DynaGuard: Armoring Canary-Based Protections against Brute-force Attacks

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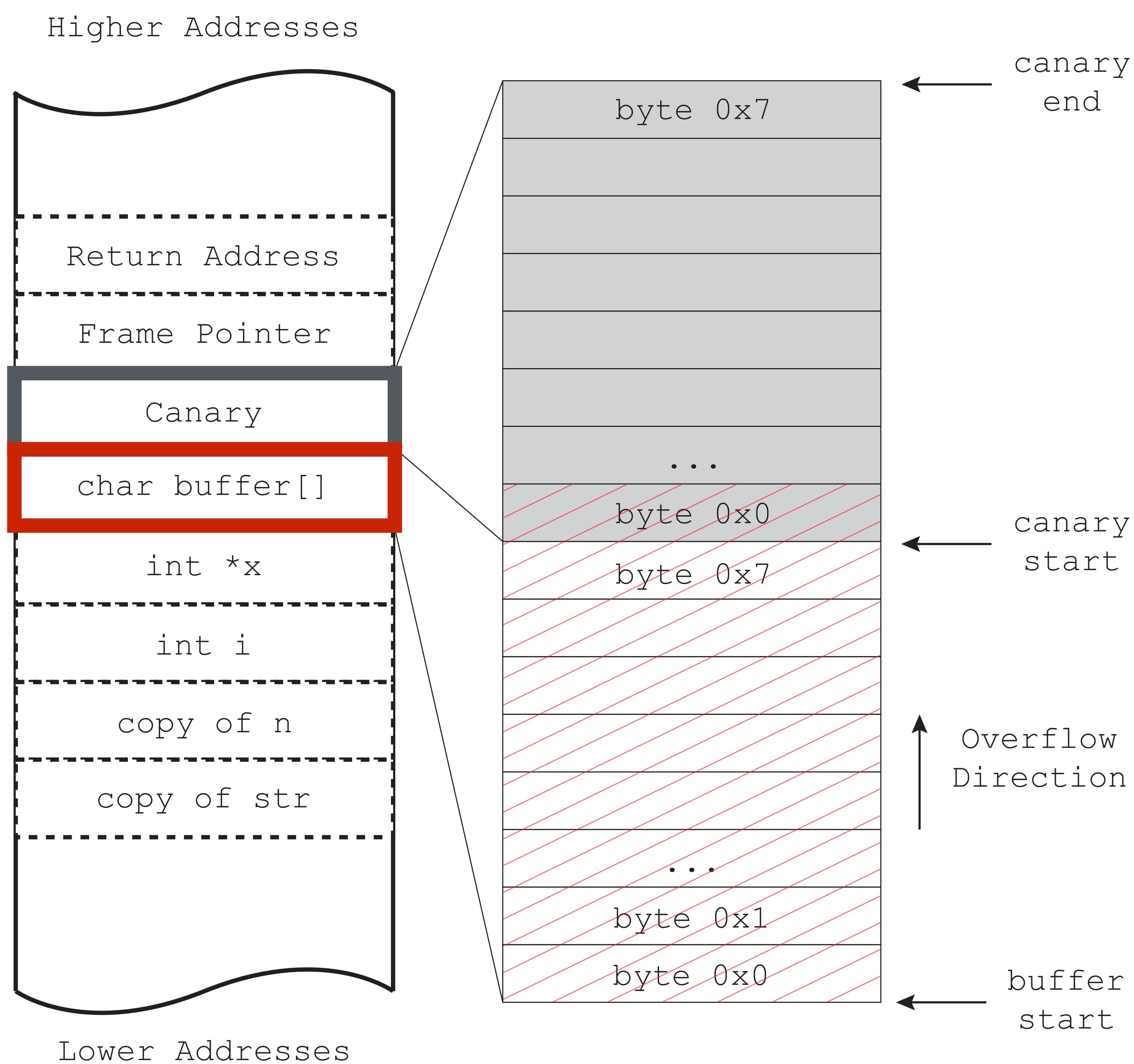
Background: Stack Smashing Protection

- Prevents the **overwrite** of the return address by a stack buffer overflow
- Places a random value after **critical** data in the stack
  - Random value: ➡ “Canary” or “Canary Cookie”
  - Critical data ➡ Return address, Frame pointer, etc.
  - The canary is 4 bytes long in x86, 8 bytes in x86-64
- Generated dynamically at the creation of each thread, and stored in the Thread-Local Storage (TLS) area
- Checked upon function epilogue
- Supported in GCC, Microsoft VS (/GS) and LLVM

Background: Stack Smashing Protection

```
int vuln(int n, char *str)
{

   int i;
   int *x = NULL;
   char buffer[8];

   ...

   /* unbounded copy */
   memcpy(buffer, str, n);

   ...

}
```



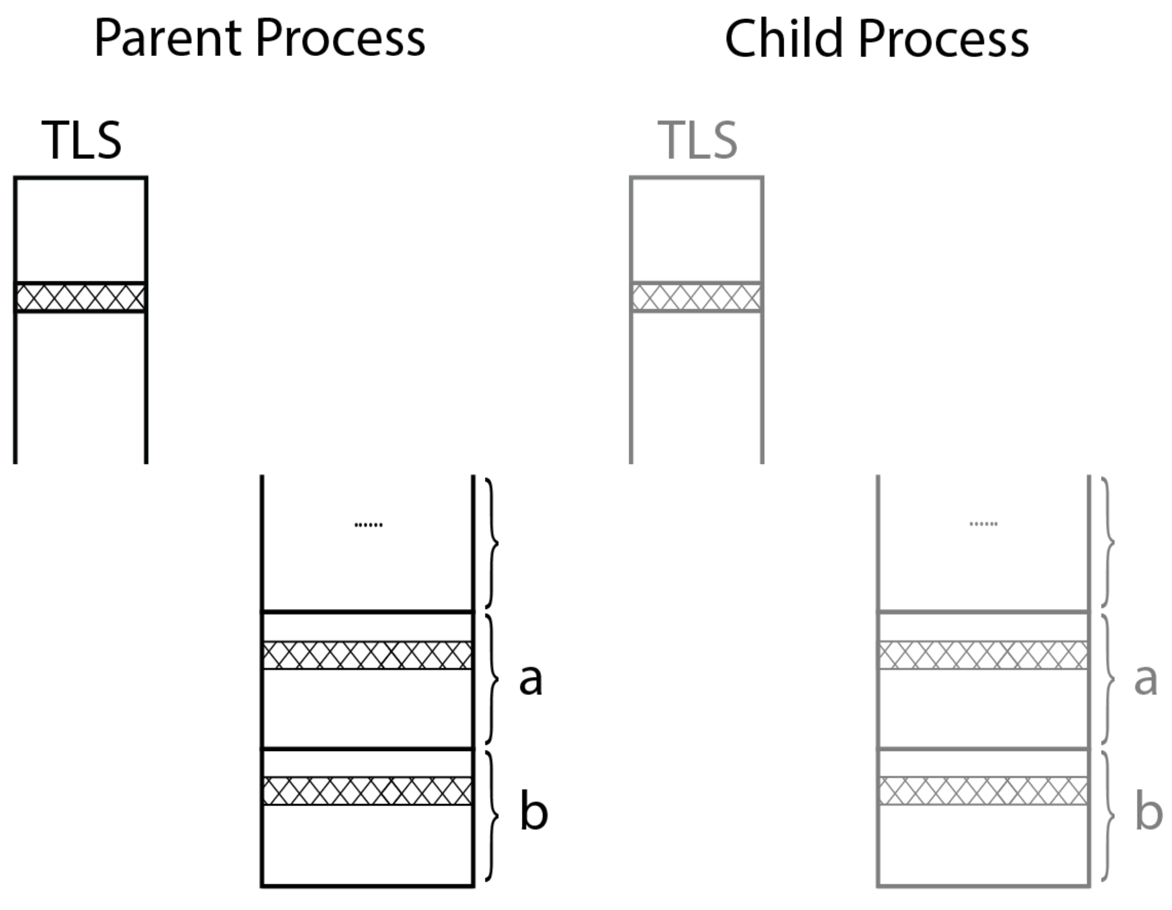
Canary Brute-force

An attacker may brute-force the canary **byte-by-byte** in very few attempts if they are able to perform the following steps:

- Force child processes to be forked by the same parent process
- Verify if these child processes crashed or not
- Overwrite a single byte of the canary each time until all the bytes are recovered

