SPAM

Stateless Permutation of Application Memory With LLVM

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Columbia University

10/8/20

About us

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Memory Safety is a serious problem!

Computing Sep 6

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

The tech giant gave a rare statement that bristled at Google's analysis of the novel hacking operation.

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The New York Times

WhatsApp Rushes to Fix Security Flaw Exposed in Hacking of Lawyer's Phone

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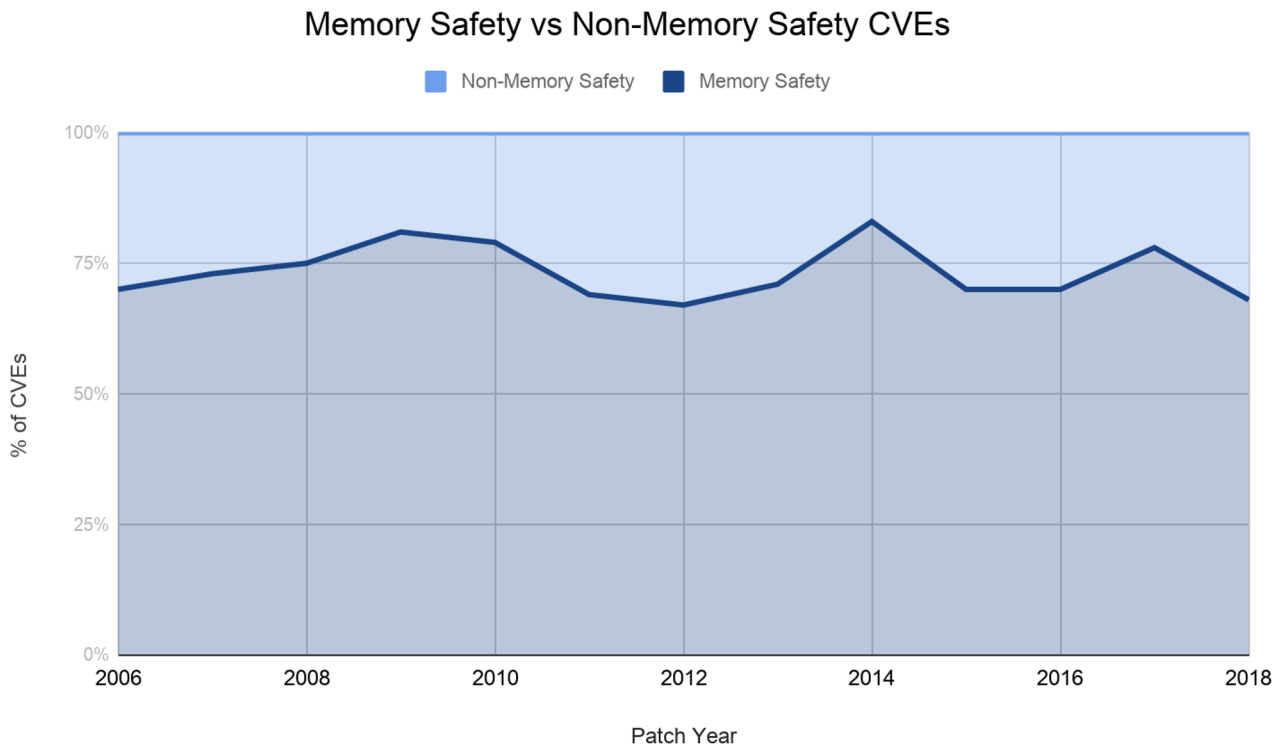
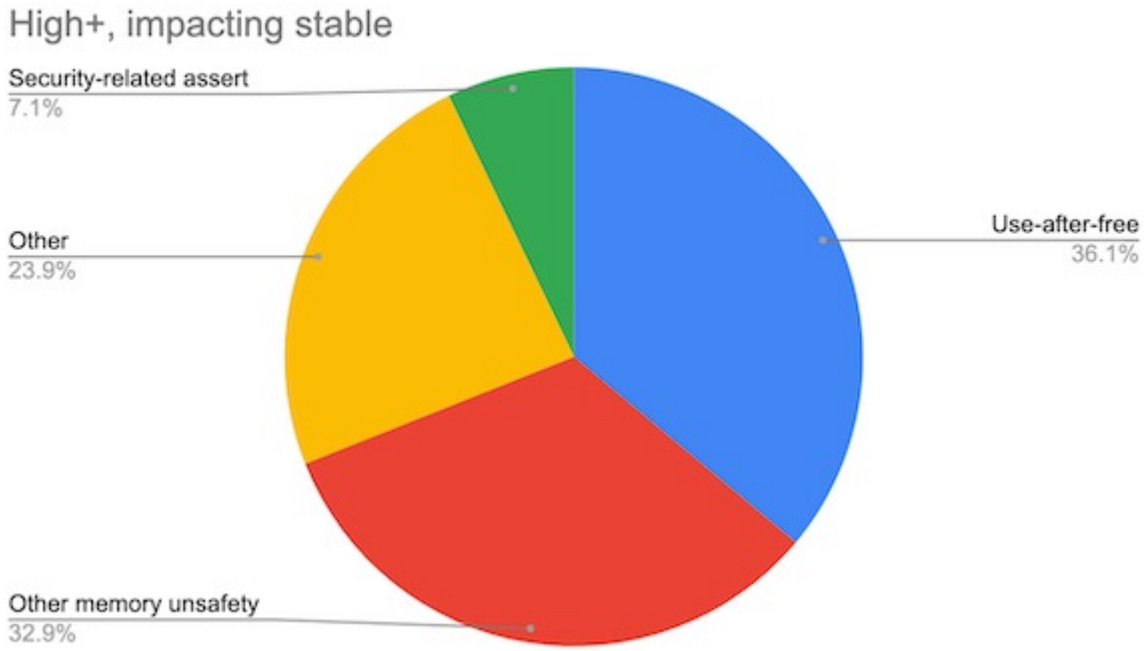
It’s easy to make mistakes

SEGFAULT !

Prevalence of Memory Safety Vulns



Microsoft Product CVEs



Google Chrome Bug Report 2015-2020

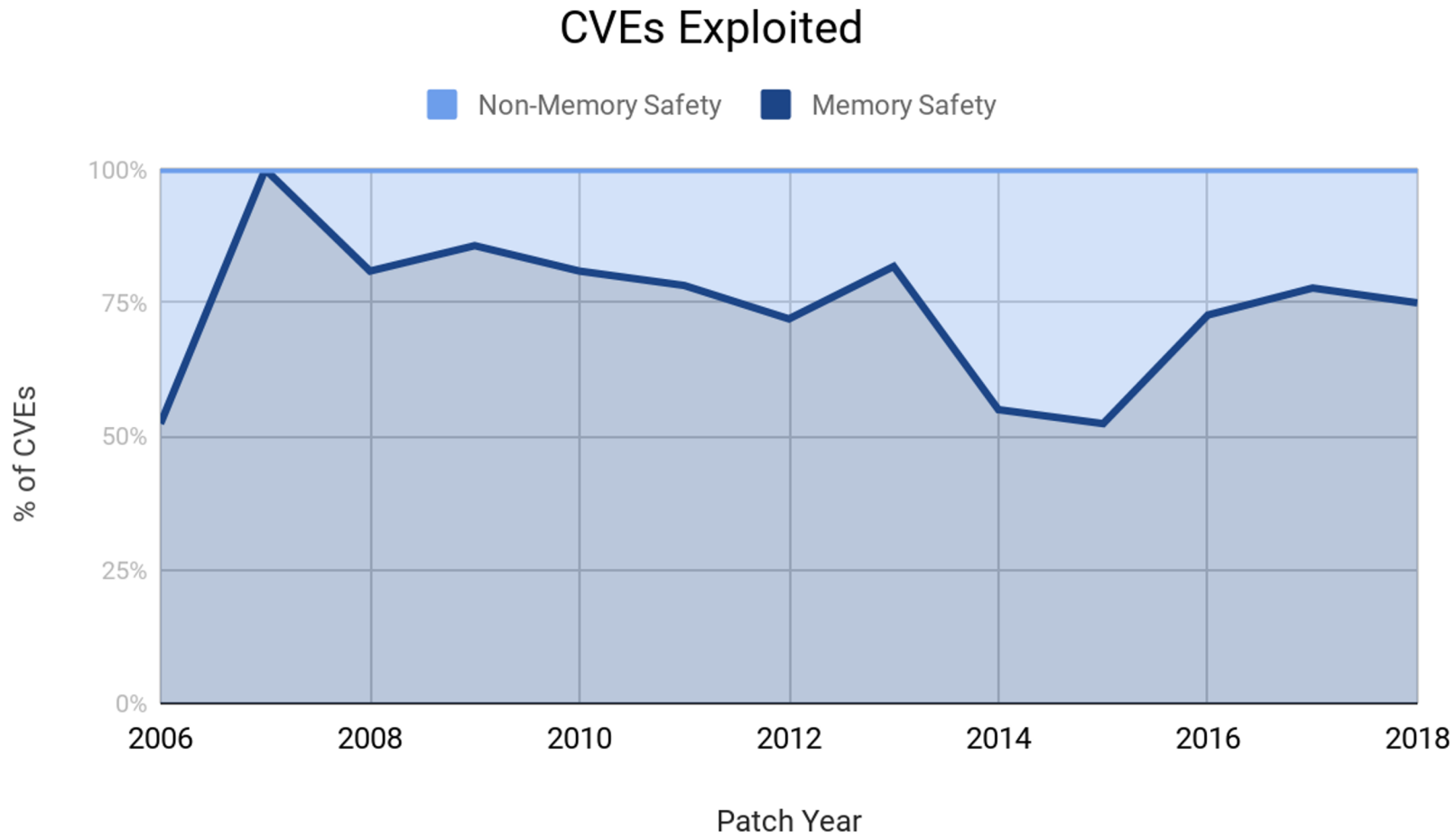
Source: *Matt Miller, Microsoft Security Response Center (MSRC) - BlueHat 2019*

Source: *https://www.chromium.org/Home/chromium-security/memory-safety*

ATTACKERS

MEMORY SAFETY

Attackers Prefer Memory Safety Vulns

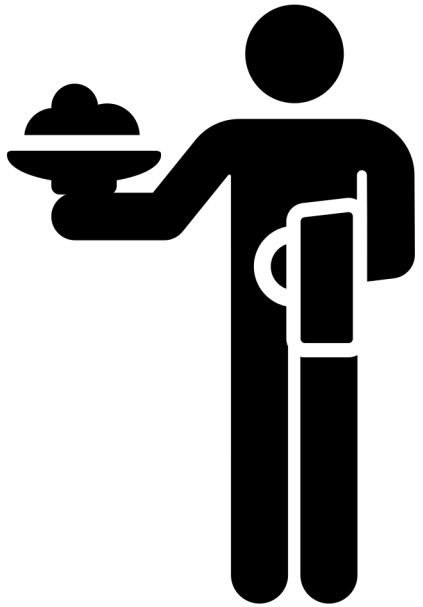


Microsoft Product Exploits

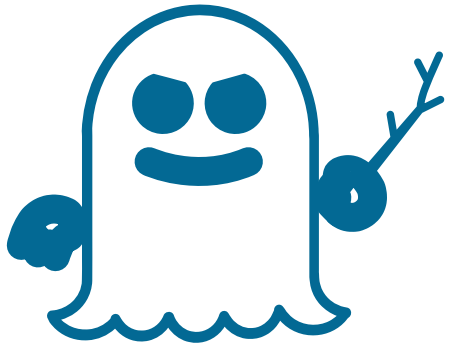
Source: *Matt Miller, Microsoft Security Response Center (MSRC) - BlueHat 2019*

À la carte solutions with additive overheads

Memory Safety Menu	Price
Intra-Object Overflow	$$$
Inter-Object Overflow	$$
Buffer-Overread	$
Control-Flow Hijack	$
Use-after-free	$$
Type Confusion	$$$
Uninitialized Reads	$$



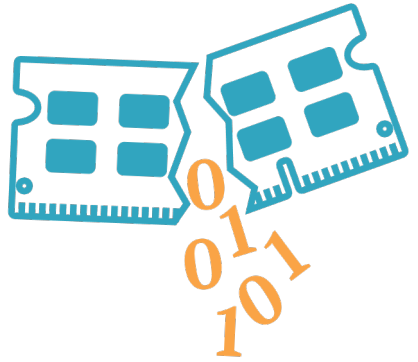
No common solution to all problems



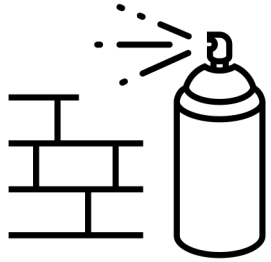
Spectre

Meltdown

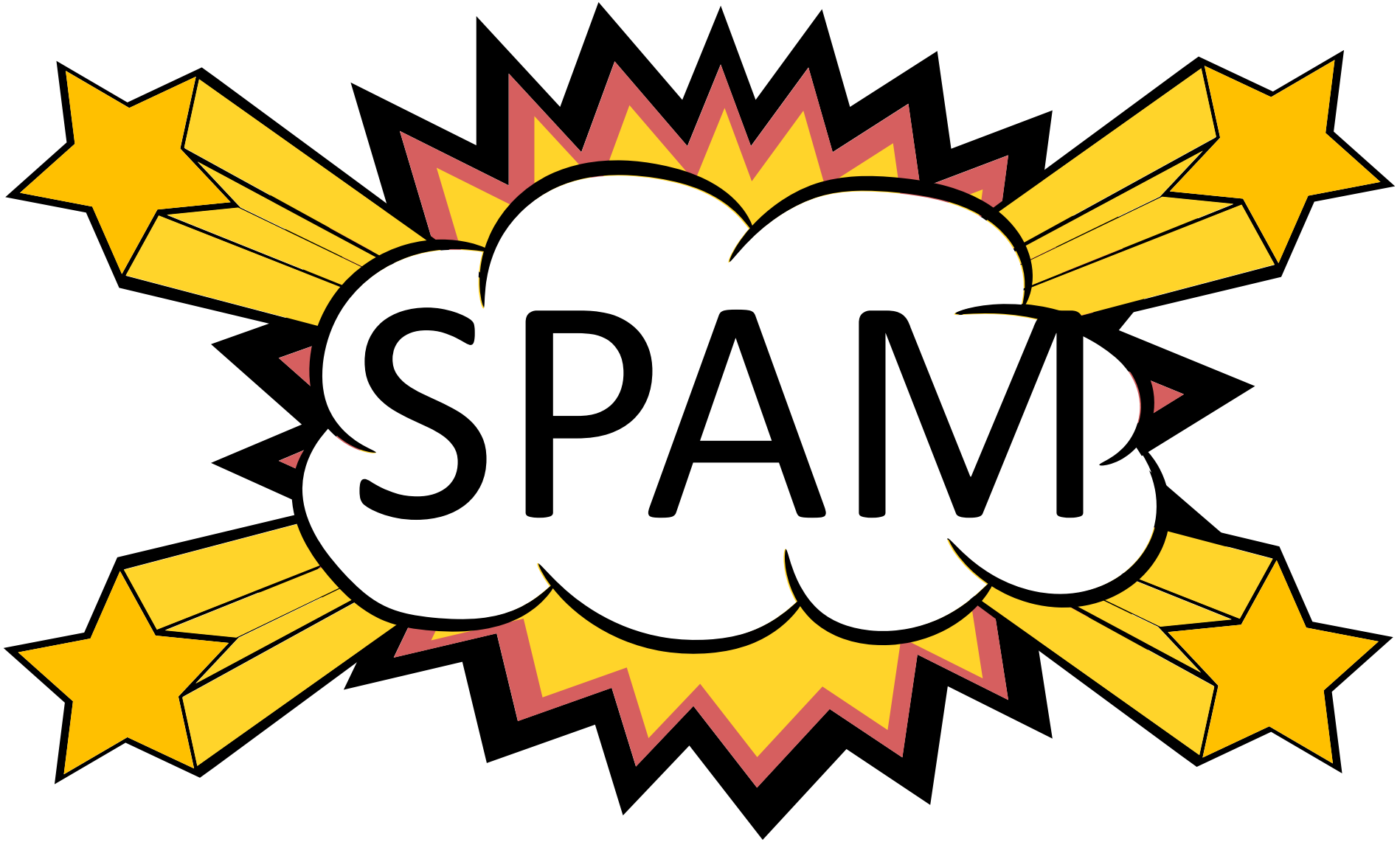
RowHammer



RamBleed



ColdBoot


SPAM

Overview

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Struct Definition

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typedef struct {
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  double b;
  char c[3];
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main.c

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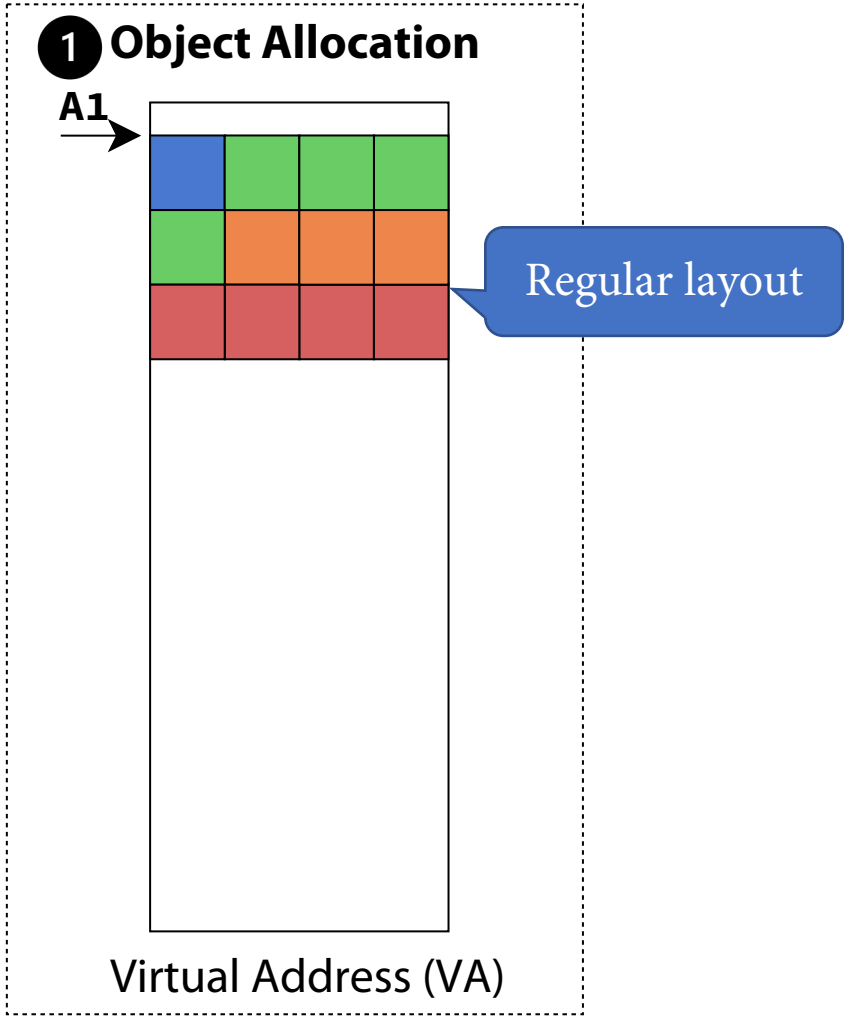

