* = *True*
and *perm-global c* = *False*
and *Mapping.lookup* (*heap-map h*) (*block-id c*) = *None*
shows *free h c* = *Error* (*LogicErr* (*MissingResource*))
using *assms free-def*
by *auto*

This case may arise if there are copies of the same capability, where only one was freed. It is worth noting that due to this, temporal safety is not guaranteed by the CHERI hardware.

lemma *free-double-free*:
assumes *c* ≠ *NULL*
and *tag c* = *True*
and *perm-global c* = *False*
and *Mapping.lookup* (*heap-map h*) (*block-id c*) = *Some Freed*
shows *free h c* = *Error* (*LogicErr* (*UseAfterFree*))
using *free-def assms*
by *force*

An incorrect offset implies the actual ptr value is not that returned by alloc. Section 7.20.3.2 of The C Standard states this leads to undefined behaviour [2]. Clang, in practice, however, terminates the C program with an invalid pointer error.

lemma *free-incorrect-cap-offset*:
assumes $c \neq NULL$
and $tag\ c = True$
and $perm\text{-}global\ c = False$
and $Mapping.lookup\ (heap\text{-}map\ h)\ (block\text{-}id\ c) = Some\ (Map\ m)$
and $offset\ c \neq 0$
shows $free\ h\ c = Error\ (LogicErr\ (Unhandled\ 0))$
using *free-def assms*
by *force*

lemma *free-incorrect-bounds*:
assumes $c \neq NULL$
and $tag\ c = True$
and $perm\text{-}global\ c = False$
and $Mapping.lookup\ (heap\text{-}map\ h)\ (block\text{-}id\ c) = Some\ (Map\ m)$
and $offset\ c = 0$
and $bounds\ m \neq (base\ c,\ base\ c + len\ c)$
shows $free\ h\ c = Error\ (LogicErr\ (Unhandled\ 0))$
unfolding *free-def*
using *assms*
by *force*

lemma *free-non-null-correct*:
assumes $c \neq NULL$
and *valid-tag*: $tag\ c = True$
and $perm\text{-}global\ c = False$
and *map-has-contents*: $Mapping.lookup\ (heap\text{-}map\ h)\ (block\text{-}id\ c) = Some\ (Map\ m)$
and *offset-correct*: $offset\ c = 0$
and *bounds-correct*: $bounds\ m = (base\ c,\ base\ c + len\ c)$
shows $free\ h\ c = Success\ (h\ (\!|\ heap\text{-}map := Mapping.update\ (block\text{-}id\ c)\ Freed\ (heap\text{-}map\ h)\ |\!),$
$c\ (\!|\ tag := False\ |\!))$
unfolding *free-def*
using *assms*
by *simp*

lemma *free-cond*:
assumes $free\ h\ c = Success\ (h',\ cap)$
shows $c \neq NULL \Longrightarrow tag\ c = True$
and $c \neq NULL \Longrightarrow perm\text{-}global\ c = False$
and $c \neq NULL \Longrightarrow offset\ c = 0$
and $c \neq NULL \Longrightarrow \exists\ m.\ Mapping.lookup\ (heap\text{-}map\ h)\ (block\text{-}id\ c) = Some\ (Map\ m) \wedge$
$bounds\ m = (base\ c,\ base\ c + len\ c)$

and $c \neq NULL \Longrightarrow Mapping.lookup\ (heap\text{-}map\ h')\ (block\text{-}id\ c) = Some\ Freed$
and $c \neq NULL \Longrightarrow cap = c\ (\!|\ tag := False\ |\!)$
and $c = NULL \Longrightarrow (h,\ c) = (h',\ cap)$
proof −
assume $c \neq NULL$
thus $tag\ c = True$
using *assms* **unfolding** *free-def*
by (*meson result.simps*(4))
next
assume $c \neq NULL$
thus $perm\text{-}global\ c = False$
using *assms* **unfolding** *free-def*
by (*meson result.simps*(4))
next
assume $c \neq NULL$
thus $offset\ c = 0$
using *assms* **unfolding** *free-def*
by (*smt* (*verit*, *ccfv-SIG*) *not-None-eq option.simps*(4) *option.simps*(5) *result.distinct*(1) *t.exhaust t.simps*(4) *t.simps*(5))
next
assume $c \neq NULL$
thus $\exists\ m.\ Mapping.lookup\ (heap\text{-}map\ h)\ (block\text{-}id\ c) = Some\ (Map\ m) \wedge$
$bounds\ m = (base\ c,\ base\ c + len\ c)$
using *assms* **unfolding** *free-def*
by (*metis assms free-double-free free-incorrect-bounds free-incorrect-cap-offset free-nonexistant-obj not-Some-eq result.distinct*(1) *t.exhaust*)
next
assume $c \neq NULL$
hence $h' = h\ (\!|\ heap\text{-}map := Mapping.update\ (block\text{-}id\ c)\ Freed\ (heap\text{-}map\ h)\ |\!)$
using *assms* **unfolding** *free-def*
by (*smt* (*verit*, *ccfv-SIG*) *free-nonexistant-obj not-Some-eq option.simps*(4) *option.simps*(5) *prod.inject result.distinct*(1) *result.exhaust result.inject*(1) *t.exhaust t.simps*(4) *t.simps*(5))
thus $Mapping.lookup\ (heap\text{-}map\ h')\ (block\text{-}id\ c) = Some\ Freed$
by *fastforce*
next
assume $c \neq NULL$
thus $cap = c\ (\!|\ tag := False\ |\!)$
using *assms* **unfolding** *free-def*
by (*smt* (*verit*, *ccfv-SIG*) *not-Some-eq option.simps*(4) *option.simps*(5) *prod.inject result.distinct*(1) *result.inject*(1) *t.exhaust t.simps*(4) *t.simps*(5))
next
assume $c = NULL$
thus $(h,\ c) = (h',\ cap)$
using *free-null assms*
by *force*
qed

lemmas *free-cond-non-null* = *free-cond*(1) *free-cond*(2) *free-cond*(3) *free-cond*(4)

free-cond(*5*) *free-cond*(*6*)

lemma *double-free*:
assumes *free h c* = *Success* (*h'*, *cap*)
and *cap* ≠ *NULL*
shows *free h' cap* = *Error* (*C2Err TagViolation*)
proof −
have *cap* = *c* (| *tag* := *False* |) ⟹ *tag cap* = *False*
by *fastforce*
thus *?thesis*
using *assms free-cond*(*6*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?h'*=*h'* **and** *?cap*=*cap*]
free-false-tag[**where** *?c*=*cap* **and** *?h*=*h'*] *free-cond*(*7*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?h'*=*h'* **and** *?cap*=*cap*]
by *blast*
qed

lemma *free-next-block*:
assumes *free h cap* = *Success* (*h'*, *cap'*)
shows *next-block h* = *next-block h'*
proof −
consider (*null*) *cap* = *NULL* | (*non-null*) *cap* ≠ *NULL* **by** *blast*
then show *?thesis*
proof (*cases*)
case *null*
then show *?thesis*
using *free-null assms null*
by *simp*
next
case *non-null*
then show *?thesis*
using *assms free-cond-non-null*[*OF assms non-null*]
unfolding *free-def*
by (*auto split*: *option.split-asm t.split-asm*)
qed
qed

lemma *load-null-error*:
load h NULL t = *Error* (*C2Err TagViolation*)
unfolding *load-def*
by *simp*

lemma *load-false-tag*:
assumes *tag c* = *False*
shows *load h c t* = *Error* (*C2Err TagViolation*)
unfolding *load-def*
using *assms*
by *presburger*

lemma *load-false-perm-load*:

assumes *tag c = True*
and *perm-load c = False*
shows *load h c t = Error (C2Err PermitLoadViolation)*
unfolding *load-def*
using *assms*
by *presburger*

lemma *load-bound-over*:
assumes *tag c = True*
and *perm-load c = True*
and *offset c + |t|$_\tau$ > base c + len c*
shows *load h c t = Error (C2Err LengthViolation)*
unfolding *load-def*
using *assms*
by *presburger*

lemma *load-bound-under*:
assumes *tag c = True*
and *perm-load c = True*
and *offset c + |t|$_\tau$ ≤ base c + len c*
and *offset c < base c*
shows *load h c t = Error (C2Err LengthViolation)*
unfolding *load-def*
using *assms*
by *presburger*

lemma *load-misaligned*:
assumes *tag c = True*
and *perm-load c = True*
and *offset c + |t|$_\tau$ ≤ base c + len c*
and *offset c ≥ base c*
and *offset c mod |t|$_\tau$ ≠ 0*
shows *load h c t = Error (C2Err BadAddressViolation)*
unfolding *load-def*
using *assms*
by *force*

lemma *load-nonexistant-obj*:
assumes *tag c = True*
and *perm-load c = True*
and *offset c + |t|$_\tau$ ≤ base c + len c*
and *offset c ≥ base c*
and *offset c mod |t|$_\tau$ = 0*
and *Mapping.lookup (heap-map h) (block-id c) = None*
shows *load h c t = Error (LogicErr MissingResource)*
unfolding *load-def*
using *assms*
by *auto*

lemma *load-load-after-free*:
assumes *tag c* = *True*
and *perm-load c* = *True*
and *offset c* + $|t|_\tau$ ≤ *base c* + *len c*
and *offset c* ≥ *base c*
and *offset c mod* $|t|_\tau$ = *0*
and *Mapping.lookup* (*heap-map h*) (*block-id c*) = *Some Freed*
shows *load h c t* = *Error* (*LogicErr UseAfterFree*)
unfolding *load-def*
using *assms*
by *fastforce*

lemma *load-cap-on-heap-bounds-fail-1*:
assumes *tag c* = *True*
and *perm-load c* = *True*
and *offset c* + $|t|_\tau$ ≤ *base c* + *len c*
and *offset c* ≥ *base c*
and *offset c mod* $|t|_\tau$ = *0*
and *Mapping.lookup* (*heap-map h*) (*block-id c*) = *Some* (*Map m*)
and *is-contiguous-bytes* (*content m*) (*nat* (*offset c*)) $|t|_\tau$
and *t* = *Cap*
and ¬ *is-contiguous-zeros* (*content m*) (*nat* (*offset c*)) $|t|_\tau$
and *offset c* < *fst* (*bounds m*)
shows *load h c t* = *Error* (*LogicErr BufferOverrun*)
unfolding *load-def retrieve-tval-def*
using *assms*
by *fastforce*

lemma *load-cap-on-heap-bounds-fail-2*:
assumes *tag c* = *True*
and *perm-load c* = *True*
and *offset c* + $|t|_\tau$ ≤ *base c* + *len c*
and *offset c* ≥ *base c*
and *offset c mod* $|t|_\tau$ = *0*
and *Mapping.lookup* (*heap-map h*) (*block-id c*) = *Some* (*Map m*)
and *is-contiguous-bytes* (*content m*) (*nat* (*offset c*)) $|t|_\tau$
and *t* = *Cap*
and ¬ *is-contiguous-zeros* (*content m*) (*nat* (*offset c*)) $|t|_\tau$
and *offset c* + $|t|_\tau$ > *snd* (*bounds m*)
shows *load h c t* = *Error* (*LogicErr BufferOverrun*)
unfolding *load-def retrieve-tval-def*
using *assms*
by *fastforce*

lemma *load-cap-on-membytes-fail*:
assumes *tag c* = *True*
and *perm-load c* = *True*
and *offset c* + $|t|_\tau$ ≤ *base c* + *len c*
and *offset c* ≥ *base c*

