CSE 127: Computer Security

Stack Buffer Overflows

Deian Stefan

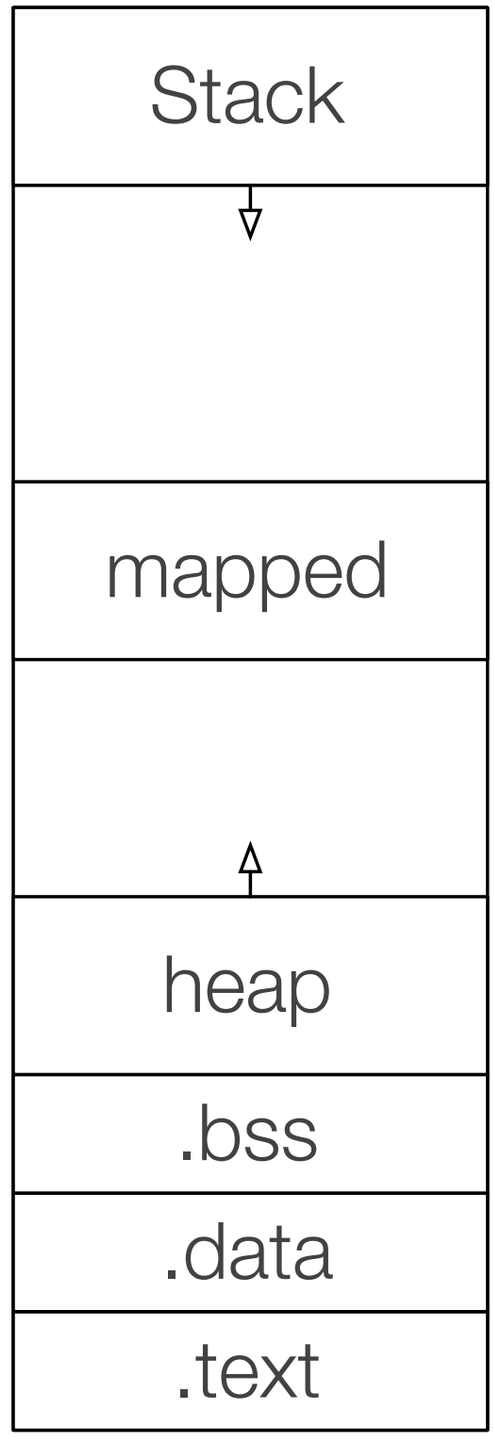
Slides adopted from Kirill Levchenko

Today

- Review: stack overflow attacks
- Shellcode
- Defenses

Process Memory Layout

- Stack
- Heap
- Data
  - Static variables
- Text
  - Executable code



The Stack

- Function local variables
- Function arguments
- Control state

The Stack

- Stack divided into **frames**
  - Frame stores locals and args to called functions
- **Stack pointer** points to
  - x86: Stack grows down (from high to low addresses)
  - x86: Stored in `ESP` register
- **Frame pointer** points to
  - Also called **base pointer**
  - x86: Stored in `EBP` register

The Stack

- Stack divided into **frames**
  - Frame stores locals and args to called functions
- **Stack pointer** points to top of stack
  - x86: Stack grows down (from high to low addresses)
  - x86: Stored in `ESP` register
- **Frame pointer** points to caller's stack frame
  - Also called **base pointer**
  - x86: Stored in `EBP` register

Function Call Example

```
int foobar(int a, int b, int c)
{
    int xx = a + 2;
    int yy = b + 3;
    int zz = c + 4;
    int sum = xx + yy + zz;

    return xx * yy * zz + sum;
}

int main()
{
    return foobar(77, 88, 99);
}
```