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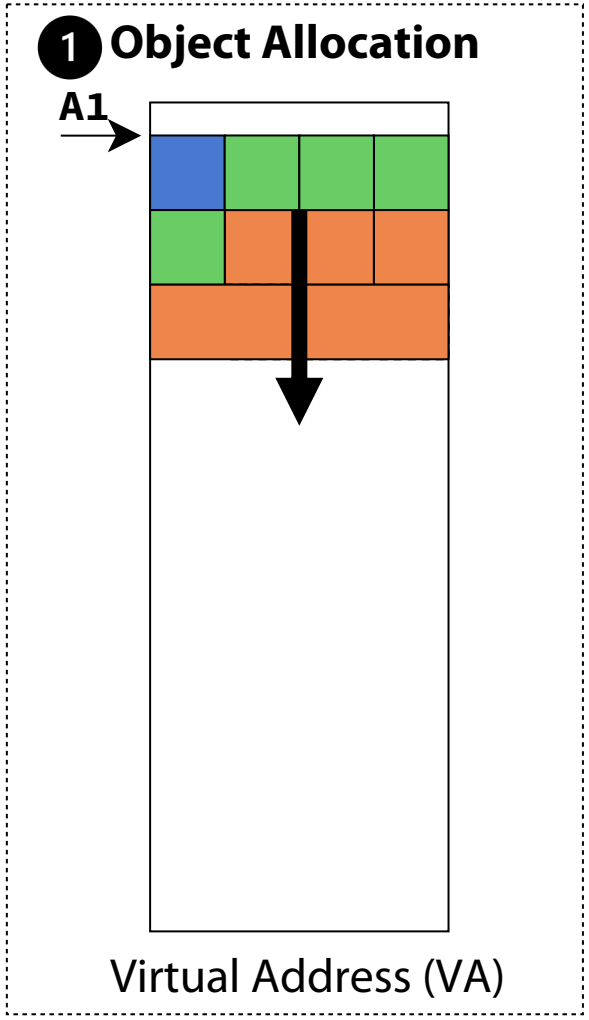

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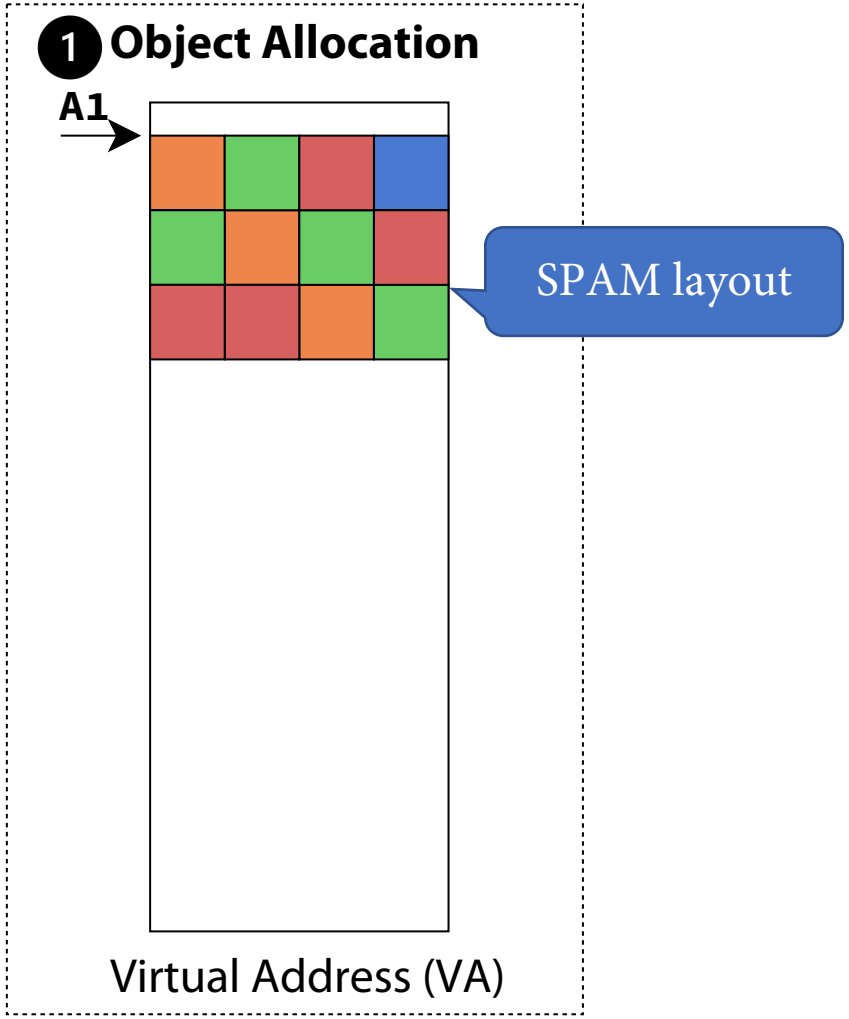

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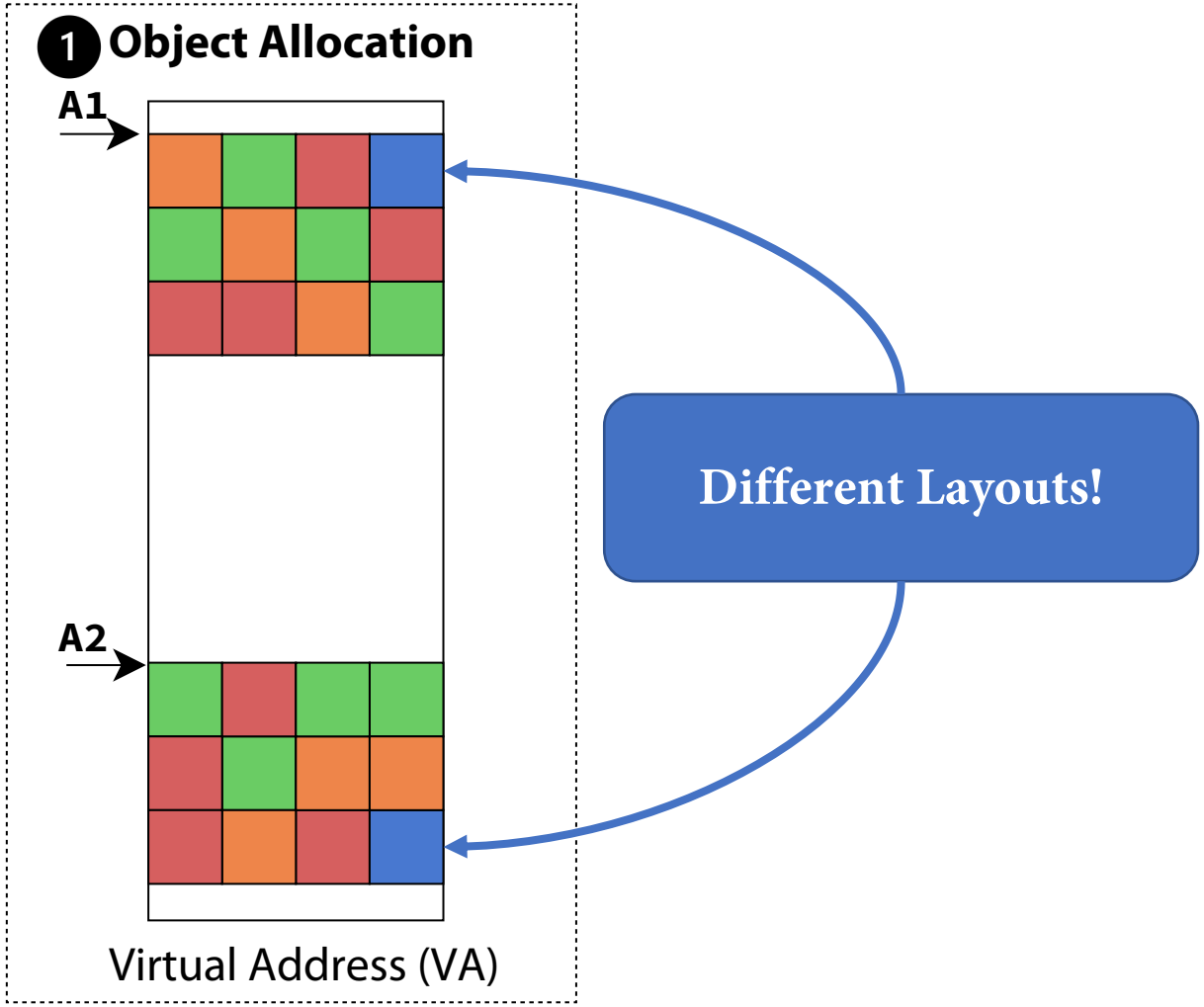

Object Allocation

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Generating Permutations

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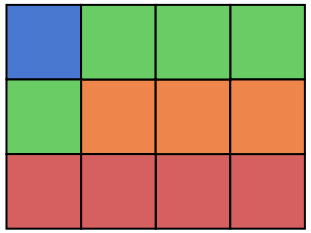

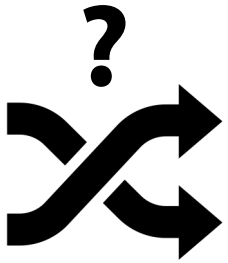

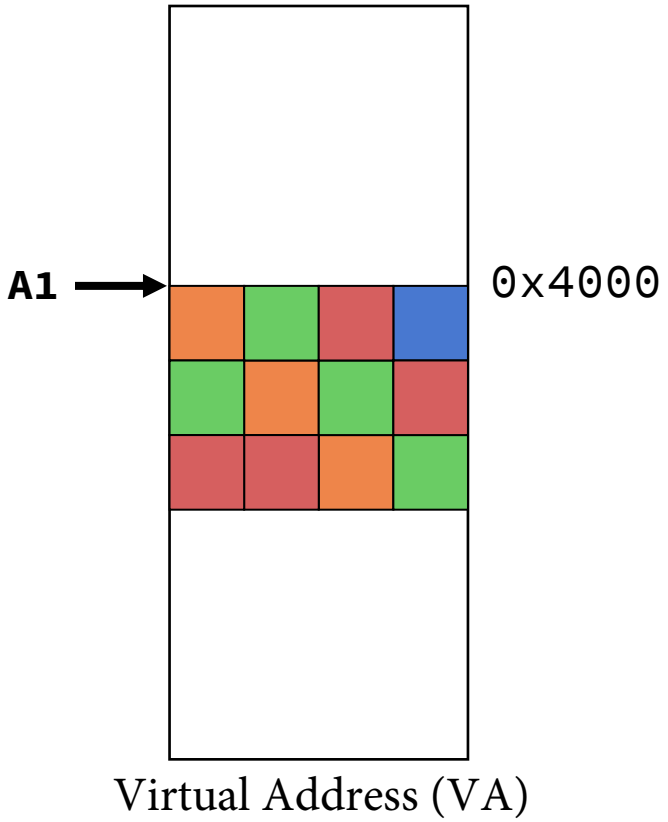

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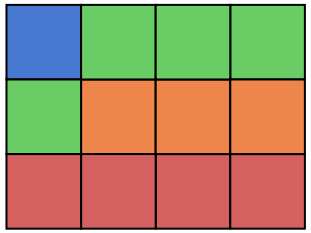

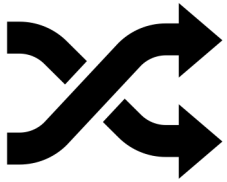

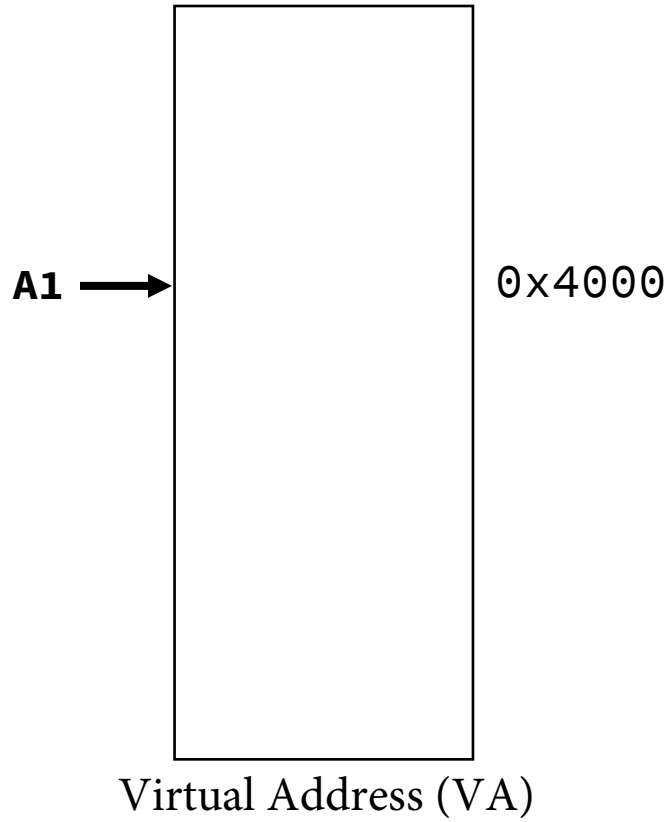

1. Request memory from allocator.

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Generating Permutations

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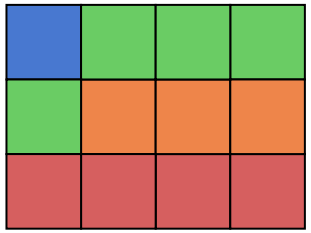

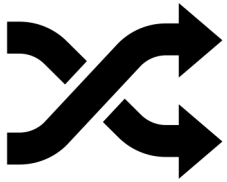

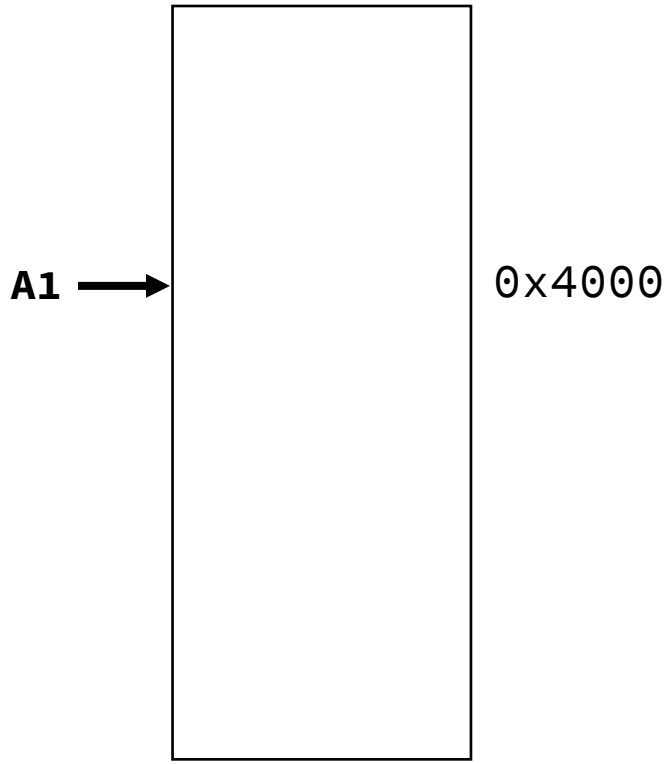

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2. Use address as key for permutation.

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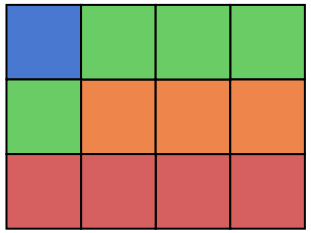

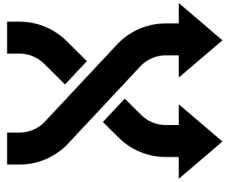

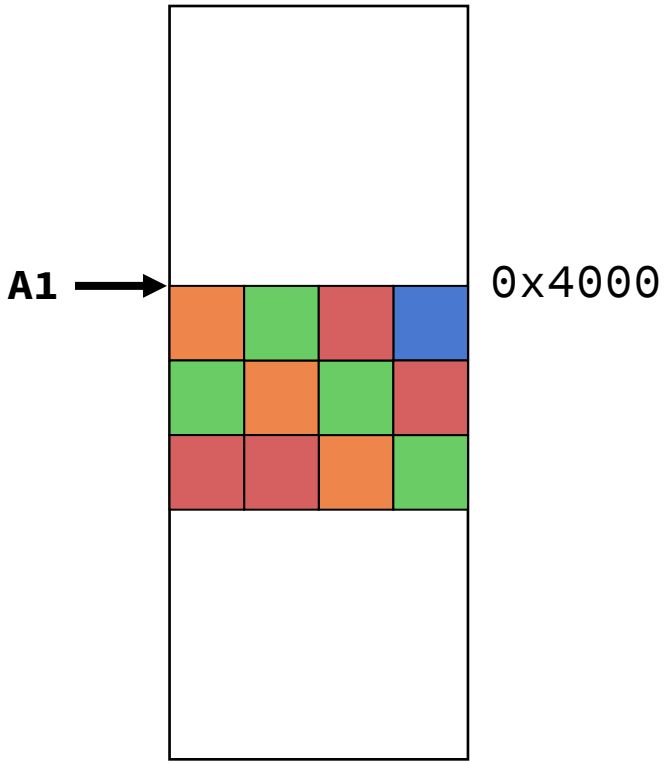

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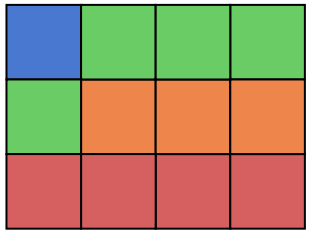

