black hat EUROPE 2016

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Bypassing clang's SafeStack for Fun and Profit

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Outline

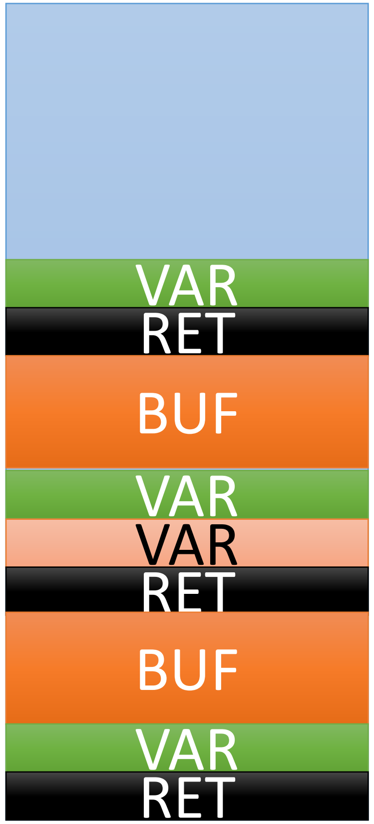
- SafeStack
- Neglected Pointers
- Thread Spraying
- Allocation Oracles
- Conclusion

SafeStack

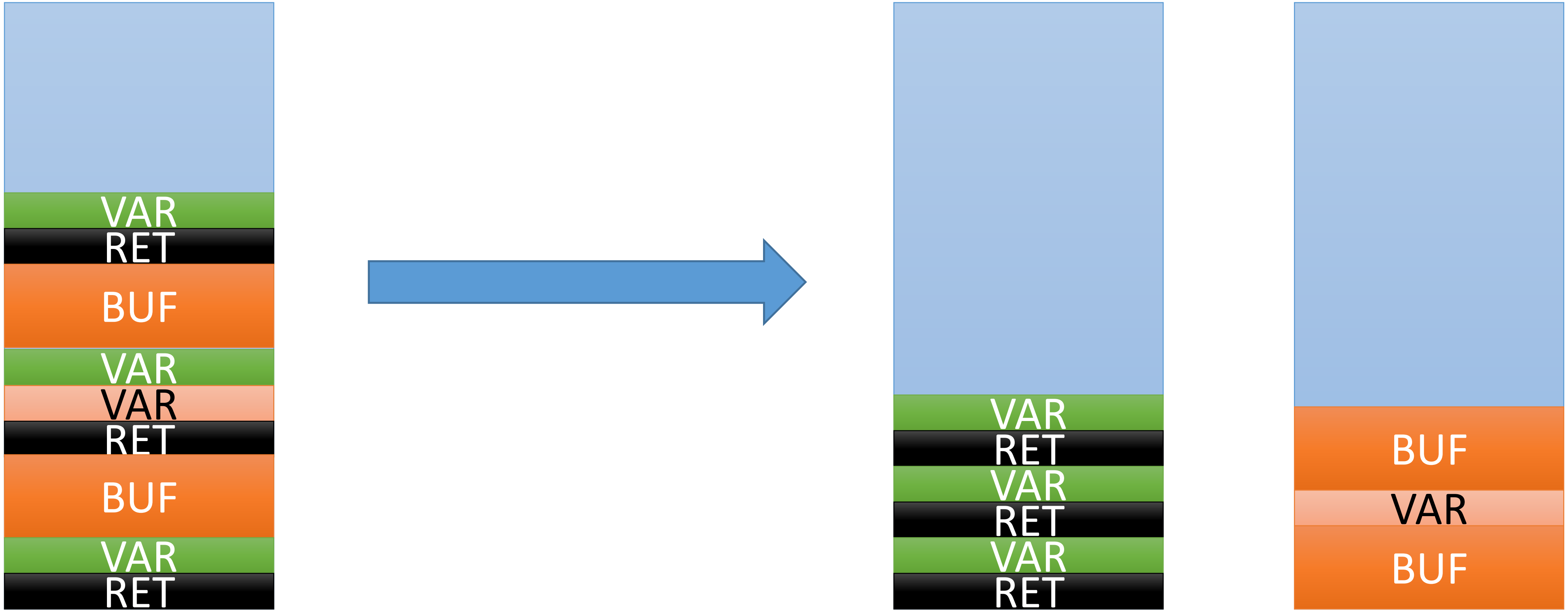
- New security feature in LLVM
- Protect against stack based control-flow hijacks

- In research proposals:
  - Code-Pointer Integrity (Kuznetsov et al., 2014) (origin SafeStack)
  - ASLR-Guard (Lu et al., 2015)

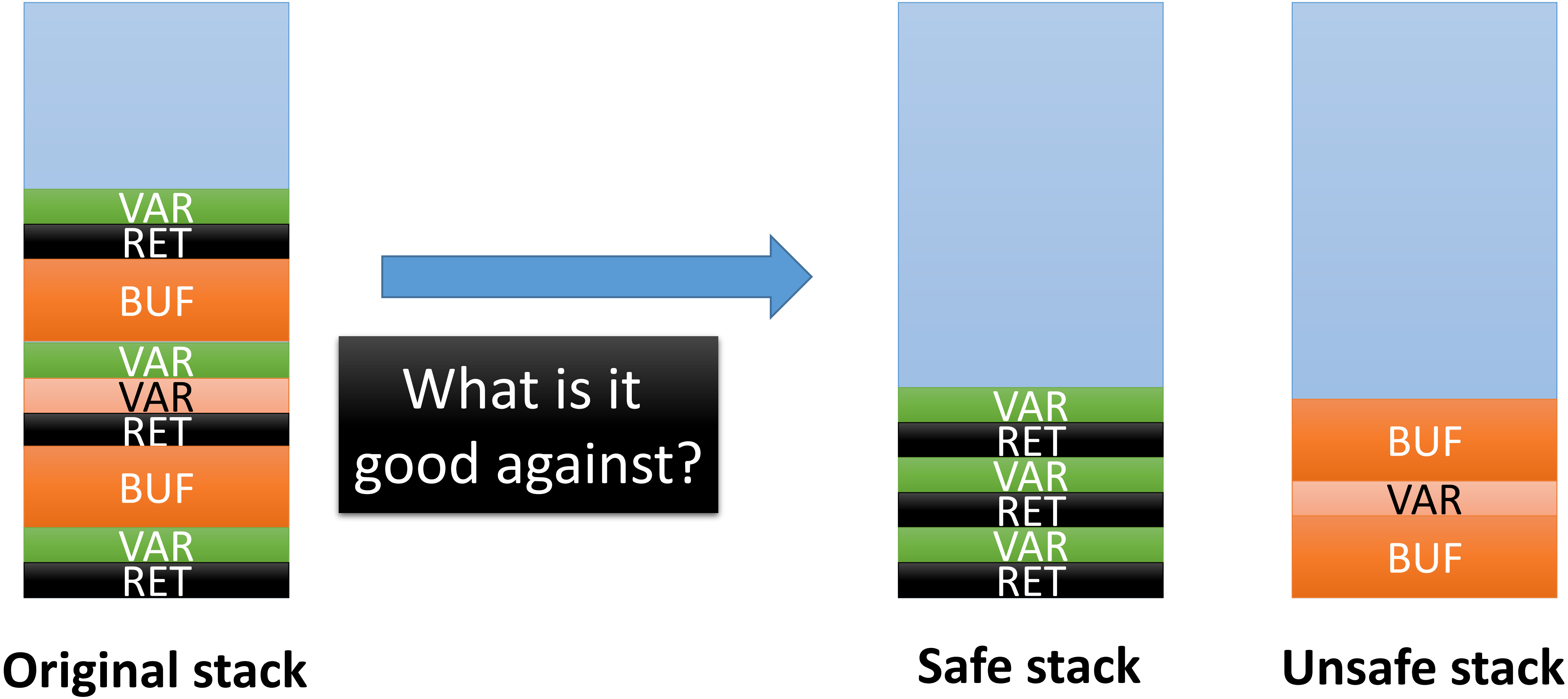
- Also proposed for integrating in GCC
  - https://gcc.gnu.org/ml/gcc/2016-04/msg00083.html

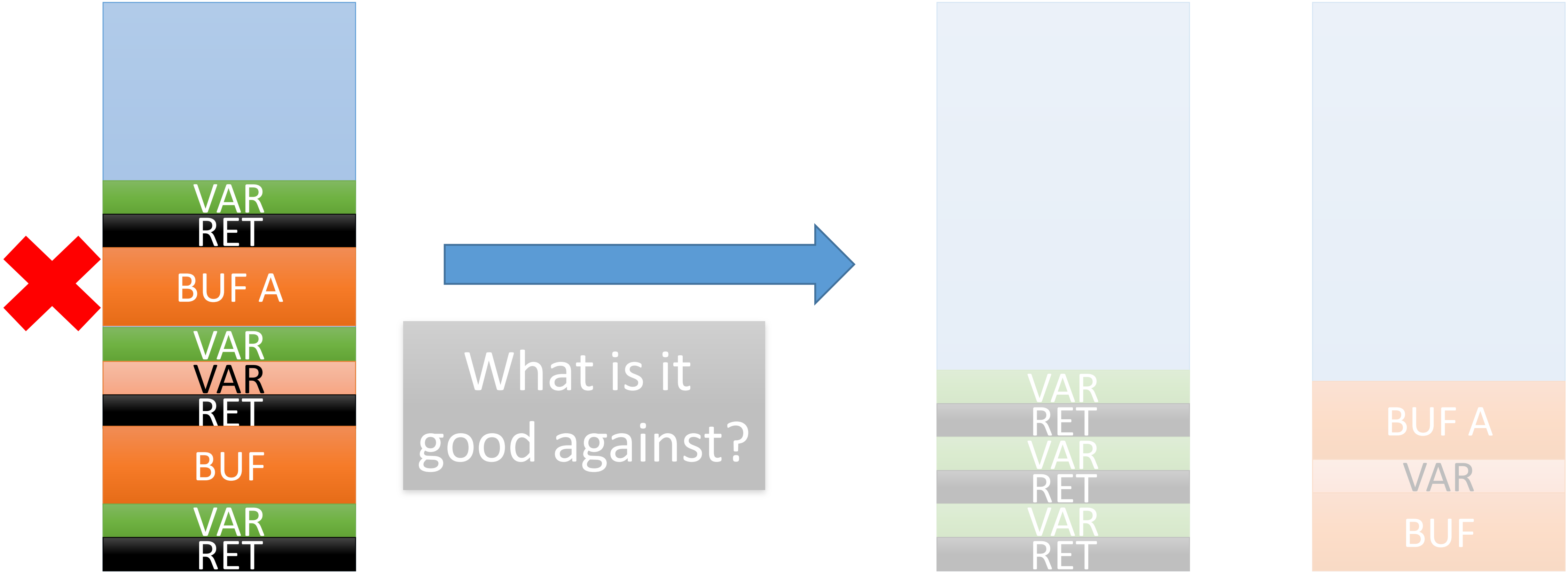


Original stack

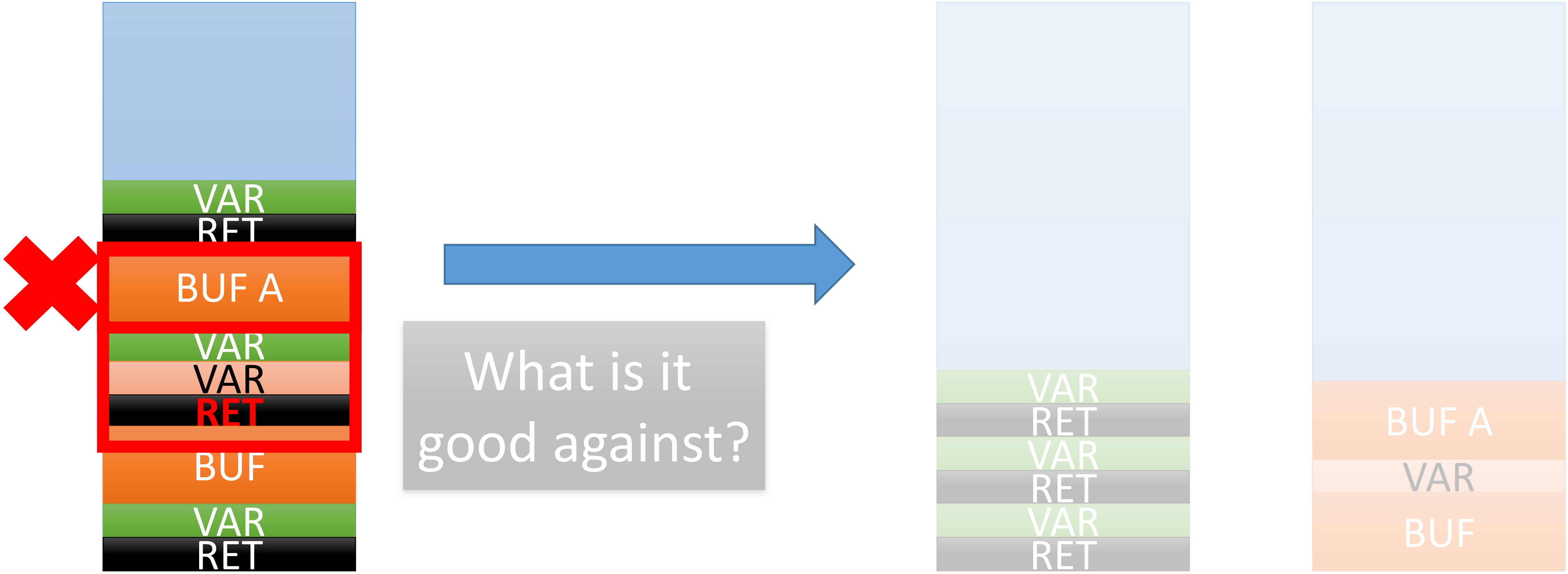


Original stack **Safe stack** **Unsafe stack**


VAR
RET
BUF
VAR
VAR
RET
BUF
VAR
RET
What is it good against?
VAR
RET
VAR
RET
VAR
RET
BUF
VAR
BUF
Original stack
Safe stack
Unsafe stack



