CSE 610 Special Topics:
System Security - Attack and Defense for Binaries

Instructor: Dr. Ziming Zhao

Location: Frnczk 408, North campus
Time: Monday, 5:00 PM - 7:50 PM

Homework-4

Walkthrough: hw-4

Crackme-5: overwrite function pointer on stack

Maze2

Last Class

1. Stack-based buffer overflow-3
    a. Inject shellcode into environment variable and command line arg
    b. Overwrite saved %ebp; Frame-pointer attack
    c. Return-to-libc (32-bit); We will discuss 64 bit Ret2libc after ROP
2. Defenses
    a. Data Execution Prevention (DEP)

This Class

1. Defenses
    a. Direct defense
    b. Stack Cookie; Canary - How to bypass
    c. Shadow stack
    d. Sandbox - seccomp

Attacker’s Goal

Take control of the victim’s machine

- Hijack the execution flow of a running program
- Execute arbitrary code

Requirements

- Inject attack code or attack parameters
- Abuse vulnerability and modify memory such that control flow is redirected

Change of control flow

- ***alter a code pointer*** (RET, function pointer, etc.)
- change memory region that should not be accessed

Overflow Types

Overflow some ***code pointer***

- Overflow memory region on the stack
  - overflow function return address
  - overflow function frame (base) pointer
  - overflow longjmp buffer
- Overflow (dynamically allocated) memory region on the heap
- Overflow function pointers
  - stack, heap, BSS

Other pointers?

Can we exploit other pointers as well?

1. Memory that is used in a **value** to influence mathematical operations, conditional jumps.
2. Memory that is used as a **read pointer** (or offset), allowing us to force the program to access arbitrary memory.
3. Memory that is used as a **write pointer** (or offset), allowing us to force the program to overwrite arbitrary memory.
4. Memory that is used as a **code pointer** (or offset), allowing us to redirect program execution!

Typically, you use one or more vulnerabilities to achieve multiple of these effects.

Defenses

- Prevent buffer overflow
  - A direct defense
  - Could be accurate but could be slow
  - Good in theory, but not practical in real world

- Make exploit harder
  - An indirect defense
  - Could be inaccurate but could be fast
  - Simple in theory, widely deployed in real world

Examples

- Base and bound check
  - Prevent buffer overflow!
  - A direct defense
- Stack Cookie
  - An indirect defense
  - Prevent overwriting return address
- Data execution prevention (DEP, NX, etc.)
  - An indirect defense
  - Prevent using of shellcode on stack

Spatial Memory Safety – Base and Bound check

char *a
- char *a_base;
- char *a_bound;

a = (char*)malloc(512)
- a_base = a;
- a_bound = a+512

Access must be between [a_base, a_bound)
- a[0], a[1], a[2], …, and a[511] are OK
- a[512] NOT OK
- a[-1] NOT OK

Spatial Memory Safety – Base and Bound check

Propagation

- char *b = a;
  - b_base = a_base;
  - b_bound = a_bound;
- char *c = &b[2];
  - c_base = b_base;
  - c_bound = b_bound;

Overhead - Based and Bound

+2x overhead on storing a pointer

- char *a
    - char *a_base;
    - char *a_bound;

+2x overhead on assignment

- char *b = a;
    - b_base = a_base;
    - b_bound = a_bound;

+2 comparisons added on access

- c[i]
    - if(c+i >= c_base)
    - if(c+i < c_bound)

SoftBound: Highly Compatible and Complete Spatial Memory Safety for C

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Abstract

The serious bugs and security vulnerabilities facilitated by C/C++'s lack of bounds checking are well known, yet C and C++ remain in widespread use. Unfortunately, C's arbitrary pointer arithmetic,

dress on the stack, address space randomization, non-executable stack), vulnerabilities persist. For one example, in November 2008 Adobe released a security update that fixed several serious buffer overflows [2]. Attackers have reportedly exploited these buffer-

PLDI 09

HardBound: Architectural Support for Spatial Safety of the C Programming Language

