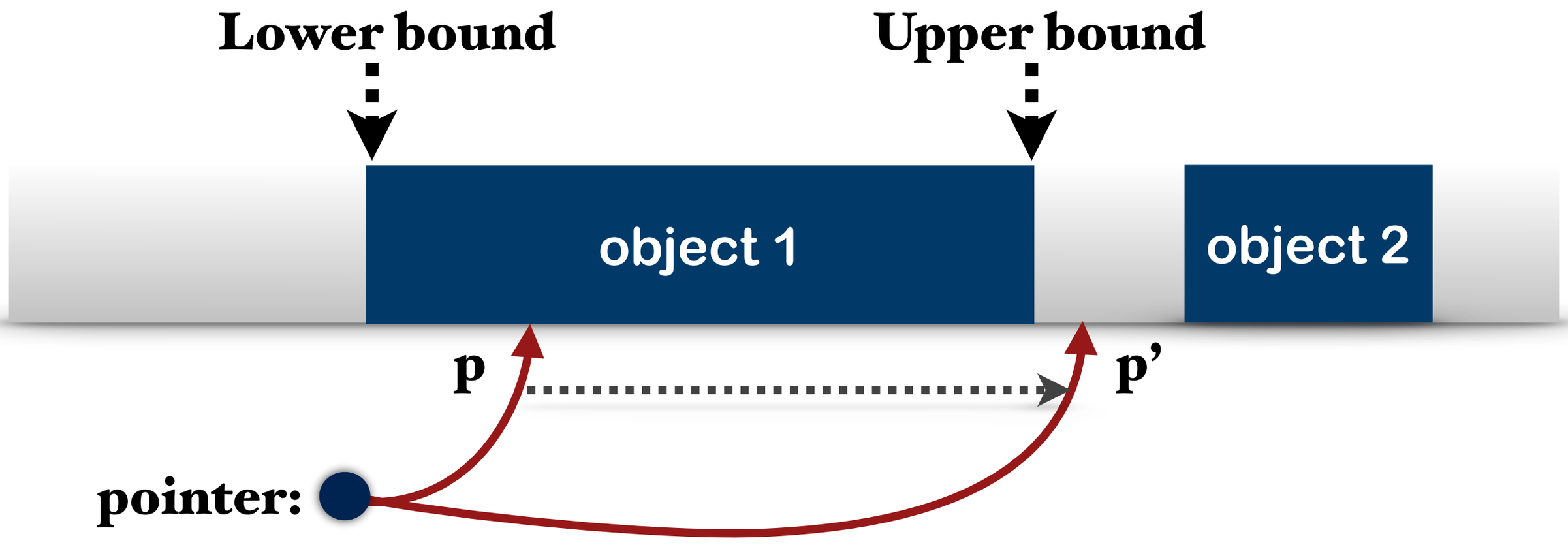
FRAMER: A Tagged-pointer Capability Model with Memory Safety Applications

Myoung Jin Nam (Korea University)

Periklis Akritidis (Niometrics)

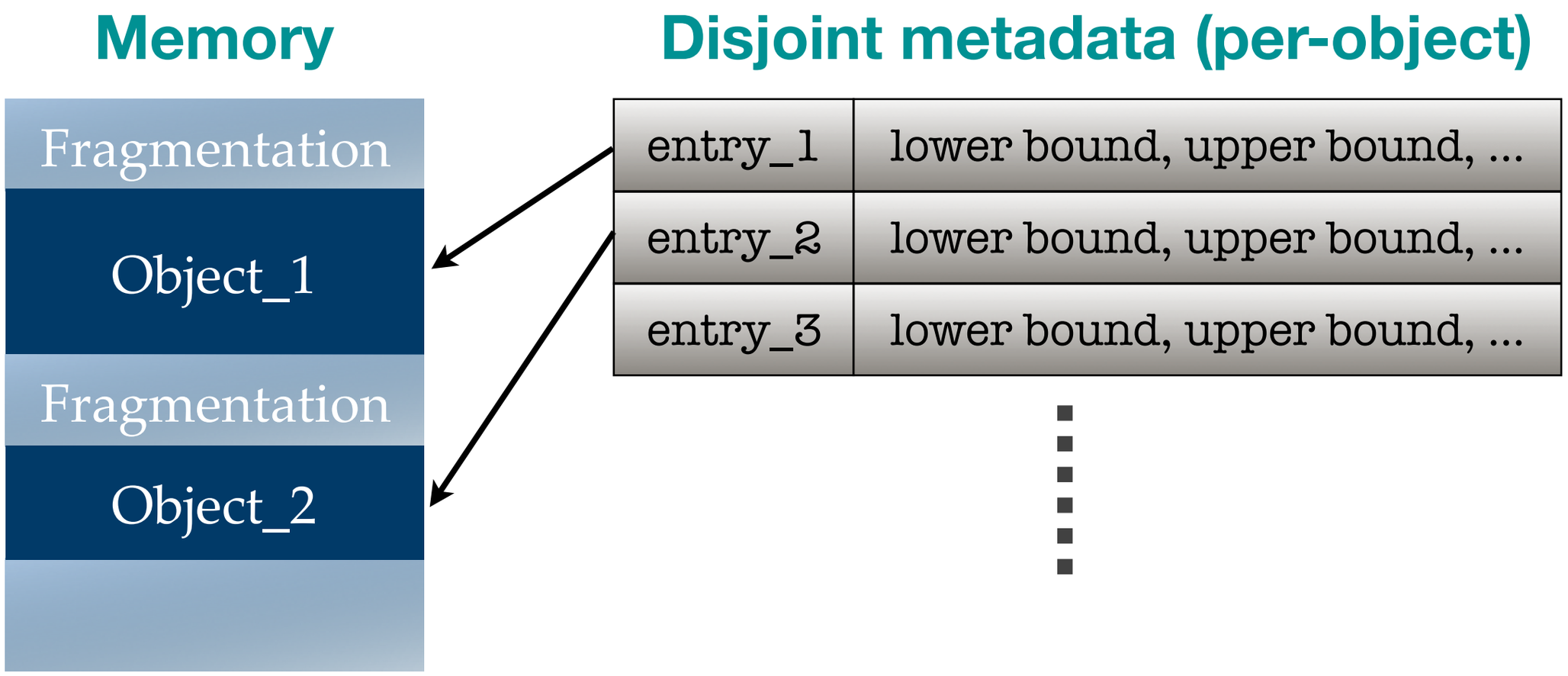
David J Greaves (University of Cambridge)

Spatial Memory Safety



Check lower bound <= p' <= upper bound

Tracking Pointers/Objects



What if there are zillions of objects (objects) to track?

Trade-offs

- For the better speed, previous solutions trade-off..
  - Compatibility (Fat Pointers)
  - Precision (Baggy Bounds)
  - Memory space (Address Sanitizer)
  - Full meaningful 48 bits of address space (SGXBounds)
  - Determinism (ARM's Memory Tagging Extension)

Our Trade-offs

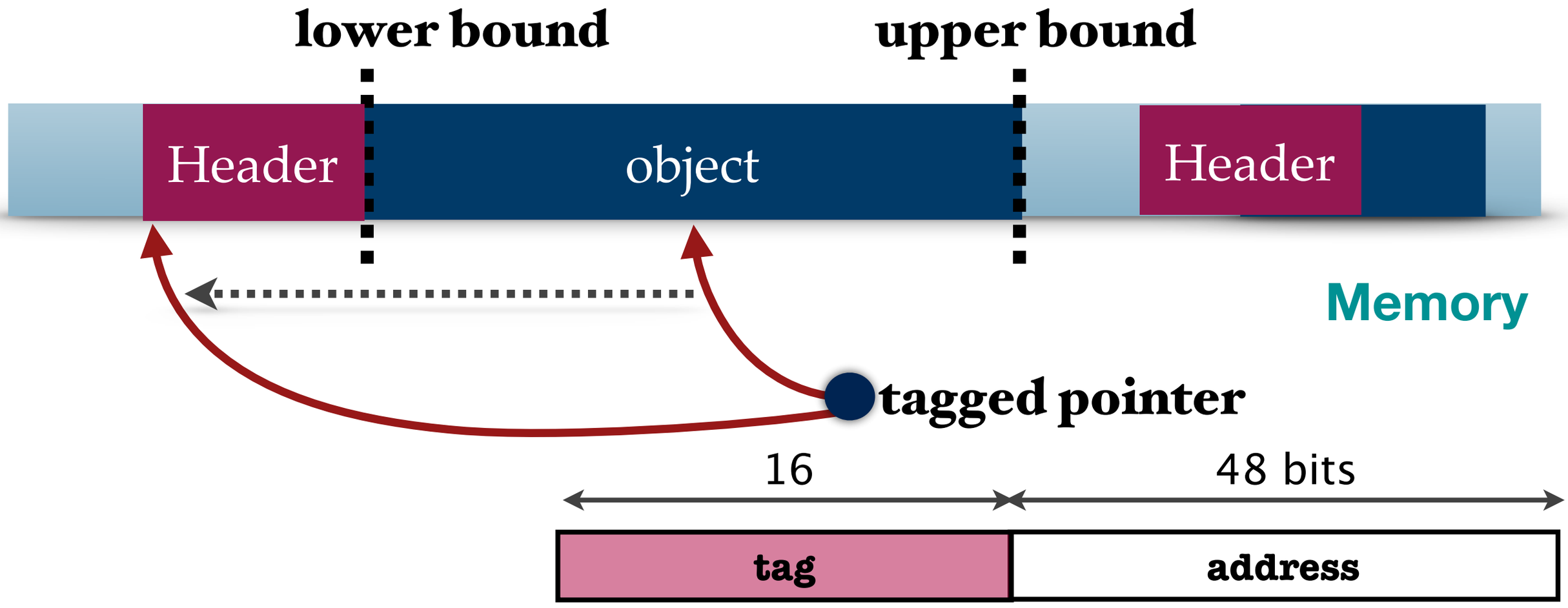
- We secure
  - Deterministic memory protection
  - Data memory efficiency
    - Full 48 bits of address space
- We sacrifice
  - Dynamic instructions counts
    - Rein the increase in extra cache misses for metadata access
    - Tolerate the growth in instructions for arithmetic operations