and *offset c mod* $|t|_\tau = 0$
and *Mapping.lookup* (*heap-map h*) (*block-id c*) = *Some* (*Map m*)
and *is-contiguous-bytes* (*content m*) (*nat* (*offset c*)) $|t|_\tau$
and $t = Cap$
and $\neg$ *is-contiguous-zeros* (*content m*) (*nat* (*offset c*)) $|t|_\tau$
and *offset c* $\geq$ *fst* (*bounds m*)
and *offset c* + $|t|_\tau \leq$ *snd* (*bounds m*)
shows *load h c t* = *Success Undef*
unfolding *load-def retrieve-tval-def*
using *assms*
by *fastforce*

lemma *load-null-cap-on-membytes*:
assumes *tag c* = *True*
and *perm-load c* = *True*
and *offset c* + $|t|_\tau \leq$ *base c* + *len c*
and *offset c* $\geq$ *base c*
and *offset c mod* $|t|_\tau = 0$
and *Mapping.lookup* (*heap-map h*) (*block-id c*) = *Some* (*Map m*)
and *is-contiguous-bytes* (*content m*) (*nat* (*offset c*)) $|t|_\tau$
and $t = Cap$
and *offset c* $\geq$ *fst* (*bounds m*)
and *offset c* + $|t|_\tau \leq$ *snd* (*bounds m*)
and *is-contiguous-zeros* (*content m*) (*nat* (*offset c*)) $|t|_\tau$
shows *load h c t* = *Success* (*Cap-v NULL*)
unfolding *load-def retrieve-tval-def*
using *assms*
by *fastforce*

lemma *load-u8-on-membytes*:
assumes *tag c* = *True*
and *perm-load c* = *True*
and *offset c* + $|t|_\tau \leq$ *base c* + *len c*
and *offset c* $\geq$ *base c*
and *offset c mod* $|t|_\tau = 0$
and *Mapping.lookup* (*heap-map h*) (*block-id c*) = *Some* (*Map m*)
and *offset c* $\geq$ *fst* (*bounds m*)
and *offset c* + $|t|_\tau \leq$ *snd* (*bounds m*)
and *is-contiguous-bytes* (*content m*) (*nat* (*offset c*)) $|t|_\tau$
and $t = Uint8$
shows *load h c t* = *Success* (*Uint8-v* (*decode-u8-list* (*retrieve-bytes* (*content m*) (*nat* (*offset c*)) $|t|_\tau$)))
unfolding *load-def retrieve-tval-def*
using *assms*
by *fastforce*

lemma *load-s8-on-membytes*:
assumes *tag c* = *True*
and *perm-load c* = *True*

and *offset c* + $|t|_\tau \leq$ *base c* + *len c*
and *offset c* $\geq$ *base c*
and *offset c mod* $|t|_\tau$ = *0*
and *Mapping.lookup* (*heap-map h*) (*block-id c*) = *Some* (*Map m*)
and *offset c* $\geq$ *fst* (*bounds m*)
and *offset c* + $|t|_\tau \leq$ *snd* (*bounds m*)
and *is-contiguous-bytes* (*content m*) (*nat* (*offset c*)) $|t|_\tau$
and *t* = *Sint8*
shows *load h c t* = *Success* (*Sint8-v* (*decode-s8-list* (*retrieve-bytes* (*content m*) (*nat* (*offset c*)) $|t|_\tau$)))
unfolding *load-def retrieve-tval-def*
using *assms*
by *fastforce*

lemma *load-u16-on-membytes*:
assumes *tag c* = *True*
and *perm-load c* = *True*
and *offset c* + $|t|_\tau \leq$ *base c* + *len c*
and *offset c* $\geq$ *base c*
and *offset c mod* $|t|_\tau$ = *0*
and *Mapping.lookup* (*heap-map h*) (*block-id c*) = *Some* (*Map m*)
and *offset c* $\geq$ *fst* (*bounds m*)
and *offset c* + $|t|_\tau \leq$ *snd* (*bounds m*)
and *is-contiguous-bytes* (*content m*) (*nat* (*offset c*)) $|t|_\tau$
and *t* = *Uint16*
shows *load h c t* = *Success* (*Uint16-v* (*cat-u16* (*retrieve-bytes* (*content m*) (*nat* (*offset c*)) $|t|_\tau$)))
unfolding *load-def retrieve-tval-def*
using *assms*
by *fastforce*

lemma *load-s16-on-membytes*:
assumes *tag c* = *True*
and *perm-load c* = *True*
and *offset c* + $|t|_\tau \leq$ *base c* + *len c*
and *offset c* $\geq$ *base c*
and *offset c mod* $|t|_\tau$ = *0*
and *Mapping.lookup* (*heap-map h*) (*block-id c*) = *Some* (*Map m*)
and *offset c* $\geq$ *fst* (*bounds m*)
and *offset c* + $|t|_\tau \leq$ *snd* (*bounds m*)
and *is-contiguous-bytes* (*content m*) (*nat* (*offset c*)) $|t|_\tau$
and *t* = *Sint16*
shows *load h c t* = *Success* (*Sint16-v* (*cat-s16* (*retrieve-bytes* (*content m*) (*nat* (*offset c*)) $|t|_\tau$)))
unfolding *load-def retrieve-tval-def*
using *assms*
by *fastforce*

lemma *load-u32-on-membytes*:

assumes *tag c = True*
and *perm-load c = True*
and *offset c + |t|$_\tau$ ≤ base c + len c*
and *offset c ≥ base c*
and *offset c mod |t|$_\tau$ = 0*
and *Mapping.lookup (heap-map h) (block-id c) = Some (Map m)*
and *offset c ≥ fst (bounds m)*
and *offset c + |t|$_\tau$ ≤ snd (bounds m)*
and *is-contiguous-bytes (content m) (nat (offset c)) |t|$_\tau$*
and *t = Uint32*
shows *load h c t = Success (Uint32-v (cat-u32 (retrieve-bytes (content m) (nat (offset c)) |t|$_\tau$)))*
unfolding *load-def retrieve-tval-def*
using *assms*
by *fastforce*

lemma *load-s32-on-membytes*:
assumes *tag c = True*
and *perm-load c = True*
and *offset c + |t|$_\tau$ ≤ base c + len c*
and *offset c ≥ base c*
and *offset c mod |t|$_\tau$ = 0*
and *Mapping.lookup (heap-map h) (block-id c) = Some (Map m)*
and *offset c ≥ fst (bounds m)*
and *offset c + |t|$_\tau$ ≤ snd (bounds m)*
and *is-contiguous-bytes (content m) (nat (offset c)) |t|$_\tau$*
and *t = Sint32*
shows *load h c t = Success (Sint32-v (cat-s32 (retrieve-bytes (content m) (nat (offset c)) |t|$_\tau$)))*
unfolding *load-def retrieve-tval-def*
using *assms*
by *fastforce*

lemma *load-u64-on-membytes*:
assumes *tag c = True*
and *perm-load c = True*
and *offset c + |t|$_\tau$ ≤ base c + len c*
and *offset c ≥ base c*
and *offset c mod |t|$_\tau$ = 0*
and *Mapping.lookup (heap-map h) (block-id c) = Some (Map m)*
and *offset c ≥ fst (bounds m)*
and *offset c + |t|$_\tau$ ≤ snd (bounds m)*
and *is-contiguous-bytes (content m) (nat (offset c)) |t|$_\tau$*
and *t = Uint64*
shows *load h c t = Success (Uint64-v (cat-u64 (retrieve-bytes (content m) (nat (offset c)) |t|$_\tau$)))*
unfolding *load-def retrieve-tval-def*
using *assms*
by *fastforce*

lemma *load-s64-on-membytes*:
assumes *tag c* = *True*
and *perm-load c* = *True*
and *offset c* + $|t|_\tau$ ≤ *base c* + *len c*
and *offset c* ≥ *base c*
and *offset c mod* $|t|_\tau$ = *0*
and *Mapping.lookup* (*heap-map h*) (*block-id c*) = *Some* (*Map m*)
and *offset c* ≥ *fst* (*bounds m*)
and *offset c* + $|t|_\tau$ ≤ *snd* (*bounds m*)
and *is-contiguous-bytes* (*content m*) (*nat* (*offset c*)) $|t|_\tau$
and *t* = *Sint64*
shows *load h c t* = *Success* (*Sint64-v* (*cat-s64* (*retrieve-bytes* (*content m*) (*nat* (*offset c*)) $|t|_\tau$)))
unfolding *load-def retrieve-tval-def*
using *assms*
by *fastforce*

lemma *load-not-cap-in-mem*:
assumes *tag c* = *True*
and *perm-load c* = *True*
and *offset c* + $|t|_\tau$ ≤ *base c* + *len c*
and *offset c* ≥ *base c*
and *offset c mod* $|t|_\tau$ = *0*
and *Mapping.lookup* (*heap-map h*) (*block-id c*) = *Some* (*Map m*)
and *offset c* ≥ *fst* (*bounds m*)
and *offset c* + $|t|_\tau$ ≤ *snd* (*bounds m*)
and ¬ *is-contiguous-bytes* (*content m*) (*nat* (*offset c*)) $|t|_\tau$
and ¬ *is-cap* (*content m*) (*nat* (*offset c*))
shows *load h c t* = *Success Undef*
unfolding *load-def retrieve-tval-def*
using *assms*
by *fastforce*

lemma *load-not-contiguous-cap-in-mem*:
assumes *tag c* = *True*
and *perm-load c* = *True*
and *offset c* + $|t|_\tau$ ≤ *base c* + *len c*
and *offset c* ≥ *base c*
and *offset c mod* $|t|_\tau$ = *0*
and *Mapping.lookup* (*heap-map h*) (*block-id c*) = *Some* (*Map m*)
and *offset c* ≥ *fst* (*bounds m*)
and *offset c* + $|t|_\tau$ ≤ *snd* (*bounds m*)
and ¬ *is-contiguous-bytes* (*content m*) (*nat* (*offset c*)) $|t|_\tau$
and *is-cap* (*content m*) (*nat* (*offset c*))
and *mc* = *get-cap* (*content m*) (*nat* (*offset c*))
and ¬ *is-contiguous-cap* (*content m*) *mc* (*nat* (*offset c*)) $|t|_\tau$
and *t* ≠ *Uint8*
and *t* ≠ *Sint8*

shows *load h c t = Success Undef*
unfolding *load-def retrieve-tval-def Let-def*
using *assms*
by (*clarsimp split*: *cctype.split*)

lemma *load-cap-frag-u8*:
assumes *tag c = True*
and *perm-load c = True*
and *offset c + |t|$_\tau$ ≤ base c + len c*
and *offset c ≥ base c*
and *offset c mod |t|$_\tau$ = 0*
and *Mapping.lookup* (*heap-map h*) (*block-id c*) = *Some* (*Map m*)
and *offset c ≥ fst* (*bounds m*)
and *offset c + |t|$_\tau$ ≤ snd* (*bounds m*)
and ¬ *is-contiguous-bytes* (*content m*) (*nat* (*offset c*)) *|t|$_\tau$*
and *is-cap* (*content m*) (*nat* (*offset c*))
and *mc = get-cap* (*content m*) (*nat* (*offset c*))
and *t = Uint8*
and *tagval = the* (*Mapping.lookup* (*tags m*) (*cap-offset* (*nat* (*offset c*))))
and *tg* = (*case perm-cap-load c of False ⇒ False | True ⇒ tagval*)
and *nth-frag = of-nth* (*the* (*Mapping.lookup* (*content m*) (*nat* (*offset c*))))
shows *load h c t = Success* (*Cap-v-frag* (*mem-capability.extend mc* ⦇ *tag = False* ⦈) *nth-frag*)
unfolding *load-def retrieve-tval-def Let-def*
using *assms*
by (*clarsimp simp add*: *sizeof-def split*: *cctype.split*)