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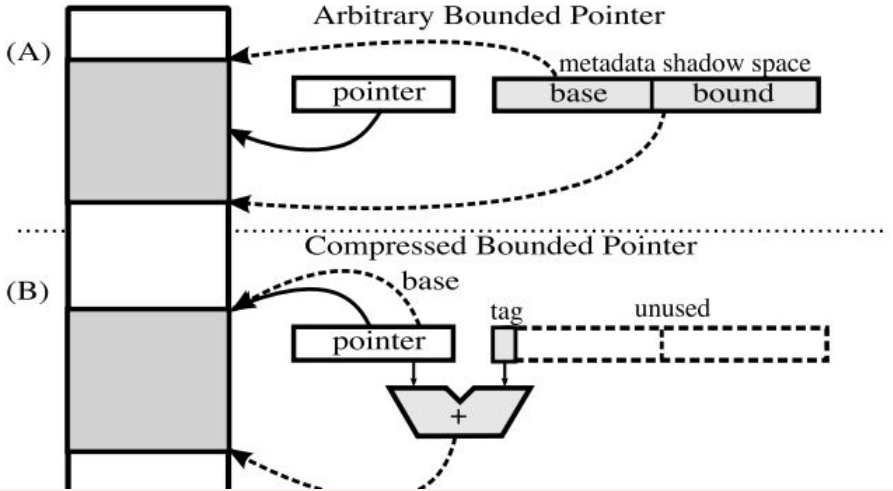
Abstract

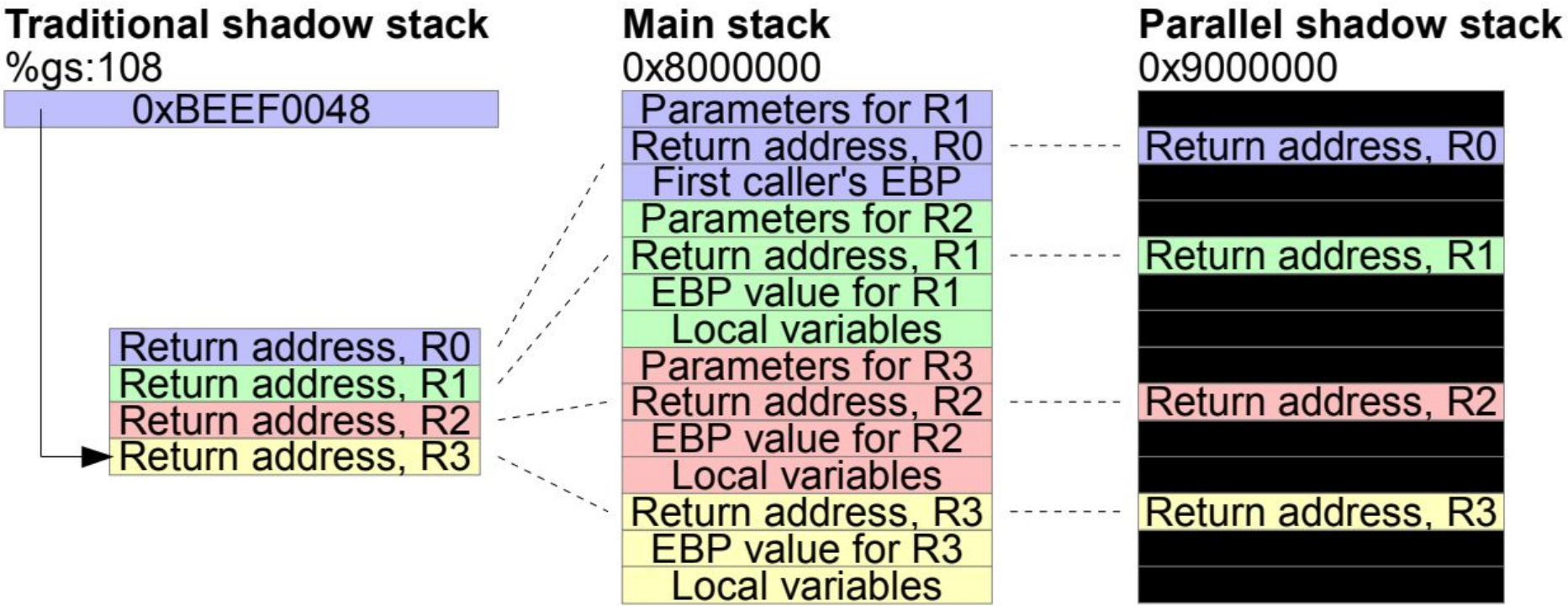
The C programming language is at least as well known for its absence of spatial memory safety guarantees (*i.e.*, lack of bounds checking) as it is for its high performance. C's unchecked pointer arithmetic and array indexing allow simple programming mistakes to lead to erroneous executions, silent data corruption, and security vulnerabilities. Many prior proposals have tackled enforcing spatial safety in C programs by checking pointer and array accesses. However, existing software-only proposals have significant drawbacks that may prevent wide adoption, including: unacceptably high runtime overheads, lack of completeness, incompatible pointer representations, or need for non-trivial changes to existing C source code and compiler infrastructure.