Hardware implementation will largely resolve our sacrifice

Goals and Challenges

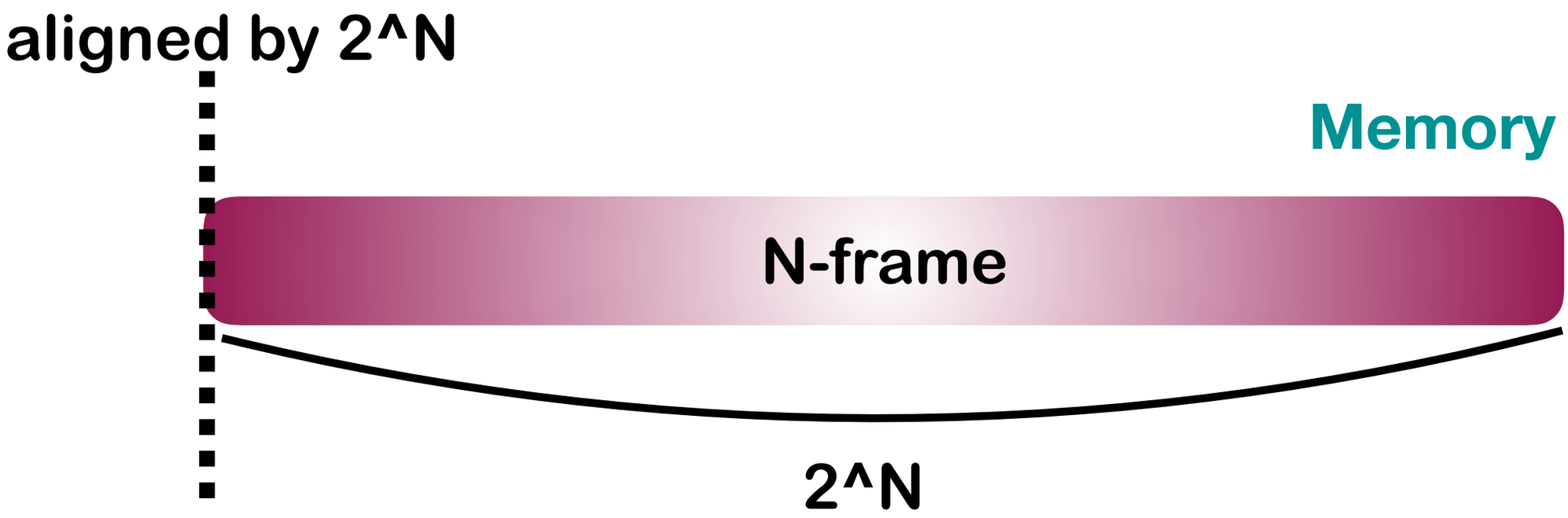
- Derivation of metadata location from a tagged pointer
  - What to stuff unused top 16 bits in a 64-bit pointer?
    - Generic and complete encoding
      - No assumptions on object location, size, or alignment
- Deterministic bounds checking
  - Do not reply on probability
  - Resolve false negatives from violation of intended referents that challenged object-tracking approaches