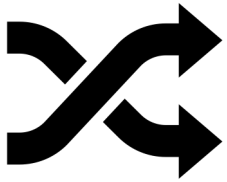

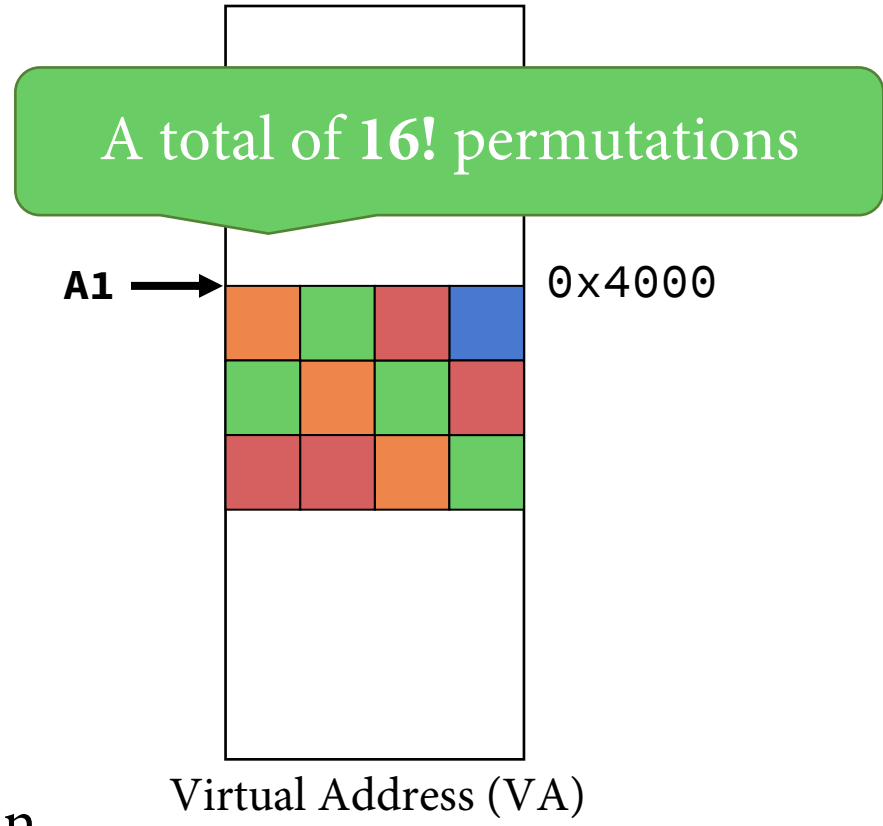

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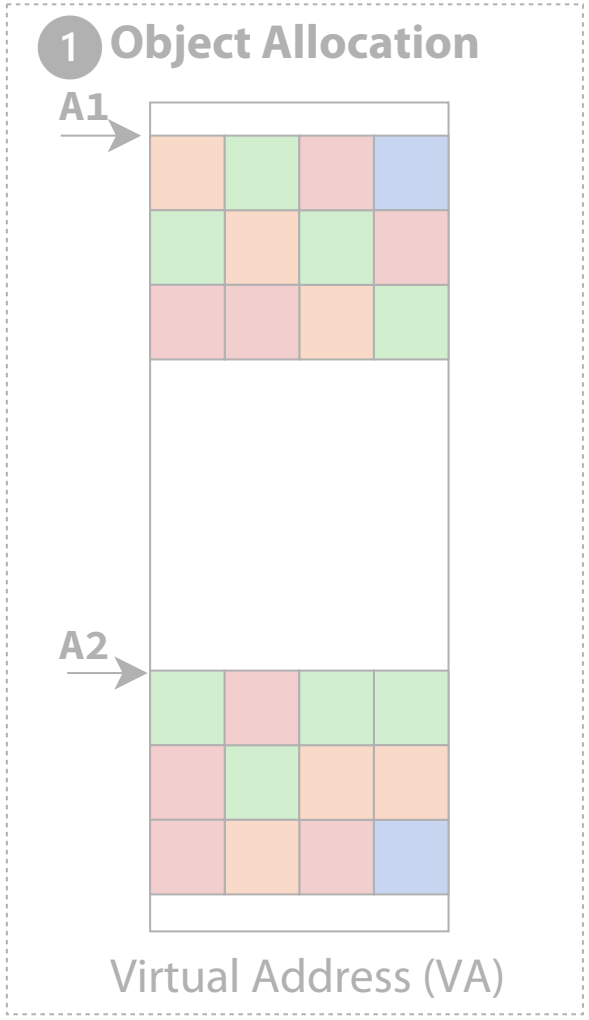

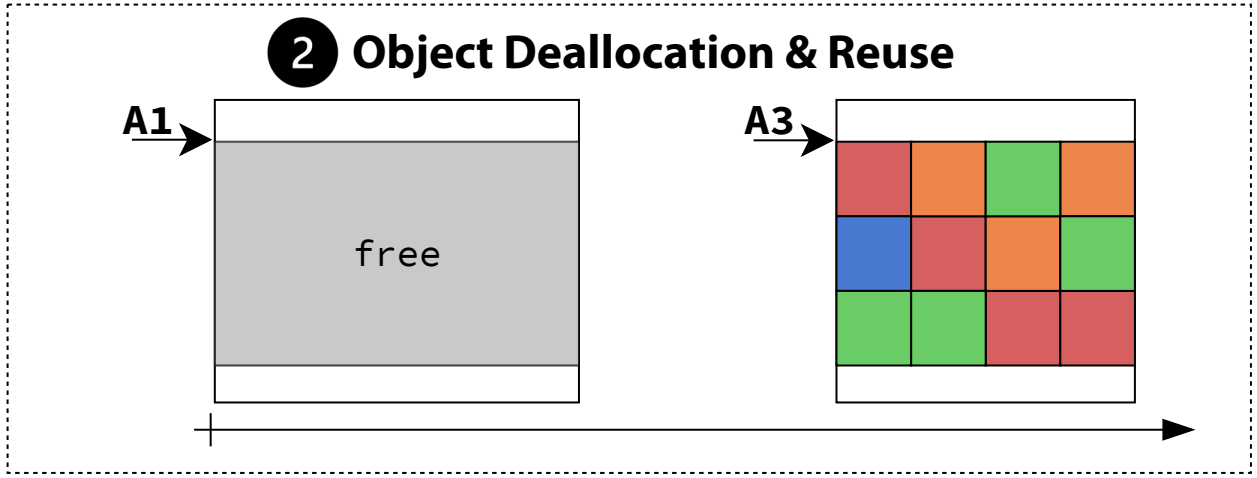

Object Deallocation & Reuse

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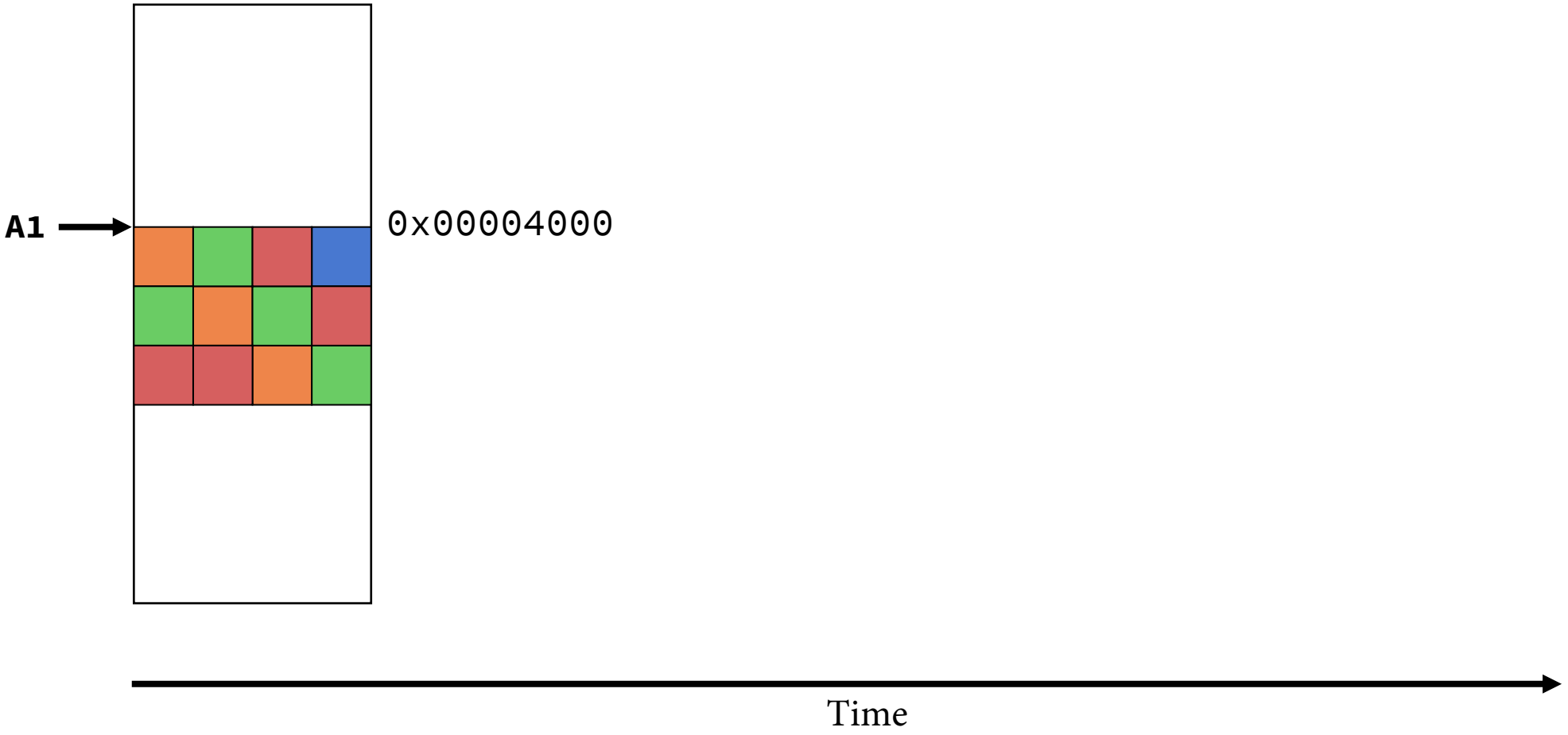

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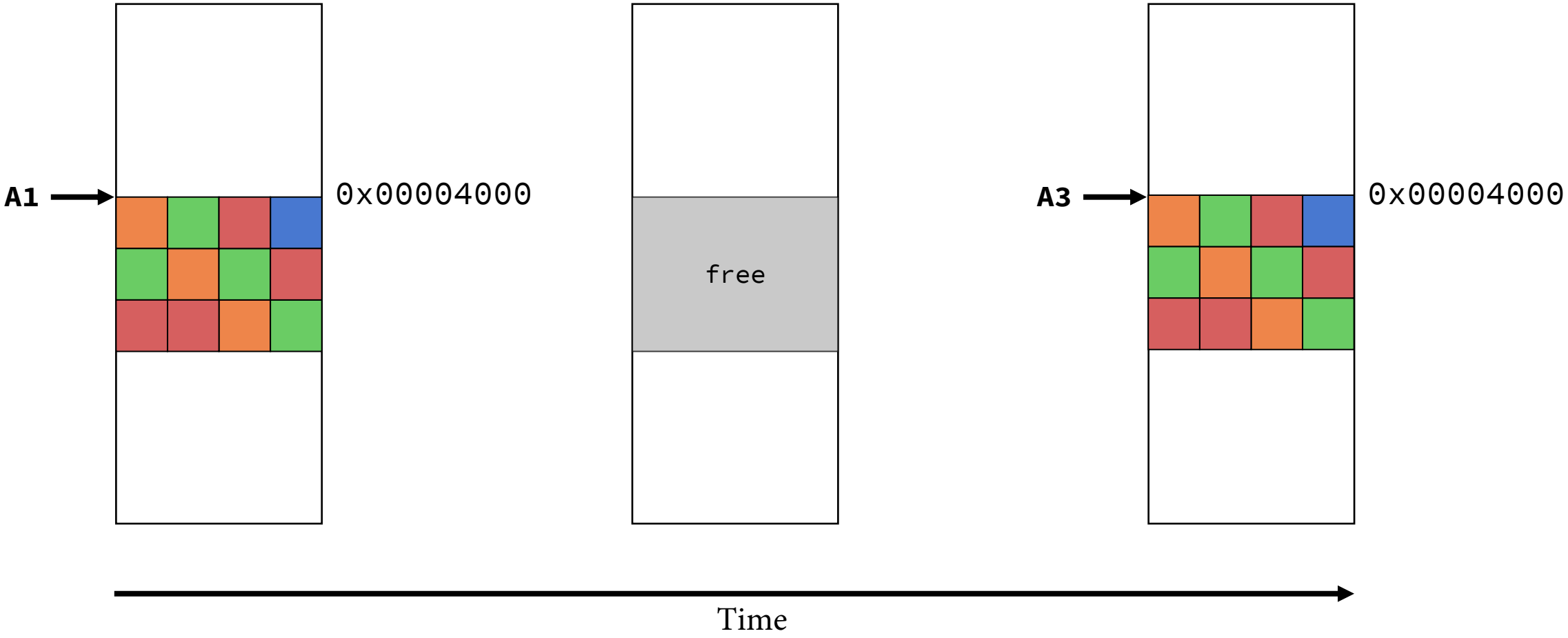

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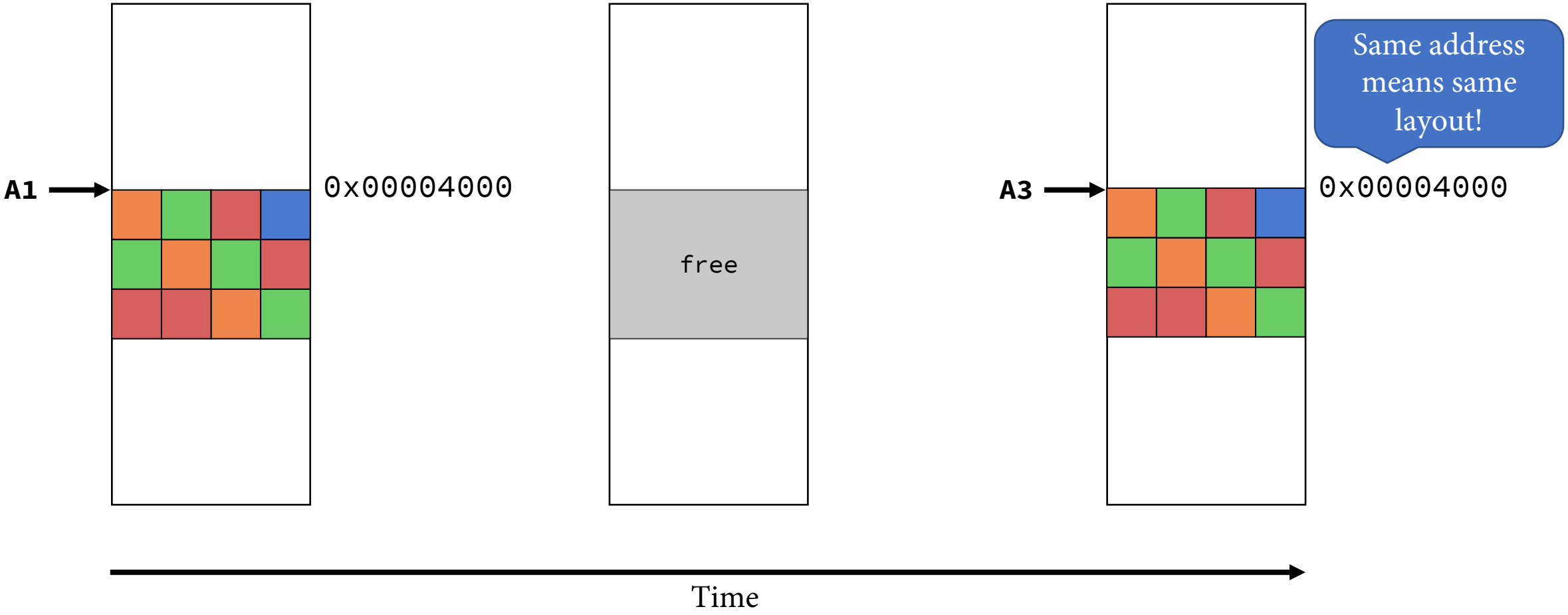

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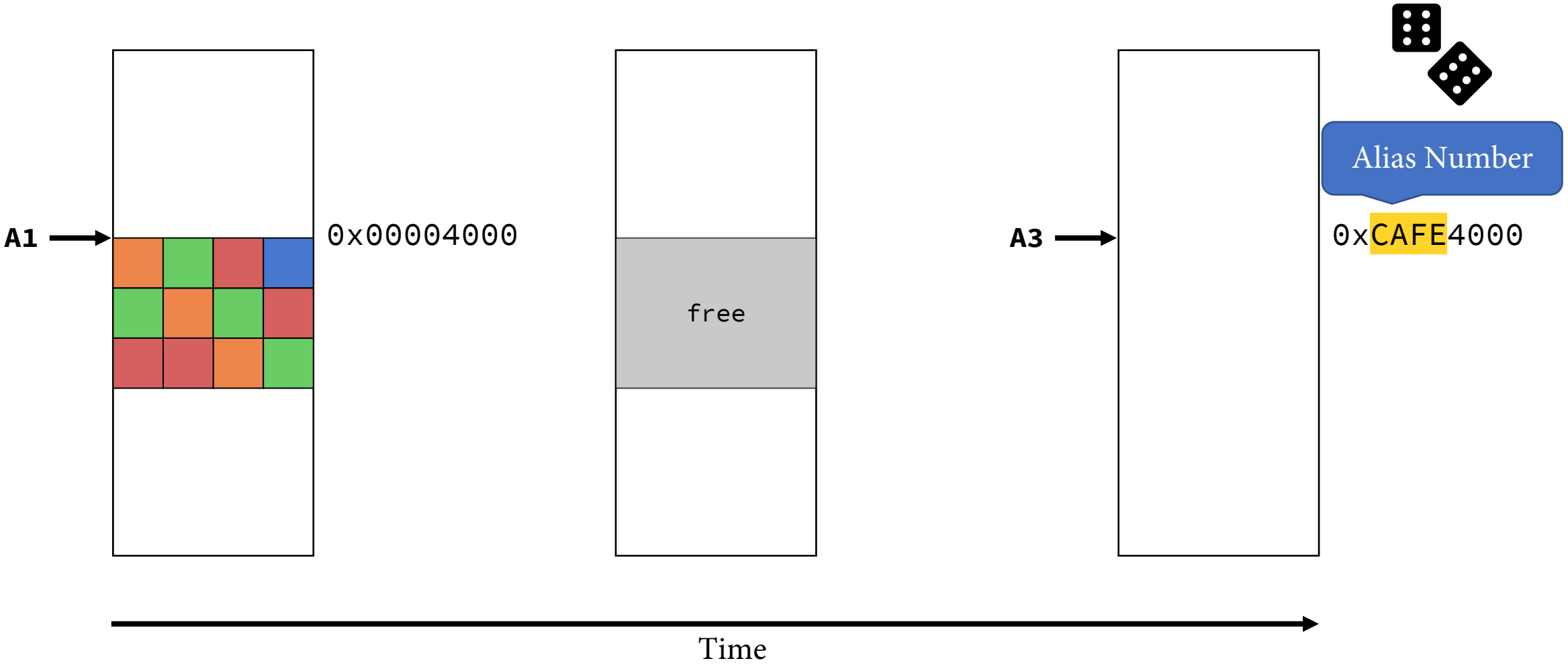

