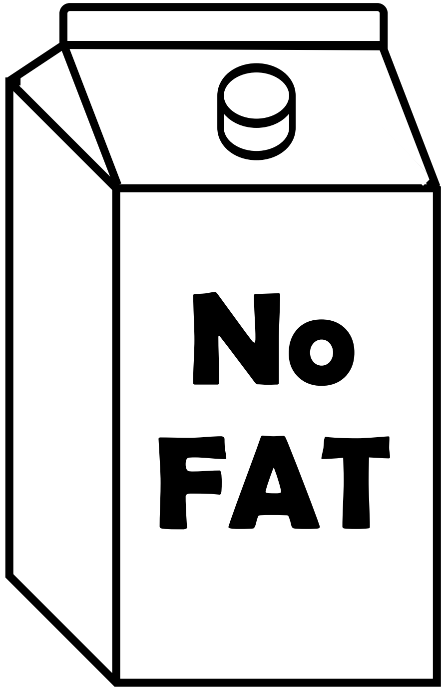

Architectural Support for Low Overhead Memory Safety Checks

Mohamed Tarek Ibn Ziad, Miguel Arroyo, Evgeny Manzhosov,
Ryan Piersma and Simha Sethumadhavan

COLUMBIA | ENGINEERING
The Fu Foundation School of Engineering and Applied Science

06/16/2021

Memory Safety is a serious problem!

Computing Sep 6

Apple says China's Uighur Muslims were targeted in the recent iPhone hacking campaign

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EDITOR'S PICK | 42,742 views | Nov 21, 2018, 07:00am

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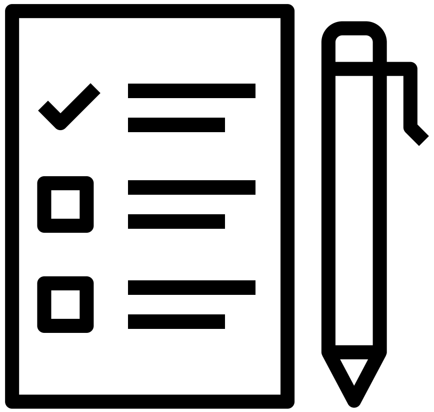

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Akshaya Asokan (asokan_akshaya) • January 28, 2021

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Chrome: 70% of all security bugs are memory safety issues

Google software engineers are looking into ways of eliminating memory management-related bugs from Chrome.

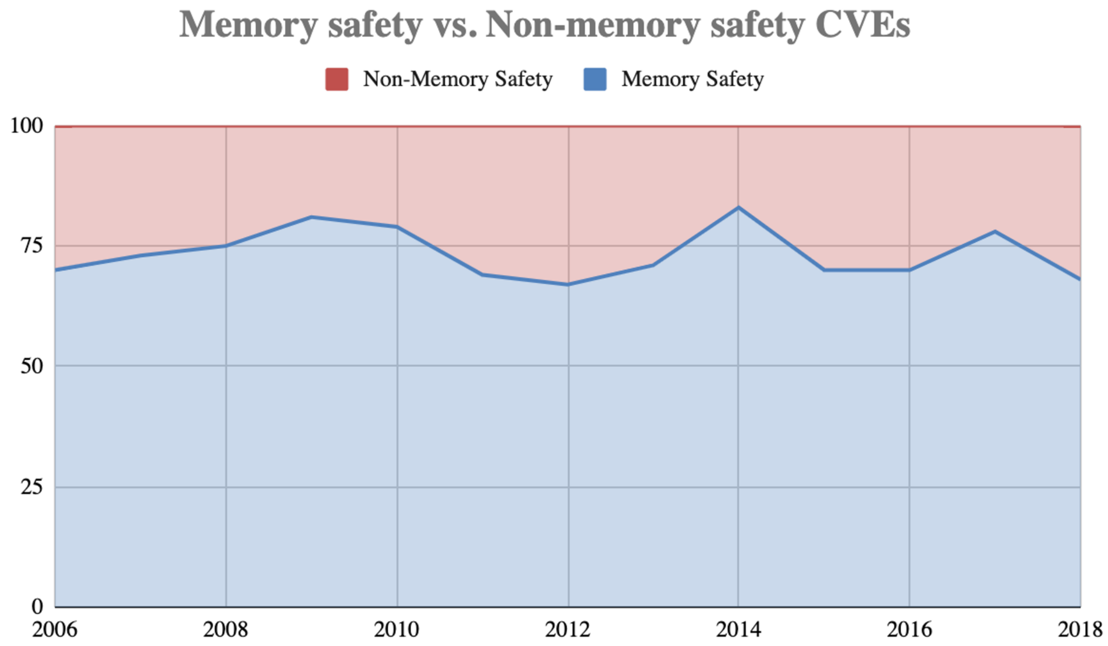
It’s easy to make mistakes

It’s easy to make mistakes

SEGFAULT!


TEEN COMIX
BRANSON '15
NO FEAR
WHAT ABOUT MEMORY SAFETY VULNERABILITIES?
ONE FEAR

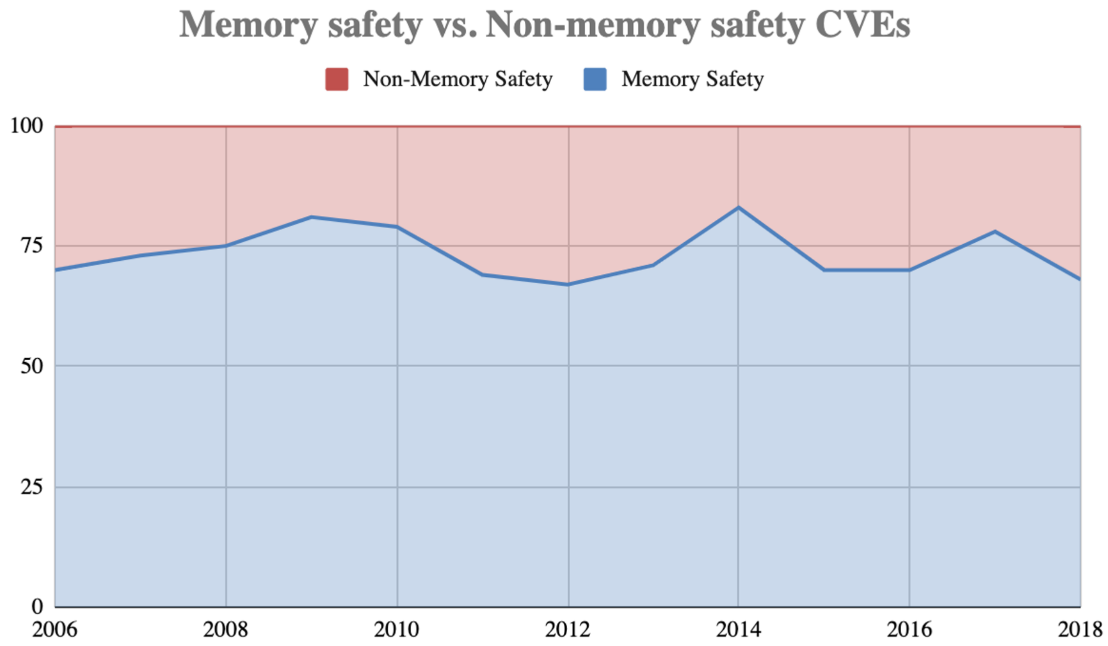
Prevalence of Memory Safety Vulns



Microsoft Product CVEs

Source: *Matt Miller, Microsoft Security Response Center (MSRC) - BlueHat 2019*

Prevalence of Memory Safety Vulns



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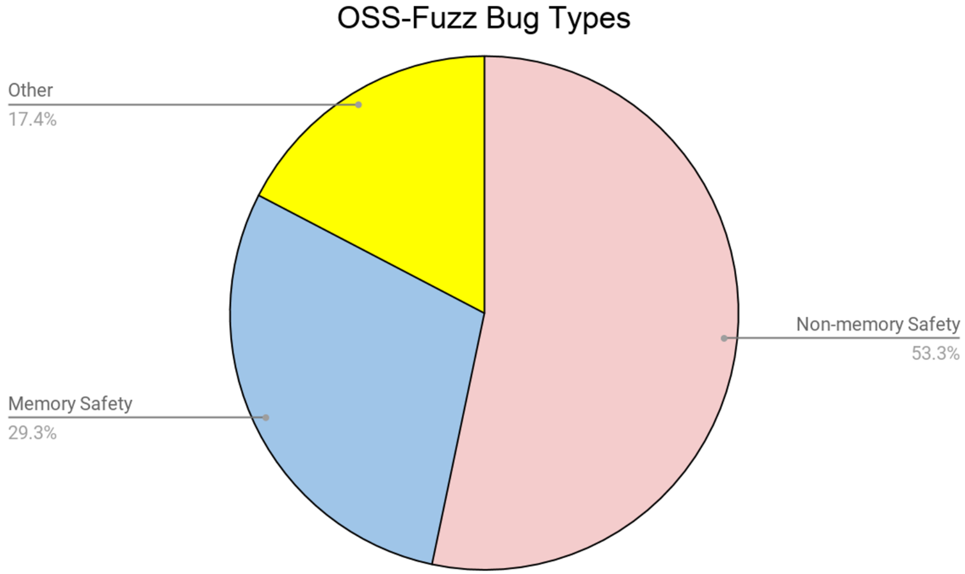


Google OSS-Fuzz bugs from 2016-2018.

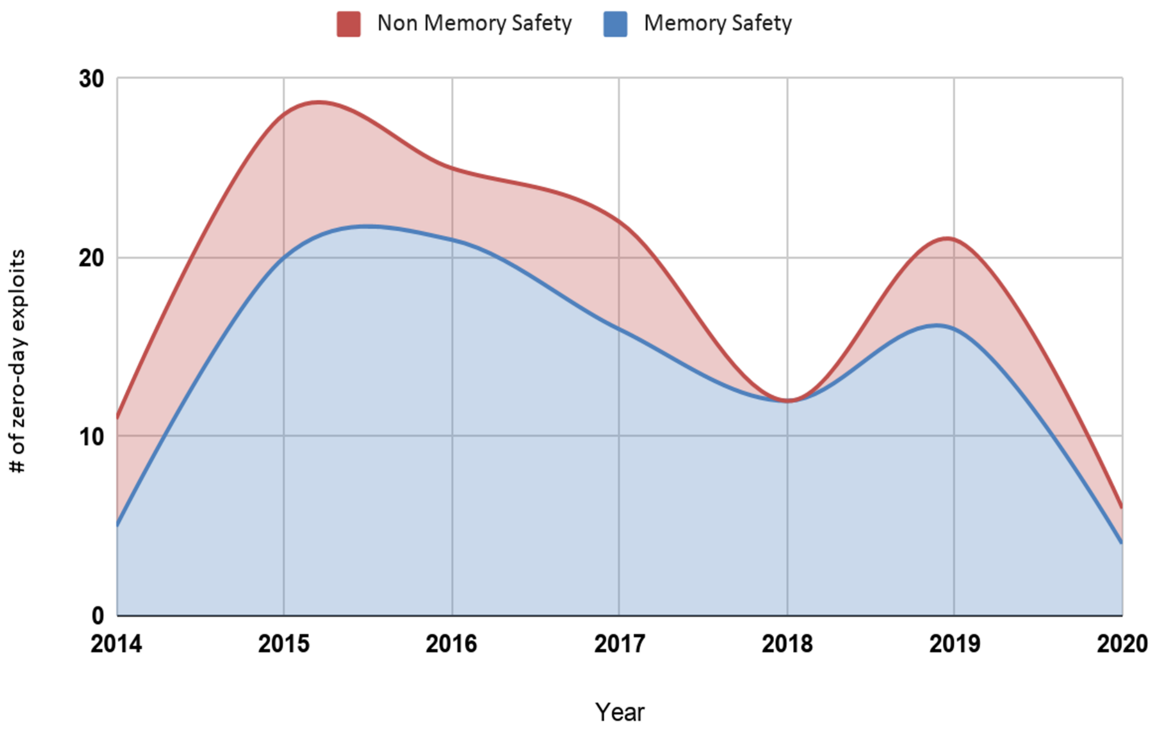
Source: *Matt Miller, Microsoft Security Response Center (MSRC) - BlueHat 2019*

Source: *https://security.googleblog.com/2018/11/a-new-chapter-for-oss-fuzz.html*