lemma *load-cap-frag-s8*:
assumes *tag c = True*
and *perm-load c = True*
and *offset c + |t|$_\tau$ ≤ base c + len c*
and *offset c ≥ base c*
and *offset c mod |t|$_\tau$ = 0*
and *Mapping.lookup* (*heap-map h*) (*block-id c*) = *Some* (*Map m*)
and *offset c ≥ fst* (*bounds m*)
and *offset c + |t|$_\tau$ ≤ snd* (*bounds m*)
and ¬ *is-contiguous-bytes* (*content m*) (*nat* (*offset c*)) *|t|$_\tau$*
and *is-cap* (*content m*) (*nat* (*offset c*))
and *mc = get-cap* (*content m*) (*nat* (*offset c*))
and ¬ *is-contiguous-cap* (*content m*) *mc* (*nat* (*offset c*)) *|t|$_\tau$*
and *t = Sint8*
and *tagval = the* (*Mapping.lookup* (*tags m*) (*cap-offset* (*nat* (*offset c*))))
and *tg* = (*case perm-cap-load c of False ⇒ False | True ⇒ tagval*)
and *nth-frag = of-nth* (*the* (*Mapping.lookup* (*content m*) (*nat* (*offset c*))))
shows *load h c t = Success* (*Cap-v-frag* (*mem-capability.extend mc* ⦇ *tag = False* ⦈) *nth-frag*)
unfolding *load-def retrieve-tval-def Let-def*
using *assms*

by (*clarsimp simp add*: *sizeof-def split*: *cctype.split*)

lemma *load-bytes-on-capbytes-fail*:
assumes *tag c* = *True*
and *perm-load c* = *True*
and *offset c* + |*t*|$_\tau$ ≤ *base c* + *len c*
and *offset c* ≥ *base c*
and *offset c mod* |*t*|$_\tau$ = *0*
and *Mapping.lookup* (*heap-map h*) (*block-id c*) = *Some* (*Map m*)
and *offset c* ≥ *fst* (*bounds m*)
and *offset c* + |*t*|$_\tau$ ≤ *snd* (*bounds m*)
and ¬ *is-contiguous-bytes* (*content m*) (*nat* (*offset c*)) |*t*|$_\tau$
and *is-cap* (*content m*) (*nat* (*offset c*))
and *mc* = *get-cap* (*content m*) (*nat* (*offset c*))
and *is-contiguous-cap* (*content m*) *mc* (*nat* (*offset c*)) |*t*|$_\tau$
and *t* ≠ *Cap*
and *t* ≠ *Uint8*
and *t* ≠ *Sint8*
shows *load h c t* = *Success Undef*
unfolding *load-def retrieve-tval-def Let-def*
using *assms*
by (*clarsimp split*: *cctype.split*)

lemma *load-cap-on-capbytes*:
assumes *tag c* = *True*
and *perm-load c* = *True*
and *offset c* + |*t*|$_\tau$ ≤ *base c* + *len c*
and *offset c* ≥ *base c*
and *offset c mod* |*t*|$_\tau$ = *0*
and *Mapping.lookup* (*heap-map h*) (*block-id c*) = *Some* (*Map m*)
and *offset c* ≥ *fst* (*bounds m*)
and *offset c* + |*t*|$_\tau$ ≤ *snd* (*bounds m*)
and ¬ *is-contiguous-bytes* (*content m*) (*nat* (*offset c*)) |*t*|$_\tau$
and *is-cap* (*content m*) (*nat* (*offset c*))
and *mc* = *get-cap* (*content m*) (*nat* (*offset c*))
and *is-contiguous-cap* (*content m*) *mc* (*nat* (*offset c*)) |*t*|$_\tau$
and *t* = *Cap*
and *tagval* = *the* (*Mapping.lookup* (*tags m*) (*nat* (*offset c*)))
and *tg* = (*case perm-cap-load c of False* ⇒ *False* | *True* ⇒ *tagval*)
shows *load h c t* = *Success* (*Cap-v* (*mem-capability.extend mc* (‖ *tag* = *tg* ‖)))
unfolding *load-def retrieve-tval-def*
using *assms*
by (*clarsimp split*: *cctype.split*)
(*smt* (*verit*) *assms*(*5*) *nat-int nat-less-le nat-mod-distrib of-nat-0-le-iff semiring-1-class.of-nat-0*)

lemma *load-cond-hard-cap*:
assumes *load h c t* = *Success ret*
shows *tag c* = *True*

and *perm-load c = True*
and *offset c + |t|$_\tau$ ≤ base c + len c*
and *offset c ≥ base c*
and *offset c mod |t|$_\tau$ = 0*
proof −
show *tag c = True*
using *assms result.distinct(1)*
unfolding *load-def*
by *metis*
next
show *perm-load c = True*
using *assms result.distinct(1)*
unfolding *load-def*
by *metis*
next
show *offset c + |t|$_\tau$ ≤ base c + len c*
using *assms result.distinct(1) linorder-not-le*
unfolding *load-def*
by *metis*
next
show *offset c ≥ base c*
using *assms result.distinct(1) linorder-not-le*
unfolding *load-def*
by *metis*
next
show *offset c mod |t|$_\tau$ = 0*
using *assms result.distinct(1)*
unfolding *load-def*
by *metis*
qed

lemma *load-cond-bytes*:
assumes *load h c t = Success ret*
and *ret ≠ Undef*
and ∀ *x. ret ≠ Cap-v x*
and ∀ *x n . ret ≠ Cap-v-frag x n*
shows ∃ *m. Mapping.lookup (heap-map h) (block-id c) = Some (Map m)*
∧ *offset c ≥ fst (bounds m)*
∧ *offset c + |t|$_\tau$ ≤ snd (bounds m)*
∧ *is-contiguous-bytes (content m) (nat (offset c)) |t|$_\tau$*
proof (*cases ret*)
case (*Cap-v x9*)
thus *?thesis*
using *assms(3)*
by *blast*
next
case (*Cap-v-frag x101 x102*)
thus *?thesis*
using *assms(4)*

by *blast*
next
case *Undef*
thus *?thesis*
using *assms(2)*
by *simp*
qed (*insert assms(1) load-cond-hard-cap*[**where** *?h=h* **and** *?c=c* **and** *?t=t* **and** *?ret=ret*], *clarsimp*, *unfold load-def retrieve-tval-def*, *clarsimp split*: *option.split-asm t.split-asm*, *smt* (*z3*) *assms(2) assms(3) assms(4) cctype.exhaust cctype.simps(73) cctype.simps(74) cctype.simps(75) cctype.simps(76) cctype.simps(77) cctype.simps(78) cctype.simps(79) cctype.simps(80) cctype.simps(81) result.distinct(1) result.inject(1)*)+

lemma *load-cond-cap*:
assumes *load h c t = Success ret*
and ∃ *x*. *ret = Cap-v x*
shows ∃ *m mc tagval tg*.
Mapping.lookup (*heap-map h*) (*block-id c*) = *Some* (*Map m*) ∧
offset c ≥ *fst* (*bounds m*) ∧
offset c + $|t|_\tau$ ≤ *snd* (*bounds m*) ∧
(*is-contiguous-bytes* (*content m*) (*nat* (*offset c*)) $|t|_\tau$ ⟶
is-contiguous-zeros (*content m*) (*nat* (*offset c*)) $|t|_\tau$ ∧
ret = Cap-v NULL) ∧
(¬ *is-contiguous-bytes* (*content m*) (*nat* (*offset c*)) $|t|_\tau$ ⟶
is-cap (*content m*) (*nat* (*offset c*)) ∧
mc = get-cap (*content m*) (*nat* (*offset c*)) ∧
is-contiguous-cap (*content m*) *mc* (*nat* (*offset c*)) $|t|_\tau$ ∧
t = Cap ∧
tagval = the (*Mapping.lookup* (*tags m*) (*nat* (*offset c*))) ∧
tg = (*case perm-cap-load c of False* ⇒ *False* | *True* ⇒ *tagval*))
using *assms(2)*
proof (*cases ret*)
case (*Cap-v ca*)
show *?thesis*
using *assms load-cond-hard-cap*[**where** *?h=h* **and** *?c=c* **and** *?t=t* **and** *?ret=ret*]
by (*clarsimp*, *simp only*: *load-def retrieve-tval-def Let-def*, *clarsimp split*: *option.split-asm*, *clarsimp split*: *t.split-asm*, *rename-tac x nth map*, *subgoal-tac int* (*fst* (*bounds map*)) ≤ *int* $|t|_\tau$ ∗ *nth* ∧ *int* $|t|_\tau$ ∗ *nth* + *int* $|t|_\tau$ ≤ *int* (*snd* (*bounds map*)), *clarsimp split*: *cctype.split-asm*, *safe*; *force?*)
(*metis ccval.distinct(105) ccval.distinct(107) ccval.inject(9) is-cap.elims(2) linorder-not-le result.distinct(1)*)+
qed *blast*+

lemma *load-cond-cap-frag*:
assumes *load h c t = Success ret*
and ∃ *x n*. *ret = Cap-v-frag x n*
shows ∃ *m mc tagval tg nth-frag*.
Mapping.lookup (*heap-map h*) (*block-id c*) = *Some* (*Map m*) ∧
offset c ≥ *fst* (*bounds m*) ∧

offset c + $|t|_\tau$ ≤ *snd* (*bounds m*) ∧
(*is-contiguous-bytes* (*content m*) (*nat* (*offset c*)) $|t|_\tau$ ⟶
is-contiguous-zeros (*content m*) (*nat* (*offset c*)) $|t|_\tau$ ∧
ret = *Cap-v NULL*) ∧
(¬ *is-contiguous-bytes* (*content m*) (*nat* (*offset c*)) $|t|_\tau$ ⟶
is-cap (*content m*) (*nat* (*offset c*)) ∧
mc = *get-cap* (*content m*) (*nat* (*offset c*)) ∧
(*t* = *Uint8* ∨ *t* = *Sint8*) ∧
tagval = *the* (*Mapping.lookup* (*tags m*) (*nat* (*offset c*))) ∧
tg = (*case perm-cap-load c of False* ⇒ *False* | *True* ⇒ *tagval*) ∧
nth-frag = *of-nth* (*the* (*Mapping.lookup* (*content m*) (*nat* (*offset c*)))))
using *assms*(*2*)
proof (*cases ret*)
case (*Cap-v-frag x101 x102*)
show *?thesis*
using *assms load-cond-hard-cap*[**where** *?h*=*h* **and** *?c*=*c* **and** *?t*=*t* **and** *?ret*=*ret*]
by (*clarsimp*, *simp only*: *load-def retrieve-tval-def Let-def*, *clarsimp split*: *option.split-asm*, *clarsimp split*: *t.split-asm if-split-asm cctype.split-asm*)
qed (*simp add*: *type-uniq assms*(*2*))+

lemma *store-null-error*:
store h NULL v = *Error* (*C2Err TagViolation*)
unfolding *store-def*
by *simp*

lemma *store-false-tag*:
assumes *tag c* = *False*
shows *store h c v* = *Error* (*C2Err TagViolation*)
unfolding *store-def*
using *assms*
by *presburger*

lemma *store-false-perm-store*:
assumes *tag c* = *True*
and *perm-store c* = *False*
shows *store h c v* = *Error* (*C2Err PermitStoreViolation*)
unfolding *store-def*
using *assms*
by *presburger*

lemma *store-cap-false-perm-cap-store*:
assumes *tag c* = *True*
and *perm-store c* = *True*
and *perm-cap-store c* = *False*
and ∃ *cv*. *v* = *Cap-v cv* ∧ *tag cv* = *True*
shows *store h c v* = *Error* (*C2Err PermitStoreCapViolation*)
unfolding *store-def*
using *assms*