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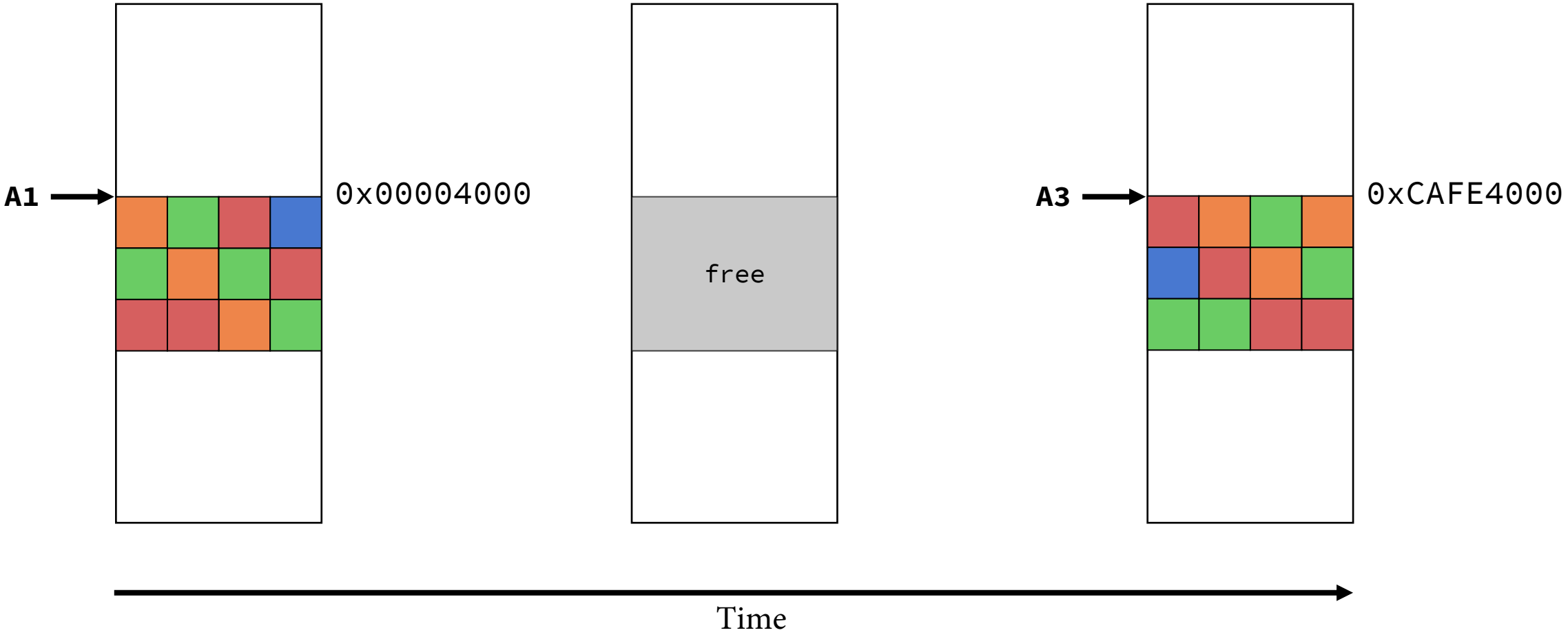

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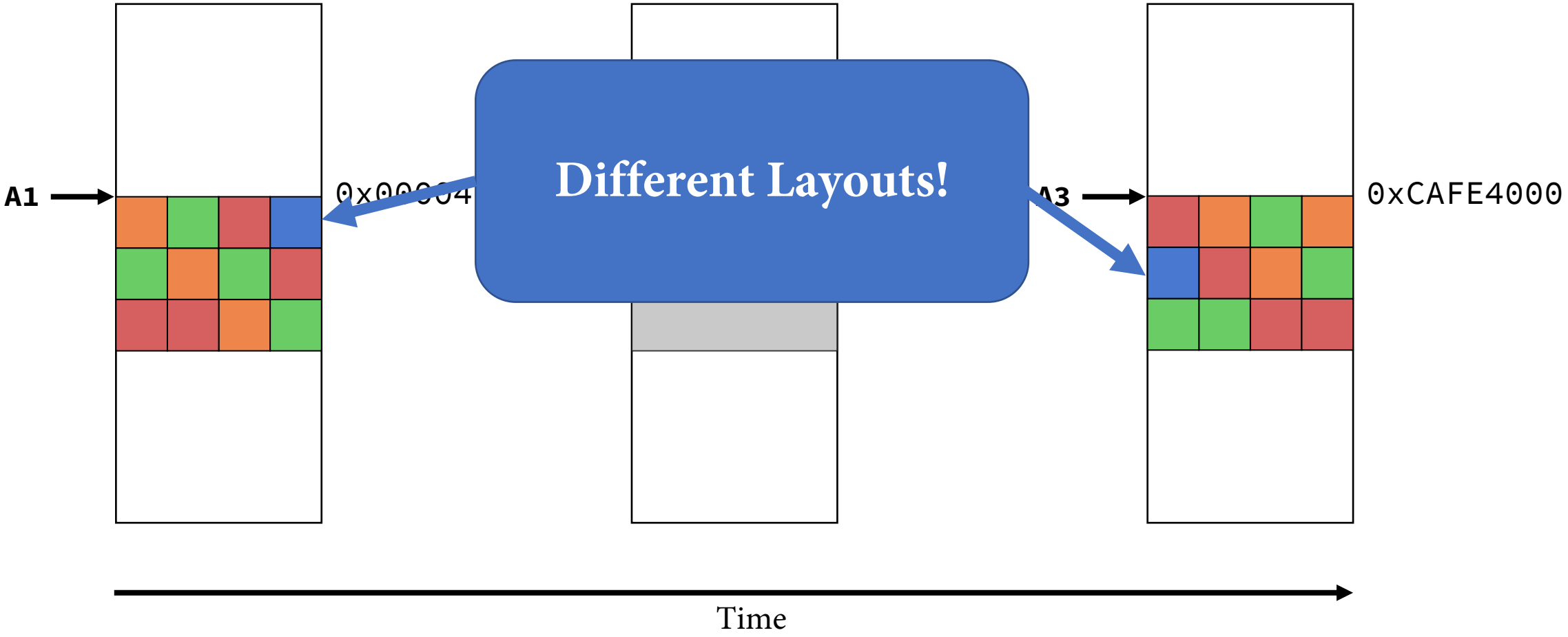

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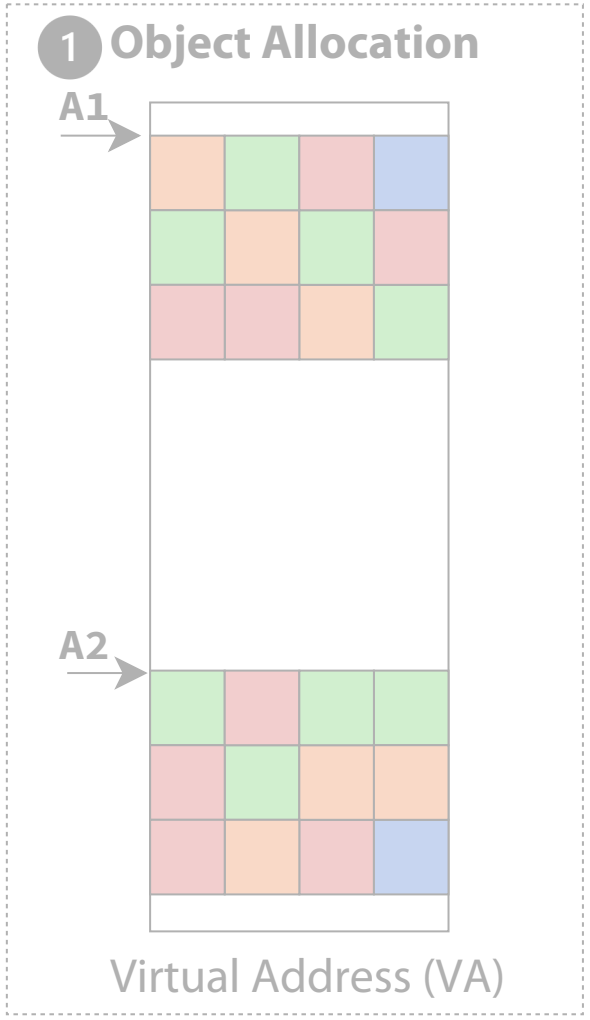

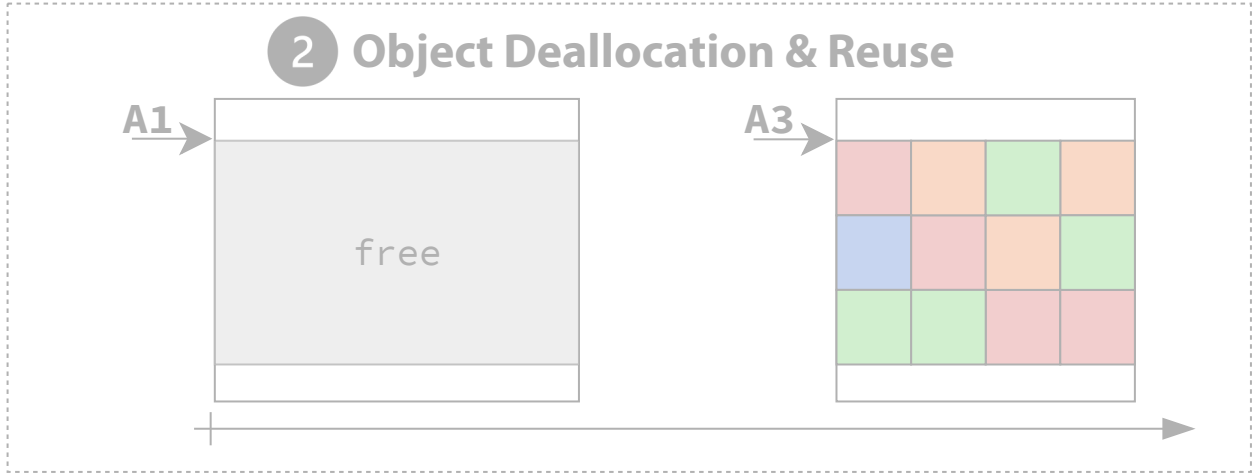

3 Multi-Dimensional Objects

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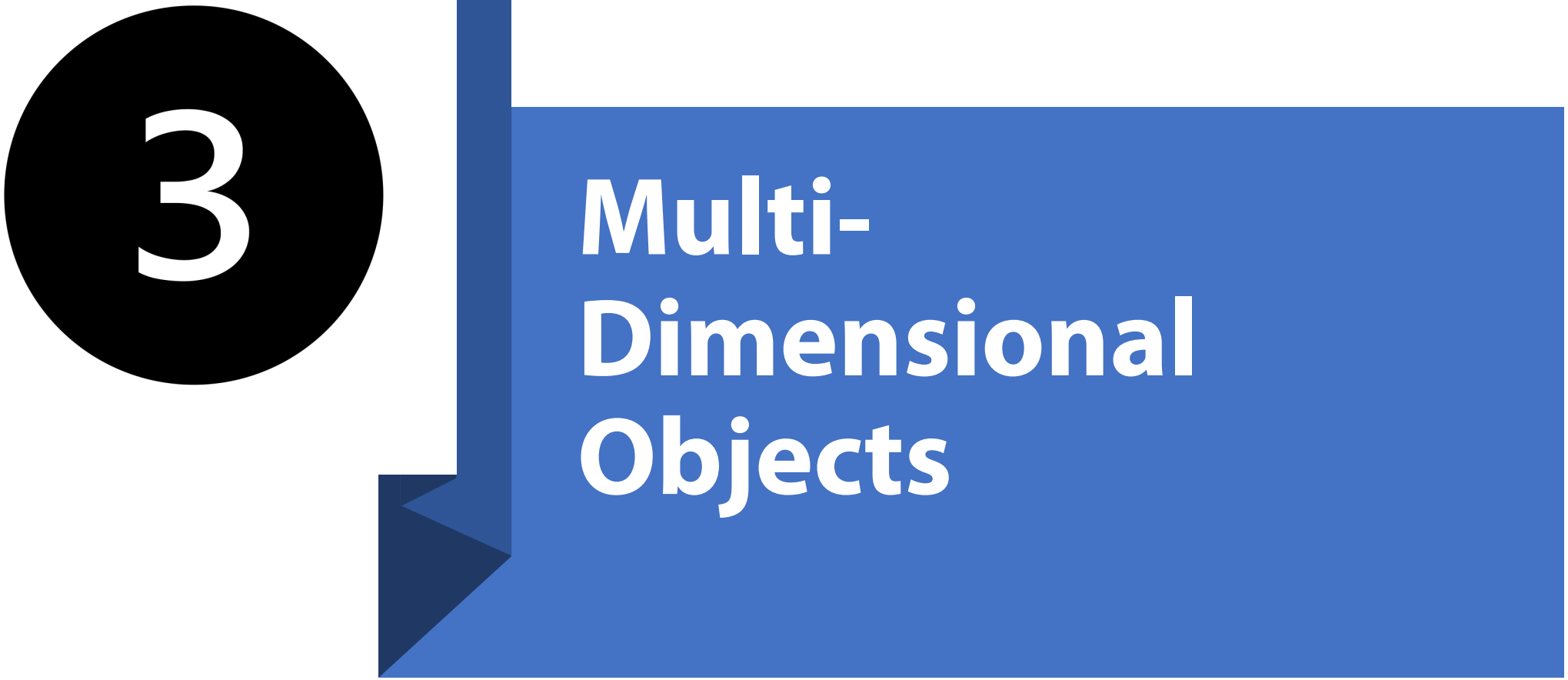
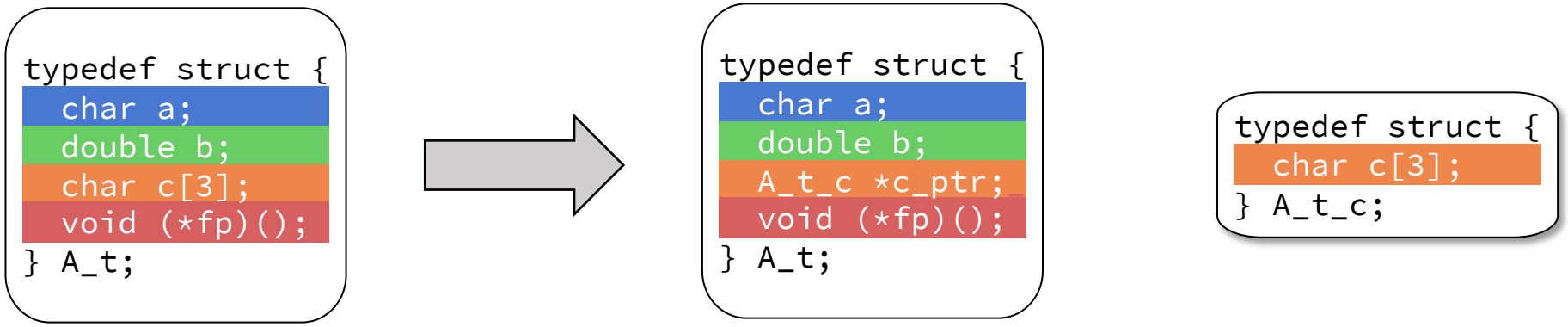

3
Multi-
Dimensional
Objects

Multi-Dimensional Objects

Buf2Ptr Transformation



Multi-Dimensional Objects

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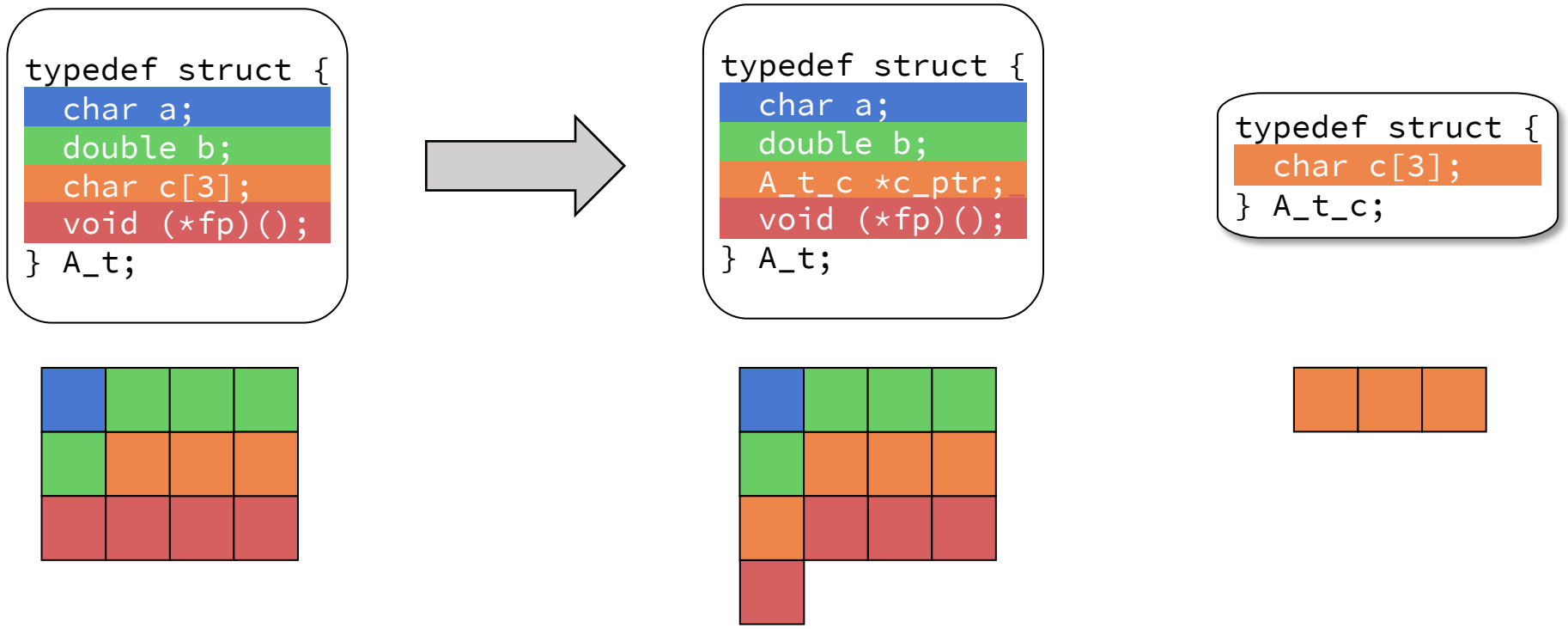

