FRAMER: A Cache-friendly Software-based Capability Model

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Abstract  
Fine-grained memory protection for C and C++ programs must track individual objects (or pointers), and store bounds information per object (pointer). Its cost is dominated by metadata updates and lookups, making efficient metadata management the key for minimizing performance impact. Existing approaches reduce metadata management overheads by sacrificing precision, breaking binary compatibility by changing object memory layout, or wasting space by excessive alignment or large shadow memory spaces.

We propose FRAMER, a software capability model for object-granularity memory protection. Its efficient per-object metadata management mechanism enables direct access to metadata by calculating their location from a tagged pointer to the object and, for large objects, a compact supplementary table. The number of bits in this tag and the size of the supplementary table are balanced to minimize both using a novel technique.

FRAMER is a general proposal for object metadata management with potential applications in memory safety, type safety, thread safety and garbage collection that improves over previous solutions by (1) increasing locality of reference by having objects carry their metadata, (2) streamlining expensive metadata lookups, (3) saving space by avoiding superfluous alignment and padding, (4) avoiding internal object memory layout changes.

1 Introduction

Despite advances in software defenses, exploitation of systems code written in low-level languages such as C and C++ is still possible. Security exploits use memory safety vulnerabilities to corrupt or leak sensitive data, and hijack a vulnerable program’s logic. In response, several defenses have been proposed for making software exploitation hard.

Current defenses fall in two basic categories: those that let memory corruption happen, but harden the program to prevent exploitation, and those that try to detect and block memory corruption in the first place. For instance, Control-flow Integrity (CFI) [1] contains all control flows in a statically computed Control-flow Graph (CFG), while Address Space Layout Randomization (ASLR) hides the available CFG when the process executes. Both approaches can offer only probabilistic security [8, 25], since memory corruption is still possible, albeit exploitation is much harder.

A general approach to detect and block memory corruption is through tracking the bounds of object allocations [2, 3, 9–11, 13, 18, 20, 21, 23, 31]. The program is instrumented accordingly to use bounds information for blocking unintended accesses to objects [2, 9, 11, 18, 20, 23]. These systems can offer deterministic guarantees, since now memory corruption is prevented in the first place, however tracking all objects (or pointers) incurs heavy performance overheads.

Some existing techniques trade off compatibility for high locality of references, however, it is desirable to minimise the disruption owing to tacit assumptions by programmers and compatibility with existing code or libraries that cannot be recompiled. In particular, so-called fat pointers [21] impose incompatibility issues with external modules, especially pre-compiled libraries in software-based solutions.

With these limitations in mind, Object-capability models [6, 14, 27, 28] using hardware-supported tags become very attractive, because they can manage compatibility and control runtime costs. But they are not supported in today’s mainstream processor architectures, and cannot entirely avoid undesirable overheads such as metadata management related memory accesses just by virtue of being hardware-based.

In this paper, we present FRAMER, a software-based capability model using tagged pointers for fast metadata access. FRAMER provides an efficient per-object metadata management that enables direct access to metadata by calculating their location using the (currently) unused top 16 bits of a 64-bit pointer to the object and a supplementary table. The key considerations behind FRAMER are as follows.
Firstly, FRAMER is highly cache-friendly, as objects carry their own metadata in an associated header. We enable the memory manager freedom to allocate the header near the object to maximise spatial locality which has positive effects at all levels of the memory hierarchy. Headers can vary in size, which may be useful in some applications. Headers can also be shared over object instances (although we do not develop that aspect in this paper). Our evaluation shows excellent D-cache performance where the performance impact of software checking is, to a fair extent, mitigated by improved IPC.

Secondly, the address of a header holding metadata is derived from tagged pointers. We encode relative location of the header in spare bits at the top of a pointer. This streamlines expensive metadata lookup, which has been the performance bottleneck of deterministic memory safety approaches. A supplementary table is used only for cases where the location information cannot be directly addressed with the additional 16-bits in the pointer. The address of the corresponding entry in the table is also calculated from the tagged pointer. This table is small compared to typical shadow memory implementations.

Thirdly, we avoid waste of memory space and approximate bounds checking, unlike existing approaches, by encoding and using relative location for metadata access. We provide precise memory safety without excessive padding and superfluous alignment. The average of normalised space overheads of our approach is very low at 1.23 for full checking.

Fourthly, our approach facilitates compatibility. Our tag is encoded in spare bits at the top of a pointer, but the pointer size is unchanged. Headers can vary in size, unlike approaches that store the header at a system-wide fixed offset from the object.

The contributions of this paper are the following:

- We design, implement and evaluate FRAMER, a generic framework for fast and practical object-metadata management with potential applications in memory safety, type safety and garbage collection.
- We present a case study by applying FRAMER to an application for spatial safety. We further discuss potential applications for temporal safety and type confusion prevention.
- A thorough evaluation shows that FRAMER is cache-friendly. The average normalised L1 dcache misses (MPKI) is 0.76 and 0.53 for store-only and full-checking, respectively. The miss rate is reduced since the additional operations we add have high cache affinity which dilutes the underlying miss rate of the application.

2 FRAMER Approach

In this section we provide a high-level idea of how FRAMER attempts to handle per-object metadata efficiently. In a nutshell, the basic idea is to place per-object metadata as close to its object (i.e. in a header), and streamline metadata lookup in the data structure by calculating the location only from (1) an inbound pointer and (2) additional information tagged in the spare 16 bits. For achieving this, instead of using absolute location (i.e., one word of an address) of each object, or a valid range for each pointer, we use relative location compact enough to be encoded in the 16 spare bits of 64-bit pointer. There are cases where relative location information cannot be used due to derivation fails. This is when allocating large objects or a large contiguous region of smaller objects. We use a supplementary table only for these cases, and the address of its corresponding entry is also derived from a tagged pointer.

We are now going to present the concept of frames. In Section 2.3 we thoroughly present how metadata are actually stored for each different object.

2.1 Frame Definitions

FRAMER stores metadata for all small objects in separate blocks that are placed nearby by FRAMER's memory manager. User blocks are unchanged in layout, but their metadata can be accessed with minimal additional cache misses at all levels of the memory hierarchy. We record a mapping between a block and its metadata using the top 16 bits of a 64-bit pointer, which are spare in contemporary CPUs. As we show below, the code to resolve the metadata address from the inbound pointer is very fast. It does not involve any time-consuming traversal/lookup for metadata access.