Source: http://eli.thegreenplace.net/2011/02/04/where-the-top-of-the-stack-is-on-x86/

```
_foobar:
    ; ebp must be preserved across calls. Since
    ; this function modifies it, it must be
    ; saved.
    push    ebp
    ; From now on, ebp points to the current stack
    ; frame of the function
    mov     ebp, esp
    ; Make space on the stack for local variables
    sub     esp, 16
    ; eax <-- a. eax += 2. then store eax in x
    mov     eax, DWORD PTR [ebp+8]
    add     eax, 2
    mov     DWORD PTR [ebp-4], eax
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    ;   mov esp, ebp ; pop ebp
    leave
    ret
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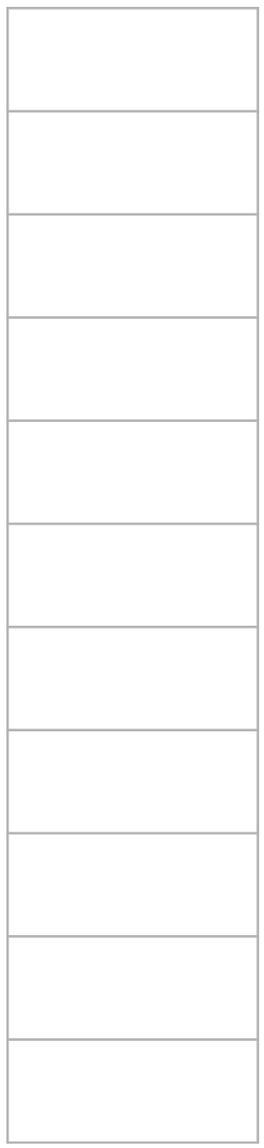

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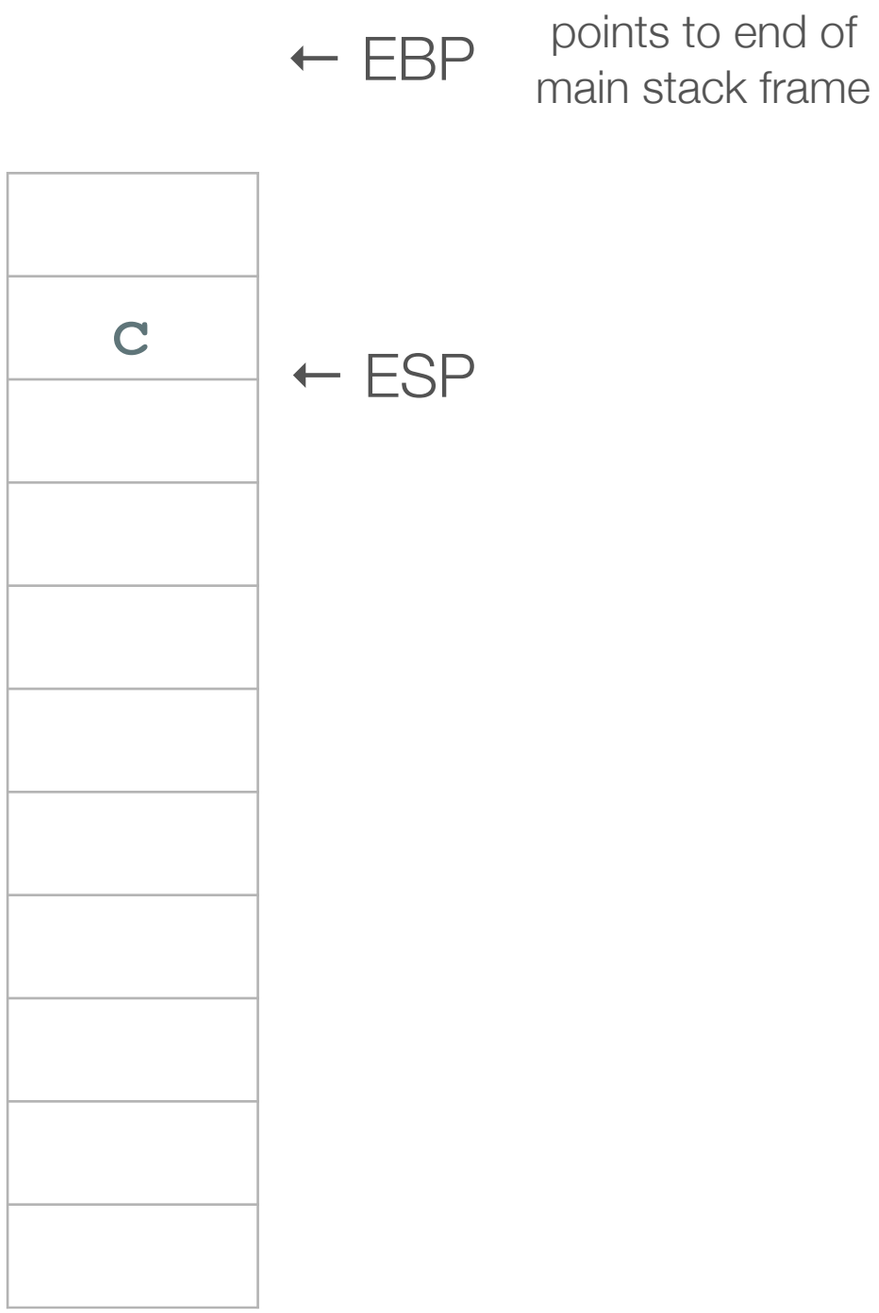

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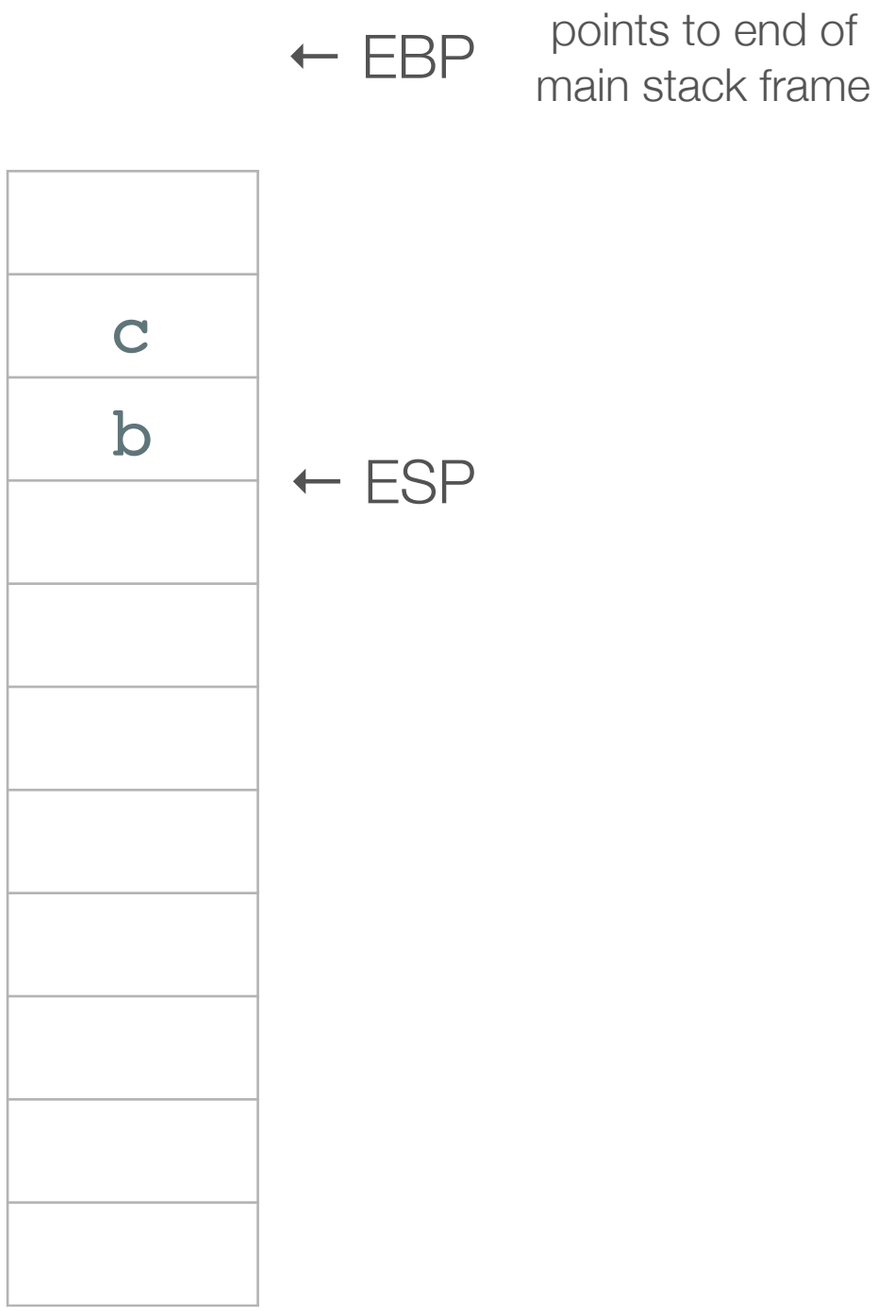

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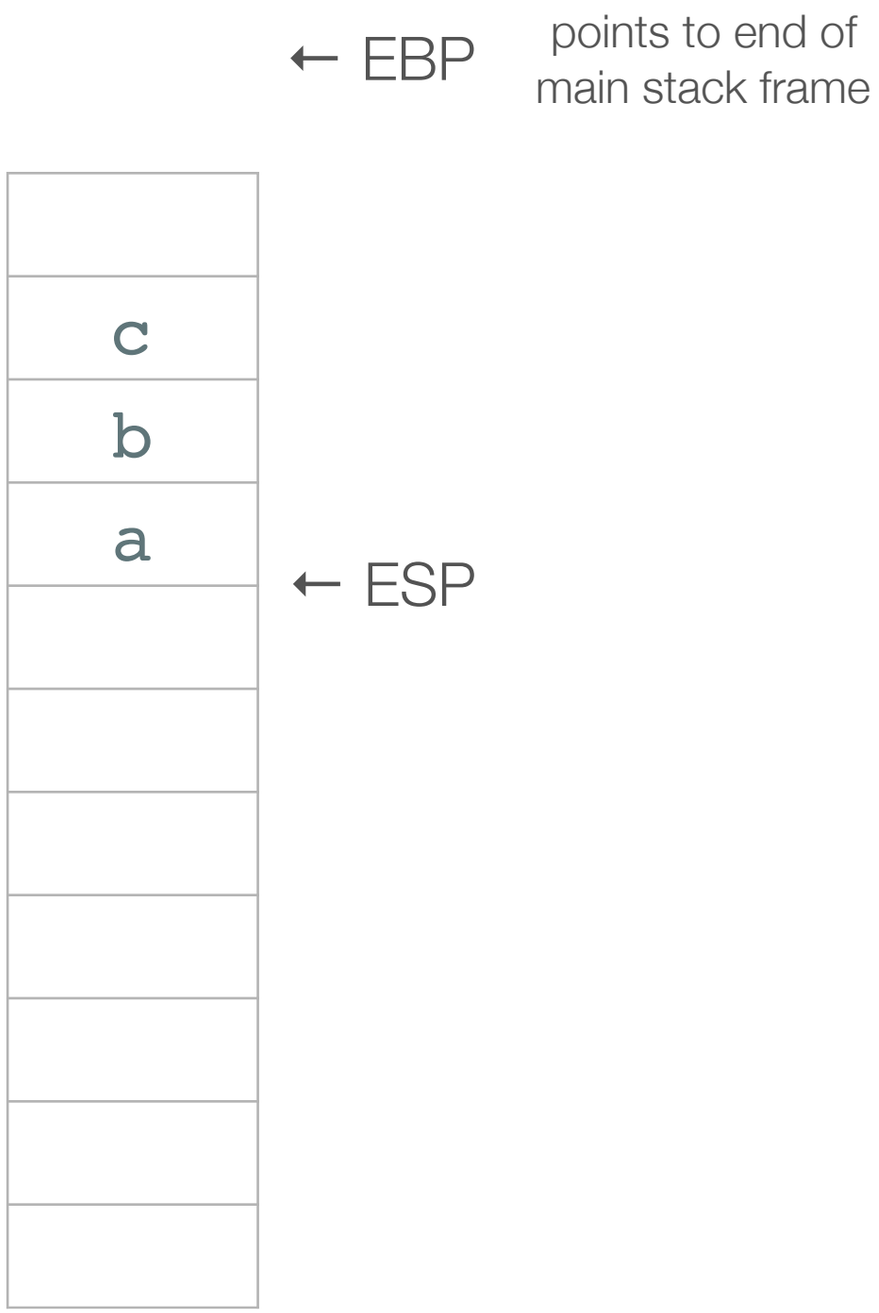

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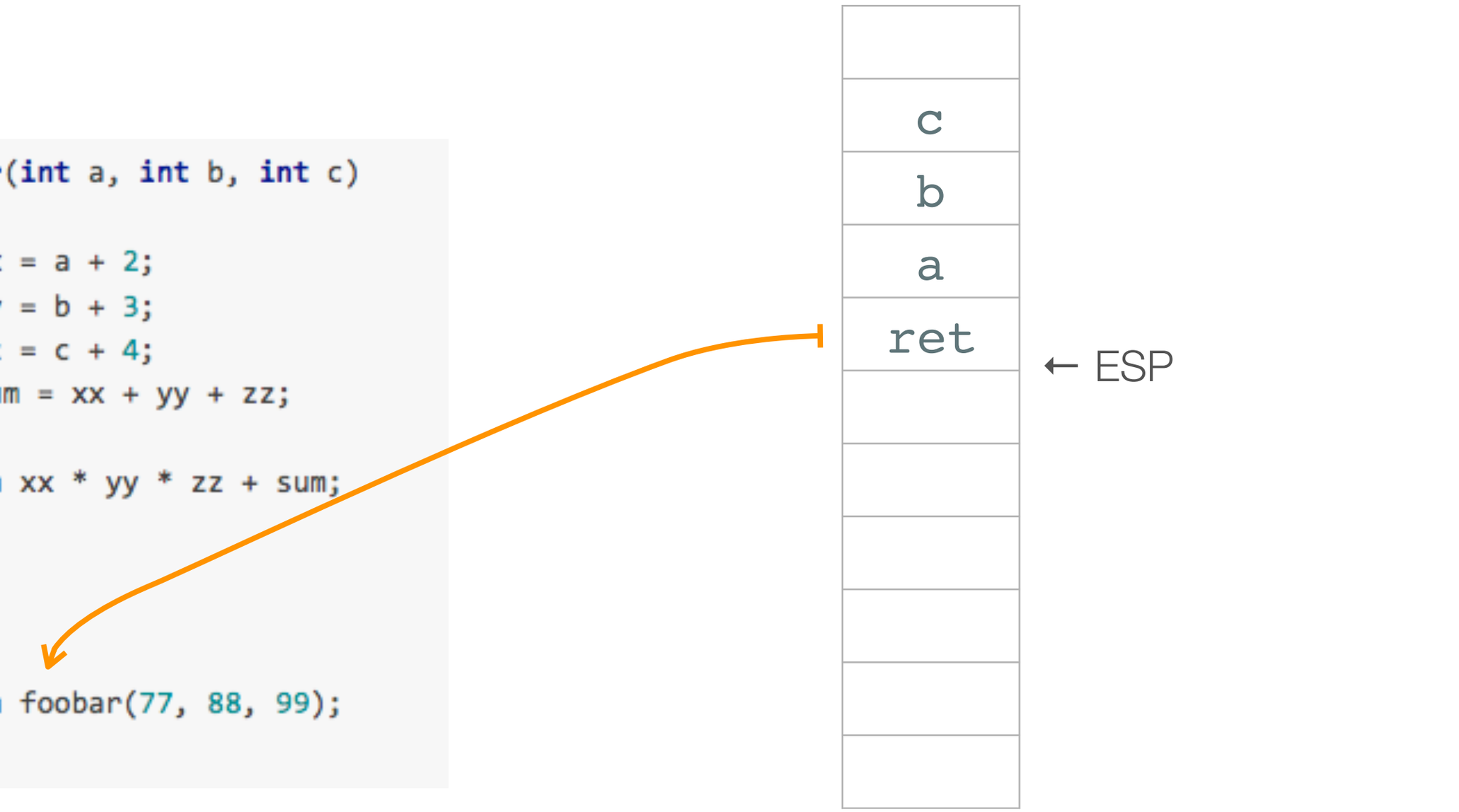

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    ;