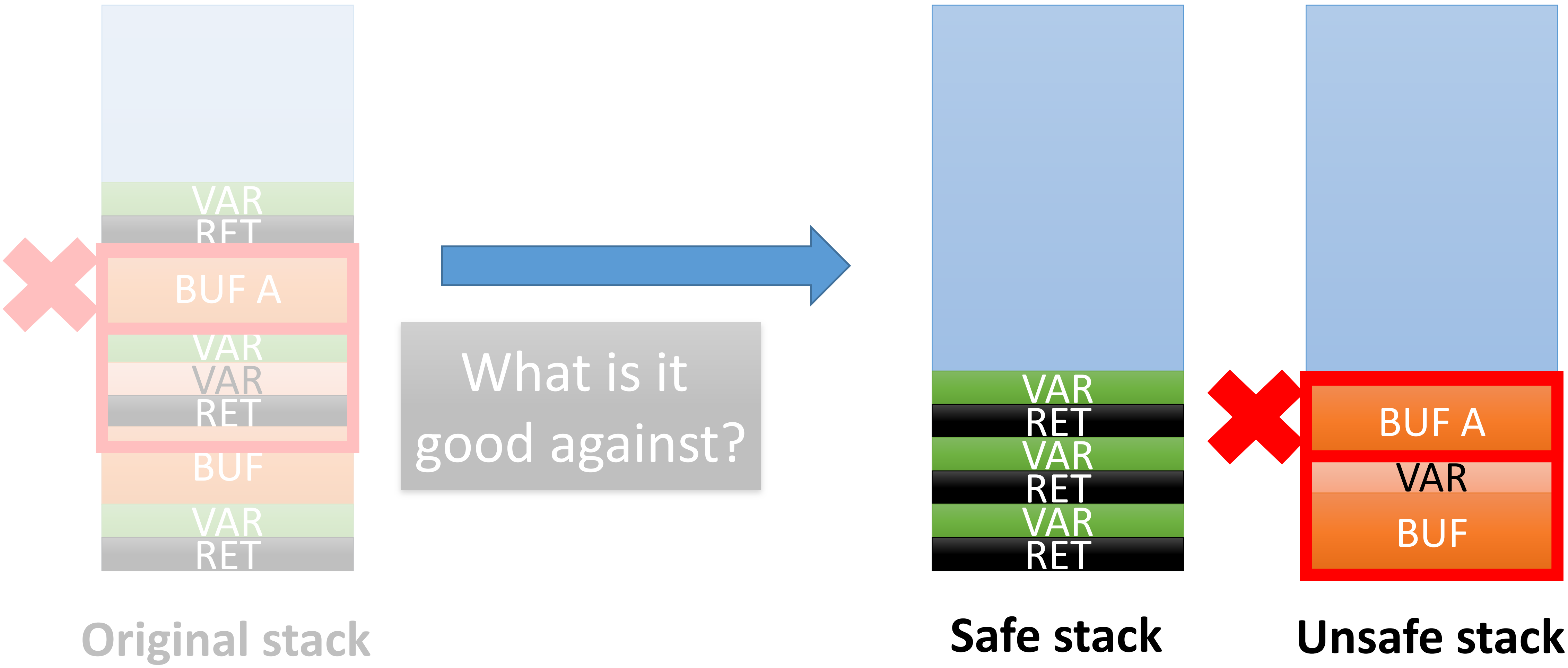
Original stack Safe stack Unsafe stack

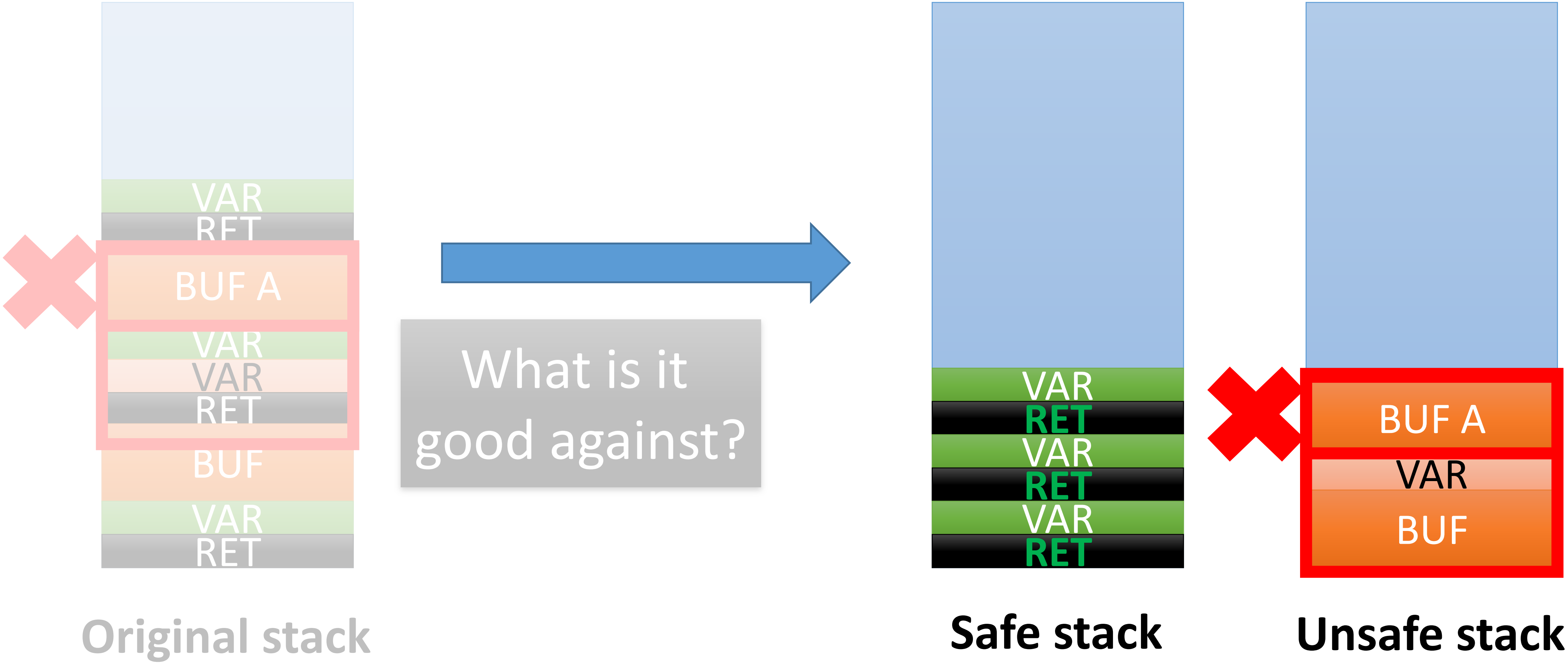


Original stack

Safe stack

Unsafe stack


VAR
RET
BUF A
VAR
VAR
RET
BUF
VAR
RET
Original stack
What is it good against?
VAR
RET
VAR
RET
VAR
RET
Safe stack
BUF A
VAR
BUF
Unsafe stack


VAR
RET
BUF A
VAR
VAR
RET
BUF
VAR
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Original stack
What is it good against?
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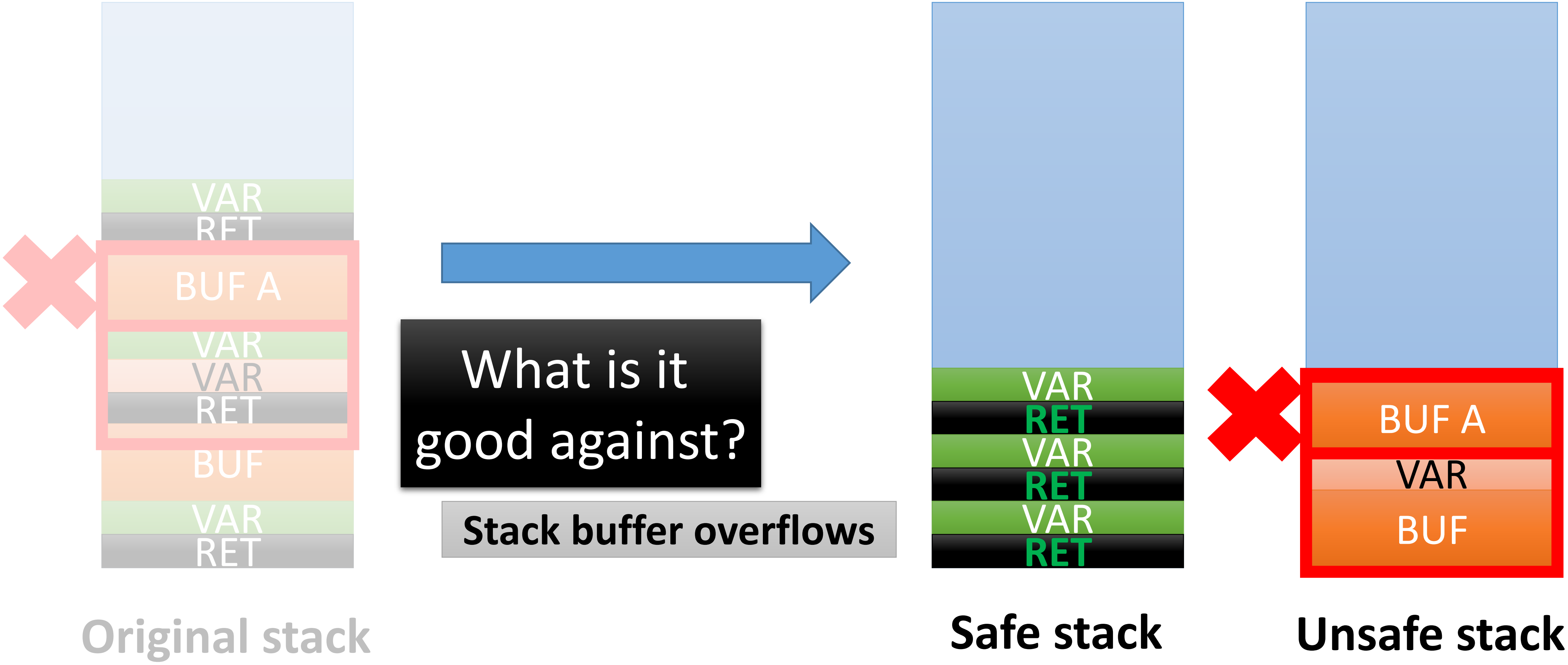
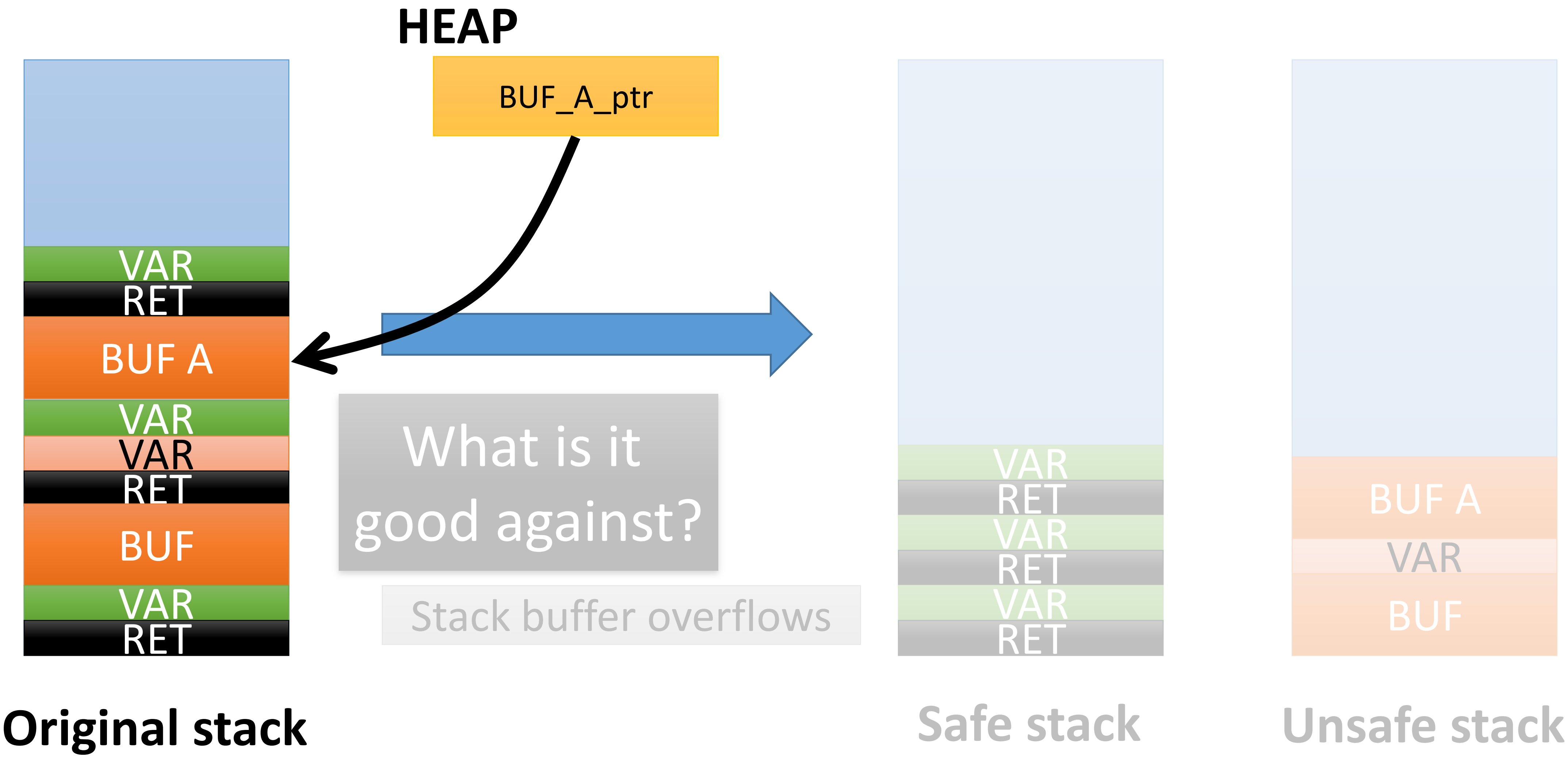
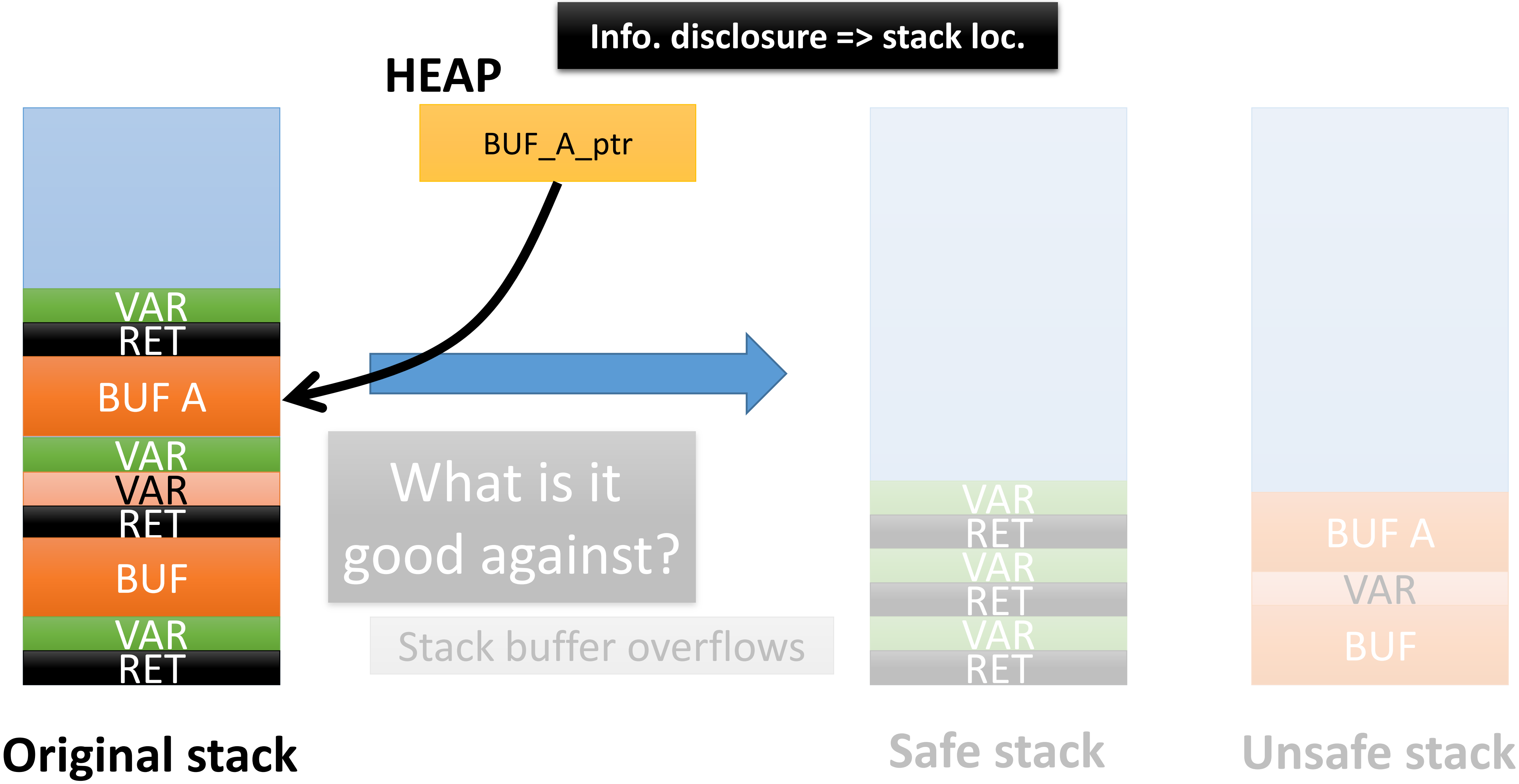
RET
VAR
RET
VAR
RET
Safe stack
BUF A
VAR
BUF
Unsafe stack


VAR
RET
BUF A
VAR
VAR
RET
BUF
VAR
RET
Original stack
What is it good against?
Stack buffer overflows
VAR
RET
VAR
RET
VAR
RET
Safe stack
BUF A
VAR
BUF
Unsafe stack


HEAP
BUF_A_ptr
VAR
RET
BUF A
VAR
VAR
RET
BUF
VAR
RET
What is it good against?
Stack buffer overflows
VAR
RET
VAR
RET
VAR
RET
BUF A
VAR
BUF
Original stack
Safe stack
Unsafe stack


