Bypassing clang's SafeStack for Fun and Profit

Enes Göktaş, Angelos Economopoulos, Robert Gawlik, Benjamin Kollenda, Elias Athanasopoulos, Georgios Portokalidis, Cristiano Giuffrida, Herbert Bos

Outline

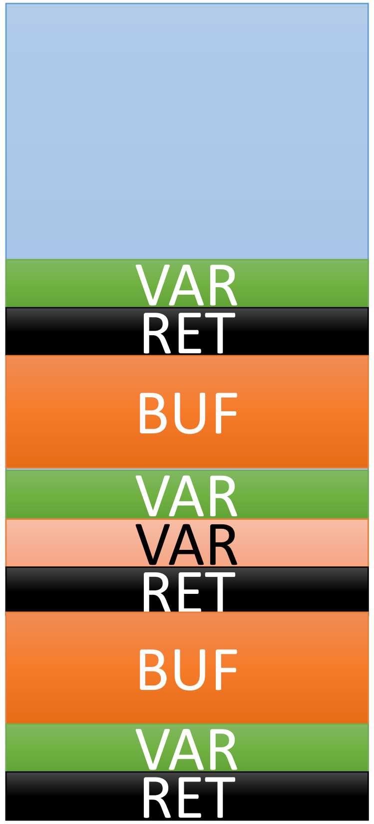
- SafeStack
- Neglected Pointers
- Thread Spraying
- Allocation Oracles
- Conclusion

SafeStack

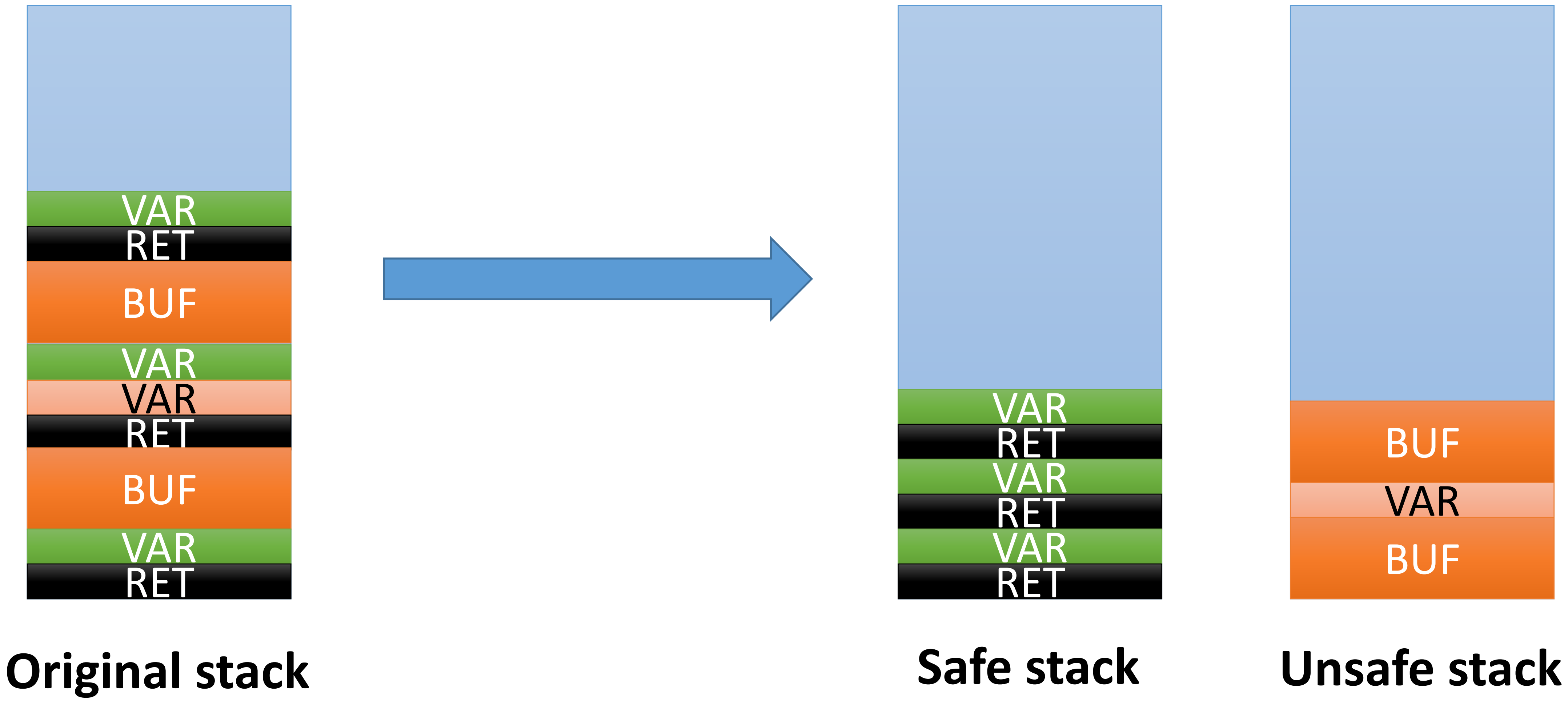
- New security feature in LLVM
- Protect against stack based control-flow hijacks

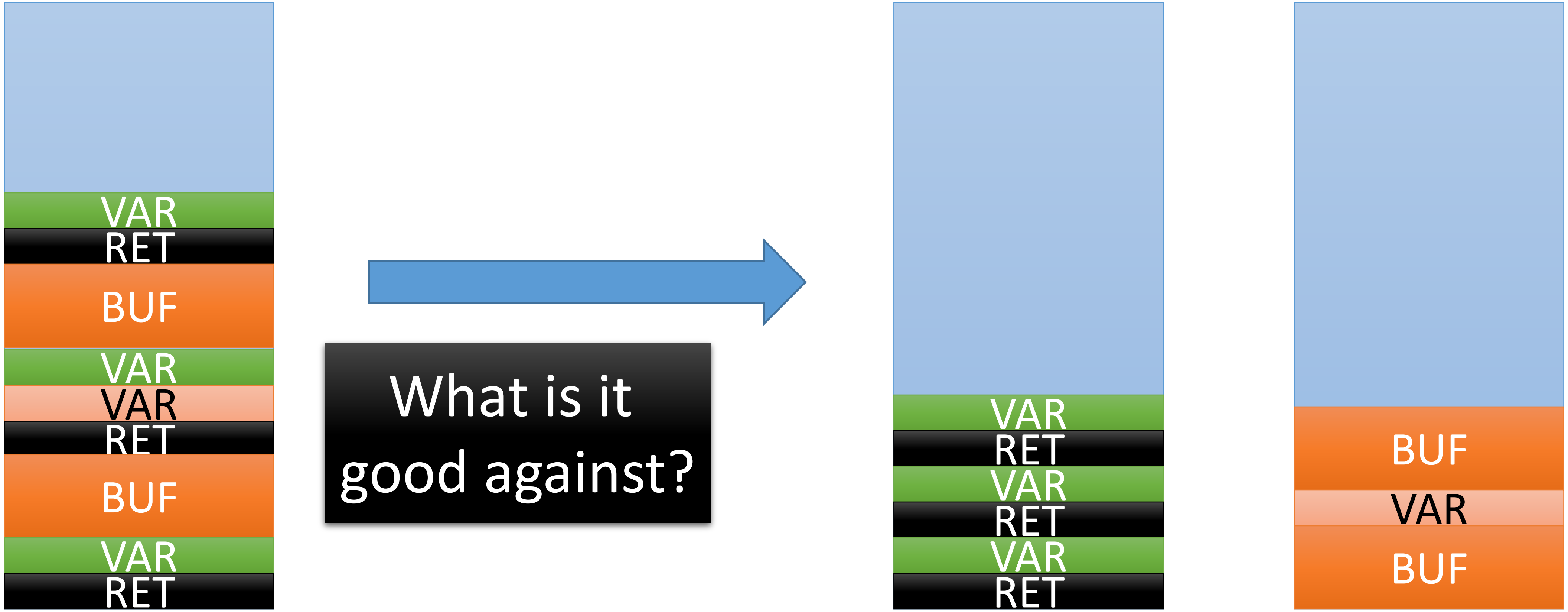
- In research proposals:
  - Code-Pointer Integrity (Kuznetsov et al., 2014) (origin SafeStack)
  - ASLR-Guard (Lu et al., 2015)

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

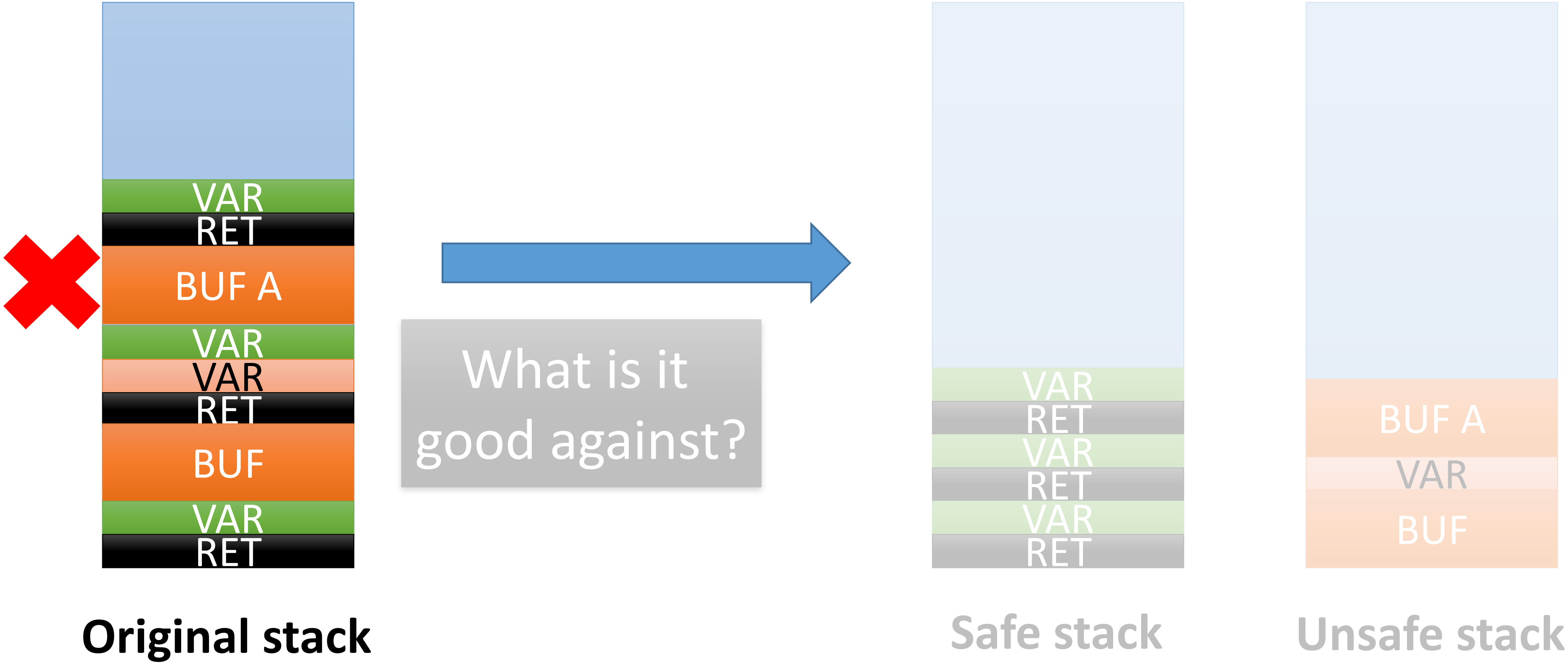


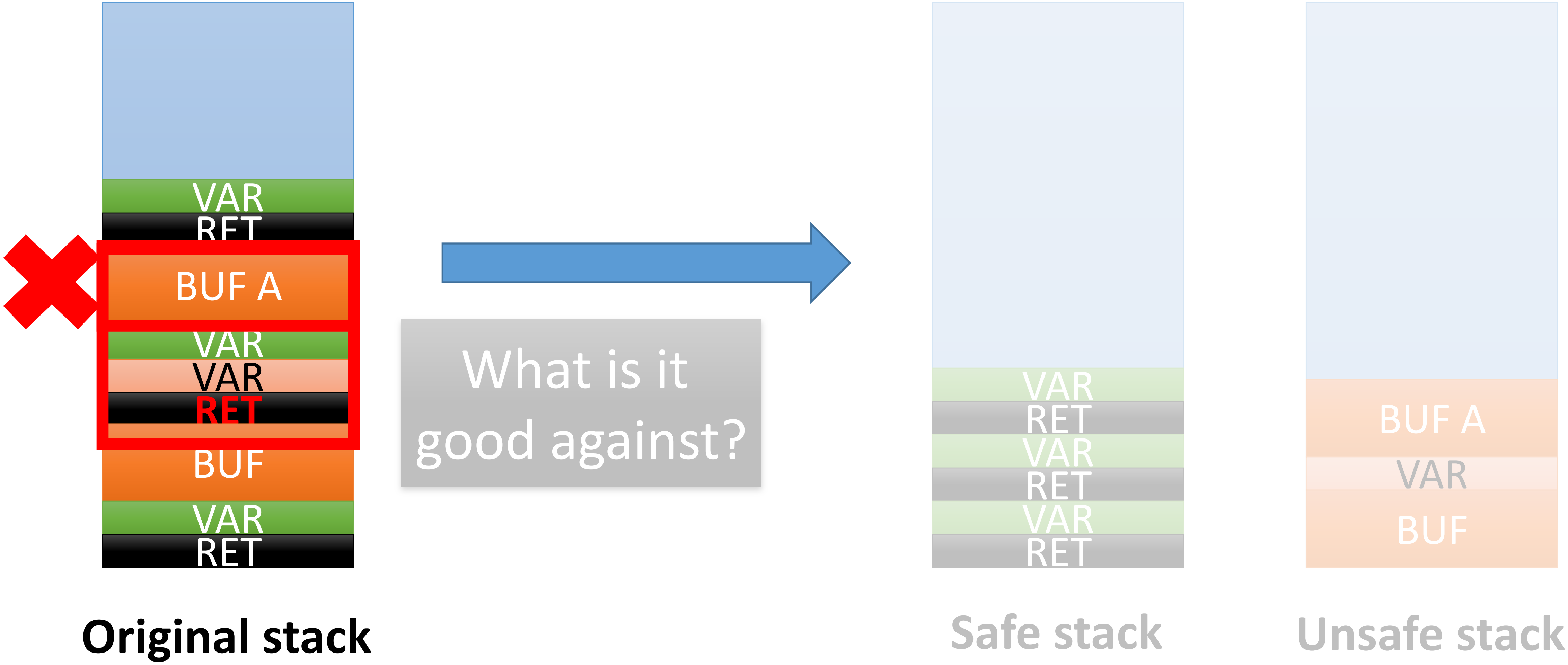
Original stack


VAR
RET
BUF
VAR
VAR
RET
BUF
VAR
RET
Original stack
VAR
RET
VAR
RET
VAR
RET
Safe stack
BUF
VAR
BUF
Unsafe stack