Multi-Dimensional Objects

Allocation & Permutation

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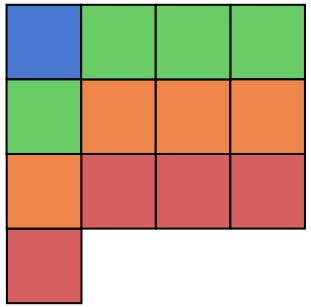
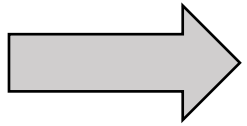
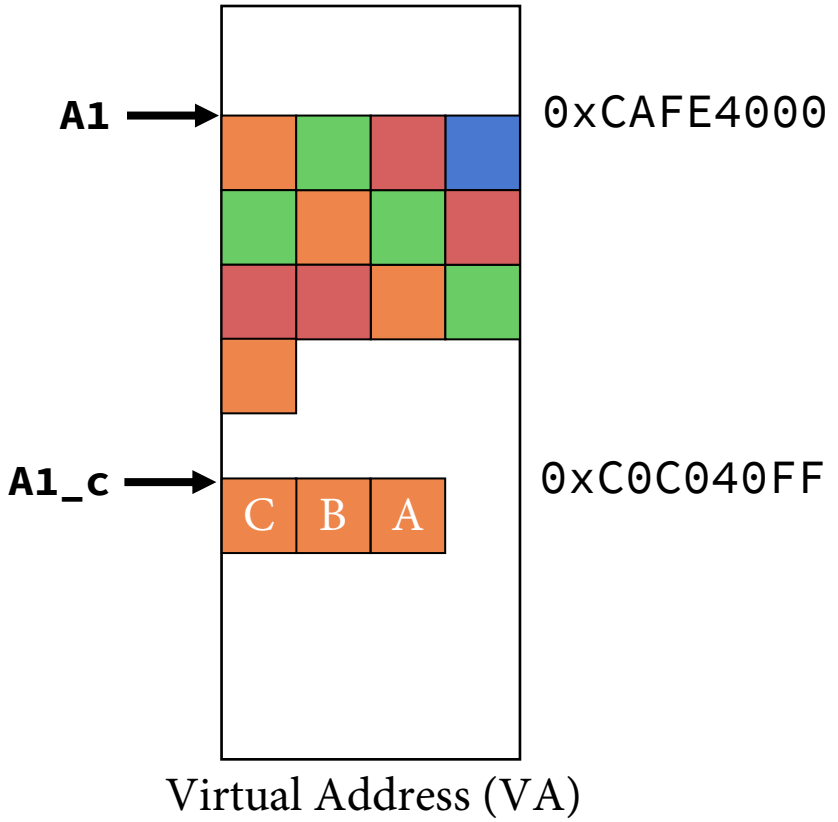
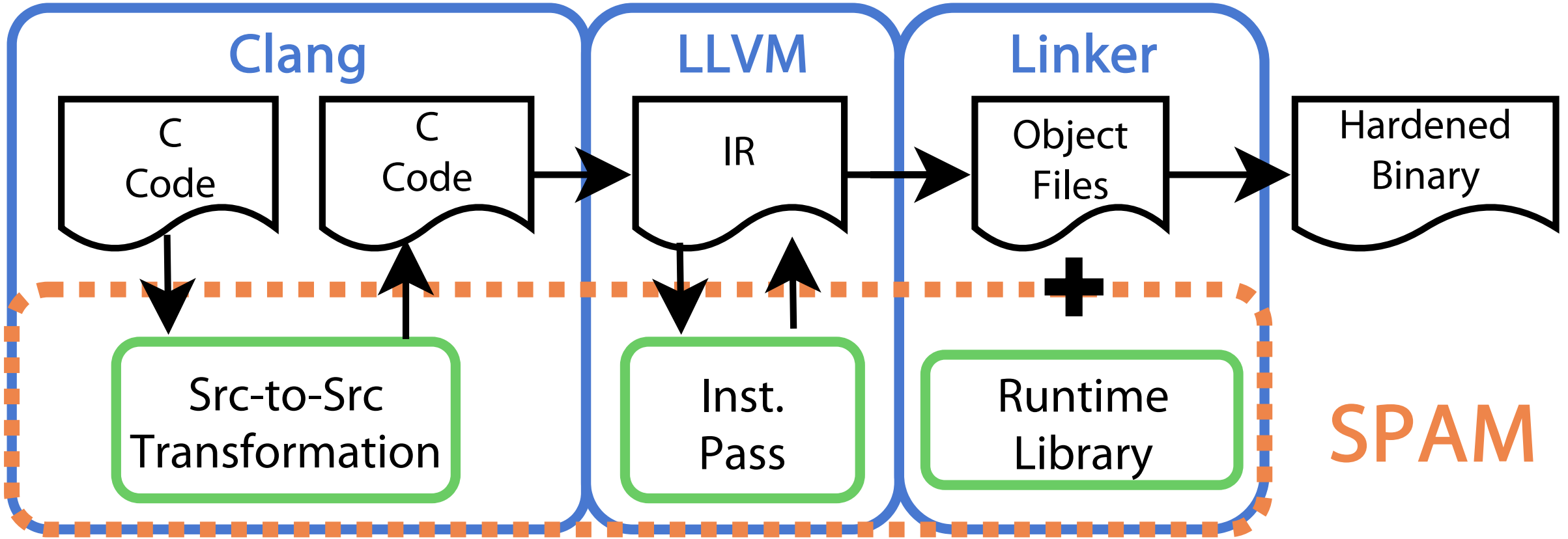




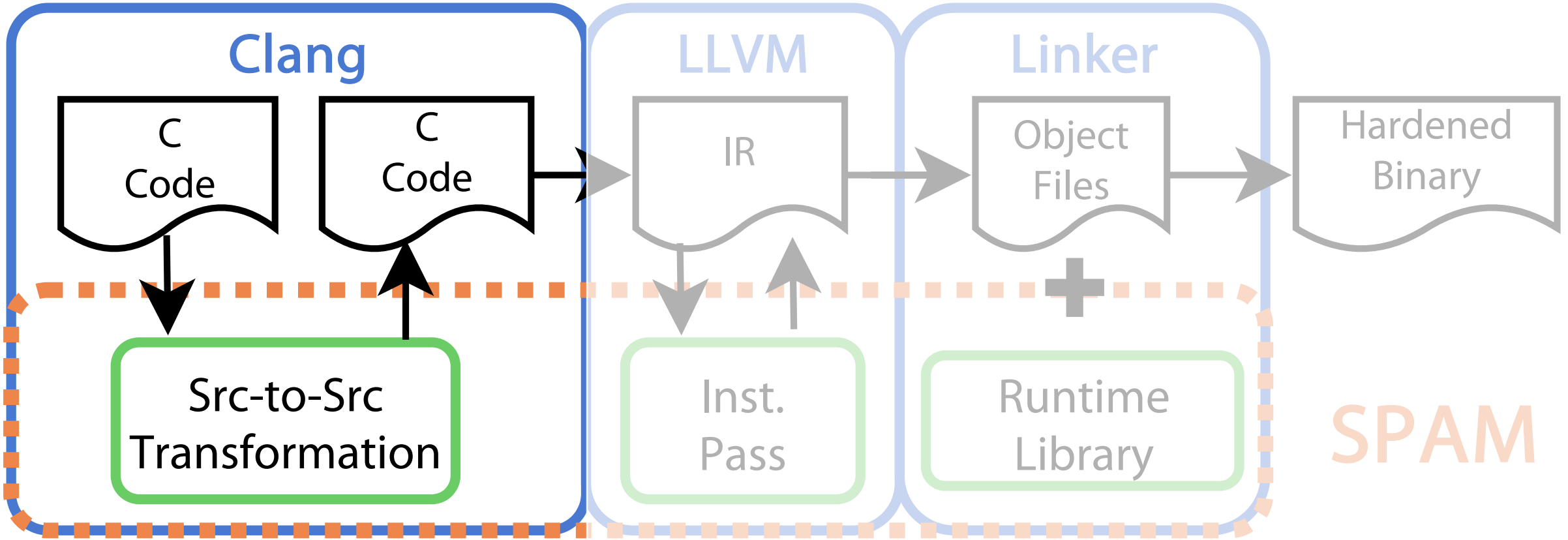


Implementation

Framework


Clang
LLVM
Linker
C Code
C Code
IR
Object Files
Hardened Binary
Src-to-Src Transformation
Inst. Pass
Runtime Library
SPAM

Framework


Clang
C Code
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Buf2Ptr: Source-to-Source Transformation

```
struct Foo {
  char buf[10];
};
```

(a) Original

```
// Promoted Type
struct Foo_buf {
  char buf[10];
};
struct Foo {
  struct Foo_buf *p_buf;
};
```

(b) Transformed

Buf2Ptr: Source-to-Source Transformation

```
struct Foo {
  char buf[10];
};
```

```
// Promoted Type
struct Foo_buf {
  char buf[10];
};
struct Foo {
  struct Foo_buf *p_buf;
};
```

```
struct Foo *f = malloc(
  sizeof(struct Foo));
```

```
// Promoted Allocations
struct Foo *f = malloc(
sizeof(struct Foo));
f->p_buf = malloc(
sizeof(struct Foo_buf));
```

(a) Original

(b) Transformed

Buf2Ptr: Source-to-Source Transformation

```
struct Foo {
  char buf[10];
};
```

```
// Promoted Type
struct Foo_buf {
  char buf[10];
};
struct Foo {
  struct Foo_buf *p_buf;
};
```

```
struct Foo *f = malloc(
  sizeof(struct Foo));
```

```
// Promoted Allocations
struct Foo *f = malloc(
sizeof(struct Foo));
f->p_buf = malloc(
sizeof(struct Foo_buf));
```

```
f->buf[7] = 'A';
```

```
// Promoted Usages
f->p_buf->buf[7] = 'A';
```

(a) Original

(b) Transformed

Buf2Ptr: Source-to-Source Transformation

```
struct Foo {
  char buf[10];
};
```

```
struct Foo *f = malloc(
  sizeof(struct Foo));
```

```
f->buf[7] = 'A';
```

```
free(f);
```

(a) Original

```
// Promoted Type
struct Foo_buf {
  char buf[10];
};
struct Foo {
  struct Foo_buf *p_buf;
};
```

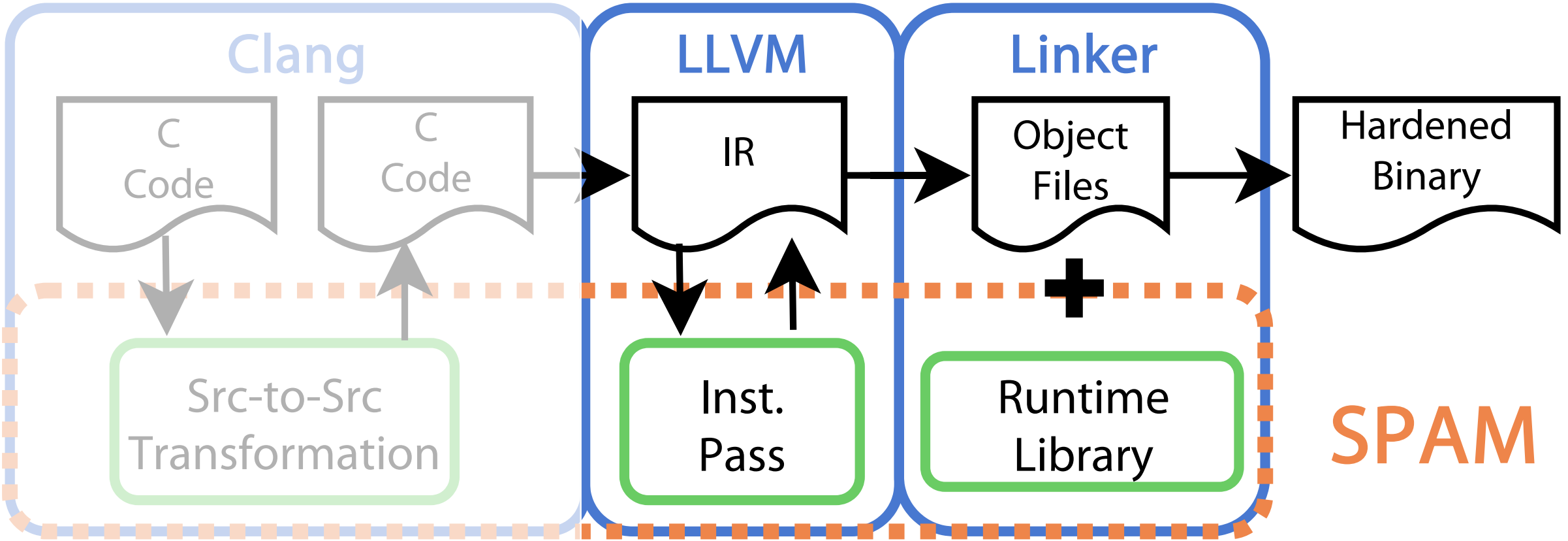
```
// Promoted Allocations
struct Foo *f = malloc(
sizeof(struct Foo));
f->p_buf = malloc(
sizeof(struct Foo_buf));
```

```
// Promoted Usages
f->p_buf->buf[7] = 'A';
```

```
// Promoted Deallocations
free(f->p_buf);
free(f);
```

(b) Transformed

Framework

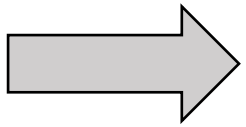

Clang
C Code
C Code
Src-to-Src Transformation
LLVM
IR
Inst. Pass
Linker
Object Files
Runtime Library
Hardened Binary
SPAM

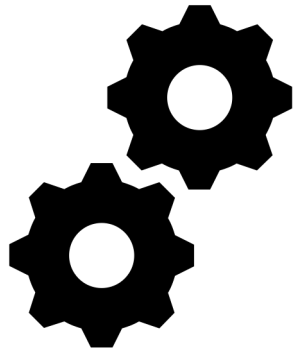
Instrumentation & Runtime

```c
#include <stdio.h>
#include <stdlib.h>

int main()
{
    char *p = malloc(128);
    *p = 'A';
    printf("%c\n", *p);
    return 0;
}
```

Instrumentation & Runtime

```c
#include <stdio.h>
#include <stdlib.h>

int main()
{
    char *p = malloc(128);
    *p = 'A';
    printf("%c\n", *p);
    return 0;
}
```





Baseline Compilation

Flags: `-O0`

Instrumentation & Runtime

```c
#include <stdio.h>
#include <stdlib.h>

int main()
{
    char *p = malloc(128);
    *p = 'A';
    printf("%c\n", *p);
    return 0;
}
```

```
define i32 @main() {
  %ptr = call i8* @malloc(i64 128)



  store i8 65, i8* %ptr, align 1



  %load = load i8, i8* %ptr, align 1

  %conv = sext i8 %load to i32
  %print = call i32 (i8*, ...) @printf(i8*
           getelementptr inbounds ([4 x
           i8], [4 x i8]* @.str, i32 0, i32 0),
           i32 %conv)
  ret i32 0
}
```

Instrumentation & Runtime

```c
#include <stdio.h>
#include <stdlib.h>

int main()
{
    char *p = malloc(128);
    *p = 'A';
    printf("%c\n", *p);
    return 0;
}
```

```
define i32 @main() {
  %ptr = call i8* @malloc(i64 128)



  store i8 65, i8* %ptr, align 1



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  %conv = sext i8 %load to i32
  %print = call i32 (i8*, ...) @printf(i8*
           getelementptr inbounds ([4 x
           i8], [4 x i8]* @.str, i32 0, i32 0),
           i32 %conv)
  ret i32 0
}
```
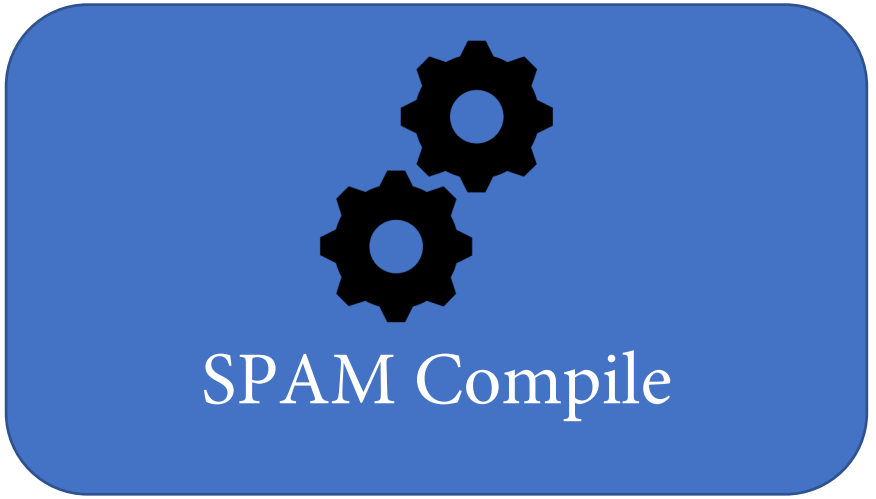



Instrumentation & Runtime

SPAM Runtime

```c
#include <stdio.h>
#include <stdlib.h>

int main()
{
    char *p = malloc(128);
    *p = 'A';
    printf("%c\n", *p);
    return 0;
}
```

```
define i32 @main() {
  %ptr = call i8* @spam_malloc(i64 128)

  %store_off = call i8* @spam_get_perm_offset(i8* %ptr, i8* %ptr)

  store i8 65, i8* %store_off, align 1

  %load_off = call i8* @spam_get_perm_offset(i8* %ptr, i8* %ptr)

  %load = load i8, i8* %load_off, align 1

  %conv = sext i8 %load to i32
  %print = call i32 (i8*, ...) @printf(i8*
           getelementptr inbounds ([4 x
           i8], [4 x i8]* @.str, i32 0, i32 0),
           i32 %conv)
  ret i32 0
}
```

Instrumentation & Runtime

To tag/untag Alias Number from pointer.

```c
#include <stdio.h>
#include <stdlib.h>

int main()
{
    char *p = malloc(128);
    *p = 'A';
    printf("%c\n", *p);
    return 0;
}
```

```
define i32 @main() {
  %ptr = call i8* @spam_malloc(i64 128)

  %store_off = call i8* @spam_get_perm_offset(i8* %ptr, i8* %ptr)

  store i8 65, i8* %store_off, align 1

  %load_off = call i8* @spam_get_perm_offset(i8* %ptr, i8* %ptr)

  %load = load i8, i8* %load_off, align 1

  %conv = sext i8 %load to i32
  %print = call i32 (i8*, ...) @printf(i8*
           getelementptr inbounds ([4 x
           i8], [4 x i8]* @.str, i32 0, i32 0),
           i32 %conv)
  ret i32 0
}
```

Instrumentation & Runtime

Returns pointer with calculated permuted offset.

```c
#include <stdio.h>
#include <stdlib.h>

int main()
{
    char *p = malloc(128);
    *p = 'A';
    printf("%c\n", *p);
    return 0;
}
```

```
define i32 @main() {
  %ptr = call i8* @spam_malloc(i64 128)

  %store_off = call i8* @spam_get_perm_offset(i8* %ptr, i8* %ptr)

  store i8 65, i8* %store_off, align 1

  %load_off = call i8* @spam_get_perm_offset(i8* %ptr, i8* %ptr)

  %load = load i8, i8* %load_off, align 1

  %conv = sext i8 %load to i32
  %print = call i32 (i8*, ...) @printf(i8*
           getelementptr inbounds ([4 x
           i8], [4 x i8]* @.str, i32 0, i32 0),
           i32 %conv)
  ret i32 0
}
```

Instrumentation & Runtime

Global Support

```
void RegisterGlobal(void *Ptr)
```

For `.data` section hook into `.ctor` to permute on program load.