by *force*

lemma *store-cap-false-perm-cap-store-local*:
assumes *tag c* = *True*
and *perm-store c* = *True*
and *perm-cap-store c* = *True*
and *perm-cap-store-local c* = *False*
and ∃ *cv*. *v* = *Cap-v cv* ∧ *tag cv* = *True* ∧ *perm-global cv* = *False*
shows *store h c v* = *Error* (*C2Err PermitStoreLocalCapViolation*)
unfolding *store-def*
using *assms*
by *force*

lemma *store-bound-over*:
assumes *tag c* = *True*
and *perm-store c* = *True*
and ⋀ *cv*. ⟦ *v* = *Cap-v cv*; *tag cv* ⟧ ⟹ *perm-cap-store c* ∧ (*perm-cap-store-local c* ∨ *perm-global cv*)
and *offset c* + |*memval-type v*|$_\tau$ > *base c* + *len c*
shows *store h c v* = *Error* (*C2Err LengthViolation*)
unfolding *store-def*
using *assms*
by (*clarsimp split*: *ccval.split*)

lemma *store-bound-under*:
assumes *tag c* = *True*
and *perm-store c* = *True*
and ⋀ *cv*. ⟦ *v* = *Cap-v cv*; *tag cv* ⟧ ⟹ *perm-cap-store c* ∧ (*perm-cap-store-local c* ∨ *perm-global cv*)
and *offset c* + |*memval-type v*|$_\tau$ ≤ *base c* + *len c*
and *offset c* < *base c*
shows *store h c v* = *Error* (*C2Err LengthViolation*)
unfolding *store-def*
using *assms*
by (*clarsimp split*: *ccval.split*)

lemma *store-misaligned*:
assumes *tag c* = *True*
and *perm-store c* = *True*
and ⋀ *cv*. ⟦ *v* = *Cap-v cv*; *tag cv* ⟧ ⟹ *perm-cap-store c* ∧ (*perm-cap-store-local c* ∨ *perm-global cv*)
and *offset c* + |*memval-type v*|$_\tau$ ≤ *base c* + *len c*
and *offset c* ≥ *base c*
and *offset c mod* |*memval-type v*|$_\tau$ ≠ *0*
shows *store h c v* = *Error* (*C2Err BadAddressViolation*)
unfolding *store-def*
using *assms*
by (*clarsimp split*: *ccval.split*)

lemma *store-undef-val*:
assumes *tag c* = *True*
and *perm-store c* = *True*
and $\bigwedge$ *cv*. ⟦ *v* = *Cap-v cv*; *tag cv* ⟧ ⟹ *perm-cap-store c* ∧ (*perm-cap-store-local c* ∨ *perm-global cv*)
and *offset c* + |*memval-type v*|$_\tau$ ≤ *base c* + *len c*
and *offset c* ≥ *base c*
and *offset c mod* |*memval-type v*|$_\tau$ = *0*
and *v* = *Undef*
shows *store h c v* = *Error* (*LogicErr* (*Unhandled 0*))
unfolding *store-def*
using *assms*
by *auto*

lemma *store-nonexistant-obj*:
assumes *tag c* = *True*
and *perm-store c* = *True*
and $\bigwedge$ *cv*. ⟦ *v* = *Cap-v cv*; *tag cv* ⟧ ⟹ *perm-cap-store c* ∧ (*perm-cap-store-local c* ∨ *perm-global cv*)
and *offset c* + |*memval-type v*|$_\tau$ ≤ *base c* + *len c*
and *offset c* ≥ *base c*
and *offset c mod* |*memval-type v*|$_\tau$ = *0*
and *v* ≠ *Undef*
and *Mapping.lookup* (*heap-map h*) (*block-id c*) = *None*
shows *store h c v* = *Error* (*LogicErr MissingResource*)
unfolding *store-def*
using *assms*
by (*clarsimp split*: *ccval.split*)

lemma *store-store-after-free*:
assumes *tag c* = *True*
and *perm-store c* = *True*
and $\bigwedge$ *cv*. ⟦ *v* = *Cap-v cv*; *tag cv* ⟧ ⟹ *perm-cap-store c* ∧ (*perm-cap-store-local c* ∨ *perm-global cv*)
and *offset c* + |*memval-type v*|$_\tau$ ≤ *base c* + *len c*
and *offset c* ≥ *base c*
and *offset c mod* |*memval-type v*|$_\tau$ = *0*
and *v* ≠ *Undef*
and *Mapping.lookup* (*heap-map h*) (*block-id c*) = *Some Freed*
shows *store h c v* = *Error* (*LogicErr UseAfterFree*)
unfolding *store-def*
using *assms*
by (*clarsimp split*: *ccval.split*)

lemma *store-bound-violated-1*:
assumes *tag c* = *True*
and *perm-store c* = *True*
and $\bigwedge$ *cv*. ⟦ *v* = *Cap-v cv*; *tag cv* ⟧ ⟹ *perm-cap-store c* ∧ (*perm-cap-store-local c* ∨ *perm-global cv*)

and *offset c* + |*memval-type v*|$_\tau$ ≤ *base c* + *len c*
and *offset c* ≥ *base c*
and *offset c mod* |*memval-type v*|$_\tau$ = *0*
and *v* ≠ *Undef*
and *Mapping.lookup* (*heap-map h*) (*block-id c*) = *Some* (*Map m*)
and *offset c* < *fst* (*bounds m*)
shows *store h c v* = *Error* (*LogicErr BufferOverrun*)
unfolding *store-def* **using** *assms*
by (*clarsimp split*: *ccval.split*)

lemma *store-bound-violated-2*:
assumes *tag c* = *True*
and *perm-store c* = *True*
and ⋀ *cv*. ⟦ *v* = *Cap-v cv*; *tag cv* ⟧ ⟹ *perm-cap-store c* ∧ (*perm-cap-store-local c* ∨ *perm-global cv*)
and *offset c* + |*memval-type v*|$_\tau$ ≤ *base c* + *len c*
and *offset c* ≥ *base c*
and *offset c mod* |*memval-type v*|$_\tau$ = *0*
and *v* ≠ *Undef*
and *Mapping.lookup* (*heap-map h*) (*block-id c*) = *Some* (*Map m*)
and *offset c* + |*memval-type v*|$_\tau$ > *snd* (*bounds m*)
shows *store h c v* = *Error* (*LogicErr BufferOverrun*)
unfolding *store-def* **using** *assms*
by (*clarsimp split*: *ccval.split*)

lemma *store-success*:
assumes *tag c* = *True*
and *perm-store c* = *True*
and ⋀ *cv*. ⟦ *v* = *Cap-v cv*; *tag cv* ⟧ ⟹ *perm-cap-store c* ∧ (*perm-cap-store-local c* ∨ *perm-global cv*)
and *offset c* + |*memval-type v*|$_\tau$ ≤ *base c* + *len c*
and *offset c* ≥ *base c*
and *offset c mod* |*memval-type v*|$_\tau$ = *0*
and *v* ≠ *Undef*
and *Mapping.lookup* (*heap-map h*) (*block-id c*) = *Some* (*Map m*)
and *offset c* ≥ *fst* (*bounds m*)
and *offset c* + |*memval-type v*|$_\tau$ ≤ *snd* (*bounds m*)
shows ∃ *ret*. *store h c v* = *Success ret* ∧
next-block ret = *next-block h* ∧
heap-map ret = *Mapping.update* (*block-id c*) (*Map* (*store-tval m* (*nat* (*offset c*)) *v*)) (*heap-map h*)
unfolding *store-def*
using *assms*
by (*clarsimp split*: *ccval.split*)

lemma *store-cond-hard-cap*:
assumes *store h c v* = *Success ret*
shows *tag c* = *True*
and *perm-store c* = *True*

and $\bigwedge$ *cv*. ⟦ *v* = *Cap-v cv*; *tag cv* ⟧ ⟹ *perm-cap-store c* ∧ (*perm-cap-store-local c* ∨ *perm-global cv*)
and *offset c* + |*memval-type v*|$_\tau$ ≤ *base c* + *len c*
and *offset c* ≥ *base c*
and *offset c mod* |*memval-type v*|$_\tau$ = *0*
proof −
show *tag c* = *True*
using *assms* **unfolding** *store-def*
by (*meson result.simps*(*4*))
next
show *perm-store c* = *True*
using *assms* **unfolding** *store-def*
by (*meson result.simps*(*4*))
next
show $\bigwedge$ *cv*. ⟦ *v* = *Cap-v cv*; *tag cv* ⟧ ⟹ *perm-cap-store c* ∧ (*perm-cap-store-local c* ∨ *perm-global cv*)
using *assms* **unfolding** *store-def*
by (*metis* (*no-types*, *lifting*) *assms result.simps*(*4*) *store-cap-false-perm-cap-store store-cap-false-perm-cap-store-local*)
next
show *offset c* + |*memval-type v*|$_\tau$ ≤ *base c* + *len c*
using *assms* **unfolding** *store-def*
by (*meson linorder-not-le result.simps*(*4*))
next
show *offset c* ≥ *base c*
using *assms* **unfolding** *store-def*
by (*meson linorder-not-le result.simps*(*4*))
next
show *offset c mod* |*memval-type v*|$_\tau$ = *0*
using *assms* **unfolding** *store-def*
by (*meson linorder-not-le result.simps*(*4*))
qed

lemma *store-cond-bytes-bounds*:
assumes *store h c val* = *Success h′*
and ∀ *x*. *val* ≠ *Cap-v x*
shows ∃ *m*. *Mapping.lookup* (*heap-map h*) (*block-id c*) = *Some* (*Map m*)
∧ *offset c* ≥ *fst* (*bounds m*)
∧ *offset c* + |*memval-type val*|$_\tau$ ≤ *snd* (*bounds m*)
using *store-cond-hard-cap*[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*val* **and** *?ret*=*h′*, *OF assms*(*1*)] *assms*
unfolding *store-def*
by (*simp split*: *ccval.split-asm*; *simp split*: *option.split-asm t.split-asm*)
(*metis nle-le order.strict-iff-not result.distinct*(*1*))+

lemma *store-cond-bytes*:
assumes *store h c val* = *Success h′*
and ∀ *x*. *val* ≠ *Cap-v x*
shows ∃ *m*. *Mapping.lookup* (*heap-map h′*) (*block-id c*) = *Some* (*Map m*)