ATTACKERS

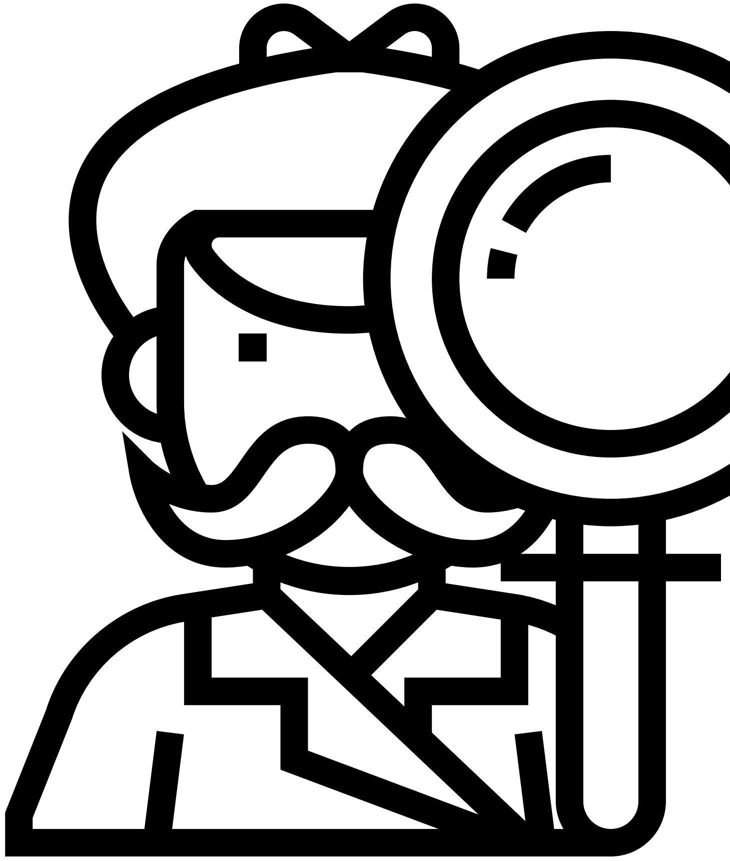
MEMORY SAFETY

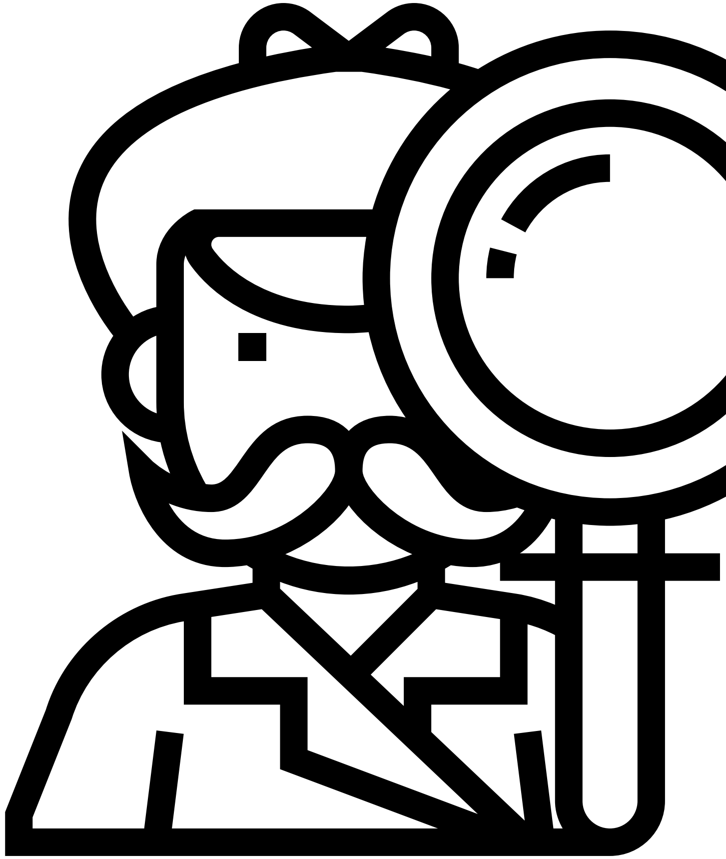
Attackers prefer Memory Safety Vulns



Zero-day "in the wild" exploits
from 2014-2020

Source: *Google Project Zero, 0day "In the Wild" spreadsheet. Last updated: April 2020*





Modern software design is useful for security

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Increasing adoption of binning allocators

- Maintains memory locality.
- Implicit lookup of allocation information.

Modern software design is useful for security

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- Maintains memory locality.
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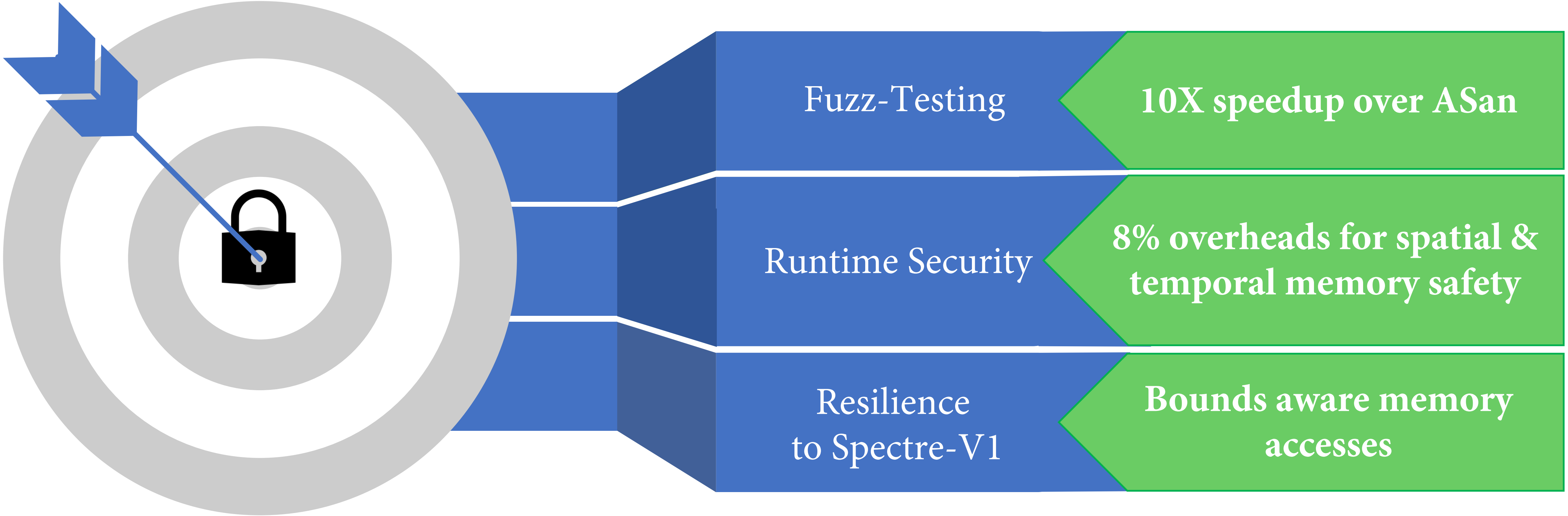
FreeBSD

mi-malloc

tcMalloc

The benefits of No-FAT

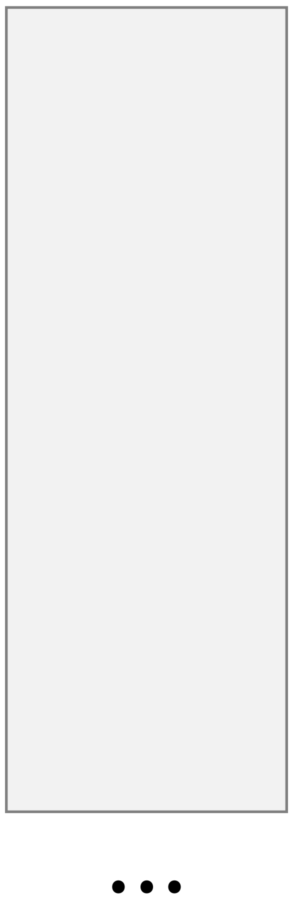


Binning Memory Allocators

101

Binning Memory Allocators

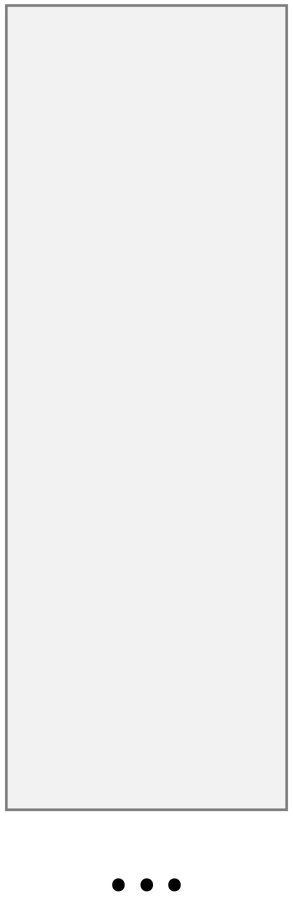
```
int main() {
  char* ptr = malloc(12);
  …
}
```



Virtual Memory

Binning Memory Allocators

```c
int main() {
    char* ptr = malloc(12);
    …
}
```

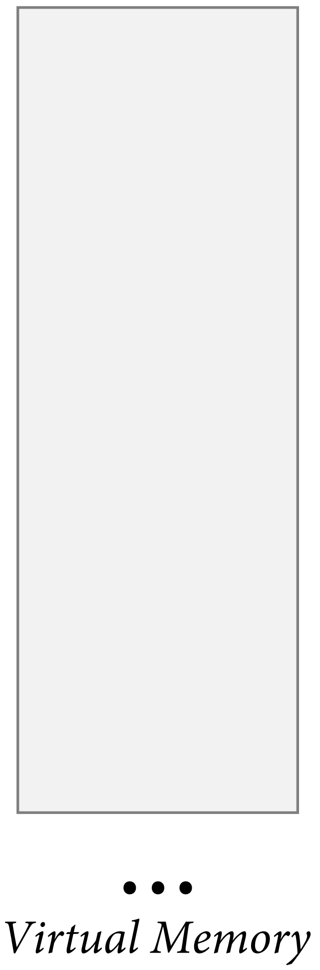


Virtual Memory

Binning Memory Allocators

```
int main() {
    char* ptr = malloc(12);
    …
}
```

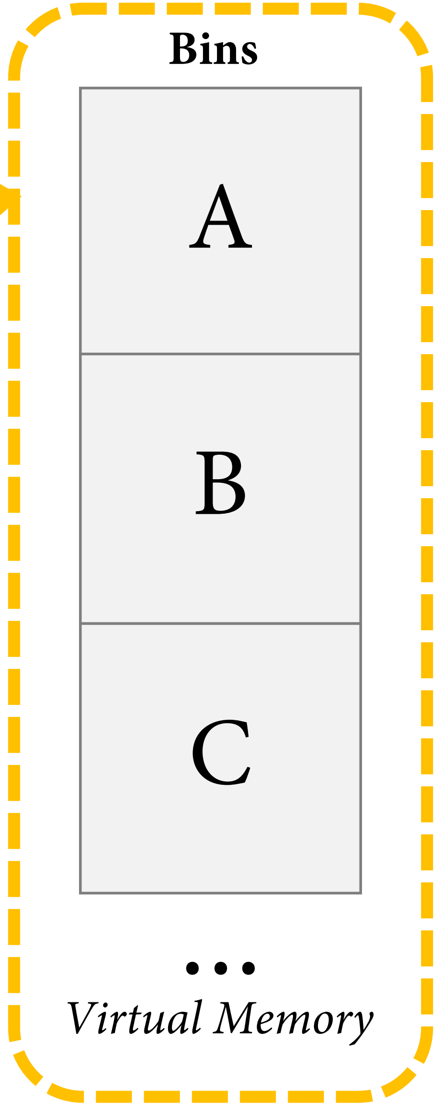
Memory is requested by the allocator.



Binning Memory Allocators

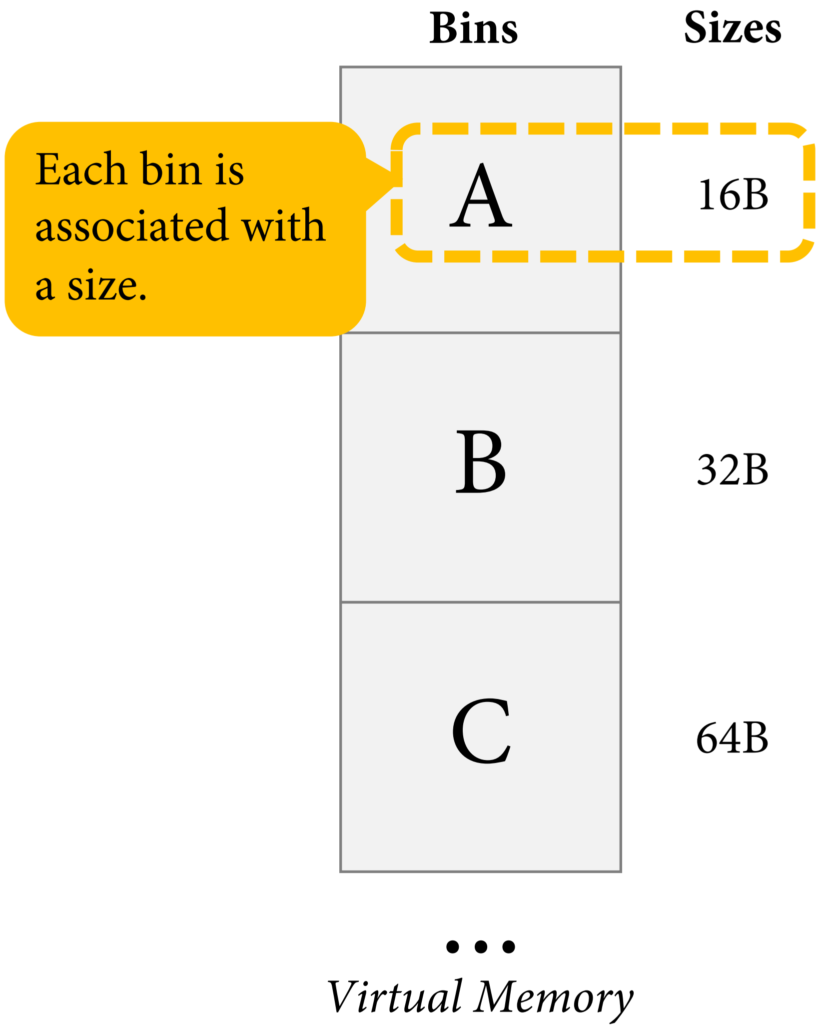
```
int main() {
  char* ptr = malloc(12);
  …
}
```

Memory is divided into bins.