ASPLOS 09

Defense-2:
Shadow Stack

Shadow Stack



https://people.eecs.berkeley.edu/~daw/papers/shadow-asiaccs15.pdf

Traditional Shadow Stack

```
SUB $4, %gs:108    # Decrement SSP
MOV %gs:108, %eax  # Copy SSP into EAX
MOV (%esp), %ecx   # Copy ret. address into
MOV %ecx, (%eax)   #     shadow stack via ECX
```

Figure 2: Prologue for traditional shadow stack.

```
MOV %gs:108, %ecx  # Copy SSP into ECX
ADD $4, %gs:108    # Increment SSP
MOV (%ecx), %edx   # Copy ret. address from
MOV %edx, (%esp)   #     shadow stack via EDX
RET
```

Figure 3: Epilogue for traditional shadow stack (overwriting).

Traditional Shadow Stack

```
MOV %gs:108, %ecx
ADD $4, %gs:108
MOV (%ecx), %edx
CMP %edx, (%esp) # Instead of overwriting,
JNZ abort        #     we compare
RET
abort:
    HLT
```

Figure 4: Epilogue for traditional shadow stack (checking).

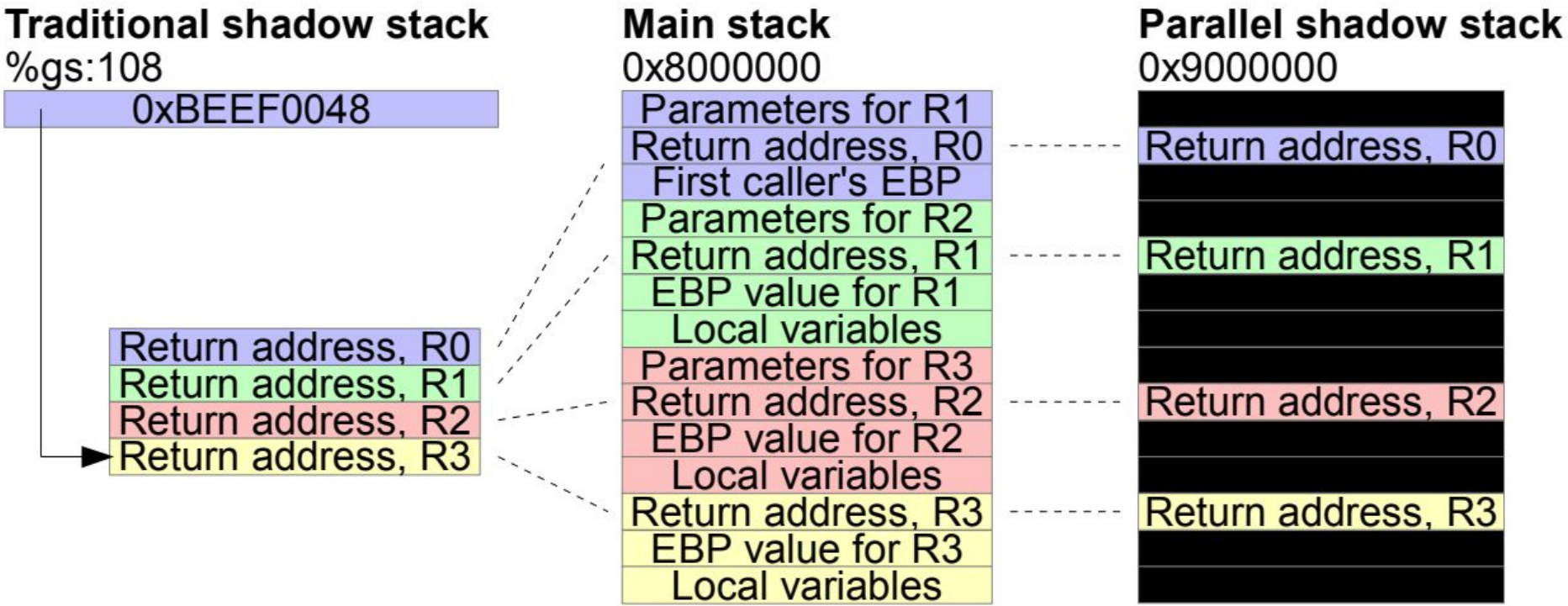
Overhead - Traditional Shadow Stack

If no attack:

- 6 more instructions
- 2 memory moves
- 1 memory compare
- 1 conditional jmp

Per function

Shadow Stack



https://people.eecs.berkeley.edu/~daw/papers/shadow-asiaccs15.pdf

Parallel Shadow Stack

```
POP 999996(%esp) # Copy ret addr to shadow stack
SUB $4, %esp # Fix up stack pointer (undo POP)
```

Figure 7: Prologue for parallel shadow stack.

```
ADD $4, %esp # Fix up stack pointer
PUSH 999996(%esp) # Copy from shadow stack
```

Figure 8: Epilogue for parallel shadow stack.

Overhead Comparison

The overhead is roughly 10% for a traditional shadow stack.

The parallel shadow stack overhead is 3.5%.

Defense-3:
Stack cookies; Canary

specific to sequential stack overflow

JANUARY 26–29, 1998 • SAN ANTONIO, TX, USA

USENIX

StackGuard: Automatic Adaptive Detection and Prevention of Buffer-Overflow Attacks

Abstract:

This paper presents a systematic solution to the persistent problem of buffer overflow attacks. Buffer overflow attacks gained notoriety in 1988 as part of the Morris Worm incident on the Internet. While it is fairly simple to fix individual buffer overflow vulnerabilities, buffer overflow attacks continue to this day. Hundreds of attacks have been discovered, and while most of the obvious vulnerabilities have now been patched, more sophisticated buffer overflow attacks continue to emerge.

We describe StackGuard: a simple compiler technique that virtually eliminates buffer overflow vulnerabilities with only modest performance penalties. Privileged programs that are recompiled with the StackGuard compiler extension no longer yield control to the attacker, but rather enter a fail-safe state. These programs require *no* source code changes at all, and are binary-compatible with existing operating systems and libraries. We describe the compiler technique (a simple patch to `gcc`), as well as a set of variations on the technique that trade-off between penetration resistance and performance. We present experimental results of both the penetration resistance and the performance impact of this technique.

StackGuard

A compiler technique that attempts to eliminate buffer overflow vulnerabilities

- No source code changes
- Patch for the function prologue and epilogue
  - Prologue: push an additional value into the stack (canary)
  - Epilogue: check the canary value hasn’t changed. If changed, exit.

Buffer Overflow Example: code/overflowret4

```
int vulfoo()
{
  char buf[30];

  gets(buf);
  return 0;
}

int main(int argc, char *argv[])
{
  vulfoo();
  printf("I pity the fool!\n");
}
```

Use “echo 0 | sudo tee /proc/sys/kernel/randomize_va_space” on Ubuntu to disable ASLR temporarily