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


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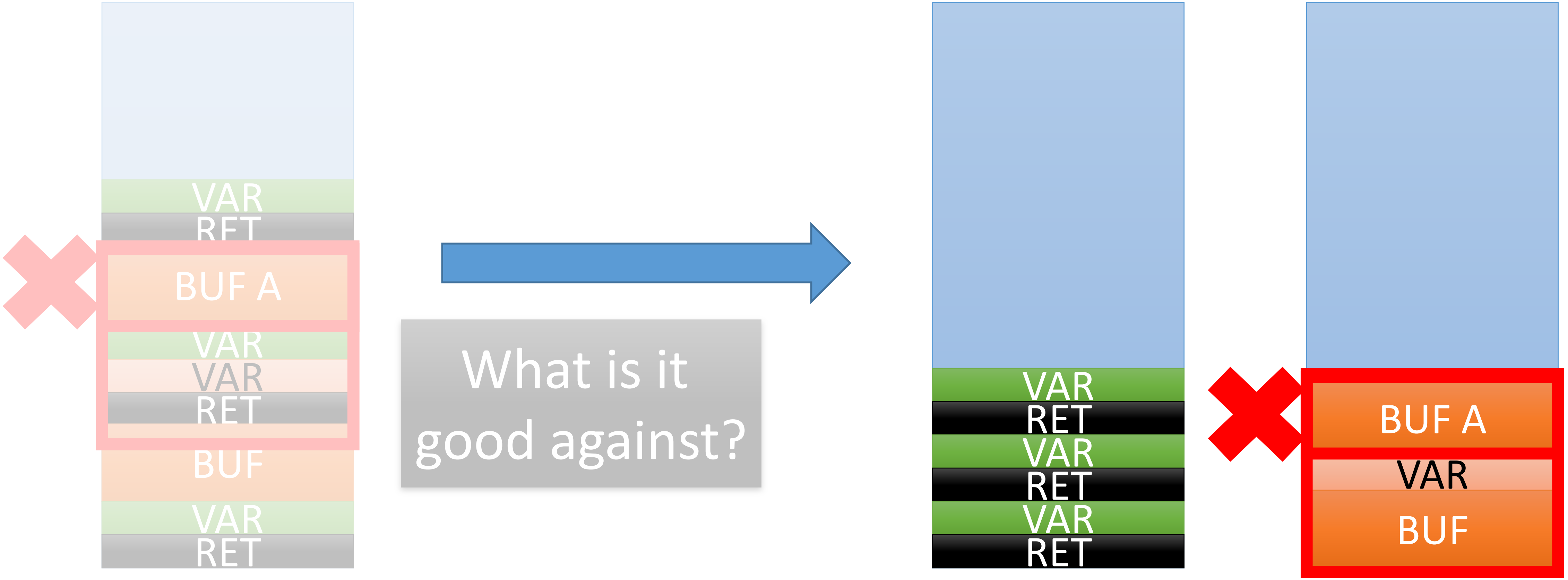
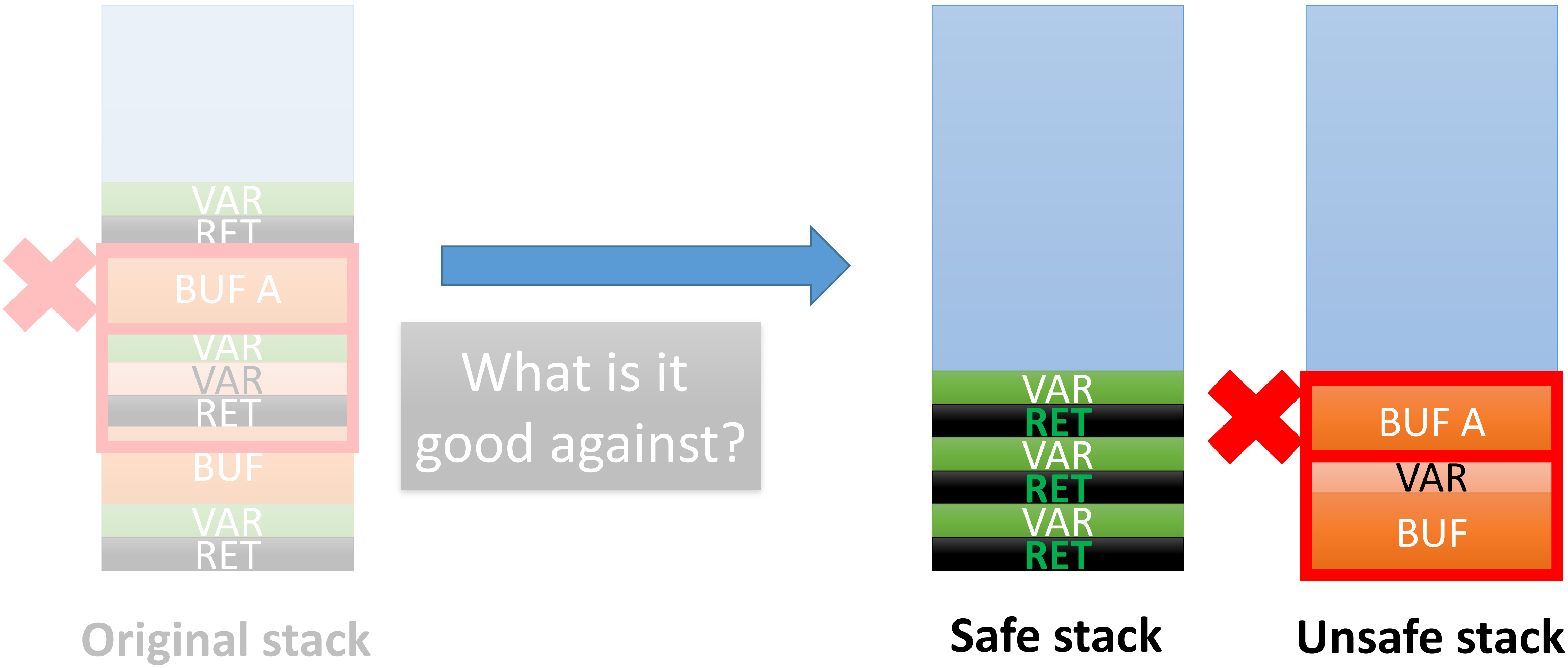
Original stack
Safe stack
Unsafe stack

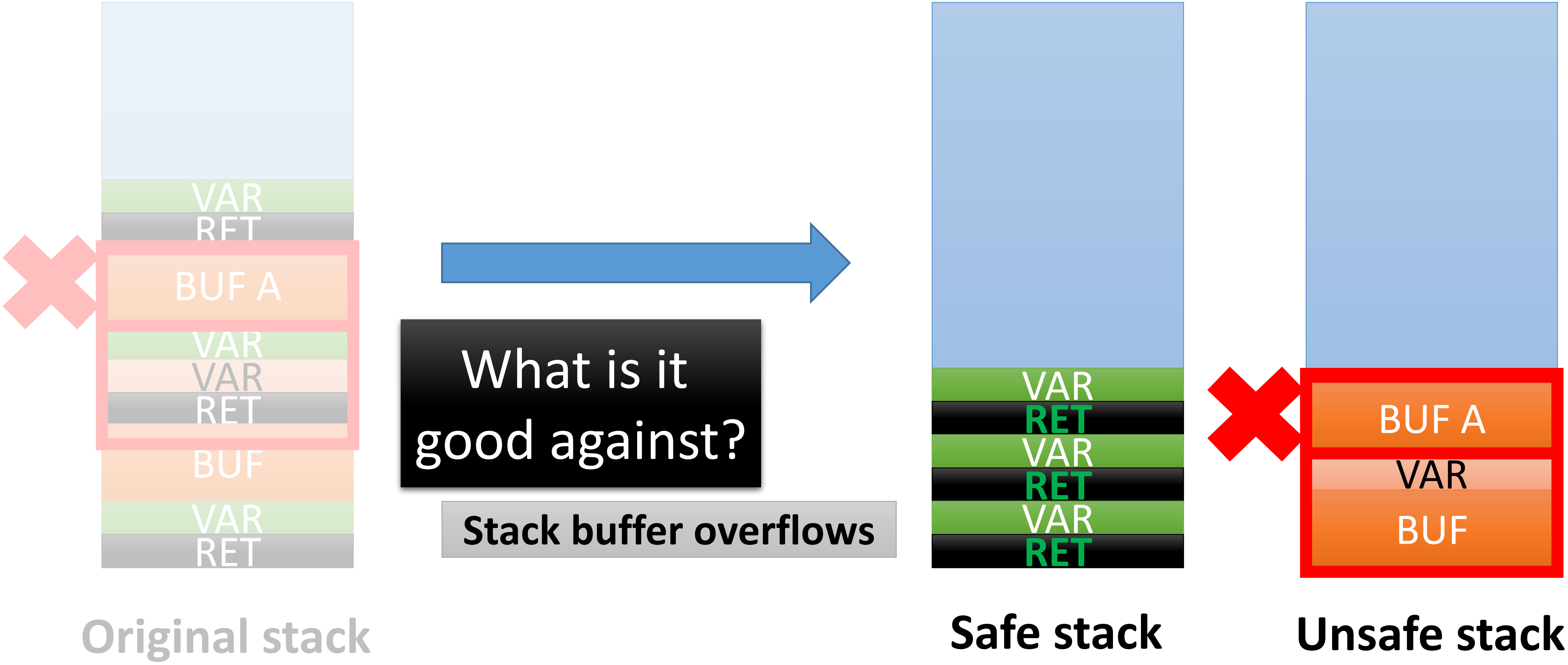


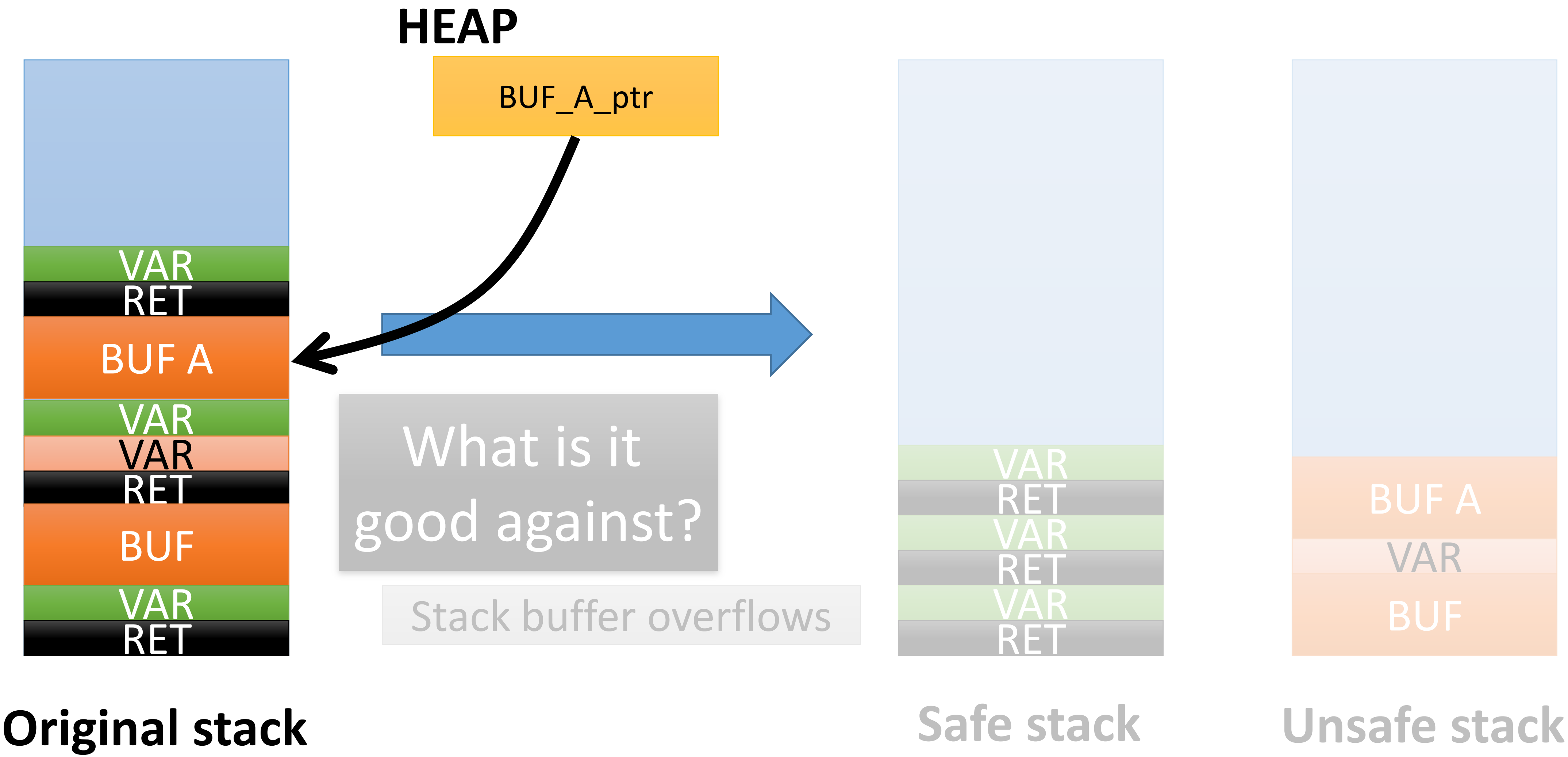
Original stack

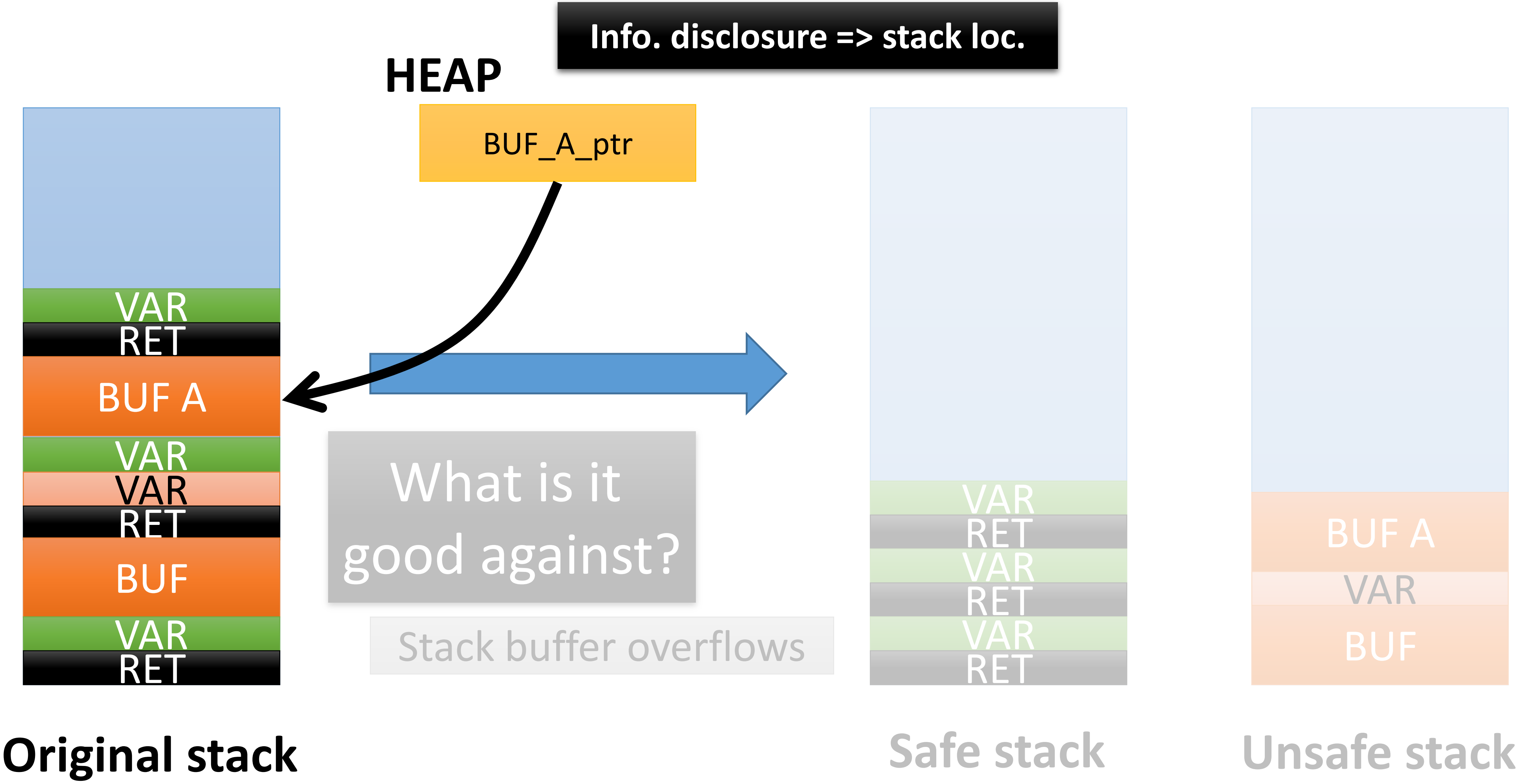
Safe stack

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
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