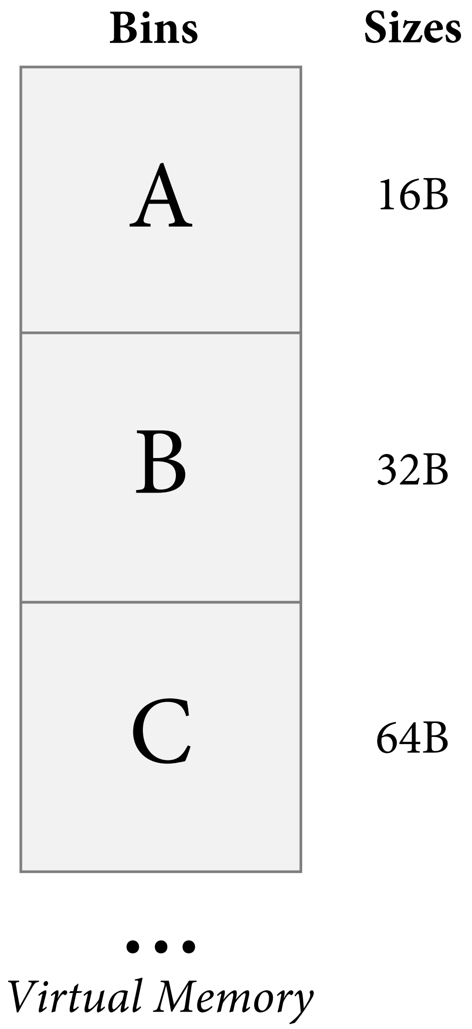
Binning Memory Allocators

```c
int main() {
   char* ptr = malloc(12);
   …
}
```



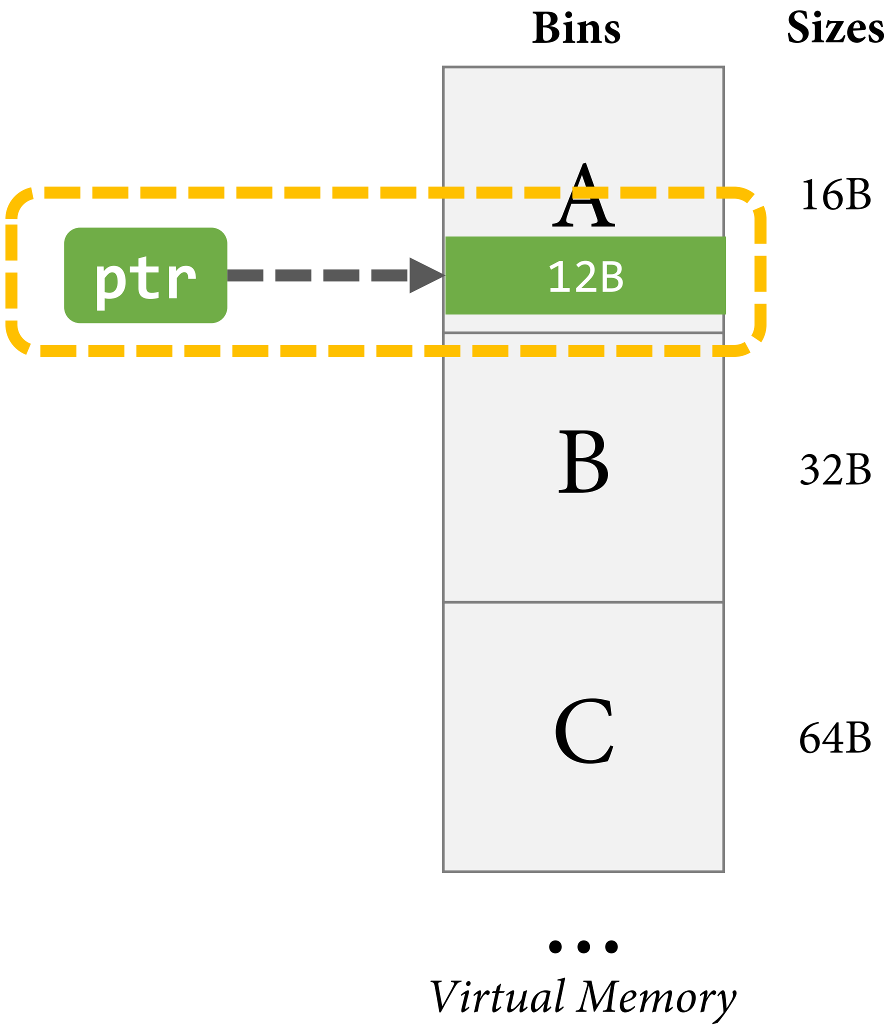
Binning Memory Allocators

```
int main() {
   char* ptr = 12B
   …
}
```



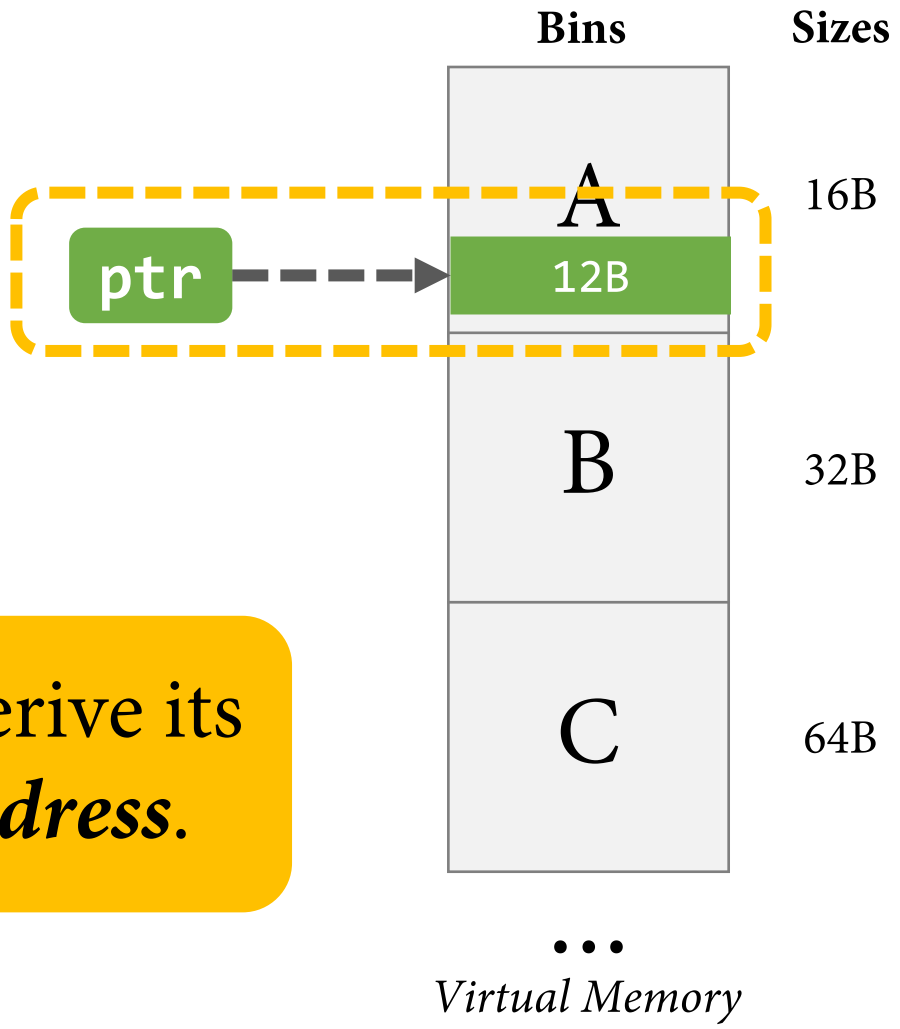
Binning Memory Allocators

```
int main() {
  char* ptr = malloc(12);
  …
}
```

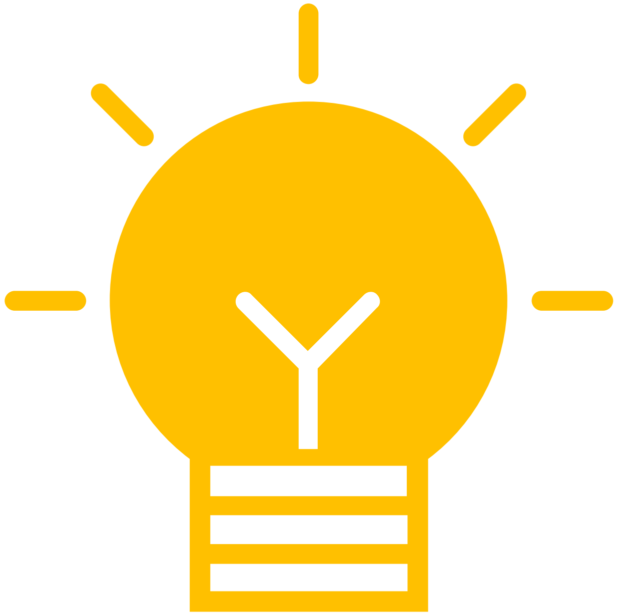


Binning Memory Allocators

```
40.  int main() {
41.    char* ptr = malloc(12);
42.    …
50.  }
```



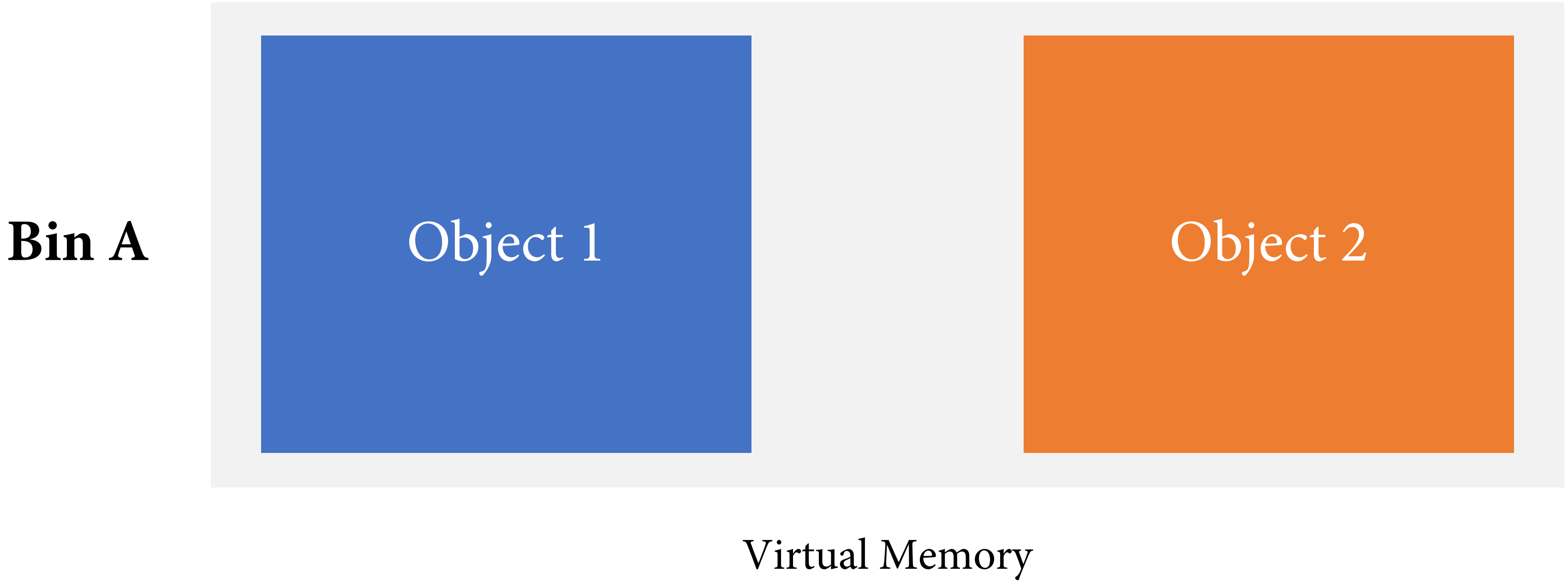
Given **any** pointer, we can derive its ***allocation size*** and ***base address***.