    mov     ebp, esp

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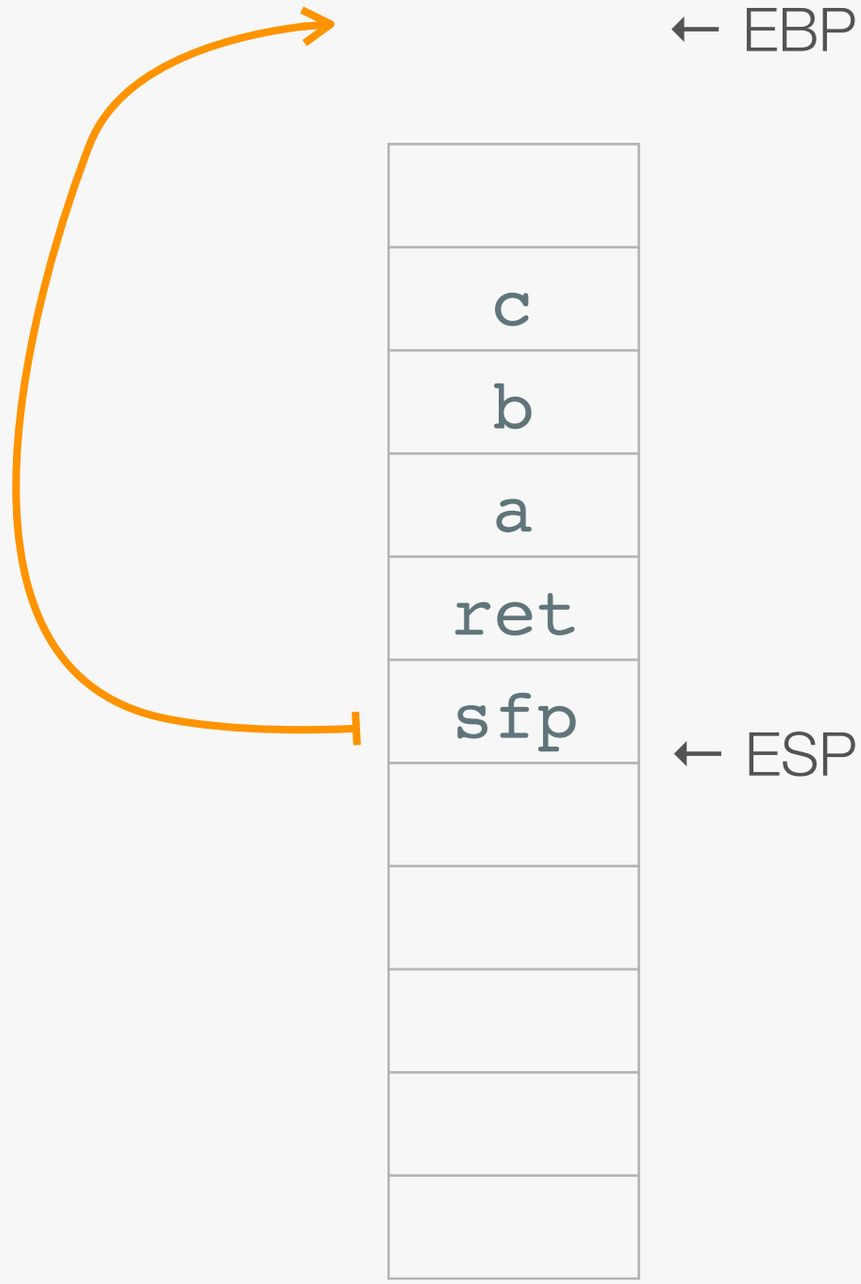

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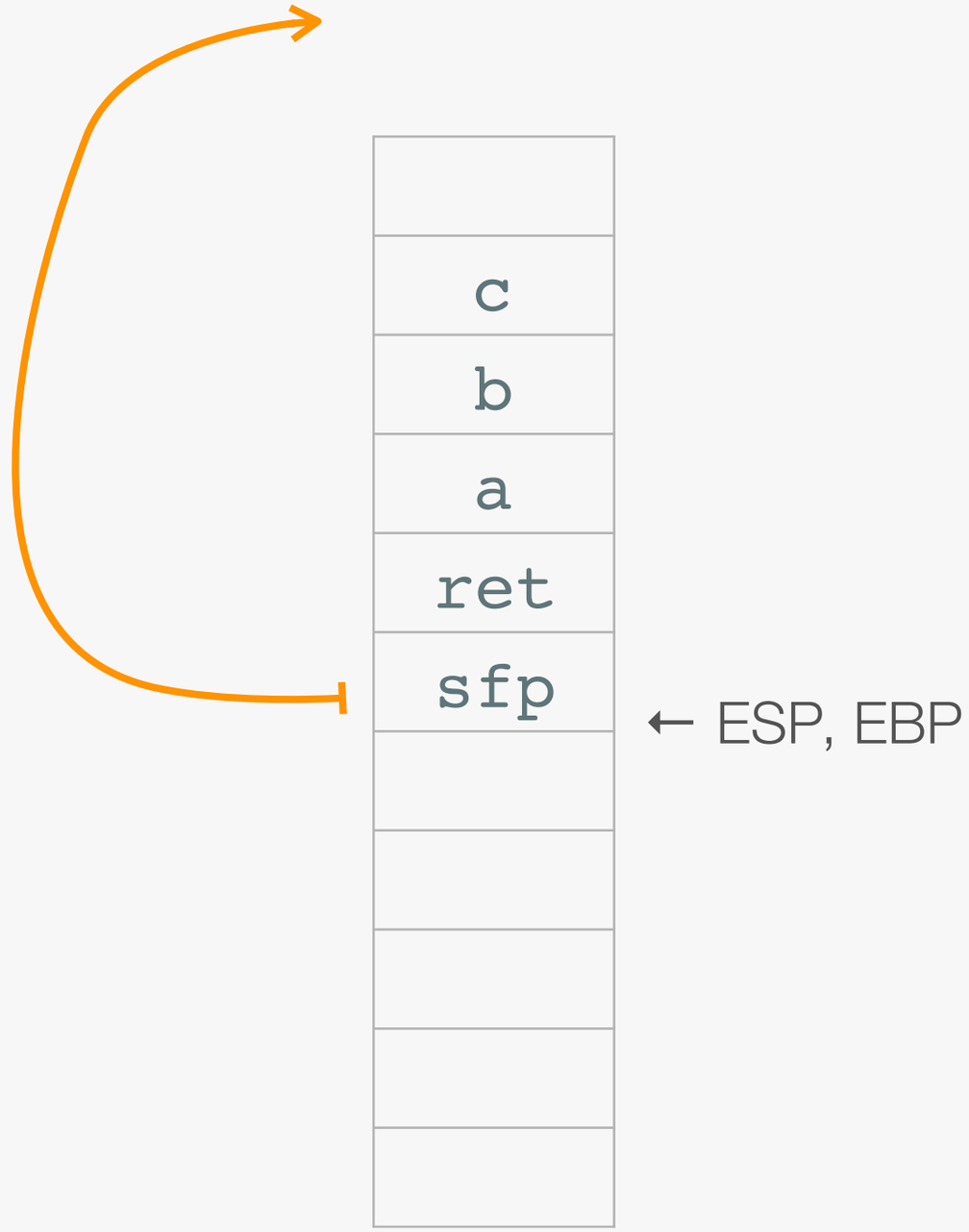

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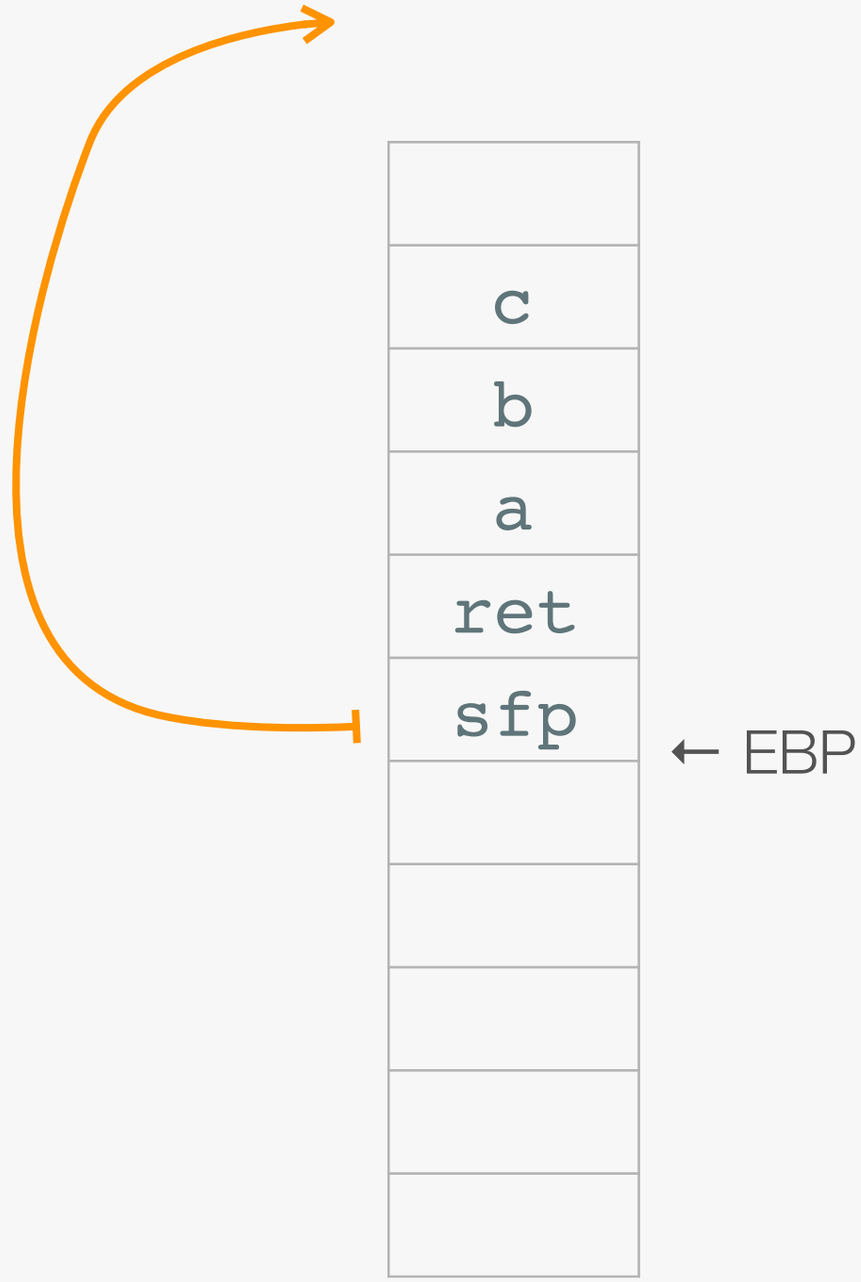

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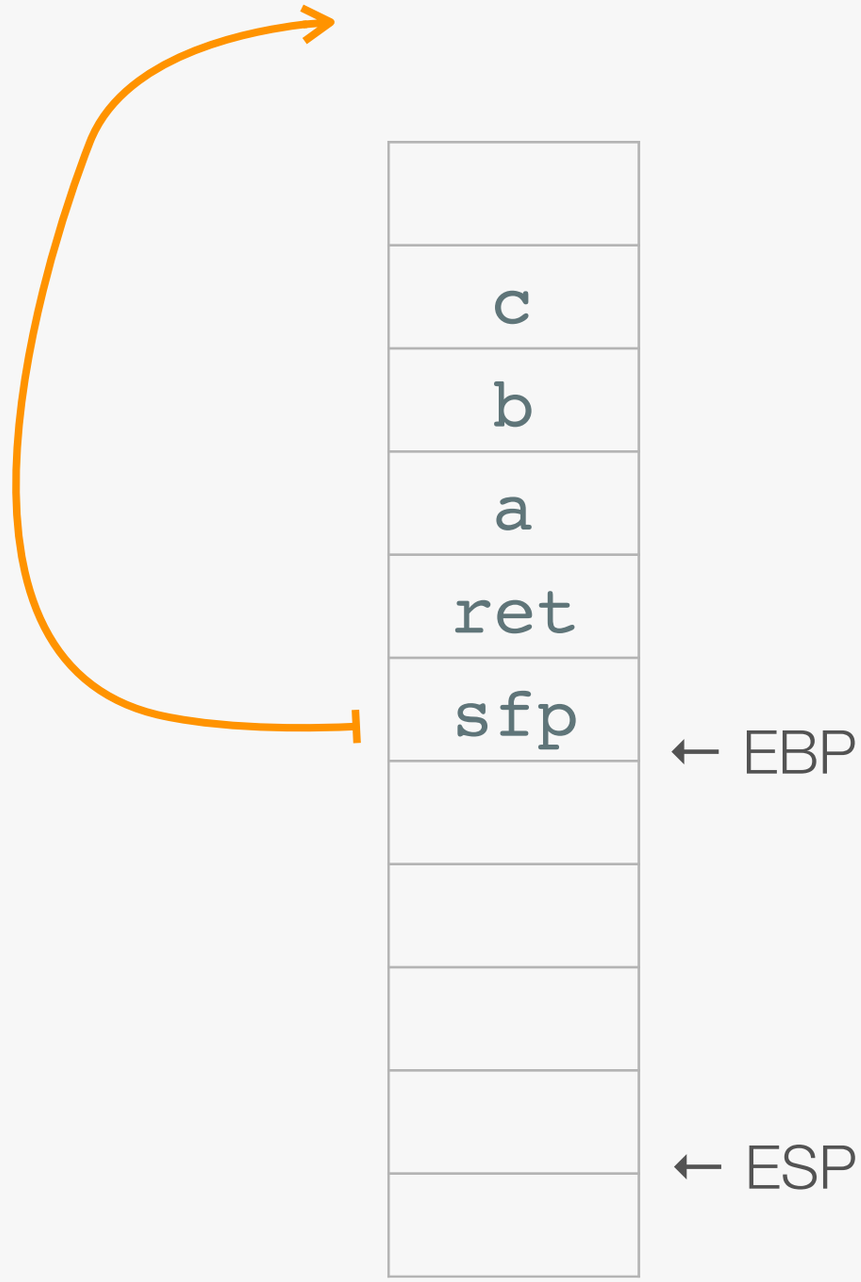

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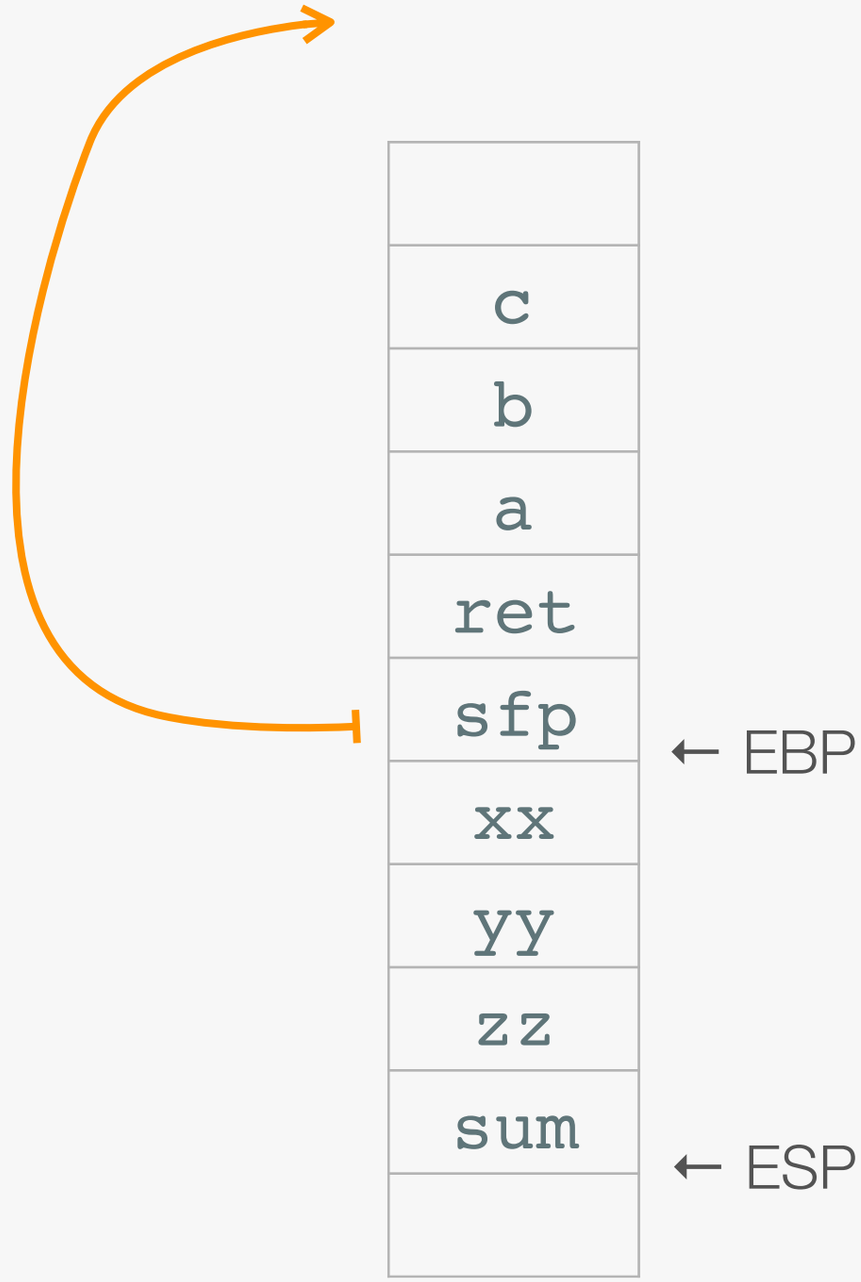

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;   mov esp, ebp