To record the relative offset between a block and its metadata we define a logical structure over the whole data space of a process, including statics, stack, heap, and memory-mapped files. The frame structures are based on frame. A frame is defined as a memory block that is $2^n$-sized and aligned by its size. Any memory object will intrinsically lie...
inside exactly one smallest bounding frame as shown in Figure 1. The base of the frame $f$ bounding an object $o$ can be obtained from any location within that frame or within that object by zeroing the least significant $n$ bits [2].

Following basic malloc semantics, FRAMER does not natively support object movement or growth. Therefore, the bounding frame is unique and determined at memory allocation. It does not change over time. The base of the frame will act as reference point to obtain the location of each object’s metadata.

A frame of size $2^n$ is called $n$-frame, where $n$ is a non-negative integer. For $0 \leq m < n$, we call $m$-frames placed inside a $n$-frame $f$, $f$’s subframes. A memory object $x$’s wrapper frame is defined as a frame containing $x$ in it, and having the base and end address of $x$ in its lower $(n - 1)$-subframe and higher $(n - 1)$-frame, respectively. For instance, in Figure 1, objects $a$, $b$ and $c$’s wrapper frames are $(n = 1)$-frame (or 1-frame), 4-frame, and 3-frame, respectively. We call an object whose wrapper frame is $n$-frame an $n$-object.

Frames have several interesting properties. Firstly, an $n$-frame is aligned by $2^m$ where $m < n$. Secondly, an object’s wrapper frame size may not grow in proportion to the object’s size. As shown in Figure 1, the object $b$ has a larger wrapper frame than $c$, even though $b$’s size is smaller. This is because the size of the wrapper frame for an object is determined by both the object’s size and location in memory. Thirdly, an object’s wrapper frame is the smallest frame containing the object inside. It is trivial to show that the wrapper frame of an object is the smallest frame having the object inside, to prove that the wrapper frame of an object is the smallest frame having the object inside, as presented in Appendix B.

We can conclude that there is no smaller frame than $o$’s wrapper frame; this is actually the unique wrapper frame, and it can be used a reference point, since it does not change once the object is allocated.

2.2 Frame Selection

Now we show how to get the size of the wrapper frame, given an object. Assume we have a $k$-object $o$. Since its wrapper frame (i.e., $k$-frame) is aligned by $2^k$ by definition, addresses of all the bytes in the frame have the same value setting of most significant $(64 - k)$ bits, and so does the address of a byte in $o$. In addition, the base and end address are located in the lower and higher $(k - 1)$-frame, respectively. This means that the $(k - 1)_{th}$ least significant bit of the base and end address must be negated.

Based on these, we can get $k = \log_2$ of the size of $o$’s wrapper frame. Let’s say $(b_0, ..., b_1, b_k)$ and $(e_0, ..., e_1, e_k)$ are bit vectors of $k$-object $o$’s base and end address respectively, and $X$ is a don’t care value. We get the $\log_2$ of the wrapper frame size by performing $\text{XOR}$ and $\text{c1z1}$ operations as follows ($b_0$ is the most significant):

\[
\begin{array}{c}
(b_{k+1}, ..., b_{k-1}, b_k) \\
(e_{k+1}, ..., e_{k-1}, e_k)
\end{array}
\oplus
\begin{array}{c}
(0, ..., 0, 1, X, ..., X)
\end{array}
\text{c1z1}
\]

2.3 Metadata Storage Management

FRAMER stores metadata per object at an address that can be derived only from (1) an inbound pointer to the object, and (2) a tag of 16 bits contained in the pointer. We encode the relative location of metadata using the wrapper frame size of each object, since this size does not change over the lifetime of the object.

Objects carry their metadata in a header associated with themselves; the address to the header is derived from the tagged pointer. Assuming the header has a size of $h$, the base address of the object is the header address plus $h$ bytes (the header type is packed-structured). For instance, in Figure 3, $a$, $b$ and $c$ are all objects containing a header, and $a$’s header size is $h$.

The header holds all necessary information of the object, such as the precise size or type information. This streamlines metadata-lookup operations and lowers cache misses; that is especially useful for programs that allocate and release small objects frequently.

FRAMER considers two core types of objects, depending on their size, namely small-framed and big-framed objects, and restructures the virtual address space as follows. FRAMER divides user space into slots that are fixed-sized by $2^{15}$ and aligned by its size, i.e., $(N = 15)$-frames. Slots are set to a size of $2^{15}$ so that the offset to the header of small-framed objects $(N \leq 15)$-objects) can be encoded in the unused 15 bits of a pointer. For instance, in Figure 3, $d_a$ is the offset to the header of the small-framed object $a$. One extra bit, in particular the 16th, is taken for the flag property, which indicates if the object is small-framed or big-framed ($(N > 15)$-objects) as shown in Figure 2.

The descriptor of big-framed objects requires more bits of information (please, see 2.3.2). For big-framed objects, FRAMER creates one array – can be interpreted as shadow space – that holds additional location information. The corresponding entry of a big-framed object is then directly accessed only with a tagged pointer. We stress here that this array is not needed for lookups associated with small-framed objects, and is smaller than typical shadow memory implementations where each entry corresponds to an aligned memory word.

Typically, we expect the number of big-framed objects to be low compared to small-framed objects. In contrast, the offset of small-framed objects can be encoded with fewer bits, but the number of the objects can be much higher. When a target program allocates/deallocates small objects, it may be expensive to track the objects individually, and to update the metadata in the disjoint metadata. Later in the paper, we
show that removing access to disjoint metadata for small-framed objects can significantly reduce runtime overheads.

### 2.3.1 Small-framed Objects

Since small-framed objects are placed in a single slot, we simply tag a pointer with the offset from the base address of the slot to the header of the object. We further turn on the most significant bit of the pointer for indicating that the particular object is small-framed. When we retrieve metadata from a header of a small-framed object, (i.e., flag==1) inbound (in-slot) pointers are derived to the base of the slot by zeroing the least significant 15 bits, and then to the address of the header by adding the offset to the base address of the slot as follows:

```
offset = (tagged_ptr & ~(1ULL << 63)) >> 48;
slotbase = untagged_ptr & ~(0x7FFF);
header_addr = slotbase + offset;
```

### 2.3.2 Big-framed Objects

Big-framed objects span several slots, thus their offset cannot be solely used as their relative location. Zeroing the least 15 significant bits (log slotsize) of an inbound pointer does not always lead to an unique slot base. For instance, in Figure 3, an object b’s inbound pointer can derive two different slots (slot0 and slot1) depending on the pointer’s value, and that is the case for object c (slot1 and slot2). Hence, for big-framed objects, we need to store additional location information in a supplementary table.