Info. disclosure => stack loc.
HEAP
BUF_A_ptr
VAR
RET
BUF A
VAR
VAR
RET
BUF
VAR
RET
What is it good against?
Stack buffer overflows
VAR
RET
VAR
RET
VAR
RET
BUF A
VAR
BUF
Original stack
Safe stack
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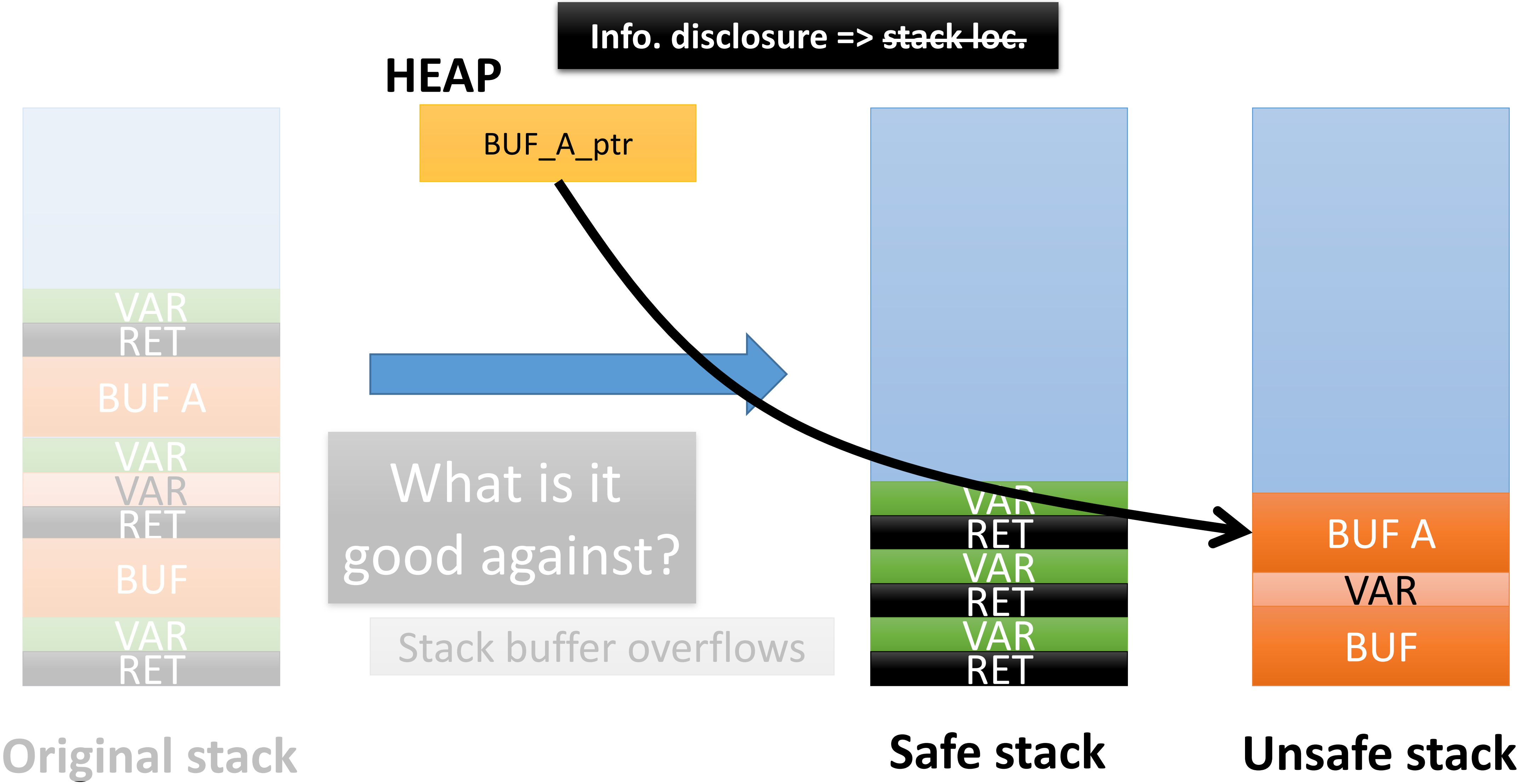
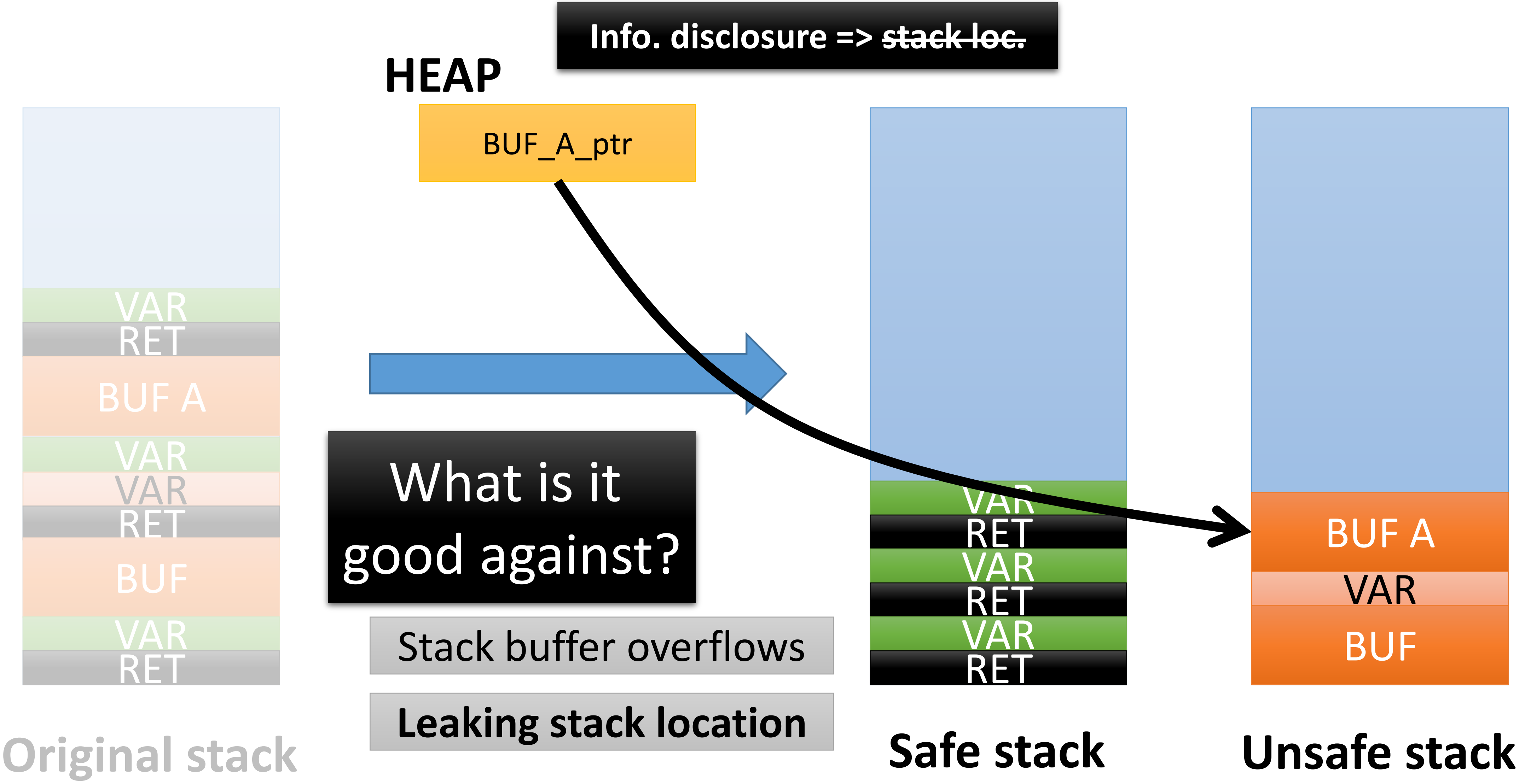
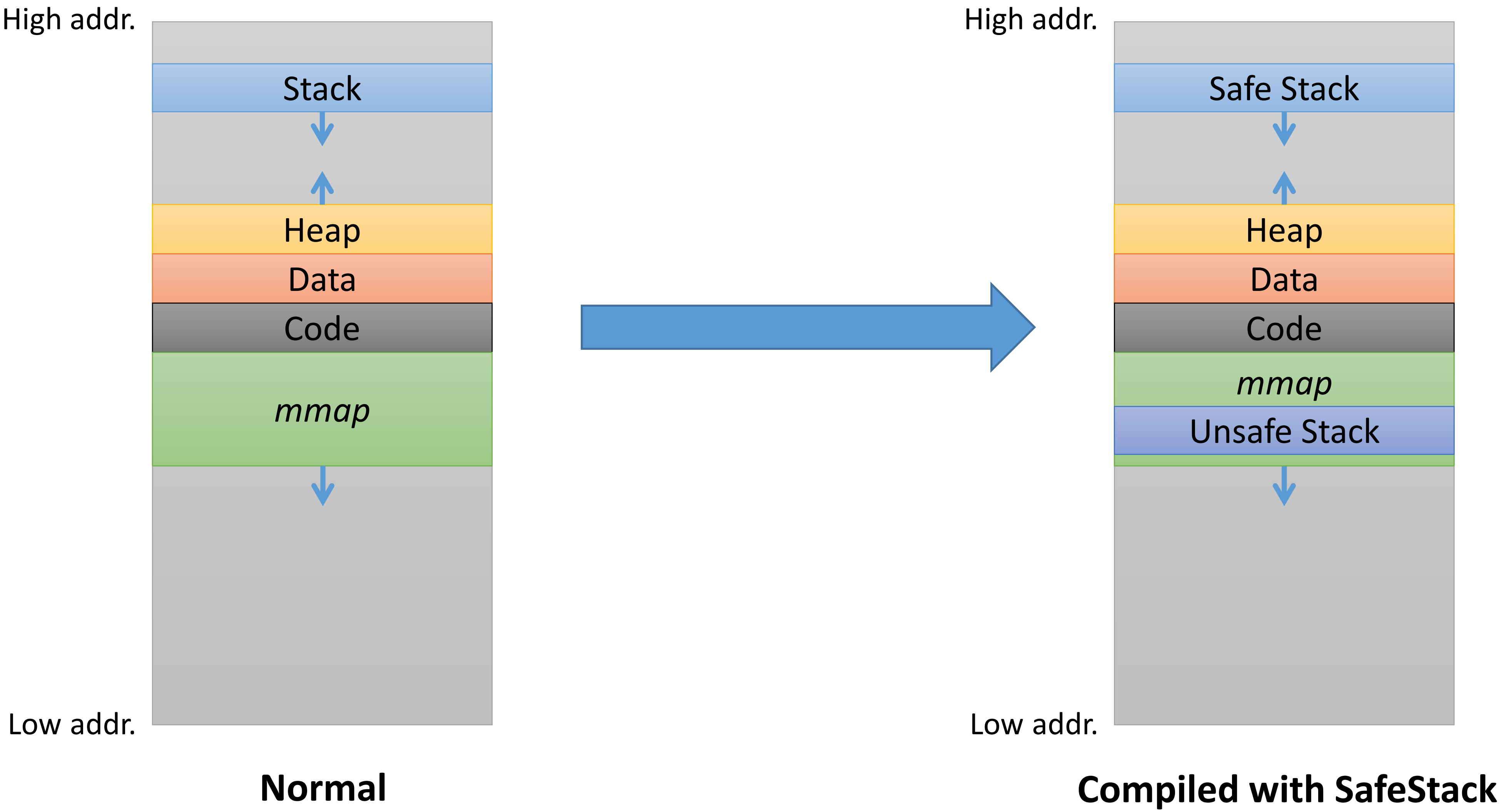
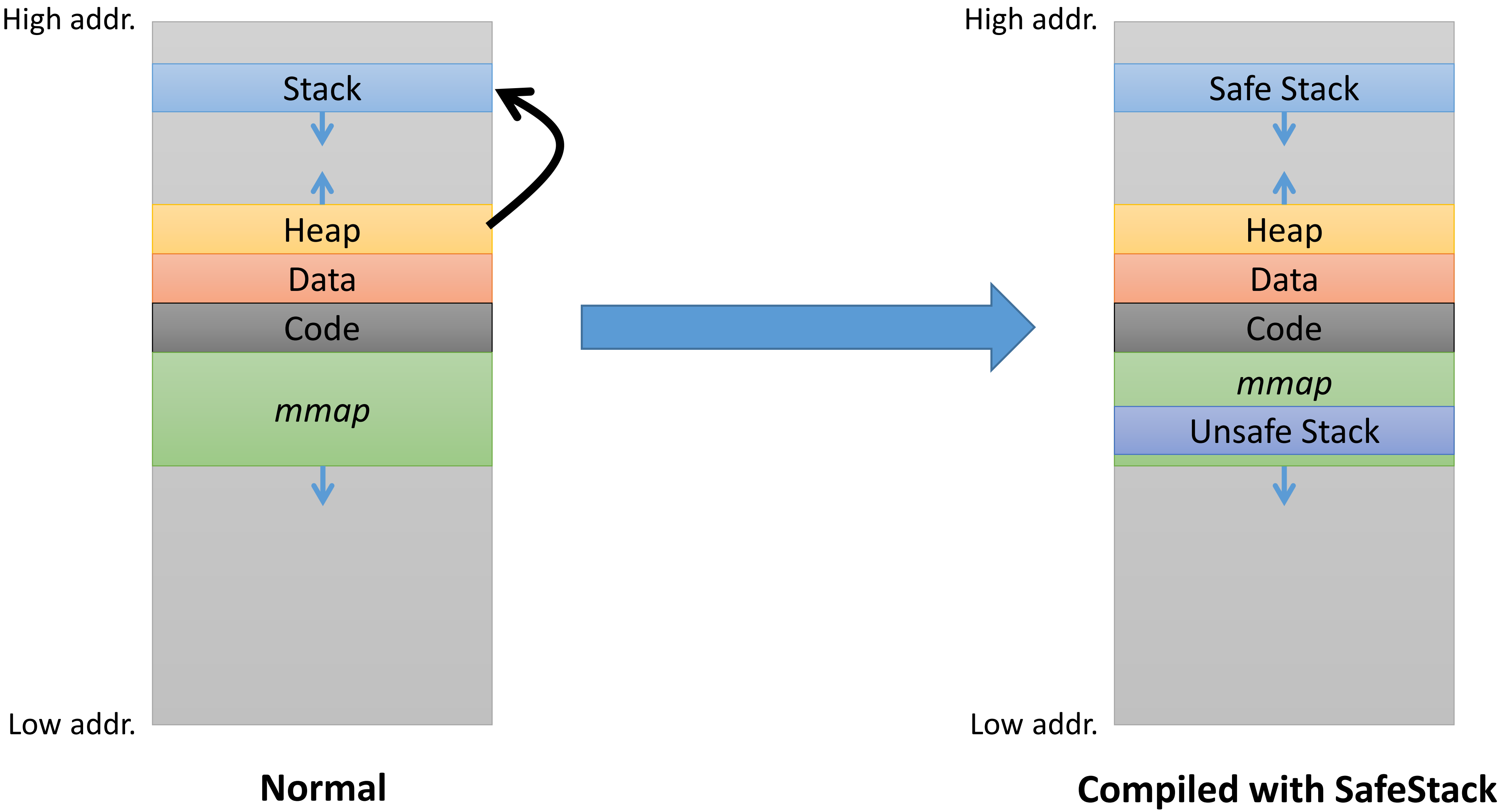

Info. disclosure => ~~stack loc.~~
HEAP
BUF_A_ptr
VAR
RET
BUF A
VAR
VAR
RET
BUF
VAR
RET
What is it good against?
Stack buffer overflows
VAR
RET
VAR
RET
VAR
RET
BUF A
VAR
BUF
Original stack
Safe stack
Unsafe stack


Info. disclosure => ~~stack loc.~~
HEAP
BUF_A_ptr
VAR
RET
BUF A
VAR
VAR
RET
BUF
VAR
RET
Original stack
What is it good against?
Stack buffer overflows
Leaking stack location
VAR
RET
VAR
RET
VAR
RET
Safe stack
BUF A
VAR
BUF
Unsafe stack