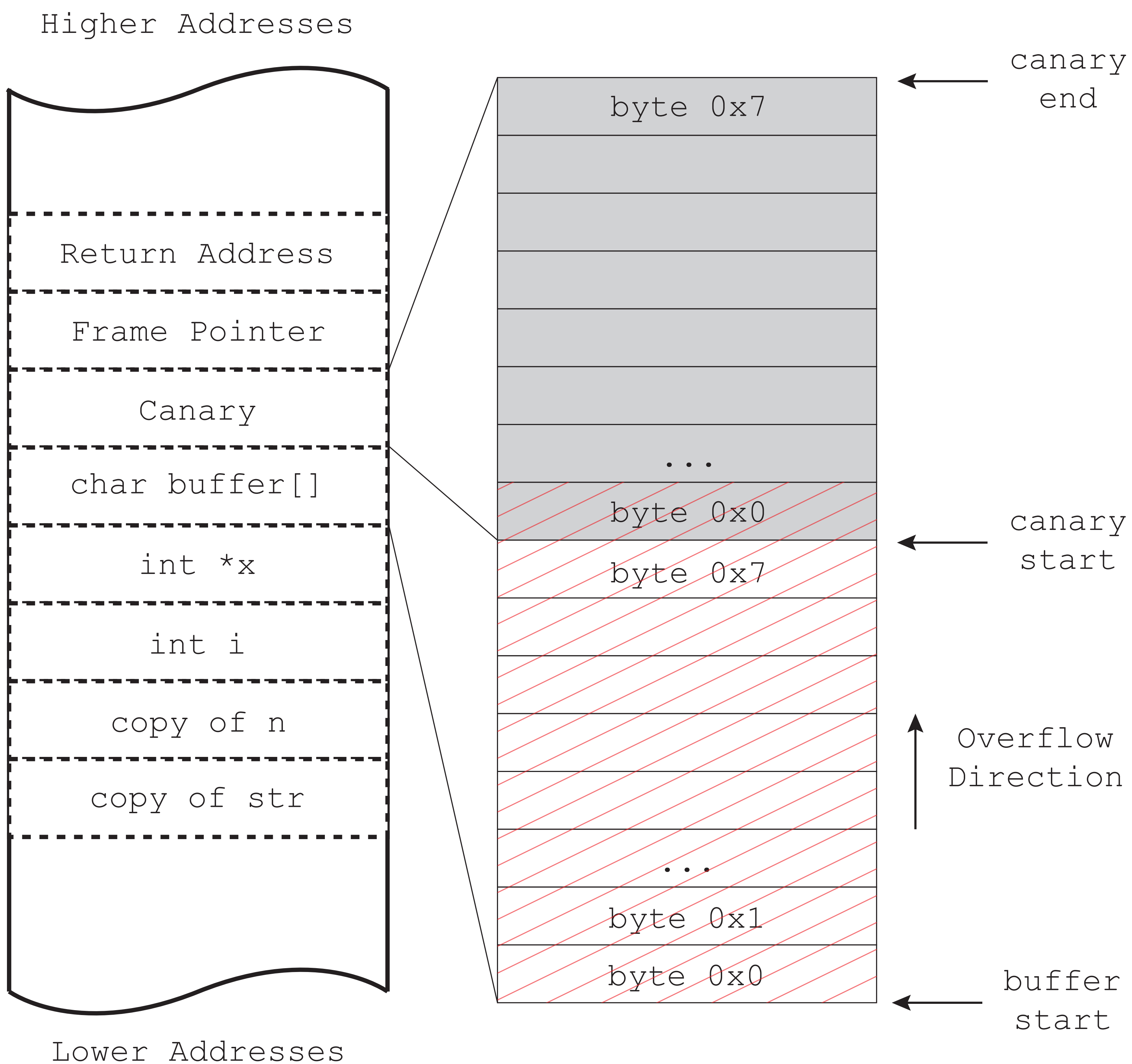
Canary Brute-force

- Possible due to the current process creation mechanism:

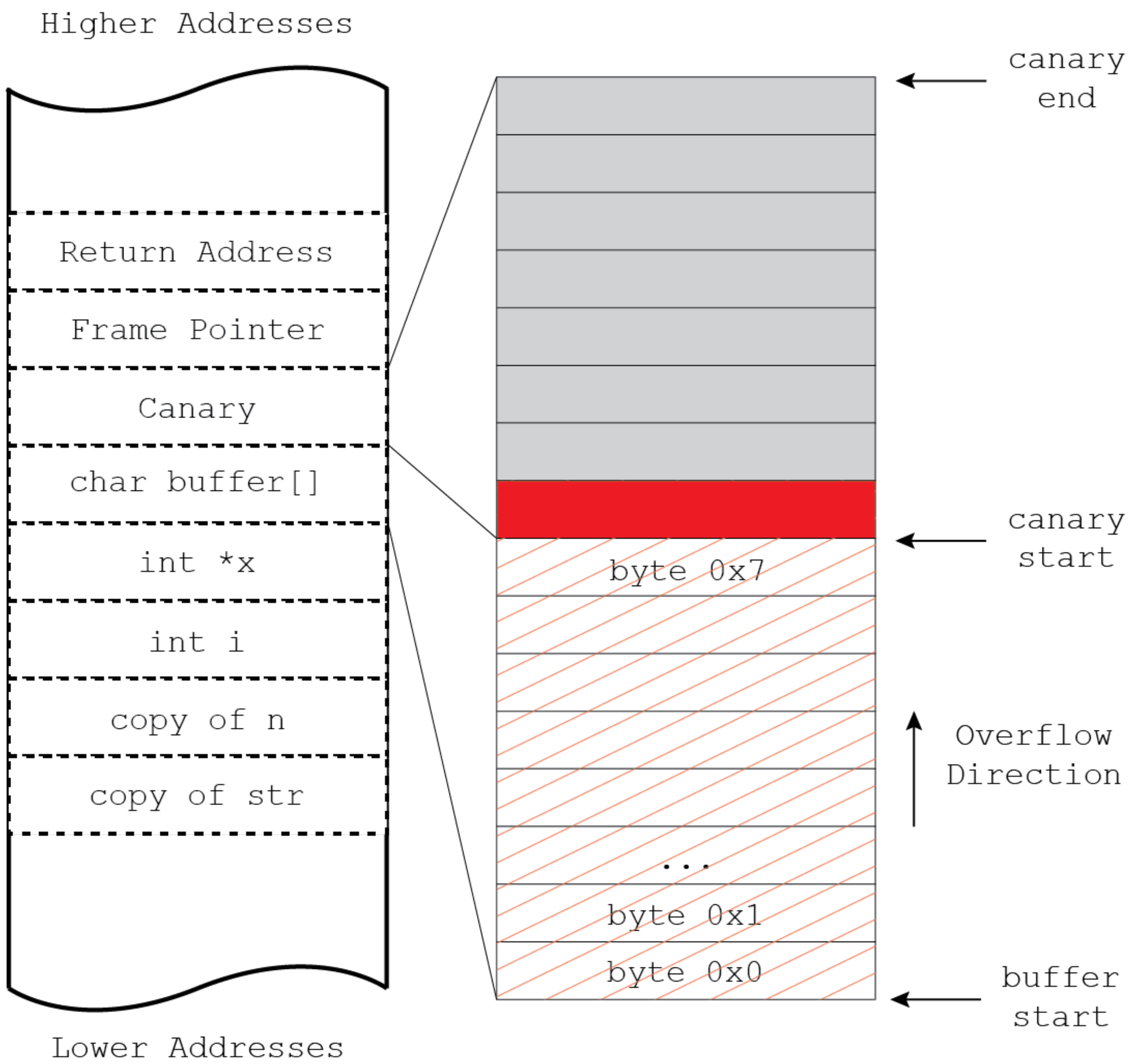


- Certain data is inherited from the parent process, although it should be different (other examples include VM side channel attacks and the PRNG state in forked processes)