Tagged Pointer



Header address is derived from a tagged pointer holding relative location

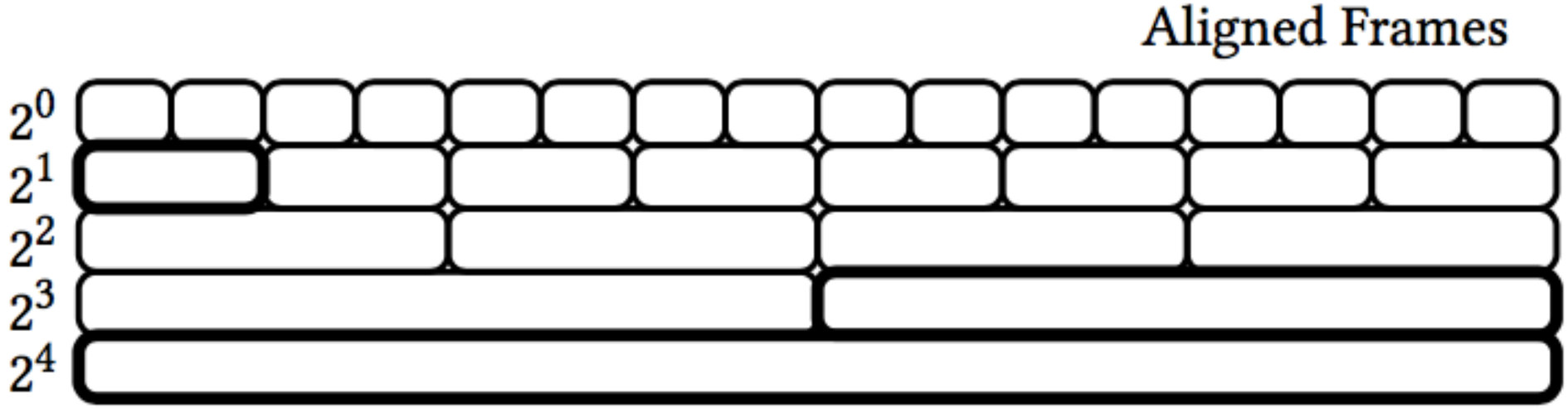
Frame 1/2



A N-frame is defined as a memory block
with the size and alignment of 2^N

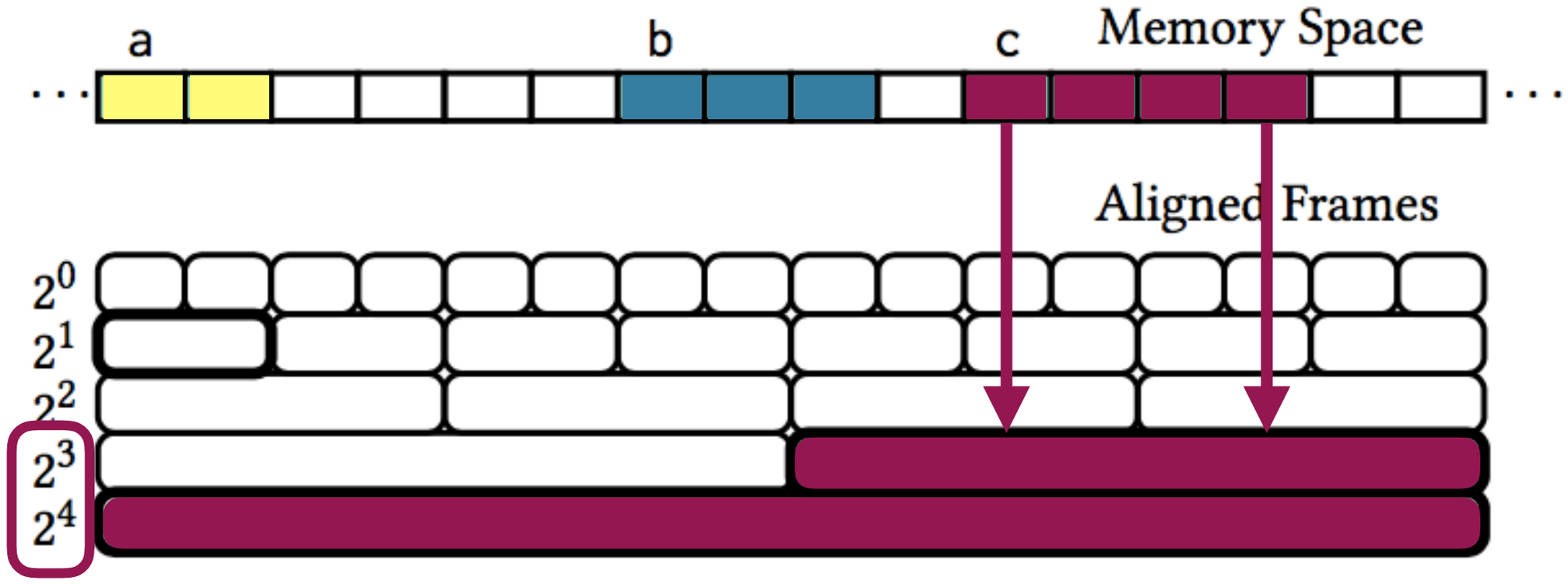
Frame 2/2

Ex) c is a 3 byte-sized object



Bounding Frame

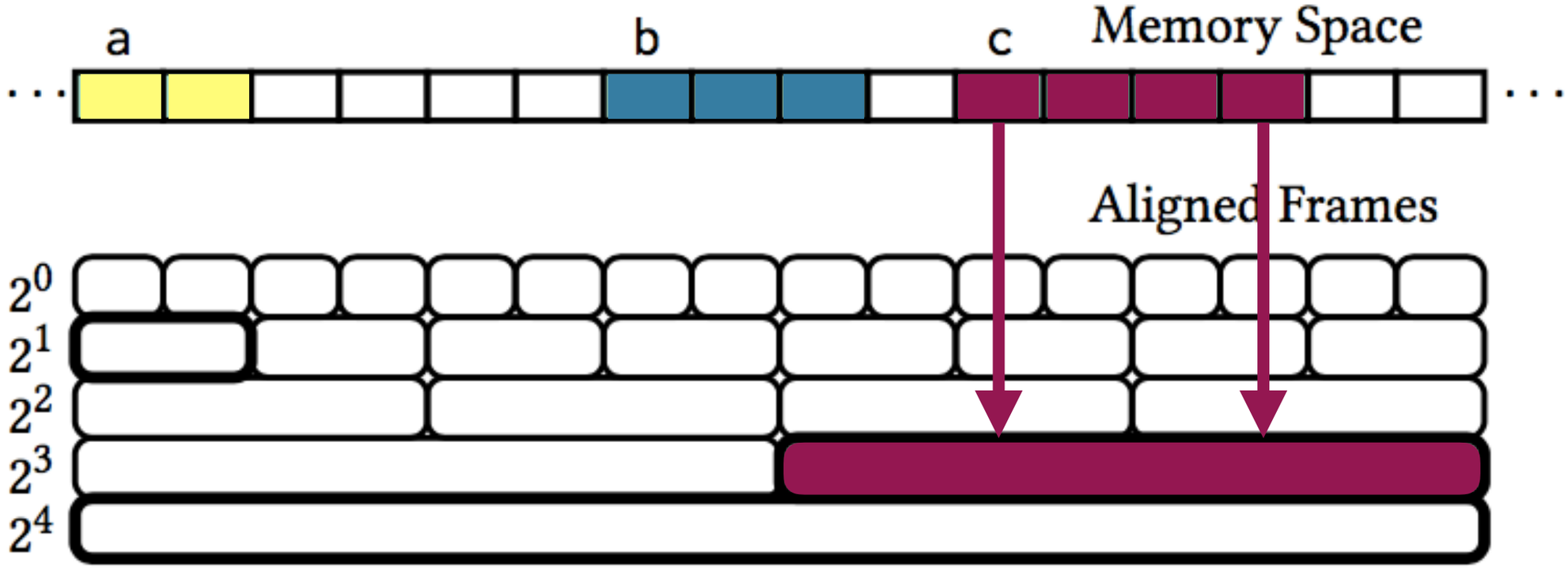
Ex) c is inside at least two bounding frames.



An object is inside at least one bounding frame.

Wrapper Frame

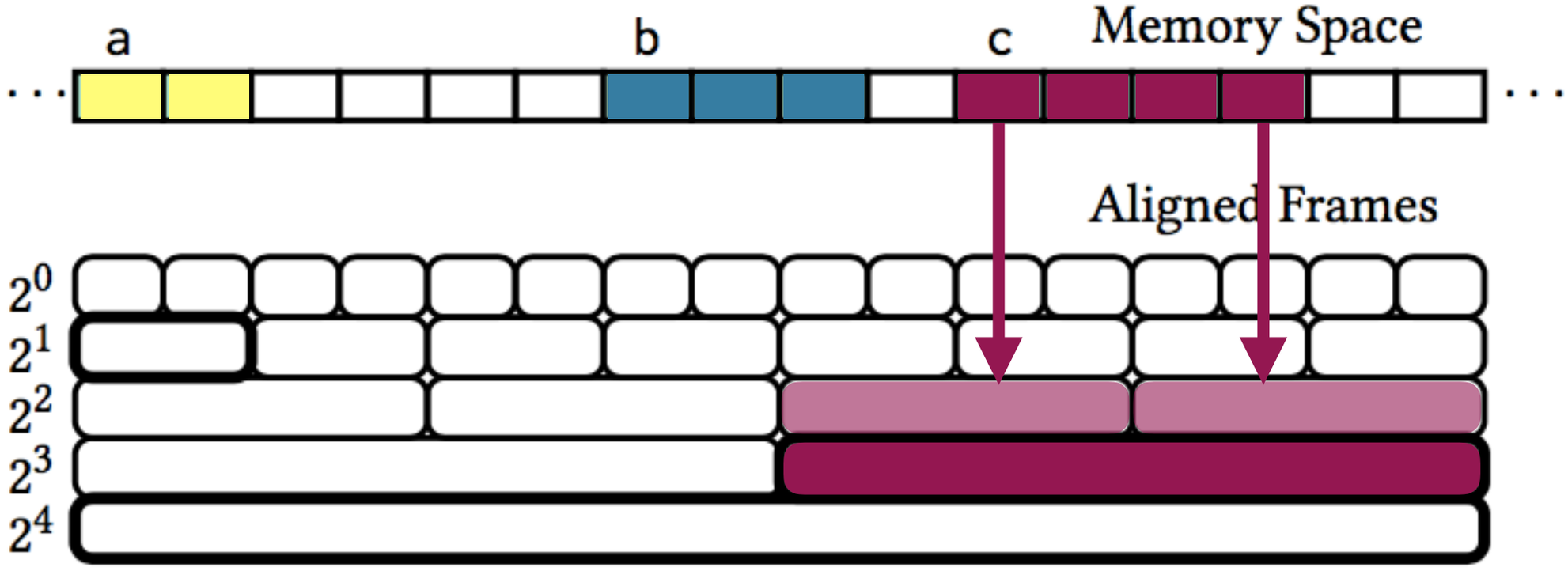
Ex) c has one wrapper frame (3-frame) and is called 3-object



An object's wrapper frame is defined as the smallest bounding frame.

Get Wrapper Frame Size 1/2

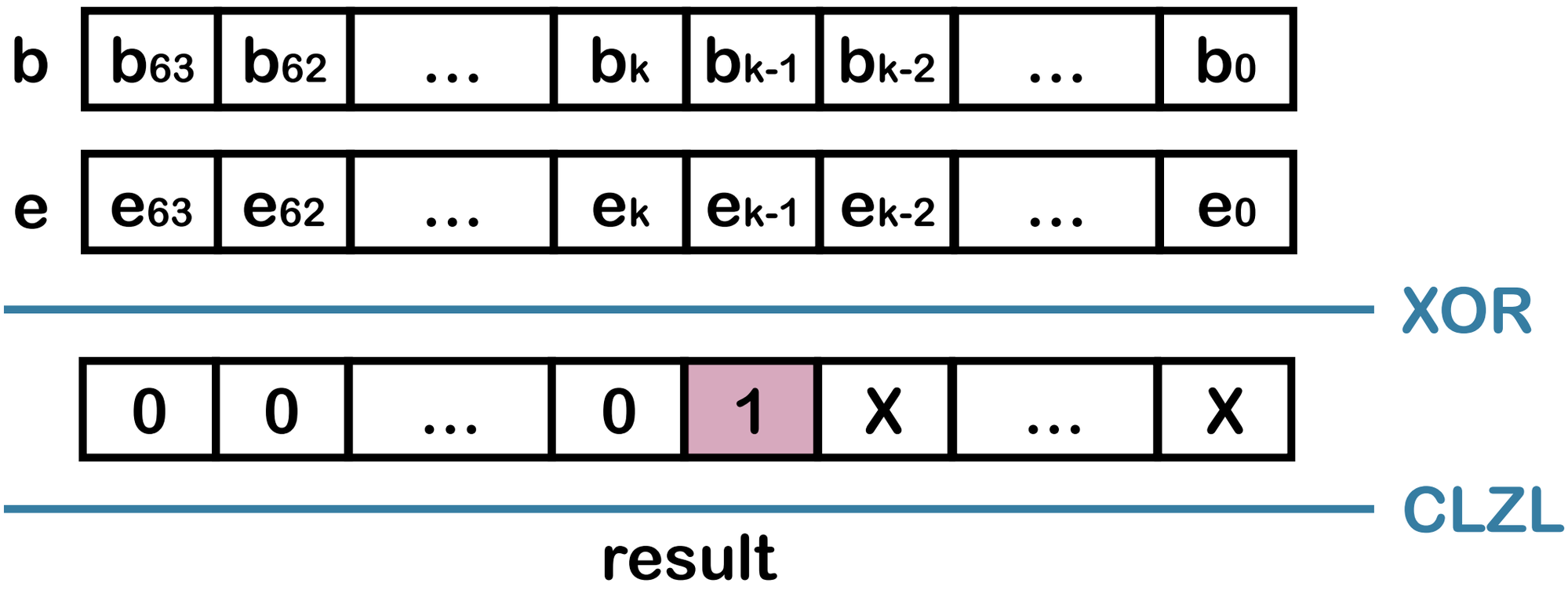
Ex) c is a (N=3)-object.



A k-object's 1st and last bytes sit in its wrapper frame's lower and higher-addressed (N-1)-subframe, respectively.