During program initialisation, we create an array, and each entry is mapped to a $2^{16}$ frame. We call such a frame division. Each entry contains one sub-array and the sub-array per division is called a division array. Each division array contains the fixed number of entries in the current implementation as follows:

```c
typedef struct Entries {
    void *hd; /* The header address */
} EntryT;
typedef struct ShadowTableEntries {
    EntryT slotarray[48]; /* 64-16 */
} DivisionT;
```

Contrary to small-framed objects, we cannot use an offset for big-framed objects, since the offset to big-framed objects from the base of each division do not fit in the 16 spare bits). Instead we tag binary logarithm of their frame size, i.e. $N$ for a frame of size $2^N$, for big-framed objects. The address of an entry in a division array is then calculated from an inbound pointer and the $N$ value, and the entry holds the address of a header. By definition, a wrapper frame of an $(N \geq 16)$-object is aligned by its size, $2^N$, therefore, the frame is also aligned by $2^{16}$. This implies that a $(N \geq 16)$-frame shares the base address with certain division, and is mapped to one division. In addition, each object has an intrinsic $N$-value, since each object has one wrapper frame. Each $2^{16}$ frame is mapped to one division array, so we keep the header address of each $(N \geq 16)$-object in one of entries of the division array.

Each $(N \geq 16)$-object is mapped to one division array, but the division array may be shared by multiple big-framed objects for their entries. In Figure 3, both division0 and 17-frame0 are mapped to division0. Their mapped division (division0) is aligned by $2^{17}$ at minimum, while division1 is aligned by $2^{16}$ at max.

Here, the tag $N$ for big-framed objects is used as an index to identify big-framed objects mapped to the same division array. For each $N \geq 16$, at most one $N$-object is mapped to one division array, so we use the value $N$ as an index of the division array, and tag $N$ in the pointer. The proof is presented in Appendix A. Given a $N$-value tagged pointer ($\text{fFlag}==0$), we derive the address of an entry as follows:

```
/* p is assumed tag-stripped offed here. */
division_base = p & (~((0)<<N));
TABLE_index =
    ((division - division_base_of_userspace_base) /((1ULL<<16)) + 1;
/* TABLE is the array for the whole program */
```
SlotT *M = TABLE + TABLE_index;
EntryT *m = M->divisionarray;
EntryT *myentry = m+(N-((log division_size)+1));

The base of the wrapper frame (i.e. the base of the division) is obtained by zeroing the least significant \(N\) bits of the pointer. We, then, get the address to its division array from the distance from the userspace base and \(\log(division_size)\) \((2^k)\). Finally we access the corresponding entry with the index \(N\) in the division array.

Entries possibly used in a division array may not always be used, since an entry corresponds to one big-framed object, which is not necessarily allocated at any given time, e.g. if object \(b\) is not allocated in the space in Figure 3, 0th element of \(division0\)'s array would be empty. This feature can be used for detecting some dangling pointers, and more details are explained in section 3.2.

We showed how to directly access per-object metadata only with a tagged pointer. Our approach eliminates expensive range-lookup or traversal in the data structure that has been bottleneck of many other approaches, allowing direct access to metadata by calculating its location while preserving high locality of reference. This mechanism can be applied to other issues, since the metadata can hold any per-object data. The base address of an object for bounds checking does not need to be stored, since the value can be obtained by adding the header address by the type size of header. This enables exact bounds checking, i.e. without approximation of bounds information.

3 FRAMER Applications

In this section we discuss how FRAMER can be used for building security applications. We focus mainly on spatial safety, nevertheless, we discuss additional case studies related to temporal safety and type checking.

3.1 Spatial Memory Safety

In a nutshell, FRAMER tracks individual memory allocations, and associates metadata with them. The metadata is stored in the header associated with an object, and the offset, or the wrapper frame information \((N\) value), is tagged in the pointer. We update the metadata, and tag at allocation; metadata is retrieved at memory access \((store, load, and memory access functions)\). Unlike other object-tracking or relative location-based approaches, FRAMER does not require bounds information retrieval at pointer arithmetic operations. Additionally, we tackle off-by-one errors without padding objects. While enforcing spatial memory safety, FRAMER also can detect temporal memory errors in some cases, such as where memory has been re-allocated.

In this section, we describe how FRAMER instruments a program by performing transformations at memory allocations, deallocations, pointer arithmetic, memory access, and at the startup/exit of functions.

3.1.1 Memory allocation and deallocation

For global and automatic aggregated objects, FRAMER creates a header-padded object, and replaces original allocations at compile time. In our current implementation, a memory object is padded into a packed-structured object whose second field is the original object as follows:

```c
struct __attribute__((packed)) HeaderT {
  unsigned TyID;
  /* TypeID of elem of an array */
  unsigned size;
};
struct {HeaderT, AllocatedT} paddedObj;
/* AllocatedT is the type of an original object, and this structure is also packed. */
```

Additionally, we replace all uses of the original object with a tagged pointer to the raw object (the second field of the paddedObj), when necessary, after type casts. Each pointer to the new object is tagged with \(N\) or its offset, and then the actual size of the object is stored in its header.

For global and static objects, the tag is a compile-time constant. Our instrumentation constructs a constant tagged pointer, and further re-writes all occurrences of global and static objects. A hook function for each global object, called during the program initialisation phase, updates the metadata in the header, and accordingly the location of the header if the object is big-framed. For stack objects, we use a hook function for each allocation for returning a tagged pointer; this pointer is further used for accessing the object. In addition, at the epilogue of each function, we insert code to reset the entry in the metadata table for each big-framed stack object.

For heap objects, we interpose calls to malloc, realloc, and calloc, at link time, to pad the user-defined size by the header size. We also re-write calls to free by calls, which reset entries used by big-framed objects, get the hidden base address of an object and finally release resources properly.

Note that all objects’ wrapper frames must be determined at run-time, even though global or static local objects are constants. This is because the size of a wrapper frame is affected by its address on memory, and not just by the object size.

3.1.2 Pointer arithmetic

Object-tracking approaches determine a pointer in-bound when the pointer is within a valid range of an object stored in the metadata. Pointers should be always checked for validity when they are involved in (pointer) arithmetic expressions.