PIE compiled program in Linux



PIE compiled program in Linux



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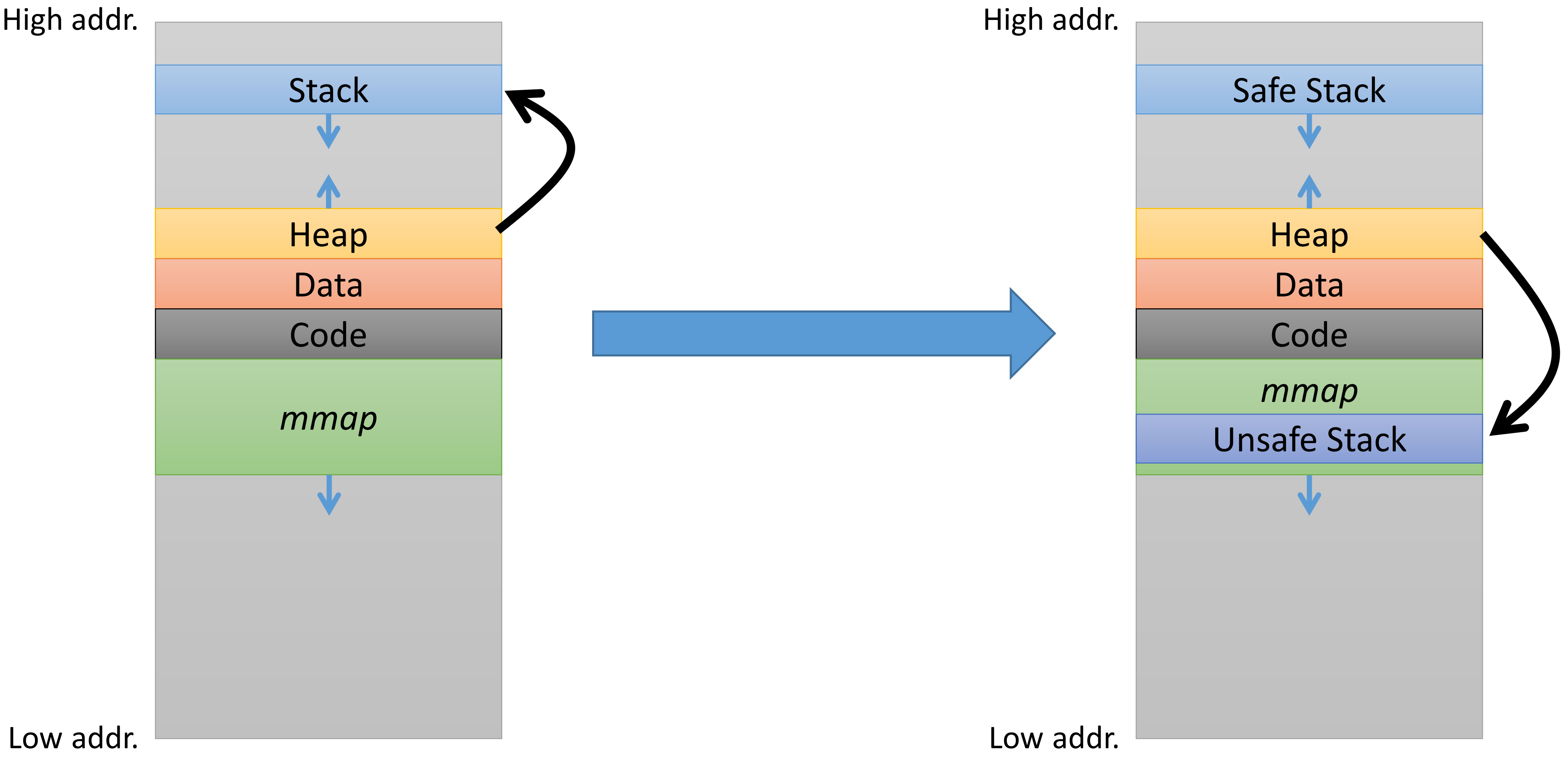
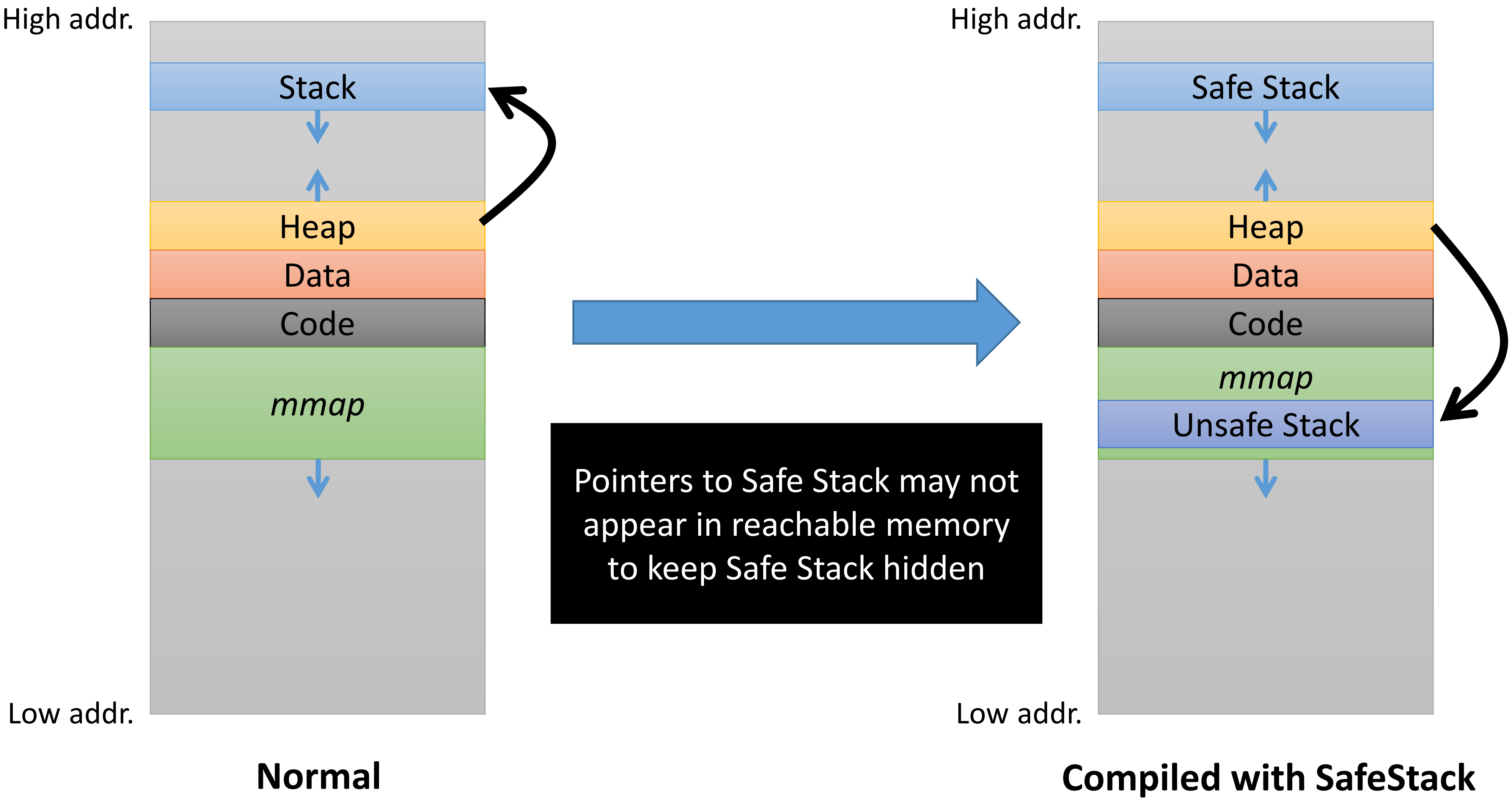


Normal | **Compiled with SafeStack**

PIE compiled program in Linux



Allocate address taken local variable on stack

test.c

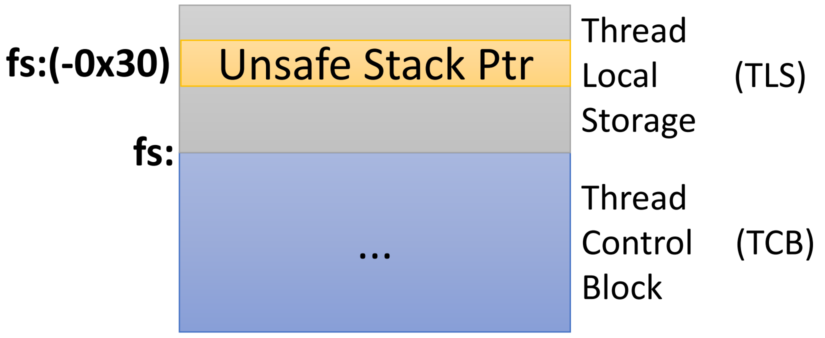
```
int main(int argc, char *argv[]){
  char buf[32];
  strcpy(buf, argv[1]);
  ...
}
```

normal

```
0x400561 : sub    $0x20,%rsp
0x400565 : mov    (%rsi),%rsi
0x400568 : lea    (%rsp),%rbx
0x40056c : mov    %rbx,%rdi
0x40056f : callq  0x400430 <strcpy@plt>
```

safestack

```
0x414625 : mov    0x2099bc(%rip),%r14
0x41462c : mov    %fs:(%r14),%r15
0x414630 : lea    -0x20(%r15),%rbx
0x414634 : mov    %rbx,%fs:(%r14)
0x414638 : mov    (%rsi),%rsi
0x41463b : mov    %rbx,%rdi
0x41463e : callq  0x400f20 <strcpy@plt>
```



test.c

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Allocate address taken local variable on stack

normal

```
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0x400568 : lea     (%rsp),%rbx
0x40056c : mov     %rbx,%rdi
0x40056f : callq   0x400430 <strcpy@plt>
```

Address of variable provided to strcpy

safestack

```
0x414625 : mov     0x2099bc(%rip),%r14
0x41462c : mov     %fs:(%r14),%r15
0x414630 : lea     -0x20(%r15),%rbx
0x414634 : mov     %rbx,%fs:(%r14)
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0x41463e : callq   0x400f20 <strcpy@plt>
```

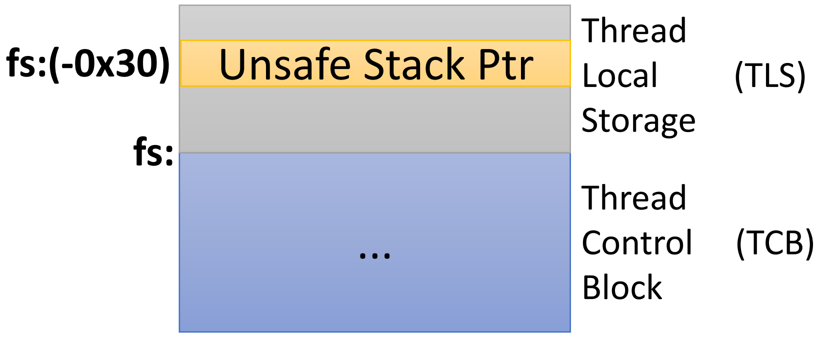

SafeStack

- Compile time instrumentation pass
  - Flag: -fsanitize=safe-stack
- Ensure stack access is “safe”
  - Address taken objects moved to alternative stack
- Prevent leaking stack location
- Relies on ASLR

SafeStack

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How safe is the SafeStack?

SafeStack

- Compile time instrumentation pass
  - Flag: -fsanitize=safe-stack
- Ensure stack access is “safe”
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How safe is the SafeStack?

Locating SafeStack

- Neglected pointers
- Thread Spraying
- Allocation Oracles

Threat Model

- Memory corruption
- Arbitrary read/write primitive
- Heap and module data disclosed
- Goal: Locate SafeStack

Neglected Pointers

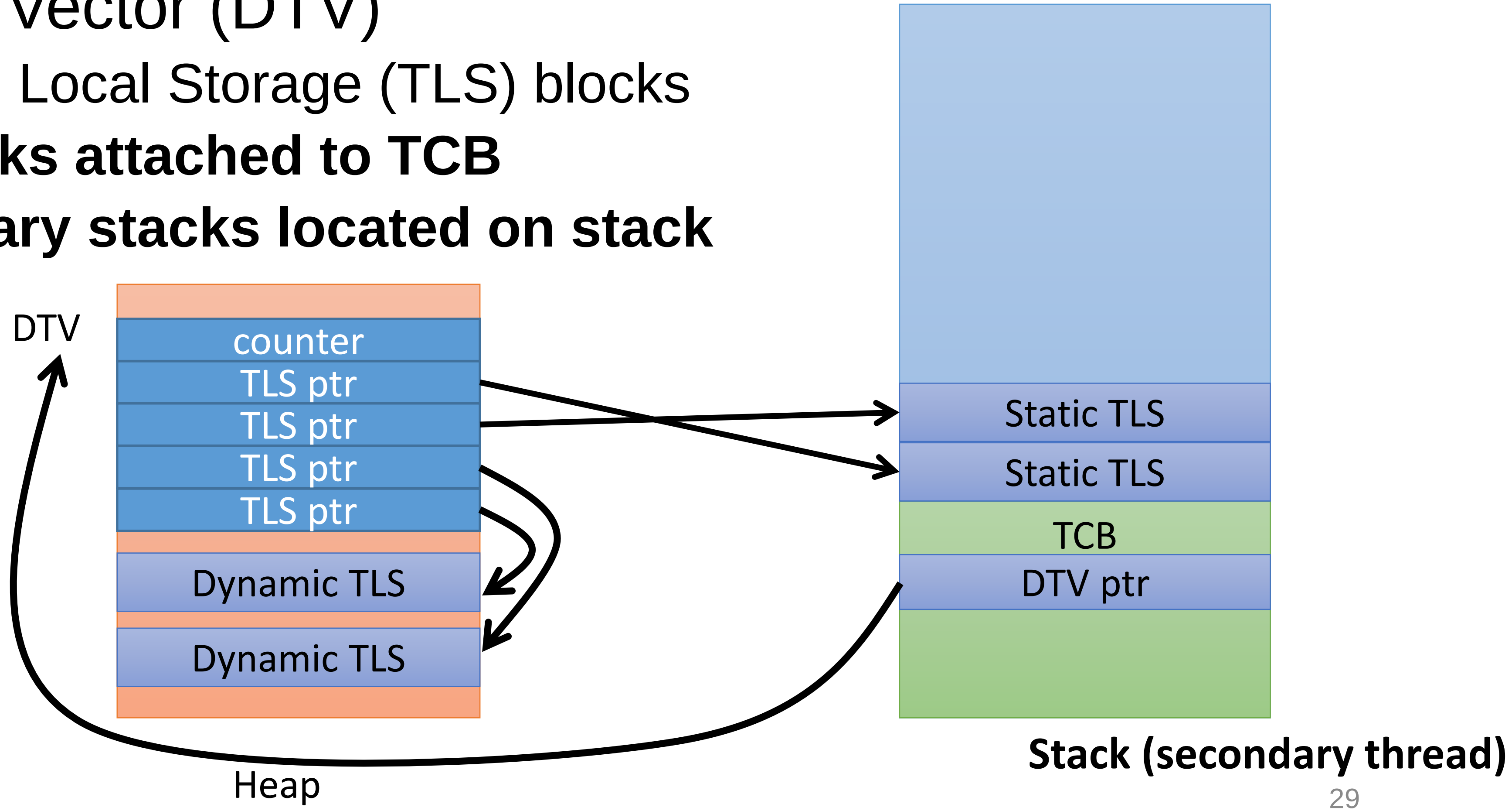
- SafeStack ensures **pointer to data on stack** wont be stored outside the stack
- Analyze programs compiled with SafeStack for unexpected pointers
  - GDB + python
  - Report pointers common among apps

Neglected Pointers

- Found pointers:
  - In heap
  - In libraries
  - Thread IDs

Neglected Pointers: Heap

- Dynamic Thread Vector (DTV)
  - Points to Thread Local Storage (TLS) blocks
  - **Static TLS blocks attached to TCB**
  - **TCB of secondary stacks located on stack**



https://www.uclibc.org/docs/tls.pdf

Neglected Pointers: Libraries

- pthread.so (linked lists):
  - stack_used – __stack_user
- libc.so
  - program_invocation_name
  - program_invocation_short_name
- libgcc.so
  - __libc_argv – __dlfcn_argv

Neglected Pointers: Libraries

- ld.so
  - rtld_global_ro
  - environ
    - _dl_argv
    - __libc_stack_end

- Pointer that can lead to TCB in ld.so
  - alloc_end
    - If app overloads malloc, e.g. Chrome and Firefox

Neglected Pointers: Thread IDs

- Surprisingly thread API uses **base of TCB** as thread IDs
  - `int pthread_create(`**`pthread_t`**` *thr, ..)`
  - `int pthread_join(`**`pthread_t`**` thr, ..)`
  - **`pthread_t`**` pthread_self()`
  - …

- *Apps* that do thread bookkeeping store thread IDs in the **heap** or *modules* in their **data** section

- E.g. libxml2.so:
  - *.bss*: mainthread = pthread_self()

- Let’s assume these implementation issues are **fixed**
- The attacker **cannot leak** safestack through pointers anymore
- The attacker could try to **randomly hit** safestack
- What could he do to increase the chance to hit a safestack?

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- The attacker **cannot leak** safestack through pointers anymore
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- What could he do to increase the chance to hit a safestack?