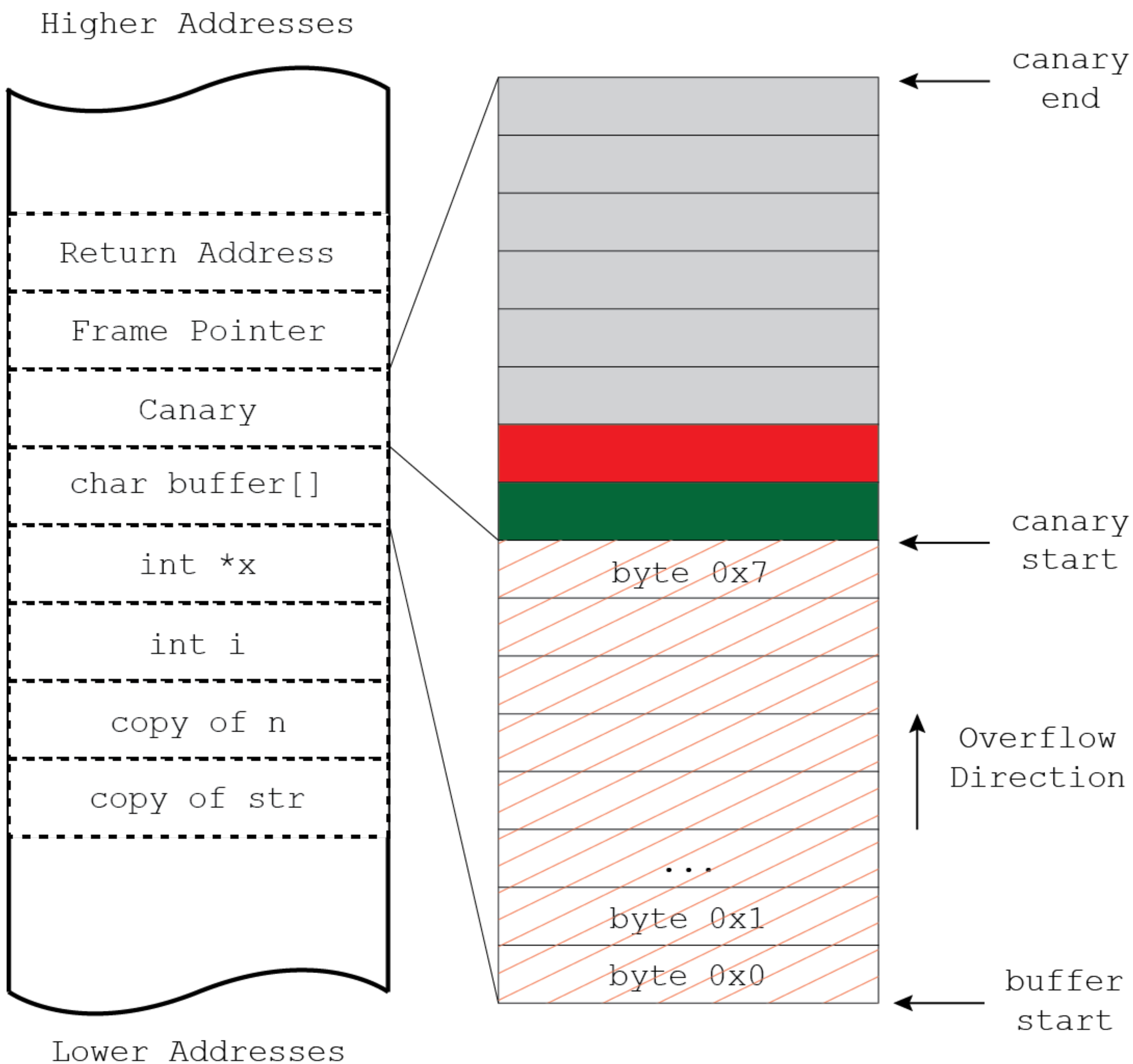
Canary Brute-force



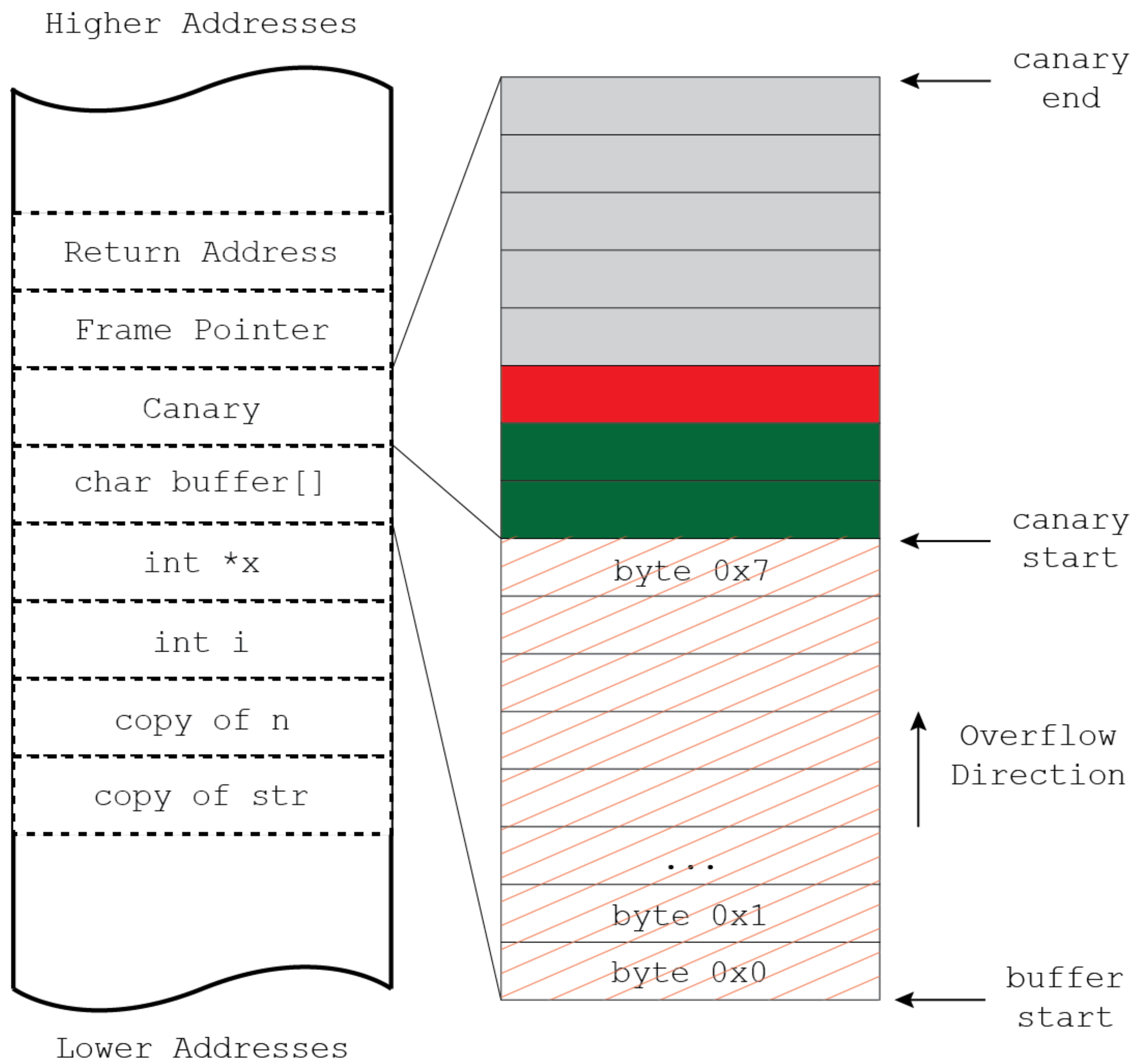
Canary Brute-force



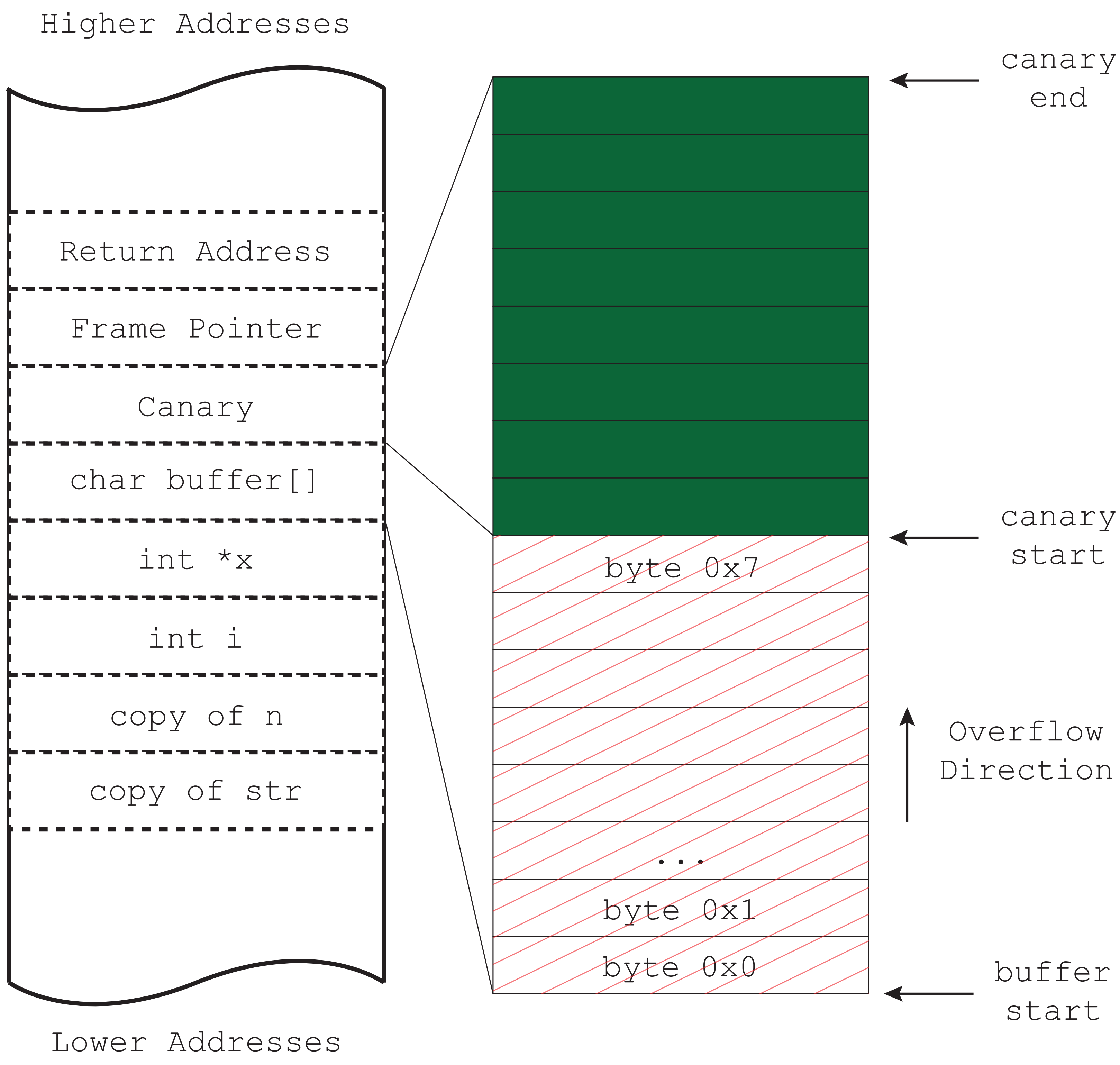
Canary Brute-force



Canary Brute-force



Canary Brute-force



A byte-by-byte brute-force requires 4*256 = 1024 attempts on average on x86 and 2048 on x86-64, assuming a fully random canary

Canary Brute-force Guessing Timeline

- **2006** — Ben Hawkes introduced the technique in RUXCON 2006 (Title: "Exploiting OpenBSD")
- **2010** — Adam Zabrocki (pi3) discussed remote stack exploitation techniques in Linux, FreeBSD and OpenBSD and among other things, revisited Ben's attack in Phrack #67
- **2013** — Nikolaos Rangos (Kingcope) released an exploit for the Nginx web-server that builds upon the previous attack(s) to construct a remote exploit
- **2014** — Andrea Bittau et al. introduced the BROP technique, which among other things, uses a generalized version of the above to leak/bypass stack canaries

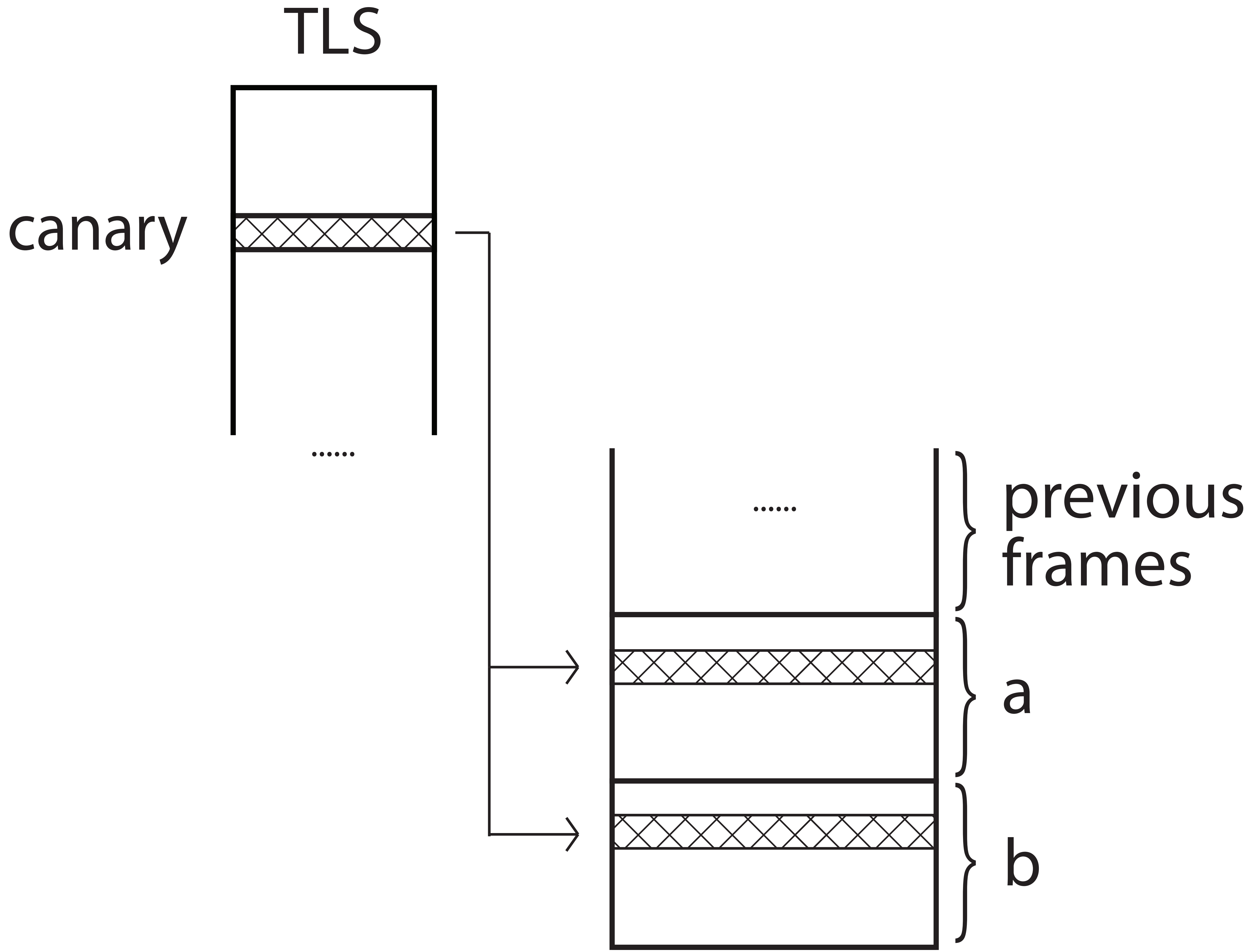
DynaGuard Design

Key idea: Upon each `fork()` update the inherited (old) canaries in the child process