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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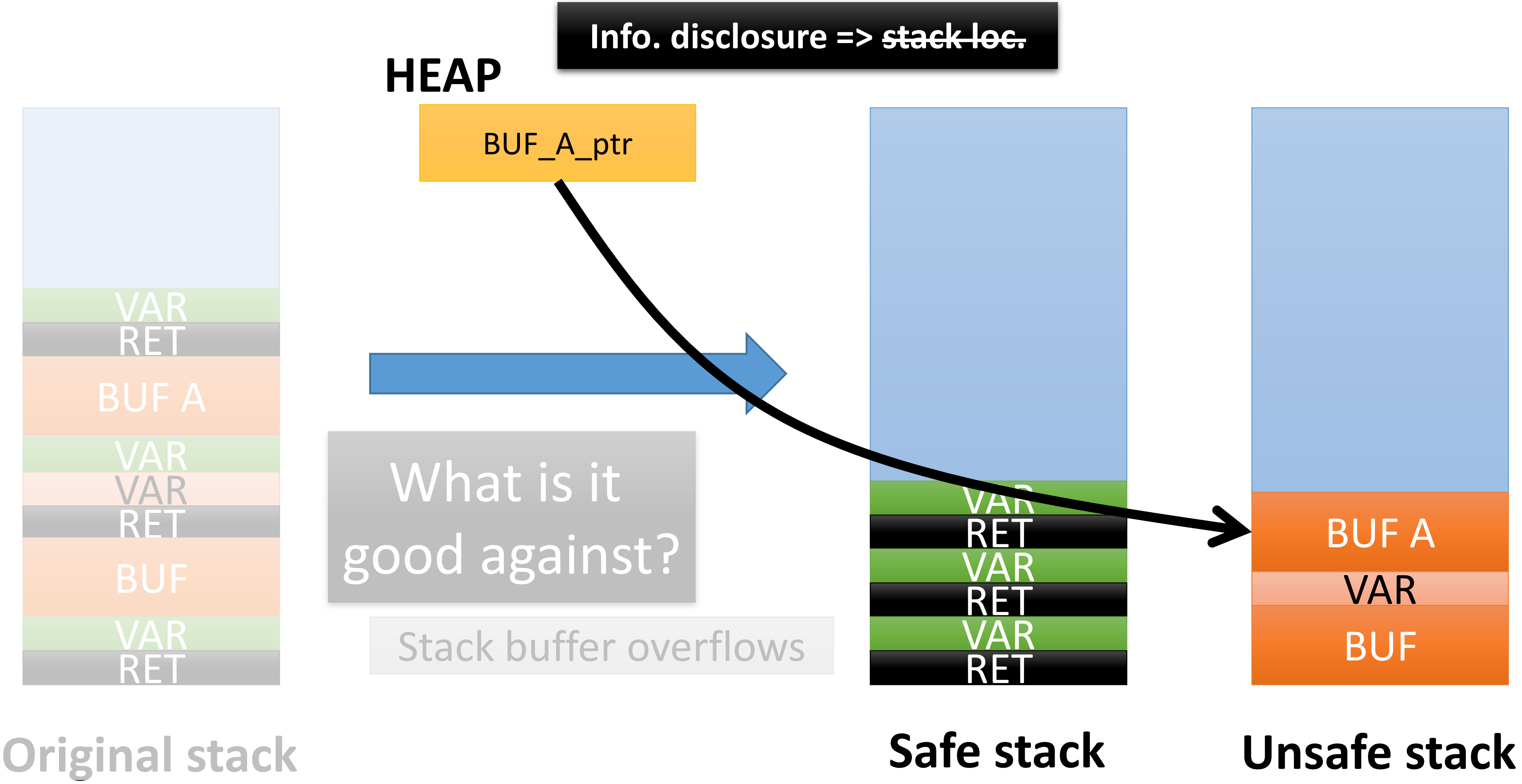
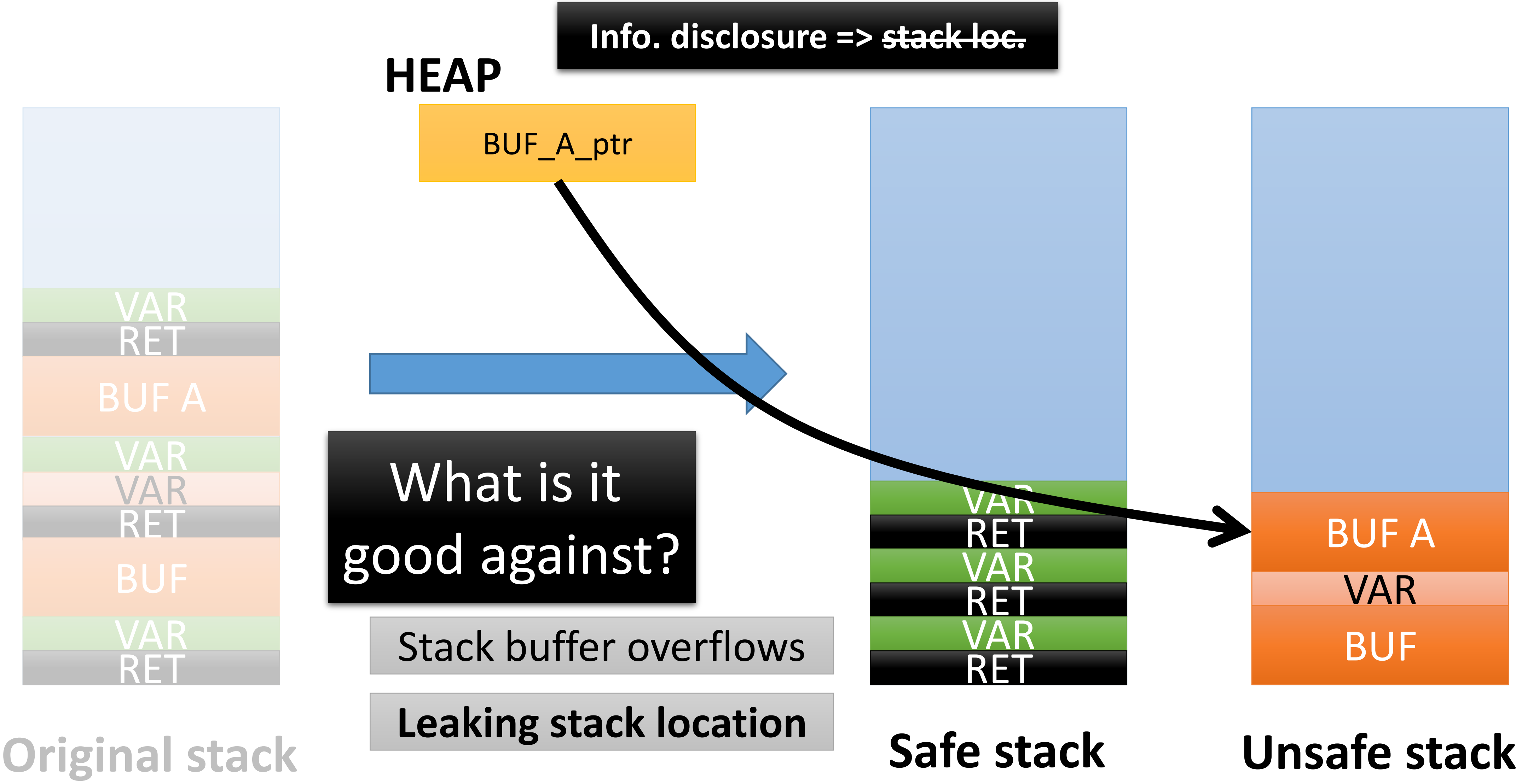
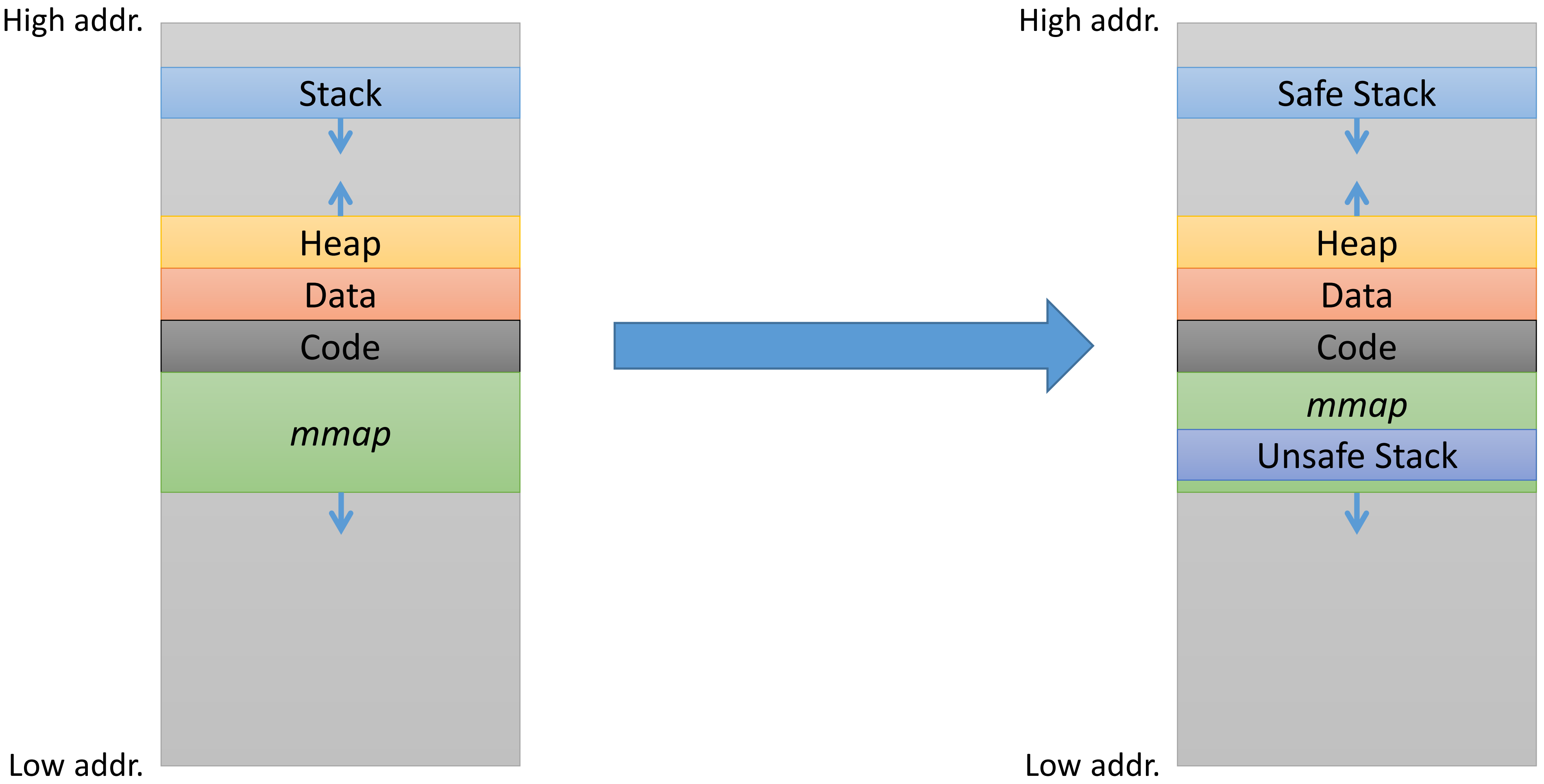

Info. disclosure => ~~stack loc.~~
HEAP
BUF_A_ptr
VAR
RET
BUF A
VAR
VAR
RET
BUF
VAR
RET
What is it good against?
Stack buffer overflows
VAR
RET
VAR
RET
VAR
RET
BUF A
VAR
BUF
Original stack
Safe stack
Unsafe stack

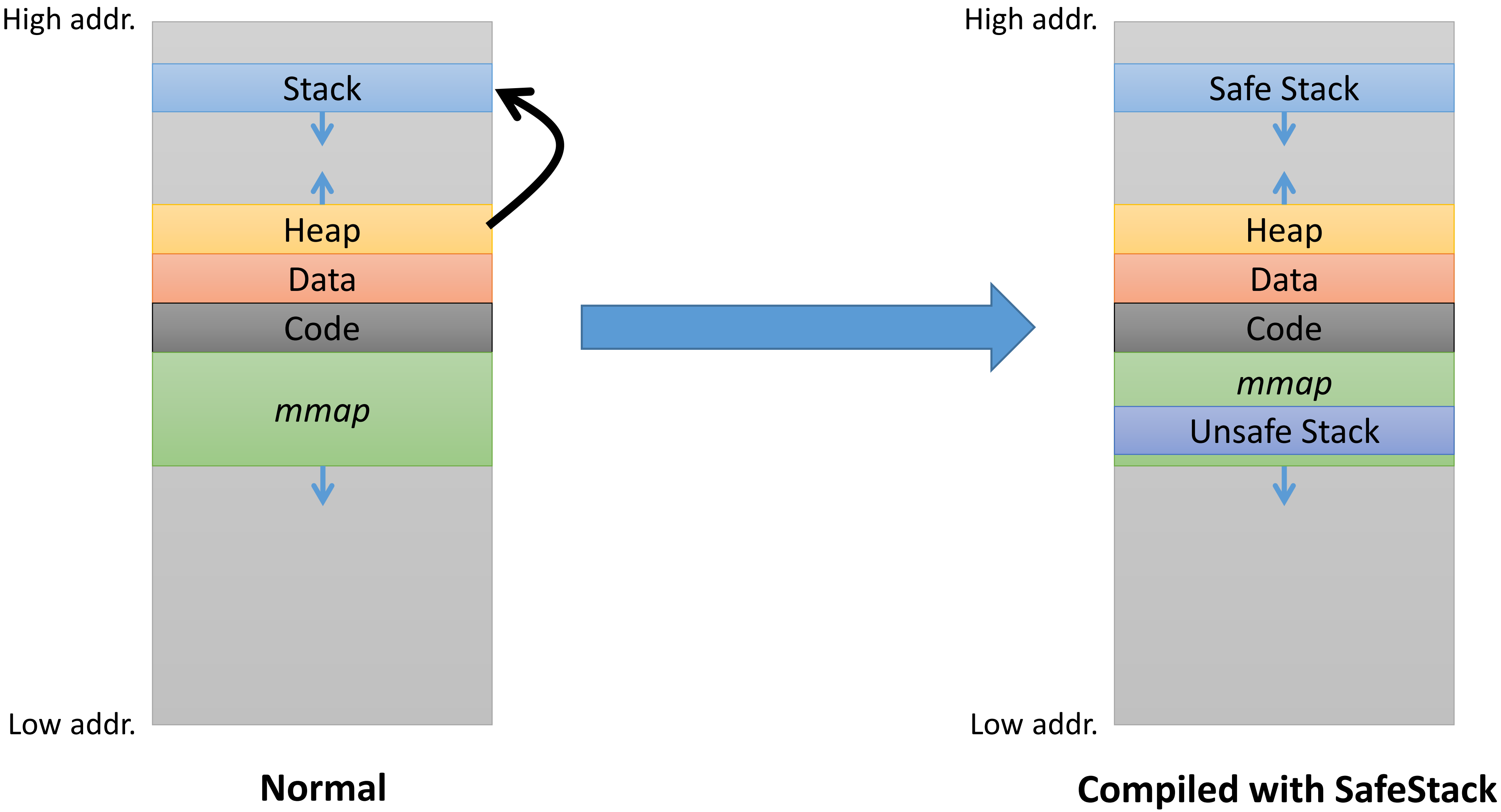

Info. disclosure => ~~stack loc.~~
HEAP
BUF_A_ptr
VAR
RET
BUF A
VAR
VAR
RET
BUF
VAR
RET
Original stack
What is it good against?
Stack buffer overflows
Leaking stack location
VAR
RET
VAR
RET
VAR
RET
Safe stack
BUF A
VAR
BUF
Unsafe stack