Bounds checking at pointer arithmetic may cause false positives, since a pointer may go beyond the boundary of its referent, but the pointer may not violate memory safety as follows:

```c
int *p;
int *a = malloc(n * sizeof(int));
```
typedef struct MyType {
  char *x; ...; int z
} Ty;
typedef struct MyType {
  char *x; ...; int z
} Ty;

tagged = handle_alloca(&padded_arr, 10, typeID(Ty), sizeof(Ty));
/* tagged= tag & (padded_arr->arr[0]) */

Ty *p;
check_inframe(p, tagged+idx); /* an optional check */
untagged_p = check_bounds(p, sizeof(int));
untagged_p->z = val;

Table 1. FRAMER inserts code, highlighted in grey, for creating a header-padded object, updating metadata and detecting memory corruption. Codes in line 4, 9, and 12 in the first column are transformed to codes in the second column.

for (p = a; p < &a[100]; p++)
  *p = 0;

On the exit of for loop, p is out of bound, but does not violate memory safety, yet, since it is not dereferenced, and this is legal in C standard.

Duplicate checks retrieving metadata at memory accesses will increase runtime overheads, so previous approaches tracking objects avoid it by padding off-one-byte [13] or marking out-of-bounds pointers at pointer arithmetic [2].

Instead of padding one byte, we just include one imaginary off-by-one byte (or multiple bytes) on memory allocation. The pad then is within the wrapper frame, and the pointer is valid as long as it is contained within the range of its wrapper frame.

We optionally perform only in-frame checking at pointer arithmetic operations. FRAMER can derive the header address from any location inside the frame, not just inbound of the object. Therefore, out-of-bounds pointers yet within the wrapper frame of the object lead to the base of the frame, as described above. Due to this feature, FRAMER can handle out-of-bounds by multiple bytes for objects having spare bytes in the wrapper frame.

/* p': the result of pointer arithmetic */
p: the pointer operand of arithmetic
n is log wrapper_size
  (or log slotsize for small-framed) */

inframe = (p'p)&(‘0)<<n;
assert(is_inframe == 0);

3.1.3 Memory access

We instrument all store and load instructions by replacing the pointer operands with a return value of a bounds-checking function, so that their pointer operands are checked and are stripped-off the tag before being dereferenced.

For metadata retrieval, hooks first read a flag from the tag to infer if the object is small or big-framed. For a small-framed object, we simply retrieve the size from its header after calculating the header location with the offset in the tag as follows:

if (flag == 1) { /* if small-framed */
  slotbase = p & (~0)<<15; /* 15 == log slotsize */
  HeaderT *hd_p = (HeaderT *)(slotbase + offset);
  obj_base = (void *)hd_p + sizeof(HeaderT);
  obj_size = hd_p->size;
}

In the case of big-framed objects, we read the N value from the tag, and then calculate the address of its corresponding entry, which holds the address of the header. Big-framed objects also have their bounds information in the header.

if (flag == 0) { /* if big-framed */
  framebase = p & ((~0)<<N);
  DivisionT* M = tablebase + shadow_index;
  EntryT *m = M->slotarray;
  EntryT *myentry = m+(N-interval);
  hd = (HeaderT*)(m->base);
}

// Ubase: the slotbase of the userspace start address.
// interval: log(division_size)

Once bounds are retrieved, we check the following:
assert (untagged_p >= base) (1)
assert (untagged_p+sizeof(T)-1 <= bound)); (2)
/* where T is the type to be accessed */

The assertion (2) aims at catching in-bound pointers causing memory corruption by typecast such as the following:

char *p = malloc(10);
int *q = p+8;
*q = 10; // memory corruption

In a similar fashion, we instrument string functions (memcpy, memmove, strcpy, memcmp, strncmp, strncpy, memchr and strncat) for bounds checking. For instance, \_\_\_wrap_strcpy performs bounds check, passes an untagged pointer to \_\_\_real_strcpy, and then restores a tag of the return value.

For instance, \_\_\_wrap_strcpy performs bounds check, passes an untagged pointer to \_\_\_real_strcpy, and then restores a tag of the return value.

```c
char *\_\_\_wrap_strcpy(char *dest, char *src)
{
    char *untagsrc = (char*)untag_ptr(src);
    size_t srclen = strlen(untagsrc);
    \_\_\_real_strcpy(
        (char *)check_bounds(dest, srclen),
        untagsrc);
    return dest;
}
```

3.2 Temporal Memory Safety

Although our primary focus in this paper is spatial safety, FRAMER can be used for detecting other types of memory errors. We now, briefly, discuss how FRAMER can be useful for detecting dangling pointers, in some cases.

Each big-framed object is mapped to an entry in a sub-table in the supplementary table, and the entry is mapped to at most one big-framed object for each N. We make sure an entry is set zero whenever a corresponding object is released. Therefore, when a big-framed object is released, and then there is an attempt to free the object (i.e. double free), we can catch the dangling pointer by checking if the entry is zero, yielding the object is already freed. In addition, we can detect use-after-free vulnerabilities by checking if the entry is zero at metadata retrieval of a particular (big-framed) object. Note that this still cannot detect temporal intended referents, i.e., an intended referent is released, a new object is allocated in the same location, and then a pointer attempts to access the first object.

Detection of dangling pointers for small-framed objects is out of scope of our current implementation.

3.3 Type Cast Checking

The majority of type casts in C programs are either upcasts (conversion from a pointer to an object to one to the first subject-object) or downcasts (in the opposite direction). Upcasts are considered safe, while memory access to an object after downcasts to it causes boundary overruns including internal overflows. This is a vulnerability commonly known as type confusion [9, 11].

Pointers upcasted/downcasted to void* are frequently passed inter-functionally as an argument. In CCured [21], void is considered to be the empty structure, and any type is a physical subtype of void. We also follow this definition of sub-typing. We can safely upcast a pointer to any type into void*. However, when a down-casted pointer from void* to any other type is about to be dereferenced, we need to check bounds at runtime.

Detection of downcasted pointers is crucial this approach, since user program’s data (arrays and structure-typed objects) are usually neighboring with other objects’ header holding metadata, and unsafe pointer type casts can pollute metadata. Here, we are reluctant to halt the program for every downcast, since it is very common for C programmers to downcast inside an object instance when they are well-aware of the structure. We can detect memory overwrites to another distinctive object caused by downcasts only by just adding track of structure-typed object and using our current implementation for bounds checking. Unlike fat pointers, we do not need to check internal overflows by unsafe downcasts to protect metadata, since metadata is placed outside an object.