From Bins to Security

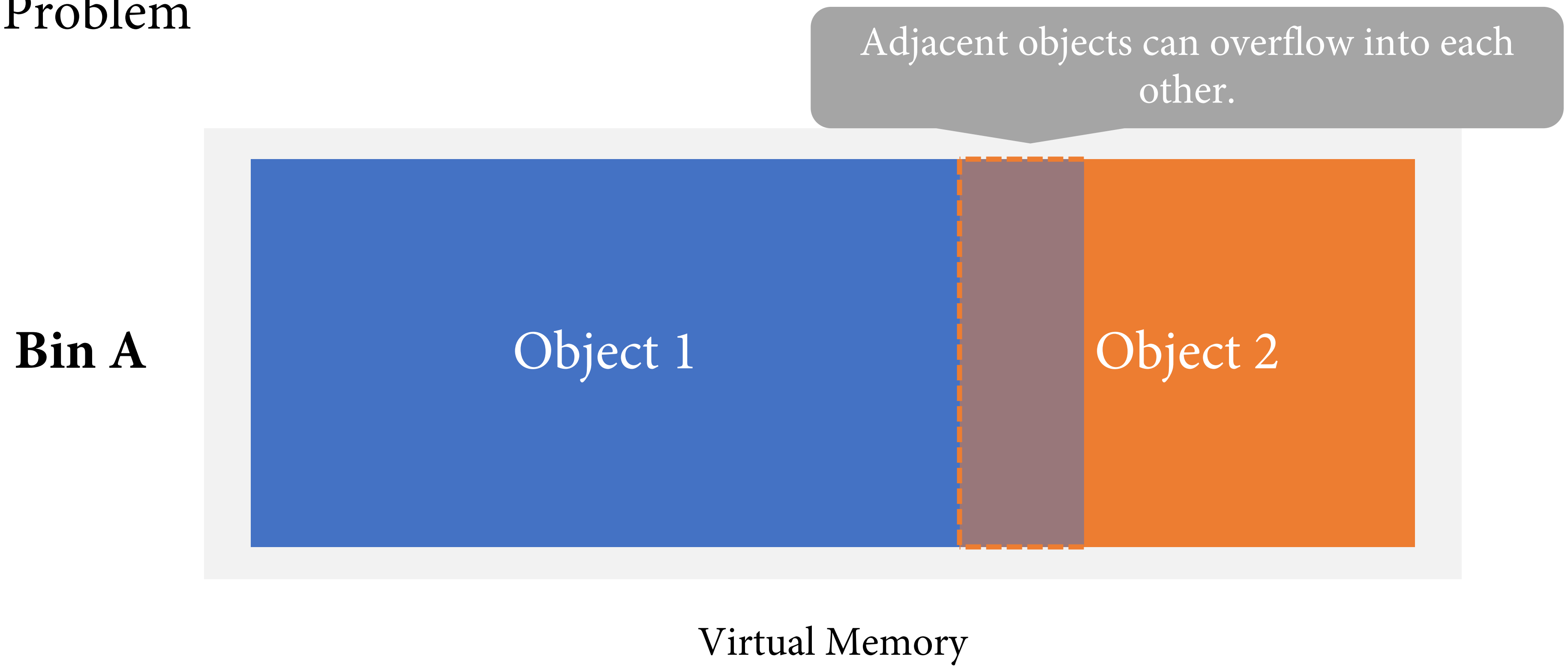
Spatial Memory Safety (Inter-Object)

The Problem



Spatial Memory Safety (Inter-Object)

The Problem



Spatial Memory Safety (Inter-Object)

```
int main() {
  char* ptr = malloc(12);
  ptr[1] = ‘A’;
  …
}
```

Spatial Memory Safety (Inter-Object)

```
int main() {
  char* ptr = malloc(12);
  ptr[1] = ‘A’;   ➡   store ptr[1],‘A’
  …
}
```

Spatial Memory Safety (Inter-Object)

```
int main() {
  char* ptr = malloc(12);
  ptr[1] = ‘A’;
  …
}
```

→

```
s_store ptr[1],‘A’, ptr_trusted_base
```

We add **one extra** operand for loads/stores.

Spatial Memory Safety (Inter-Object)

```
int main() {
  char* ptr = malloc(12);
  ptr[1] = ‘A’;
  …
}
```

$ptr_{trusted\_base}$

s_store ptr[1],‘A’,$ptr_{trusted\_base}$

Spatial Memory Safety (Inter-Object)

```
int main() {
  char* ptr = malloc(12);
  ptr[1] = ‘A’;
  …
}
```

s_store ptr[1], ‘A’ $\texttt{ptr}_{\texttt{trusted\_base}}$

The compiler **propagates** the allocation base address.

Spatial Memory Safety (Inter-Object)

```
int main() {
  char* ptr = malloc(12);
  ptr[1] = ‘A’;
  …
}
```

```
s_store ptr[1],‘A’,ptr_trusted_base
```

Spatial Memory Safety (Inter-Object)

```
s_store ptr[1],‘A’,ptr_trusted_base
```

Spatial Memory Safety (Inter-Object)

s_store ptr[1],'A',$ptr_{trusted\_base}$

↓ ↓

ptr[1] $ptr_{trusted\_base}$

Spatial Memory Safety (Inter-Object)

`s_store ptr[1],'A',ptr`$_{trusted\_base}$

`offset` = `ptr[1]` − `ptr`$_{trusted\_base}$

Spatial Memory Safety (Inter-Object)

`s_store ptr[1],'A',ptr`$_{trusted\_base}$

offset = ptr[1] − ptr$_{trusted_base}$

size = getSize(ptr$_{trusted_base}$)

Spatial Memory Safety (Inter-Object)

$s\_store\ ptr[1], 'A', ptr_{trusted\_base}$

$offset = ptr[1] - ptr_{trusted\_base}$

$size = getSize(ptr_{trusted\_base})$

Bounds Check

$offset < size$?

Spatial Memory Safety (Inter-Object)

The **allocation size** information is made **available** to the hardware to verify memory accesses.

`size` = `getSize(` $ptr_{trusted\_base}$ `)`

Bounds Check

`offset` < `size` ?

Spatial Memory Safety (Inter-Object)

```
int main() {
  char* ptr = malloc(12);
  ptr[1] = 'A';
  …
}
```

$ptr_{trusted\_base}$

s_store ptr[1],'A',$ptr_{trusted\_base}$

Spatial Memory Safety (Inter-Object)

```
int main() {
  char* ptr = malloc(12);
  ptr[1] = 'A';
  …
  foo(ptr);
}
```

$ptr_{trusted\_base}$

s_store ptr[1],'A',$ptr_{trusted\_base}$

Let's pass the pointer to another context (e.g., `foo`).

Spatial Memory Safety (Inter-Object)

```
int main() {
   char* ptr = malloc(12);
   ptr[1] = 'A';
   …
   foo(ptr);
}
void Foo (char* xptr){
    …
    xptr[7] = 'B';
    …
}
```

$ptr_{trusted\_base}$

s_store ptr[1],'A',$ptr_{trusted\_base}$

Spatial Memory Safety (Inter-Object)

```
int main() {
   char* ptr = malloc(12);
   ptr[1] = ‘A’;
   …
   foo(ptr);
}
void Foo (char* xptr){
    …
    xptr[7] = ‘B’;
    …
}
```

$ptr_{trusted\_base}$

s_store ptr[1],‘A’,$ptr_{trusted\_base}$

→ s_store xptr[7],‘A’,$xptr_{trusted\_base}$

Spatial Memory Safety (Inter-Object)

```
int main() {
    char* ptr = malloc(12);
    ptr[1] = 'A';
    …
    foo(ptr);
}
void Foo (char* xptr){
    …
    xptr[7] = 'B';
    …
}
```

$ptr_{trusted\_base}$

s_store ptr[1],'A',$ptr_{trusted\_base}$

s_store xptr[7],'A',$xptr_{trusted\_base}$

How do we get this?

Spatial Memory Safety (Inter-Object)

```
int main() {
  char* ptr = malloc(12);
  ptr[1] = ‘A’;
   …
   foo(ptr);
}
void Foo (char* xptr){
    …
    xptr[7] = ‘B’;
    …
}
```

$ptr_{trusted\_base}$

s_store ptr[1],‘A’,$ptr_{trusted\_base}$

$xptr_{trusted\_base}$ ← compBase(xptr[7])

s_store xptr[7],‘A’,$xptr_{trusted\_base}$

Spatial Memory Safety (Inter-Object)

```
xptr_trusted base ← compBase(xptr[7])
```

Spatial Memory Safety (Inter-Object)

$\texttt{xptr}_{\texttt{trusted base}} \leftarrow$ `compBase(xptr[7])`

`Bin` = `xptr` >> $\texttt{log}_2\texttt{(S)}$ where `S` is the size of the bins.

Spatial Memory Safety (Inter-Object)

`xptr`$_{\texttt{trusted base}}$ ← `compBase(xptr[7])`

`Bin` = `xptr` >> `log`$_2$`(S)` where S is the size of the bins.

`size` = `getSize( Bin )`

Spatial Memory Safety (Inter-Object)

$xptr_{trusted\_base} \leftarrow$ `compBase(xptr[7])`

$Bin = xptr >> \log_2(S)$ where S is the size of the bins.

$size = getSize(Bin)$

$xptr_{trusted\_base} = \lfloor xptr \times (1/size) \rfloor \times size$

Spatial Memory Safety (Inter-Object)

$xptr_{trusted\_base} \leftarrow$ `compBase(xptr[7])`

$Bin = xptr \gg \log_2(S)$ where S is the size of the bins.

$size = getSize(Bin)$

$xptr_{trusted\_base} = \lfloor xptr \times (1/size) \rfloor \times size$

Base pointer is **implicitly** derived!

Spatial Memory Safety (Inter-Object)

```
int main() {
  char* ptr = malloc(12);
  ptr[1] = ‘A’;
  …
  foo(ptr);
}
```

```
ptr_trusted_base
s_store ptr[1],‘A’,ptr_trusted_base
```

Spatial Memory Safety (Inter-Object)

```
int main() {
   char* ptr = malloc(12);
   ptr[1] = ‘A’;
   ptr = ptr + 100;
   …
   foo(ptr);
}
```

$ptr_{trusted\_base}$

s_store ptr[1],‘A’,$ptr_{trusted\_base}$

Pointer arithmetic can push the pointer out-of-bounds before calling `foo`!

Spatial Memory Safety (Inter-Object)

```
int main() {
  char* ptr = malloc(12);
  ptr[1] = 'A';
  ptr = ptr + 100;
  verifyBounds ptr,ptr_trusted_base
  …
  foo(ptr);
}
```

$ptr_{trusted\_base}$

s_store ptr[1],'A',$ptr_{trusted\_base}$

verifyBounds ptr,$ptr_{trusted\_base}$

Verify the bounds of all pointers that escape to memory (or another function).

Spatial Memory Safety (Intra-Object)

The Problem

Spatial Memory Safety (Intra-Object)

The Problem

```
typedef struct {
  char a;
  double b;
  char c[3];
  void (*fp)();
} A_t;
```

Adjacent fields can be overflowed into.

Spatial Memory Safety (Intra-Object)

```
typedef struct {
  char a;
  double b;
  char c[3];
  void (*fp)();
} A_t;
```

→

```
typedef struct {
  char a;
  double b;
  A_t_c *c_ptr;
  void (*fp)();
} A_t;
```

+

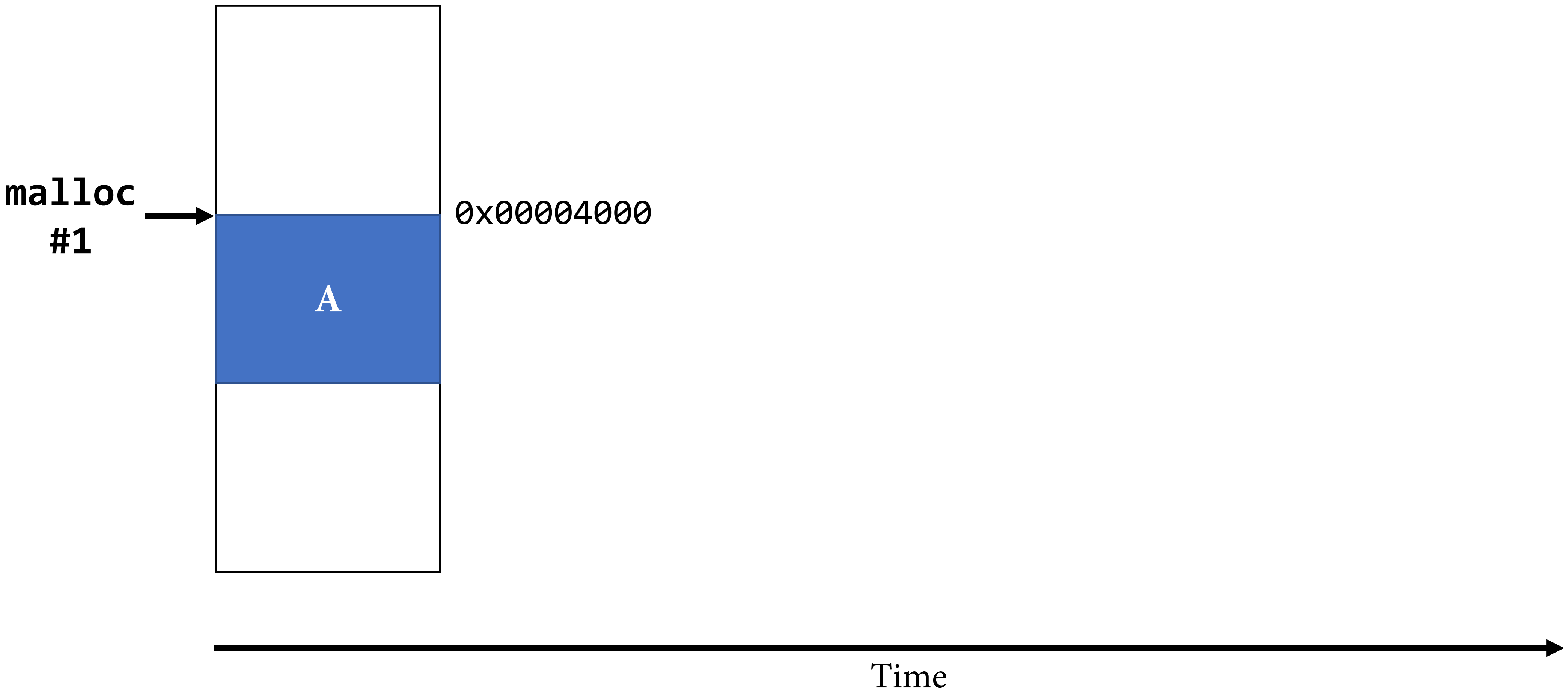
```
typedef struct {
  char c[3];
} A_t_c;
```

The **Buf2Ptr** transformation promotes intra-allocation buffers to standalone allocations.