PIE compiled program in Linux

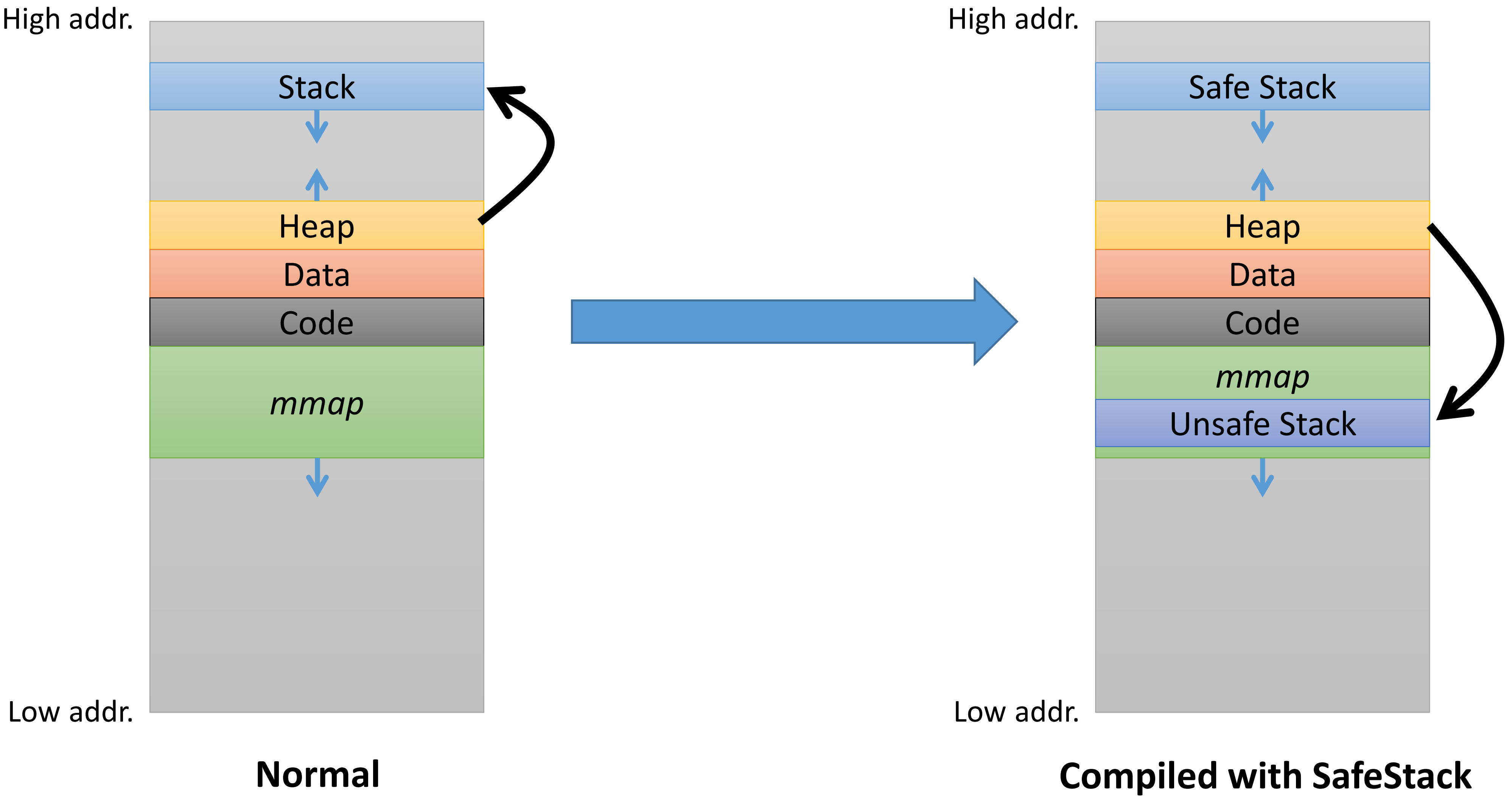


Normal **Compiled with SafeStack**

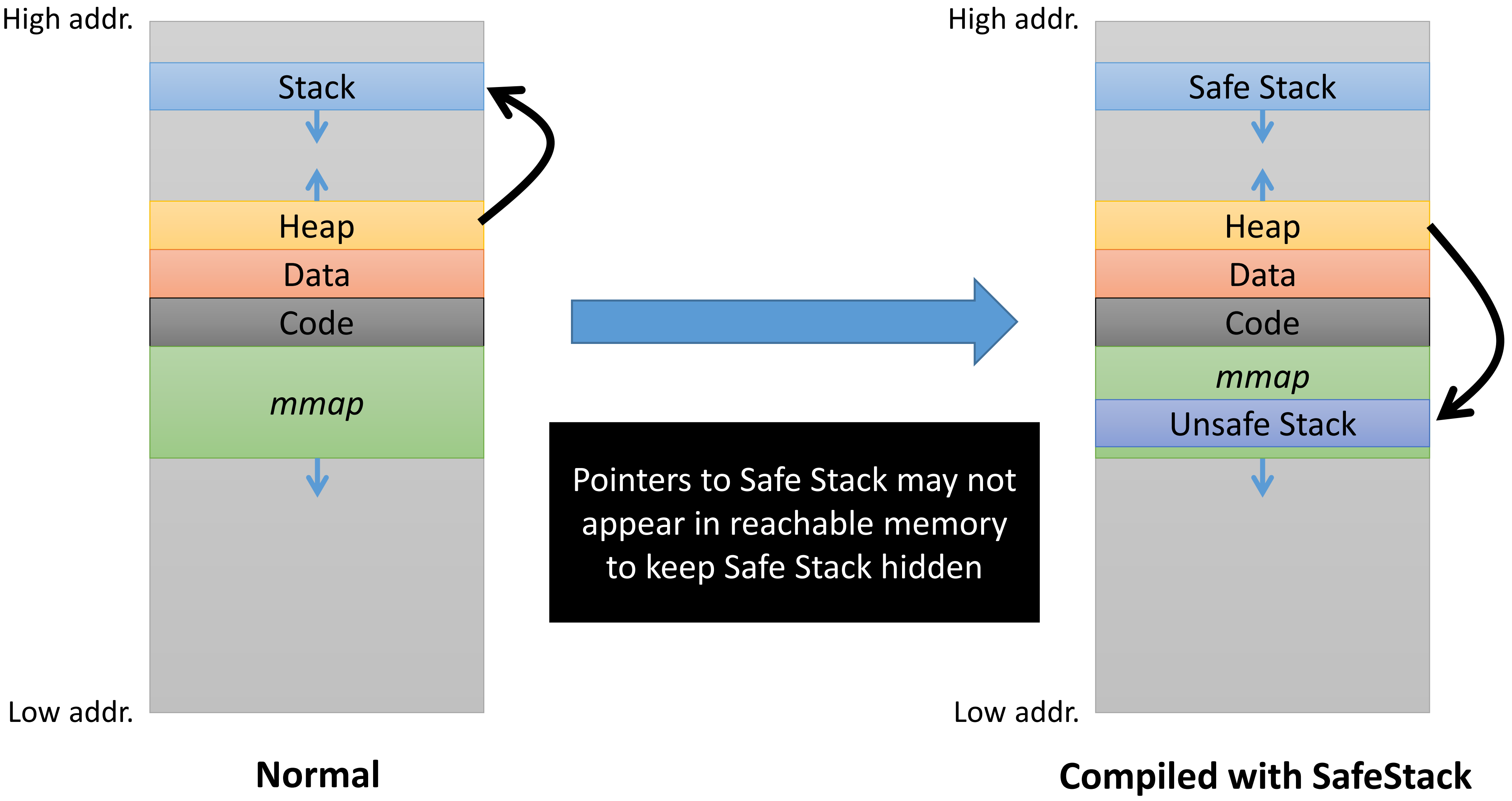
PIE compiled program in Linux



PIE compiled program in Linux



PIE compiled program in Linux



test.c

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

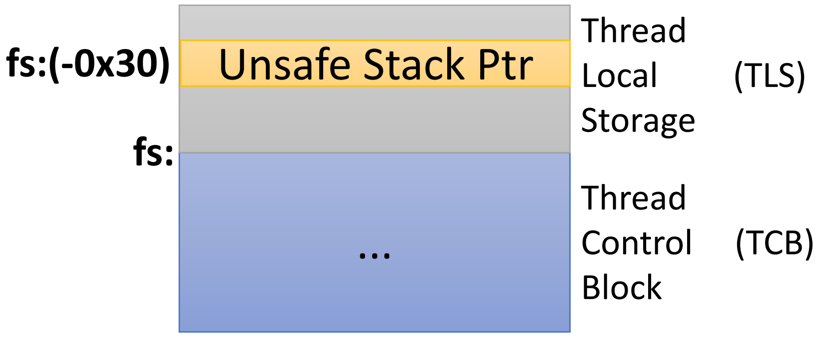
Allocate address taken local variable on stack