With and without Canary 32bit

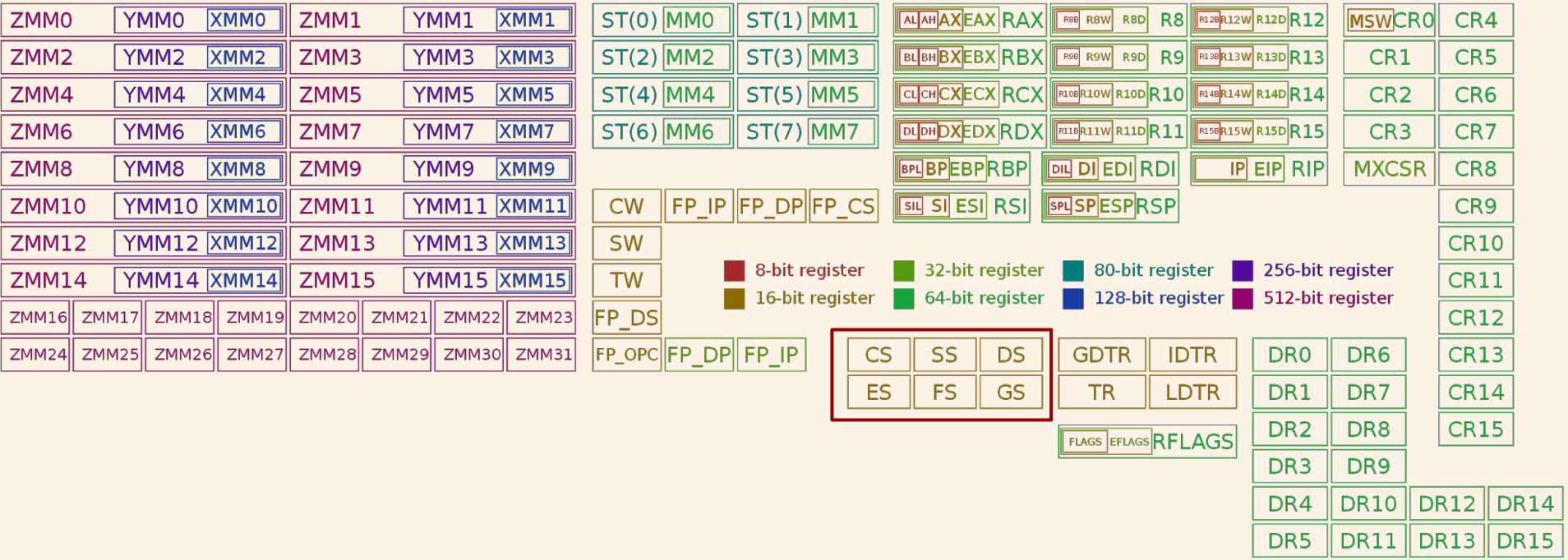
or4

```
000011ed <vulfoo>:
   11ed:f3 0f 1e fb        endbr32
   11f1: 55                push   %ebp
   11f2: 89 e5             mov    %esp,%ebp
   11f4: 53                push   %ebx
   11f5: 83 ec 34          sub    $0x34,%esp
   11f8: e8 64 00 00 00             call   1261 <__x86.get_pc_thunk.ax>
   11fd: 05 d7 2d 00 00             add    $0x2dd7,%eax
   1202: 83 ec 0c          sub    $0xc,%esp
   1205: 8d 55 d0                   lea    -0x30(%ebp),%edx
   1208: 52                push   %edx
   1209: 89 c3             mov    %eax,%ebx
   120b: e8 70 fe ff ff             call   1080 <gets@plt>
   1210: 83 c4 10          add    $0x10,%esp
   1213: b8 00 00 00 00             mov    $0x0,%eax
   1218: 8b 5d fc          mov    -0x4(%ebp),%ebx
   121b: c9                leave
   121c: c3                ret
```

or4nx

```
0000120d <vulfoo>:
   120d:f3 0f 1e fb        endbr32
   1211: 55                push   %ebp
   1212: 89 e5             mov    %esp,%ebp
   1214: 53                push   %ebx
   1215: 83 ec 34          sub    $0x34,%esp
   1218: e8 81 00 00 00             call   129e <__x86.get_pc_thunk.ax>
   121d: 05 b3 2d 00 00             add    $0x2db3,%eax
   1222: 65 8b 0d 14 00 00 00       mov    %gs:0x14,%ecx
   1229: 89 4d f4          mov    %ecx,-0xc(%ebp)
   122c: 31 c9             xor    %ecx,%ecx
   122e: 83 ec 0c          sub    $0xc,%esp
   1231: 8d 55 cc          lea    -0x34(%ebp),%edx
   1234: 52                push   %edx
   1235: 89 c3             mov    %eax,%ebx
   1237: e8 54 fe ff ff             call   1090 <gets@plt>
   123c: 83 c4 10          add    $0x10,%esp
   123f: b8 00 00 00 00             mov    $0x0,%eax
   1244: 8b 4d f4          mov    -0xc(%ebp),%ecx
   1247: 65 33 0d 14 00 00 00       xor    %gs:0x14,%ecx
   124e: 74 05             je     1255 <vulfoo+0x48>
   1250: e8 db 00 00 00             call   1330 <__stack_chk_fail_local>
   1255: 8b 5d fc          mov    -0x4(%ebp),%ebx
   1258: c9                leave
   1259: c3                ret
```