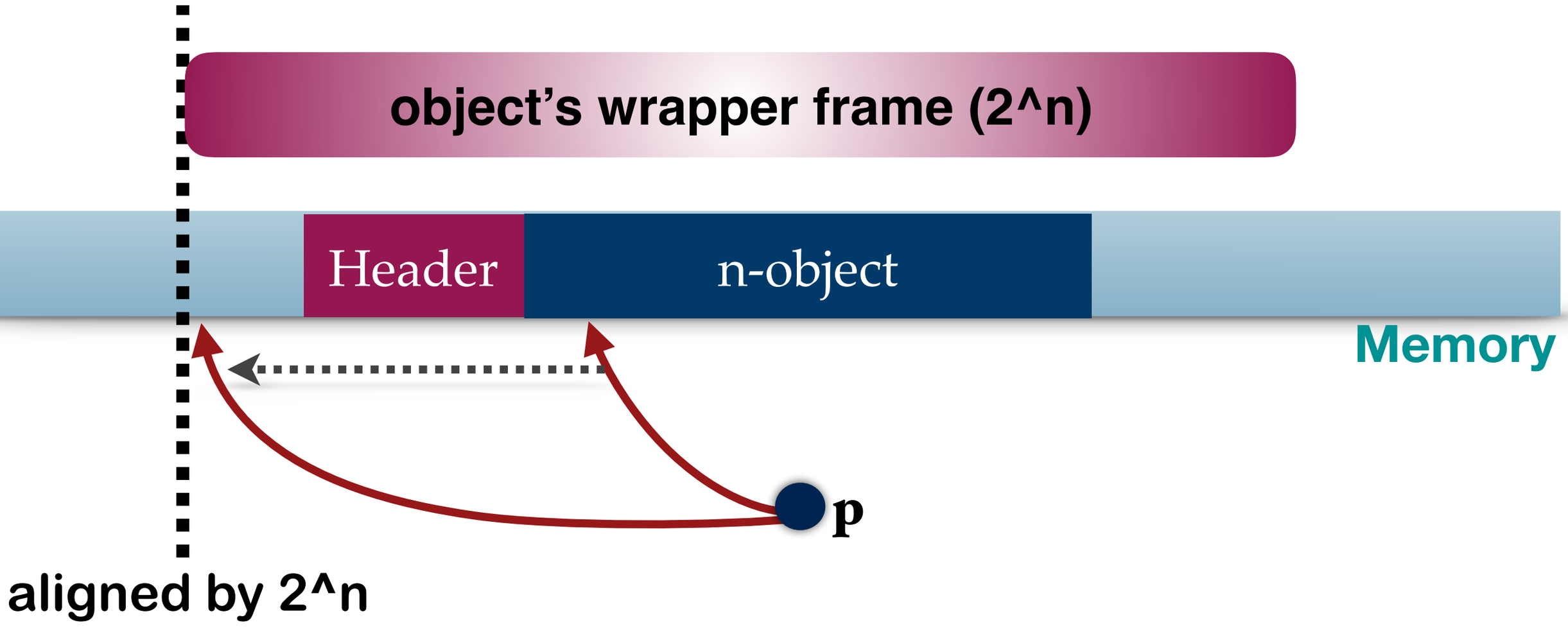
Get Wrapper Frame Size 2/2

lower bound b= [63:0]
upper bound e= [63:0]
X: don't care value



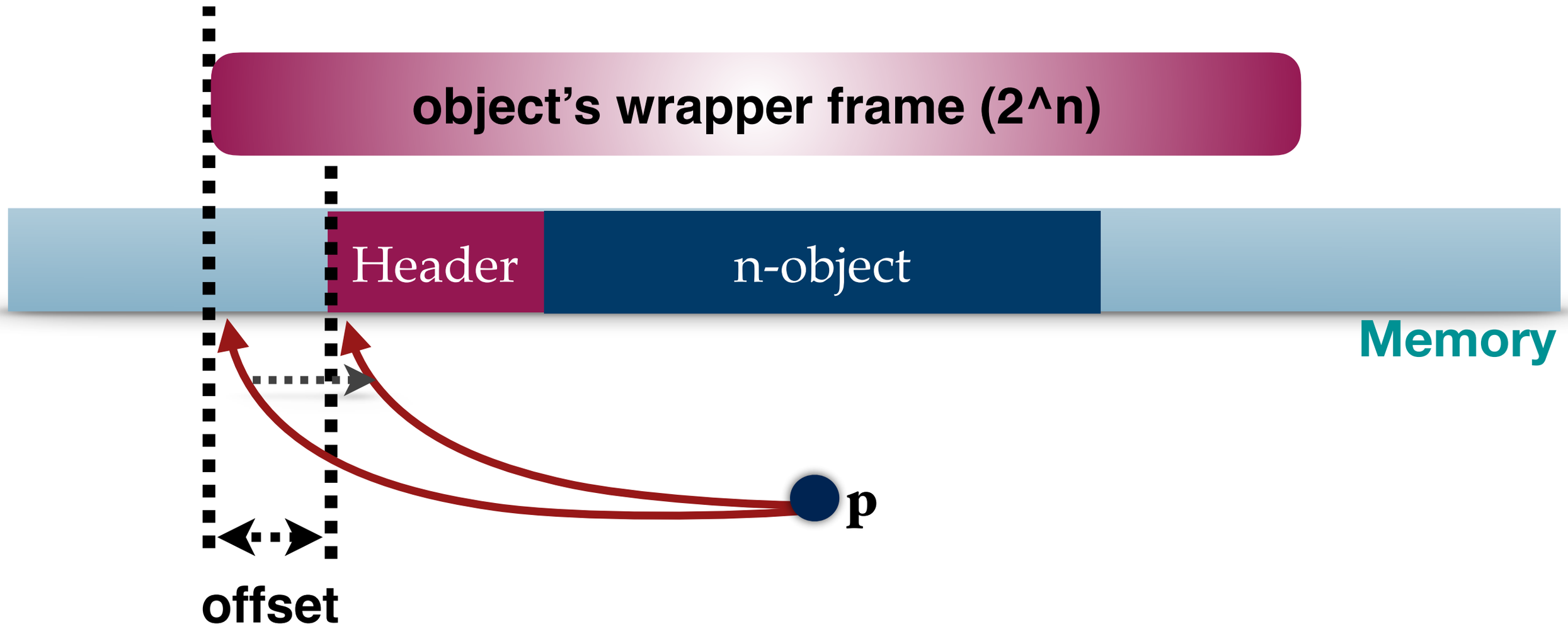
log 2 (wrapper frame size) = 64 - result = k

Get Header Location 1/2



1. Get the base of the wrapper frame= p & ((~0)<<n)

Get Header Location 2/2



2. Add the offset to the wrapper frame base.

Tag space is too small!

- We need the followings to derive the header location

  1) binary logarithm of wrapper frame size, N

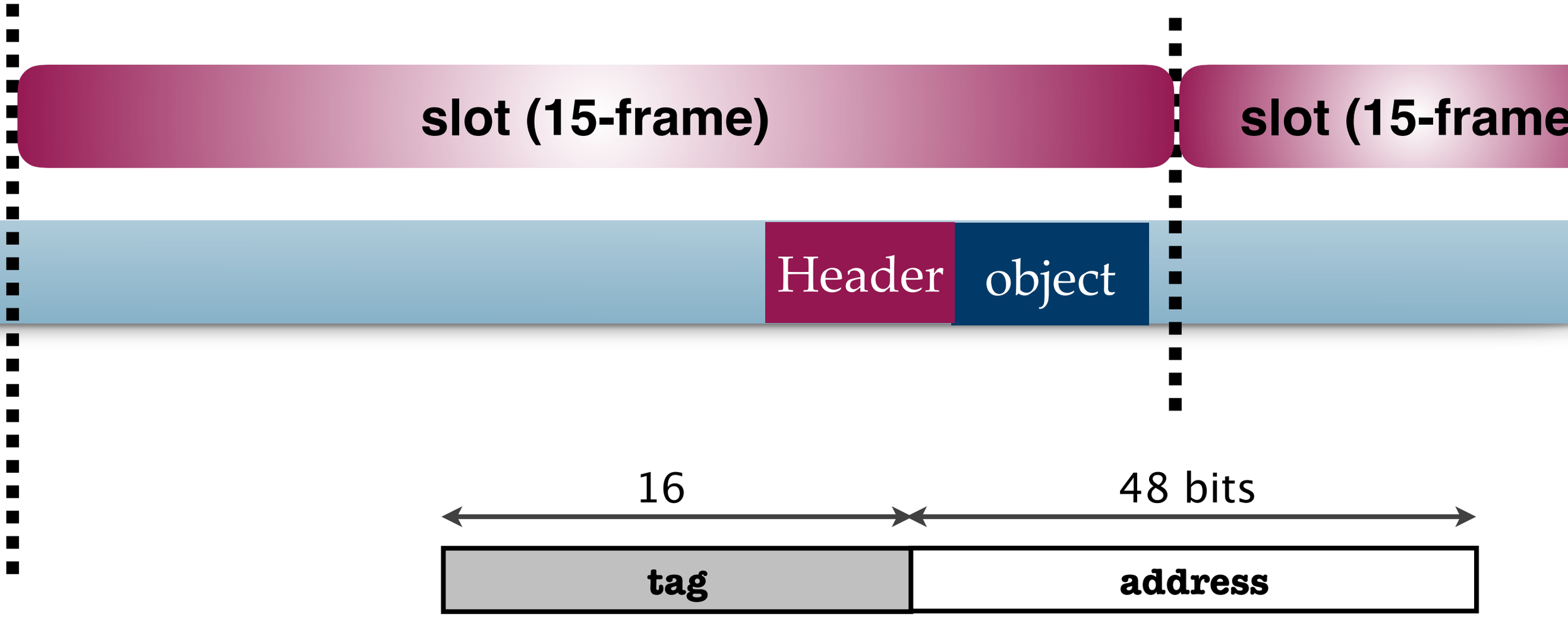
  - this fits in top 16 bits of a 64 bit pointer.