For strict type checking, we hook the typecast instruction (bitcast instruction in LLVM for pointer type casts), and use type information. For this, we collect all the identified types used in a program at compile time and place them into a table. The table contain LLVM’s basic types and all the identified structures.

We can build physical sub-typing graph either at static or at runtime, and perform more efficient type information retrieval.

4 Implementation

This section describes implementation specifics of FRAMER on creation of the metadata table and handling memory allocation/deallocation in LLVM intermediate representation (IR). Additionally, we discuss compiler optimisations and how we offer compatibility with existing code.

4.1 Overview

Our instrumentation works on LLVM intermediate representation (IR) compiled from source code in C. Definitions of hooks functions in C are compiled into LLVM IR along with the target C code, and then FRAMER transformation and optimisation passes are applied to the IR code along with standard optimisation passes provided by LLVM. FRAMER’s transformation pass is implemented as an LLVM Link Time Optimization (LTO) pass for the whole program analysis, and run as the first LTO pass on gold linker [15]. We modified the LLVM LTO pass manager, so that we can select optimisation passes, and run in the order that we want. We run our instrumentation pass first, and then LLVM built-in optimisation passes and ours.
4.2 Shadow Space

We insert a prologue/epilogue that are performed on program startup/exit. Prologue reserves address space for the metadata table, and pages are allocated on demand. On program exit, FRAMER releases the space for metadata table. FRAMER creates a fixed-sized division array currently, but this can be optimised, since some of the entries are never used. In particular, the number of entries possibly used depends on the alignment of the corresponding division, e.g., division0 in Figure 3, is aligned by $2^{17}$ at minimum, so at least 2 entries are used, while division1 aligned by $2^{16}$, not by $2^{17}$, has only one entry used over the program’s lifetime.

4.3 Global or static objects

During compile time, a global or static array is replaced with a padded one, and its pointer is tagged in LLVM constant expression (ConstExpr) selecting either N or offset (N or offset is also constructed to LLVM ConstExpr). The actual value of the tag is then assigned a concrete value by the base and end address passed to the tag in ConstExpr. The pointer in ConstExpr to the raw object (i.e., the 2nd field) takes over all the occurrences of the pointer to the original one, and it is passed to the hook function for global objects. We insert a hook function for each global/static object for updating metadata, and for some cases, for initializing at the beginning of main function.

We also replace the occurrences in an initializer of other global objects (both non-arrays and arrays) or in an operand of an instruction with a tagged pointer to newly created arrays. Currently, constant expressions that we generated could not be used as an initializer of global objects due to select constant expression, so we initialise non-constant global arrays at the beginning of main function. As for constant global arrays, we do not initialize them in the current version.

4.3.1 Stack objects

To replace an original stack object with a header-padded one, for each alloca instruction, we insert a new {HeaderT, r} -typed AllocaInst, where r is the type of an original object. FRAMER replaces all the uses of the original alloca with a pointer to the second field in GetElementPtrInst deletes the original one, and then passes the new pointer to a hook function. The hook for alloca generates a tag value, updates bounds information in metadata storage, and then returns a tagged pointer. Since LLVM pulls alloca for non-dynamic arrays to the entry basic block of each function, these operations are inserted to the entry basic block.

We instrument function epilogues to reset entries for big-framed non-static objects. Call to this function epilogue is added right before Return or Unreachable instructions of basic blocks, that are not always the last basic block of each function. It resets only a corresponding entry of big-framed stack objects. The scope of dynamic arrays can be tracked by LLVM’s intrinsic functions, 11vm.stackrestore and 11vm.stacksave, however, we do not handle, currently, variable-lengthy arrays.

4.4 Compiler Optimisations

4.4.1 Non-array objects

We do not track non-array objects that are not involved with pointer arithmetic, e.g., int-typed objects. It is redundant to perform bounds checking or un-tagging for pointers to them. We filter off simple cases, easily recognised, from being checked. In the general case, it is not trivial to determine if a pointer is untagged, i.e., a corresponding object is being tracked or not, at compile time, since back-tracing the assignment for the pointer requires whole-program static analysis.

4.4.2 Safe pointer arithmetic

We just strip off a tag instead of bounds check for pointers involved with pointer arithmetic and proven in-bound at static time. For pointers shown in the following example, we insert runtime checks only comparing its index to the count of array elements to avoid metadata retrieval and increase in dynamic instruction counts.

```c
int a[10];
... *(a+n)...
assert(n < 10);
```

In some SPEC benchmarks, there are some memory accesses out-of-bounds at static time, but we do not report memory errors since it may be unreachable. We insert a termination instruction for this case so that it can reported.
We measured the performance of Framer on C benchmarks that are inside loops to minimise code size. Inlining functions can improve performance, however it can bring more performance degradation due to the bigger size of the code (runtime checks are called basically at every iteration). We modified SAFECODE’s loop optimisation passes. We apply hoisting checks to monotonic loops, and pull loop invariants that do not change throughout the loop, and scalars to the pre-header of each monotonic loop. This pass works on each loop, and if there are inner loops, it handles them first. While iterating bounds checks inside each loop, we determine if the pointer is hoistable. If hoistable, we place a scalar evolution expression along with its runtime checks outside the loop, and delete the old checks inside loop.

### 4.4.3 Hoist Checks outside loops

Loop-invariant expressions can be hoisted out of loops, thus improving run-time performance by executing the expression only once rather than at each iteration. We modified SAFECODE’s loop optimisation passes. We apply hoisting checks to monotonic loops, and pull loop invariants that do not change throughout the loop, and scalars to the pre-header of each monotonic loop. This pass works on each loop, and if there are inner loops, it handles them first. While iterating bounds checks inside each loop, we determine if the pointer is hoistable. If hoistable, we place a scalar evolution expression along with its runtime checks outside the loop, and delete the old checks inside loop.

### 4.4.4 Inlining function calls in the loop

Inlining functions can improve performance, however it can bring more performance degradation due to the bigger size of the code (runtime checks are called basically at every memory access). Currently, we only inline bounds checks that are inside loops to minimise code size.

### 4.5 Interoperability

FRAMER ensures compatibility between instrumented modules and regular pointer representation in pre-compiled non-instrumented libraries. We strip off tagged pointers before passing them to non instrumented functions. External functions can be easily recognised, since FRAMER is implemented as an LTO pass having full control of the instrumented code.

FRAMER adds a header to objects for tracking, but this does not introduce incompatibility, since it does not change the internal memory layout of objects or pointers.