Reduce the entropy through *Thread Spraying*

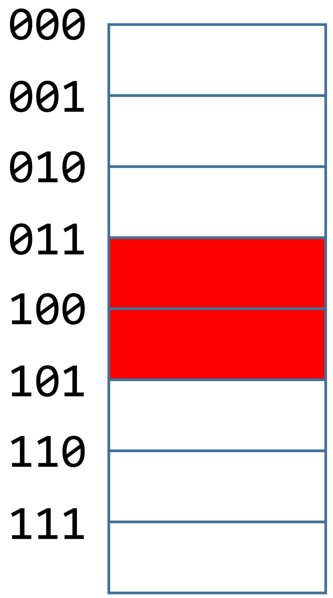
Entropy

- Degree of randomness
- Given in bits

- Example:
  - 3 bit address space
  - 8 blocks of 1 byte

  - Hide data

(2^1)



Entropy: 2 bits

Hit chance: $\frac{1}{2^2} = \frac{1}{4}$

Worst case #probes: $2^2 = 4$

Entropy

- Degree of randomness
- Given in bits

- Example:
  - 3 bit address space
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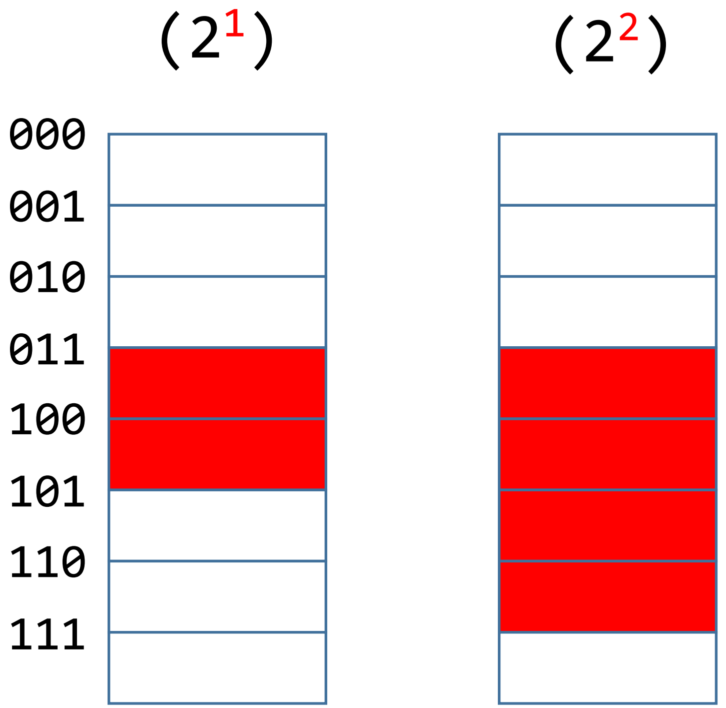
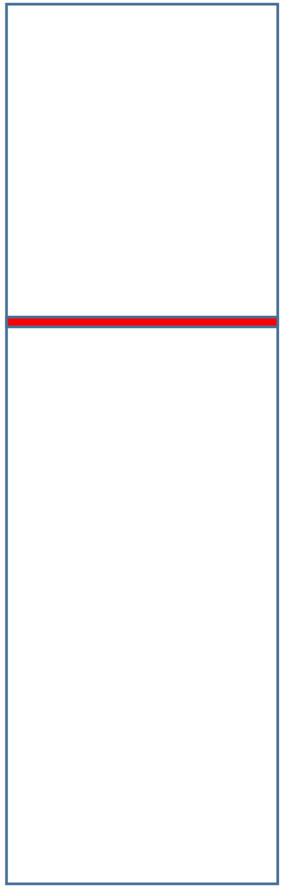


Entropy:	2 bits	1 bit
Hit chance:	$\frac{1}{2^2} = \frac{1}{4}$	$\frac{1}{2^1} = \frac{1}{2}$
Worst case #probes:	$2^2 = 4$	$2^1 = 2$

64 bit address space

Hide: 1 byte

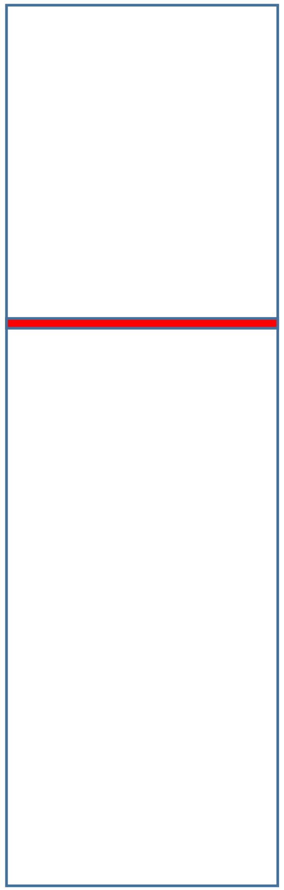


Entropy: 64 bits

Hide: 1 byte

64 bit address space

Linux user space only uses 47 bit



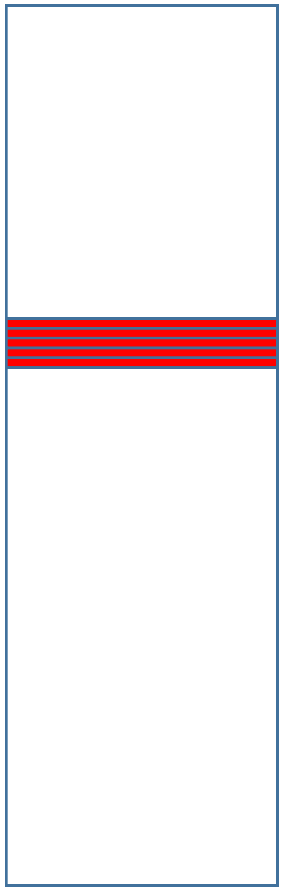
Entropy: 47 bits

64 bit address space

Linux user space only uses 47 bit

1 page: 4096 bytes = 2^{12} bytes

Hide: 4096 bytes



Entropy: 35 bits

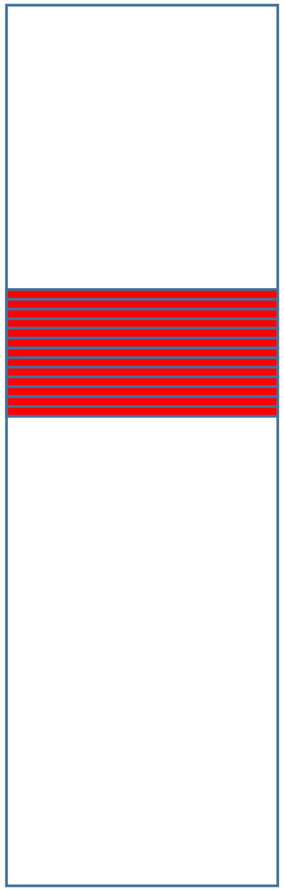
64 bit address space

Linux user space only uses 47 bit

1 page: 4096 bytes = 2^{12} bytes

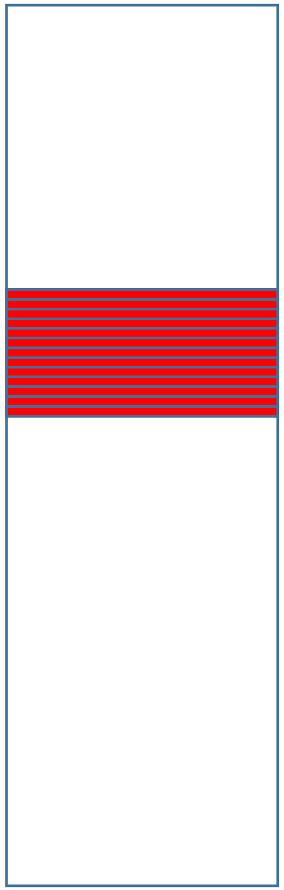
Safe Stack of 8 MB = 2^{23} bytes = 2^{11} pages

Hide: 2^{23} bytes



Entropy: 24 bits

Hide: 2^{23} bytes



Entropy: 24 bits

64 bit address space

Linux user space only uses 47 bit

1 page: 4096 bytes = 2^{12} bytes

Safe Stack of 8 MB = 2^{23} bytes = 2^{11} pages

Thread Spraying

Legitimately spawn as many threads as possible

Hide: 2^{24} bytes

64 bit address space

Linux user space only uses 47 bit

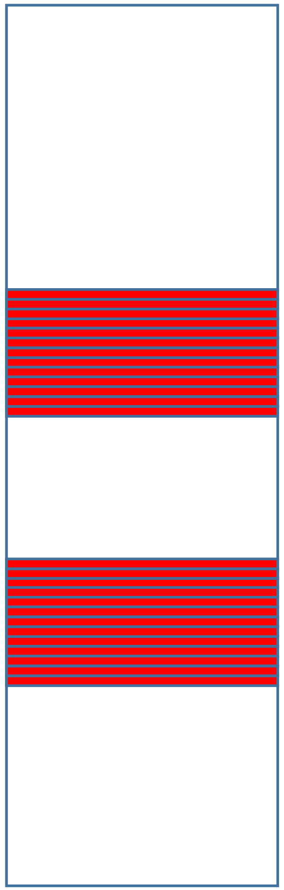
1 page: 4096 bytes = 2^{12} bytes

Safe Stack of 8 MB = 2^{23} bytes = 2^{11} pages

Thread Spraying

Legitimately spawn as many threads as possible

Spawn a new thread



Entropy: 23 bits

Hide: 2^{25} bytes

64 bit address space

Linux user space only uses 47 bit

1 page: 4096 bytes = 2^{12} bytes

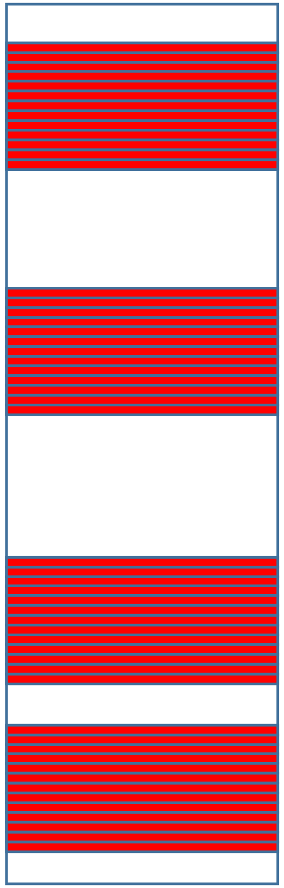
Safe Stack of 8 MB = 2^{23} bytes = 2^{11} pages

Thread Spraying

Legitimately spawn as many threads as possible

Spawn a new thread

Spawn 2 more threads



Entropy: 22 bits

64 bit address space

Linux user space only uses 47 bit

1 page: 4096 bytes = 2^{12} bytes

Safe Stack of 8 MB = 2^{23} bytes = 2^{11} pages

Thread Spraying

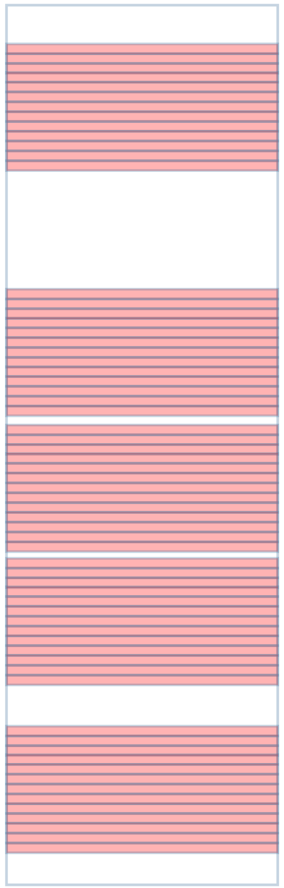
Legitimately spawn as many threads as possible

Spawn a new thread

Spawn 2 more threads

Spawn 128k threads = 2^{17} stacks

Hide: 2^{40} bytes



Entropy: 7 bits

Hide: 2^{40} bytes

64 bit address space

Linux user space only uses 47 bit

1 page: 4096 bytes = 2^{12} bytes

Safe Stack of 8 MB = 2^{23} bytes = 2^{11} pages

Thread Spraying

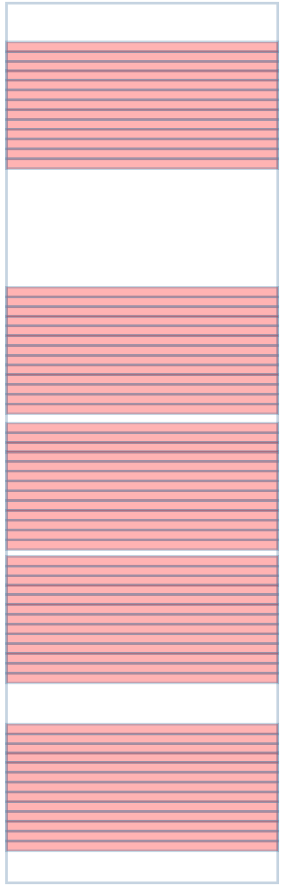
Legitimately spawn as many threads as possible

Spawn a new thread

Spawn 2 more threads

Spawn 128k threads = 2^{17} stacks

Drops worst case #probes to 128



Entropy: 7 bits

Hide: 2^{40} bytes

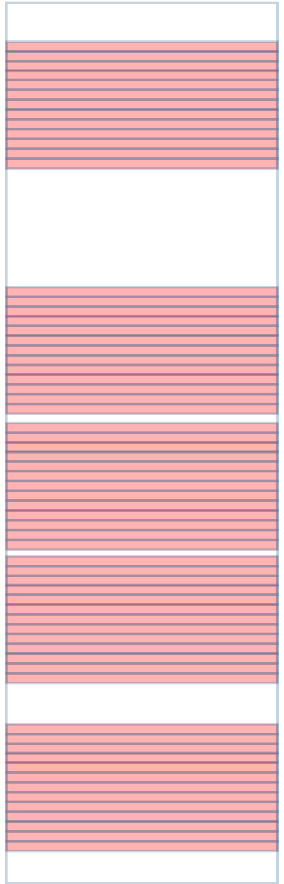
64 bit address space

Linux user space only uses 47 bit

Mmap entropy is 40 bit => worst case #probes is 1 (2^0)

1 page: 4096 bytes = 2^{12} bytes

Safe Stack of 8 MB = 2^{23} bytes = 2^{11} pages



Thread Spraying

Legitimately spawn as many threads as possible

Spawn a new thread

Spawn 2 more threads

Spawn 128k threads = 2^{17} stacks

Drops worst case #probes to 128

Entropy: 7 bits

Inspected apps

- Firefox
- MySQL

Thread Spraying: Firefox

- New thread per dedicated web worker in JS
- 20 web workers per domain
- Web worker thread stack size = 2MB ; entropy = 19 bits
- 20 Threads drops entropy to about 15 bits

Linux stack entropy = 40 bits
2MB occupies 21 bits in AS
40 - 21 bits = 19 bits of entropy
#probes = 524288

#probes = 32768

Thread Spraying: Firefox

Linux stack entropy = 40 bits
2MB occupies 21 bits in AS
40 - 21 bits = 19 bits of entropy
#probes = 524288

- New thread per dedicated web worker in JS
- 20 web workers per domain
- Web worker thread stack size = 2MB ; entropy = 19 bits
- 20 Threads drops entropy to about 15 bits

#probes = 32768

- Load pages from different domains through iframes
  - => Unlimited web worker threads
- 16.384 Web workers drop entropy to 5 bits

#probes = 32

Thread Spraying: MySQL

- New thread per network connection
- Max connections 151
- Thread stack size = 256KB ; entropy = 22 bits
- 151 connections drops entropy to about 15 bits

Thread Spraying: MySQL

- New thread per network connection
- Max connections 151
- Thread stack size = 256KB ; entropy = 22 bits
- 151 connections drops entropy to about 15 bits

- **4096** connections drops entropy to 10 bits
  - max_connections = 4096
- Stack size of **256 MB** can drop entropy to 0 bits
  - connection_attrib.stack_size = 0x10000000

Thread Spraying: MySQL

- New thread per network connection
- Max connections 151
- Thread stack size = 256KB ; entropy
- 151 connections drops entropy to ab

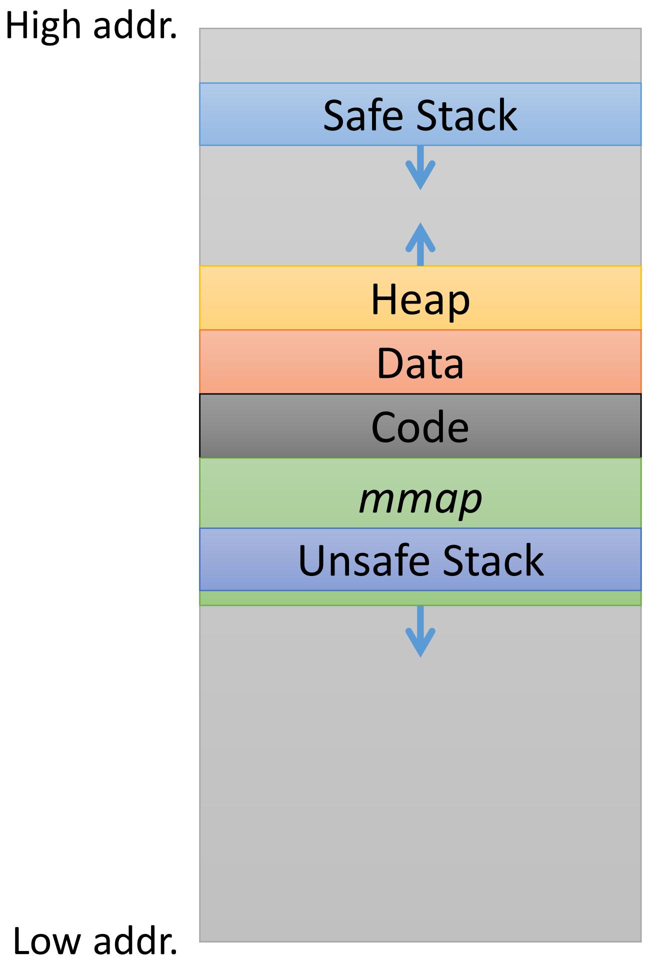
Exhausted 0x7F.. address region.
Address 0x7F0000000000 has
safestack with a very high chance.