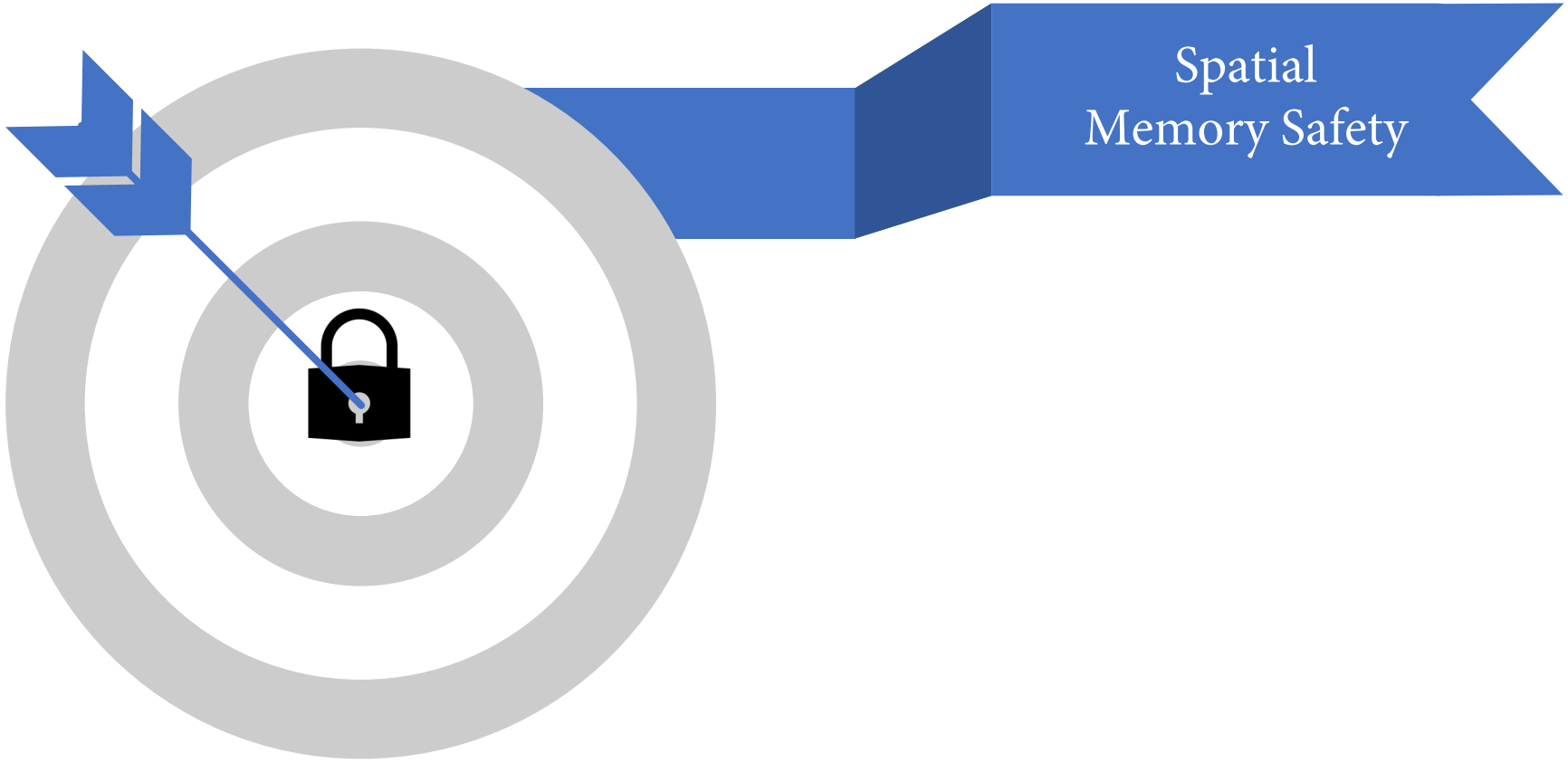
Stack Support

```
void *RegisterStack(void *Ptr)
```

For variables passed by OS (e.g. `argv`) hook into `main` to permute on start.

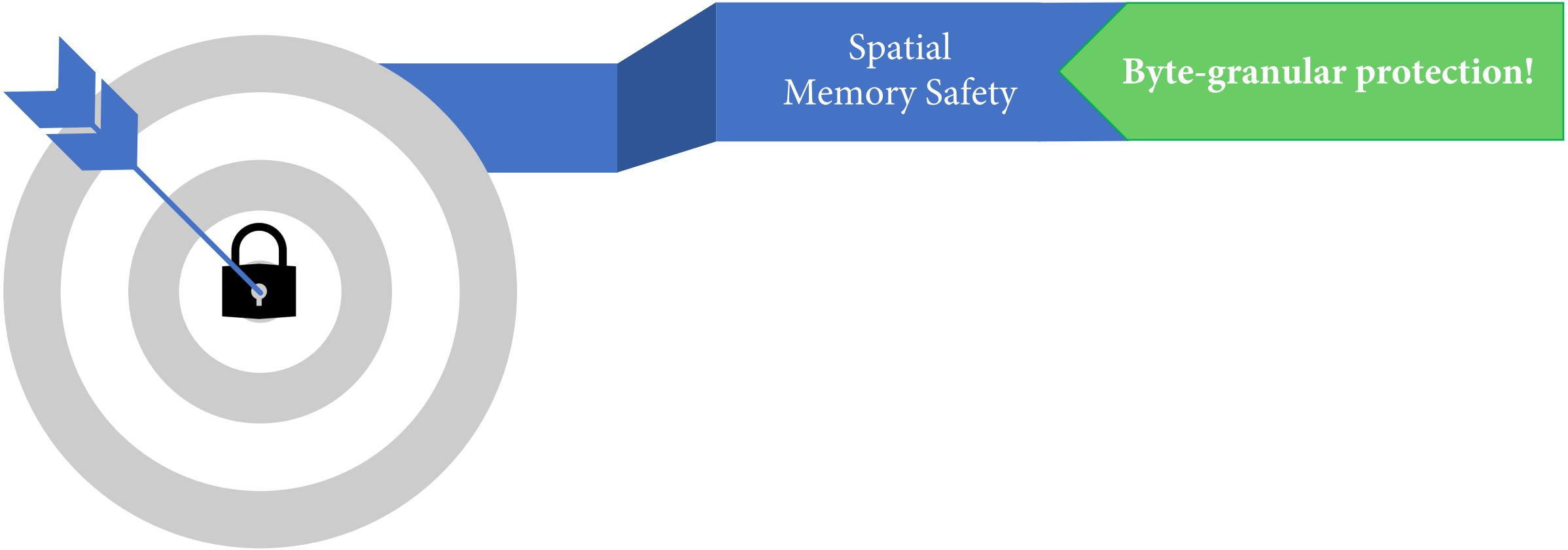
Why SPAM?

SPAM Benefits

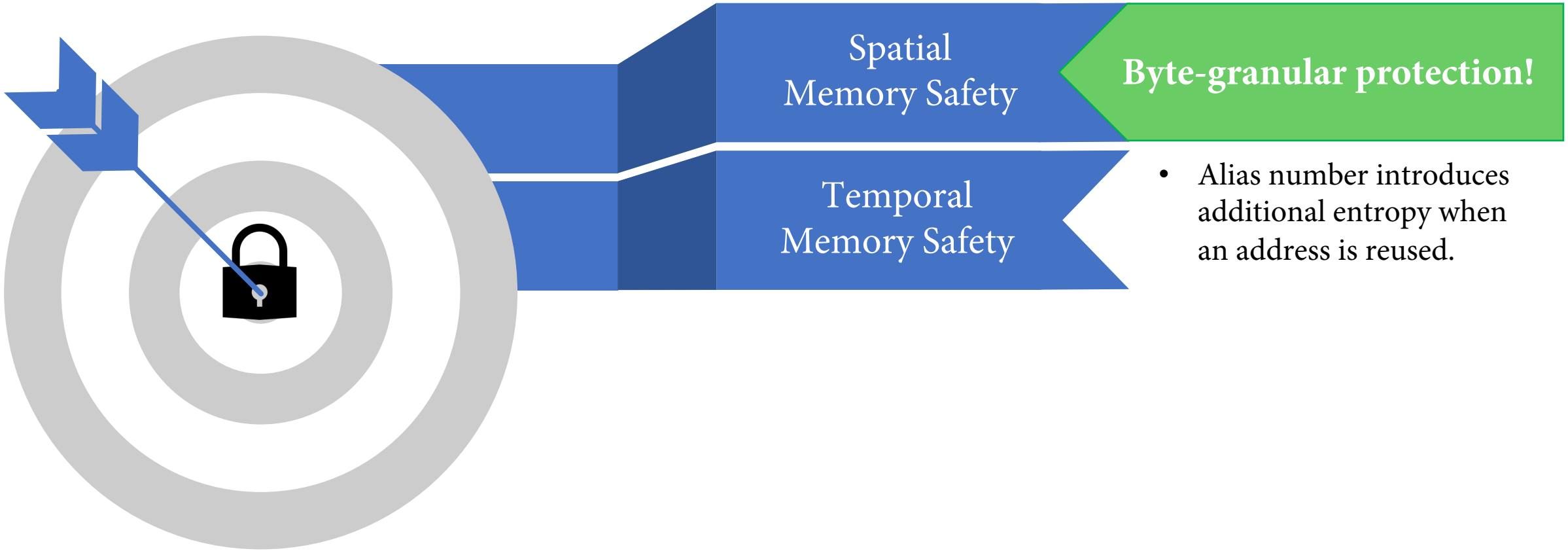


- Every object instance (allocation) is permuted independently.
- Overflows within an object (intra) are transformed.

SPAM Benefits

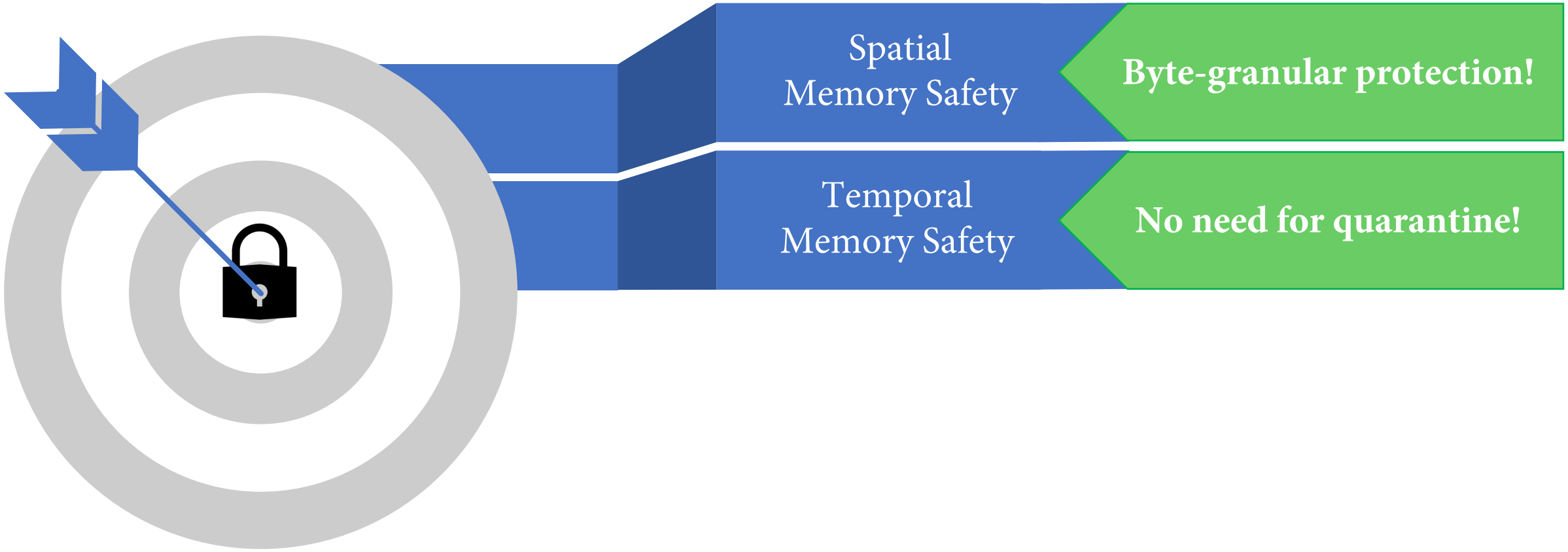


SPAM Benefits

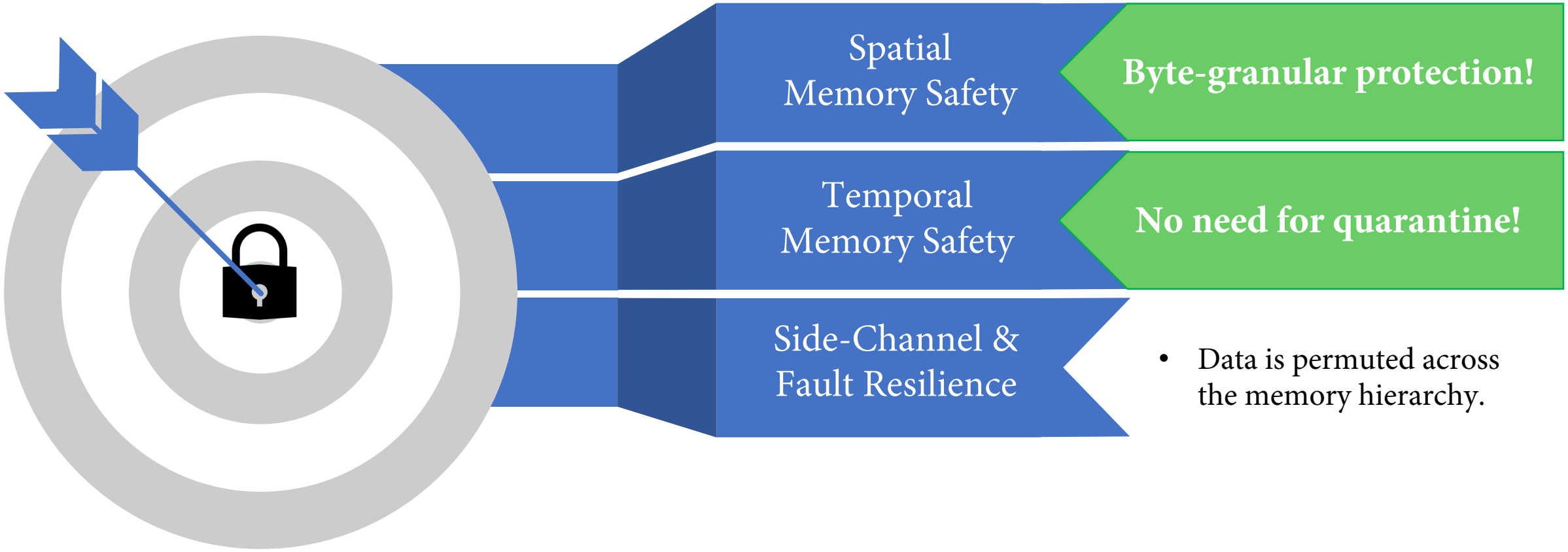


- Alias number introduces additional entropy when an address is reused.

SPAM Benefits

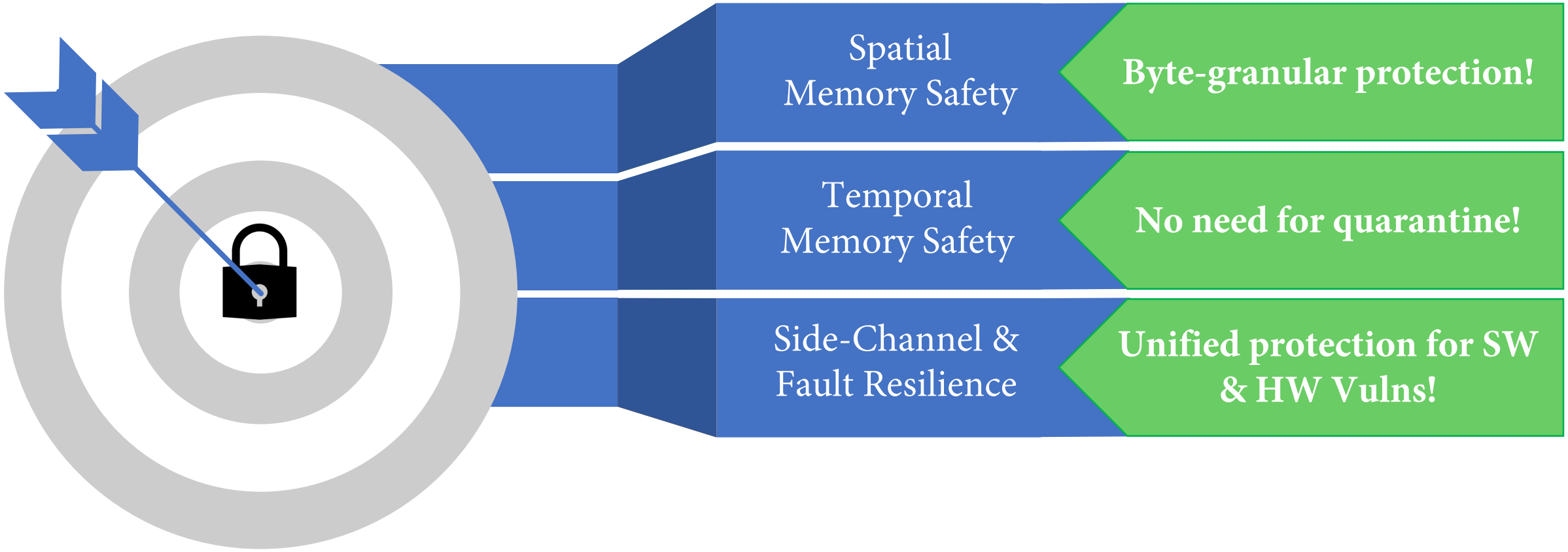


SPAM Benefits

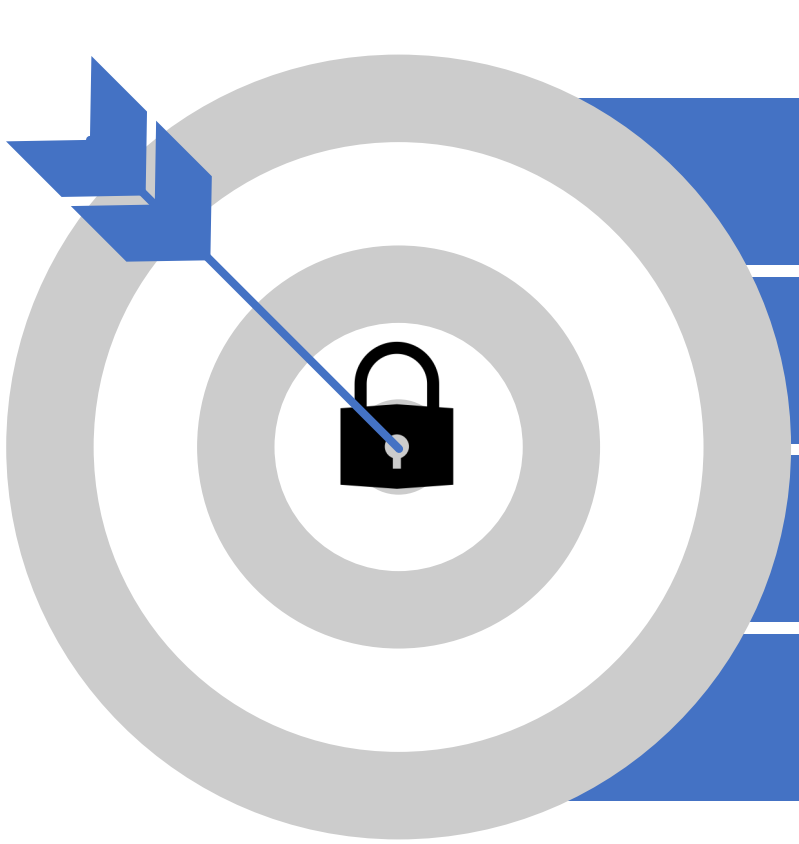


- Data is permuted across the memory hierarchy.