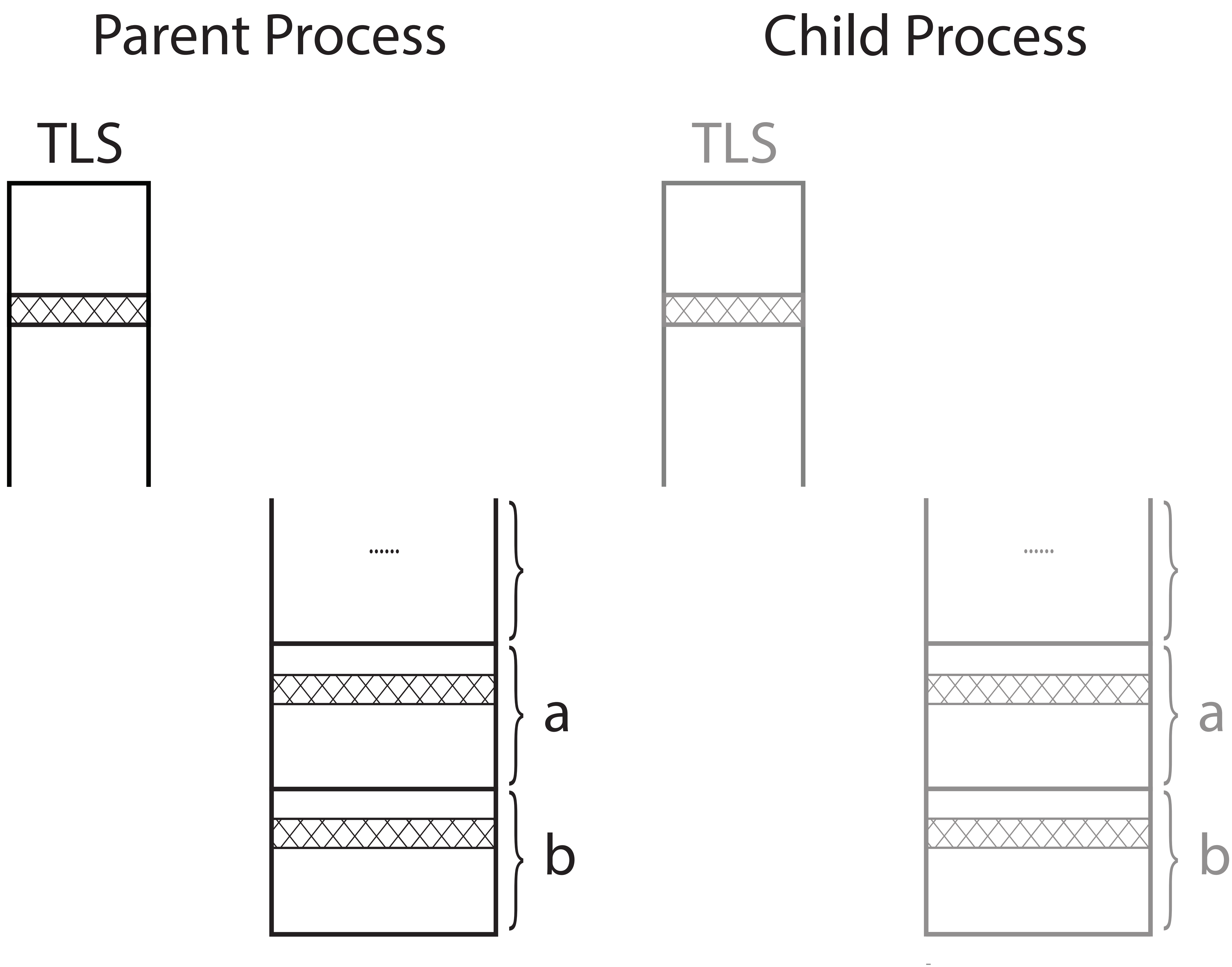
- Update the canary in the TLS of the new (child) process
- Update the canaries in all inherited stack frames (from the parent process) with the new canary value

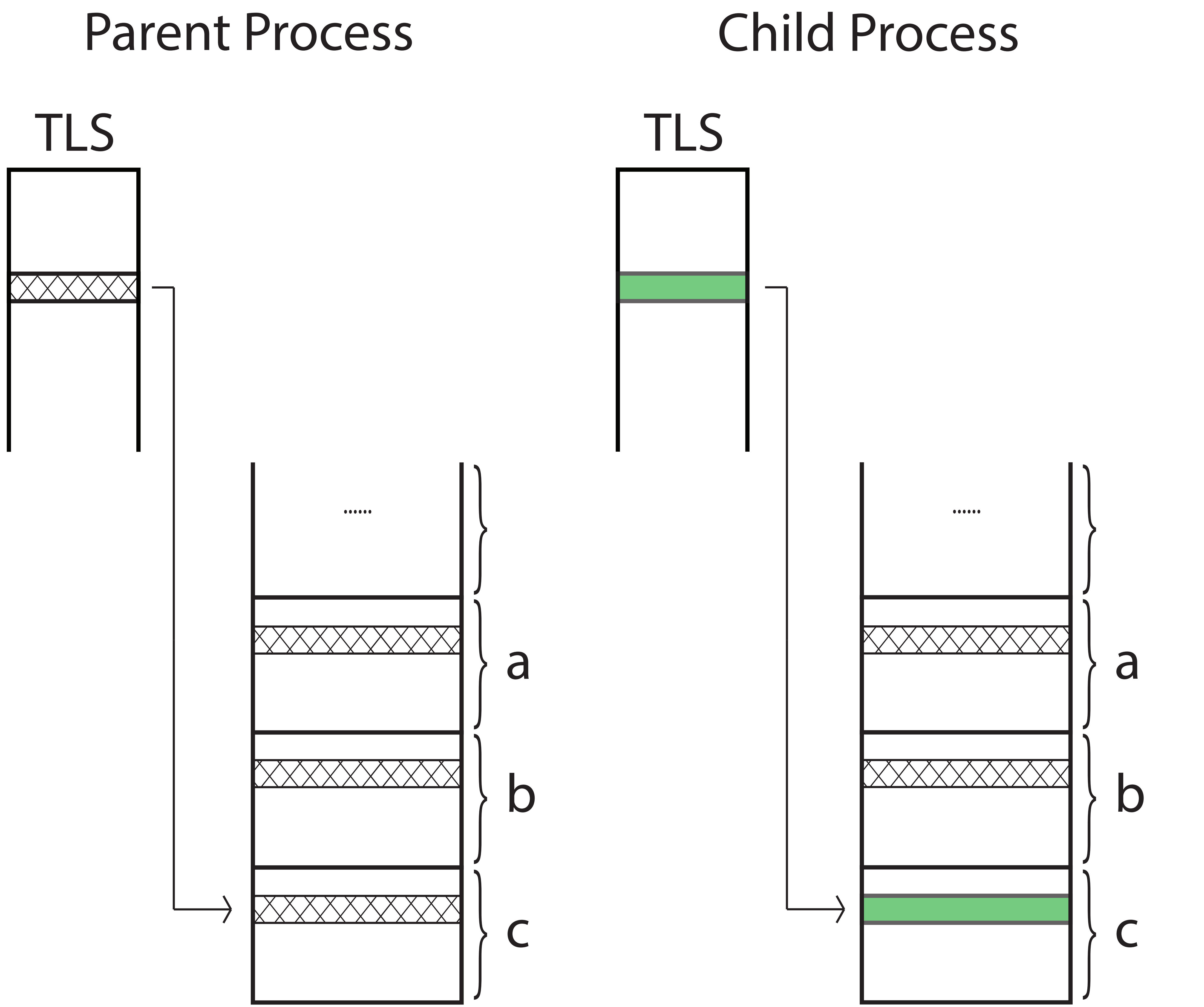
Simply updating the canary in the TLS* for new (child) processes is not enough as it will cause a false abort if execution reaches one of the parent's inherited frames