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

Allocate address taken local variable on stack

Address of variable provided to strcpy

normal

```
0x400561 : sub    $0x20,%rsp
0x400565 : mov    (%rsi),%rsi
0x400568 : lea    (%rsp),%rbx
0x40056c : mov    %rbx,%rdi
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```

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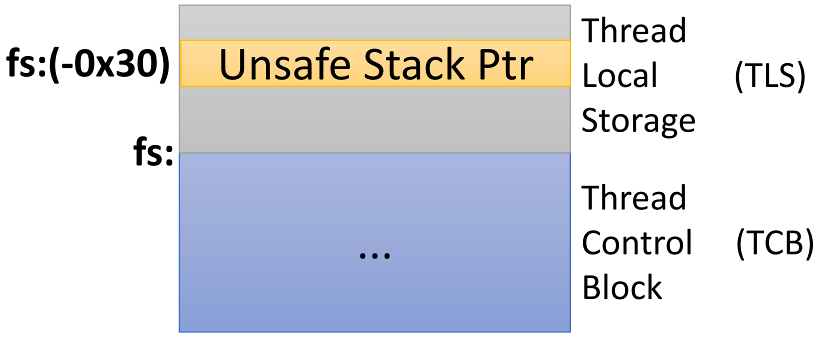

SafeStack

- 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

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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

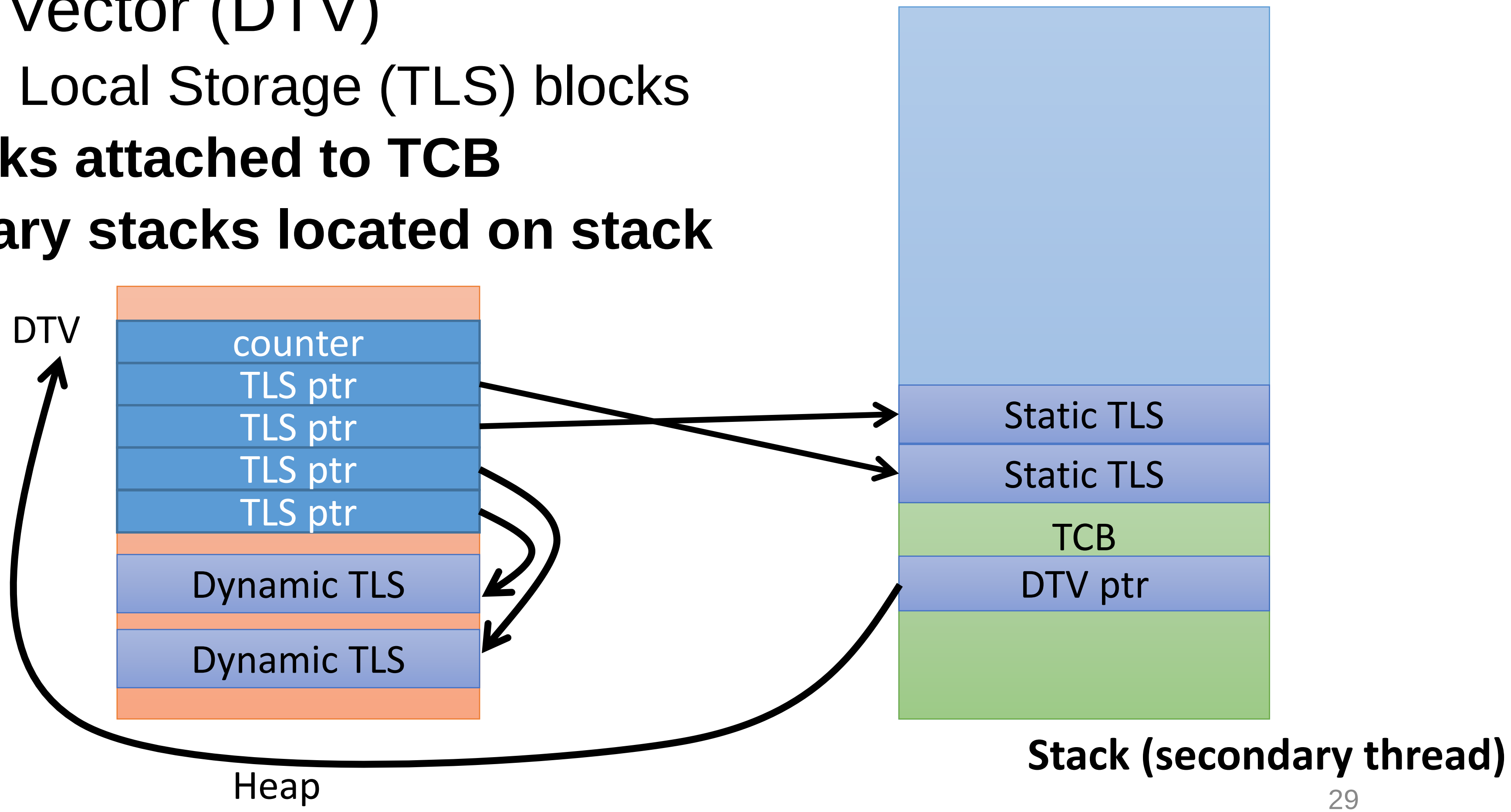
- Analyze programs compiled with SafeStack for unexpected pointers
  - GDB + python
  - Report pointers common among apps

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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- What could he do to increase the chance to hit a safestack?

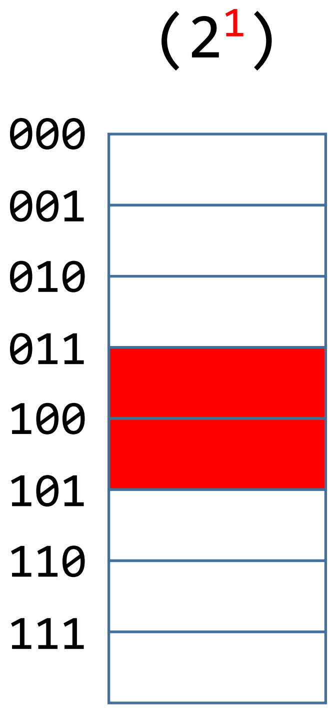
Reduce the entropy through *Thread Spraying*

Entropy

- Degree of randomness
- Given in bits

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

  - Hide data



Entropy: 2 bits

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

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

Entropy

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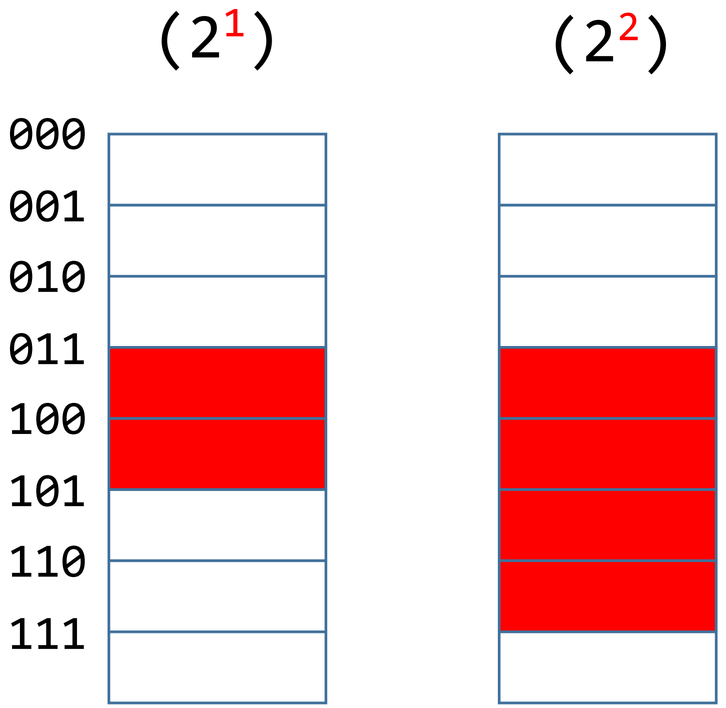
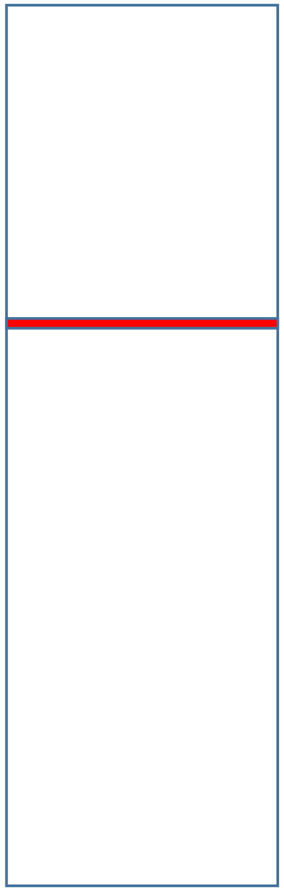


Entropy:	2 bits	1 bit
Hit chance:	$\frac{1}{2^{2}} = \frac{1}{4}$	$\frac{1}{2^{1}} = \frac{1}{2}$
Worst case #probes:	$2^{2} = 4$	$2^{1} = 2$

Hide: 1 byte

64 bit address space

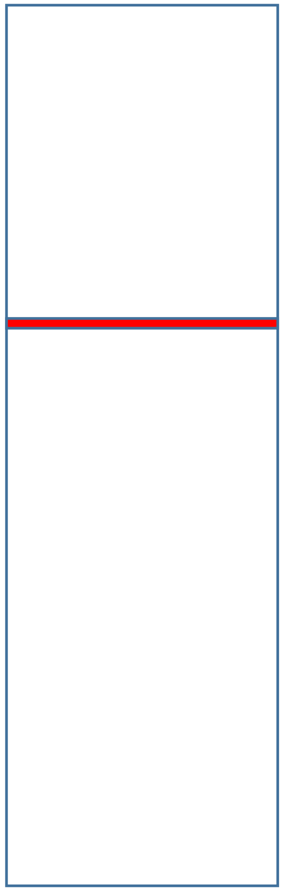