SPAM Benefits



SPAM Benefits



Spatial Memory Safety

Byte-granular protection!

Temporal Memory Safety

No need for quarantine!

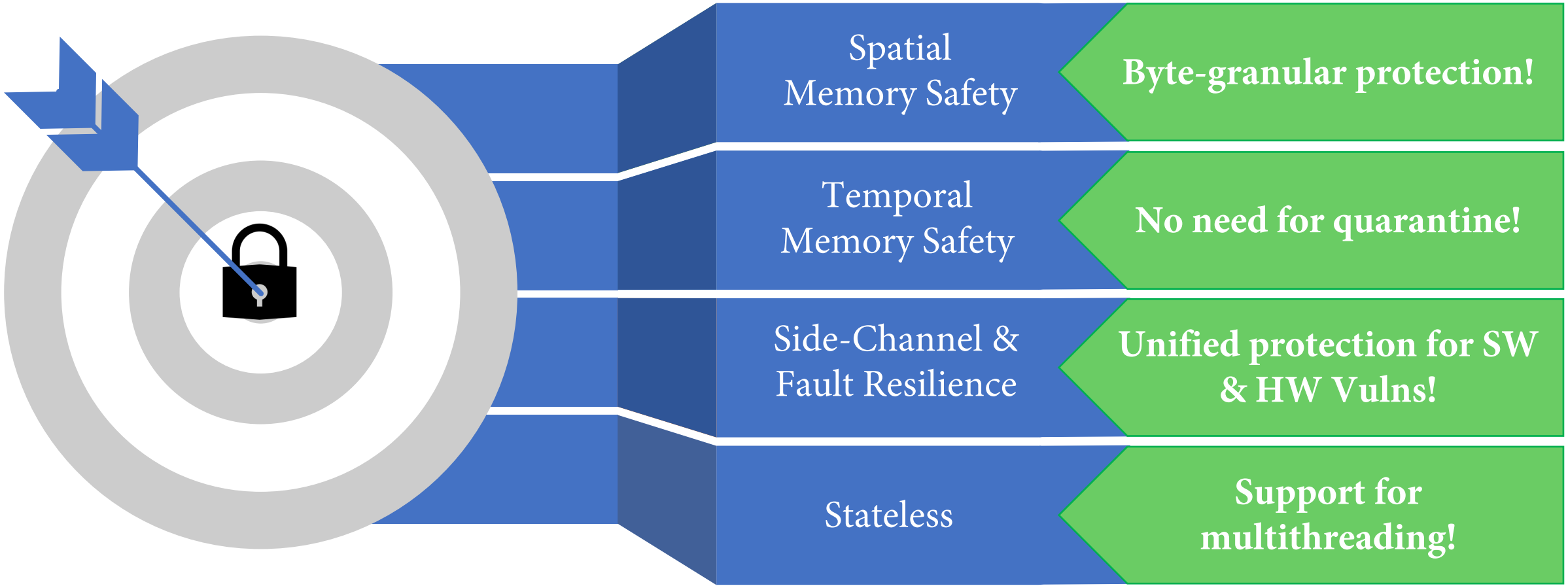
Side-Channel & Fault Resilience

Unified protection for SW & HW Vulns!

Stateless

- No opportunity for manipulation by an attacker.

SPAM Benefits



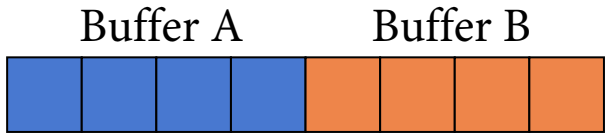
Resilience to Common Exploits

Resilience to Common Exploits

1

Buffer Over-/Under-flows

Cannot reliably corrupt memory.

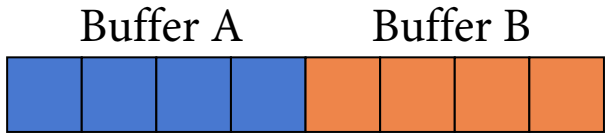


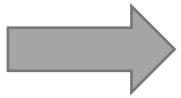
Resilience to Common Exploits

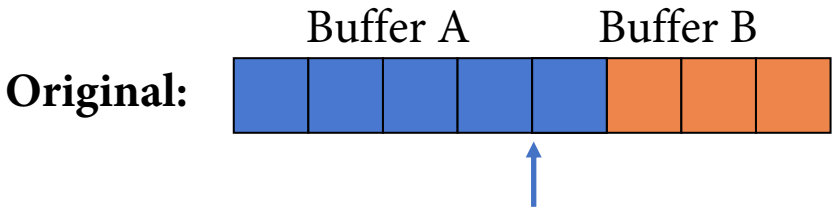
1

Buffer Over-/Under-flows

Cannot reliably corrupt memory.





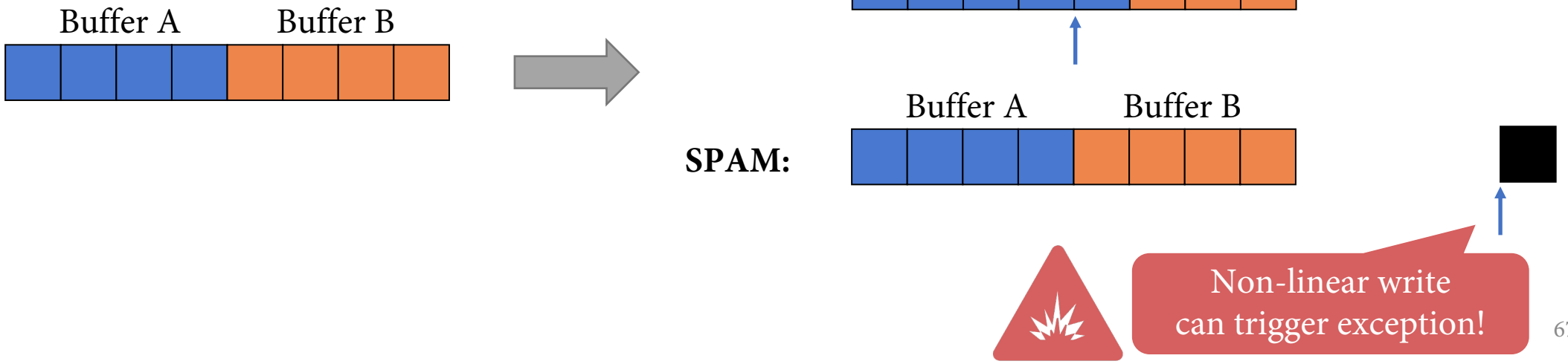


Resilience to Common Exploits

1

Buffer Over-/Under-flows

Cannot reliably corrupt memory.

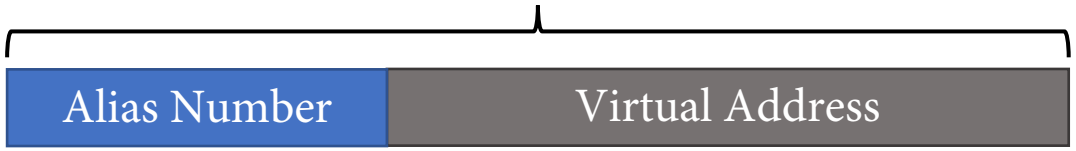


Resilience to Common Exploits

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

2. **Use-after-free**
   Each instance permutated independently.

Alias number provides multiple permutations.



Resilience to Common Exploits

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

2. **Use-after-free**
   Each instance permutated independently.

3. **Speculative Attacks**
   Speculative load uses a different permutation to access the permuted data.

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

  secret = a[i];

  // secret is leaked
  val = b[64 * secret];
}
```

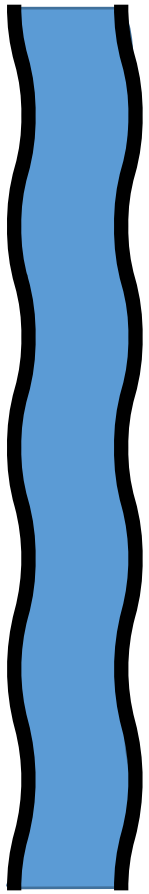
Unpredictable!

- Attacker will end up with an unpredictable value in `secret` due as the permutation depends on the address of `a[i]`.

SPAM Meets Reality

SPAM Meets Reality

Compatibility with Uninstrumented Code



SPAM
Permuted Domain

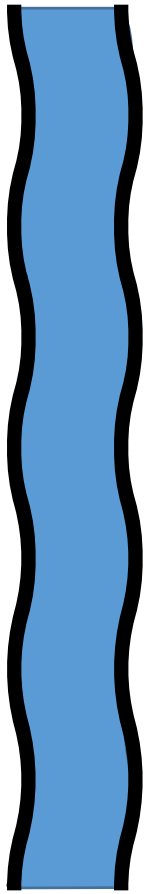
External
Unpermuted Domain

SPAM Meets Reality

Compatibility with Uninstrumented Code

```c
#include <stdio.h>
#include <stdlib.h>

int main()
{
    char *p = malloc(128);
    *p = 'A';
    printf("%c\n", *p);
    return 0;
}
```

SPAM
Permuted Domain

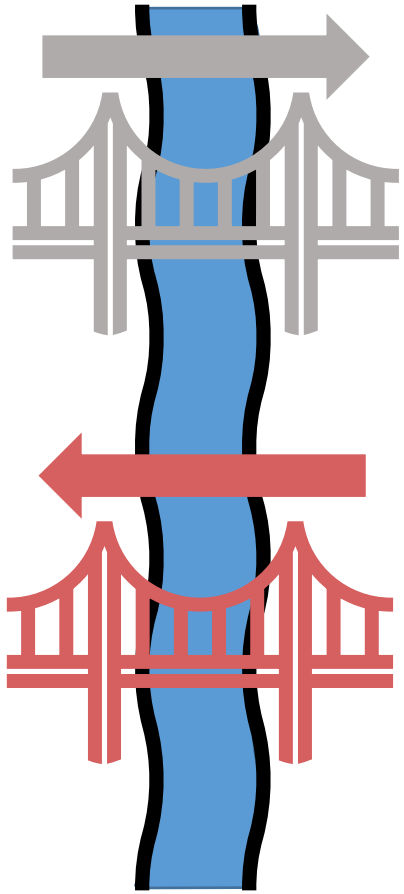


```c
int printf(const char *fmt, ...) {
    int err;

    va_list ap;
    va_start(ap, fmt);
    err = _dvprintf(fmt, ap);
    va_end(ap);

    return err;
}
```

External
Unpermuted Domain

SPAM Meets Reality

Compatibility with Uninstrumented Code

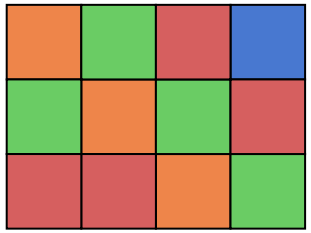


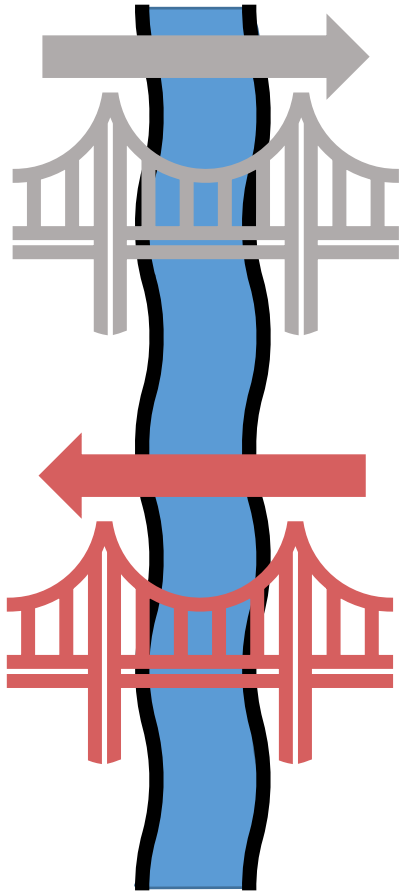
SPAM
Permuted Domain

External
Unpermuted Domain

SPAM Meets Reality

Compatibility with Uninstrumented Code





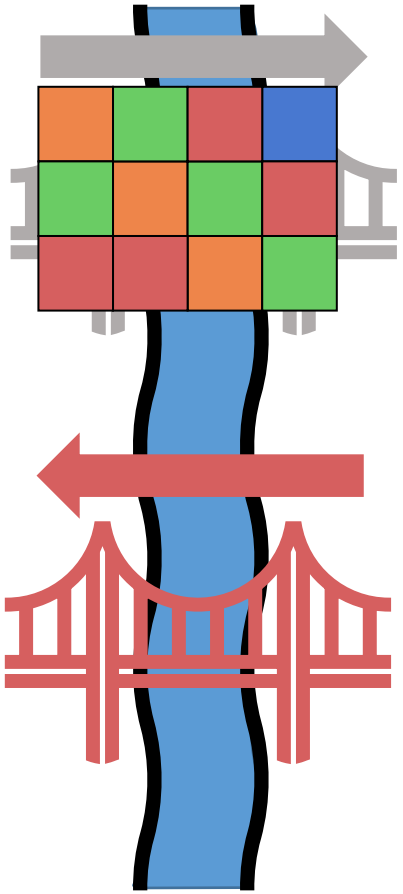
Other Memory

SPAM Permuted Domain

External Unpermuted Domain

SPAM Meets Reality

Compatibility with Uninstrumented Code



Other Memory

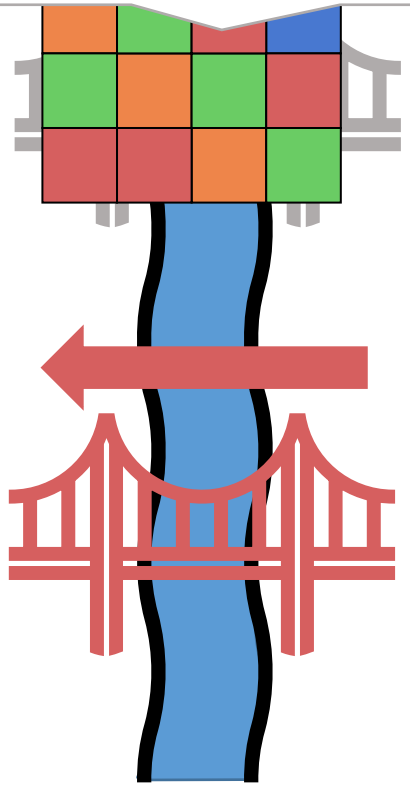
SPAM Permuted Domain

External Unpermuted Domain

SPAM Meets Reality

Compatibility with Uninstrumented Code