Temporal Memory Safety

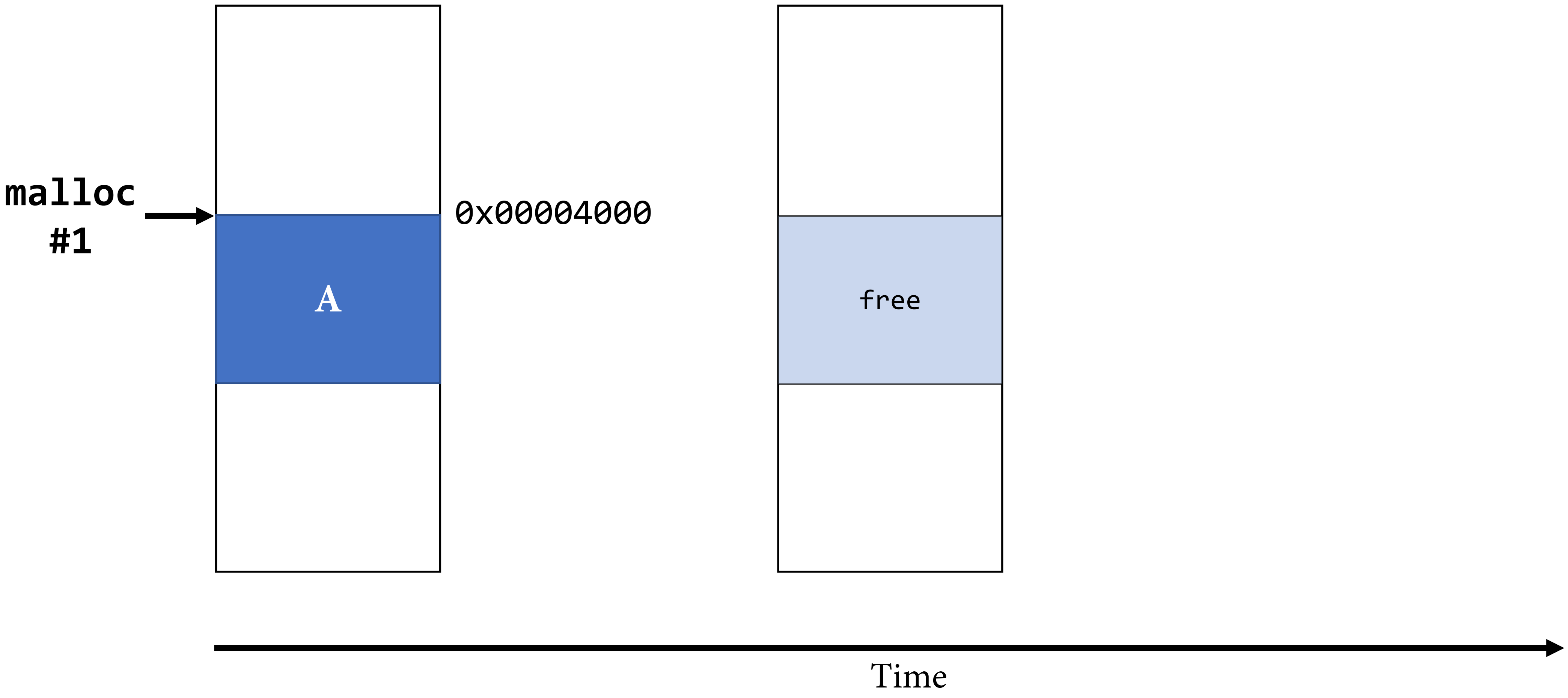
Temporal Memory Safety

The Problem



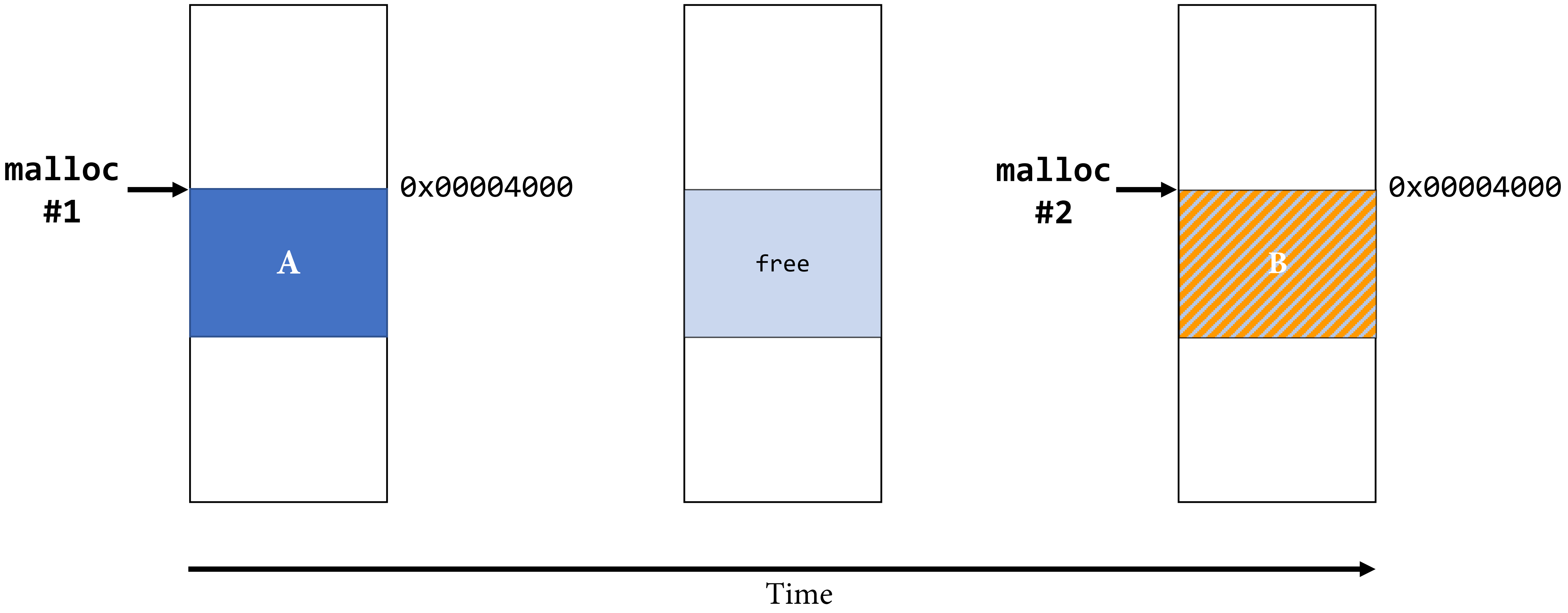
Temporal Memory Safety

The Problem



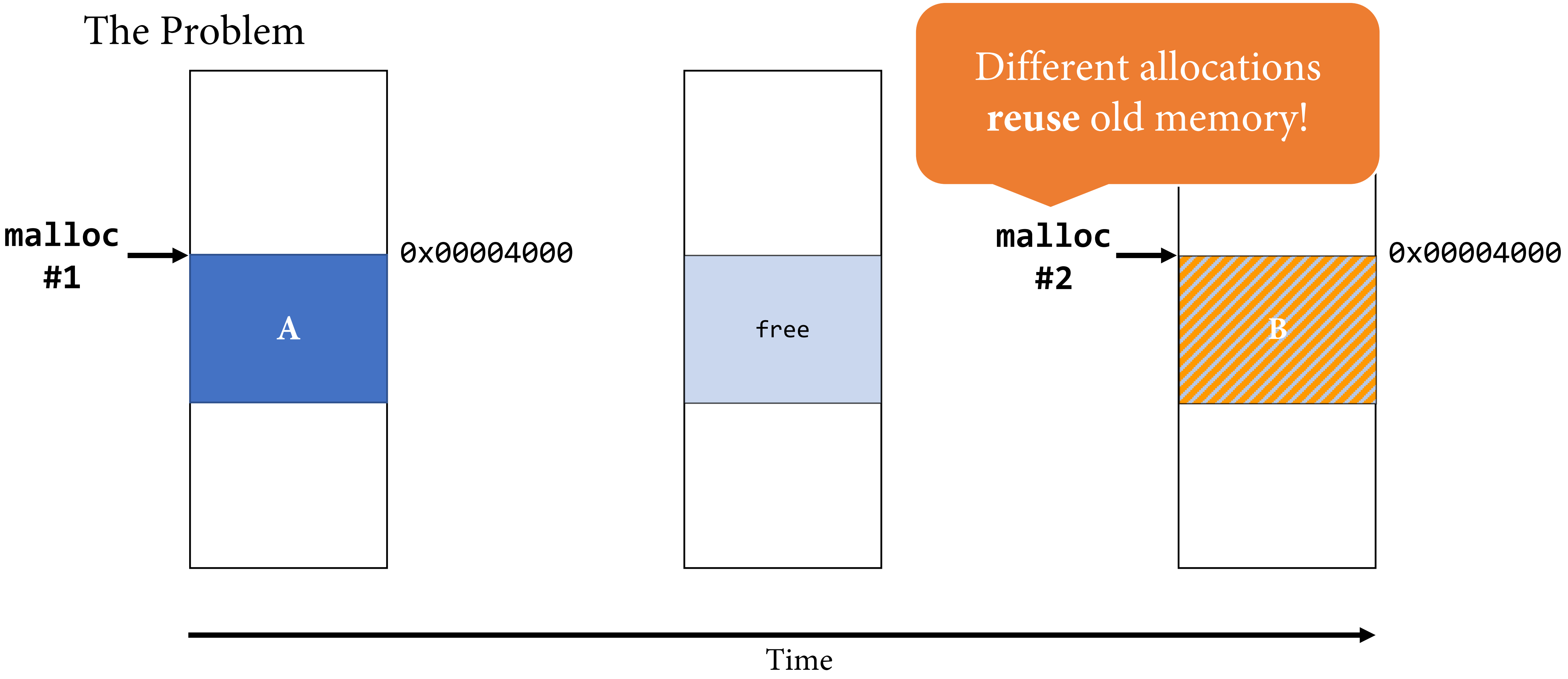
Temporal Memory Safety

The Problem

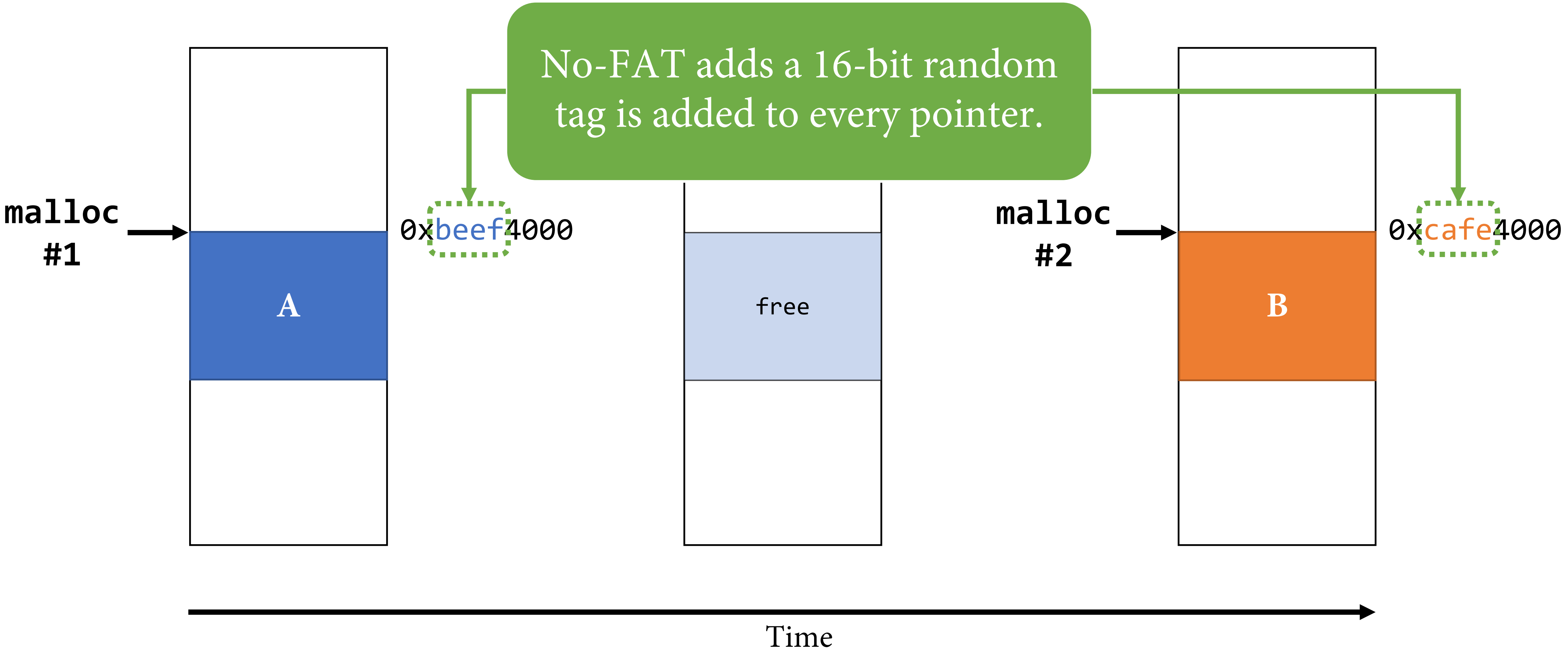


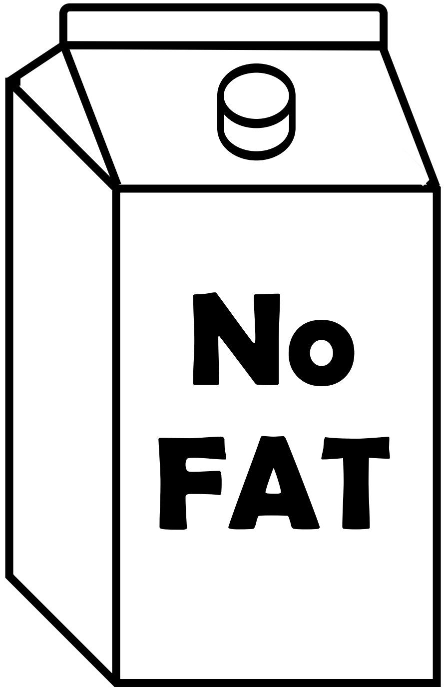
Temporal Memory Safety

The Problem



Temporal Memory Safety





ISA Extensions

ISA Extensions

1. `s_store Addr, Dest, BaseAddr`

2. `s_load  Addr, Src,  BaseAddr`

ISA Extensions

1. `s_store` *Addr*, *Dest*, *BaseAddr*
2. `s_load` *Addr*, *Src*, *BaseAddr*
3. `verifyBounds` *Addr*, *BaseAddr*

ISA Extensions

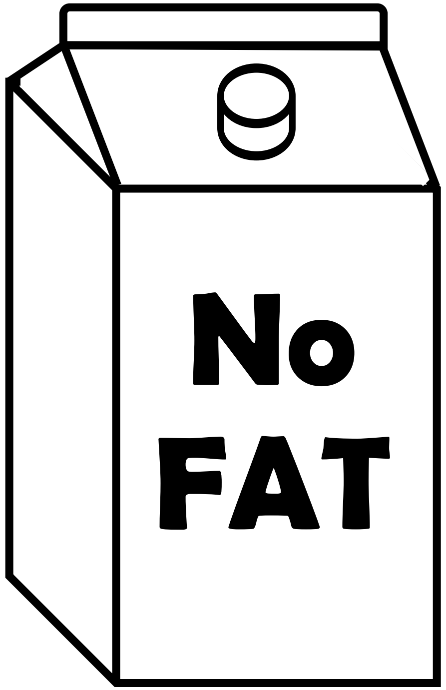
1. `s_store` *`Addr, Dest, BaseAddr`*
2. `s_load` *`Addr, Src, BaseAddr`*
3. `verifyBounds` *`Addr, BaseAddr`*

Exceptions are thrown in the case the target memory address does not match `BaseAddr`.