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; Which cleans the allocated locals and restores
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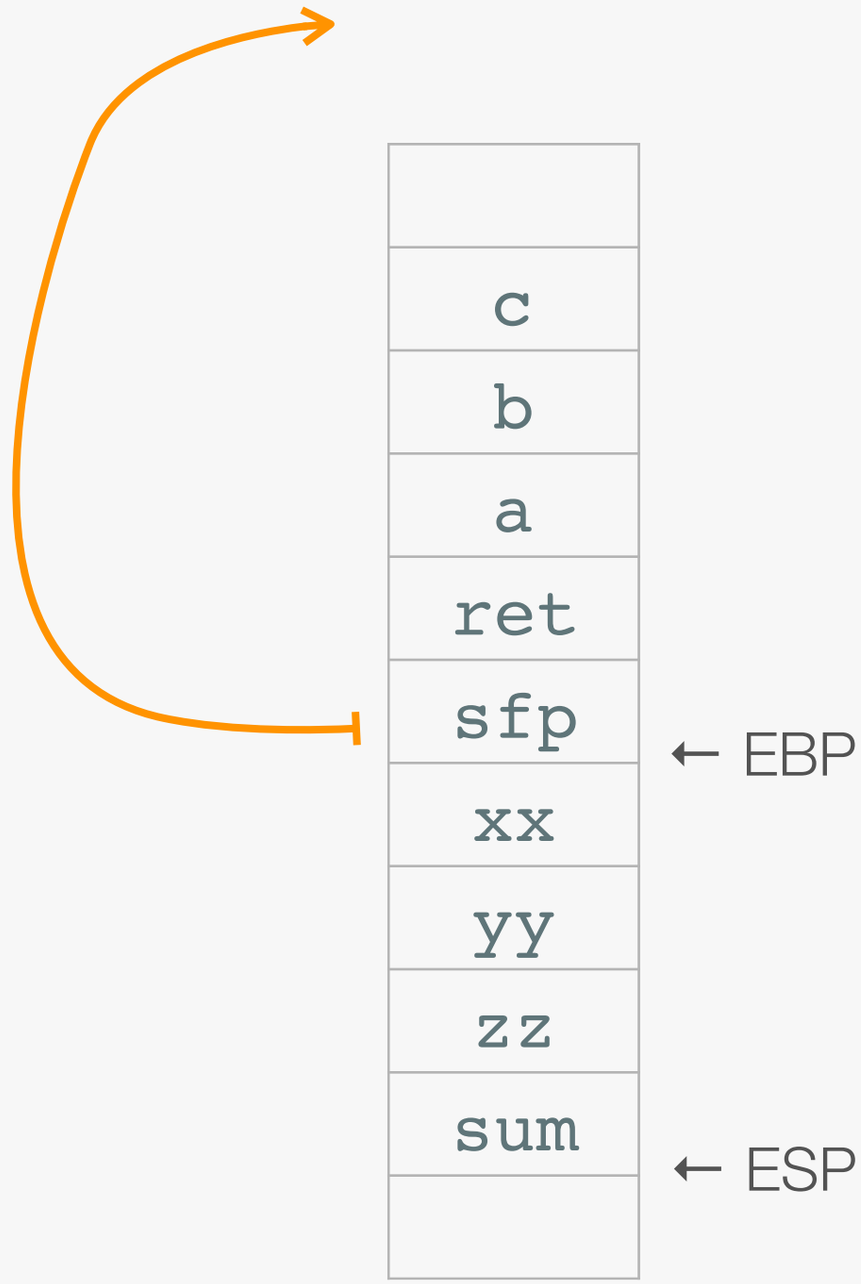

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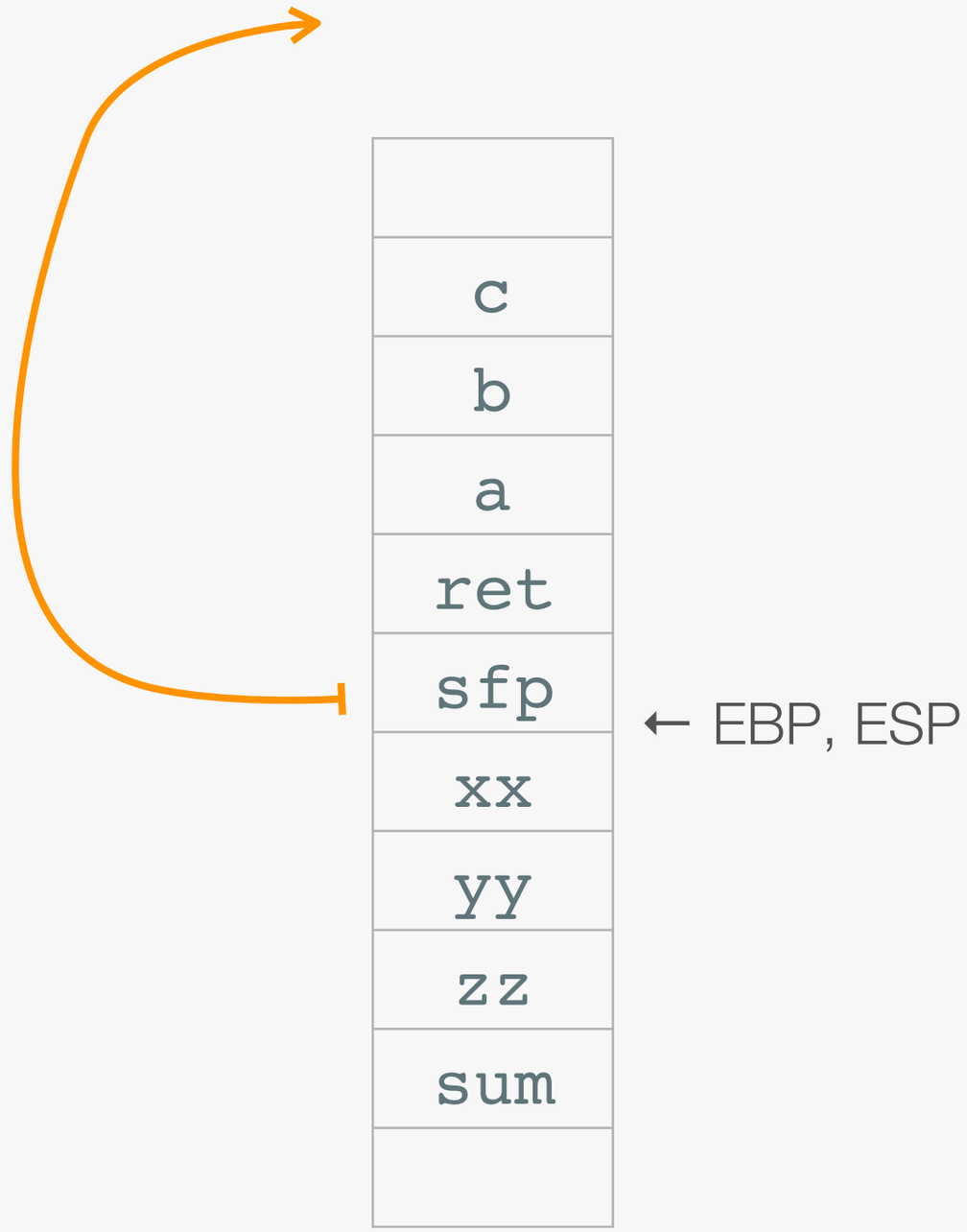

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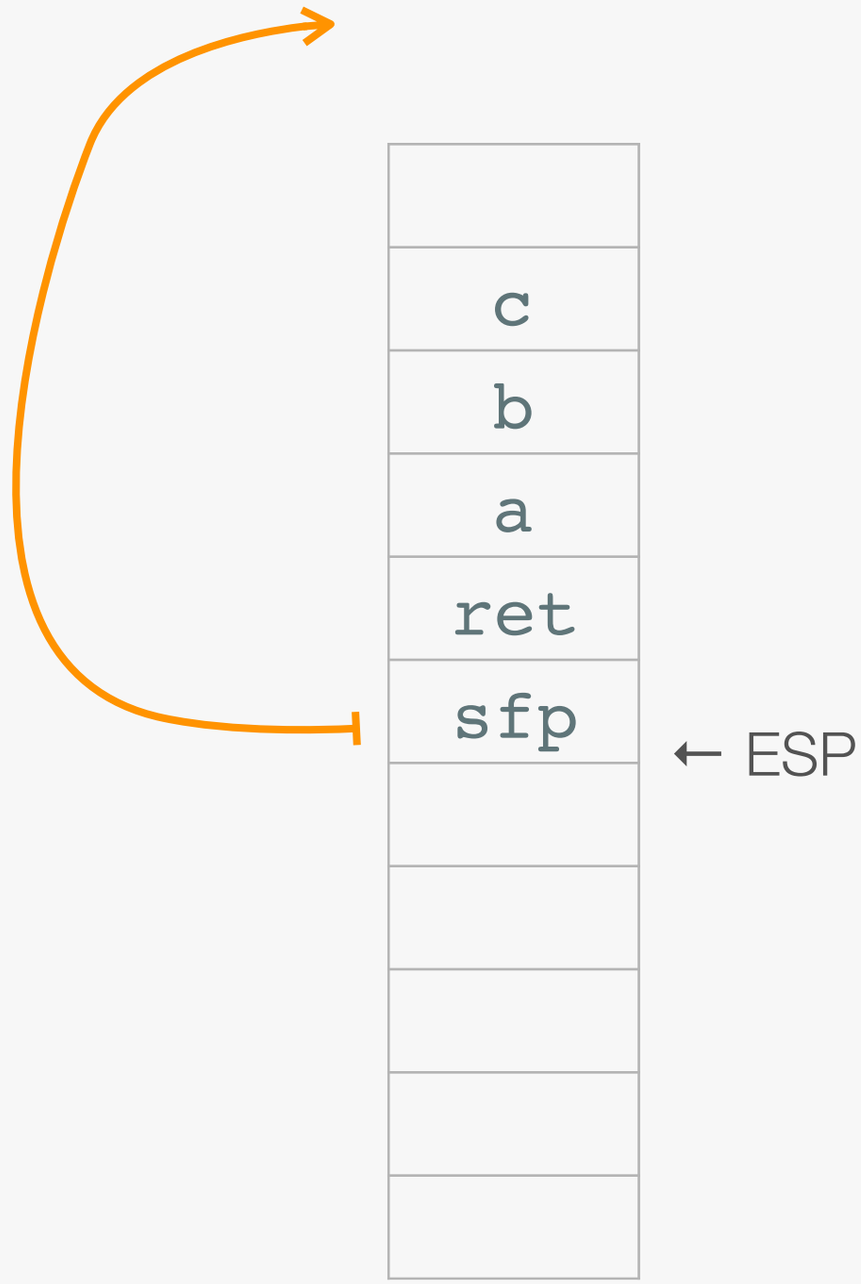

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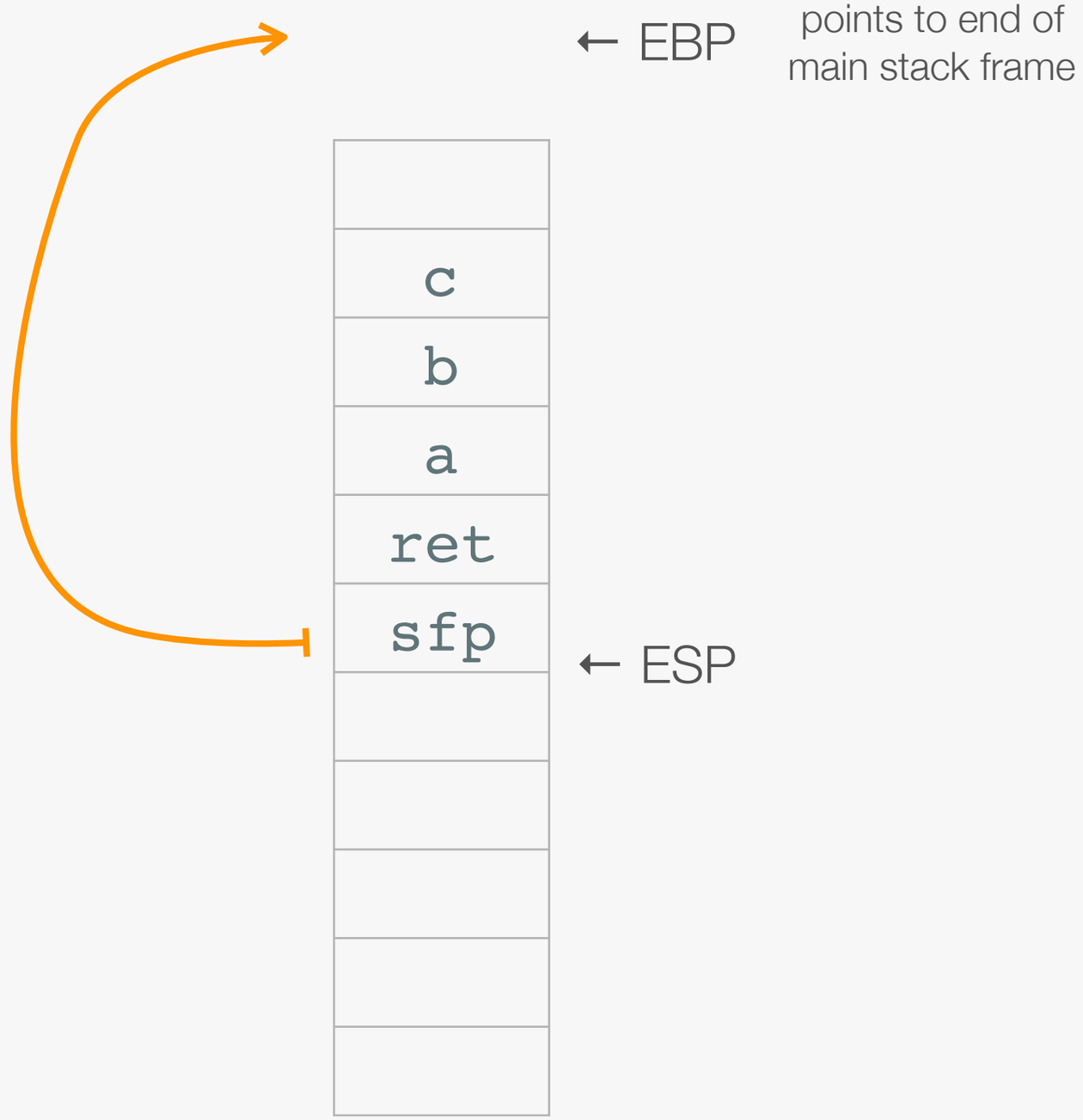

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With Buffers