Function parameters with certain attributes such as Sret are untagged, even if the callee is an instrumented one, since Load and Store to the structure may be assumed by the callee for this pointer parameter.

A remaining limitation involves tagged pointers stored in data structures that are accessed and used by non-instrumented libraries. On architectures that do not ignore unused high-order bits of tagged pointers, this has to be addressed by the programmer using explicit operations in the source code.

### 5 Evaluation

We measured the performance of Framer on C benchmarks from the full set of Olden, Ptdist, and a subset of SPEC CPU 2006 (certain C++ tests are currently not supported). For each benchmark we measured three binary versions: un-instrumented, only store-checked and full (both load and store checking enabled). Binaries were compiled with the regular LLVM-c1ang version 4.0 using optimisation level -02. Measurements were taken on Intel(R) Xeon(R) CPU E5-2687W v3 with 132 GB RAM. Results were gathered using perf. Table 2 summarises the average of metrics of the baseline and the two instrumented tests.

**Memory overhead:** Our metadata header was a generous 64 bytes per object. The big-frame array had 48 elements for each (216-frame) in use where the element size was 8 bytes. The header size and the number of elements of each sub-array can be reduced, but this is our early implementation. Currently all the header objects were aligned by 16 for compatibility with the llvm.memset intrinsic function that sometimes assumes this alignment. Despite inflation of space using larger than needed headers and slot array entries and some changes of alignment, we see Framer’s space overheads are very low at 1.22 and 1.23. The latter figure reflects the code inflation for instrumenting as well as loads, but the amount of data was stored was the same.

The memory overheads of Framer is low and stable compared to other approaches [2, 19, 24] The average memory overhead is 22% for both store-only and full checking, and except two tests, perlbench.1 and yacr2, the average overhead is not greater than 50%.

**Performance Loss:** Performance was impacted far less than would be expected from the additional dynamic instruction count (metric columns 2 and 3). The rise in IPC (column 4) is quite considerable on average, although the figure varies greatly by benchmark. The original IPC ranged from 0.23 to 3.20 but after instrumentation there was half as much variation. Figure 5 shows the slowdown per benchmark (relative number of additional cycles). The average is 60% for store-only and 212% for full checking.

**Data cache misses:** A primary goal of Framer is to allow flexible relationships between object and header locality so that additional cache misses from metadata access can be minimised. We do not analyse L1 instruction cache miss rate since this generally has negligible performance effect on modern processors, despite our slightly inflated code. To explain the measured increase in IPC we analyse L1 D-cache misses and branch prediction misses. The baseline D-cache miss rate was 0.8% (Table 2) but this improves with Framer enabled owing to repeated access to the same cache data.

In Figure 7, we normalise cache misses to the uninstrumented figure. The average normalised L1 D-cache misses (MPKI) is 0.76 and 0.53 for store-only and full-checking, respectively. The miss rate is reduced since the additional operations we add have high cache affinity which dilutes the underlying miss rate of the application. Moreover, L1 D-cache misses after instrumentation do not increase in proportion to increase in the number of dynamic instruction. The overall cache miss rate is low and stable compared to other methodologies [18, 24], especially ones using disjoint metadata.

**Instructions executed:** Framer increases dynamic instruction count by 166% for store-only, and 419% for full
checking. Along with additional data access for metadata manipulation, this increase in instructions executed is the main contributor to runtime overhead. Our dynamic instruction penalty arises from setting up and using tagged pointers. Certain operations are easily verified at compile time. If all checking could be performed statically there would be no runtime overhead. But Framer inserts tags on all pointers and use sites that are readily checkable at compile time still suffer run-time overhead from pointer stripping operations since all major architectures require the top bits to be zero (or special pointer authentication code in ARM8) to avoid a segmentation fault. In addition, we sometimes have to dynamically strip the tag field even for untagged pointers, i.e. pointers to objects not tracked for bounds checking, when it is uncertain if the pointer is tagged or not. This is because it is very difficult to find the value (definition) for a variable at the level of intermediate representation. Future implementations can optimise the case where conservative analysis reveals the tag never needs to be added.

**Branch misses:** Additional conditional branches arise in Framer from checking whether a big or small frame is used and in the pointer validity checks themselves.

As shown in Table 2 col 7, the dynamic branch density decreases slightly under Framer instrumentation, but the

### Table 2. Summary averages over all benchmarks (first three columns normalised)

|                  | Memory footprint | Runtime (cycles) | Dynamic instructions | IPC  | Load density | D-cache MPKI | Branch density | B-cache MPKI |
|------------------|------------------|------------------|----------------------|------|--------------|---------------|----------------|--------------|
| Baseline         | 1.00             | 1.00             | 1.00                 | 1.68 | 0.28         | 7.92          | 0.19           | 1.68         |
| Store-only       | 1.22             | 1.60             | 2.66                 | 2.17 | 0.20         | 6.04          | 0.15           | 0.93         |
| Full check       | 1.23             | 3.12             | 5.19                 | 2.54 | 0.14         | 4.16          | 0.17           | 0.48         |

**Figure 5.** Normalized runtime overheads

**Figure 6.** Normalised dynamic instruction count
branch mis-prediction rate greatly decreases (col8). The averages of normalised branch misses for store-only and full-checking are 0.53 and 0.28, respectively. This shows the additional branches added achieve highly accurate branch prediction and that branch predictors are not being overloaded.

Of the new branches added, the ones checking small/large frame size are completely statically predictable owing to the checking code instances being associated with a given object. And the ones checking pointer validity also predict perfectly since no out-of-bounds errors are detected.