$\wedge$ *offset c* $\geq$ *fst* (*bounds m*)
$\wedge$ *offset c* + |*memval-type val*|$_\tau$ $\leq$ *snd* (*bounds m*)
using *store-cond-hard-cap*[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*val* **and** *?ret*=*h'*, *OF assms*(*1*)] *assms*
unfolding *store-def*
by (*simp split*: *ccval.split-asm*; *simp split*: *option.split-asm t.split-asm*)
(*auto split*: *if-split-asm simp add*: *store-tval-def*)

lemma *store-cond-cap-bounds*:
assumes *store h c val* = *Success h'*
and *val* = *Cap-v x*
shows $\exists$ *m*. *Mapping.lookup* (*heap-map h*) (*block-id c*) = *Some* (*Map m*)
$\wedge$ *offset c* $\geq$ *fst* (*bounds m*)
$\wedge$ *offset c* + |*memval-type val*|$_\tau$ $\leq$ *snd* (*bounds m*)
proof −
have *cap-perms*: ¬(¬ *perm-cap-store c* $\wedge$ *tag x*) $\wedge$ ¬(¬ *perm-cap-store-local c* $\wedge$ *tag x* $\wedge$ ¬ *perm-global x*)
using *store-cond-hard-cap*(*1*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*val* **and** *?ret*=*h'*, *OF assms*(*1*)]
store-cond-hard-cap(*2*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*val* **and** *?ret*=*h'*, *OF assms*(*1*)]
store-cond-hard-cap(*3*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*val* **and** *?ret*=*h'* **and** *?cv*=*x*, *OF assms*(*1*)]
store-cond-hard-cap(*4*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*val* **and** *?ret*=*h'*, *OF assms*(*1*)]
store-cond-hard-cap(*5*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*val* **and** *?ret*=*h'*, *OF assms*(*1*)]
store-cond-hard-cap(*6*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*val* **and** *?ret*=*h'*, *OF assms*(*1*)]
assms
unfolding *store-def*
by *blast*
thus *?thesis*
using *store-cond-hard-cap*(*1*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*val* **and** *?ret*=*h'*, *OF assms*(*1*)]
store-cond-hard-cap(*2*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*val* **and** *?ret*=*h'*, *OF assms*(*1*)]
store-cond-hard-cap(*3*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*val* **and** *?ret*=*h'* **and** *?cv*=*x*, *OF assms*(*1*)]
store-cond-hard-cap(*4*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*val* **and** *?ret*=*h'*, *OF assms*(*1*)]
store-cond-hard-cap(*5*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*val* **and** *?ret*=*h'*, *OF assms*(*1*)]
store-cond-hard-cap(*6*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*val* **and** *?ret*=*h'*, *OF assms*(*1*)]
assms
by (*simp split*: *ccval.split option.split-asm t.split-asm add*: *store-def cap-perms*)
(*metis linorder-not-le result.distinct*(*1*))
qed

lemma *store-cond-cap*:
assumes *store h c val = Success h′*
and *val = Cap-v v*
shows ∃ *m. Mapping.lookup* (*heap-map h′*) (*block-id c*) = *Some* (*Map m*)
∧ *offset c* ≥ *fst* (*bounds m*)
∧ *offset c* + |*memval-type val*|$_\tau$ ≤ *snd* (*bounds m*)
proof −
have *cap-perms*: ¬(¬ *perm-cap-store c* ∧ *tag v*) ∧ ¬(¬ *perm-cap-store-local c* ∧ *tag v* ∧ ¬ *perm-global v*)
using *store-cond-hard-cap*(*1*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*val* **and** *?ret*=*h′*, *OF assms*(*1*)]
store-cond-hard-cap(*2*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*val* **and** *?ret*=*h′*, *OF assms*(*1*)]
store-cond-hard-cap(*3*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*val* **and** *?ret*=*h′* **and** *?cv*=*v*, *OF assms*(*1*)]
store-cond-hard-cap(*4*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*val* **and** *?ret*=*h′*, *OF assms*(*1*)]
store-cond-hard-cap(*5*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*val* **and** *?ret*=*h′*, *OF assms*(*1*)]
store-cond-hard-cap(*6*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*val* **and** *?ret*=*h′*, *OF assms*(*1*)]
assms
by *blast*
show *?thesis*
using *store-cond-hard-cap*(*1*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*val* **and** *?ret*=*h′*, *OF assms*(*1*)]
store-cond-hard-cap(*2*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*val* **and** *?ret*=*h′*, *OF assms*(*1*)]
store-cond-hard-cap(*3*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*val* **and** *?ret*=*h′* **and** *?cv*=*v*, *OF assms*(*1*)]
store-cond-hard-cap(*4*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*val* **and** *?ret*=*h′*, *OF assms*(*1*)]
store-cond-hard-cap(*5*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*val* **and** *?ret*=*h′*, *OF assms*(*1*)]
store-cond-hard-cap(*6*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*val* **and** *?ret*=*h′*, *OF assms*(*1*)]
assms
by (*clarsimp split*: *ccval.split option.split-asm t.split-asm simp add*: *store-def cap-perms*)
(*smt* (*verit*) *Mapping.lookup-update assms*(*1*) *result.distinct*(*1*) *result.sel*(*1*) *store-bound-violated-2 store-cond-hard-cap*(*3*) *store-def store-success store-tval-disjoint-bounds*)
qed

lemma *store-cond*:
assumes *store h c val = Success h′*
shows ∃ *m. Mapping.lookup* (*heap-map h′*) (*block-id c*) = *Some* (*Map m*)
∧ *offset c* ≥ *fst* (*bounds m*)
∧ *offset c* + |*memval-type val*|$_\tau$ ≤ *snd* (*bounds m*)

using *store-cond-bytes*[*OF assms*(*1*)] *store-cond-cap*[*OF assms*(*1*)]
by *blast*

lemma *store-bounds-preserved*:
assumes *store h c v* = *Success h'*
and *Mapping.lookup* (*heap-map h*) (*block-id c*) = *Some* (*Map m*)
and *Mapping.lookup* (*heap-map h'*) (*block-id c*) = *Some* (*Map m'*)
shows *bounds m* = *bounds m'*
using *assms store-cond-hard-cap*[*OF assms*(*1*)]
proof (*cases v*)
case (*Uint8-v x1*)
thus *?thesis*
using *assms store-cond-hard-cap*[*OF assms*(*1*)]
unfolding *store-def*
by (*clarsimp split*: *if-split-asm*) (*blast intro*: *store-tval-disjoint-bounds*)
next
case (*Sint8-v x2*)
thus *?thesis*
using *assms store-cond-hard-cap*[*OF assms*(*1*)]
unfolding *store-def*
by (*clarsimp split*: *if-split-asm*) (*blast intro*: *store-tval-disjoint-bounds*)
next
case (*Uint16-v x3*)
thus *?thesis*
using *assms store-cond-hard-cap*[*OF assms*(*1*)]
unfolding *store-def*
by (*clarsimp split*: *if-split-asm*) (*blast intro*: *store-tval-disjoint-bounds*)
next
case (*Sint16-v x4*)
thus *?thesis*
using *assms store-cond-hard-cap*[*OF assms*(*1*)]
unfolding *store-def*
by (*clarsimp split*: *if-split-asm*) (*blast intro*: *store-tval-disjoint-bounds*)
next
case (*Uint32-v x5*)
thus *?thesis*
using *assms store-cond-hard-cap*[*OF assms*(*1*)]
unfolding *store-def*
by (*clarsimp split*: *if-split-asm*) (*blast intro*: *store-tval-disjoint-bounds*)
next
case (*Sint32-v x6*)
thus *?thesis*
using *assms store-cond-hard-cap*[*OF assms*(*1*)]
unfolding *store-def*
by (*clarsimp split*: *if-split-asm*) (*blast intro*: *store-tval-disjoint-bounds*)
next
case (*Uint64-v x7*)
thus *?thesis*
using *assms store-cond-hard-cap*[*OF assms*(*1*)]

unfolding *store-def*
by (*clarsimp split*: *if-split-asm*) (*blast intro*: *store-tval-disjoint-bounds*)
next
case (*Sint64-v x8*)
thus *?thesis*
using *assms store-cond-hard-cap*[*OF assms*(*1*)]
unfolding *store-def*
by (*clarsimp split*: *if-split-asm*) (*blast intro*: *store-tval-disjoint-bounds*)
next
case (*Cap-v x9*)
moreover hence ¬(¬ *perm-cap-store c* ∧ *tag x9*) ∧ ¬(¬ *perm-cap-store-local c* ∧ *tag x9* ∧ ¬ *perm-global x9*)
using *assms store-cond-hard-cap*[*OF assms*(*1*)]
unfolding *store-def*
by *blast*
ultimately show *?thesis*
using *assms store-cond-hard-cap*[*OF assms*(*1*)]
unfolding *store-def*
by (*simp split*: *if-split-asm add*: *store-tval-def*; *auto*)
next
case (*Cap-v-frag x101 x102*)
thus *?thesis*
using *assms store-cond-hard-cap*[*OF assms*(*1*)]
unfolding *store-def*
by (*clarsimp split*: *if-split-asm*) (*blast intro*: *store-tval-disjoint-bounds*)
next
case *Undef*
thus *?thesis*
using *assms store-cond-hard-cap*[*OF assms*(*1*)]
unfolding *store-def*
by *force*
qed

lemma *store-cond-cap-frag*:
assumes *store h c val* = *Success h′*
and *val* = *Cap-v-frag v n*
shows ∃ *m*. *Mapping.lookup* (*heap-map h′*) (*block-id c*) = *Some* (*Map m*)
using *store-cond-hard-cap*[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*val* **and** *?ret*=*h′*, *OF assms*(*1*)] *assms*
unfolding *store-def*
by (*simp split*: *ccval.split-asm*; *simp split*: *option.split-asm t.split-asm*)
(*metis Mapping.lookup-update heap.select-convs*(*2*) *heap.surjective heap.update-convs*(*2*) *result.distinct*(*1*) *result.sel*(*1*))

lemma *store-undef-false*:
assumes *store h c Undef* = *Success ret*
shows *False*
using *store-cond-hard-cap*[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*Undef* **and** *?ret*=*ret*, *OF assms*] *assms*

```
  unfolding store-def
  by simp

lemma load-after-alloc-size-fail:
  assumes alloc h c s = Success (h', cap)
    and |t|_τ > s
  shows load h' cap t = Error (C2Err LengthViolation)
proof −
  have tag cap = True
    using assms alloc-def
    by auto
  moreover have perm-load cap = True
    using assms alloc-def
    by force
  moreover have base cap = 0
    using assms alloc-def
    by fastforce
  moreover have len cap = s
    using assms alloc-def
    by auto
  ultimately show ?thesis
    using assms load-def by auto
qed
```

5.1.2 Good Variable Laws

The properties defined above are intermediate results. Properties that govern the correctness while executing are the *good variable* laws. The most important ones are:

- load after alloc
- load after free
- load after store

The *load after store* case requires particular attention. For disjoint cases within the same block (refer to load_after_store_disjoint_2 and load_after_store_disjoint_3), extra attention must be paid to the tagged memory, where the updated tag may occur at a location specified *before* whatever was given by the capability offset. This is why the lemma retrieve_stored_tval_disjoint_2 requires an additional constraint where capability values are aligned. Of course, this is not a problem for load_after_store_disjoint_3 since the capability conditions state that offsets must be aligned.

For the compatible case, as stated in the paper [6], extra care has to be put in the cases where we load capabilities and capability fragments. For this, we have three cases:

- load_after_store_prim
- load_after_store_cap
- load_after_store_cap_frag

The load_after_store_prim case returns the exact value that was stored. The load_after_store_cap case returns the stored capability with the tag bit dependent on the permissions of the capability provided to load. Finally, the load_after_store_cap_frag case returns the capability fragment with the tag bit falsifed.