```
example1.c:
---------------------------------------
void function(int a, int b, int c) {
   char buffer1[5];
   char buffer2[10];
}

void main() {
  function(1,2,3);
}
---------------------------------------
```

```
bottom of                                                          top of
memory                                                             memory
          buffer2       buffer1   sfp   ret   a     b     c
<------   [           ][        ][    ][    ][    ][    ][    ]

top of                                                          bottom of
stack                                                              stack
```

(source: AlephOne)

With Buffers

```
 buffer            sfp   ret   *str
[                ][    ][    ][    ]
```

- `strcpy` will copy memory from `str` to `buffer`
- So?
  - ➤

```
example2.c
----------------------------
void function(char *str) {
   char buffer[16];

   strcpy(buffer,str);
}

void main() {
  char large_string[256];
  int i;

  for( i = 0; i < 255; i++)
    large_string[i] = 'A';

  function(large_string);
}
----------------------------
```

(source: AlephOne)

With Buffers

```
 buffer            sfp   ret   *str
[                ][    ][    ][    ]
```

- `strcpy` will copy memory from `str` to `buffer` until '\0'
- So?
  - if length of string longer than buffer, `strcpy` will copy string over *`sfp`* and *`ret`*

```
example2.c
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void function(char *str) {
   char buffer[16];

   strcpy(buffer,str);
}

void main() {
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  for( i = 0; i < 255; i++)
    large_string[i] = 'A';

  function(large_string);
}
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(source: AlephOne)

Stack Buffer Overflow

- If source string of `strcpy` controlled by attacker (and destination is on the stack)
  - Attacker gets to control where the function returns by overwriting ***`ret`***
  - Attacker gets to transfer control to anywhere!
- Where do you jump?

Taking Control

- Let's jump to code that does what we want
- **Where?** We have control of string!
  - Put code in string
  - Jump to start of string

```
bottom of  DDDDDDDDEEEEEEEEEEEE  EEEE  FFFF  FFFF  FFFF  FFFF     top of
memory     89ABCDEF0123456789AB  CDEF  0123  4567  89AB  CDEF     memory
           buffer                sfp   ret   a     b     c

<------   [                    ][    ][    ][    ][    ]


top of                                                          bottom of
stack                                                               stack
```

Taking Control

- Let's jump to code that does what we want
- **Where?** We have control of string!
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           buffer                sfp   ret   a     b     c

<------   [SSSSSSSSSSSSSSSSSSS][SSSS][0xD8][0x01][0x02][0x03]


top of                                                            bottom of
stack                                                                stack
```

Shellcode

- **Shellcode:** small code fragment that receives initial control in an control flow hijack exploit
  - Control flow hijack: taking control of instruction ptr
- Earliest attacks used shellcode to exec a shell
  - Target a setuid root program, gives you root shell

Shellcode

```
void main() {
    char *name[2];
    name[0] = "/bin/sh";
    name[1] = NULL;
    execve(name[0], name, NULL);
}
```

Shellcode

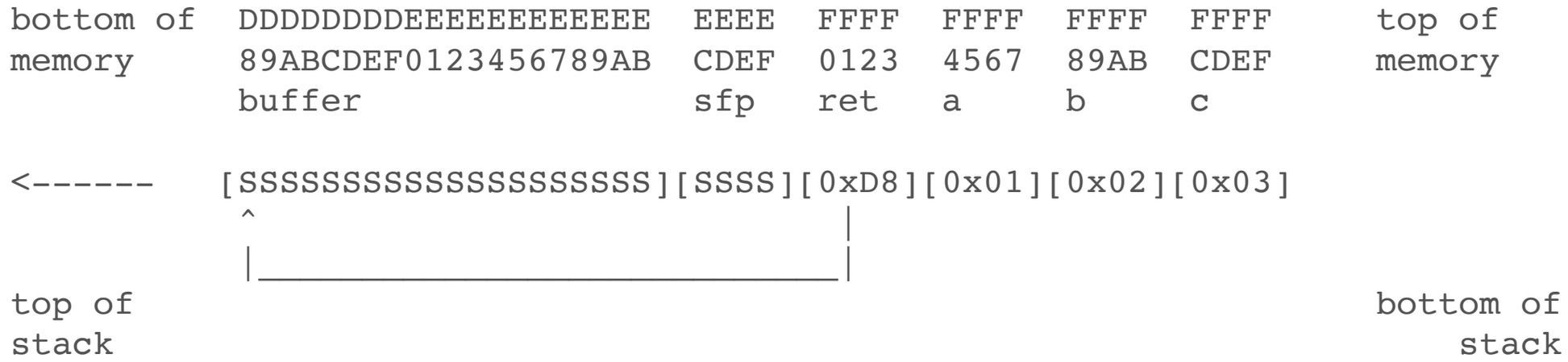
- Can we just take output from gcc/clang?
  - A: yes B: no

Shellcode

- There some restrictions
  - Shellcode cannot contain null characters ‘\0’
  - Why not?
  - Recipe:

```
a) Have the null terminated string "/bin/sh" somewhere in memory.
b) Have the address of the string "/bin/sh" somewhere in memory
   followed by a null long word.
c) Copy 0xb into the EAX register.
d) Copy the address of the address of the string "/bin/sh" into the
   EBX register.
e) Copy the address of the string "/bin/sh" into the ECX register.
f) Copy the address of the null long word into the EDX register.
g) Execute the int $0x80 instruction.
```

Why does this not really work?



How can we address this?