ISA Extensions

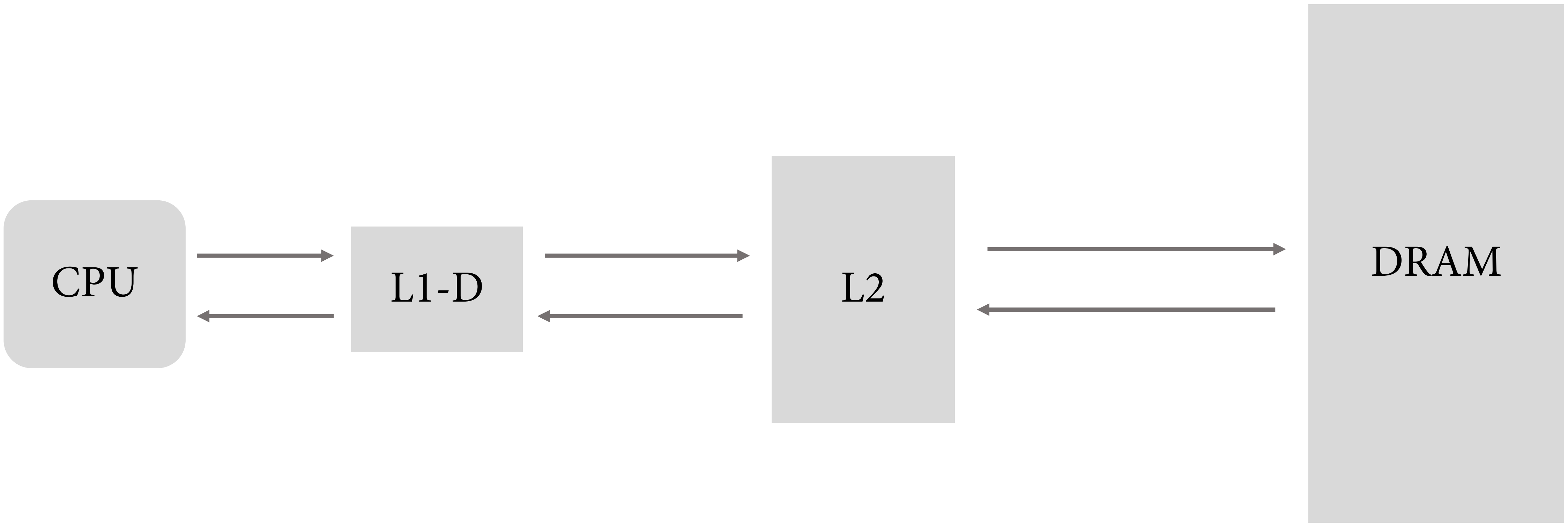
1. `s_store Addr, Dest, BaseAddr`
2. `s_load Addr, Src, BaseAddr`
3. `verifyBounds Addr, BaseAddr`
4. `compBase Addr, Dest`

Exceptions are thrown in the case the target memory address does not match `BaseAddr`.

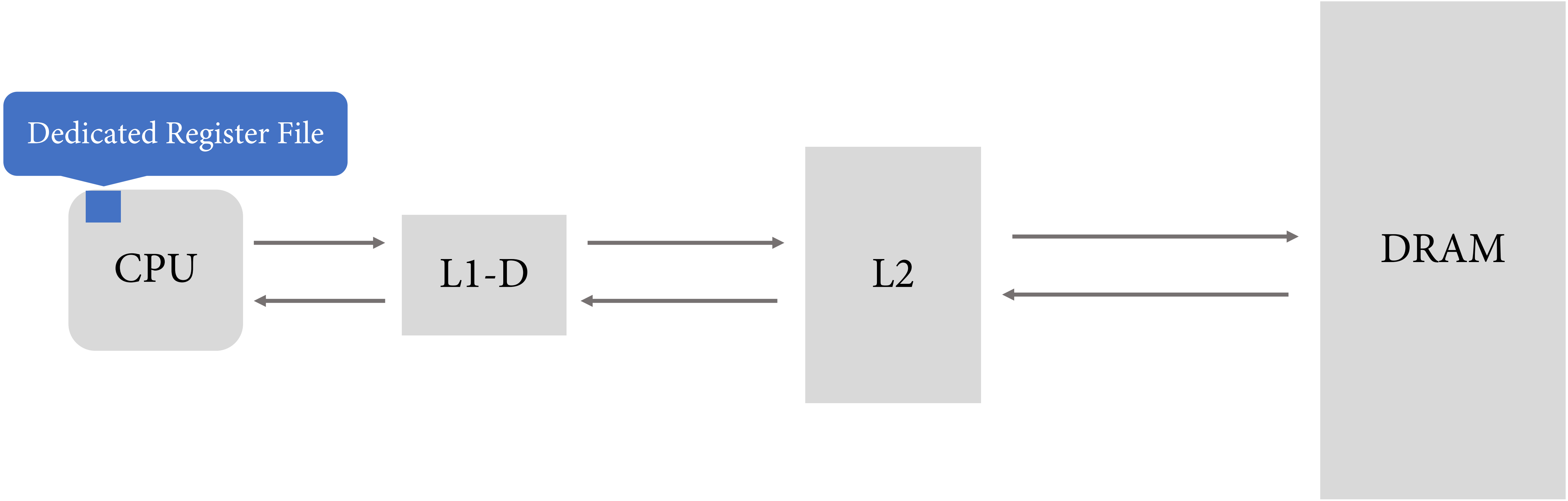


Microarchitectural Overview

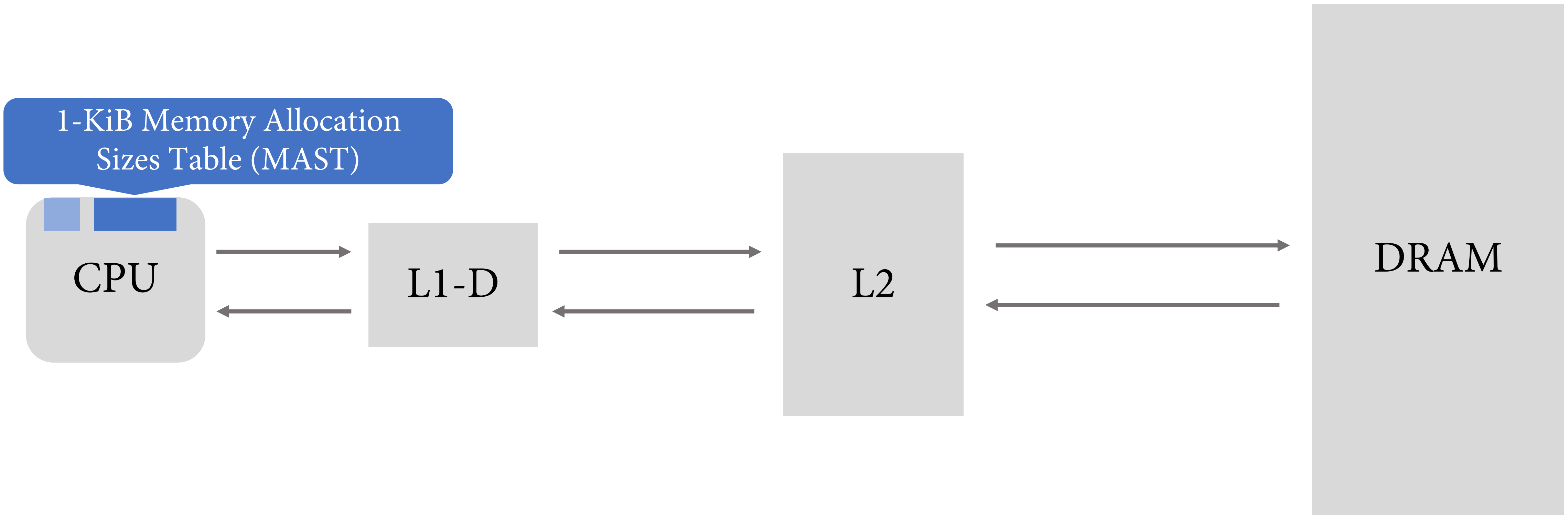
Microarchitectural Overview



Microarchitectural Overview



Microarchitectural Overview



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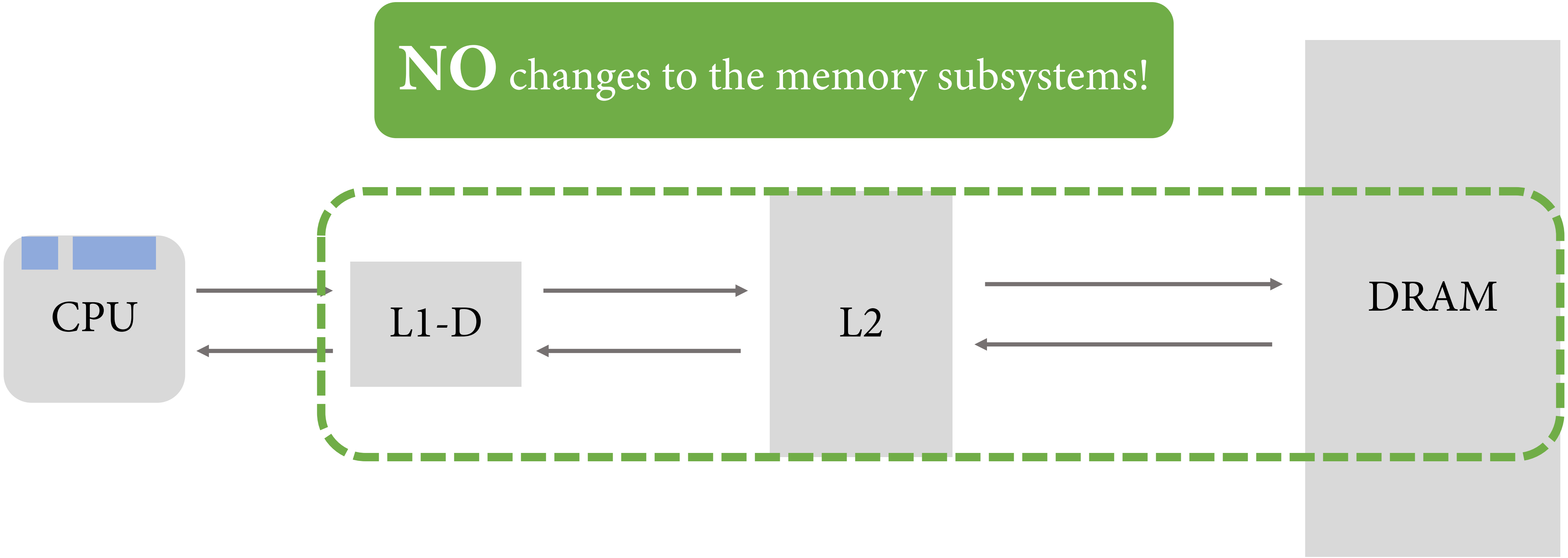
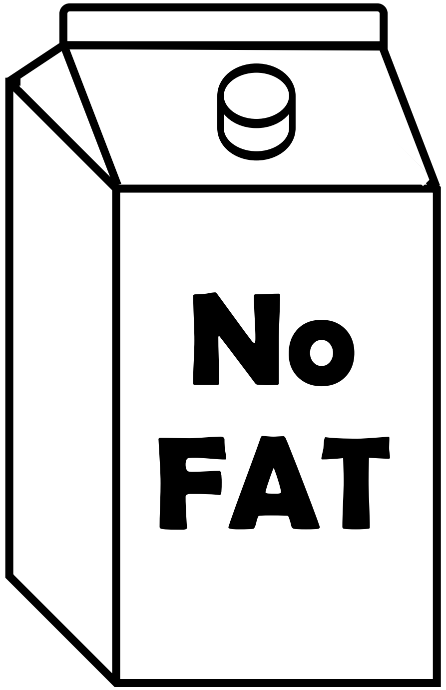




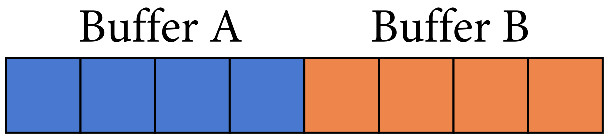
Resilience to Common Exploits

Resilience to Common Exploits

1

Buffer Over-/Under-flows

Cannot corrupt memory.