Finally, we note that there are slight differences to the CompCert version of the Good Variable Law due to the differences in the type and value system. Thus, there are cases in the CompCert version that are trivial in our case.

theorem *load-after-alloc-1*:
  assumes *alloc h c s* = *Success* (*h′*, *cap*)
    and $|t|_\tau \leq s$
  shows *load h′ cap t* = *Success Undef*
proof −
  let *?m* = (|*bounds* = (*0*, *s*), *content* = *Mapping.empty*, *tags* = *Mapping.empty*|)
  have *tag cap* = *True*
    using *assms*(*1*) *alloc-def*
    by *fastforce*
  moreover have *perm-load cap* = *True*
    using *assms*(*1*) *alloc-def*
    by *fastforce*
  moreover have *offset cap* + $|t|_\tau \leq$ *base cap* + *len cap*
    using *assms alloc-def*
    by *fastforce*
  moreover have *offset cap* ≥ *base cap*
    using *assms alloc-def*
    by *fastforce*
  moreover have *offset cap mod* $|t|_\tau$ = *0*
    using *assms alloc-def*
    by *fastforce*
 moreover have *Mapping.lookup* (*heap-map h′*) (*block-id cap*) = *Some* (*Map ?m*)
    using *assms alloc-def*
    by *fastforce*
  moreover have *offset cap* ≥ *fst* (*bounds ?m*)
    using *assms alloc-def*
    by *fastforce*
  moreover have *offset cap* + $|t|_\tau \leq$ *snd* (*bounds ?m*)
    using *assms alloc-def*
    by *fastforce*
  moreover have ¬ *is-contiguous-bytes* (*content ?m*) (*nat* (*offset cap*)) $|t|_\tau$
  proof −
    have ∃ *n*. $|t|_\tau$ = *Suc n*
      using *not0-implies-Suc sizeof-nonzero*

```
      by force
    thus ?thesis
      using assms alloc-def
      by fastforce
  qed
  moreover have ¬ is-cap (content ?m) (nat (offset cap))
    by simp
  ultimately show ?thesis
    using load-not-cap-in-mem
    by presburger
qed

theorem load-after-alloc-2:
  assumes alloc h c s = Success (h', cap)
    and |t|_τ ≤ s
    and block-id cap ≠ block-id cap'
  shows load h' cap' t = load h cap' t
  using assms unfolding alloc-def load-def
  by force

theorem load-after-free-1:
  assumes free h c = Success (h', cap)
  shows load h cap t = Error (C2Err TagViolation)
proof −
  consider (null) c = NULL | (non-null) c ≠ NULL by blast
  then show ?thesis
  proof (cases)
    case null
    moreover hence c = cap
      using assms free-null
      by force
    ultimately show ?thesis
      using load-null-error assms
      by blast
  next
    case non-null
    hence cap = c (| tag := False |)
     using assms free-cond(6)[where ?h=h and ?c=c and ?h'=h' and ?cap=cap]

      by presburger
    moreover hence tag cap = False
      using assms
      by force
    ultimately show ?thesis using load-false-tag
      by blast
  qed
qed

theorem load-after-free-2:
```

assumes *free h c = Success (h', cap)*
and *block-id cap ≠ block-id cap'*
shows *load h cap' t = load h' cap' t*
using *assms free-cond[OF assms(1)]*
unfolding *free-def load-def*
by *fastforce*

theorem *load-after-store-disjoint-1*:
assumes *store h c val = Success h'*
and *block-id c ≠ block-id c'*
shows *load h c' t = load h' c' t*
using *assms store-cond-hard-cap[OF assms(1)]*
unfolding *store-def load-def*
by (*clarsimp split*: *ccval.split-asm option.split-asm t.split-asm if-split-asm*)

theorem *load-after-store-disjoint-2*:
assumes *store h c v = Success h'*
and *offset c' + |t|$_\tau$ ≤ offset c*
shows *load h' c' t = load h c' t*
using *assms store-cond[OF assms(1)] store-cond-hard-cap[OF assms(1)]*
apply (*clarsimp simp add*: *store-def load-def split*: *if-split-asm option.split t.split option.split-asm t.split-asm*)
apply (*intro conjI impI*)
apply (*smt* (*z3*) *lookup-update' option.discI*)
apply (*rule allI*, *rule conjI*, *rule impI*)
apply (*simp add*: *lookup-update'*)
apply (*rule allI*, *rule conjI*, *rule impI*)
apply (*smt* (*z3*) *Mapping.lookup-update Mapping.lookup-update-neq option.distinct*(*1*) *option.inject store-tval-disjoint-bounds t.distinct*(*1*) *t.inject*)
apply (*rule conjI*, *rule impI*)
apply (*smt* (*z3*) *Mapping.lookup-update Mapping.lookup-update-neq option.distinct*(*1*) *option.sel store-tval-disjoint-bounds t.distinct*(*1*) *t.sel*)
apply (*intro impI conjI allI*)
apply (*metis* (*no-types*, *lifting*) *Mapping.lookup-update-neq option.distinct*(*1*))
apply (*metis* (*no-types*, *lifting*) *lookup-update' option.inject t.discI*)
apply (*smt* (*z3*) *Mapping.lookup-update Mapping.lookup-update-neq option.inject store-tval-disjoint-bounds t.inject*)
apply (*metis* (*no-types*, *lifting*) *lookup-update' option.sel store-tval-disjoint-bounds t.sel*)
using *retrieve-stored-tval-disjoint-1*
apply (*smt* (*z3*) *int-nat-eq lookup-update' of-nat-0-le-iff of-nat-add of-nat-le-iff option.sel t.sel*)
done

theorem *load-after-store-disjoint-3*:
assumes *store h c v = Success h'*
and *offset c + |memval-type v|$_\tau$ ≤ offset c'*
shows *load h' c' t = load h c' t*
using *assms store-cond[OF assms(1)] store-cond-hard-cap[OF assms(1)]*

apply (*clarsimp simp add*: *store-def load-def split*: *if-split-asm option.split t.split option.split-asm t.split-asm*)
apply (*rule conjI*)
apply (*smt* (*z3*) *lookup-update′ option.discI*)
apply (*rule allI*, *rule conjI*)
apply (*simp add*: *lookup-update′*)
apply (*rule allI*, *rule conjI*)
apply (*smt* (*z3*) *Mapping.lookup-update Mapping.lookup-update-neq option.distinct*(*1*) *option.inject store-tval-disjoint-bounds t.distinct*(*1*) *t.inject*)
apply (*rule conjI*)
apply (*smt* (*z3*) *Mapping.lookup-update Mapping.lookup-update-neq option.distinct*(*1*) *option.sel store-tval-disjoint-bounds t.distinct*(*1*) *t.sel*)
apply (*intro impI conjI allI*)
apply (*metis* (*no-types*, *lifting*) *Mapping.lookup-update-neq option.distinct*(*1*))
apply (*metis* (*no-types*, *lifting*) *lookup-update′ option.inject t.discI*)
apply (*smt* (*z3*) *Mapping.lookup-update Mapping.lookup-update-neq option.inject store-tval-disjoint-bounds t.inject*)
apply (*metis* (*no-types*, *lifting*) *lookup-update′ option.sel store-tval-disjoint-bounds t.sel*)
using *retrieve-stored-tval-disjoint-2*
apply (*smt* (*z3*) *int-nat-eq lookup-update′ memval-type.simps nat-int nat-mod-distrib of-nat-add of-nat-le-0-iff of-nat-le-iff option.sel t.sel*)
done

theorem *load-after-store-prim*:
assumes *store h c val* = *Success h′*
and ∀ *v*. *val* ≠ *Cap-v v*
and ∀ *v n*. *val* ≠ *Cap-v-frag v n*
and *perm-load c* = *True*
shows *load h′ c* (*memval-type val*) = *Success val*
using *assms*(*1*) *store-cond-hard-cap*[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*val* **and** *?ret*=*h′*, *OF assms*(*1*)]
store-cond-bytes[*OF assms*(*1*) *assms*(*2*)] *retrieve-stored-tval-any-perm*[*OF - - assms*(*3*)]
by (*clarsimp simp add*: *store-def load-def split*: *if-split-asm option.split-asm t.split-asm ccval.split*)
(*safe*; *clarsimp simp add*: *assms*)

theorem *load-after-store-cap*:
assumes *store h c* (*Cap-v v*) = *Success h′*
and *perm-load c* = *True*
shows *load h′ c* (*memval-type* (*Cap-v v*)) = *Success* (*Cap-v* (*v* (| *tag* := *case perm-cap-load c of False* => *False* | *True* => *tag v* |))))
using *store-cond-hard-cap*(*1*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*Cap-v v* **and** *?ret*=*h′*, *OF assms*(*1*)]
store-cond-hard-cap(*2*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*Cap-v v* **and** *?ret*=*h′*, *OF assms*(*1*)]
store-cond-hard-cap(*3*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*Cap-v v* **and** *?ret*=*h′* **and** *?cv*=*v*, *OF assms*(*1*) *refl*]

store-cond-hard-cap(*4*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*Cap-v v* **and** *?ret*=*h'*, *OF assms*(*1*)]
store-cond-hard-cap(*5*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*Cap-v v* **and** *?ret*=*h'*, *OF assms*(*1*)]
store-cond-hard-cap(*6*)[**where** *?h*=*h* **and** *?c*=*c* **and** *?v*=*Cap-v v* **and** *?ret*=*h'*, *OF assms*(*1*)]
assms
retrieve-stored-tval-cap[**where** *?val*=*Cap-v v* **and** *?v*=*v*, *OF refl*]
retrieve-stored-tval-cap-no-perm-cap-load[**where** *?val*=*Cap-v v* **and** *?v*=*v*, *OF refl*]
apply (*clarsimp*, *simp split*: *ccval.split*; *safe*; *clarsimp*)
apply (*simp only*: *load-def*; *clarsimp split*: *option.split*)
apply (*simp add*: *sizeof-def split*: *t.split*, *safe*)
subgoal
by (*blast dest*: *store-cond-cap*)
subgoal
by (*metis option.sel store-cond-cap t.distinct*(*1*))
subgoal
apply (*simp add*: *sizeof-def store-def*)
apply (*subgoal-tac* ¬(¬ *perm-cap-store c* ∧ *tag v*) ∧ ¬(¬ *perm-cap-store-local c* ∧ *tag v* ∧ ¬ *perm-global v*); *presburger?*)
apply (*clarsimp split*: *if-split-asm*)
apply (*simp split*: *option.split-asm t.split-asm if-split-asm*)
apply *clarsimp*
apply (*smt* (*verit*, *best*) ‹*offset c* + *int* |*memval-type* (*Cap-v v*)|$_\tau$ ≤ *int* (*base c* + *len c*)› ‹*offset c mod int* |*memval-type* (*Cap-v v*)|$_\tau$ = *0*› *assms*(*1*) *ccval.distinct*(*107*) *lookup-update' option.sel result.inject*(*1*) *result.simps*(*4*) *store-bound-violated-2 store-cond-cap store-cond-hard-cap*(*3*) *store-success t.sel*)
done
subgoal
apply (*simp add*: *sizeof-def store-def*)
apply (*subgoal-tac* ¬(¬ *perm-cap-store c* ∧ *tag v*) ∧ ¬(¬ *perm-cap-store-local c* ∧ *tag v* ∧ ¬ *perm-global v*); *presburger?*)
apply (*clarsimp split*: *if-split-asm*)
apply (*simp split*: *option.split-asm t.split-asm if-split-asm*)
apply (*clarsimp simp add*: *sizeof-def*)
apply (*smt* (*verit*, *ccfv-SIG*) *Mapping.lookup-update assms*(*1*) *heap.select-convs*(*2*) *heap.surjective heap.update-convs*(*2*) *store-bounds-preserved*)
done
subgoal
apply (*simp add*: *store-def*)
apply (*subgoal-tac* ¬(¬ *perm-cap-store c* ∧ *tag v*) ∧ ¬(¬ *perm-cap-store-local c* ∧ *tag v* ∧ ¬ *perm-global v*); *presburger?*)
apply (*clarsimp split*: *if-split-asm option.split-asm t.split-asm*)
apply (*cases perm-cap-load c*; *clarsimp*)
done
done

theorem *load-after-store-cap-frag*:

assumes *store h c (Cap-v-frag c′ n) = Success h′*
and *perm-load c*
shows *load h′ c (memval-type (Cap-v-frag c′ n)) = Success (Cap-v-frag (c′ (| tag := False |)) n)*
using *assms(1) store-cond-hard-cap*[**where** *?h=h* **and** *?c=c* **and** *?v=Cap-v-frag c′ n* **and** *?ret=h′*, *OF assms(1)*]
retrieve-stored-tval-cap-frag[**where** *?val=Cap-v-frag c′ n* **and** *?c=c′* **and** *?n=n* **and** *?off=nat (offset c)* **and** *?b=(perm-cap-load c)*, *OF refl*, *simplified*]
unfolding *store-def*
apply (*simp split*: *option.split-asm t.split-asm option.split t.split add*: *load-def assms(2)*, *safe*; *simp split*: *if-split-asm*)
using *assms(1) store-cond-cap-frag* **apply** *blast*
apply (*metis assms(1) option.sel store-cond-cap-frag t.distinct(1)*)
apply (*metis assms(1) store-bounds-preserved*)
apply (*metis assms(1) store-bounds-preserved*)
apply (*metis Mapping.lookup-update heap.select-convs(2) heap.surjective heap.update-convs(2) option.sel t.sel*)
done