```
bottom of  DDDDDDDDEEEEEEEEEEEE  EEEE  FFFF  FFFF  FFFF  FFFF     top of
memory     89ABCDEF0123456789AB  CDEF  0123  4567  89AB  CDEF     memory
           buffer                sfp   ret   a     b     c

<------    [                   ][    ][    ][    ][    ][    ]


top of                                                    bottom of
stack                                                         stack
```

How can we address this?

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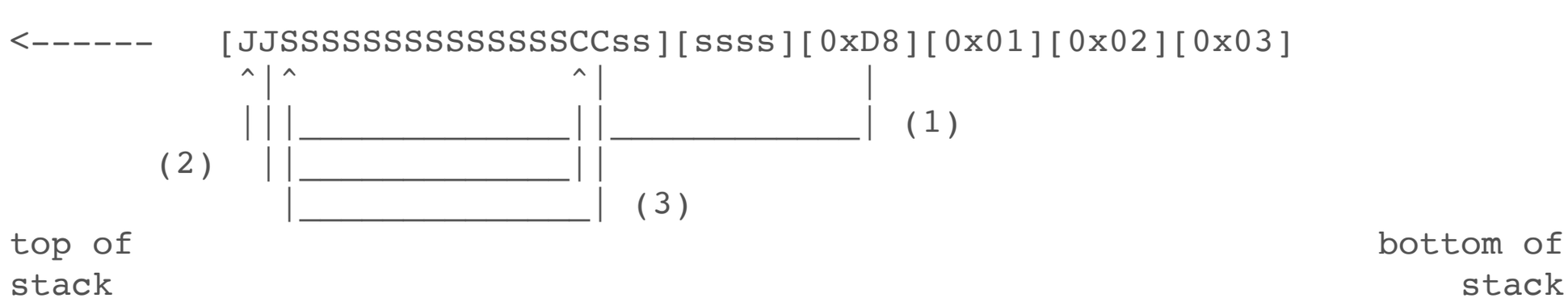

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memory     89ABCDEF0123456789AB  CDEF  0123  4567  89AB  CDEF     memory
           buffer                sfp   ret   a     b     c

<------    [NNNNNNNNNSSSSSSSSSS][SSSS][0xDE][0xDE][0xDE][0xDE]
                 ^                          |
                 |__________________________|
top of                                                   bottom of
stack                                                        stack
```

Metasploit to the rescue!

```
msf payload(shell_bind_tcp) > generate -h
Usage: generate [options]

Generates a payload.

OPTIONS:

    -E        Force encoding.
    -b   The list of characters to avoid: '\x00\xff'
    -e   The name of the encoder module to use.
    -f   The output file name (otherwise stdout)
    -h        Help banner.
    -i   the number of encoding iterations.
    -k        Keep the template executable functional
    -o   A comma separated list of options in VAR=VAL format.
    -p   The Platform for output.
    -s   NOP sled length.
    -t   The output format: raw,ruby,rb,perl,pl,c,js_be,js_le,java,dll,exe,exe-small,elf,macho,vba,v
    -x   The executable template to use
```

Buffer Overflow Defenses

- Avoid unsafe functions
- Stack canary
- Separate control stack
- Address Space Layout Randomization (ASLR)
- Memory writable or executable, not both (W^X)
- Control flow integrity (CFI)

Avoiding Unsafe Functions

- strcpy, strcat, gets, etc.
- **Plus:** Good idea in general
- **Minus:** Requires manual code rewrite
- **Minus:** Non-library functions may be vulnerable
  - E.g. user creates their own strcpy
- **Minus:** No guarantee you found everything
- **Minus:** alternatives are also error-prone

Even printf is tricky

If `buf` is under control of attacker is: `printf("%s\n", buf)` safe?

A: yes, B: no

Even printf is tricky

If `buf` is under control of attacker

is: `printf(buf)` safe?

A: yes, B: no

Even printf is tricky

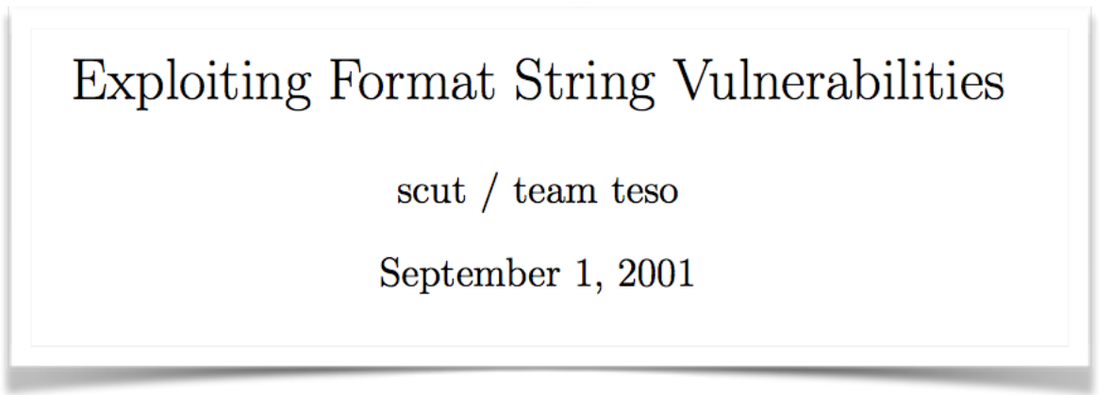
Is `printf("%s\n)` safe?

A: yes, B: no

Even printf is tricky

printf can be used to read and write memory

- ➠ control flow hijacking!



Exploiting Format String Vulnerabilities

scut / team teso

September 1, 2001

https://crypto.stanford.edu/cs155/papers/formatstring-1.2.pdf

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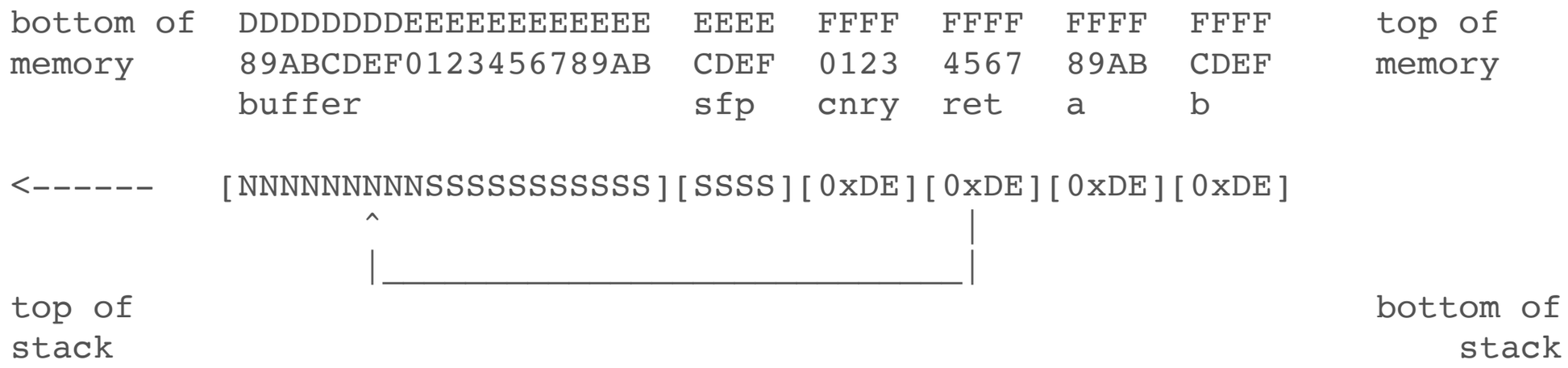
Stack Canary

- Special value placed before return address
  - Secret random value chosen at program start
  - String terminator ‘\0’
- Gets overwritten during buffer overflow
- Check canary before jumping to return address
- Automatically inserted by compiler
  - GCC: -fstack-protector or -fstack-protector-strong

```
bottom of  DDDDDDDDEEEEEEEEEEEE  EEEE  FFFF  FFFF  FFFF  FFFF     top of
memory     89ABCDEF0123456789AB  CDEF  0123  4567  89AB  CDEF     memory
           buffer                sfp   cnry  ret   a     b

<------    [                     ][    ][    ][    ][    ][    ]


top of                                                        bottom of
stack                                                             stack
```


bottom of memory
DDDDDDDDEEEEEEEEEEEE
89ABCDEF0123456789AB
buffer
EEEE
CDEF
sfp
FFFF
0123
cnry
FFFF
4567
ret
FFFF
89AB
a
FFFF
CDEF
b
top of memory
<------
[NNNNNNNNNSSSSSSSSSS][SSSS][0xDE][0xDE][0xDE][0xDE]
top of stack
bottom of stack

Stack Canary

- **Plus:** No code changes required, only recompile
- **Minus:**
- **Minus:**
- **Minus:**

Stack Canary

- **Plus:** No code changes required, only recompile
- **Minus:** Performance penalty per return
- **Minus:** Only protects against stack smashing
- **Minus:** Fails if attacker can read memory