  2) offset (wrapper frame base ~ header)

  - this may NOT.
  - ex) (N=20)-object's offset is up to 19 bits.

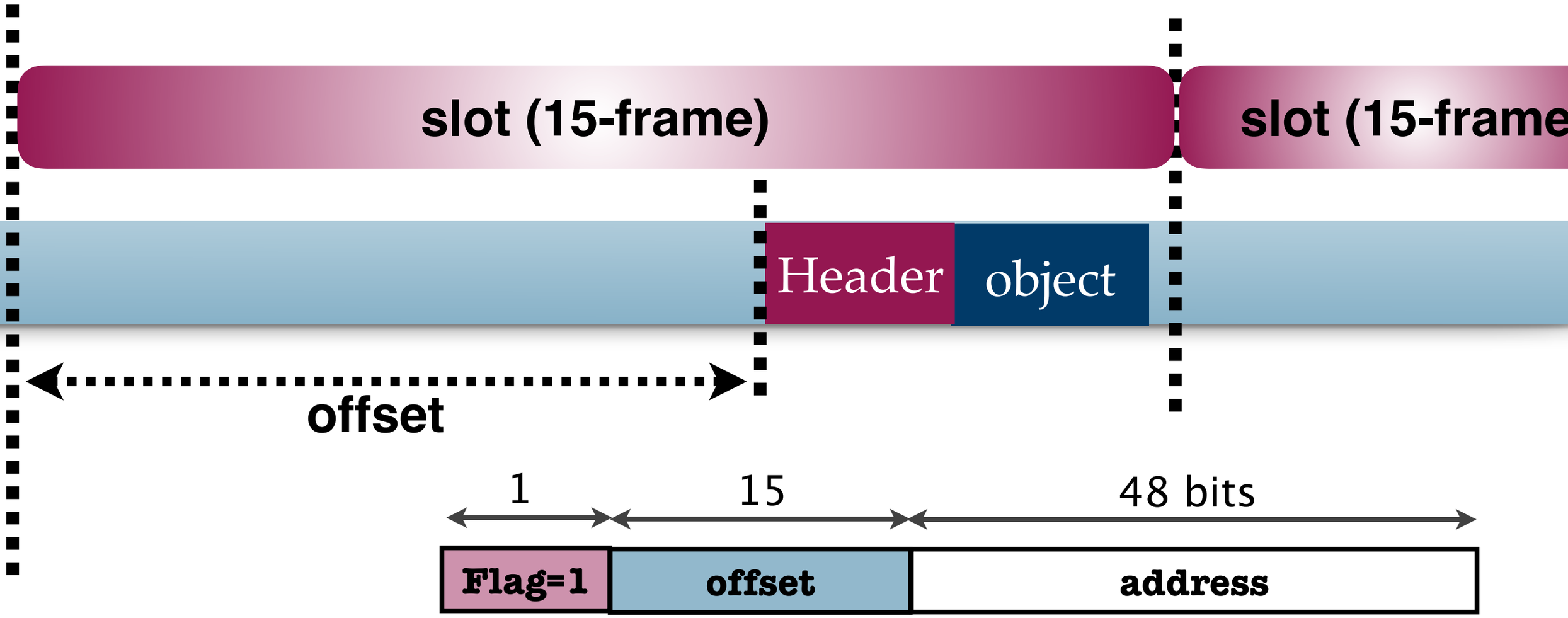
We need more tricks to squeeze information and stuff a tag.

Slot



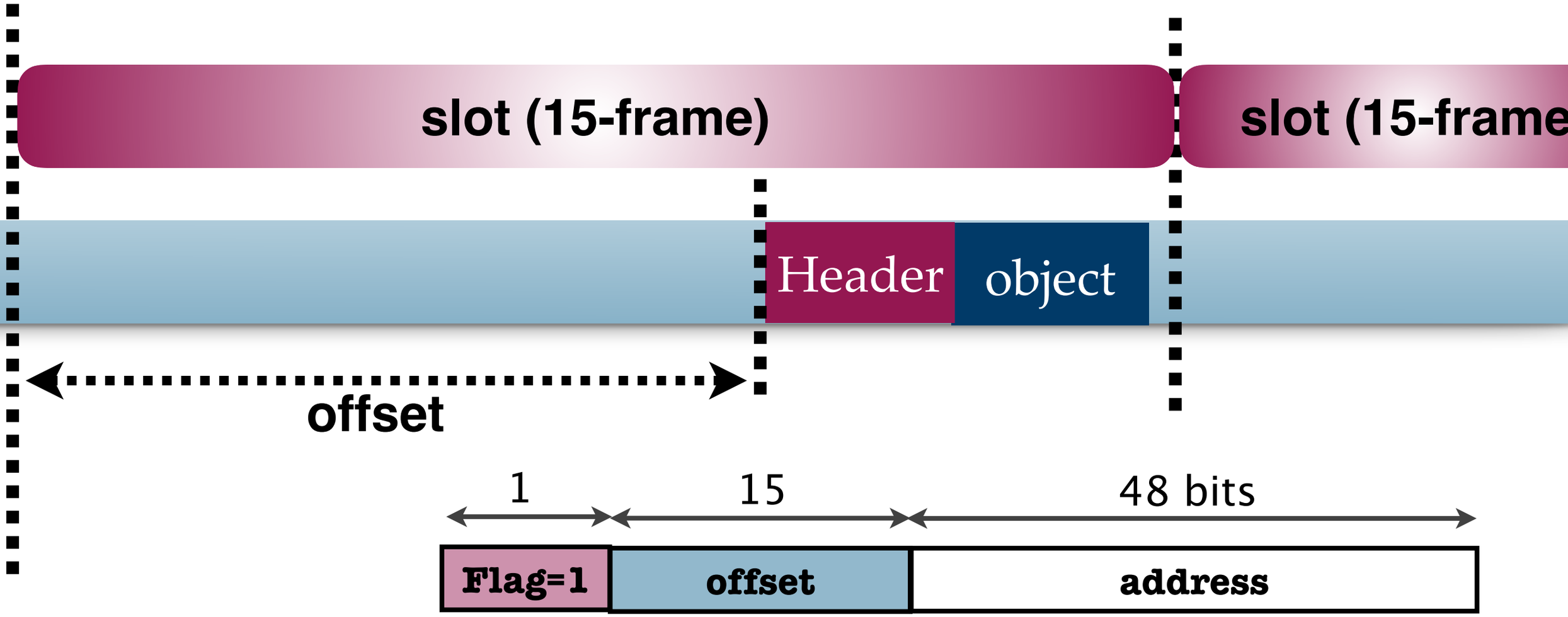
We divide memory space into slots, (N=15)-frame

Tagging (N<=15)-objects



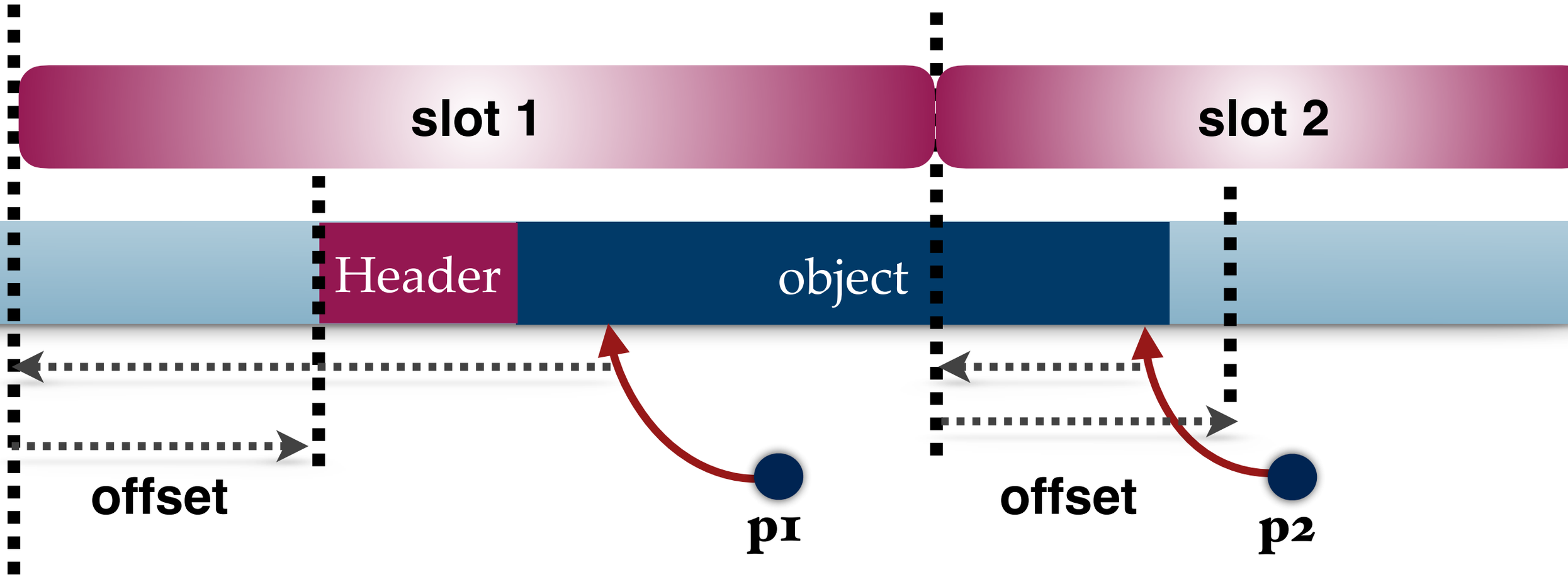
For (N<=15)-objects, we tag an offset and turn on flag.