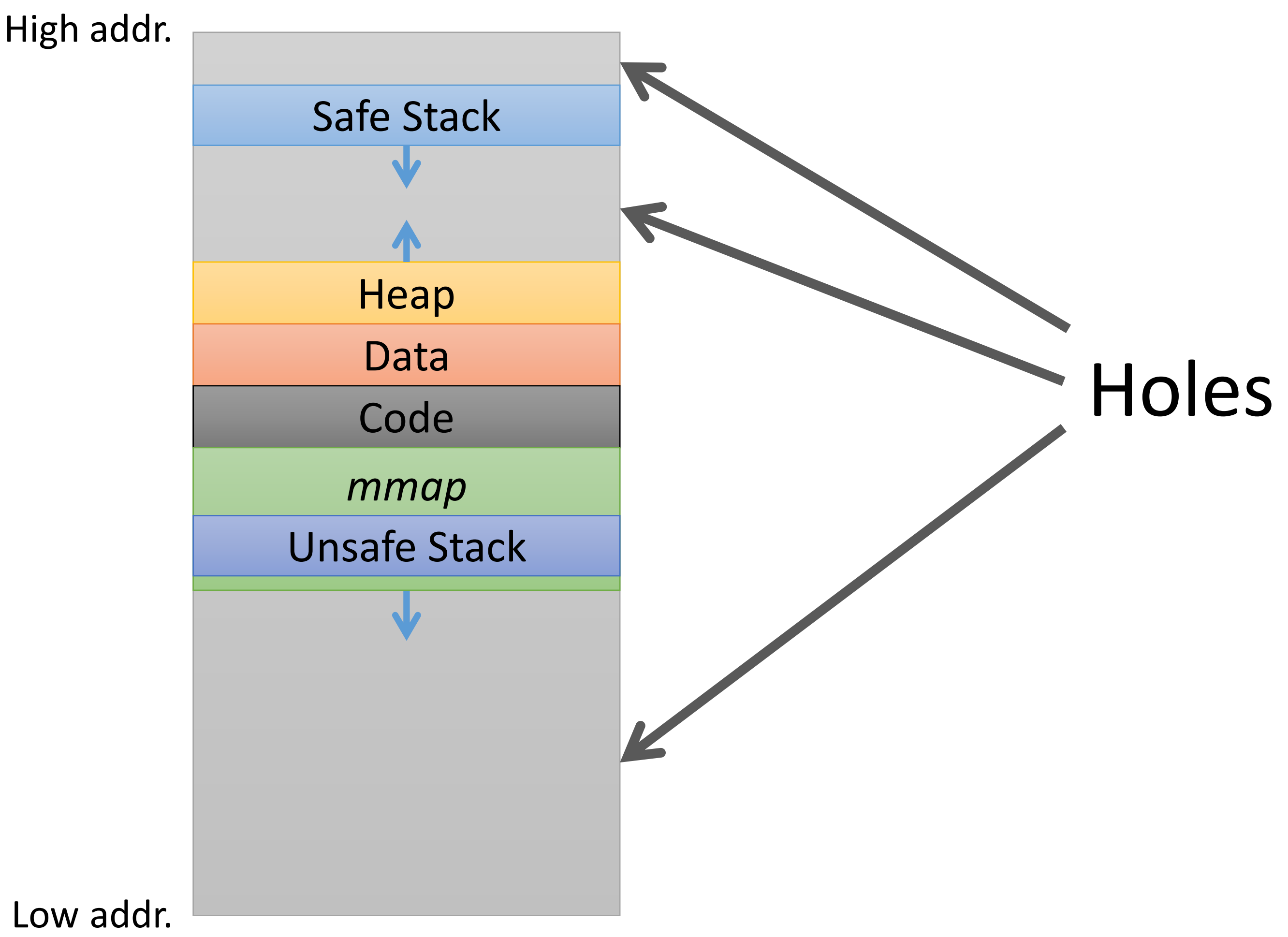
- **4096** connections drops entropy to 10 bits
  - max_connections = 4096
- Stack size of **256 MB** can drop entropy to 0 bits
  - connection_attrib.stack_size = 0x10000000

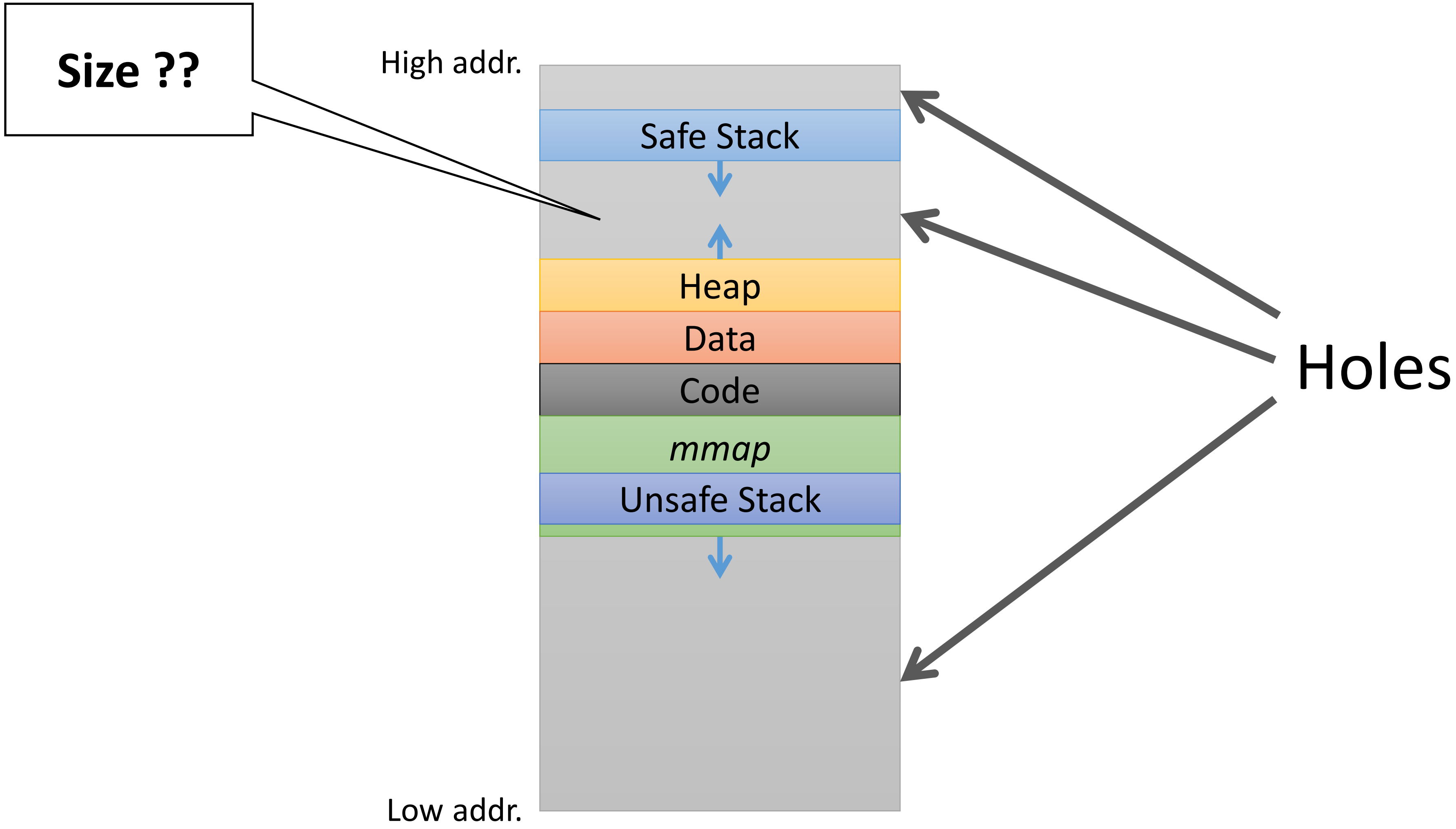
- By spraying lots of threads
  - ASLR can be weakened
  - Chance to hit safestack can be increased

- Spraying might not always be possible

- Another approach to find the safestack:
  - Allocation Oracles


High addr.
Safe Stack
Heap
Data
Code
mmap
Unsafe Stack
Low addr.


High addr.
Safe Stack
Heap
Data
Code
mmap
Unsafe Stack
Low addr.
Holes


Size ??
High addr.
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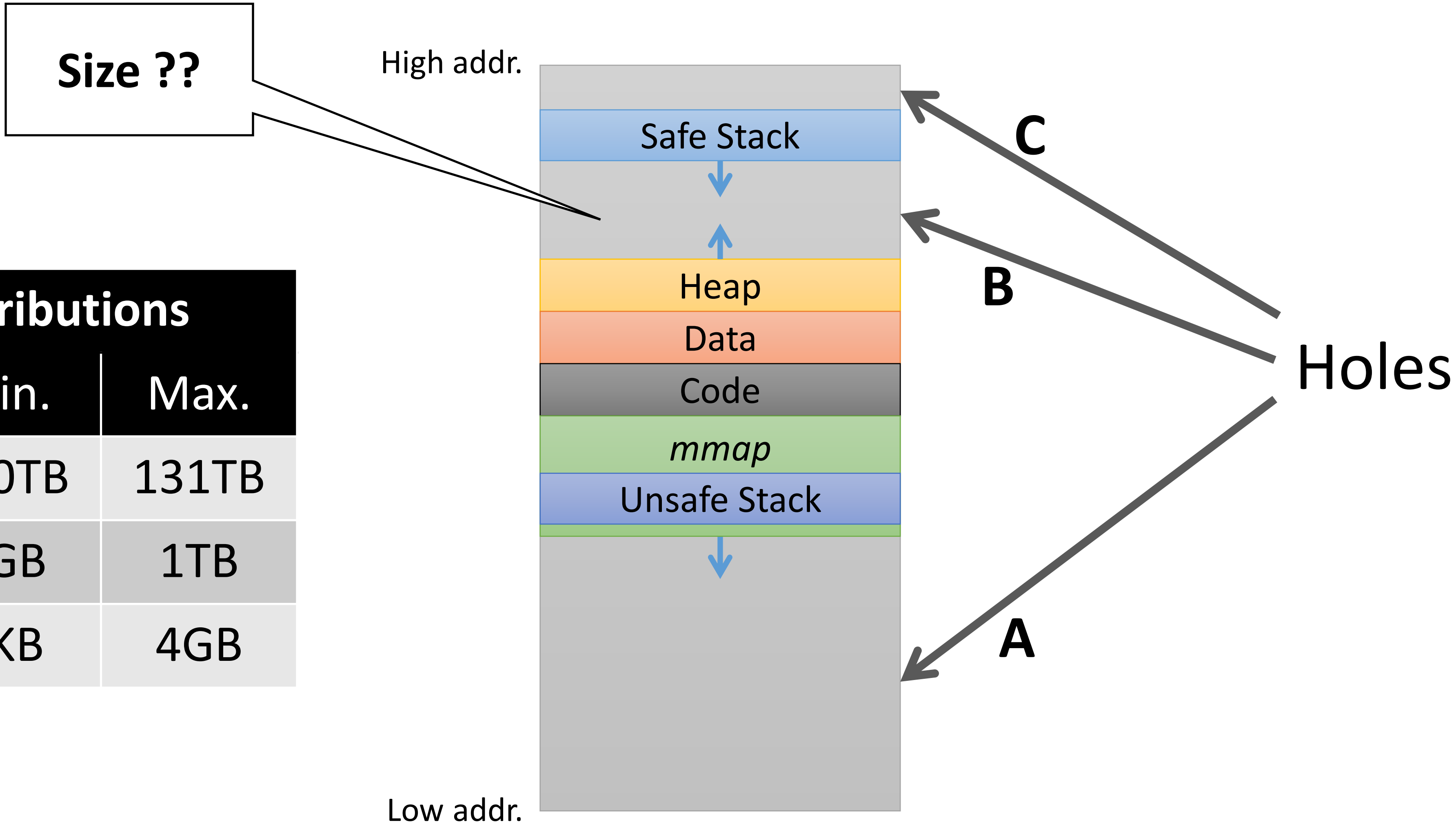
Holes



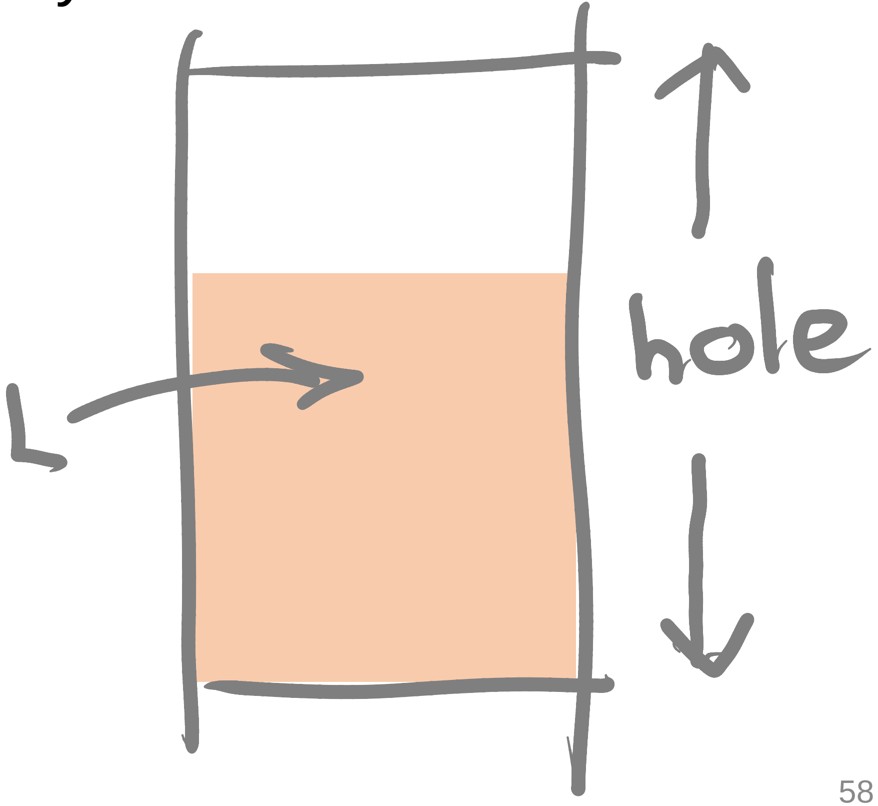
Size Distributions		
Hole	Min.	Max.
A	130TB	131TB
B	1GB	1TB
C	4KB	4GB

So look for the holes

- Intuition:
  - repeatedly allocate large chunks of memory of size **L** until we find the "right size"

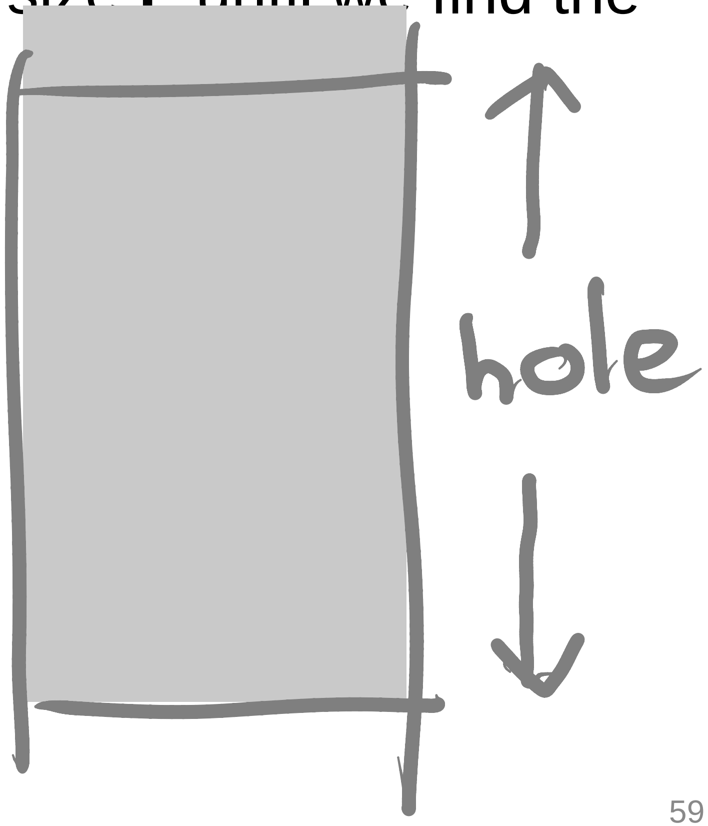
Succeeds!

Sizeof(Hole) ≥ L



So look for the holes

- Intuition:
  - repeatedly allocate large chunks of memory of size **L**, until we find the "right size"



Too large, alloc fails!

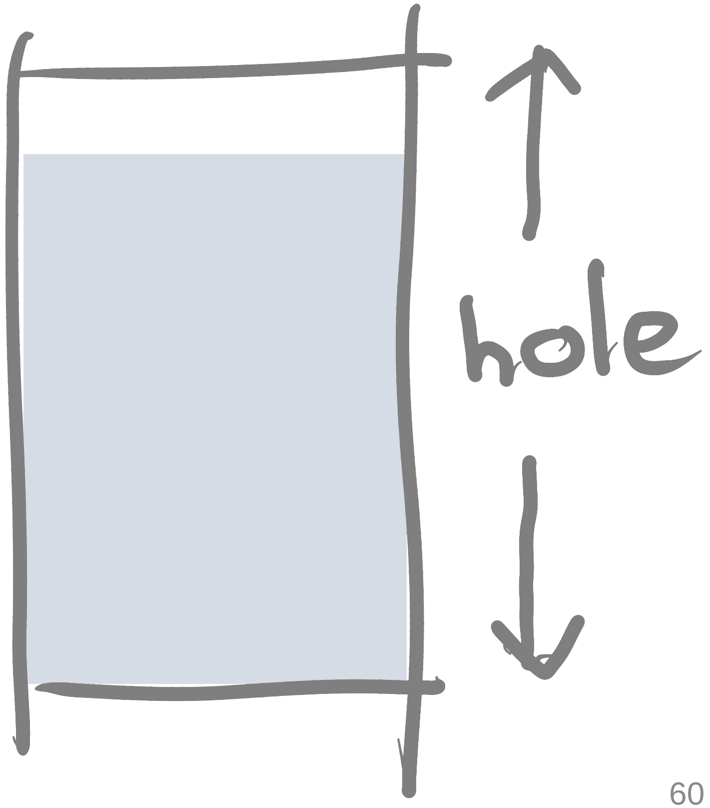
Sizeof(Hole) < L

So look for the holes

- Intuition:
  - repeatedly allocate large chunks of memory of size **L** until we find the "right size"

Succeeds!