5.1.3 Miscellaneous Laws

lemma *free-after-alloc*:
assumes *alloc h c s = Success (h′, cap)*
shows ∃! *ret. free h′ cap = Success ret*
using *alloc-def assms free-non-null-correct alloc-no-null-ret*
by *force*

lemma *store-after-alloc*:
assumes *alloc h True s = Success (h′, cap)*
and $|memval\text{-}type\ v|_\tau \leq s$
and *v ≠ Undef*
shows ∃ *h″. store h′ cap v = Success h″*
proof −
let *?m = (|bounds = (0, s), content = Mapping.empty, tags = Mapping.empty|)*
have *tag cap = True*
using *assms(1) alloc-def*
by *fastforce*
moreover have *perm-store cap = True*
using *assms(1) alloc-def*
by *fastforce*
moreover have ⋀*cv.* ⟦*v = Cap-v cv*; *tag cv*⟧ ⟹ *perm-cap-store cap* ∧ (*perm-cap-store-local cap* ∨ *perm-global cv*)
proof −
have ¬ (*case v of Cap-v cv* ⇒ ¬ *perm-cap-store cap* ∧ *tag cv* | - ⇒ *False*)
using *assms* **unfolding** *alloc-def*
by (*simp split*: *ccval.split*, *force*)
moreover have ¬ (*case v of Cap-v cv* ⇒ ¬ *perm-cap-store-local cap* ∧ *tag cv* ∧ ¬ *perm-global cv* | - ⇒ *False*)
using *assms* **unfolding** *alloc-def*

by (*simp split*: *ccval.split*, *force*)
ultimately show $\bigwedge cv.\ [\![v = Cap\text{-}v\ cv;\ tag\ cv]\!] \Longrightarrow perm\text{-}cap\text{-}store\ cap \wedge (perm\text{-}cap\text{-}store\text{-}local\ cap \vee perm\text{-}global\ cv)$
by *force*
qed
moreover have *offset cap* + $|$*memval-type v*$|_\tau \leq$ *base cap* + *len cap*
using *assms alloc-def*
by *fastforce*
moreover have *offset cap* $\geq$ *base cap*
using *assms alloc-def*
by *fastforce*
moreover have *offset cap mod* $|$*memval-type v*$|_\tau$ = *0*
using *assms alloc-def*
by *fastforce*
moreover have *Mapping.lookup* (*heap-map h'*) (*block-id cap*) = *Some* (*Map ?m*)
using *assms alloc-def*
by *fastforce*
moreover have *offset cap* $\geq$ *fst* (*bounds ?m*)
using *assms alloc-def*
by *fastforce*
moreover have *offset cap* + $|$*memval-type v*$|_\tau \leq$ *snd* (*bounds ?m*)
using *assms alloc-def*
by *fastforce*
ultimately show *?thesis*
using *store-success*[**where** *?c*=*cap* **and** *?v*=*v* **and** *?m*=$\langle$*bounds* = (*0*, *s*), *content* = *Mapping.empty*, *tags* = *Mapping.empty*$\rangle$ **and** *?h*=*h'*] *assms*(*3*)
by *simp* (*blast*)
qed

lemma *store-after-alloc-gen*:
assumes *alloc h True s* = *Success* (*h'*, *cap*)
and $|$*memval-type v*$|_\tau \leq s$
and *v* $\neq$ *Undef*
and *n mod* $|$*memval-type v*$|_\tau$ = *0*
and *offset cap* + *n* + $|$*memval-type v*$|_\tau \leq$ *base cap* + *len cap*
shows $\exists\ h''.$ *store h'* (*cap* $(\!|$ *offset* := *offset cap* + *n* $|\!)$) *v* = *Success h''*
proof −
let *?m* = $\langle$*bounds* = (*0*, *s*), *content* = *Mapping.empty*, *tags* = *Mapping.empty*$\rangle$
have *tag cap* = *True*
using *assms*(*1*) *alloc-def*
by *fastforce*
moreover have *perm-store* (*cap* $(\!|$ *offset* := *offset cap* + *n* $|\!)$) = *True*
using *assms*(*1*) *alloc-def*
by *fastforce*
moreover have $\bigwedge cv.\ [\![v = Cap\text{-}v\ cv;\ tag\ cv]\!] \Longrightarrow perm\text{-}cap\text{-}store\ (cap\ (\!|\ offset := offset\ cap + n\ |\!)) \wedge (perm\text{-}cap\text{-}store\text{-}local\ (cap\ (\!|\ offset := offset\ cap + n\ |\!)) \vee perm\text{-}global\ cv)$
proof −
have ¬ (*case v of Cap-v cv* ⇒ ¬ *perm-cap-store* (*cap* $(\!|$ *offset* := *offset cap* +

n ⦈) ∧ *tag cv* | - ⇒ *False*)
using *assms* **unfolding** *alloc-def*
by (*simp split*: *ccval.split*, *force*)
moreover have ¬ (*case v of Cap-v cv* ⇒ ¬ *perm-cap-store-local* (*cap* ⦇ *offset* := *offset cap* + *n* ⦈) ∧ *tag cv* ∧ ¬ *perm-global cv* | - ⇒ *False*)
using *assms* **unfolding** *alloc-def*
by (*simp split*: *ccval.split*, *force*)
ultimately show ⋀*cv*. ⟦*v* = *Cap-v cv*; *tag cv*⟧ ⟹ *perm-cap-store* (*cap* ⦇ *offset* := *offset cap* + *n* ⦈) ∧ (*perm-cap-store-local* (*cap* ⦇ *offset* := *offset cap* + *n* ⦈) ∨ *perm-global cv*)
by *force*
qed
moreover have *offset* (*cap* ⦇ *offset* := *offset cap* + *n* ⦈) + |*memval-type v*|$_\tau$ ≤ *base* (*cap* ⦇ *offset* := *offset cap* + *n* ⦈) + *len* (*cap* ⦇ *offset* := *offset cap* + *n* ⦈)
using *assms alloc-def*
by *fastforce*
moreover have *offset* (*cap* ⦇ *offset* := *offset cap* + *n* ⦈) ≥ *base* (*cap* ⦇ *offset* := *offset cap* + *n* ⦈)
using *assms alloc-def*
by *fastforce*
moreover have *offset* (*cap* ⦇ *offset* := *offset cap* + *n* ⦈) *mod* |*memval-type v*|$_\tau$ = *0*
using *assms alloc-def*
by *fastforce*
moreover have *Mapping.lookup* (*heap-map h'*) (*block-id* (*cap* ⦇ *offset* := *offset cap* + *n* ⦈)) = *Some* (*Map ?m*)
using *assms alloc-def*
by *fastforce*
moreover have *offset* (*cap* ⦇ *offset* := *offset cap* + *n* ⦈) ≥ *fst* (*bounds ?m*)
using *assms alloc-def*
by *fastforce*
moreover have *offset* (*cap* ⦇ *offset* := *offset cap* + *n* ⦈) + |*memval-type v*|$_\tau$ ≤ *snd* (*bounds ?m*)
using *assms alloc-def*
by *fastforce*
ultimately show *?thesis*
using *store-success*[**where** *?c*=(*cap* ⦇ *offset* := *offset cap* + *n* ⦈) **and** *?v*=*v* **and** *?m*=⦇*bounds* = (*0*, *s*), *content* = *Mapping.empty*, *tags* = *Mapping.empty*⦈ **and** *?h*=*h'*] *assms*(*3*)
by *simp* (*blast*)
qed

5.2 Well-formedness of actions

lemma *alloc-wellformed*:
assumes $\mathcal{W}_\mathfrak{f}$(*heap-map h*)
and *alloc h True s* = *Success* (*h'*, *cap*)
shows $\mathcal{W}_\mathfrak{f}$(*heap-map h'*)
using *assms*

by (*simp add*: *alloc-def wellformed-def*, *safe*, *erule-tac x=b* **in** *allE*, *erule-tac x=obj* **in** *allE*, *simp*)
(*smt* (*verit*, *best*) *Mapping.keys-empty Mapping.lookup-update Mapping.lookup-update-neq Set.filter-def bot-nat-0.not-eq-extremum empty-iff mem-Collect-eq object.select-convs*(*3*) *option.sel t.sel zero-less-diff*)

lemma *free-wellformed*:
assumes $\mathcal{W}_\mathfrak{f}$(*heap-map h*)
and *free h cap* = *Success* (*h'*, *cap'*)
shows $\mathcal{W}_\mathfrak{f}$(*heap-map h'*)
proof −
consider (*null*) *cap* = *NULL* | (*non-null*) *cap* ≠ *NULL* **by** *blast*
then show *?thesis*
proof (*cases*)
case *null*
show *?thesis*
using *free-null assms null*
by *simp*
next
case *non-null*
show *?thesis*
by (*smt* (*z3*) *Mapping.lookup-update-neq assms*(*1*) *assms*(*2*) *free-cond-non-null*(*3*) *free-cond-non-null*(*4*) *free-cond-non-null*(*5*) *free-def free-non-null-correct fst-conv heap.select-convs*(*2*) *heap.surjective heap.update-convs*(*2*) *option.sel result.sel*(*1*) *t.discI wellformed-def*)
qed
qed

lemma *load-wellformed*:
assumes $\mathcal{W}_\mathfrak{f}$(*heap-map h*)
and *load h c t* = *Success v*
shows $\mathcal{W}_\mathfrak{f}$(*heap-map h*)
using *assms*(*1*)
by *assumption*

lemma *store-wellformed*:
assumes $\mathcal{W}_\mathfrak{f}$(*heap-map h*)
and *store h c v* = *Success h'*
shows $\mathcal{W}_\mathfrak{f}$(*heap-map h'*)
using *store-cond-hard-cap*(*1*)[**where** *?h=h* **and** *?c=c* **and** *?v=v* **and** *?ret=h'*, *OF assms*(*2*)]
store-cond-hard-cap(*2*)[**where** *?h=h* **and** *?c=c* **and** *?v=v* **and** *?ret=h'*, *OF assms*(*2*)]
store-cond-hard-cap(*4*)[**where** *?h=h* **and** *?c=c* **and** *?v=v* **and** *?ret=h'*, *OF assms*(*2*)]
store-cond-hard-cap(*5*)[**where** *?h=h* **and** *?c=c* **and** *?v=v* **and** *?ret=h'*, *OF assms*(*2*)]
store-cond-hard-cap(*6*)[**where** *?h=h* **and** *?c=c* **and** *?v=v* **and** *?ret=h'*, *OF assms*(*2*)]

assms
apply (*simp add*: *store-def wellformed-def split*: *option.split-asm t.split-asm if-split-asm del*: *memval-type.simps*)
apply *safe*
apply (*clarsimp simp del*: *memval-type.simps*)
apply (*erule-tac x=block-id c* **in** *allE*)
apply (*rename-tac map nth block obj x*)
apply (*erule-tac x=map* **in** *allE*)
apply (*clarsimp simp del*: *memval-type.simps*)
apply (*subgoal-tac Set.filter* ($\lambda x.\ 0 < x \bmod |Cap|_\tau$) (*Mapping.keys* (*tags* (*store-tval map* (*nat* (*int* $|memval\text{-}type\ v|_\tau$ * *nth*)) *v*))) = {})
apply (*smt* (*verit*, *best*) *Mapping.lookup-update Mapping.lookup-update-neq Set.member-filter assms*(*1*) *emptyE option.sel rel-simps*(*70*) *t.sel wellformed-def*)
apply (*simp add*: *store-tval-def del*: *memval-type.simps split*: *ccval.split-asm*; *fast-force*)
done