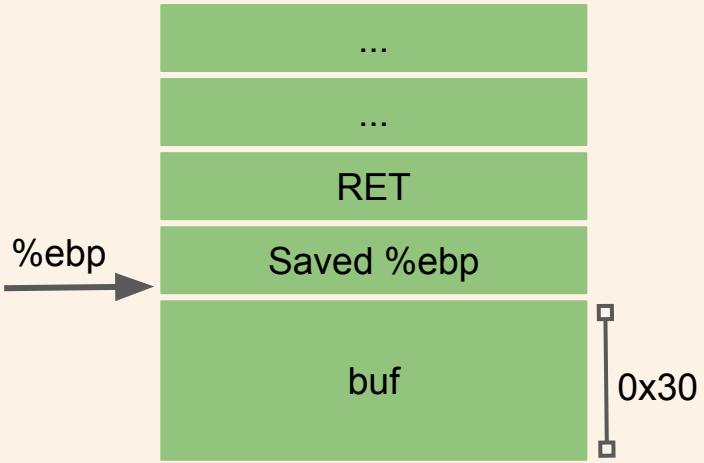
Registers on x86 and amd64



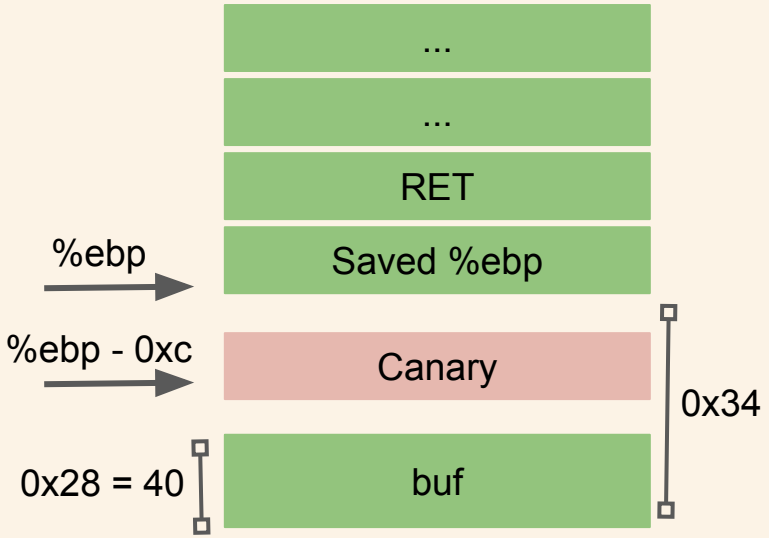
https://en.wikipedia.org/wiki/X86

With and without Canary

or4



or4nx



With and without Canary 64bit

or464

```
0000000000001169 <vulfoo>:
   1169:f3 0f 1e fa        endbr64
   116d:55                 push   %rbp
   116e:48 89 e5           mov    %rsp,%rbp
   1171:48 83 ec 30              sub    $0x30,%rsp
   1175:48 8d 45 d0              lea    -0x30(%rbp),%rax
   1179:48 89 c7           mov    %rax,%rdi
   117c: b8 00 00 00 00          mov    $0x0,%eax
   1181:e8 ea fe ff ff     callq  1070 <gets@plt>
   1186:b8 00 00 00 00           mov    $0x0,%eax
   118b:c9                 leaveq
   118c: c3                retq
```

or464nx

```
0000000000001189 <vulfoo>:
   1189:f3 0f 1e fa        endbr64
   118d:55                 push   %rbp
   118e:48 89 e5           mov    %rsp,%rbp
   1191:48 83 ec 30              sub    $0x30,%rsp
   1195:64 48 8b 04 25 28 00     mov    %fs:0x28,%rax
   119c: 00 00
   119e:48 89 45 f8              mov    %rax,-0x8(%rbp)
   11a2:31 c0              xor    %eax,%eax
   11a4:48 8d 45 d0              lea    -0x30(%rbp),%rax
   11a8:48 89 c7           mov    %rax,%rdi
   11ab:b8 00 00 00 00           mov    $0x0,%eax
   11b0:e8 db fe ff ff           callq  1090 <gets@plt>
   11b5:b8 00 00 00 00           mov    $0x0,%eax
   11ba:48 8b 55 f8              mov    -0x8(%rbp),%rdx
   11be:64 48 33 14 25 28 00     xor    %fs:0x28,%rdx
   11c5: 00 00
   11c7: 74 05             je     11ce <vulfoo+0x45>
   11c9: e8 b2 fe ff ff          callq  1080 <__stack_chk_fail@plt>
   11ce: c9                leaveq
   11cf:  c3               retq
```

Overhead - Canary

If no attack:

- 6 more instructions
- 2 memory moves
- 1 memory compare
- 1 conditional jmp

Per function

%gs:0x14, %fs:0x28

A random canary is generated at program initialization, and stored in a global variable (pointed by %gs, %fs).