*as proposed in a recent paper

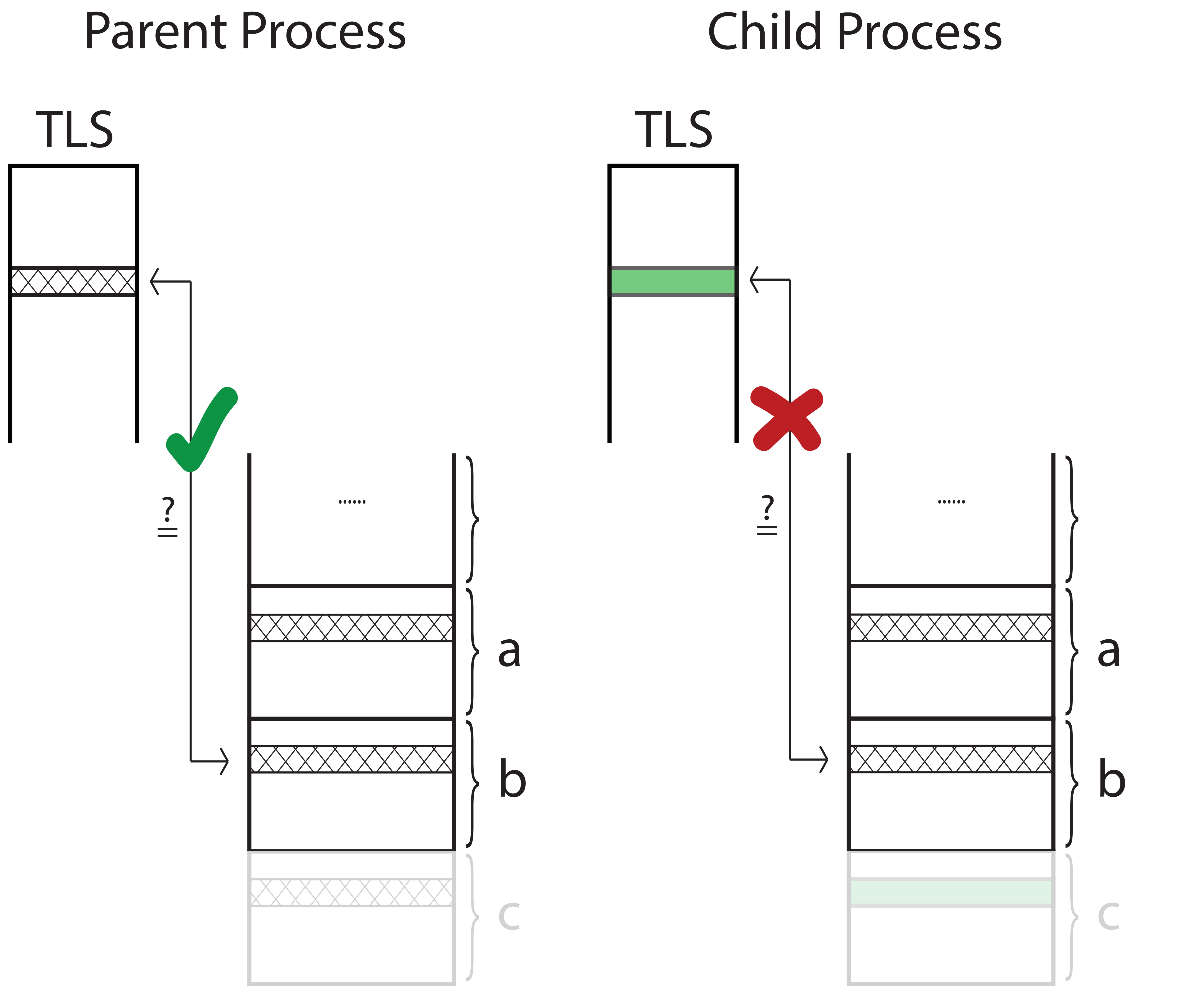


TLS
canary
......
......
previous frames
a
b

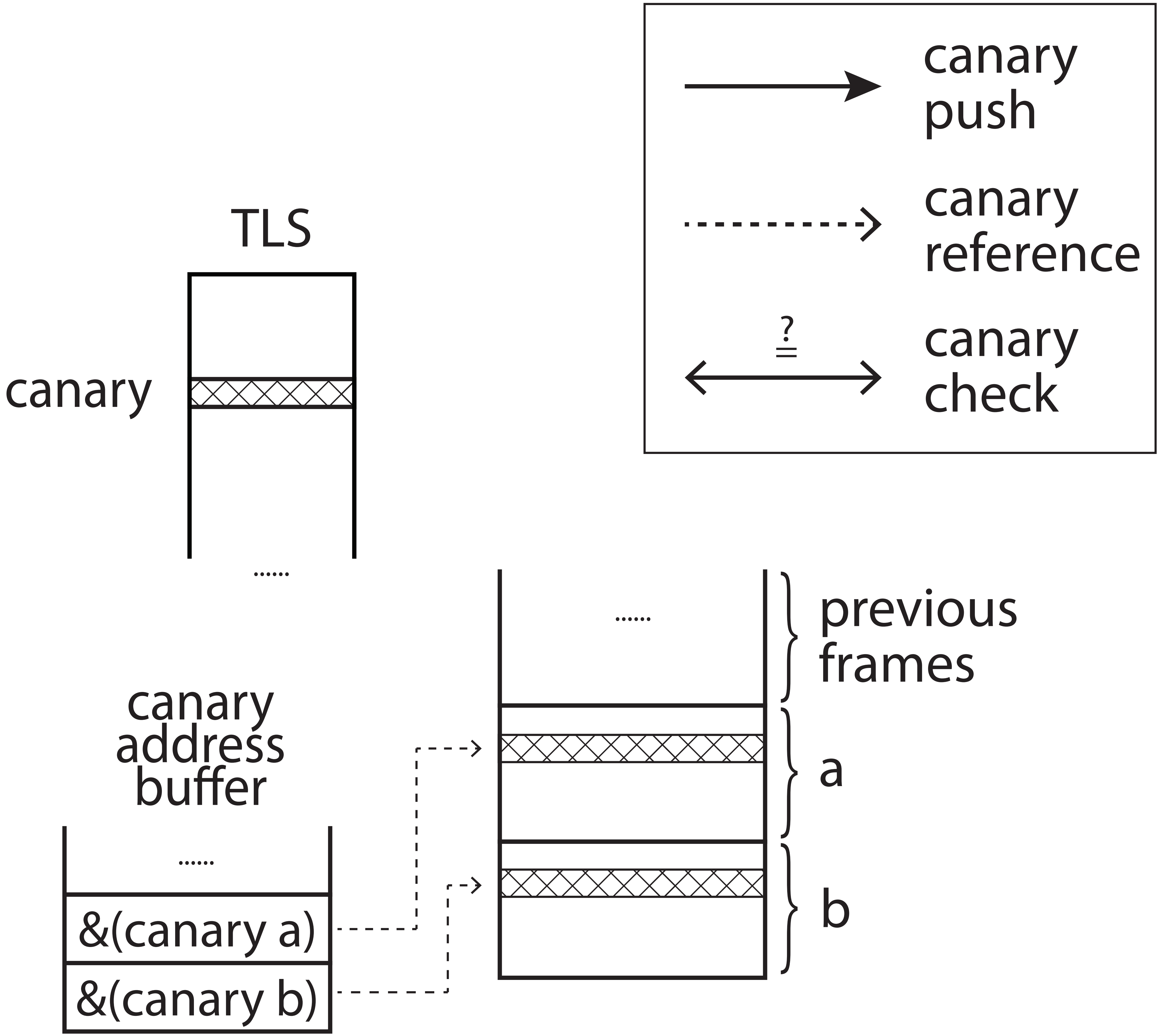

Parent Process
Child Process
TLS
TLS
......
a
b
......
a
b

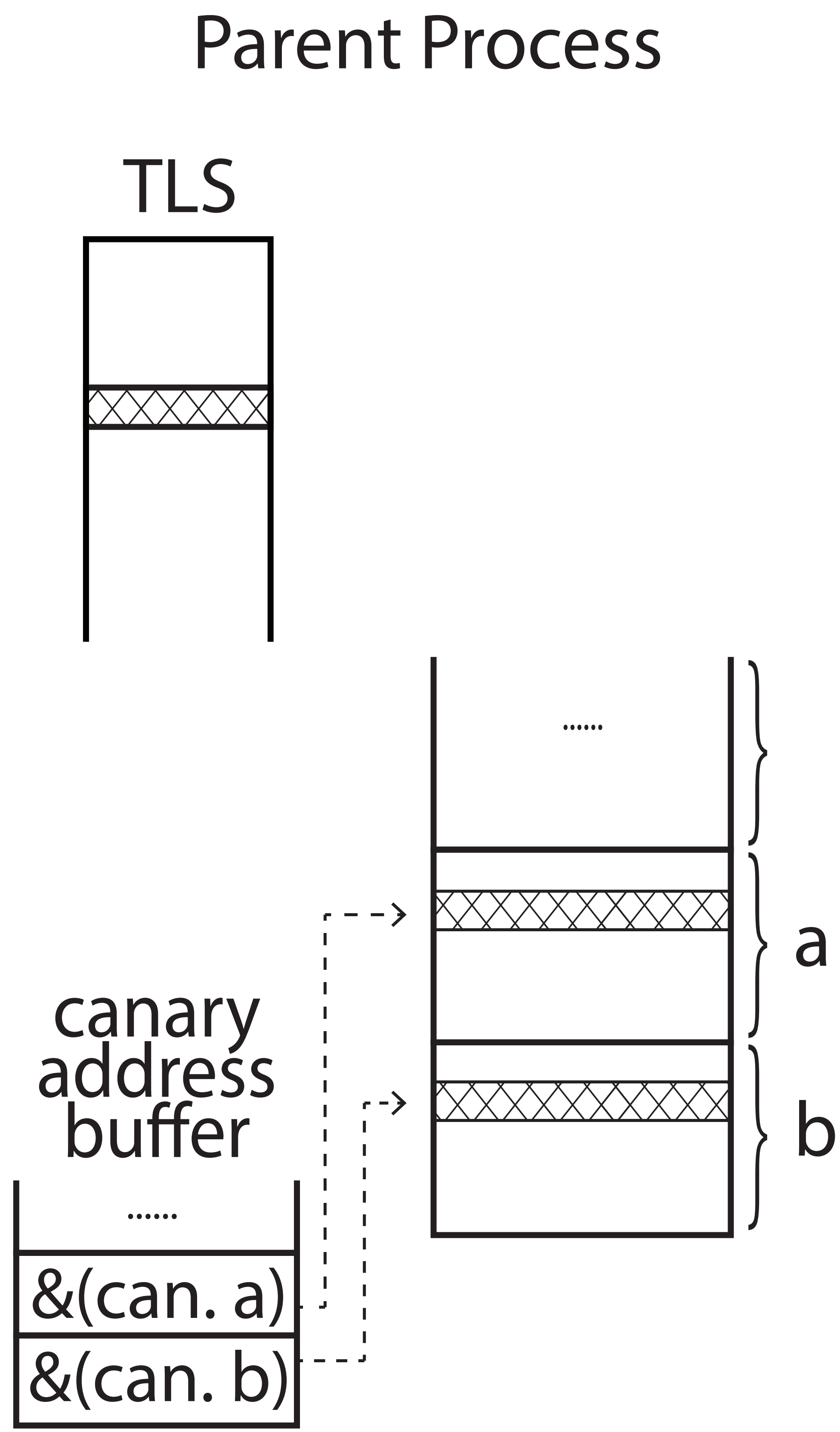


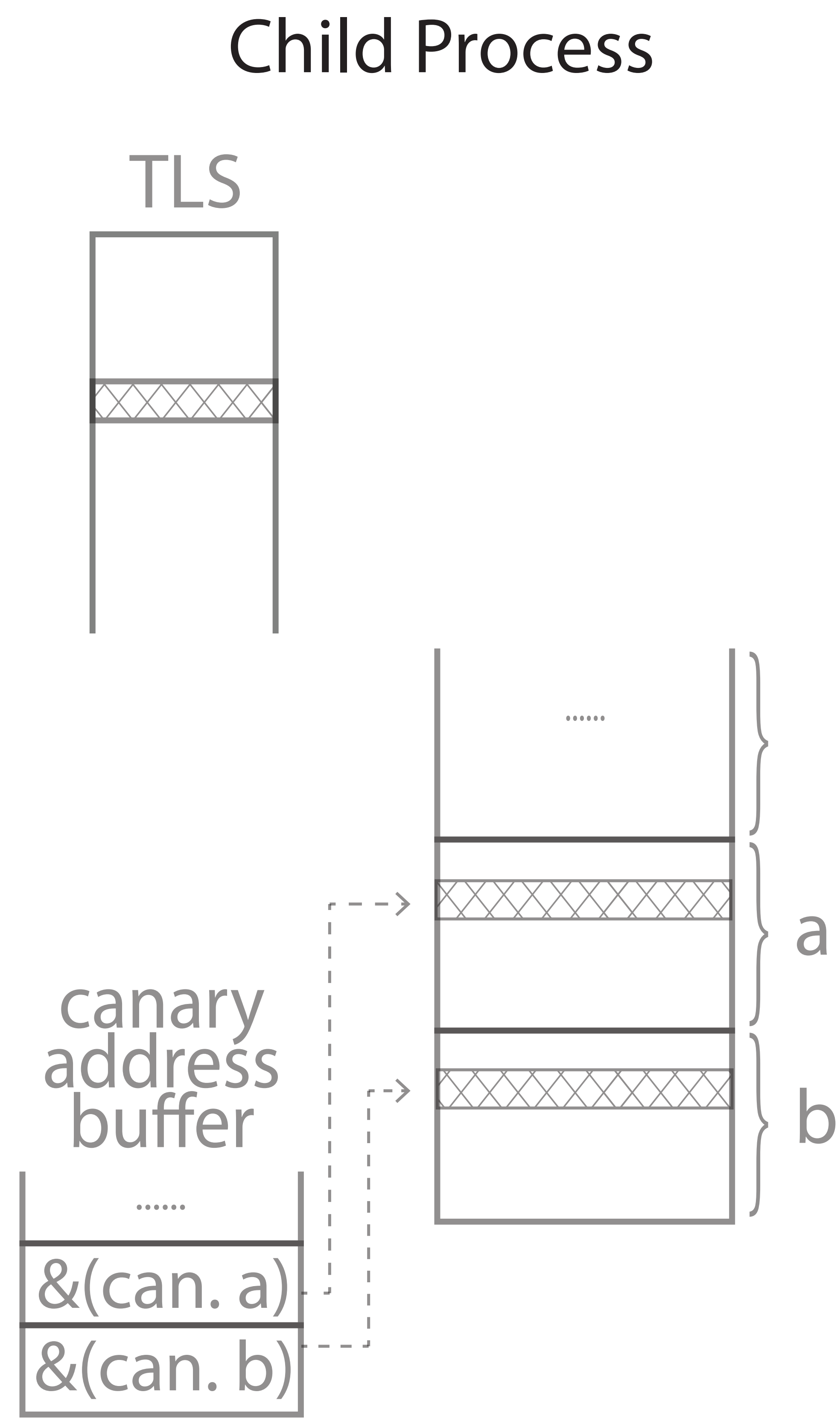
Parent Process
Child Process
TLS
TLS
......
......
a
b
c
a
b
c