Entropy: 64 bits

Hide: 1 byte

64 bit address space

Linux user space only uses 47 bit



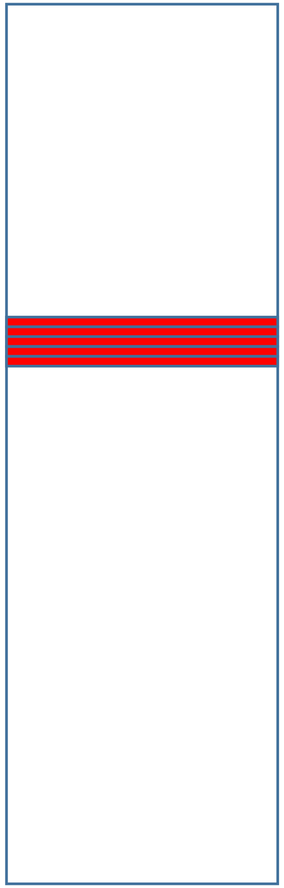
Entropy: 47 bits

Hide: 4096 bytes

64 bit address space

Linux user space only uses 47 bit

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



Entropy: 35 bits

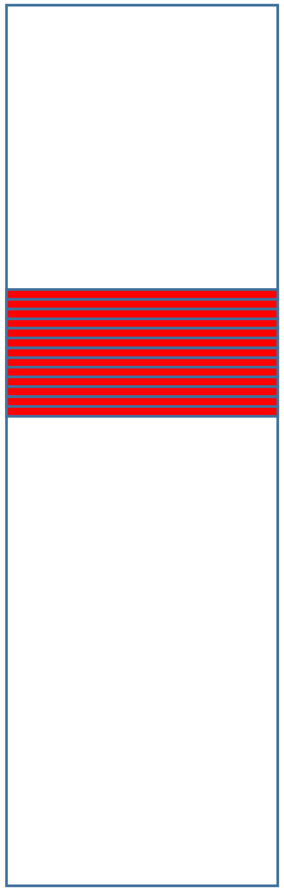
Hide: 2^{23} bytes

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



Entropy: 24 bits

Hide: 2^{23} bytes

64 bit address space

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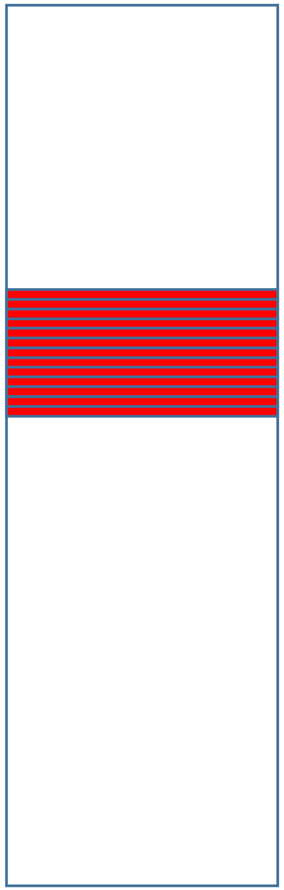
1 page: 4096 bytes = 2^{12} bytes

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

Thread Spraying

Legitimately spawn as many threads as possible



Entropy: 24 bits

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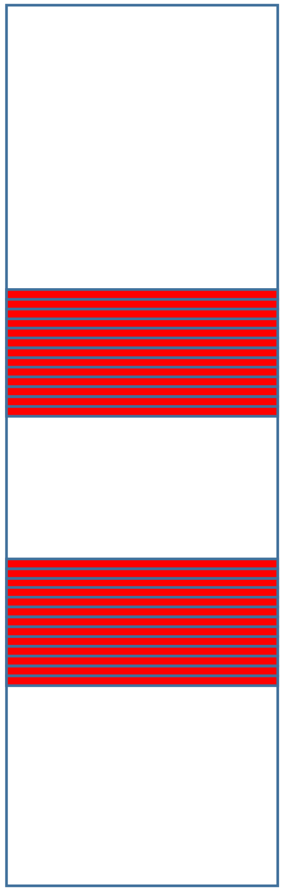
Thread Spraying

Legitimately spawn as many threads as possible

Spawn a new thread

Hide: 2^{24} bytes



Entropy: 23 bits

Hide: 2^{25} bytes

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

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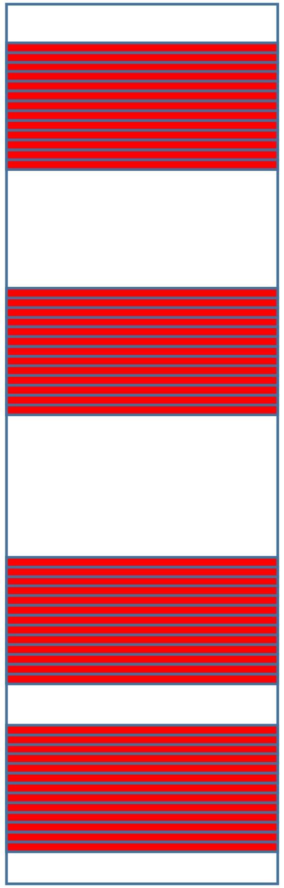
Legitimately spawn as many threads as possible

Spawn a new thread

Spawn 2 more threads



Entropy: 22 bits

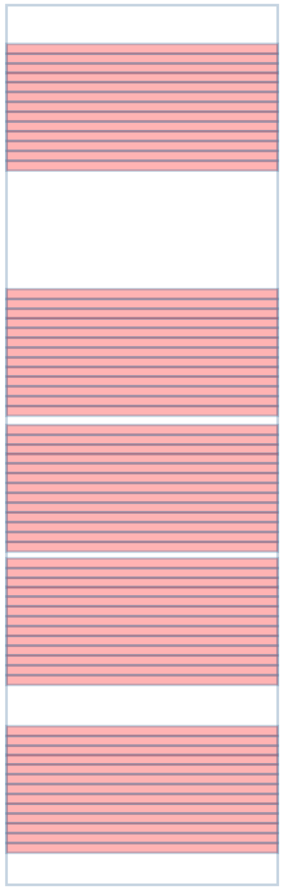
Hide: 2^{40} bytes

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

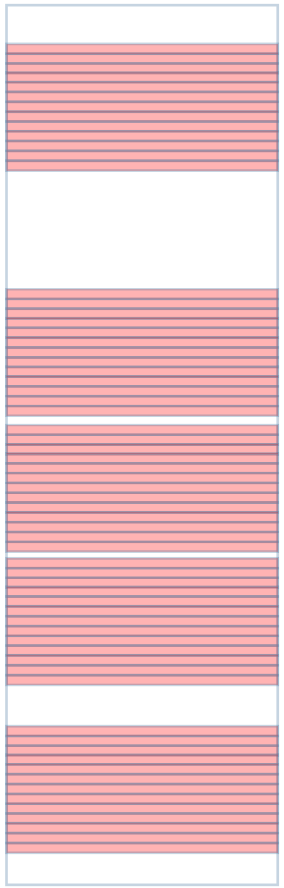
Spawn a new thread

Spawn 2 more threads

Spawn 128k threads = 2^{17} stacks

Entropy: 7 bits

Hide: 2^{40} bytes



64 bit address space

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Thread Spraying

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Drops worst case
