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

```c
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

Higher Addresses

Return Address
Frame Pointer
Canary
char buffer[]
int *x
int i
copy of n
copy of str

Lower Addresses

canary start
buffer start
Overflow Direction

byte 0x7
byte 0x0
byte 0x1
byte 0x0
...
Canary Brute-force

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Return Address
Frame Pointer
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char buffer[]
int *x
int i
copy of n
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Lower Addresses

canary end

canary start

Overflow Direction

buffer start

byte 0x7

... 

byte 0x1

byte 0x0
Canary Brute-force

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Frame Pointer
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Lower Addresses

canary end

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Overflow Direction
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byte 0x7
...
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Canary Brute-force

Higher Addresses

Return Address

Frame Pointer

Canary

char buffer[]

int *x

int i

copy of n

copy of str

Lower Addresses

buffer start

Overflow Direction

byte 0x0

byte 0x1

byte 0x7

canary start

canary end
Canary Brute-force

Higher Addresses

Return Address
Frame Pointer
Canary
char buffer[]
int *x
int i
copy of n
copy of str

Lower Addresses

canary end

canary start

Overflow Direction

buffer start

byte 0x0
byte 0x1
... 
byte 0x7
canary start
canary end

copy of str

Return Address
Frame Pointer
Canary
char buffer[]
int *x
int i
copy of n
Higher Addresses
Lower Addresses
A byte-by-byte brute-force requires $4 \times 256 = 1024$ 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)

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

previous frames
Parent Process

Child Process
TLS
canary
previous frames
canary address buffer
&(canary a)
&(canary b)
previous frames
a
b

\[ \text{canary push} \]
\[ \text{canary reference} \]
\[ ? \]
\[ \text{canary check} \]
Parent Process

Child Process

canary address buffer

TLS

TLS

&(can. a)

&(can. b)

&(can. a)

&(can. b)

Parent Process

Child Process

canary address buffer

TLS

TLS

&(can. a)

&(can. b)

&(can. a)

&(can. b)
Implementation

Two flavors: Compiler-based and DBI-based
Implementation: Compiler-based Version

- Front-ends
  - `.c`, `.i`
  - `.cc`, `.c++`, `.cxx`, `.cpp`
  - `.m`, `.mi`
  - `.java`
  - ...,
  - `.F`, `.FOR`

- Middle-end
  - GENERIC
  - GIMPLE
    - High GIMPLE
      - Low GIMPLE
      - SSA GIMPLE

- Back-end
  - RTL
    - rtl-expand
    - ...
    - rtl-vartrack
    - DynaGuard
    - rtl-dfinish
    - `*.s`
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

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

#### DynaGuard

```assembly
push   %rbp
mov    %r14, %rbp
push   %r15
lea    -0x8(%rbp),%rax
push   %r14
mov    %fs:0x2a0,%r14
mov    %fs:0x2a8,%r15
mov    %rax, (%r14, %r15, 8)
incq   %fs:0x2a8
pop    %r15
pop    %r14
mov    %fs:0x2b8,%rax
mov    %rax,-0x8(%rbp)
xor    %eax,%eax
```

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

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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

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Diagram:

- Single Address Space
  - Instr. Binary
  - DynaGuard
  - Pin Virtual Machine
  - Code Cache

- Analysis Code
  - Instr. Code
  - Native Code

- User Space
- Kernel Space
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
**Compiler-based version of DynaGuard**

**SPEC CPU2006: 1.5%**

Server applications (Phoronix and SysBench): 0.46%

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**SPEC CPU2006 Benchmarks**

- 400.perlbench
- 401.bzip2
- 403.gcc
- 429.mcf
- 455.gobmk
- 456.hmmer
- 458.sjeng
- 462.libquantum
- 464.h264ref
- 471.omnetpp
- 473.astar
- 483.xalancbmk
- 484.libquantum
- 485ENDING

**I/O-bound Benchmarks**

- Apache
- Nginx
- PostgreSQL
- SQLite
- MySQL

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Slowdown (normalized over native)

Graph showing the slowdown for various benchmarks.
DBI-based version of DynaGuard

**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

![Graph showing performance slowdown for various benchmarks](image)
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