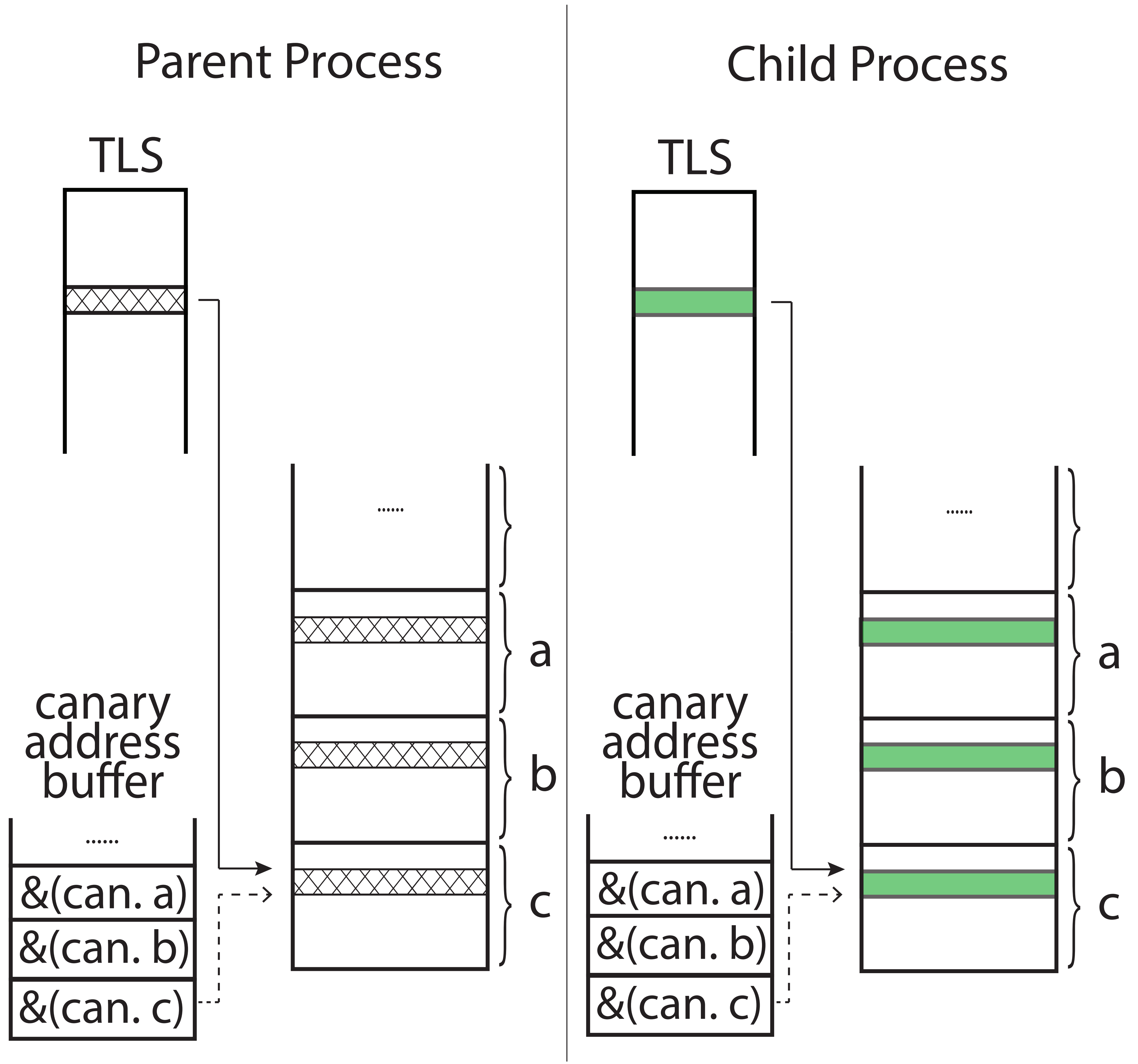


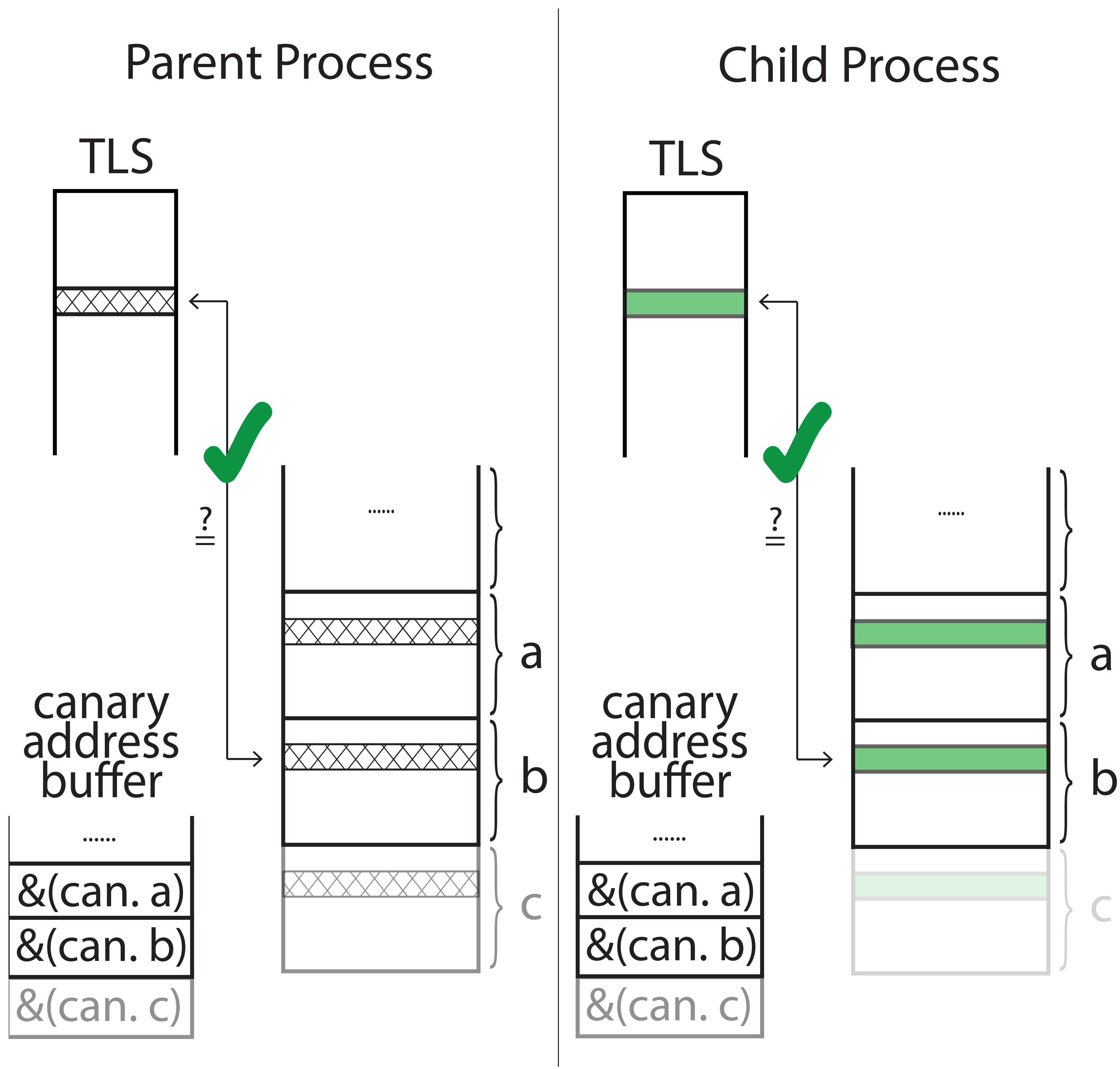
Parent Process
Child Process
TLS
TLS
......
......
?
=
?
=
a
b
c
a
b
c


canary
push
canary
reference
?
=
canary
check
TLS
canary
......
......
previous
frames
canary
address
buffer
a
......
&(canary a)
&(canary b)
b


Parent Process
TLS
......
a
b
canary
address
buffer
......
&(can. a)
&(can. b)