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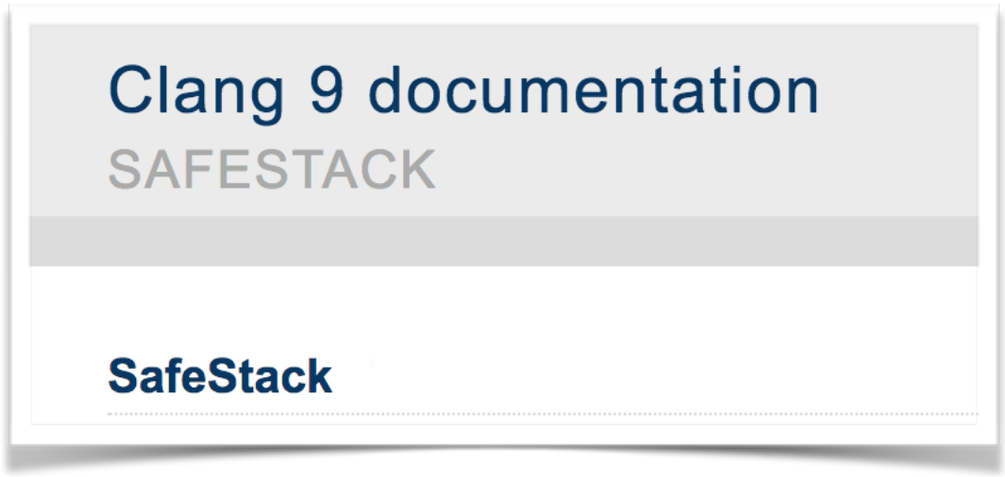
Separate Stack



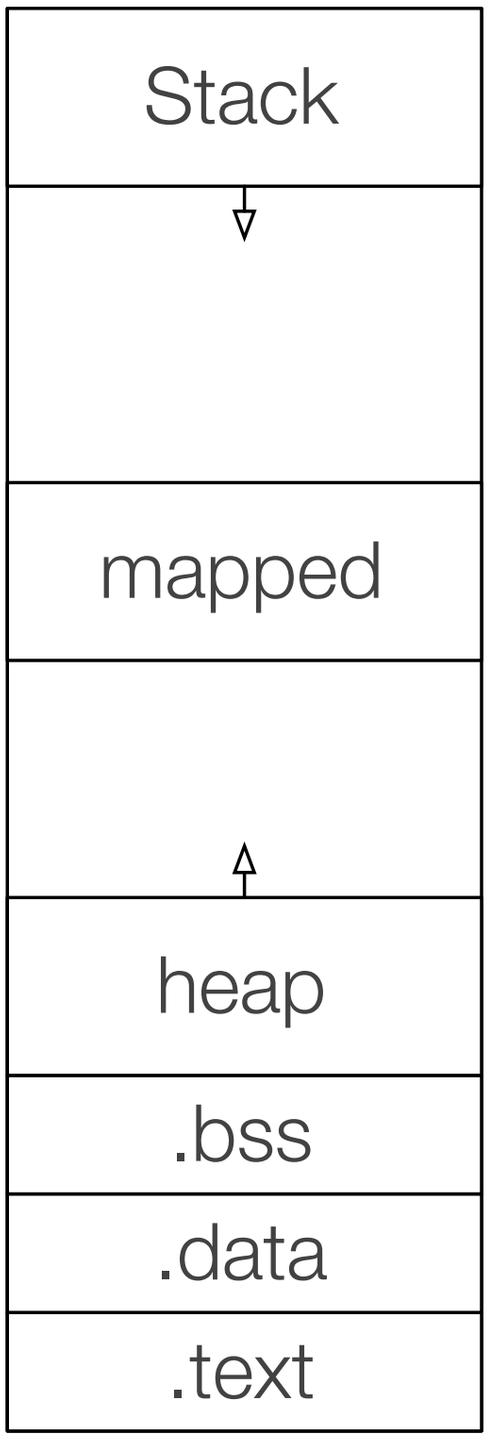
“SafeStack is an instrumentation pass that protects programs against attacks based on stack buffer overflows, without introducing any measurable performance overhead. It works by separating the program stack into two distinct regions: the safe stack and the unsafe stack. The safe stack stores **return addresses**, **register spills**, and **local variables that are always accessed in a safe way**, while the unsafe stack stores everything else. This separation ensures that buffer overflows on the unsafe stack cannot be used to overwrite anything on the safe stack.”

WebAssembly has separate stack (kind of)!

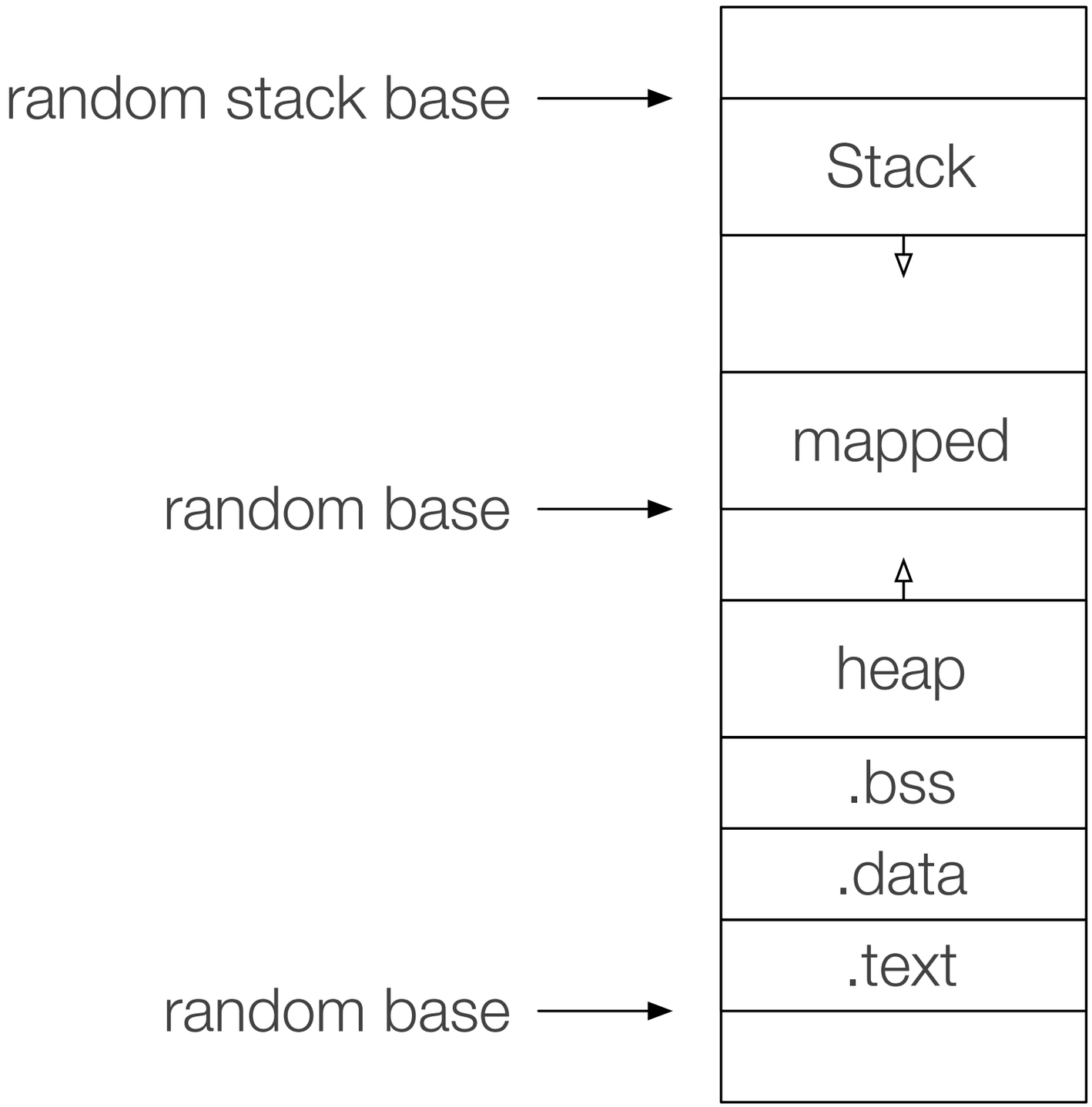
Address Space Layout Randomization

- Change location of stack, heap, code, static vars
- Works because attacker needs address of shellcode
- Layout must be unknown to attacker
  - Randomize on every launch (best)
  - Randomize at compile time
- Implemented on most modern OSes in some form

Traditional Memory Layout



PaX Memory Layout



Address Space Layout Randomization

- **Plus:** No code changes or recompile required
- **Minus:** 32-bit arch get limited protection
- **Minus:**
- **Minus:**
- **Minus:**

Address Space Layout Randomization

- **Plus:** No code changes or recompile required
- **Minus:** 32-bit arch get limited protection
- **Minus:** Fails if attacker can read memory
- **Minus:** Load-time overhead
- **Minus:** No exec img sharing between processes

W^X: write XOR execute

- Use MMU to ensure memory cannot be both writeable and executable at same time
- Code segment: executable, not writeable
- Stack, heap, static vars: writeable, not executable
- Supported by most modern processors
- Implemented by modern operating systems

W^X: write XOR execute

- **Plus:** No code changes or recompile required
- **Minus:** Requires hardware support
- **Minus:**
- **Minus:**

W^X: write XOR execute

- **Plus:** No code changes or recompile required
- **Minus:** Requires hardware support
- **Minus:** Defeated by return-oriented programming
- **Minus:** Does not protect JITed code

Buffer Overflow Defenses

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Control Flow Integrity

- Check destination of every indirect jump
  - Function returns
  - Function pointers
  - Virtual methods
- What are the valid destinations?
  -
  -

Control Flow Integrity

- Check destination of every indirect jump
  - Function returns
  - Function pointers
  - Virtual methods
- What are the valid destinations?
  - Caller of every function known at compile time
  - Class hierarchy limits possible virtual function instances

CFI

- **Plus:** No code changes or hardware support
- **Plus:** Protects against many vulnerabilities
- **Minus:**
- **Minus:**
- **Minus:**

CFI

- **Plus:** No code changes or hardware support
- **Plus:** Protects against many vulnerabilities
- **Minus:** Performance overhead
- **Minus:** Requires smarter compiler
- **Minus:** Requires having all code available