| Baseline | Store-only | Full check |
|----------|------------|------------|
| num | rate | num | rate | num | rate |
| bh | 1.1 | 2.62 | 0.9 | 3.88 | 1.2 | 2.98 |
| bisort | 0.3 | 9.22 | 0.6 | 5.71 | 1.0 | 3.28 |
| em3d | 3.9 | 0.42 | 3.9 | 0.57 | 9.2 | 0.27 |
| health | 0.2 | 8.55 | 0.3 | 6.55 | 0.3 | 5.99 |
| mst | 0.0 | 11.71 | 0.1 | 11.05 | 0.1 | 5.61 |
| perimeter | 0.2 | 2.37 | 0.3 | 2.28 | 0.3 | 1.89 |
| power | 0.2 | 0.74 | 0.2 | 0.74 | 0.2 | 0.73 |
| threadadd | 0.2 | 2.03 | 0.5 | 1.47 | 0.5 | 1.48 |
| tsp | 0.6 | 3.00 | 0.7 | 3.78 | 1.1 | 2.06 |
| voronoi | 1.1 | 5.14 | 1.2 | 5.42 | 1.2 | 4.88 |

| anagram | 1.9 | 0.28 | 3.6 | 0.18 | 6.3 | 0.16 |
| bc | 0.6 | 0.74 | 1.0 | 0.63 | 1.1 | 0.59 |
| ft | 0.3 | 69.72 | 0.3 | 55.20 | 0.5 | 35.98 |
| ks | 1.7 | 0.32 | 2.0 | 0.36 | 3.4 | 0.27 |
| yacr2 | 0.8 | 0.32 | 1.0 | 0.31 | 2.0 | 0.15 |

| peribench.1 | 6.5 | 2.78 | 9.6 | 2.24 | 12.9 | 1.90 |
| peribench.2 | 3.5 | 8.12 | 5.0 | 6.55 | 6.9 | 5.13 |
| peribench.3 | 16.6 | 0.88 | 21.4 | 0.85 | 31.6 | 0.74 |
| perlbench.4 | 0.5 | 1.43 | 0.9 | 1.24 | 1.1 | 1.17 |
| bzip2.1 | 6.4 | 2.59 | 12.2 | 1.41 | 23.0 | 0.75 |
| bzip2.2 | 6.8 | 2.83 | 12.4 | 1.57 | 24.3 | 0.82 |
| bzip2.3 | 47.6 | 4.17 | 88.8 | 2.17 | 170.5 | 1.12 |
| gcc | 0.7 | 7.40 | 0.9 | 6.53 | 1.0 | 4.89 |
| mcf | 6.1 | 47.02 | 12.5 | 23.50 | 30.2 | 9.91 |
| hmmer | 109.5 | 1.14 | 133.9 | 0.96 | 142.3 | 0.94 |
| sjeng | 103.6 | 1.06 | 183.8 | 0.80 | 223.1 | 0.90 |
| libquantum | 1.2 | 23.58 | 1.3 | 21.92 | 1.4 | 21.04 |
| h264ref | 133.1 | 1.51 | 155.2 | 1.36 | 242.6 | 0.91 |

Table 3. L1 D-Cache Counts and Miss Rates in Mega Scale: num and rate yield the total count of L1 D-cache loads and L1 D-cache miss rate, respectively.

| Base | Store-only | Full check |
|------|------------|------------|
| num | rate | num | rate | num | rate |
| bh | 0.2 | 4.35 | 0.5 | 1.88 | 1.6 | 0.66 |
| bisort | 0.2 | 2.61 | 0.5 | 1.31 | 1.4 | 0.66 |
| em3d | 7.1 | 0.11 | 7.2 | 0.12 | 23.9 | 0.04 |
| health | 0.1 | 2.48 | 0.2 | 1.55 | 0.5 | 0.85 |
| mst | 0.0 | 0.12 | 0.0 | 0.13 | 0.1 | 0.03 |
| perimeter | 0.2 | 1.14 | 0.2 | 0.91 | 0.5 | 1.09 |
| power | 0.1 | 0.36 | 0.1 | 0.34 | 0.2 | 0.30 |
| threadadd | 0.2 | 0.11 | 0.3 | 0.24 | 0.4 | 0.19 |
| tsp | 0.3 | 1.26 | 0.4 | 0.94 | 2.5 | 0.15 |
| voronoi | 0.5 | 1.32 | 0.6 | 1.17 | 0.9 | 0.82 |

| anagram | 1.1 | 2.35 | 1.3 | 1.77 | 7.0 | 0.35 |
| bc | 0.5 | 0.93 | 0.9 | 0.85 | 1.4 | 0.70 |
| ft | 0.2 | 0.54 | 0.2 | 0.45 | 1.1 | 0.11 |
| ks | 1.4 | 0.79 | 1.4 | 0.67 | 8.8 | 0.29 |
| yacr2 | 1.4 | 0.94 | 1.6 | 0.91 | 4.8 | 0.53 |

| peribench.1 | 4.7 | 0.50 | 9.9 | 0.28 | 21.9 | 0.17 |
| peribench.2 | 2.4 | 1.71 | 4.6 | 0.97 | 12.4 | 0.70 |
| peribench.3 | 11.6 | 0.41 | 21.3 | 0.38 | 65.5 | 0.18 |
| peribench.4 | 0.3 | 0.92 | 0.8 | 0.53 | 1.6 | 0.33 |
| bzip2.1 | 3.1 | 4.47 | 11.2 | 1.19 | 28.0 | 0.49 |
| bzip2.2 | 3.6 | 2.33 | 16.0 | 0.55 | 36.9 | 0.25 |
| bzip2.3 | 21.3 | 5.78 | 65.9 | 1.81 | 179.2 | 0.67 |
| gcc | 0.7 | 1.78 | 0.8 | 1.58 | 1.2 | 1.37 |
| mcf | 3.8 | 3.95 | 10.2 | 1.52 | 33.1 | 0.45 |
| hmmer | 10.4 | 0.89 | 14.9 | 0.60 | 32.0 | 0.29 |
| sjeng | 84.1 | 3.30 | 123.1 | 2.44 | 245.9 | 1.22 |
| libquantum | 1.5 | 0.25 | 1.6 | 0.22 | 1.6 | 0.22 |
| h264ref | 36.4 | 1.24 | 61.9 | 0.73 | 370.5 | 0.26 |

Table 4. Branch Misses in Mega Scale

6 Discussion

Runtime checks only at pointer arithmetic We set alignment by 16 bytes at the moment because of llvm.memset intrinsic function. On this alignment, we have spare 4 bits at the end of offset for small-framed. (We already have spare bits for big-framed ones.) Using these bits, we then can perform bounds checking only at pointer arithmetic and

mark out-of-bounds pointers. At memory access, we just check the mark, and decide to halt the execution. This way, we expect to skip duplicated runtime checks at memory access, since on getelementptr instruction (or constant expression) is used as a pointer operand of store or load instruction multiple times.

Compiler Optimisation There are more optimisations we could use. Duplicate runtime checks can be eliminated using dominator tree. SoftBound [19] reported that their simple dominator-based redundant check elimination reduced the overall average runtime overhead from 80% to 67%, and claimed more advanced runtime checks elimination [4, 29] can reduce more overheads.