Metadata Retrieval for (N<=15)-objects



if flag == true, (p & ((~0)<<$\log_2$ slot_size)) + offset

Derivation fails



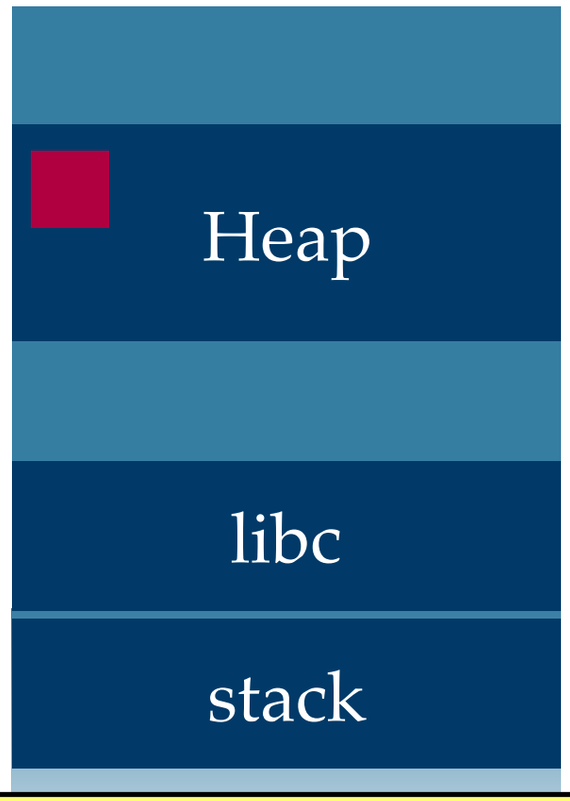
ex) p2 is derived to nowhere.

We use a supplementary table only for (N>15)-objects.

Compact Shadow Space

More recent approaches' shadow space

Application memory

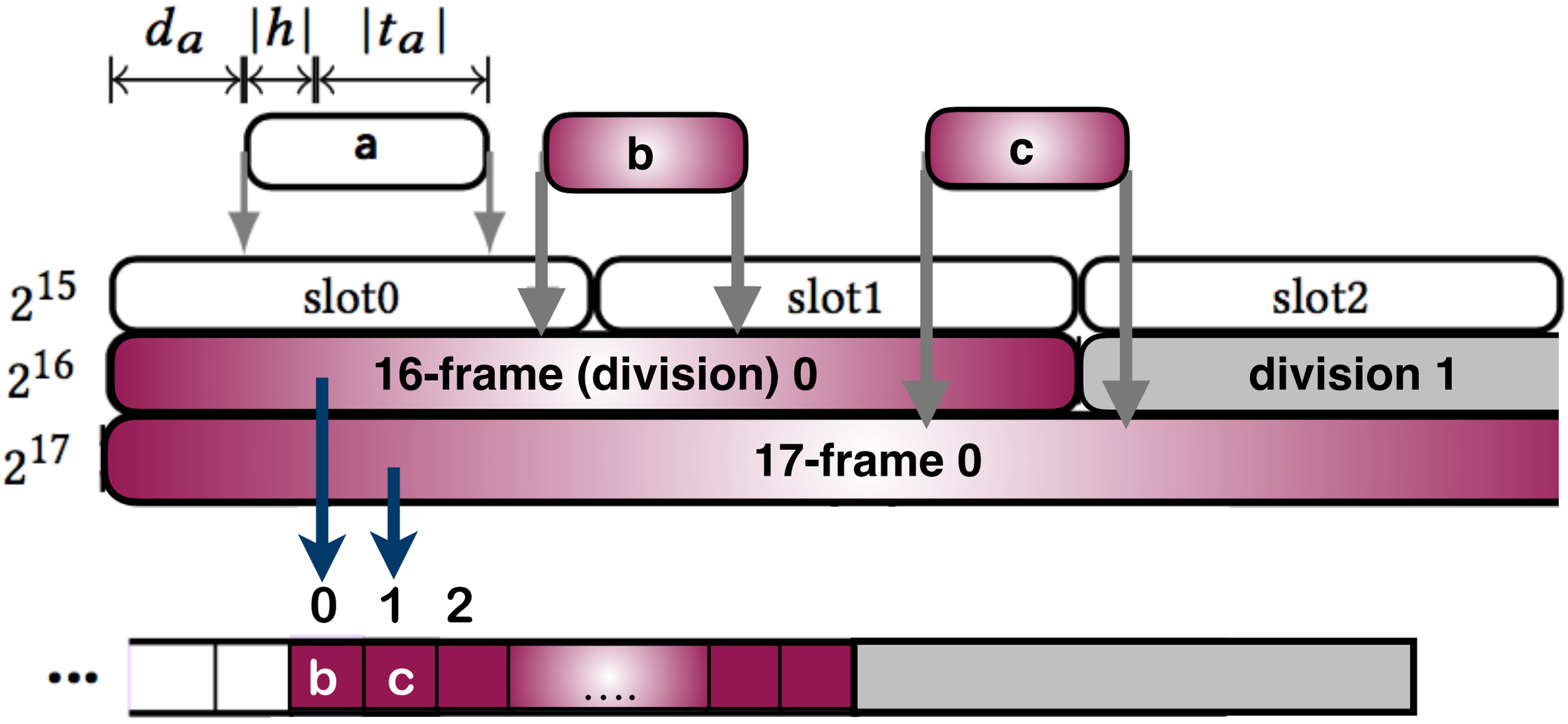


k : 1

Shadow memory

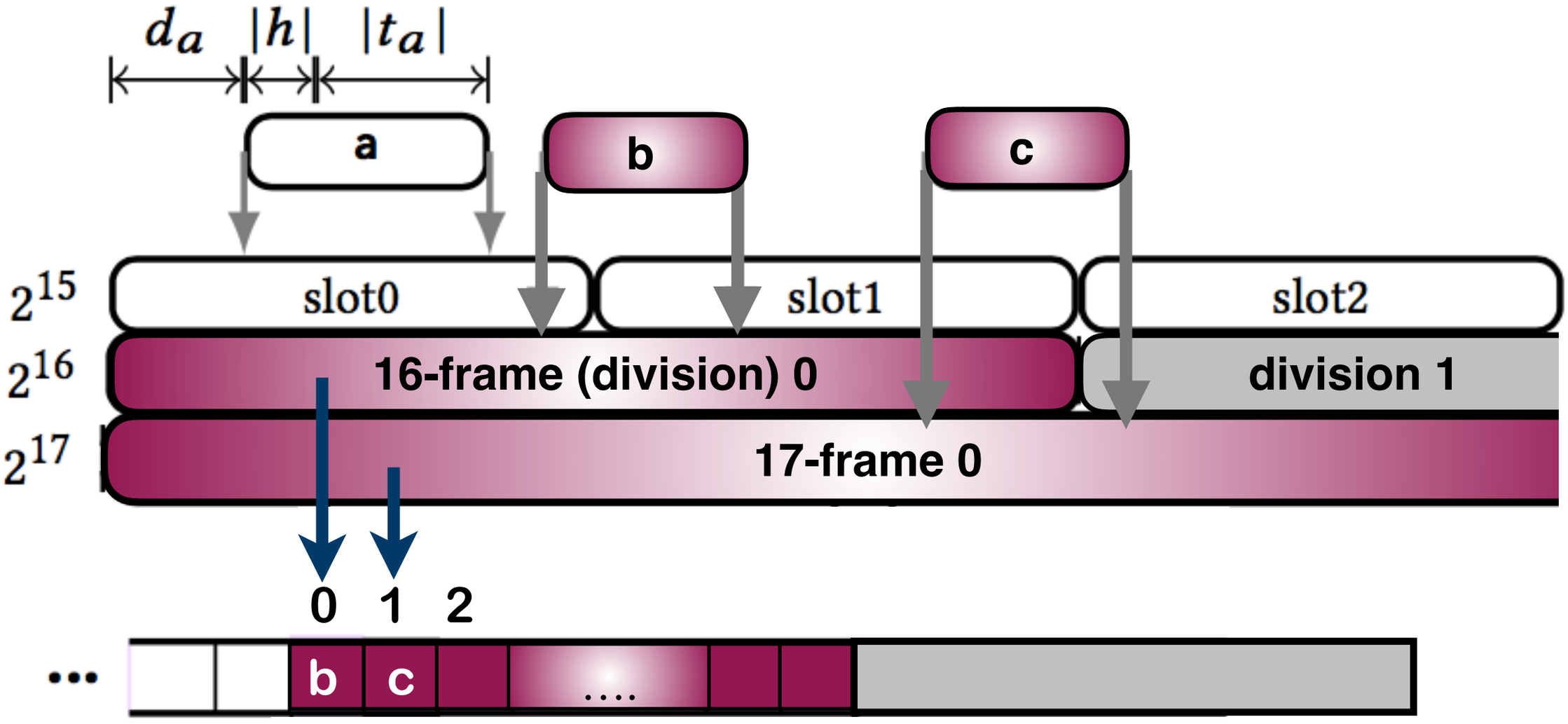
Mapping each fixed-sized memory block to an entry

FRAMER’s Mapping Table Entries 1/2



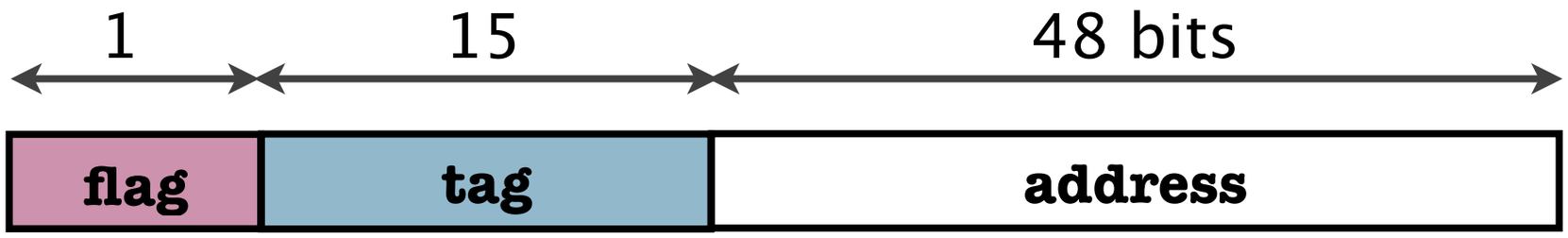
For (N>=16)-objects, we tag N value and turn off flag.