Resilience to Common Exploits

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Buffer Over-/Under-flows

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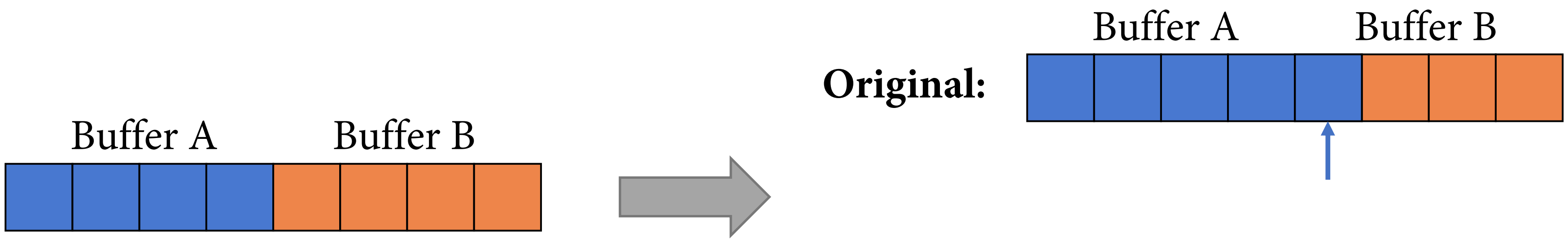
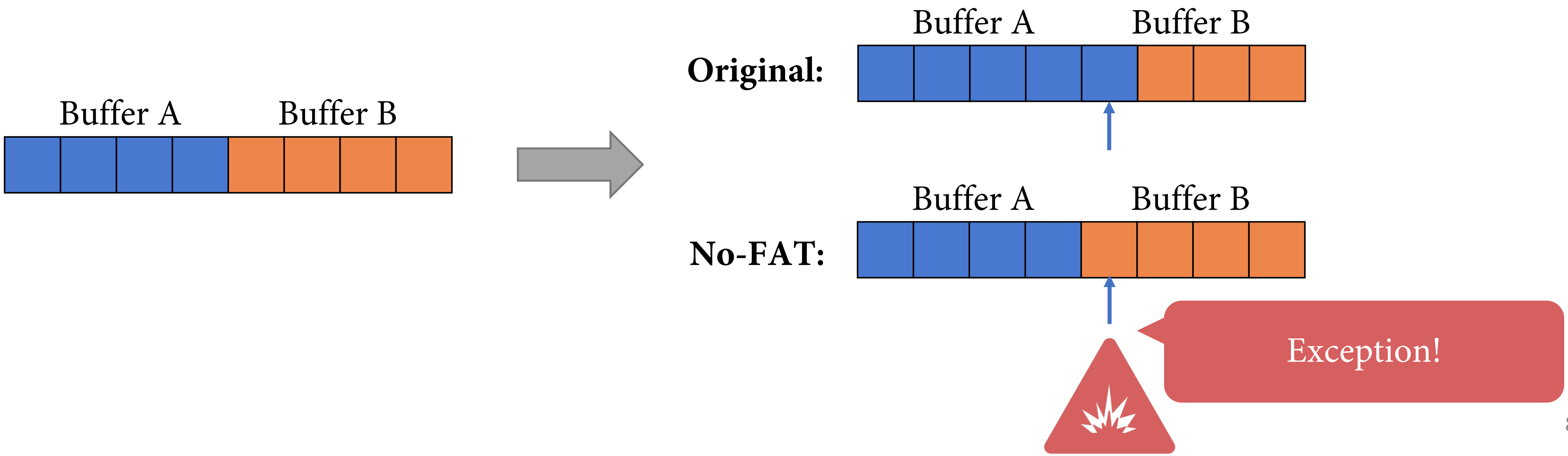


Resilience to Common Exploits

1

Buffer Over-/Under-flows

Cannot corrupt memory.



Resilience to Common Exploits

1 **Buffer Over-/Under-flows**

Cannot corrupt memory.

2 **Use-after-free**

Each allocation instance is tagged randomly.

Tag	Virtual Address

Tag is propagated with the allocation base address.

Resilience to Common Exploits

1. **Buffer Over-/Under-flows**
   Cannot corrupt memory.

2. **Use-after-free**
   Each allocation instance is tagged randomly.

3. **Spectre-V1**

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// mispredicted branch
if (i < sizeof(a)) {

  secret = a[i];

  // secret is leaked
  val = b[64 * secret];
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Detected!

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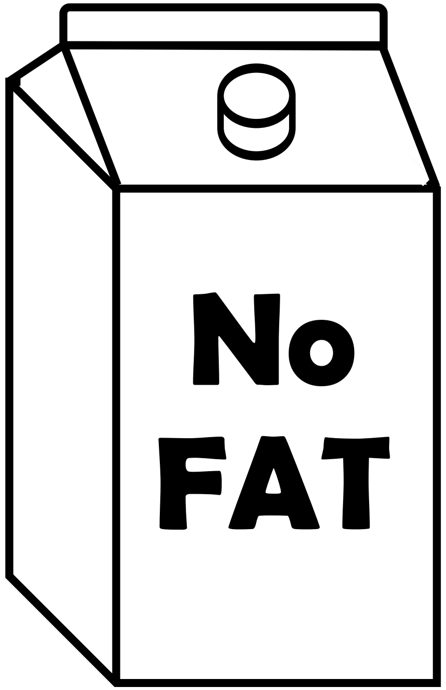

Performance

Performance Overheads

Hardware Modifications

Our measurements show minimal latency/area/power overheads.

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Software Modifications

00010010
101001101
00010010
111001001
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Performance Overheads

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Software Modifications

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- We verify pointer bounds before storing them to memory.

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Software Modifications

- Our special load/stores do not change the binary size.
- We verify pointer bounds before storing them to memory.
- We compute the allocation base address of arbitrary pointers when they are loaded from memory.

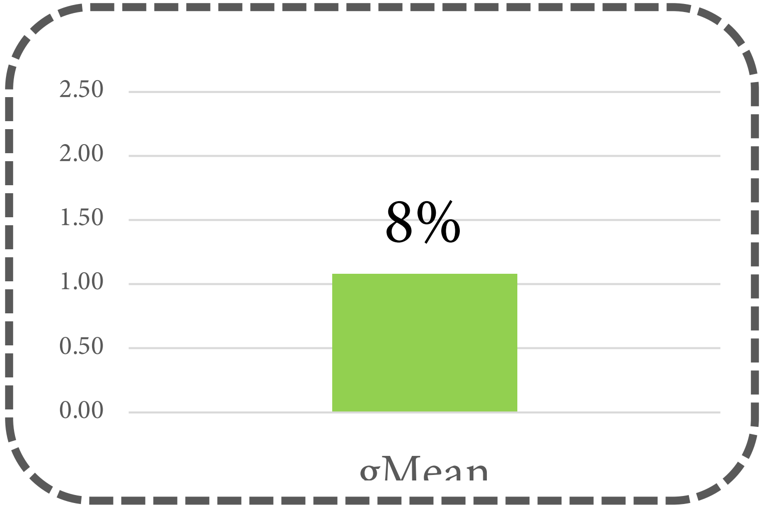
Performance Results (x86_64)

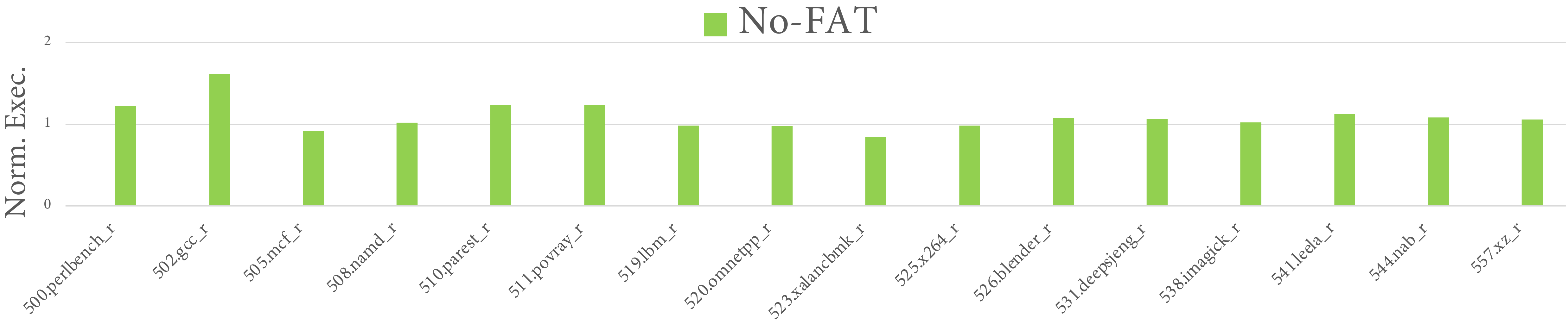
Experimental Setup

We use emulate NO-FAT on x86_64 by modifying LLVM to emit new instructions.

- `CompBase` is emulated using two multiplications followed by a `store`.
- `VerifyBounds` is emulated using dummy `stores`.

Performance Results (x86_64)





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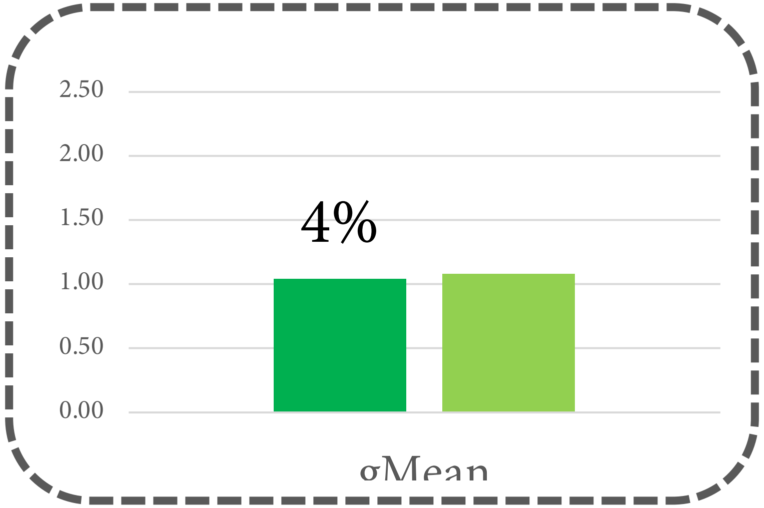

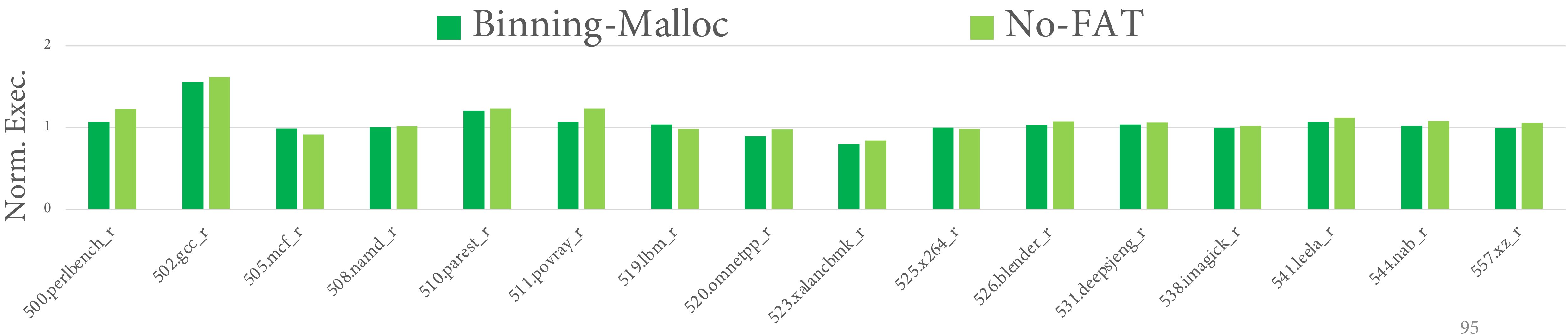

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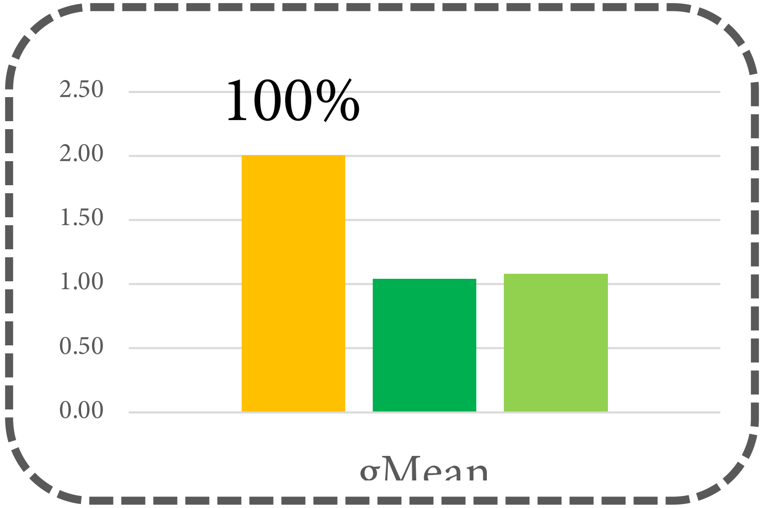