Static points-to analysis potentially enables many tags and bounds checks to be removed at compile time. A commonly-used approach is to ignore all causality and control flow restrictions and to place pointers in equivalence classes that are conglomerated at all code sites where pointers are multiplexed [26]. Multiplexing may be a conditional store or a look-up in a table of pointers. Two approaches are to
start with high-level source code or to start with machine code. Either way, whole-program dataflow analysis is ideally required to fully track pointer provenance. But legacy C and C++ code and associated programming styles make anything other than a highly-conservative and localised analysis infeasible. We speculate that code that originates from languages that had stronger type systems and programming disciplines may possibly greatly benefit from such pointer
analysis, but the gain across our benchmark suite may be small.

7 Related Work

Several approaches have been proposed for tracking memory and detecting memory-related errors. We review here systems that either track objects or pointers. Space considerations prevent us from surveying the large body of work in software hardening that is not based on tracking memory.

Object-based Tracking An object-based approach tracks bounds information per object. Associating bounds information with any object, without changing the memory layout of objects, offers compatibility with current source and pre-compiled legacy libraries. The biggest disadvantage is that it cannot detect memory-access violations when pointers exceed the bounds of intended referent [13] by pointer arithmetic, and pointing to another object. Hence, object-based approaches should take a special care for out-of-bound pointers by marking the pointers during pointer arithmetic, and sending errors when dereferenced [2]. Similarly, uninitialised pointers may point to random objects, so it is vital that all pointers are initialised. Taking care of all these introduces significant overheads.

The second disadvantage is that those approaches require range lookup of objects, which is more expensive than lookup of keys, or different representations. An early approach used a splay tree to reduce the overhead [13]. In general, it is difficult to track sub-objects such as an array in a structure [2].

Pointer-based tracking Pointer-based approaches associate bounds information with pointers and are often implemented as a fat pointer [12, 21]. Since fat pointers change the pointer representation, they require modification of the memory layout and this damages compatibility with non instrumented code.

One way to bypass this compatibility limitation is by separating bounds information from pointers. [2, 7, 13, 18] There have been several mechanisms to implement a separate data structure for metadata, and a shadow space [5, 22]. Some systems create a mirror copy of the data structure that stores metadata [21, 30]. Softbound [19] uses both a hash table and shadow space, and shows that the use of shadow space reduces runtime overhead, on average, by 2/3 than using table lookup [17]. The use of shadow space allows to manipulate metadata with just a single memory access, and reduces instruction counts for metadata access.

Shadow space can be also used for object-based approaches. AddressSanitizer [24] works in a similar way, but implements an object database. Every location in a memory maps to a corresponding entry in shadow space indicating whether the location is marked valid.

Implementation in hardware for bounds checking has been proposed to overcome runtime overheads and limitations of software-based approaches. [7, 16] checks every memory access using additional hardware instructions. Intel MPX [17] provides a hardware-accelerated pointer-based checking instrumented by the compiler. This mechanism uses ISA extension instructions for managing metadata and checking bounds leading to relatively concise code. Two new registers store bounds information. MPX supports an incremental deployment using the register, that keeps a copy value of pointers. In principle, FRAMER could utilize MPX for a faster instrumentation when used for spatial safety. The MPX approach is slow for pointer-intensive programs since it has a small number of special-purpose bounds registers (4) that is soon exceeded, requiring spill operations from regions of memory that themselves require management and consume D-cache bandwidth and capacity. We showed FRAMER is cache friendly, but it could be made even faster if a single instruction implemented the complete tag decode operation, splitting apart the tagged pointer into an untagged object pointer and separate header pointer in another register. This would be a fairly simple, register-to-register instruction, operating on general purpose registers. Since this has not used the D-cache, an enhancement would be to compare the the pointer against a bounds limit at hard-coded offset loaded from the header, but the best design requires further study.

8 Conclusion

We designed, implemented and evaluated FRAMER, a software-capability model with object-granularity memory protection for unsafe programs. Using FRAMER, a wide variety of security-focused applications can be constructed for detecting several types of memory errors. FRAMER supports a flexible association between headers of small-framed objects and the objects themselves, potentially supporting header sharing and different sized headers. For big-framed objects, which occur far less frequently, we revert to a shadow memory approach, which can be compact but will have less affinity in the D-cache, TLB and page table, but where a wide variety of encodings can meet any application requirement without impacting performance. In this paper, we used FRAMER to efficiently track the bounds of objects in C programs and apply spatial memory safety.

References

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A Proof 1

We prove that for each $N$, there exists at most one $N$-object mapped to each entry of a division array, and show $N$ identifies an object mapped to the same division array. To prove this, we assume there exist two distinctive objects, $x$ and $y$; both are $N$-objects ($N \geq 16$) mapped to the same division array. Since $x$ and $y$ are $N$-objects, their wrapper frame ($f_x$ and $f_y$) is $2^N$-sized by definition. The division is the only one that $f_x$ and $f_y$ are mapped to as shown previously, so $f_x$ and $f_y$ have the same base address as the division. In addition, both frames have the same size, so they are identical. Both base addresses of $x$ and $y$ ($b_x, b_y$) must be in the lower ($N-1$)-subframe of $f_x$ (or $f_y$), and end addresses must...
be in the other sub-frame. From this, \( b_x \) and \( b_y \) must be smaller than \( e_x \) and \( e_y \). However, the objects are distinct, so \( b_x < e_x < b_y < e_y \) or vice versa must hold. The assumption leads to a contraction. We conclude that for each \( N \), there is a unique \( N \)-object mapped to one division array.

**B Proof 2**

Given an object \( o \) and its wrapper frame \( f \), let’s assume there exists a smaller frame \( x \) that has \( o \) inside. Since \( o \) resides in both \( f \) and \( x \), we can conclude that \( x \) is a subframe of \( f \). According to the assumption, the base address of \( o \) (\( base_o \)) is within the range of \( x \), hence, we get \( base_x \leq base_o \).

Here, \( f \) is \( o \)’s wrapper frame, so \( base_o \) is placed in \( f \)’s lower subframe. \( x \) is a subframe of \( f \), hence \( x \) must be \( f \)’s lower subframe. This is resolved to contradiction between the assumption (\( x \) has \( o \) inside) and the definition of wrapper function (\( o \)’s end address in the upper subframe). Hence, we can conclude that there is no smaller frame than \( o \)’s wrapper frame; this is actually the unique wrapper frame, and it can be used a reference point.