Sizeof(Hole) ≥ L

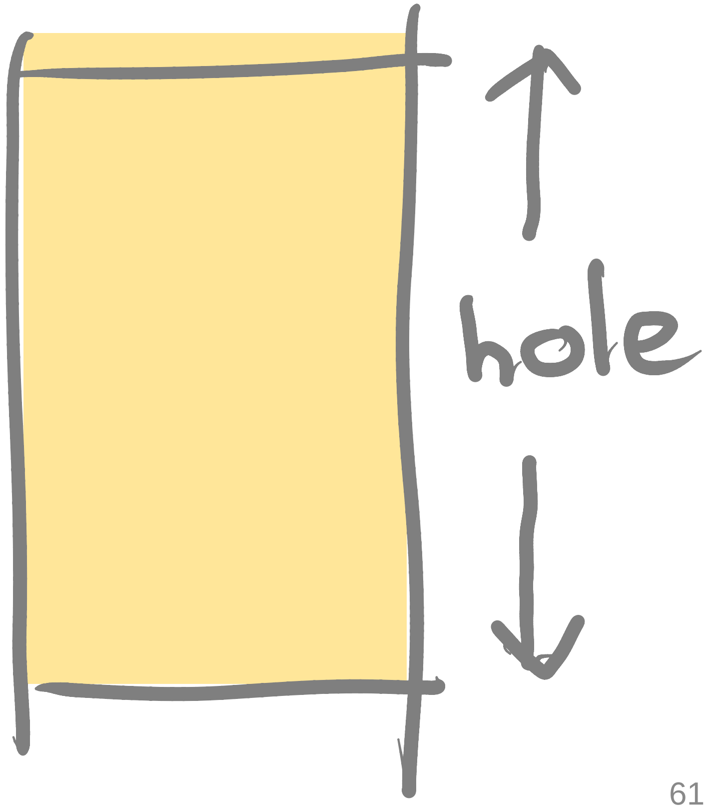


So look for the holes

- Intuition:
  - repeatedly allocate large chunks of memory of size **L** until we find the "right size"

Too large, alloc fails!

Sizeof(Hole) < L

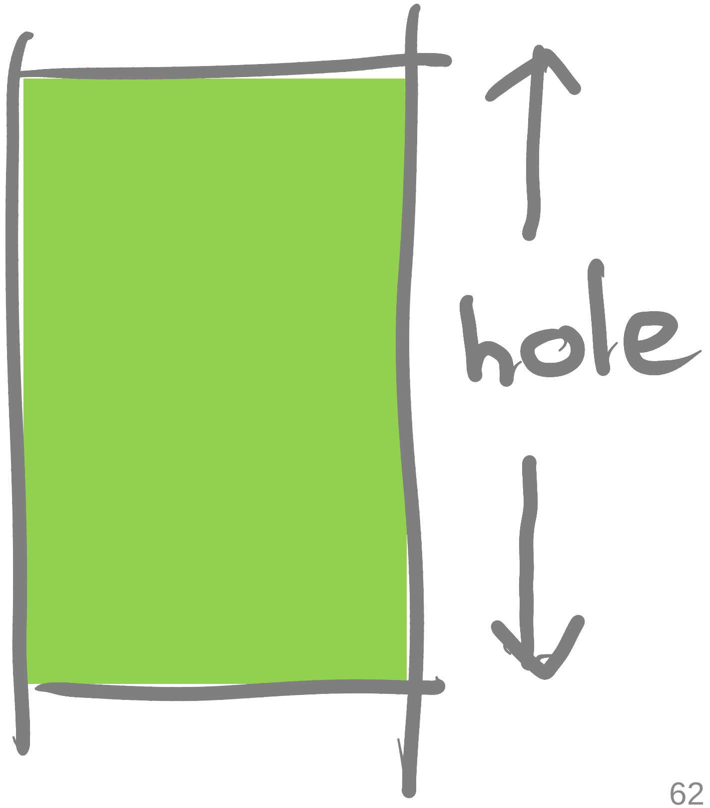


So look for the holes

- Intuition:
  - repeatedly allocate large chunks of memory of size **L** until we find the "right size"

Nailed it!

Binary search

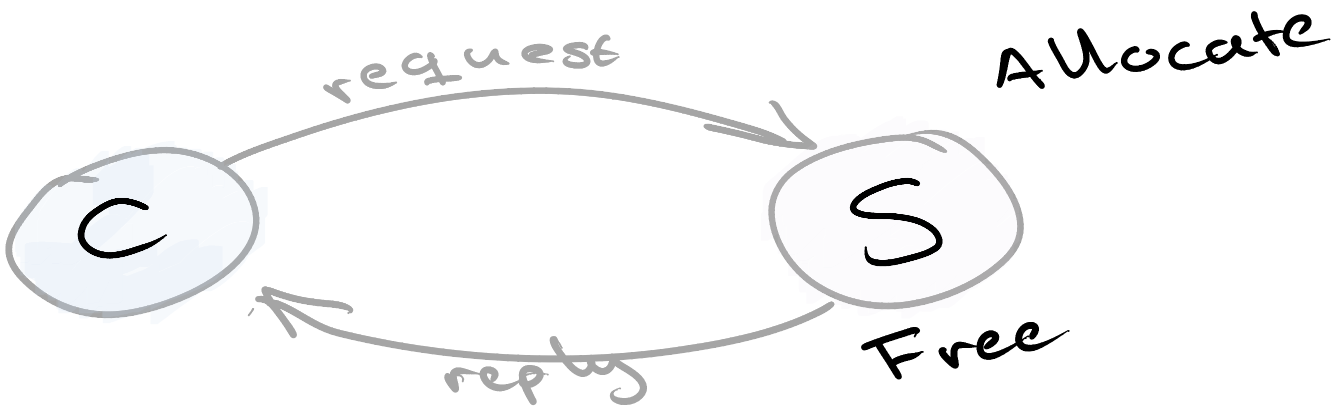


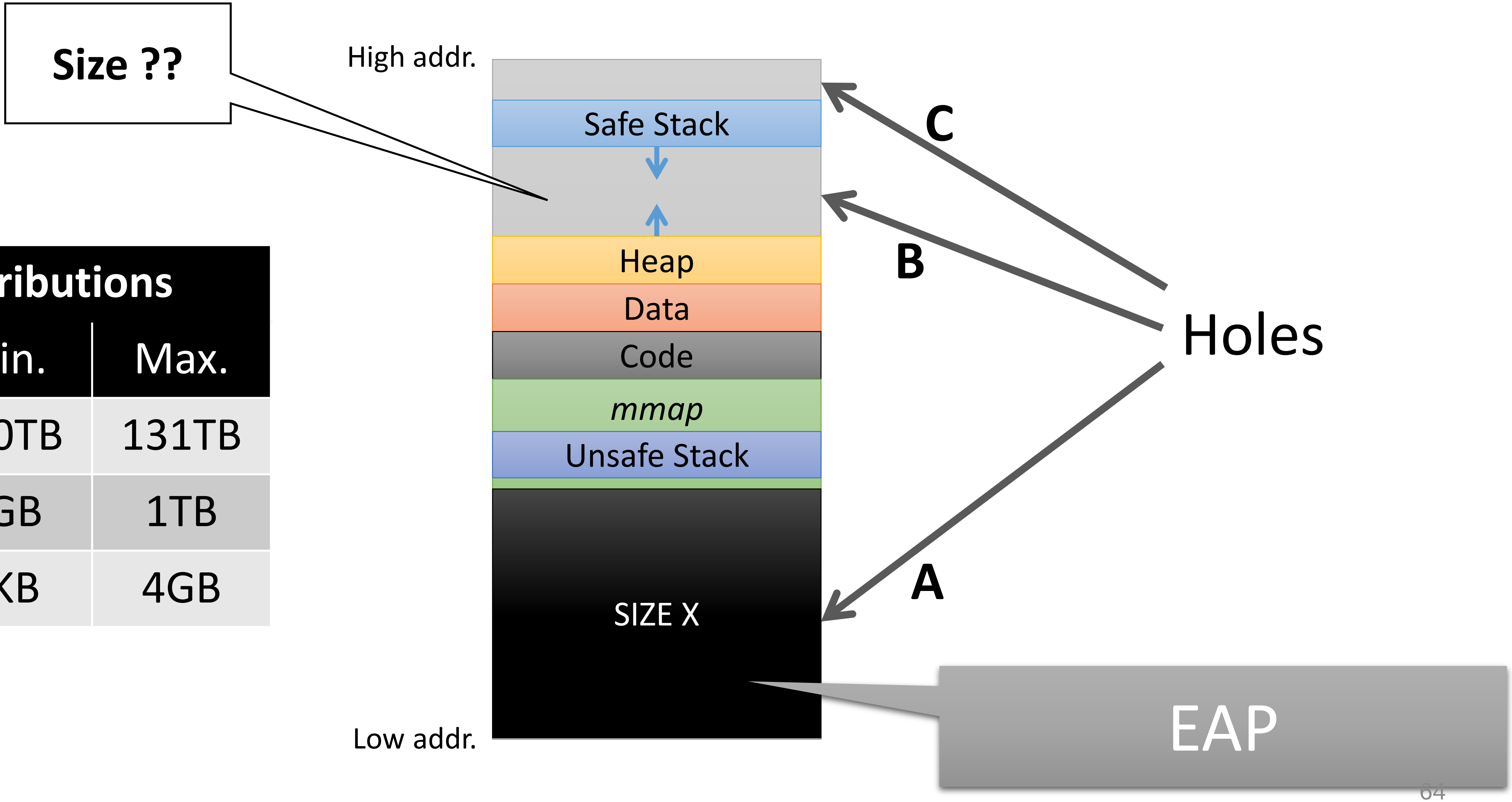
Ephemeral Allocation Primitive (EAP)

- For each probe (i.e., server request):

```
ptr = malloc(size);
...
free(ptr);
reply(result);
```

- Strategy: allocation+deallocation, repeat





Size Distributions		
Hole	Min.	Max.
A	130TB	131TB
B	1GB	1TB
C	4KB	4GB

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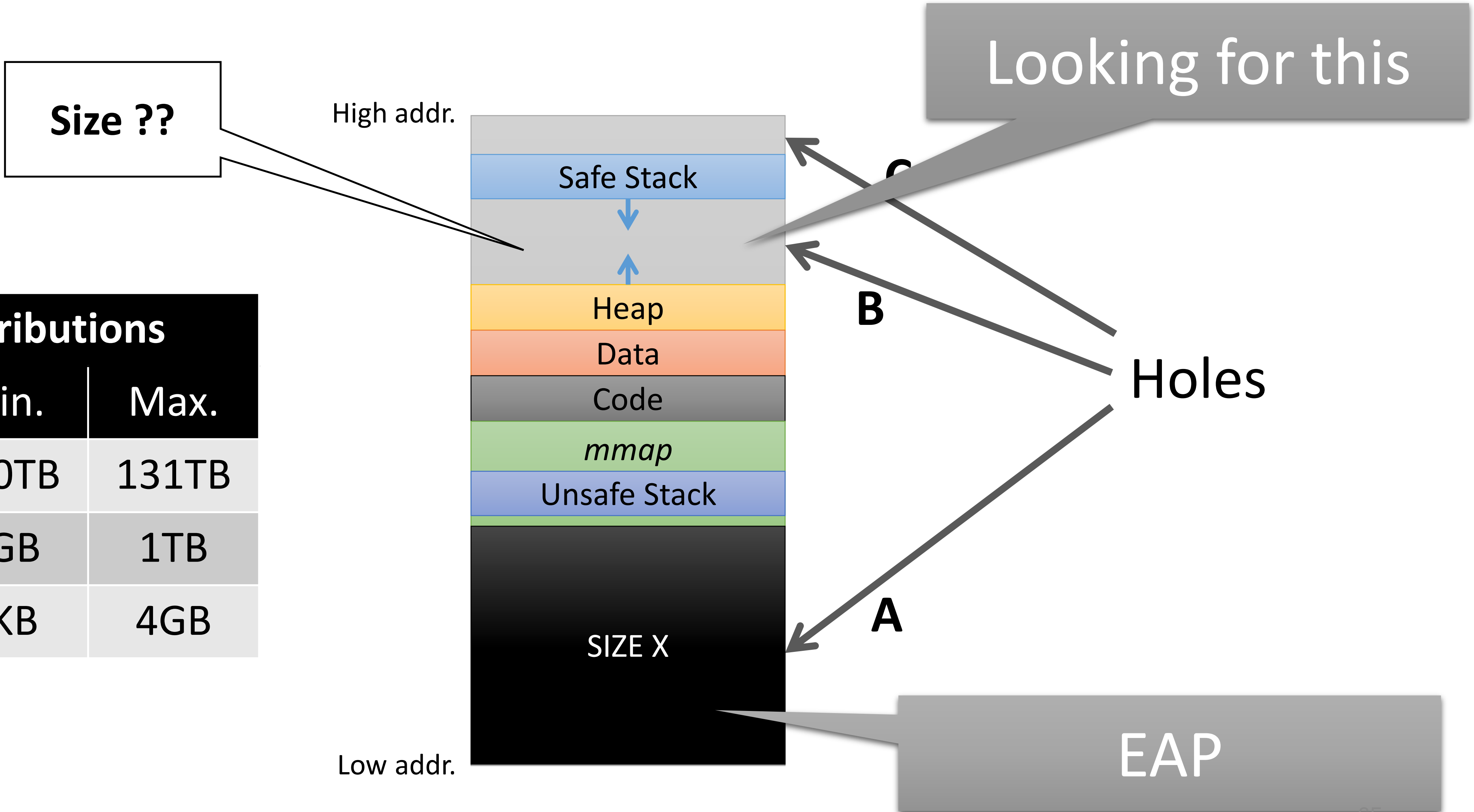
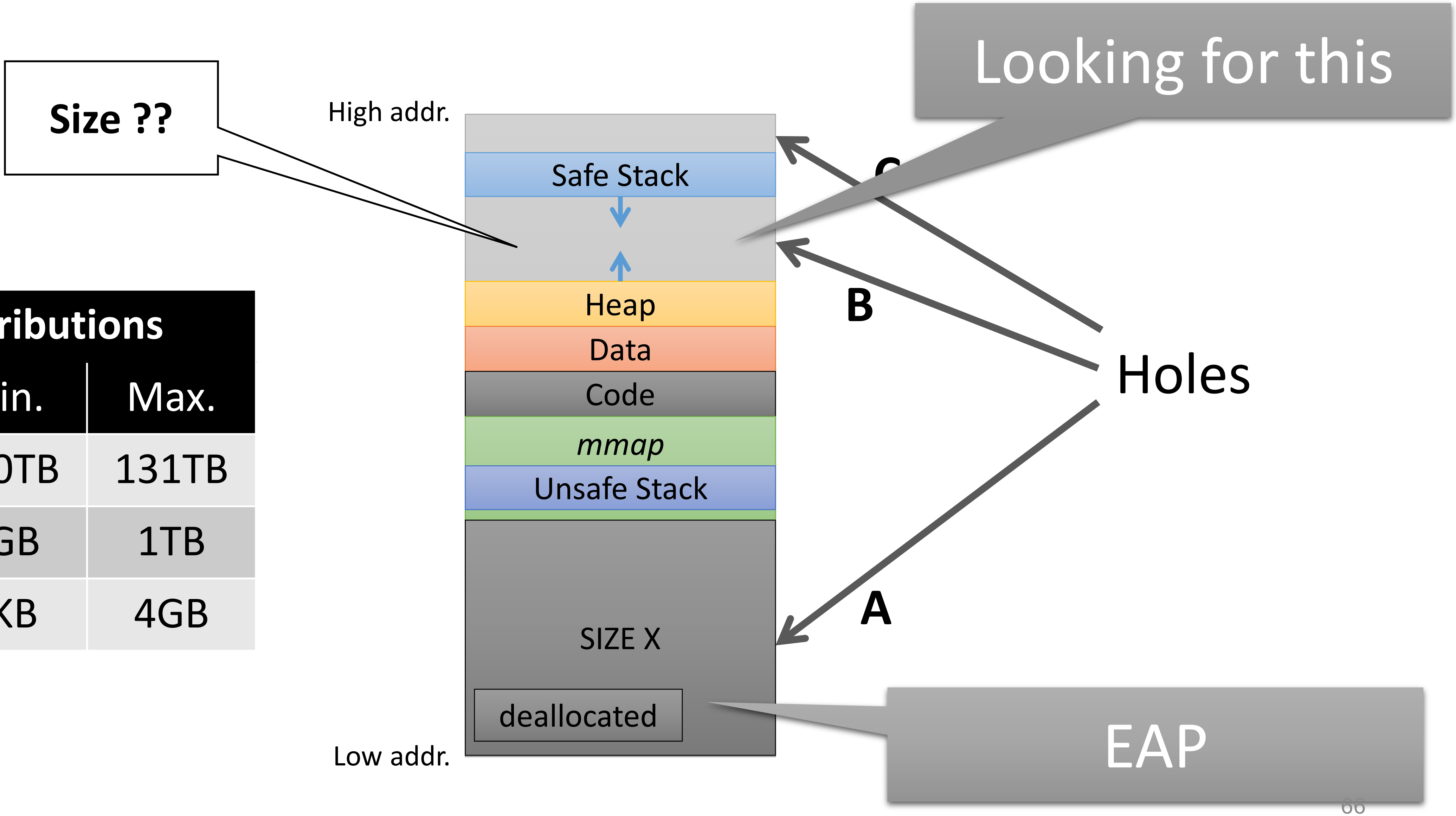