Applications on x86-64 uses FS or GS to access per thread context including Thread Local Storage (TLS).

Thread-local storage (TLS) is a computer programming method that uses static or global memory local to a thread.

Pwngdb command *tls* to get the address of tls

Data Structure
https://code.woboq.org/userspace/glibc/sysdeps/x86_64/nptl/tls.h.html

Canary Types

- Random Canary – The original concept for canary values took a pseudo random value generated when program is loaded

- Random XOR Canary – The random canary concept was extended in StackGuard version 2 to provide slightly more protection by performing a XOR operation on the random canary value with the stored control data.

- Null Canary – The canary value is set to 0x00000000 which is chosen based upon the fact that most string functions terminate on a null value and should not be able to overwrite the return address if the buffer must contain nulls before it can reach the saved address.

- Terminator Canary – The canary value is set to a combination of Null, CR, LF, and 0xFF. These values act as string terminators in most string functions, and accounts for functions which do not simply terminate on nulls such as gets().

Terminator Canary

0x000aff0d

\x00: terminates strcpy
\x0a: terminates gets (LF)
\xff: Form feed
\x0d: Carriage return

Evolution of Canary

StackGuard published at the 1998 USENIX Security. StackGuard was introduced as a set of patches to the GCC 2.7.

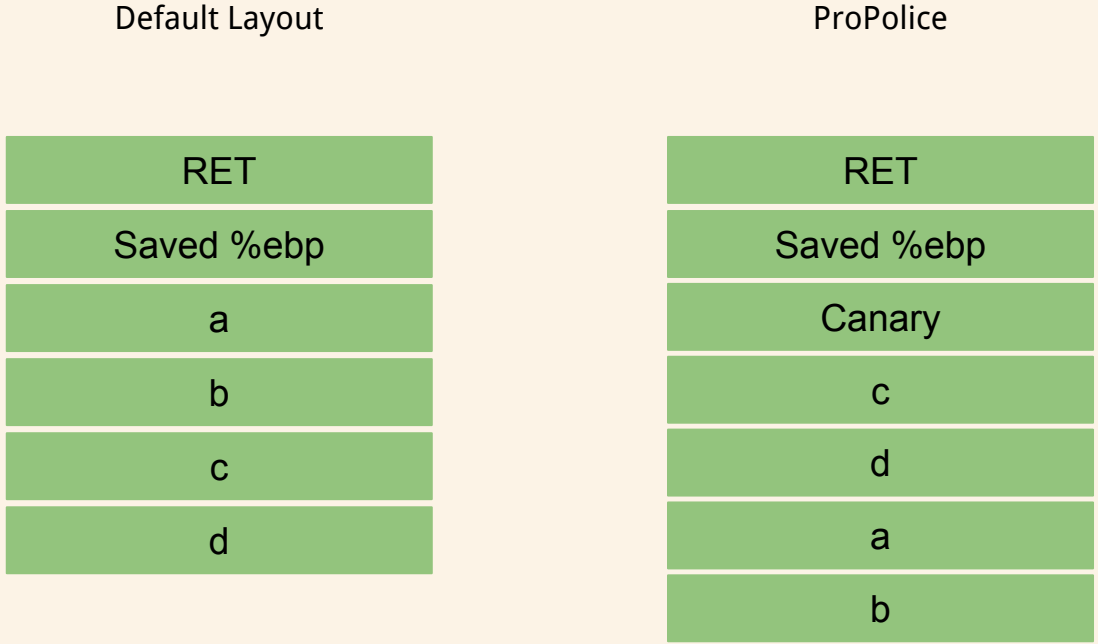
From 2001 to 2005, IBM developed ProPolice. It places buffers after local pointers in the stack frame. This helped avoid the corruption of pointers, preventing access to arbitrary memory locations.

In 2012, Google engineers implemented the -fstack-protector-strong flag to strike a better balance between security and performance. This flag protects more kinds of vulnerable functions than -fstack-protector does, but not every function, providing better performance than -fstack-protector-all. It is available in GCC since its version 4.9.