FRAMER’s Mapping Table Entries 2/2



The entry holds a header location
(or metadata).

In Summary

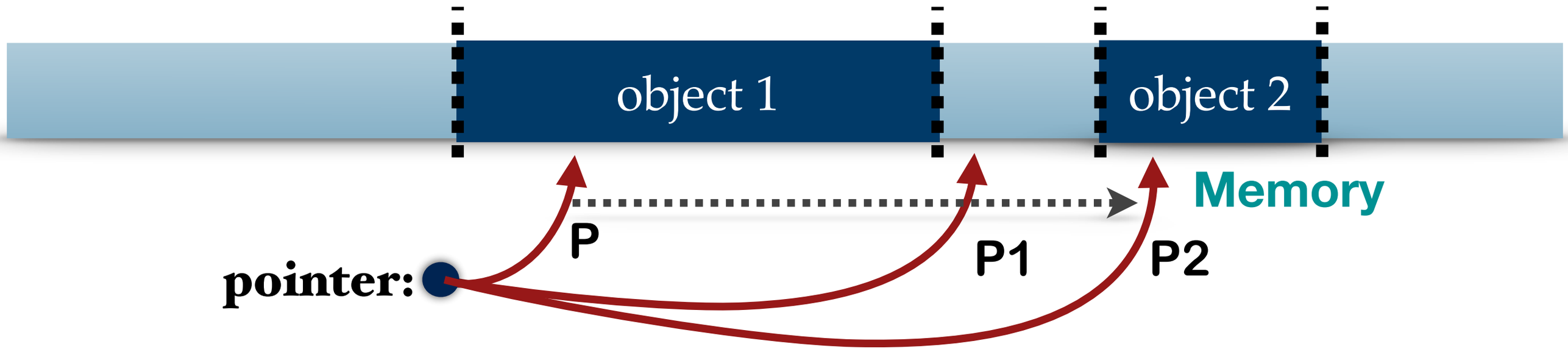


if flag==1 tag := offset (common cases)

else flag==0 tag := N (uncommon cases — 1/200,000)

Calculation of a header address is fairly simple

False Negatives



entry_1	Base, upper bound, ...	← P
entry_2	Base', upper bound', ...	← P2

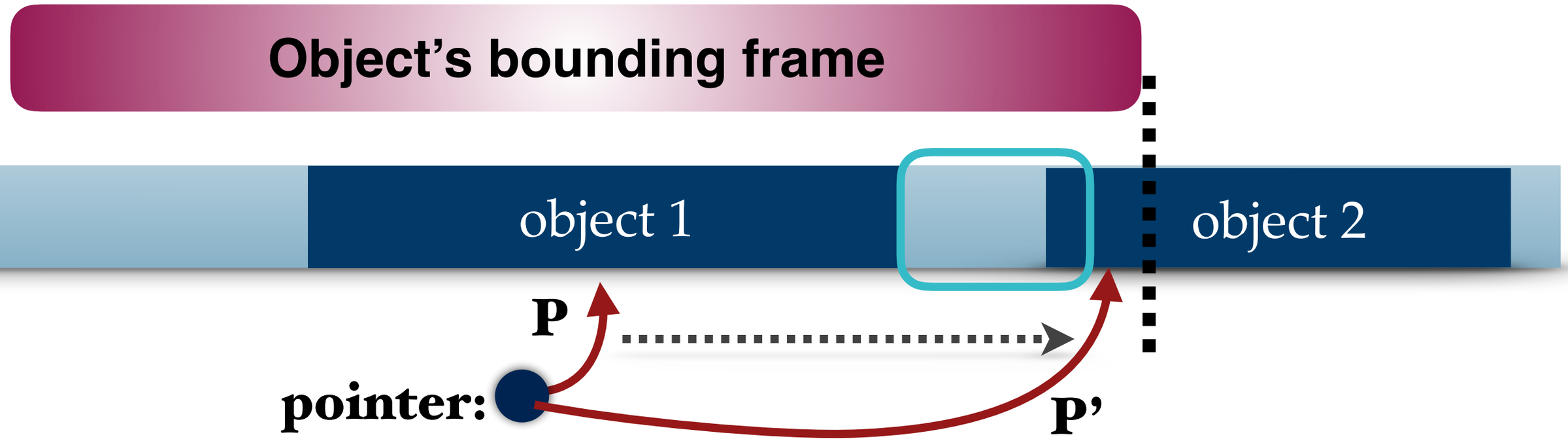
Tracking objects requires checks at pointer arithmetic to keep track of intended referents.

Now, False Positives

```
int *p;
int *a= (int*)malloc(100*sizeof(int));
for (p=a; p<&a[100];++p)
    *p=0;
/*  p == &a[100]  */
```

Should we check bounds at pointer arithmetic
AND
memory read/write??

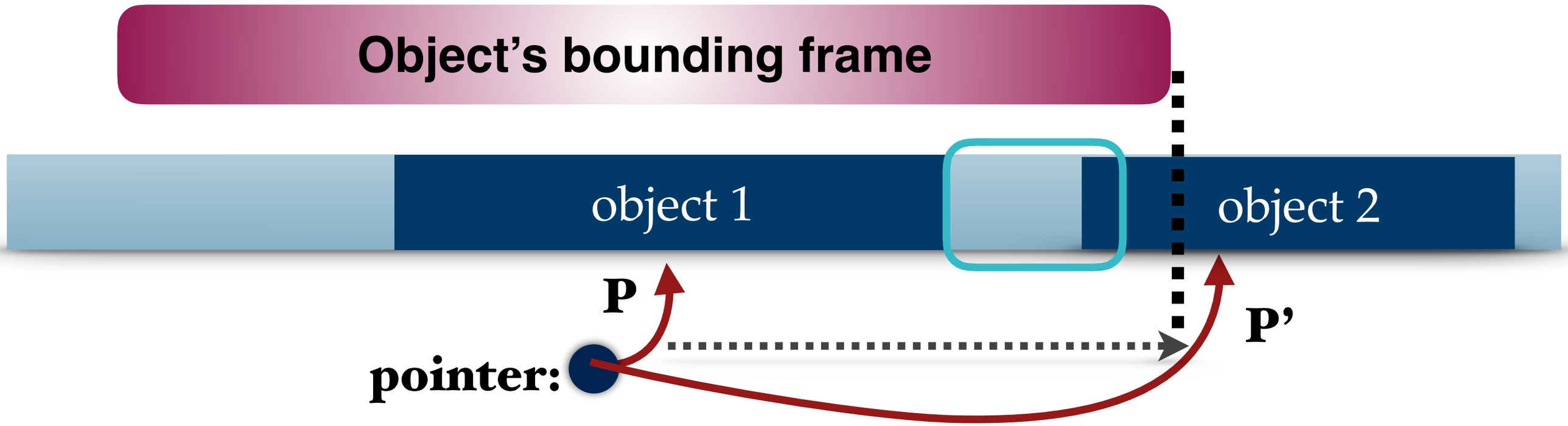
FRAMER’ s Solution



P’ even violates an intended referent,
but is still derived to header

Pad imaginary bytes when deciding a wrapper frame

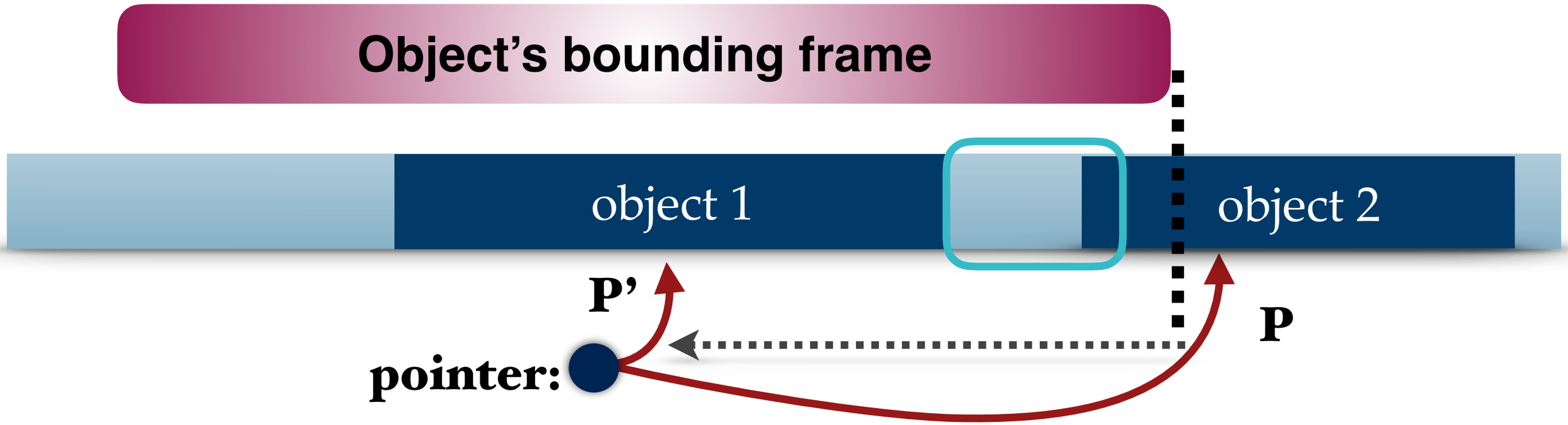
In-frame Checking 1/2



In-frame checking catches the case P'