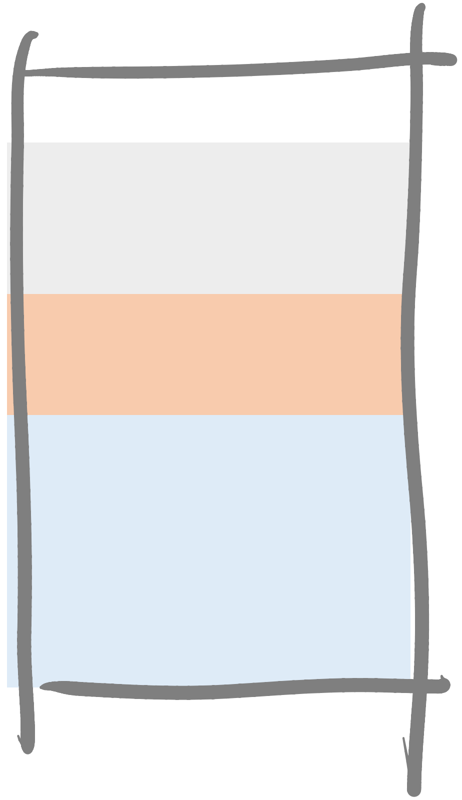
Size Distributions		
Hole	Min.	Max.
A	130TB	131TB
B	1GB	1TB
C	4KB	4GB

Persistent Allocation Primitive (PAP)

- For each request:

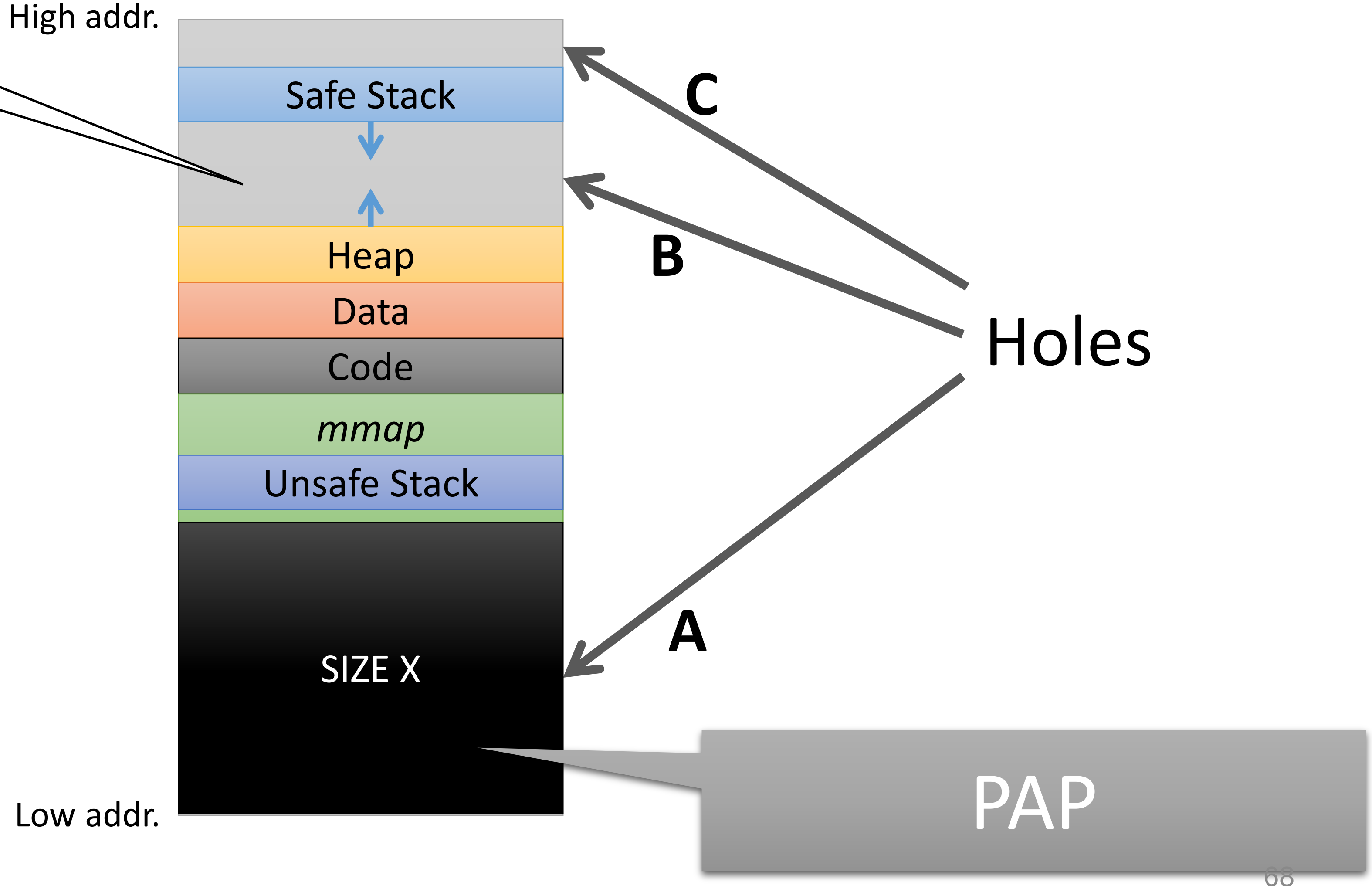
```
ptr = malloc(size);
...
reply(result);
```

- Pure persistent primitives rare
- But we can often turn *ephemeral* into *persistent*
  - Keep the connection open
  - Do not complete the req-reply



Size ??

Size Distributions		
Hole	Min.	Max.
A	130TB	131TB
B	1GB	1TB
C	4KB	4GB



Size Distributions		
Hole	Min.	Max.
A	130TB	131TB
B	1GB	1TB
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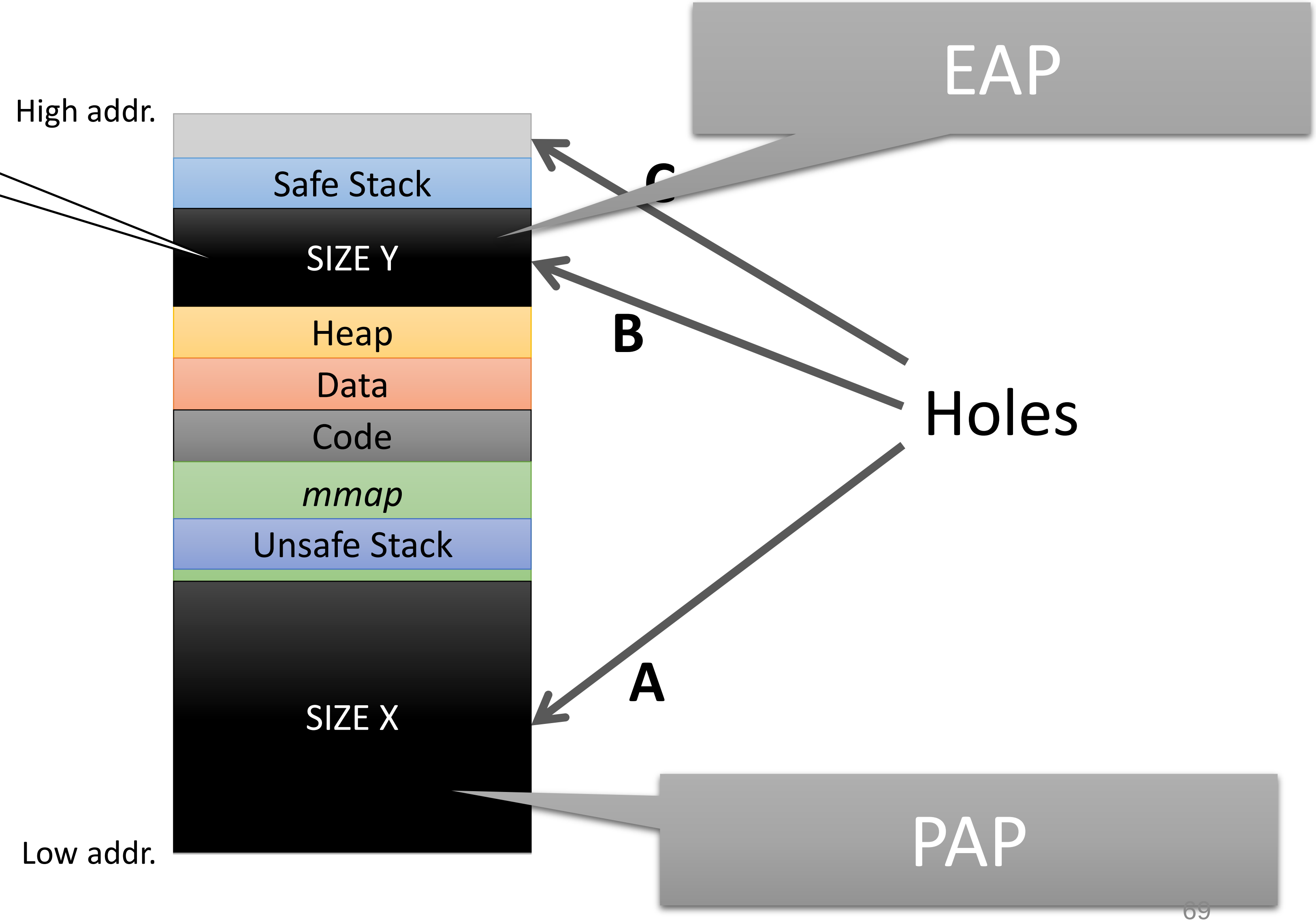

Size Distributions		
Hole	Min.	Max.
A	130TB	131TB
B	1GB	1TB
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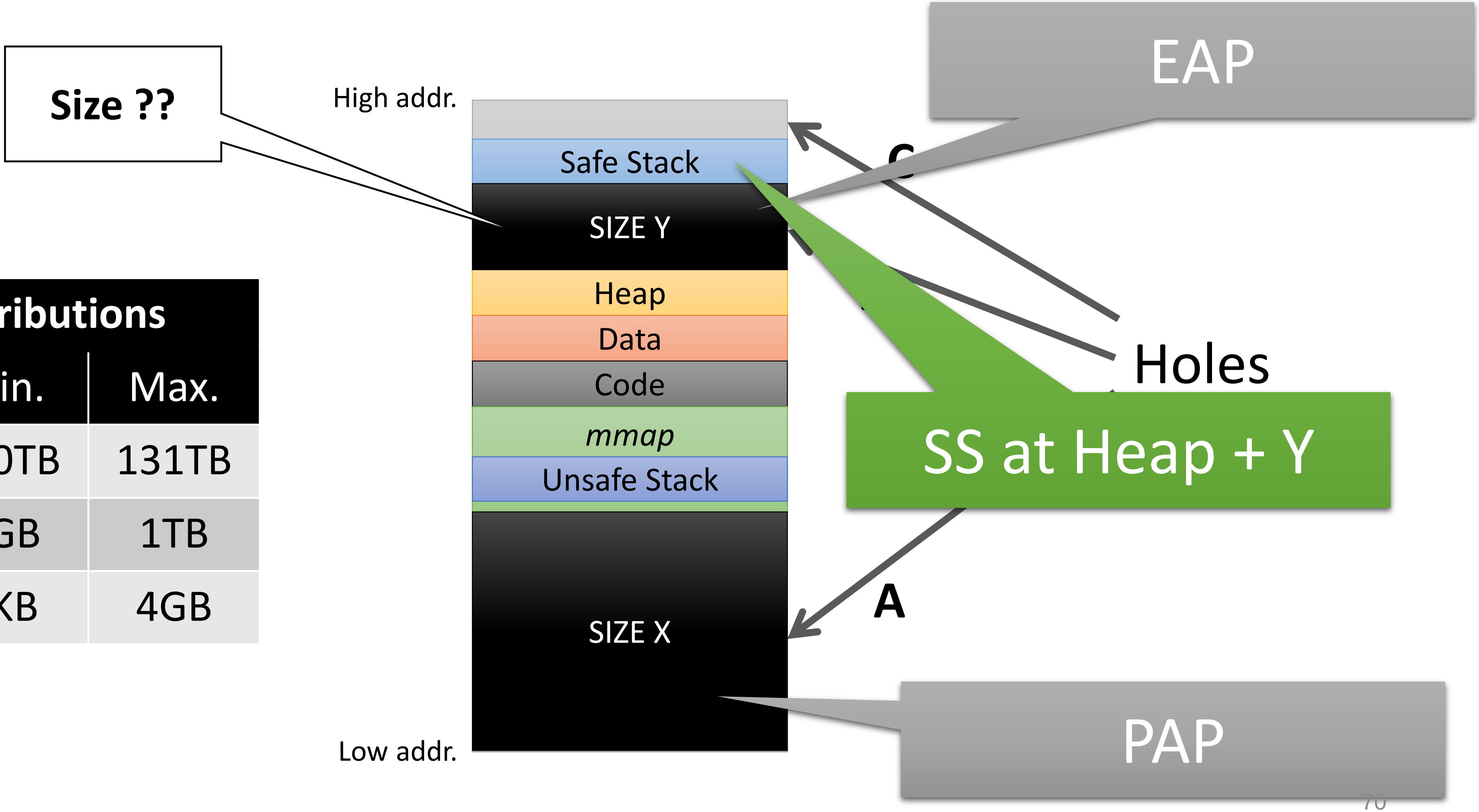


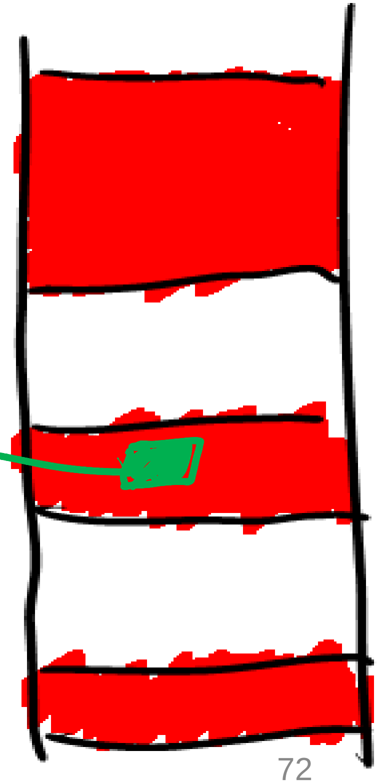
So we need

- A way to effect large allocations repeatedly
- A way to detect whether they failed

Here is what we do

- A way to effect large allocations repeatedly
- A way to detect whether they failed

```
ngx_event_accept(ngx_event_t *ev) {
    ...
    ngx_connection_t *lc = ev->data;
    ngx_listening_t *ls = cl->listening;
    ...
    c->pool = ngx_create_pool(ls->pool_size, ev->log);
    ...
}
```



- When server is in quiescent state
  - Taint all memory
  - See which bytes end up in allocation size

Here is what we do

- A way to effect large allocations repeatedly
- A way to detect whether they failed

Options

- Direct observation (most common)
  - E.g., HTTP **200** vs. **500**
- Fault side channels
  - E.g., HTTP **200** vs. **crash**
- Timing side channels
  - E.g., VMA cache **hit** vs. **miss**

Examples

- Nginx
  - Failed allocation: Connection close.
- Lighttpd
  - We crash both when
    - allocation fails (too large) and
    - succeeds (but allocation > than physical memory)
  - But in former case: crash immediately
  - In latter case, many page faults, takes a long time

Assumption

Memory overcommit:

- OS should allow (virtual) allocations beyond available physical memory
  - Common in server settings
  - Required by some applications:
    - Reddis, Hadoop, virtualization, etc.
- However, even when disabled:
  - Allocation oracles still possible
  - But attacker has to bypass overcommit restrictions

Conclusion

- Implementing safe stacks without pointers to it might not be trivial

- ASLR can be weakened by using Thread Spraying and Allocation Oracles

- Proper isolation can mitigate these attacks

https://www.usenix.org/system/files/conference/usenixsecurity16/sec16_paper_goktas.pdf
https://www.usenix.org/system/files/conference/usenixsecurity16/sec16_paper_oikonomopoulos.pdf