Child Process
TLS
......
a
b
canary
address
buffer
......
&(can. a)
&(can. b)


Parent Process
Child Process
TLS
TLS
......
a
b
c
canary address buffer
......
&(can. a)
&(can. b)
&(can. c)
......
a
b
c
canary address buffer
......
&(can. a)
&(can. b)
&(can. c)

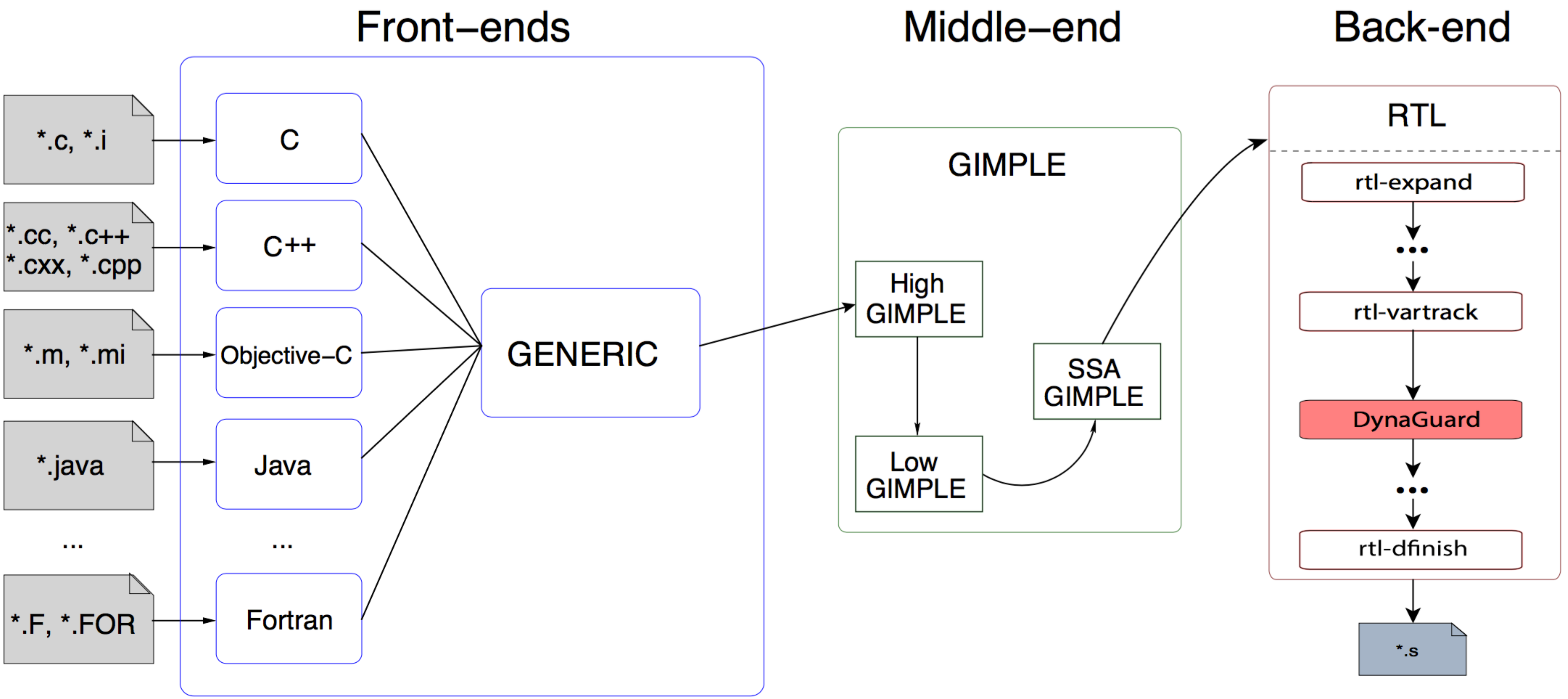


Parent Process
Child Process
TLS
TLS
......
?
=
a
b
c
canary
address
buffer
......
&(can. a)
&(can. b)
&(can. c)
......
?
=
a
b
c
canary
address
buffer
......
&(can. a)
&(can. b)
&(can. c)

Implementation

Two flavors: Compiler-based and DBI-based

Implementation: Compiler-based Version



Implementation: Compiler-based Version

- Two components:
  - GCC plugin
  - Runtime library
  - Total of ~1250 LOC

- Maintain two canaries at runtime:
  - DynaGuard-compiled code uses DynaGuard canaries
  - legacy code/libraries use the `glibc` canaries

Implementation: Compiler-based Version

- Both canaries have same entropy but are stored in different TLS offsets
- GCC plugin replaces the `glibc` canaries with the DynaGuard canaries
- DynaGuard's runtime library:
  - allocates Canary Address Buffer (CAB) in the heap for each thread, before it starts executing and deallocates it when terminating
  - performs CAB bookkeeping
  - updates all canaries in the child process's stack, as well as its TLS upon a fork()

Compiler-based Version: DynaGuard GCC Plugin

- Reserve 4 out of 8 `__padding` entries of the `tcbhead_t` struct in the TLS.
  Reserved TLS offsets range from 0x2a0 to 0x2b8:
  - CAB address stored at %fs:0x2a0
  - CAB current index: %fs:0x2a8
  - CAB size: %fs:0x2b0
  - DynaGuard canary: %fs:0x2b8

- Insert code to push/pop canary addresses in CAB upon a canary push/pop

Compiler-based Version: DynaGuard GCC Plugin

Original

```
;function prologue
push    %rbp
mov     %rsp,%rbp
sub     $0x40,%rsp
;canary stack placement
mov     %fs:0x28,%rax
mov     %rax,-0x8(%rbp)
xor     %eax,%eax

        ...

;canary check
mov     -0x8(%rbp),%rcx
xor     %fs:0x28,%rcx
je      <exit>
callq   <__stack_chk_fail@plt>
```

DynaGuard

```
push    %rbp
mov     %rsp,%rbp
sub     $0x40,%rsp
push    %r14                        (1)
push    %r15
lea     -0x8(%rbp),%rax             (2)
mov     %fs:0x2a0,%r14              (3)
mov     %fs:0x2a8,%r15              (4)
mov     %rax,(%r14,%r15,8)          (5)
incq    %fs:0x2a8                   (6)
pop     %r15                        (7)
pop     %r14
mov     %fs:0x2b8,%rax              (8)
mov     %rax,-0x8(%rbp)
xor     %eax,%eax
        ...

decq    %fs:0x2a8                   (9)
mov     -0x8(%rbp),%rcx
xor     %fs:0x2b8,%rcx              (10)
je      <exit>
callq   <__stack_chk_fail@plt>
```

Compiler-based Version: DynaGuard Runtime Library

- PIC module loaded via **`LD_PRELOAD`**
- Invoked only for CAB setup and resize operations, as well as for canary updates.
- All push/pop operations of canary addresses are implemented by the GCC plugin

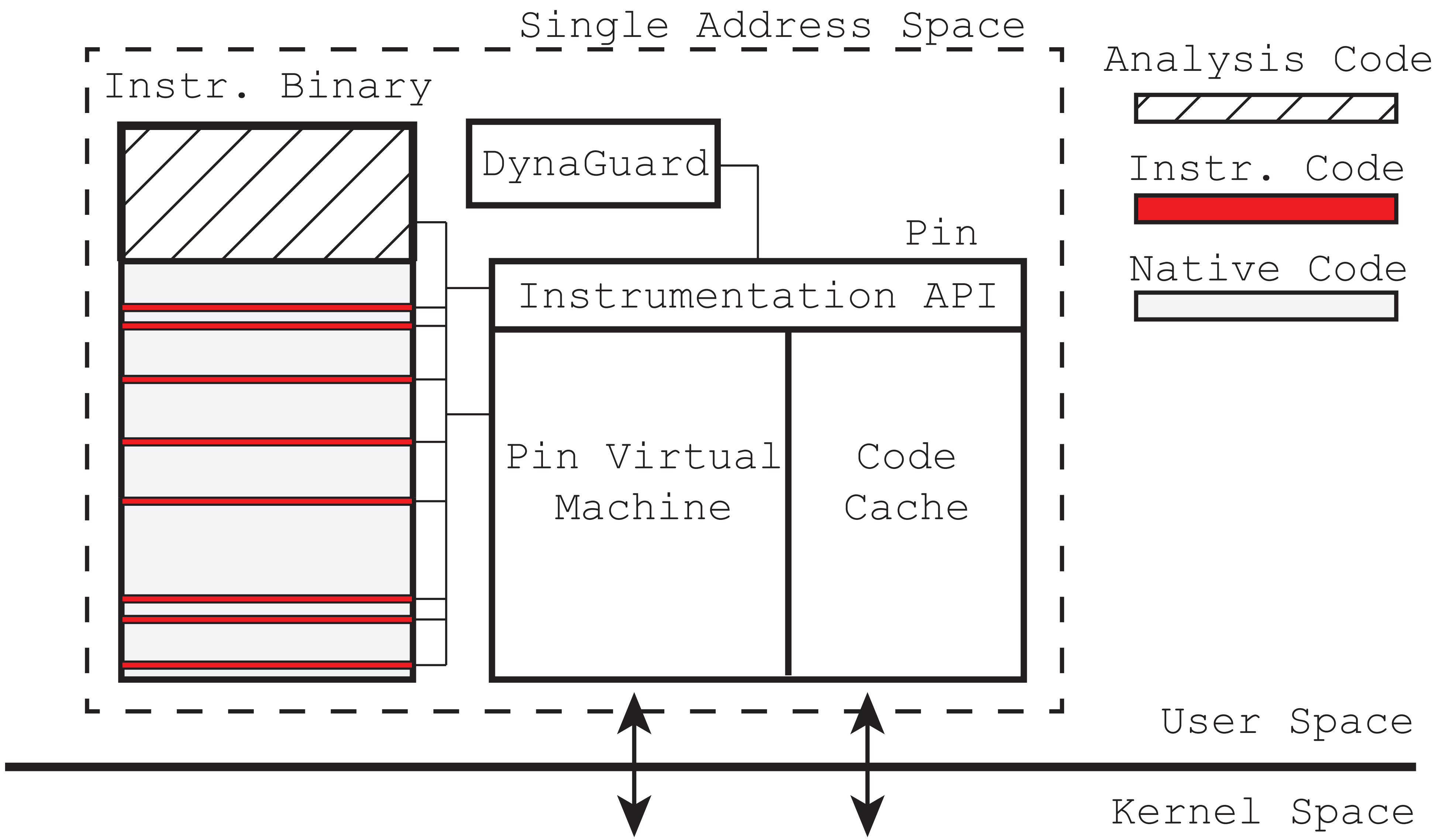
Compiler-based Version: DynaGuard Runtime Library