Check only in-frame at pointer arithmetic:
assert ((p' ^ p) & (~0ULL << N) == 0);

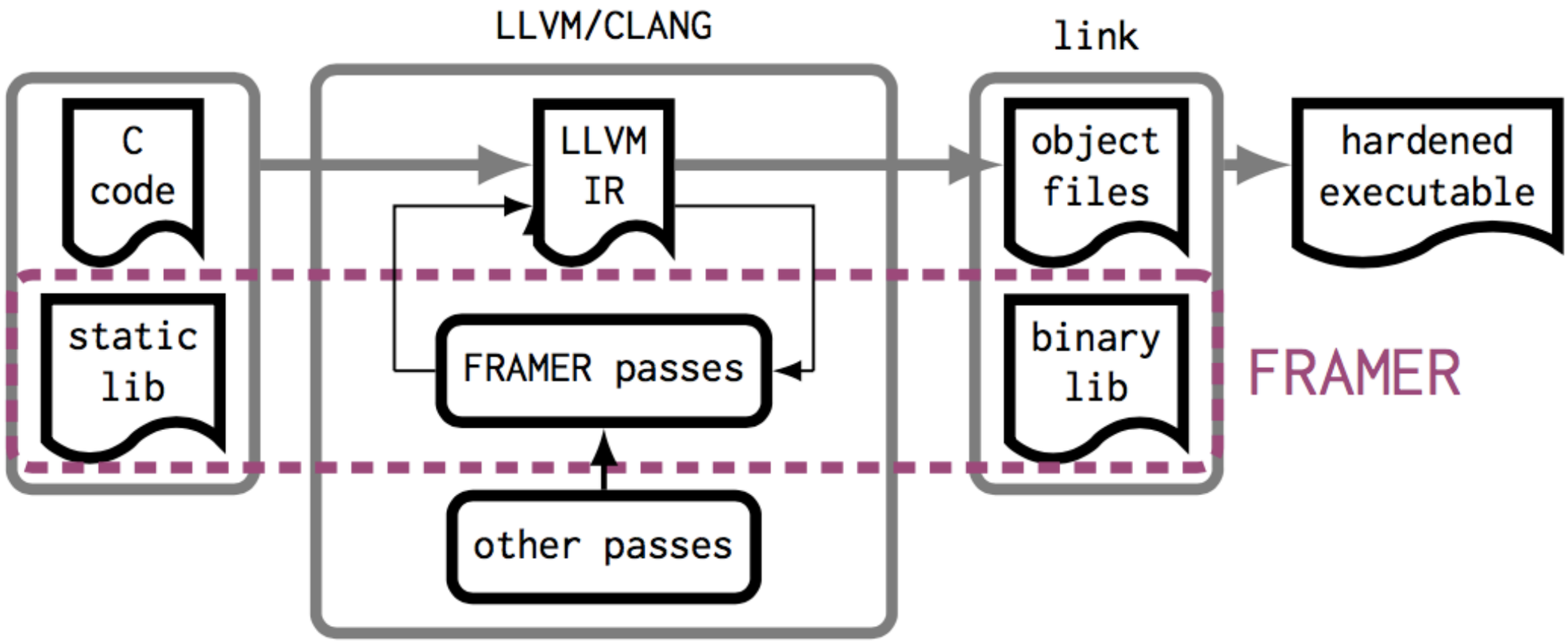
In-frame Checking 2/2



P may go back in-frame without access.

No false negative, but one kind of false positives with in-frame checking ON

FRAMER Overall Architecture



FRAMER pass is implemented as a LLVM LTO pass.

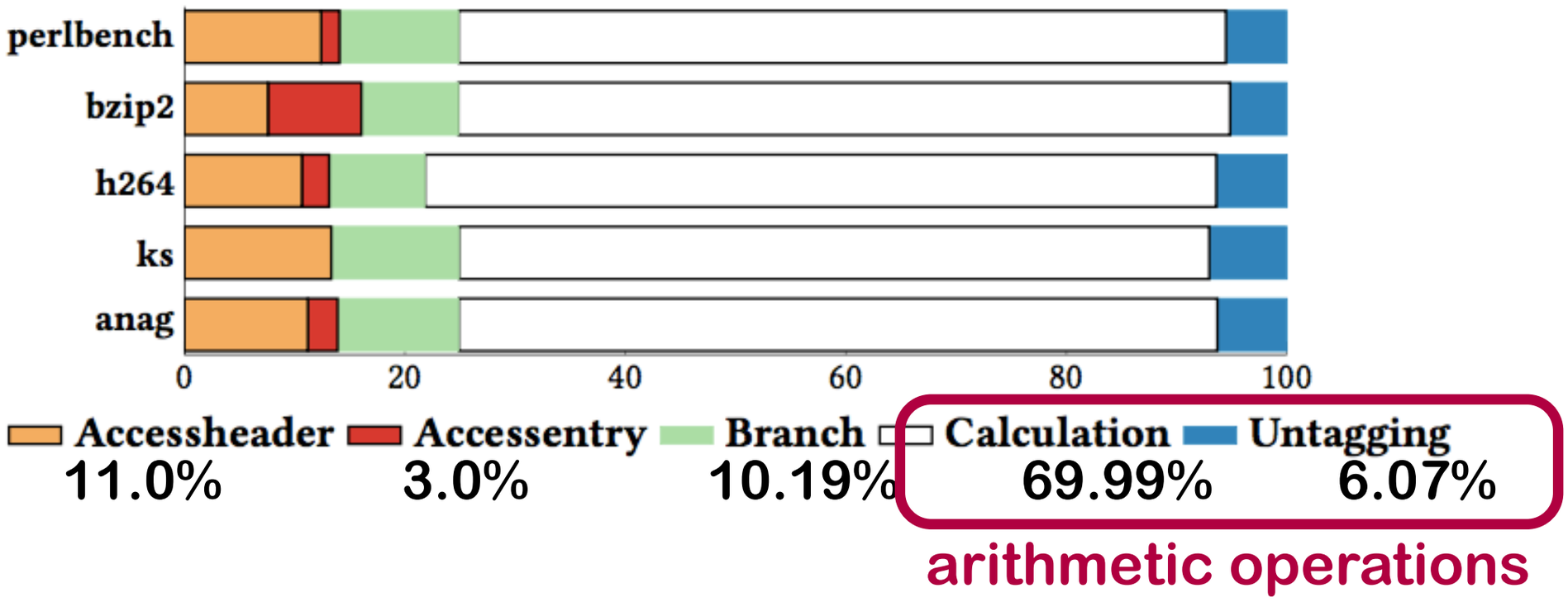
Experimental Results

- **Memory overheads (maximum resident set size)**
  - **FRAMER's store-only: 22%**
  - **FRAMER's Full: 23%**
  - **Address Sanitizer: 784%**
- **Run-time overheads (cycles)**
  - **FRAMER's store-only: 70%**
  - **FRAMER's Full: 223%**
  - **Address Sanitizer: 139%**

28 tests among Olden, Ptrdist, SPEC2006

The Cost of FRAMER

Runtime overheads for metadata management and retrieval
(overhead for bounds checking is excluded here)



ISA will largely resolve run-time overheads for calculation + untagging + bounds checking.

Contributor to Overheads

- **Memory overheads**
  - **Mandating 16 alignment for compatibility with llvm.memset**
  - **Generous header size (16 bytes)**
  - **Fixed division array size (48 elements)**
- **Run-time overheads**
  - **FRAMER's increase in dynamic instructions is high.**
    - **FRAMER (Full): 425%**
    - **Address Sanitizer: 226%**
  - **FRAMER is L1 D-cache efficient.**
    - **FRAMER's Full: 40% (miss counts)**
    - **Address Sanitizer: 131% (miss counts)**

Advantages

- Generic and sound design with many applications
  - Memory safety, Type safety, Garbage collection and etc
- Memory footprint and D-cache efficiency
  - No padding, re-alignment or grouping is required.
- Possible deployment for both stages
  - For development stage
    - Near-zero false negatives
    - Near-complete memory safety with type information
  - Practical deployment with support of customised ISA

Discussion

- The penalty of using tagged pointers
  - Tag setting up and cleaning
- More compact encoding
  - offset, the supplementary table entries
- Manipulation of memory object re-arrangement
  - Reduce/remove indirect access or branch for (N>15)-objects

Thank you!