```
void *Unpermute(void *Ptr)
```



Other Memory

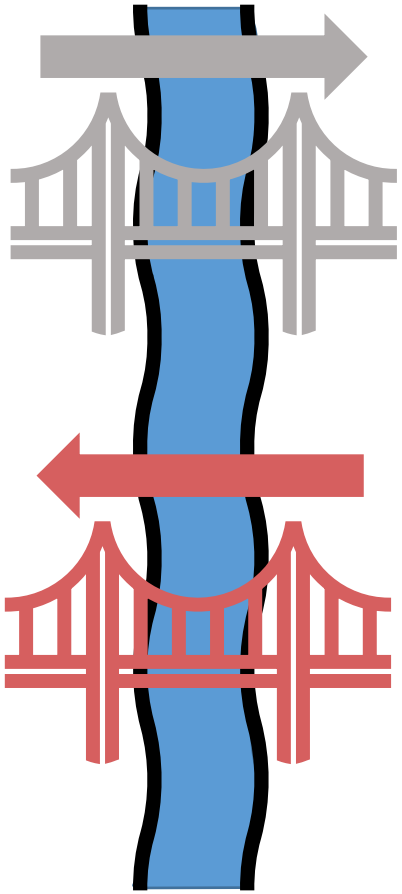
SPAM
Permuted Domain

External
Unpermuted Domain

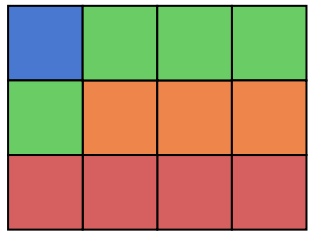
SPAM Meets Reality

Compatibility with Uninstrumented Code

Other Memory



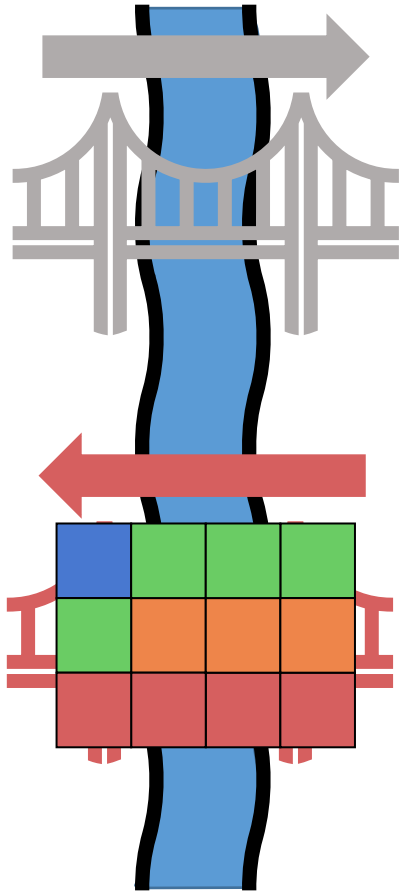
SPAM
Permuted Domain



External
Unpermuted Domain

SPAM Meets Reality

Compatibility with Uninstrumented Code



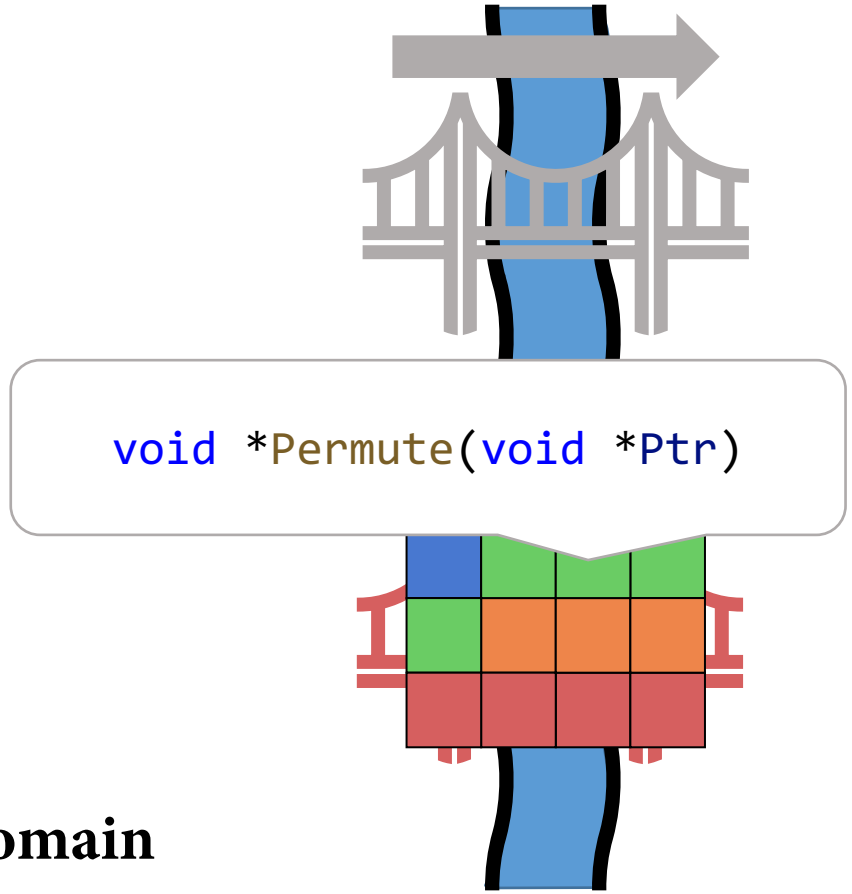
Other Memory

SPAM Permuted Domain

External Unpermuted Domain

SPAM Meets Reality

Compatibility with Uninstrumented Code



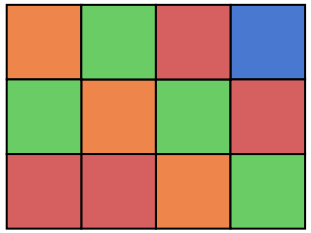
Other Memory

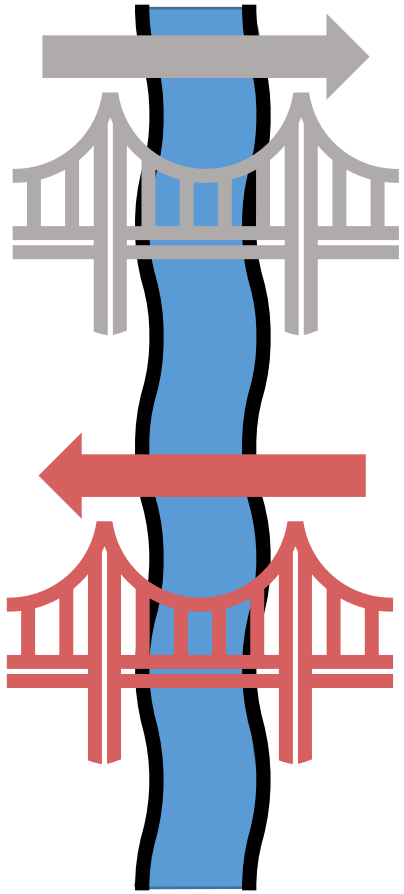
SPAM Permuted Domain

External Unpermuted Domain

SPAM Meets Reality

Compatibility with Uninstrumented Code





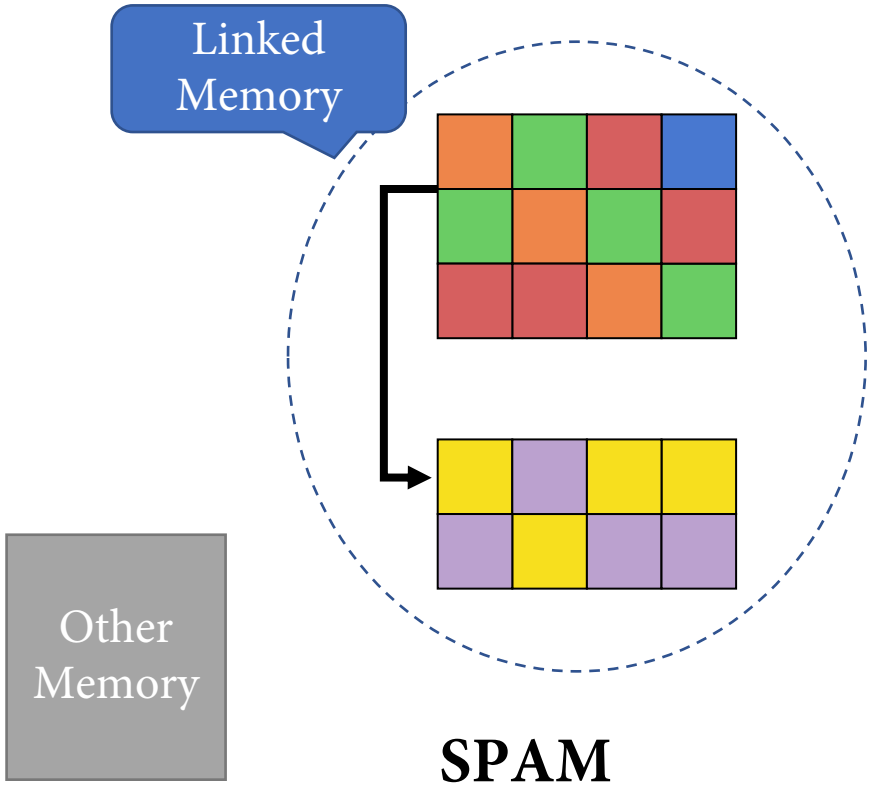
Other Memory

SPAM Permuted Domain

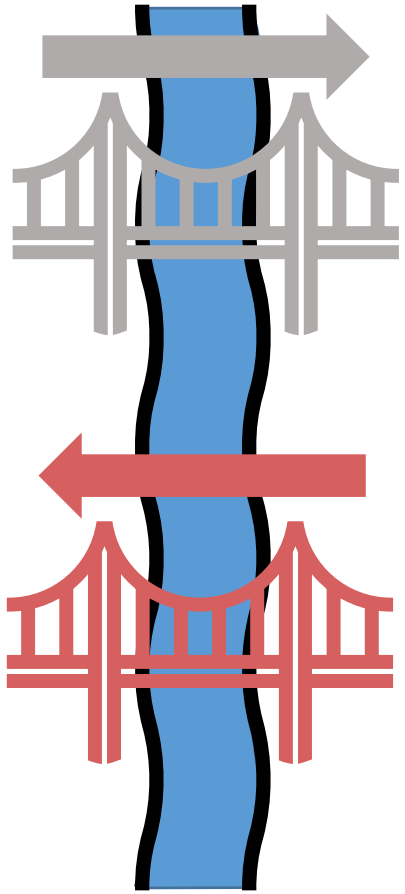
External Unpermuted Domain

SPAM Meets Reality

Compatibility with Uninstrumented Code



SPAM Permuted Domain



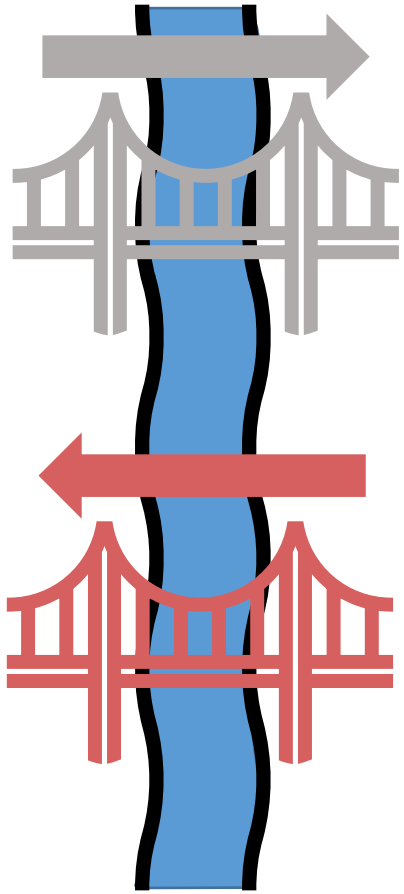
External Unpermuted Domain

SPAM Meets Reality

Compatibility with Uninstrumented Code

```
int cmp (const void * a,
         const void * b) {...}

int main() {
    ...
    qsort(b, 10, 10, cmp);
    ...
}
```

SPAM
Permuted Domain



```
void qsort(void *base,
           size_t nitems,
           size_t size,
int (*cmp)(const void *, const void*))
{...}
```

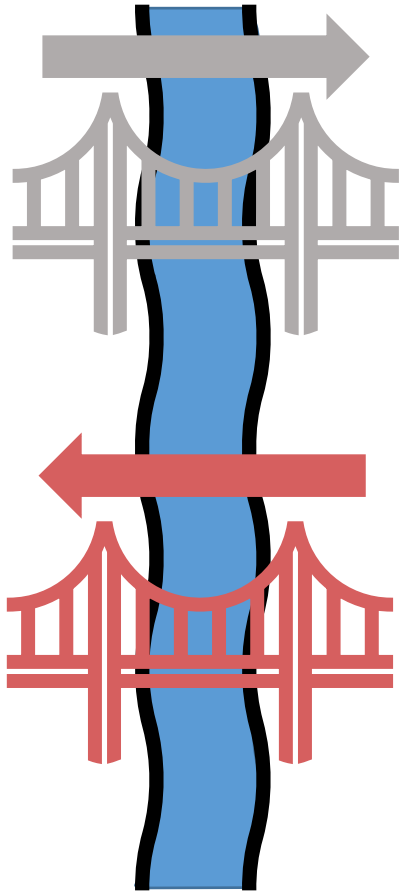
External
Unpermuted Domain

SPAM Meets Reality

Compatibility with Uninstrumented Code

```
int cmp (const void * a,
         const void * b) {...}

int main() {
    ...
    qsort(b, 10, 10, cmp);
    ...
}
```

SPAM
Permuted Domain



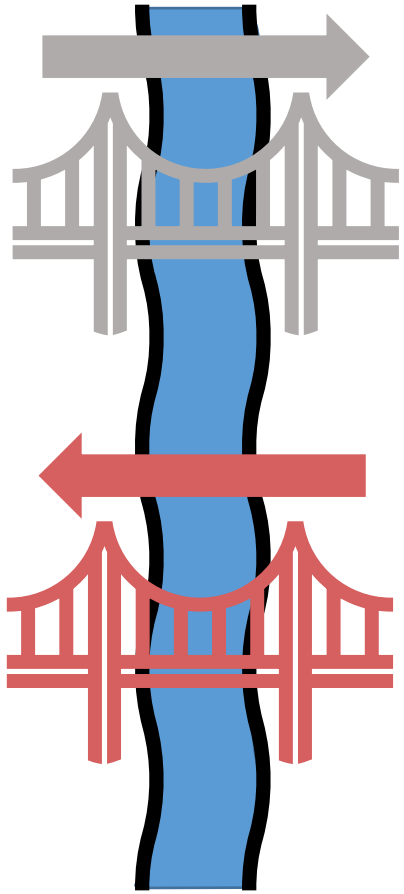
```
void qsort(void *base,
           size_t nitems,
           size_t size,
int (*cmp)(const void *, const void*))
{...}
```

External
Unpermuted Domain

SPAM Meets Reality

Compatibility with Uninstrumented Code

```
int cmp (const void * a,
         const void * b) {...}

int main() {
    ...
    qsort(b, 10, 10, cmp);
    ...
}
```



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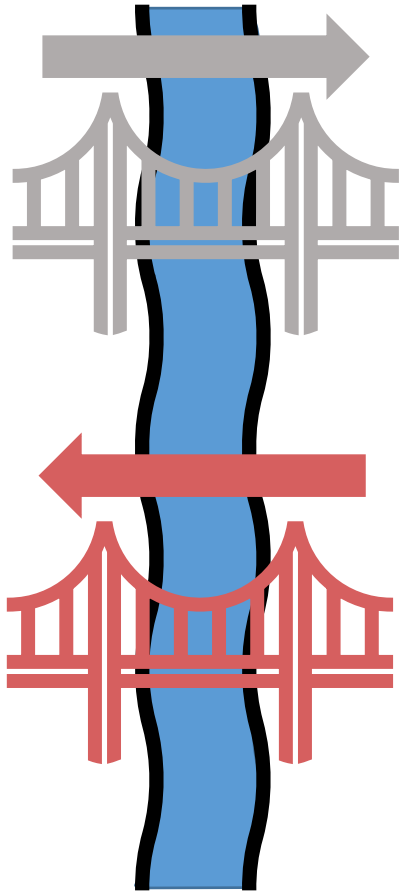

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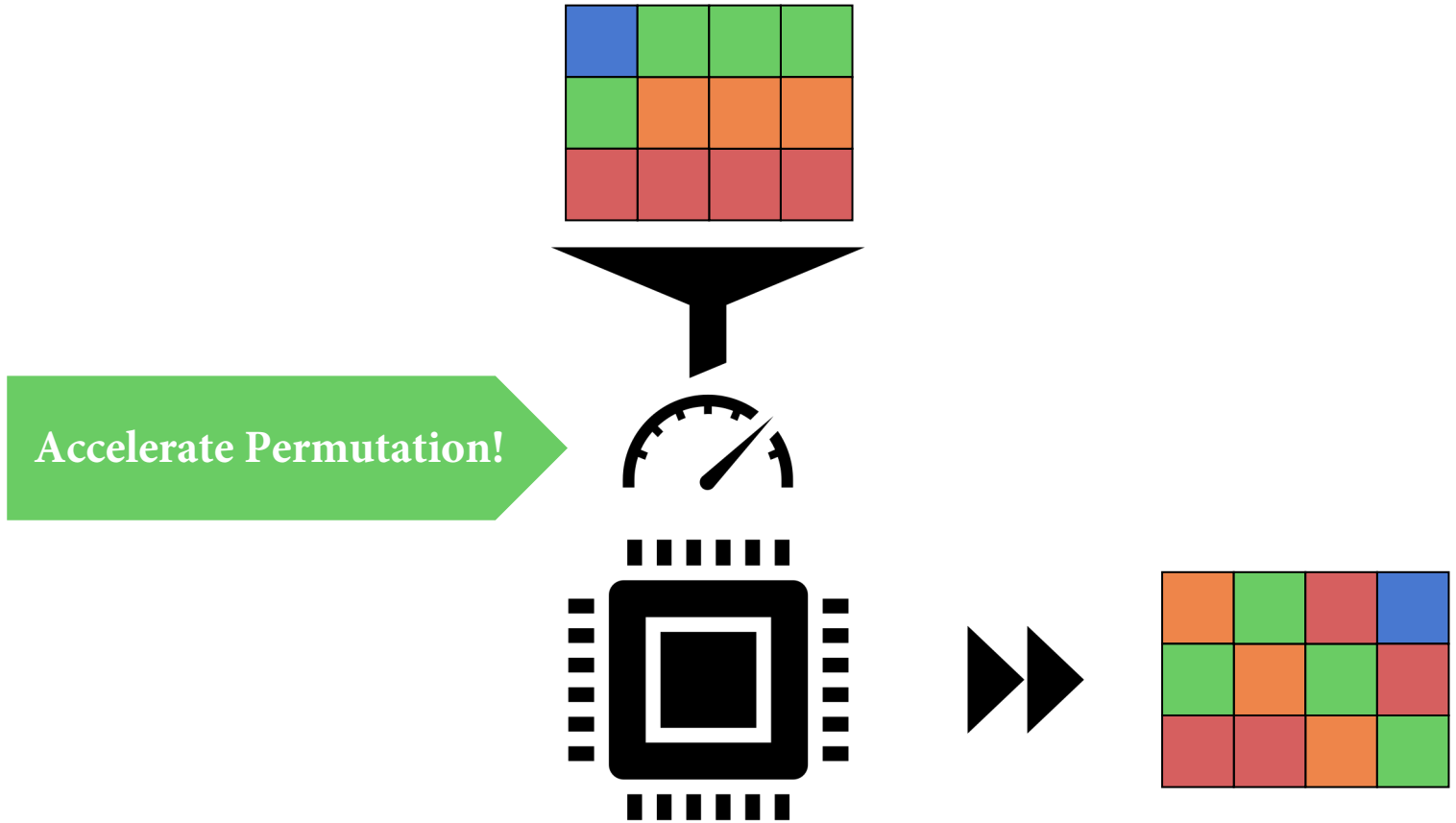
Hardware Support



SPAM Meets Reality

Hardware Support

```
%store_off = call i8* @spam_get_perm_offset(i8* %ptr, i8* %ptr)

store i8 65, i8* %store_off, align 1

%load_off = call i8* @spam_get_perm_offset(i8* %ptr, i8* %ptr)

%load = load i8, i8* %load_off, align 1
```

SPAM Meets Reality

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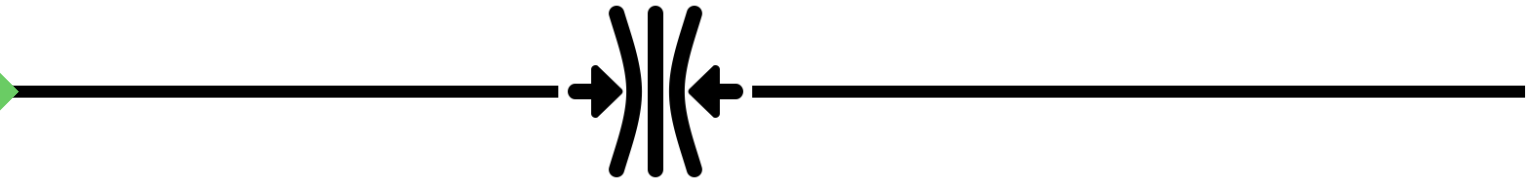
Reduce resource pressure!



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spam_store i8 65, i8* %ptr, align 1
%load = spam_load i8, i8* %ptr, align 1
```

Other Mitigations

Other Mitigations

- *ARM MTE*
  - Memory & pointers are tagged with colors.

Source: *ARM v8.5A - https://developer.arm.com/-/media/Arm%20Developer%20Community/PDF/Arm_Memory_Tagging_Extension_Whitepaper.pdf*

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Limited set of colors.

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Vulnerable to intra-object
&
type confusion.

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- *ARM MTE*
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- *Checked C*
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No temporal protection.

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Other Mitigations

No Hardware Side-Channel Resilience!

Prototype Results

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Average Performance Overheads

~2.11x overhead

2017

- C only subset of programs.

~1.4x overhead

- 2019 HTTP Archive Web Almanac workload.

~3.15x overhead

((o) Duktape

- Google Chrome's Octane 2 Benchmark Suite

~2.48x overhead

- Included Wolfcrypt benchmarks.

Unsupported Functionality

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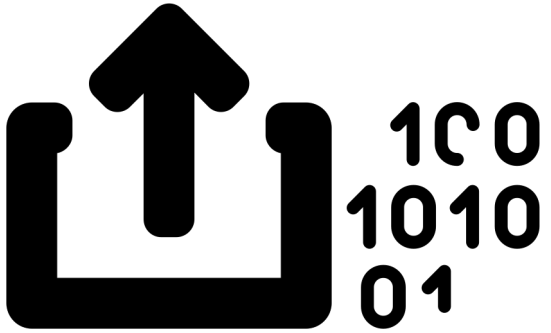
- *Inline Assembly*
  - Can be handled with lifting or (un)permute primitives.



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- *Variadic Functions*
  - Invoking functions with `va_list` as an argument (e.g. `vsprintf`) are unsupported.

```
void my_printf(const char *fmt, ...
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    char buffer[256];

    va_list ap;
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`va_list` is passed to external functions!

SPAM (in a nutshell)

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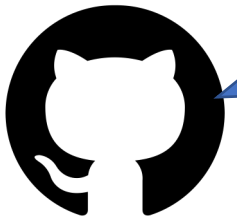
PAPER



Currently available upon request!

Checkout our technical report on Arxiv!
https://arxiv.org/abs/2007.13808