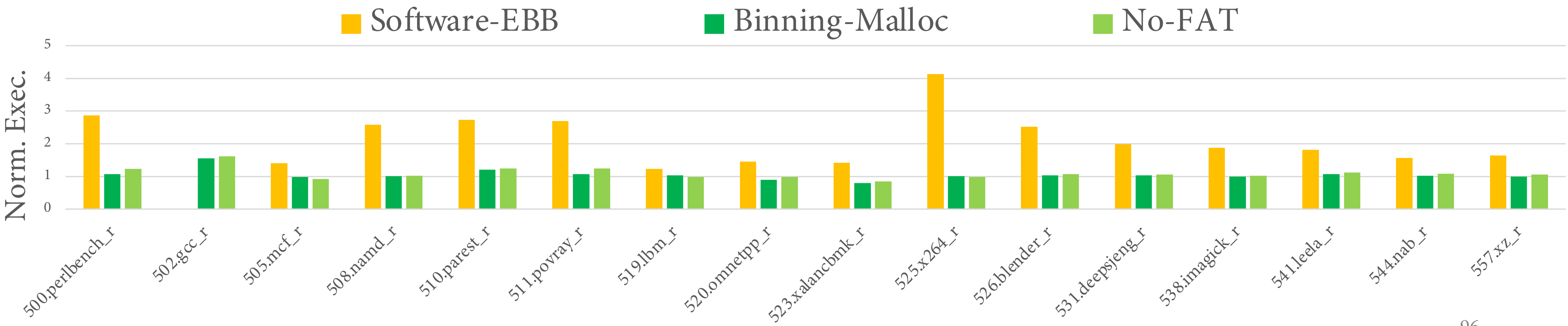

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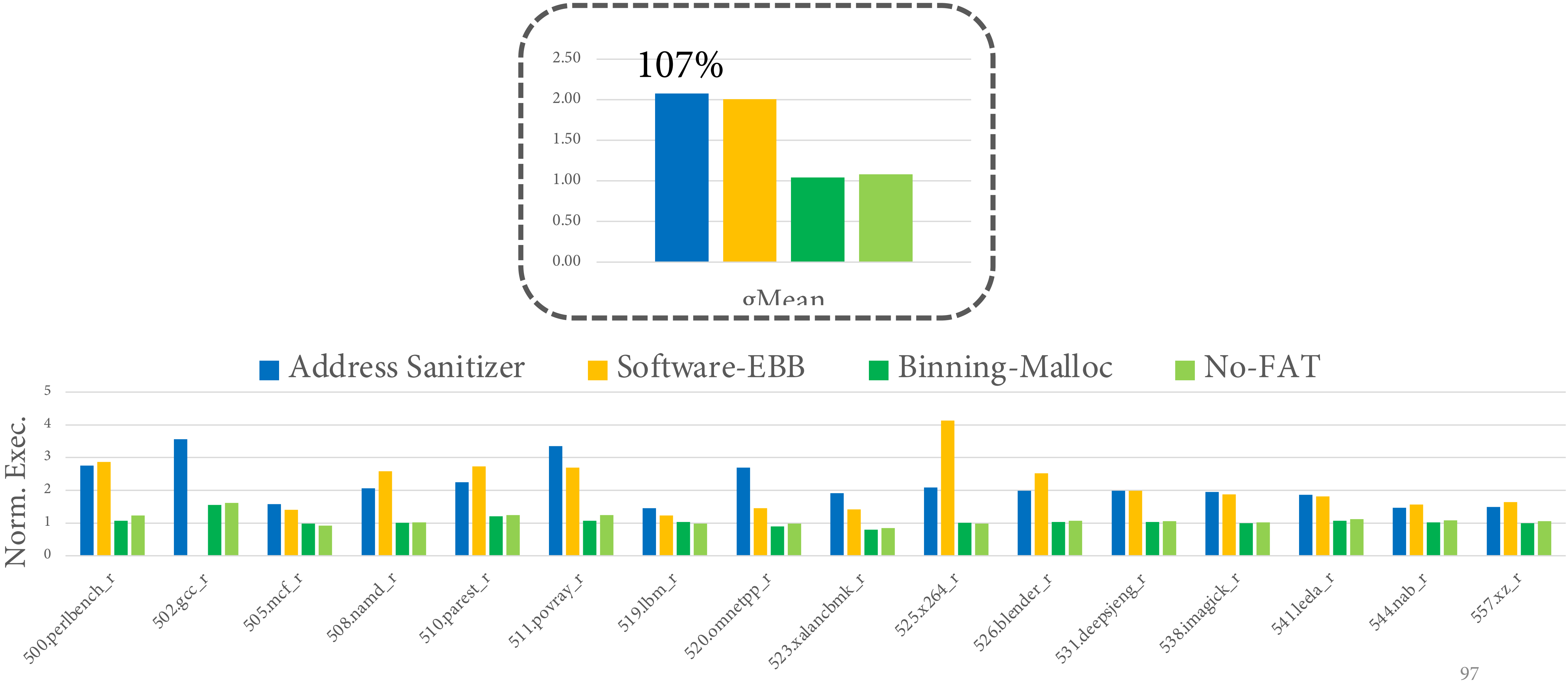

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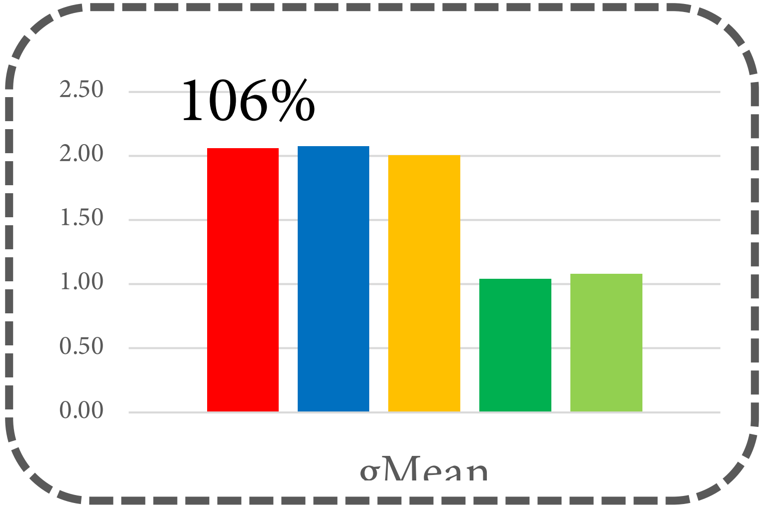
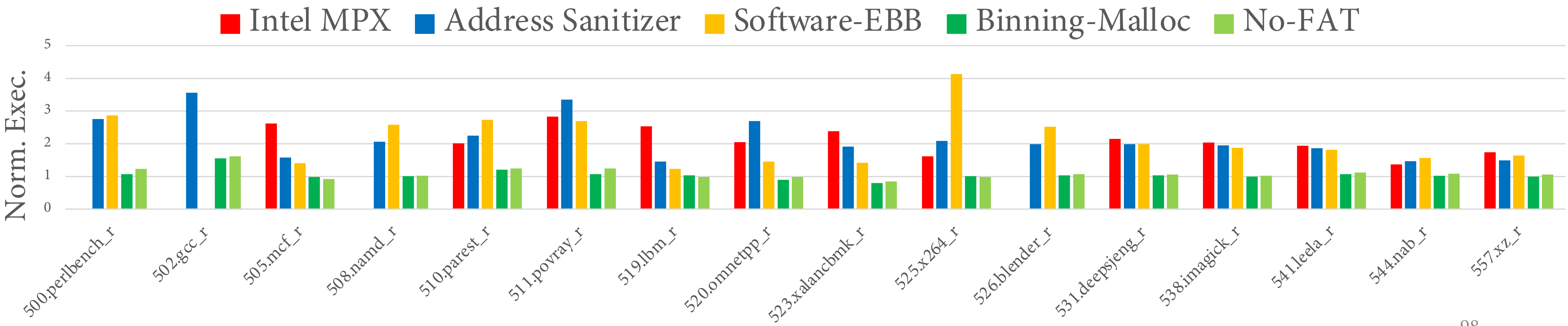
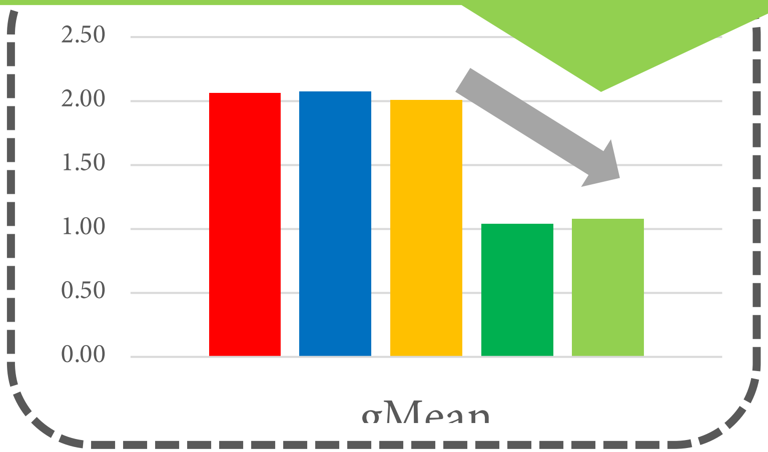
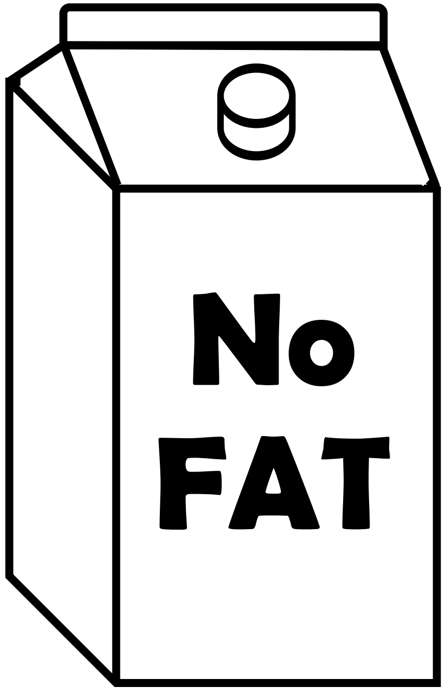




Performance Results (x86_64)

We reduce the average runtime overheads of full memory safety **from 100% to 8%!**





Related Work

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Technique	Metadata	Security Coverage

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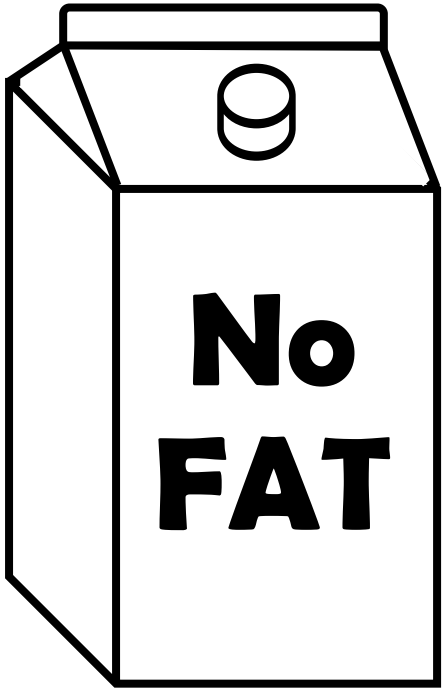
Memory Tagging	N-bits per pointer & allocation	Limited by tag width
Tripwires	N-bits per allocation	Susceptible to non-adjacent overflows
No-FAT	Fixed (1K) bits per process	Complete

Takeaways



Having no metadata

- ✓ **Improves Fuzzing**
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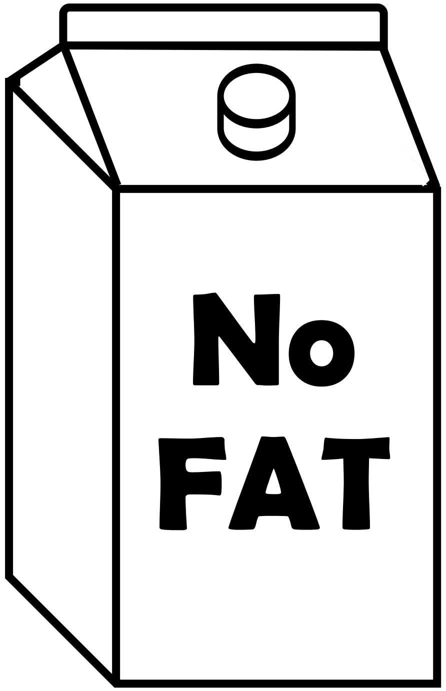
Takeaways



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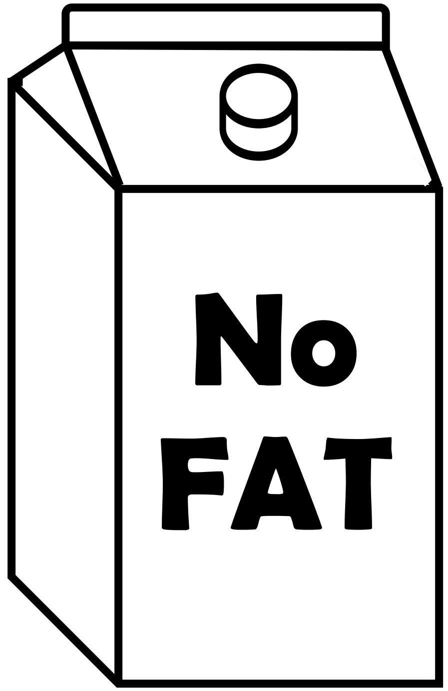
Checkout ZeRØ for end-user deployment!
https://isca21.arroyo.me

Takeaways



Having no metadata

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The benefits of having allocation sizes as an architectural feature can go well beyond memory safety!

Backup Slides