5.3 memcpy formalisation

We also formalise memcpy in Isabelle/HOL. While other higher level operations are defined in the GIL level, we formalise memcpy here and prove basic properties. memcpy works as follows: we define a mutually recursive function memcpy_prim and memcpy_cap. memcpy_prim attempts byte copies, where tags are invalidated, and memcpy_cap attempts capability copies. memcpy initially calls memcpy_cap. If either load or store fails, perhaps due to misalignment or other issues, memcpy_prim will be called instead. If memcpy_prim also fails from load or store, the operation will fail.

function *memcpy-prim* :: *heap* ⇒ *cap* ⇒ *cap* ⇒ *nat* ⇒ *heap result*
and *memcpy-cap* :: *heap* ⇒ *cap* ⇒ *cap* ⇒ *nat* ⇒ *heap result*
where
memcpy-prim h - - 0 = *Success h*
| *memcpy-cap h - - 0* = *Success h*
| *memcpy-prim h dst src* (*Suc n*) =
(*let x* = *load h src Uint8 in*
if ¬ *is-Success x then Error* (*err x*) *else*
let xs = *res x in*
if xs = *Undef then Error* (*LogicErr* (*Unhandled 0*)) *else*
let y = *store h dst xs in*
if ¬ *is-Success y then Error* (*err y*) *else*
let ys = *res y in*
memcpy-cap ys (*dst* (| *offset* := (*offset dst* + *1*) |)) (*src* (| *offset* := (*offset src*) + *1*|)) *n*)
| *memcpy-cap h dst src* (*Suc n*) =
(*if* (*Suc n*) < $|Cap|_\tau$ *then memcpy-prim h dst src* (*Suc n*)
else
let x = *load h src Cap in*
if ¬ *is-Success x then memcpy-prim h dst src* (*Suc n*) *else*

```
      let xs = res x in
      if xs = Undef then memcpy-prim h dst src (Suc n) else
      let y = store h dst xs in
      if ¬ is-Success y then memcpy-prim h dst src (Suc n) else
      let ys = res y in
     memcpy-cap ys (dst (| offset := (offset dst + |Cap|τ) |)) (src (| offset := (offset
src + |Cap|τ) |)) (Suc n − |Cap|τ))
  by (blast | metis old.nat.exhaust prod-cases3 sumE)+
```

We prove that the mutually recursive function terminates.

```
context
  notes sizeof-def[simp]
begin
termination by size-change
end
```

This is the definition of memcpy. We also check that src and dst do not overlap.

```
definition memcpy :: heap ⇒ cap ⇒ cap ⇒ nat ⇒ heap result
  where
  memcpy h dst src n ≡
    if n = 0 then
      Success h
    else if block-id dst = block-id src ∧
          ((offset src ≥ offset dst ∧ offset src < offset dst + n) ∨
           (offset dst ≥ offset src ∧ offset dst < offset src + n)) then
      Error (LogicErr (Unhandled 0))
    else memcpy-cap h dst src n

lemma memcpy-rec-wellformed:
  assumes 𝒲𝔣(heap-map h)
  shows memcpy-prim h dst src n = Success h' ⟹ 𝒲𝔣(heap-map h')
    and memcpy-cap h dst src n = Success h' ⟹ 𝒲𝔣(heap-map h')
  using assms
proof(induct h dst src n and h dst src n rule: memcpy-prim-memcpy-cap.induct)
  case (1 h uu uv)
  then show ?case
    by force
next
  case (2 h uw ux)
  then show ?case
    by force
next
  case (3 h dst src n)
  then show ?case
   by clarsimp (smt (verit) result.disc(1) result.distinct(1) result.expand result.sel(1)
store-wellformed)
next
  case (4 h dst src n)
```

then show *?case*
by *clarsimp* (*smt* (*verit*, *best*) *4.hyps*(*1*) *4.hyps*(*2*) *4.hyps*(*3*) *4.hyps*(*4*) *result.collapse*(*1*) *store-wellformed*)
qed

We also prove that memcpy preserves well-formedness.

lemma *memcpy-wellformed*:
assumes $\mathcal{W}_{\mathfrak{f}}$(*heap-map h*)
and *memcpy h dst src n* = *Success h'*
shows $\mathcal{W}_{\mathfrak{f}}$(*heap-map h'*)
using *assms* **unfolding** *memcpy-def*
by (*metis memcpy-rec-wellformed*(*2*) *result.distinct*(*1*) *result.sel*(*1*))

lemma *memcpy-cond*:
assumes *memcpy h dst src n* = *Success h'*
shows *n* > *0* ⟶ ¬ (*block-id dst* = *block-id src* ∧
((*offset src* ≥ *offset dst* ∧ *offset src* < *offset dst* + *n*) ∨
(*offset dst* ≥ *offset src* ∧ *offset dst* < *offset src* + *n*)))
using *assms* **unfolding** *memcpy-def*
by *force*

6 Miscellaneous Definitions

The following are used for catching memory leaks in Gillian.

definition *get-block-size* :: *heap* ⇒ *block* ⇒ *nat option*
where
get-block-size h b ≡
let ex = *Mapping.lookup* (*heap-map h*) *b in*
(*case ex of None* ⇒ *None* | *Some m* ⇒
(*case m of Freed* ⇒ *None* | - ⇒ *Some* (*snd* (*bounds* (*the-map m*)))))

primrec *get-memory-leak-size* :: *heap* ⇒ *nat* ⇒ *nat*
where
get-memory-leak-size - 0 = *0*
| *get-memory-leak-size h* (*Suc n*) = *get-memory-leak-size h n* +
(*case get-block-size h* (*integer-of-nat* (*Suc n*)) *of*
None ⇒ *0*
| *Some n* ⇒ *n*)

primrec *get-unfreed-blocks* :: *heap* ⇒ *nat* ⇒ *block list*
where
get-unfreed-blocks - 0 = []
| *get-unfreed-blocks h* (*Suc n*) =
(*let ex* = *Mapping.lookup* (*heap-map h*) (*integer-of-nat* (*Suc n*)) *in*
(*case ex of None* ⇒ *get-unfreed-blocks h n* | *Some m* ⇒
(*case m of Freed* ⇒ *get-unfreed-blocks h n* | - ⇒ *integer-of-nat* (*Suc n*) # *get-unfreed-blocks h n*)))

end
theory *CHERI-C-Global-Environment*
imports *CHERI-C-Concrete-Memory-Model*
begin

Here, we define the global environment. The Global Environment does the following:

1. Creates a mapping from variables to locations (or rather, the capabilities)
2. Sets global variables by invoking alloc. These variables cannot be freed by design

type-synonym *genv* = (*String.literal*, *cap*) *mapping*

definition *alloc-glob-var* :: *heap* ⇒ *bool* ⇒ *nat* ⇒ (*heap* × *cap*) *result*
where
alloc-glob-var h c s ≡
let h′ = *alloc h c s in*
Success (*fst* (*res h′*), *snd* (*res h′*) (| *perm-global* := *True* |))

definition *set-glob-var* :: *heap* ⇒ *bool* ⇒ *nat* ⇒ *String.literal* ⇒ *genv* ⇒ (*heap* × *cap* × *genv*) *result*
where
set-glob-var h c s v g ≡
let (*h′*, *cap*) = *res* (*alloc-glob-var h c s*) *in*
let g′ = *Mapping.update v cap g in*
Success (*h′*, *cap*, *g′*)

lemma *set-glob-var-glob-bit*:
assumes *alloc-glob-var h c s* = *Success* (*h′*, *cap*)
shows *perm-global cap*
using *assms*
unfolding *alloc-glob-var-def alloc-def*
by *fastforce*

lemma *set-glob-var-glob-bit-lift*:
assumes *set-glob-var h c s v g* = *Success* (*h′*, *cap*, *g′*)
shows *perm-global cap*
using *assms*
unfolding *alloc-glob-var-def set-glob-var-def alloc-def*
by *fastforce*

lemma *free-fails-on-glob-var*:
assumes *alloc-glob-var h c s* = *Success* (*h′*, *cap*)
shows *free h′ cap* = *Error* (*LogicErr* (*Unhandled 0*))

by (*metis alloc-updated-heap-and-cap assms capability.select-convs*(*1*) *free-global-cap*

mem-capability.select-convs(*10*) *mem-capability.simps*(*21*) *null-capability-def result.sel*(*1*)
alloc-glob-var-def snd-conv zero-mem-capability-ext-def)

lemma *free-fails-on-glob-lift*:
assumes *set-glob-var h c s v g* = *Success* (*h'*, *cap*, *g'*)
shows *free h' cap* = *Error* (*LogicErr* (*Unhandled 0*))
proof −
have *res*: *alloc-glob-var h c s* = *Success* (*h'*, *cap*)
using *assms*
unfolding *set-glob-var-def alloc-glob-var-def alloc-def*
by *fastforce*
show *?thesis* **using** *free-fails-on-glob-var*[*OF res*]
by *blast*
qed

7 Code Generation

Here we generate an OCaml instance of the memory model that will be used for Gillian.

export-code
null-capability init-heap next-block get-memory-leak-size get-unfreed-blocks

alloc free load store
memcpy
set-glob-var
word8-of-integer word16-of-integer word32-of-integer word64-of-integer

integer-of-word8 integer-of-word16 integer-of-word32 integer-of-word64
sword8-of-integer sword16-of-integer sword32-of-integer sword64-of-integer
integer-of-sword8 integer-of-sword16 integer-of-sword32 integer-of-sword64
integer-of-nat cast-val
C2Err LogicErr
TagViolation PermitLoadViolation PermitStoreViolation PermitStoreCapViolation
PermitStoreLocalCapViolation LengthViolation BadAddressViolation
UseAfterFree BufferOverrun MissingResource WrongMemVal MemoryNotFreed Unhandled
in *OCaml*
file-prefix *CHERI-C-Memory-Model*

end

References

[1] J. Fragoso Santos, P. Maksimović, S.-E. Ayoun, and P. Gardner. Gillian, Part i: A Multi-Language Platform for Symbolic Execution. In *Proceedings of the 41st ACM SIGPLAN Conference on Programming Language Design and Implementation*, PLDI 2020, page 927942, New York, NY, USA, 2020. Association for Computing Machinery.

[2] B. S. Institution and B. T. B. S. Institution). *The C Standard: Incorporating Technical Corrigendum 1*. Wiley, 2003.

[3] X. Leroy, A. W. Appel, S. Blazy, and G. Stewart. The CompCert Memory Model, Version 2. Research Report RR-7987, INRIA, Jun 2012.

[4] P. Maksimovic, S.-E. Ayoun, J. F. Santos, and P. Gardner. Gillian, part II: real-world verification for javascript and C. In A. Silva and K. R. M. Leino, editors, *Proceedings of the 33rd Computer Aided Verification International Conference, CAV 2021, Virtual Event, July 20-23, 2021, Part II*, volume 12760 of *Lecture Notes in Computer Science*, pages 827–850. Springer, 2021.

[5] P. Maksimovic, J. F. Santos, S.-E. Ayoun, and P. Gardner. Gillian: A Multi-Language Platform for Unified Symbolic Analysis, 2021.

[6] S. H. Park, R. Pai, and T. Melham. A Formal CHERI-C Semantics for Verification, 2022. Submitted to TACAS 2023.

[7] J. F. Santos, P. Maksimovic, S.-E. Ayoun, and P. Gardner. Gillian: Compositional Symbolic Execution for All. *CoRR*, abs/2001.05059, 2020.

[8] R. N. M. Watson, A. Richardson, B. Davis, J. Baldwin, D. Chisnall, J. Clarke, N. Filardo, S. M. Moore, E. Napierala, P. Sewell, and P. G. Neumann. CHERI C/C++ Programming Guide. Technical report, University of Cambridge, Cambridge, England, Jun 2020.