#probes to 128

Entropy: 7 bits

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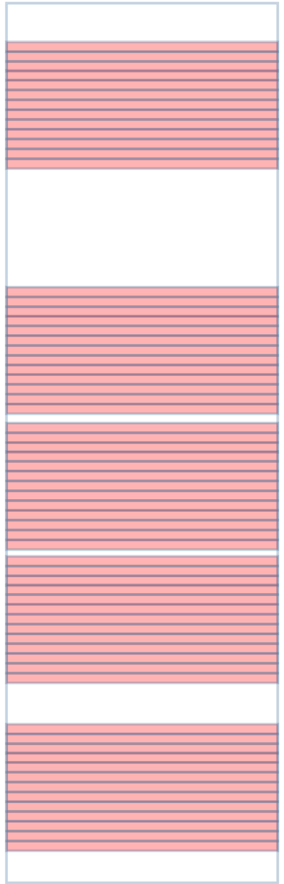

64 bit address space

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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

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- 20 web workers per domain
- Web worker thread stack size = 2MB ; entropy = 19 bits
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Linux stack entropy = 40 bits
2MB occupies 21 bits in AS
40 - 21 bits = 19 bits of entropy
#probes = 524288

#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
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- **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

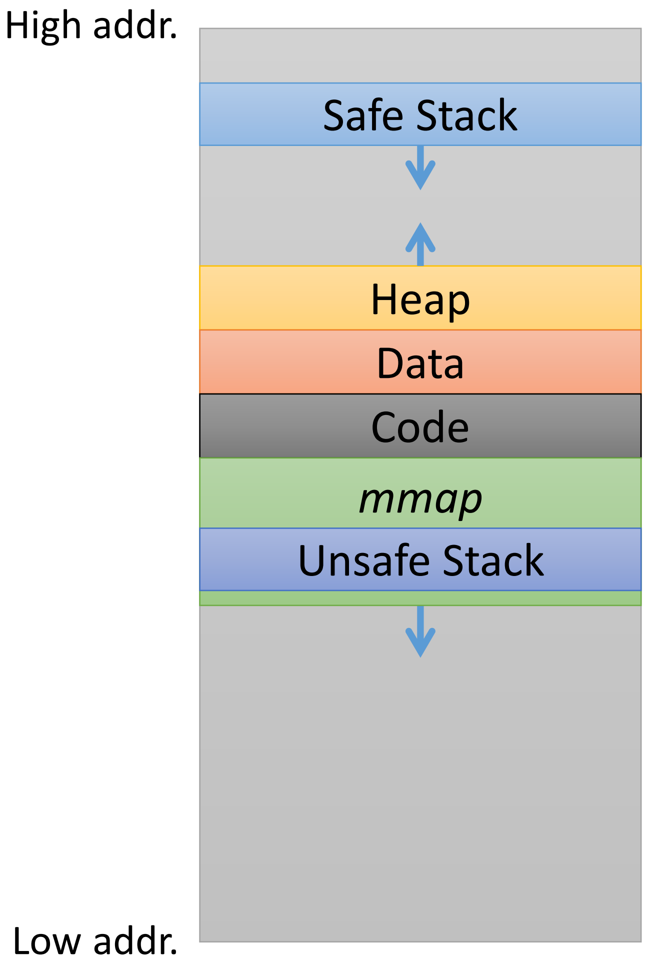
- **4096** connections drops entropy to 10 bits
  - max_connections = 4096
- Stack size of **256 MB** can drop entropy to 0 bits
  - connection_attrib.stack_size = 0x10000000

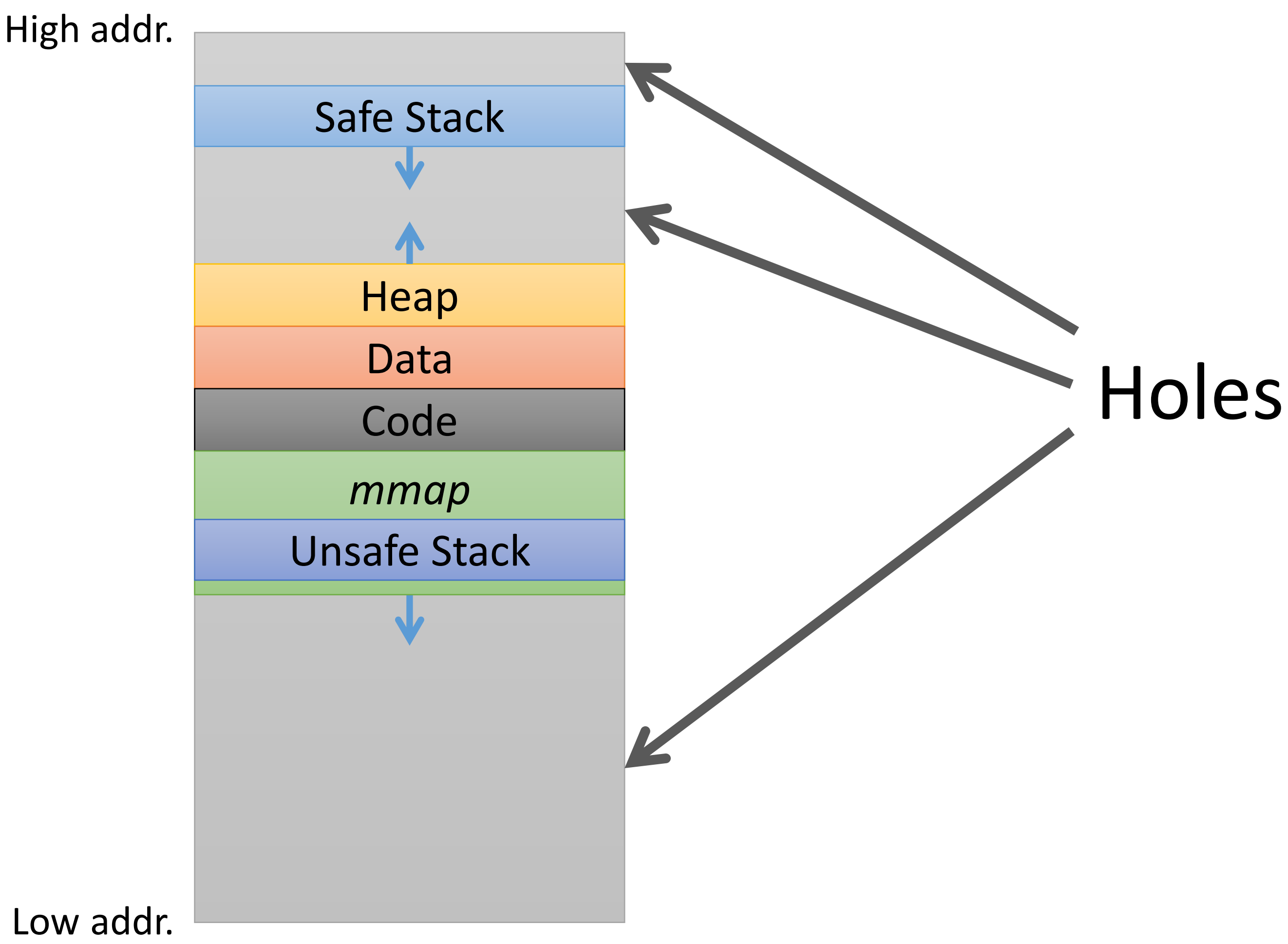
Exhausted 0x7F.. address region.
Address 0x7F0000000000 has
safestack with a very high chance.

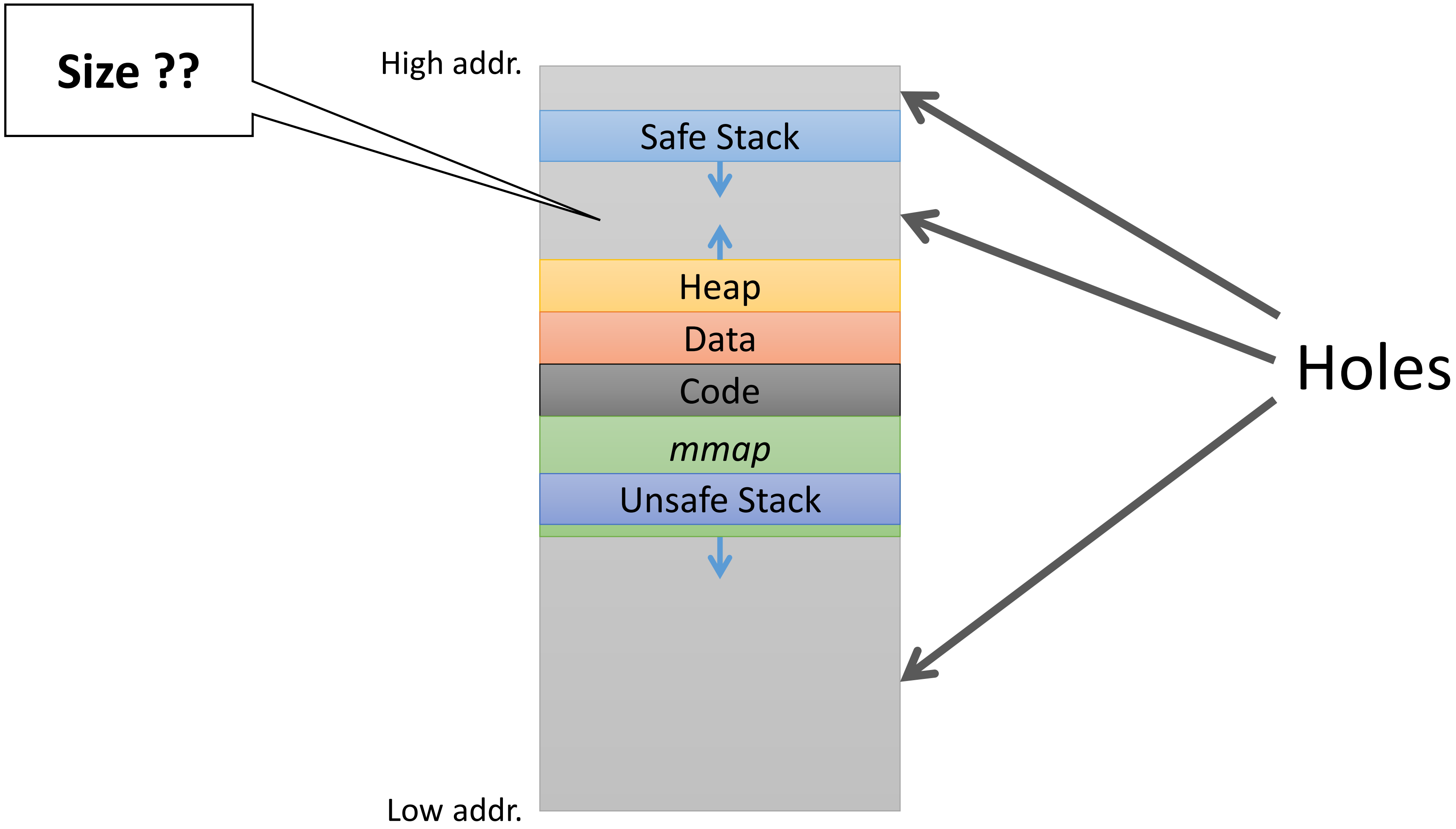
- By spraying lots of threads
  - ASLR can be weakened
  - Chance to hit safestack can be increased

- 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 ??
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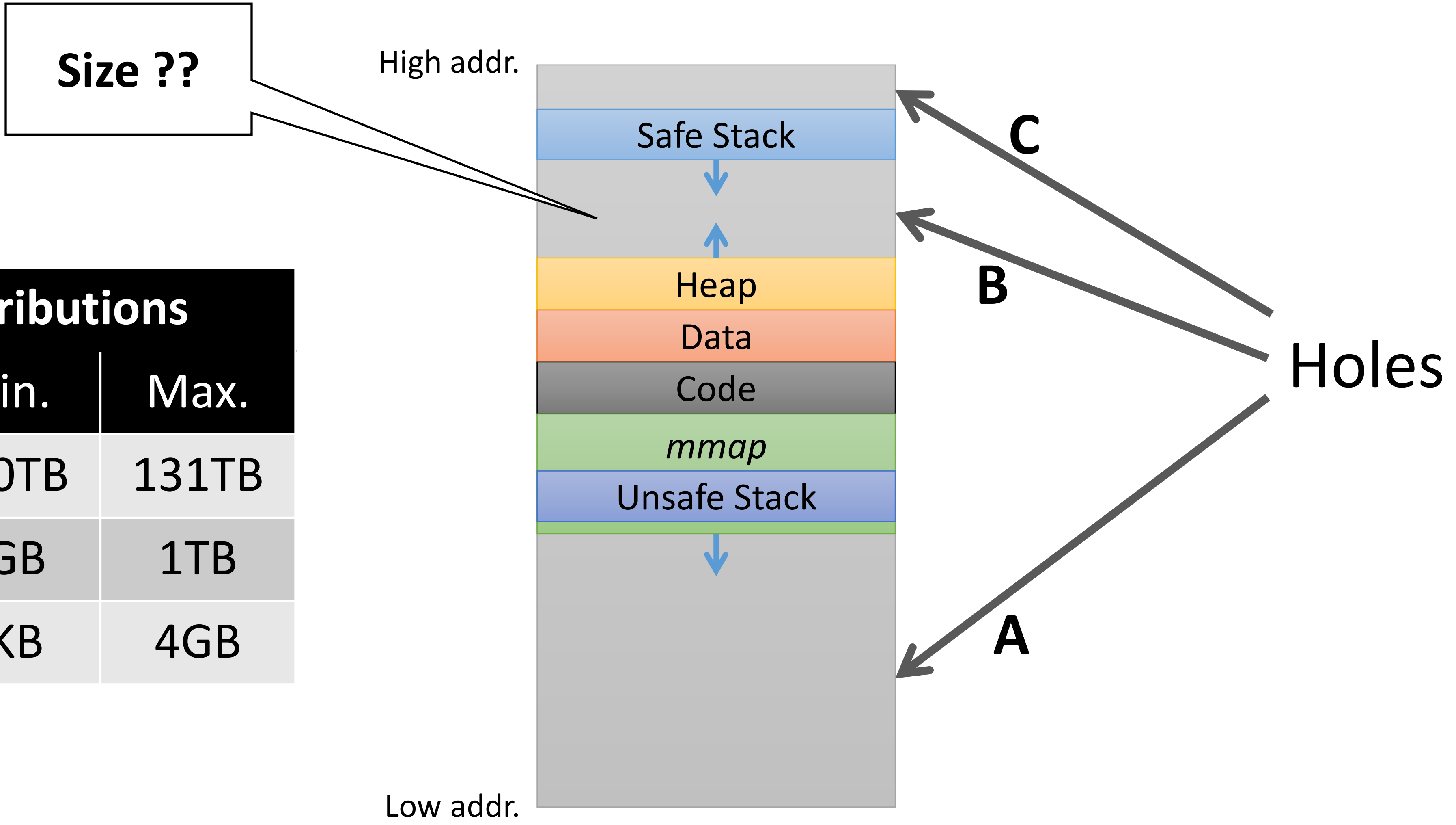


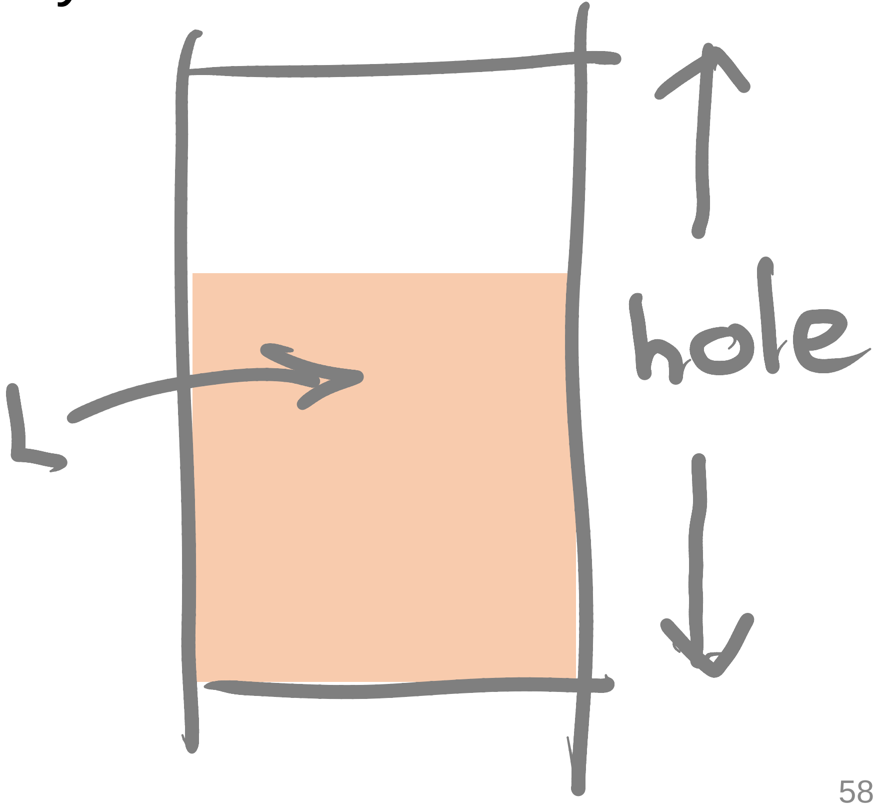
Size Distributions		
Hole	**Min.**	**Max.**
A	130TB	131TB
B	1GB	1TB
C	4KB	4GB

So look for the holes

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

Succeeds!

Sizeof(Hole) $\geq$ L