Most packages in Ubuntu are compiled with -fstack-protector since 6.10. Every Arch Linux package is compiled with -fstack-protector since 2011. All Arch Linux packages built since 4 May 2014 use -fstack-protector-strong.

ProPolice

```
int foo() {
  int a;
  int *b;
  char c[10];
  char d[3];

  b = &a;
  strcpy(c,get_c());
  *b = 5;
  strcpy(d,get_d());
  return *b;
}
```



Bypass Canary

-fstack-protector

Bypass Canary

1. Read the canary from the stack due to some information leakage vulnerabilities, e.g. format string
2. Brute force. 32-bit version. Least significant is 0, so there are 256^3 combinations = 16,777,216

If it take 1 second to guess once, it will take at most 194 days to guess the canary

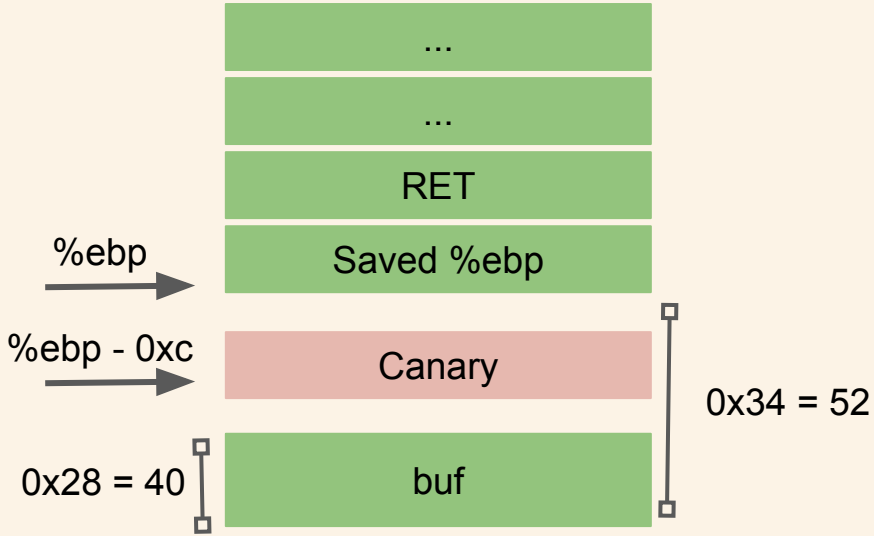
Bypass Canary - Apps using fork()

1. Canary is generated when the process is created
2. A child process will not generate a new canary
3. So, we do not need to guess 3 bytes canary at the same time. Instead, we guess one byte a time. At most 256*3 = 768 trials.

code/bypasscanary

```
#include <stdio.h>
#include <string.h>
#include <stdlib.h>
#include <unistd.h>

char g_buffer[200] = {0};
int g_read = 0;

int vulfoo()
{
	char buf[40];
	FILE *fp;

	while (1)
	{
		fp = fopen("exploit", "r");
		if (fp)
			break;}

	usleep(500 * 1000);
	g_read = 0;
	memset(g_buffer, 0, 200);
	g_read = fread(g_buffer, 1, 70, fp);
	printf("Child reads %d bytes. Guessed canary is %x.\n",
g_read, *((int*)(&g_buffer[40])));
	memcpy(buf, g_buffer, g_read);

	fclose(fp);
	remove("exploit");
	return 0;
}

int main(int argc, char *argv[])
{
	while(1)
	{
		if (fork() == 0)
		{
			//child
			printf("Child pid: %d\n", getpid());
			vulfoo();
			printf("I pity the fool!\n");
			exit(0);
		}
		else
		{
			//parent
			int status;
			printf("Parent pid: %d\n", getpid());
			waitpid(-1, &status, 0);
		}
	}
}
```

bc



Canary: 0x??????00

Demo

1. Assume ASLR is disable.
2. To make things easier, we put the shellcode in env variable.
3. Write a script to guess the canary byte by byte.
4. Send the full exploit to the program

```
export SCODE=$(python -c "print '\x90'*500 +
'\x31\xc0\x50\x68\x2f\x2f\x73\x68\x68\x2f\x62\x69\x6e\x89\xe3\x89\xc1\x89\xc2\xb0\x0b
\xcd\x80\x31\xc0\x40\xcd\x80'")
```