- Constructor routine allocates CAB in main thread
- Hooks:
  - `pthread_create` to setup the entries in TLS before `start_routine` starts executing
  - the `fork()` system call and updates all canaries in the child process's stack (before the child commences execution)
  - **stack unwinding routines** and updates the CAB accordingly
- Write-protects the last page of CAB, registers a `SIGSEGV` handler, and hooks `signal` and `sigaction`
  - If signal due to a full CAB, resize accordingly and resume execution
  - Else, invoke the original signal handler and let the application handle the signal

Implementation: DBI-based Version

Implemented using Intel's Pin DBI framework

- No source code needed
- Same design as previously except now execution occurs under Pin



Implementation: DBI-based Version

- Monitor all canary push and pop operations
- Update all canaries in the child process accordingly upon a **`fork`**
- No need for complex tracking of stack unwinding: simply track modifications of the stack pointer
- Maintain a per-thread CAB buffer, eliminating the overhead of using the Pin built-in **`trace buffer`**

Sample Function Prologue

```
push    rbp
mov     rsp,%rbp
sub     $0x40,rsp
mov     fs:0x28,%rax   (1)
mov     rax,-0x8(%rbp) (2)
```

Instrumentation Pseudocode

```
if((instruction has segment prefix)        &&
   (prefix is one of fs/gs)                &&
   (offset from fs/gs is 0x28/0x14)        &&
   (instr. is a 'mov' from mem to reg)     &&
   (next instr. is a `mov' from reg to mem)&&
   (dest. operand(register) of current instr.
    is the source operand of next instr.)) {
      insert_analysis_call(
            before_next_instr,
            push_canary(thread_context,
            canary_address))}
```

Evaluation

Effectiveness:

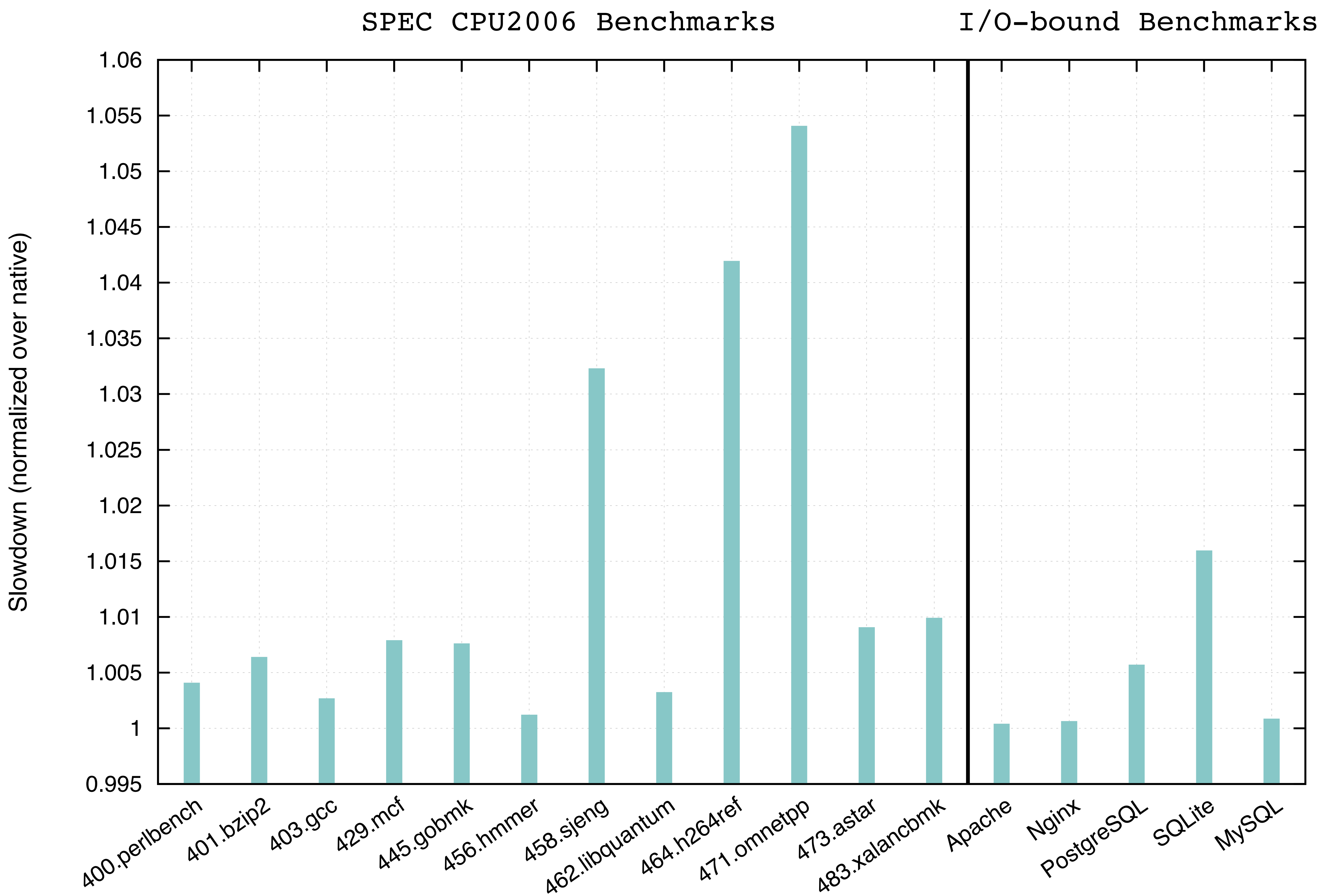
- Successfully defends against BROP and Nginx public exploits without breaking correctness

Performance:

- SPEC CPU 2006 INT benchmarks
- Popular Server Applications: Apache, Nginx, PostgreSQL, MySQL, SQLite
- Phoronix default profile for all server applications except MySQL (for which we used SysBench)
- Average overhead 1.2% in GCC version, 2.92% on top of PIN in DBI version

SPEC CPU2006: **1.5%**

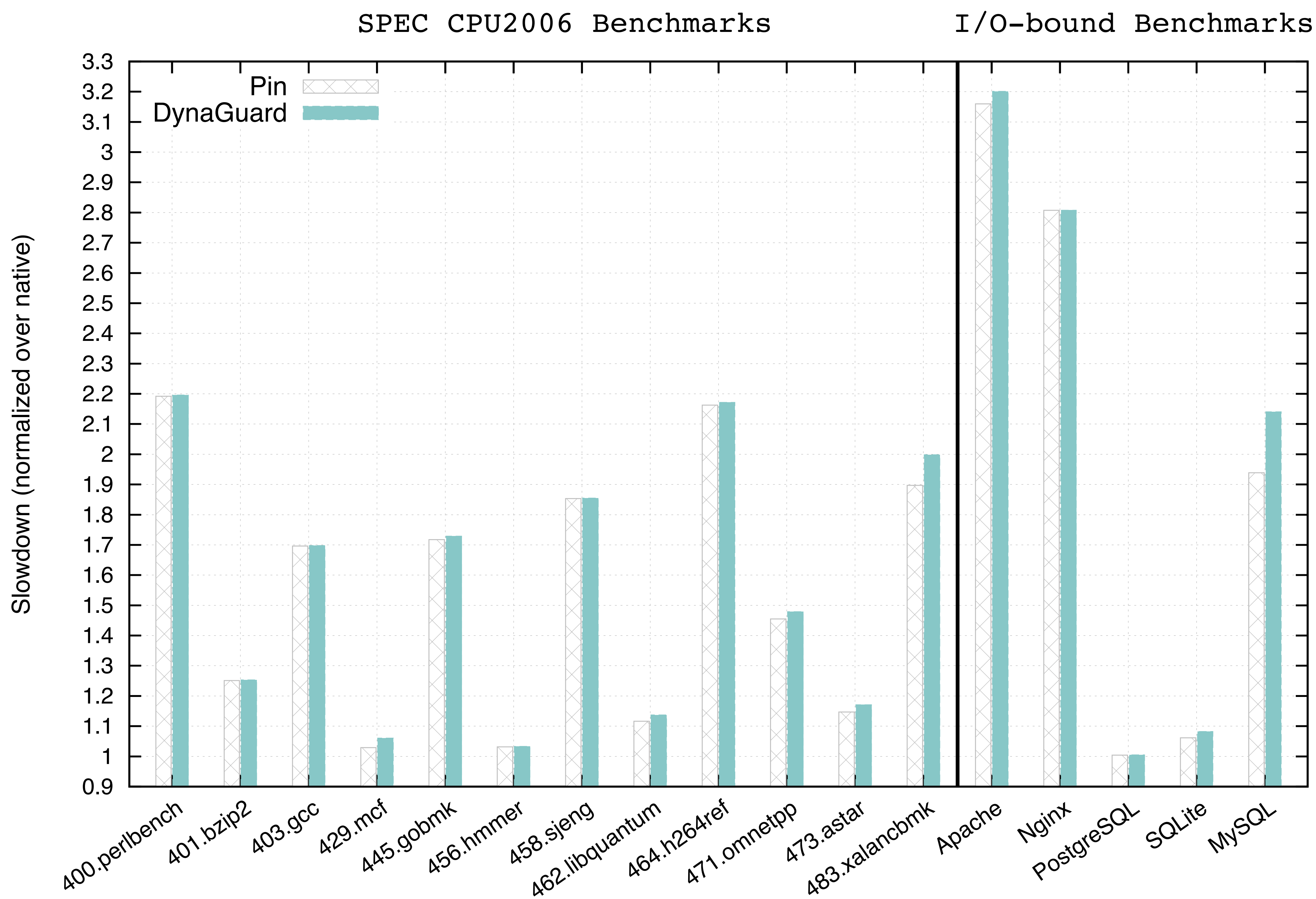
Server applications (Phoronix and SysBench): **0.46%**



SPEC CPU2006: **3.2% - 2.19x (avg 1.56x)**

PostgreSQL : **0.4%** - SQLite : **8.19%** - MySQL: **214%**- Apache: **3.2x** - Nginx: **2.8x**

Average CPU overhead **170.66%, 2.92%** atop PIN



Summary

- DynaGuard protects canary-based defenses against byte-by-byte brute forcing of the canary cookie

- Supports applications for which source code is available as well as binary-only programs
  - Offers a lightweight solution for the more general problem of memory duplication with respect to reduced entropy for security-sensitive applications (e.g., PRNGs of OpenSSL and LibreSSL)

- Has minimal incremental overhead over the respective underlying protection (e.g., GCC's SSP & Pin's native DBI respectively)

- Source code is available at https://github.com/nettrino/dynaguard