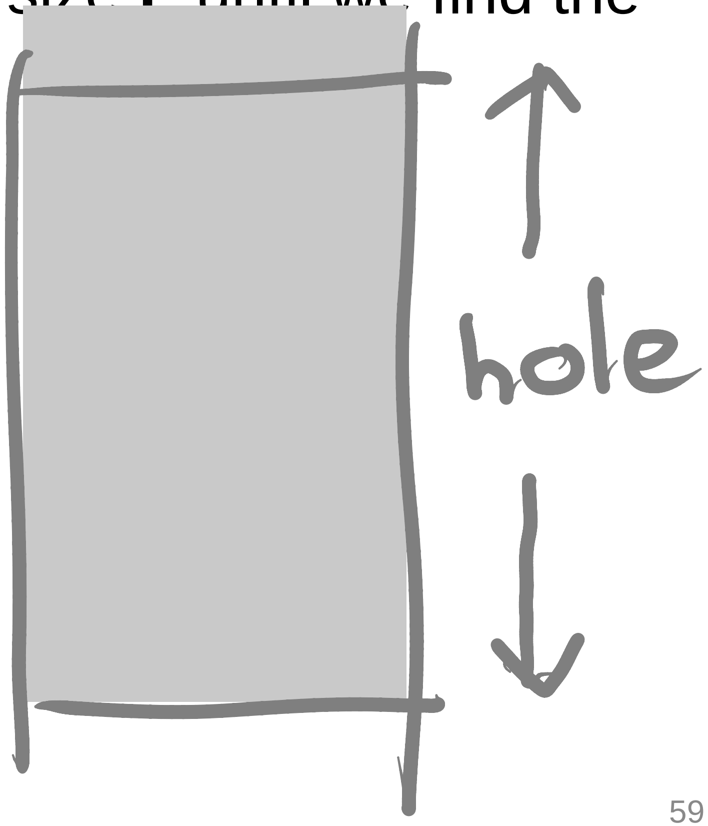


So look for the holes

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

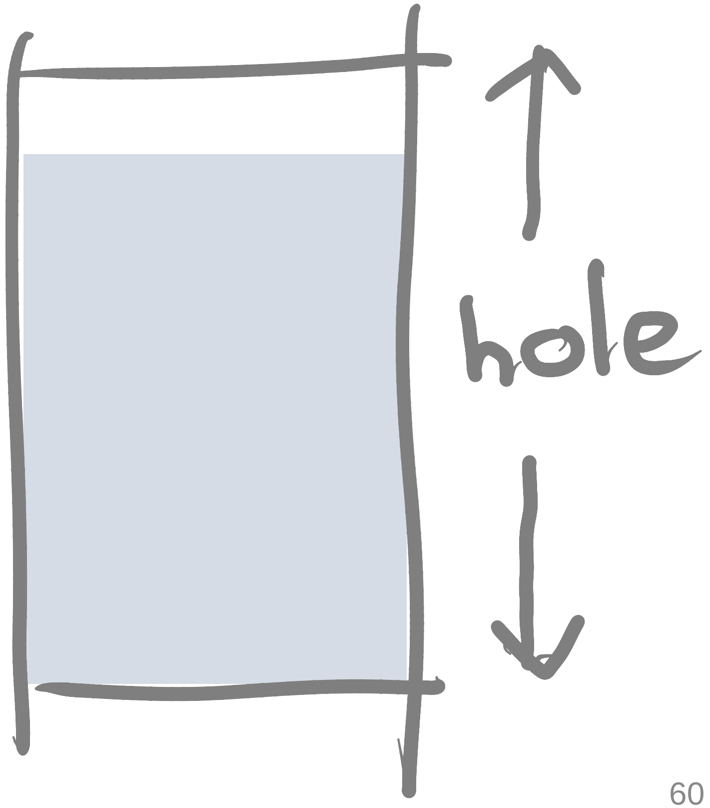
Too large, alloc fails!

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!

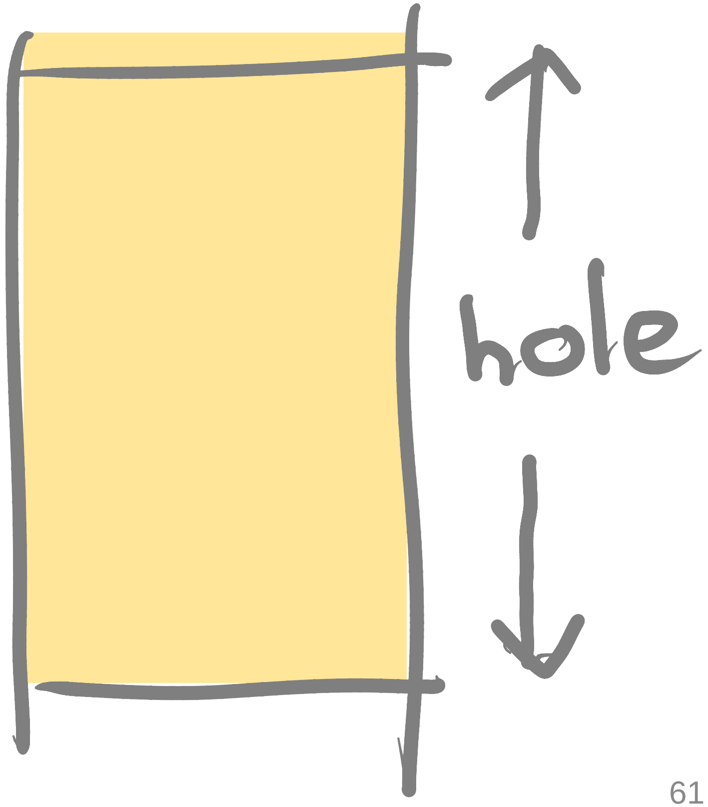
Sizeof(Hole) ≥ L

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

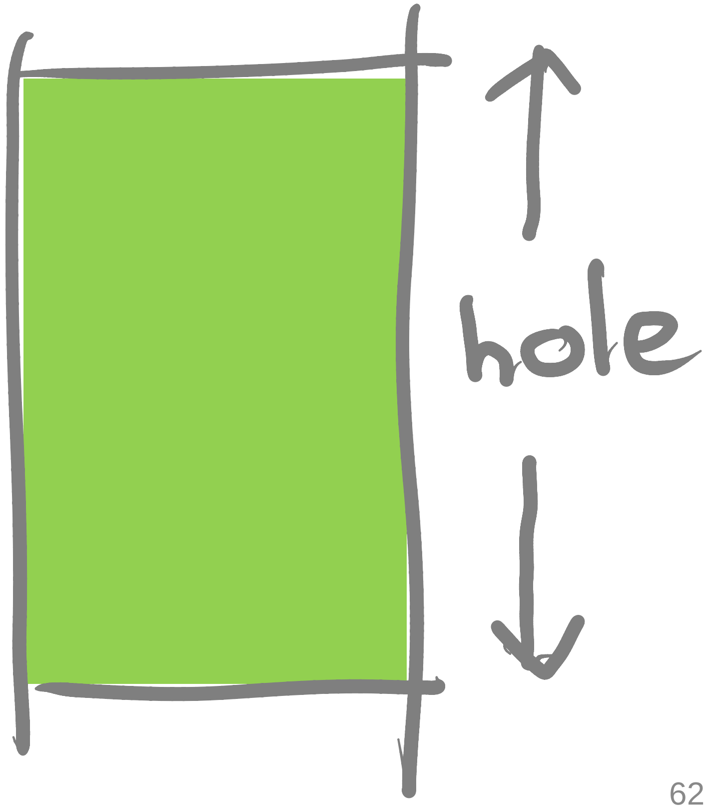


So look for the holes

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

Nailed it!

Binary search

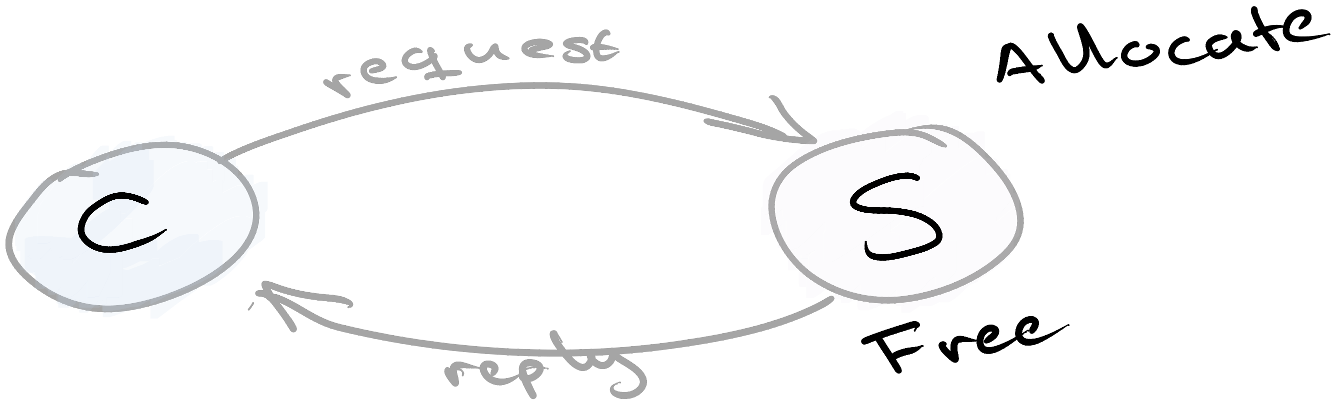


Ephemeral Allocation Primitive (EAP)

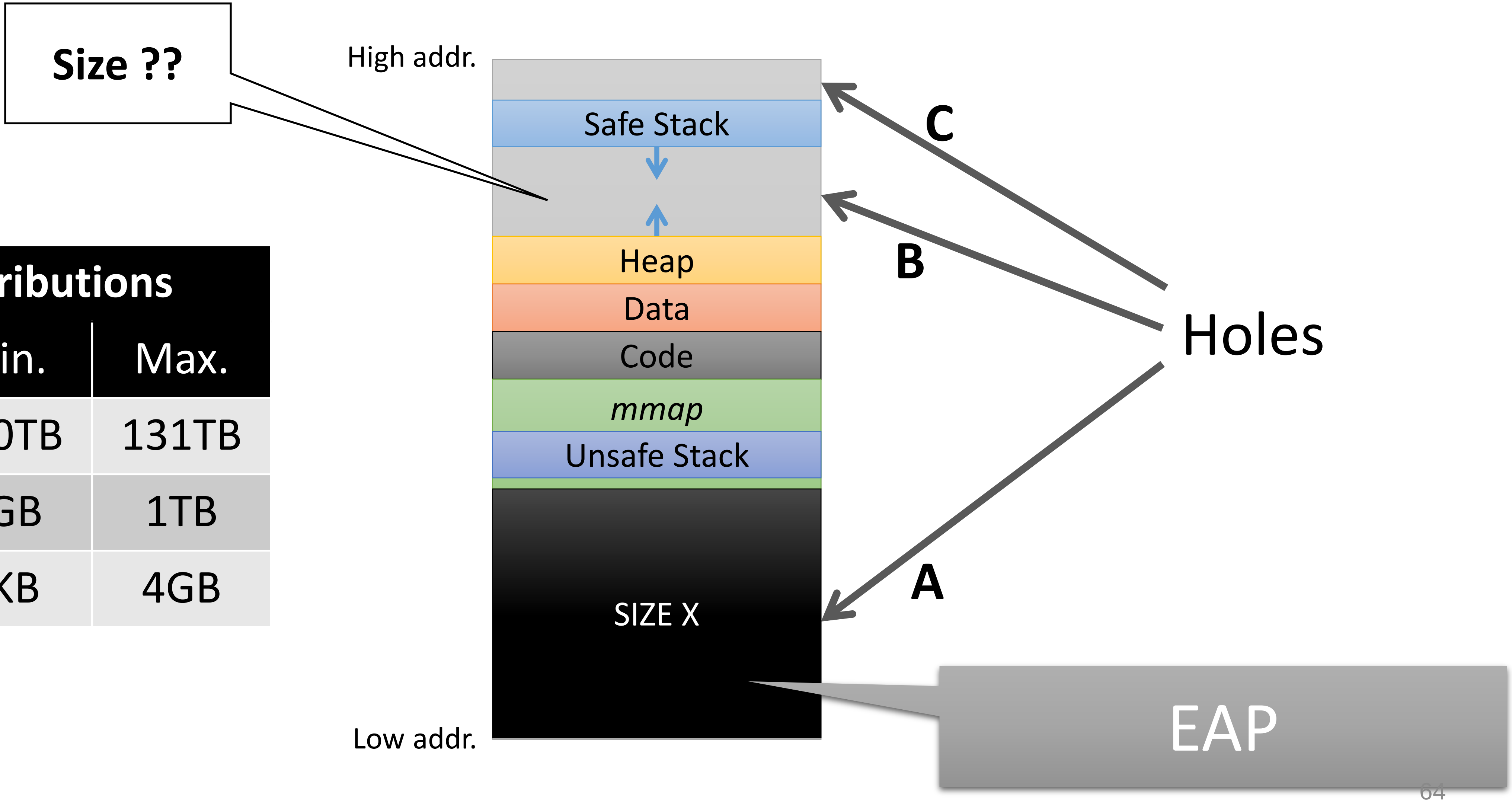
- For each probe (i.e., server request):

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

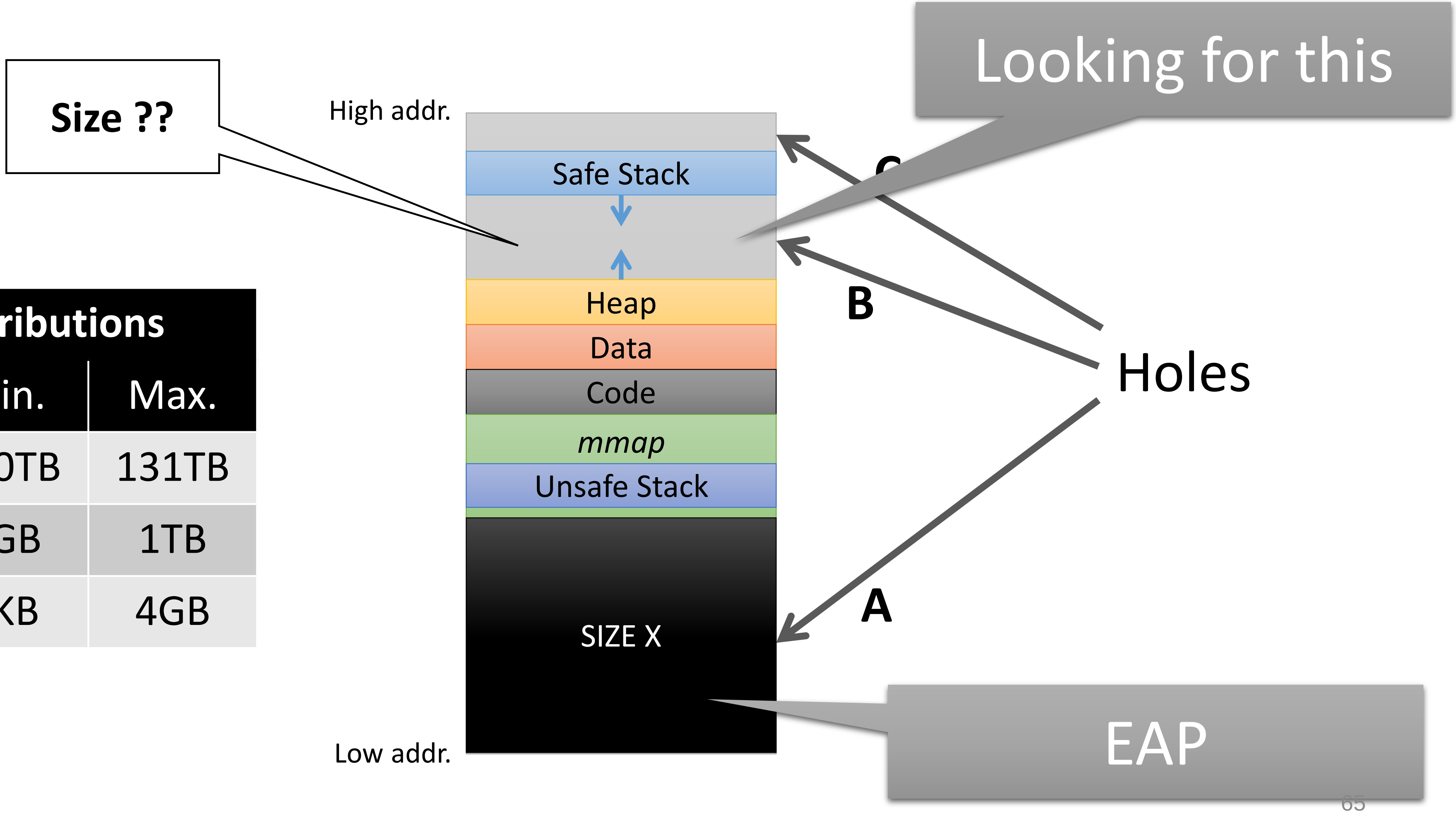
- Strategy: allocation+deallocation, repeat



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



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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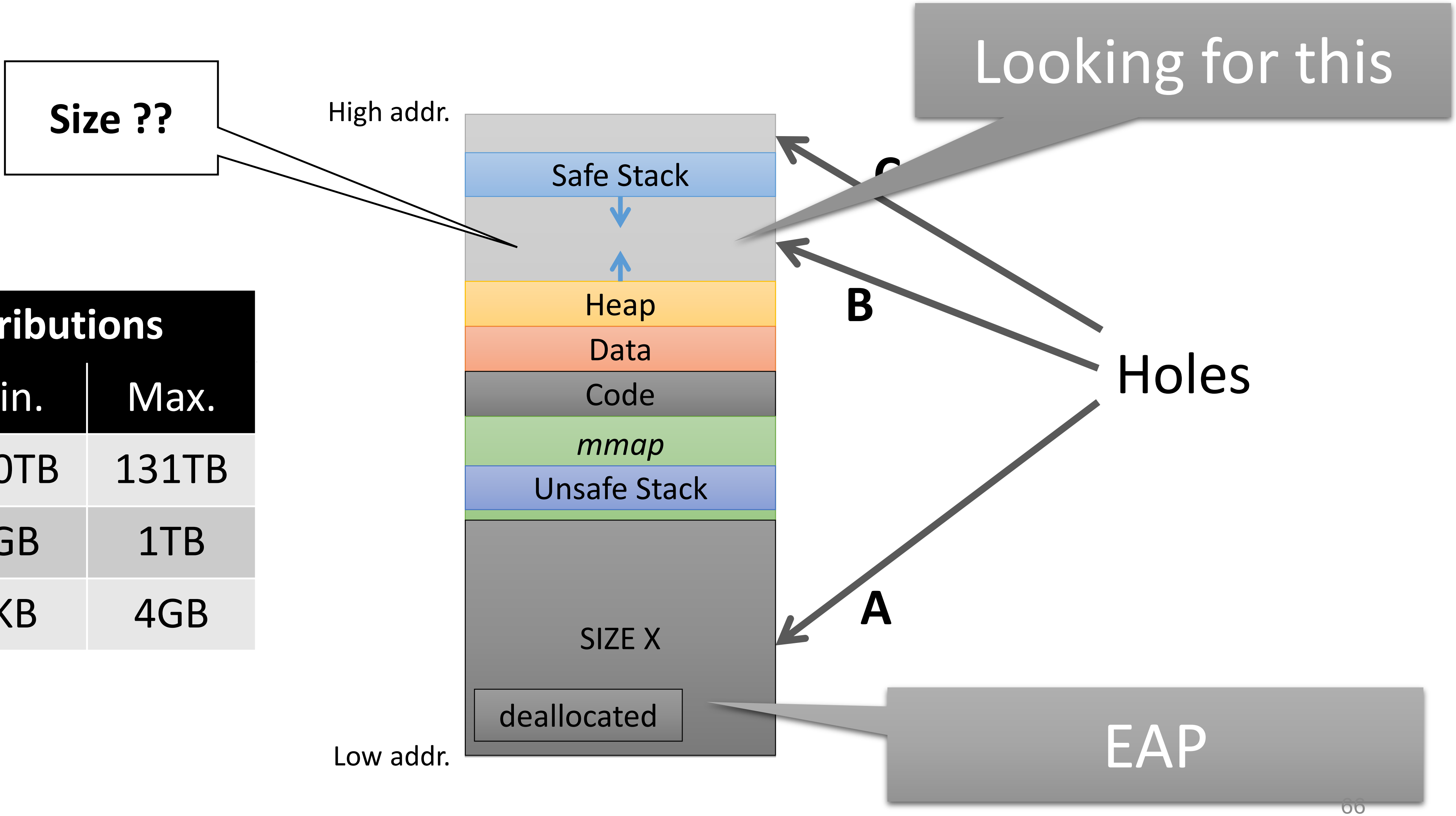
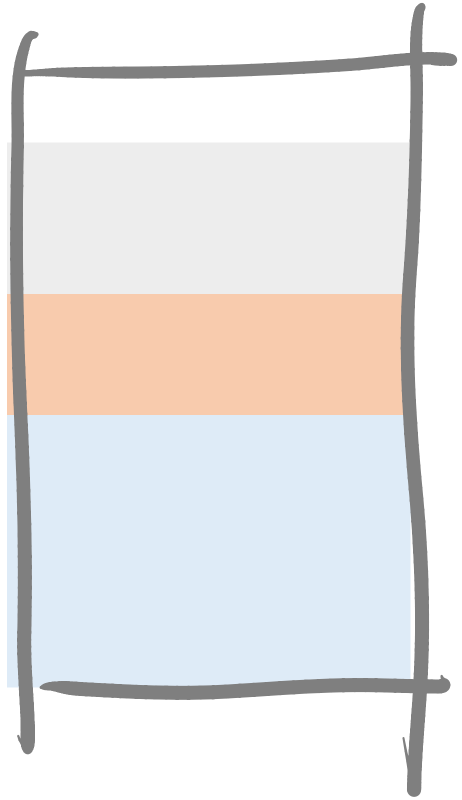


Persistent Allocation Primitive (PAP)

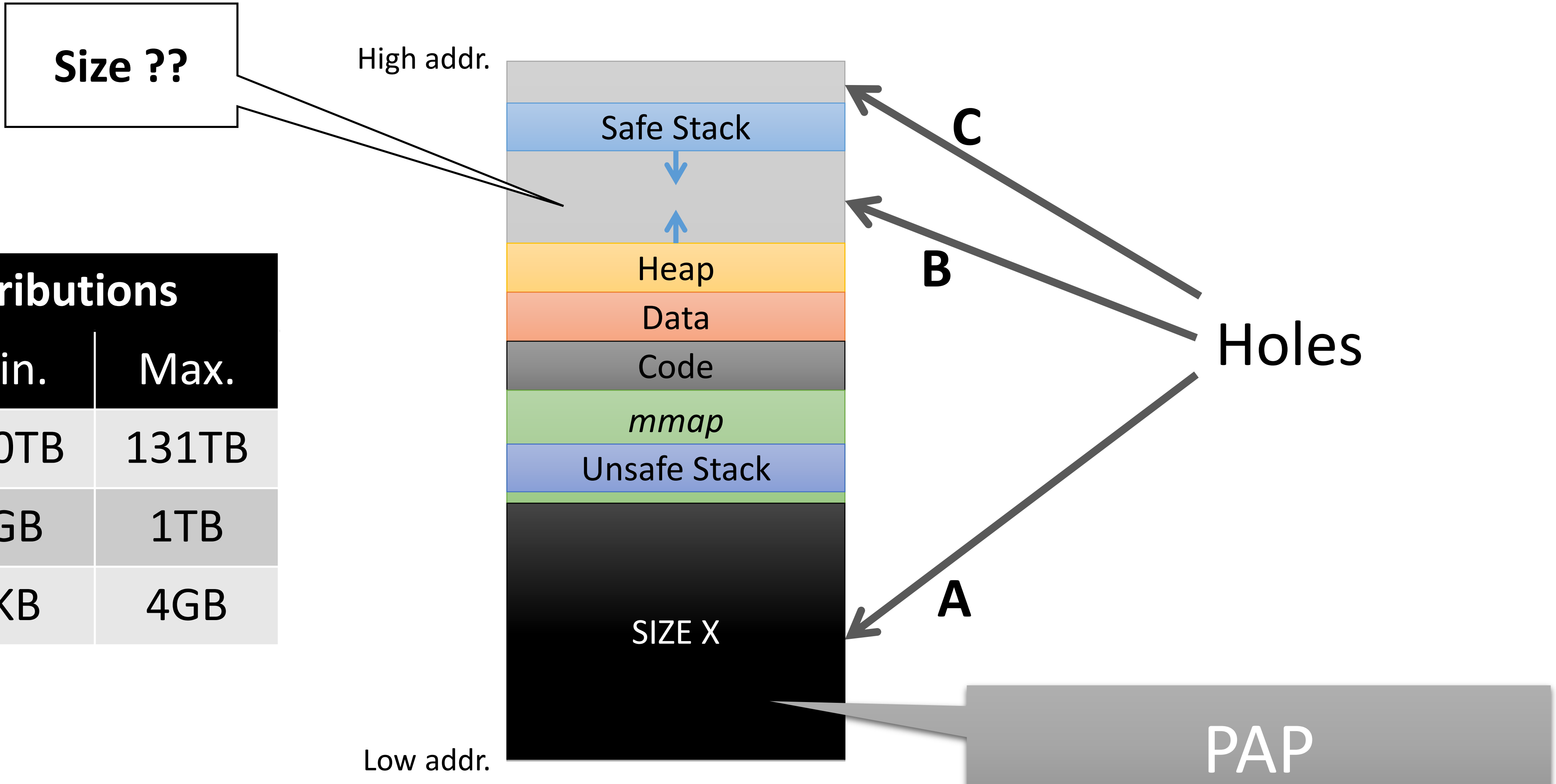
- For each request:

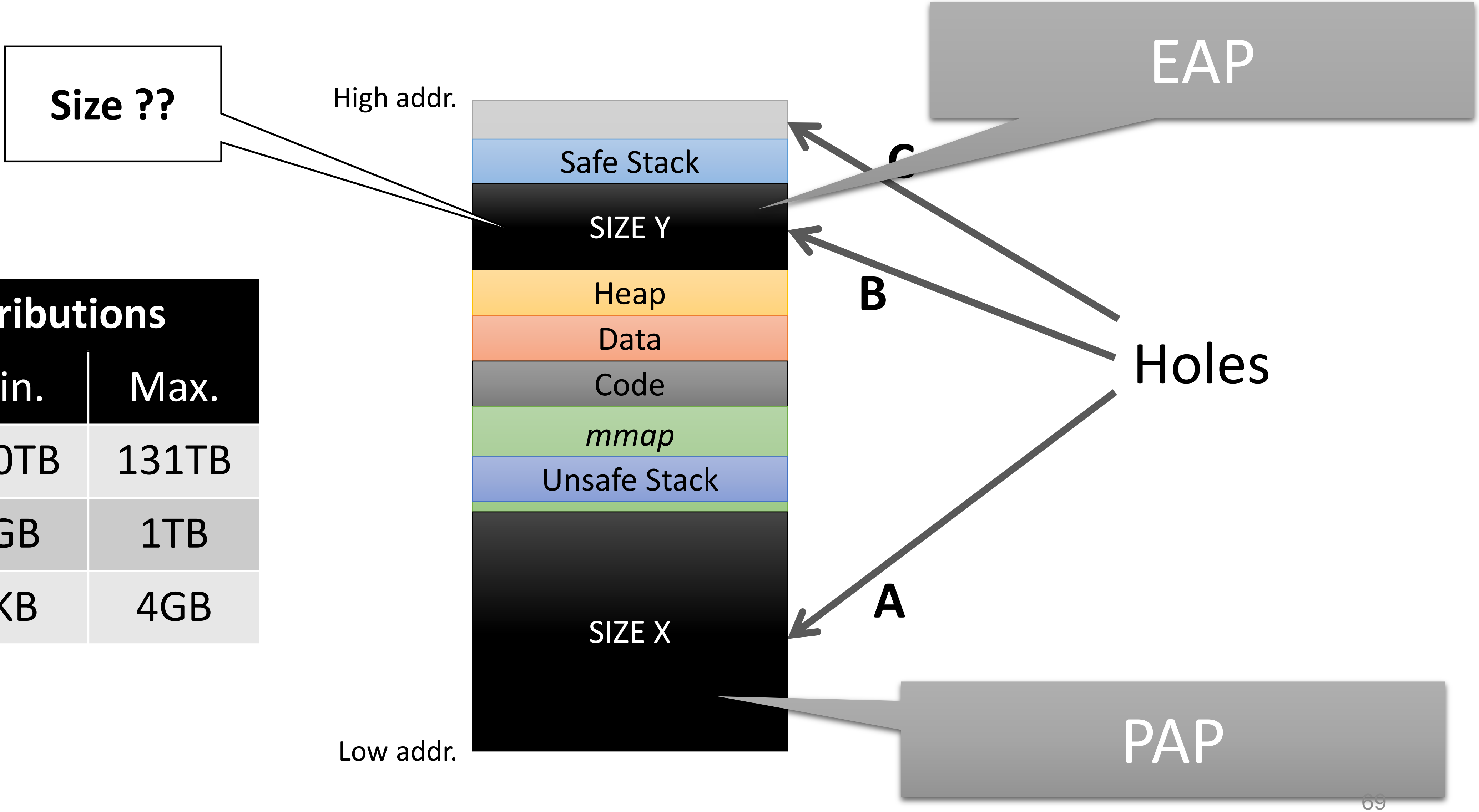
```
ptr = malloc(size);
...
reply(result);
```

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



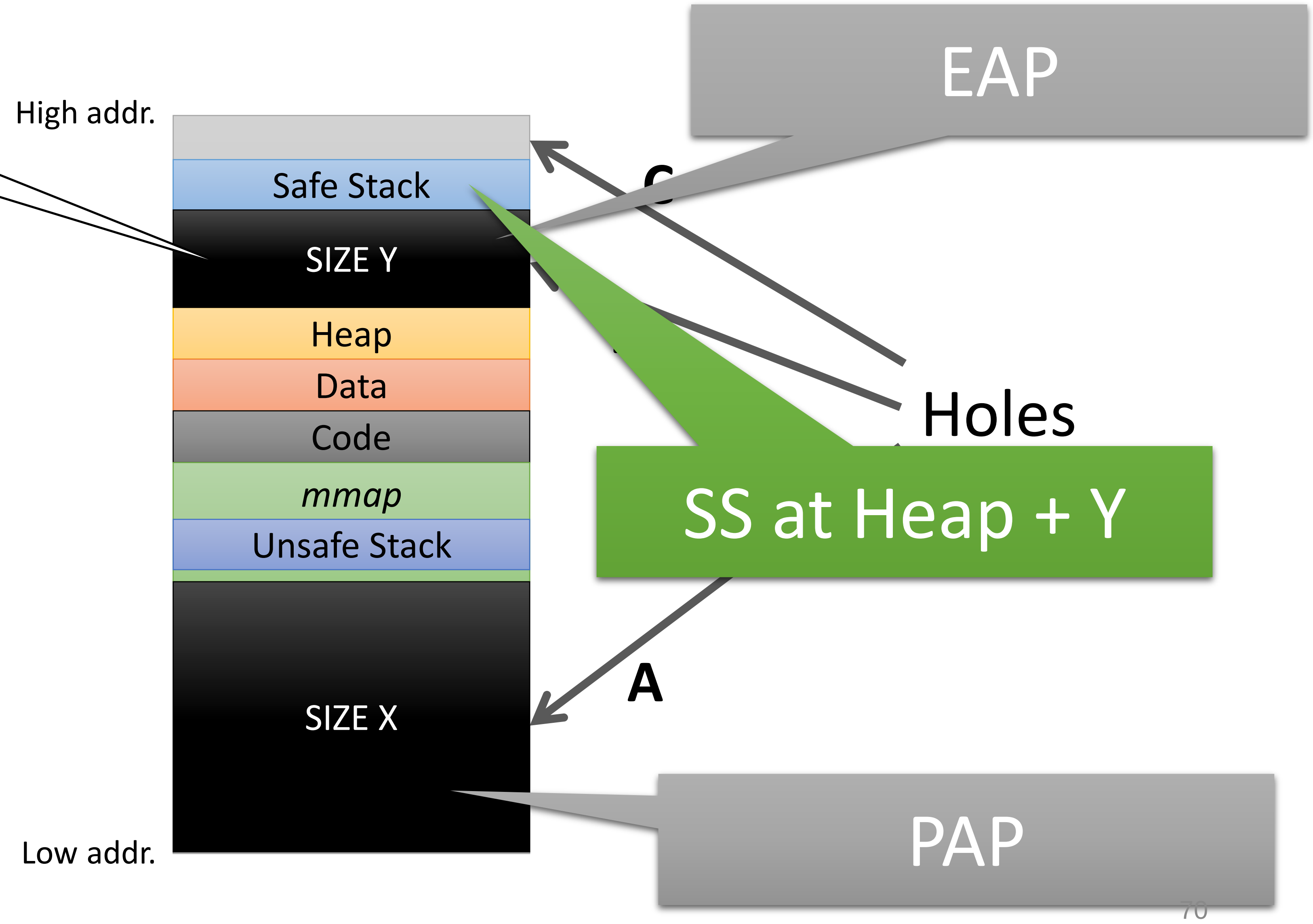
Size Distributions		
Hole	Min.	Max.
A	130TB	131TB
B	1GB	1TB
C	4KB	4GB





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

Size ??



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

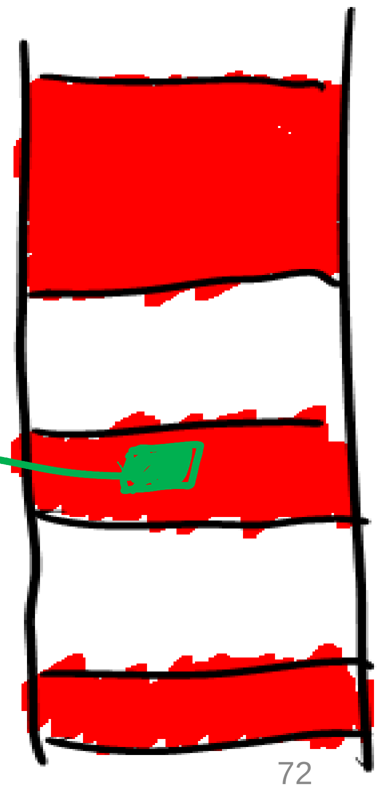
So we need

- 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