Memory management vulnerabilities

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The concrete attack examples in these slides are based on the paper:
"Low-level Software Security by Example" by Erlingsson, Younan and Piessens

Introduction: the setting of this lecture

- System model:
    - Software in a C-like language compiled to a typical modern processor
- Attack model:
    - Attacker can interact with the software by providing input and reading output
    - Attacker knows the source code, and knows how code is compiled and executed
- Objectives of the lecture are to understand:
    - How software could be attacked in this setting
    - What the vulnerabilities are that enable these attacks
    - What defenses can help remove these vulnerabilities or mitigate these attacks

Example vulnerable C program

```c
#include <stdio.h>
int main() {
	int cookie = 0;
	char buf[80];
	printf("buf: %08x cookie: %08x\n", &buf, &cookie);
	gets(buf);
	if (cookie == 0x41424344)
		printf("you win!\n");
}
```

Source: https://github.com/gerasdf/InsecureProgramming

Example vulnerable C program

```c
#include <stdio.h>
int main() {
	int cookie = 0;
	char buf[80];
	printf("buf: %08x cookie: %08x\n", &buf, &cookie);
	gets(buf);
}
```

Overview

- System model
- Attack scenarios
- Mitigating attacks
- Avoiding vulnerabilities
- Conclusions

System model

- The system under attack is a C program that has been compiled to run on a modern processor
- Hence, the details of the system under attack vary with
  - The underlying platform (processor, operating system, …)
  - The compiler used
- But fortunately, the general structure of processors, operating systems and compilers is sufficiently similar
- We will describe the system model abstractly, but for examples we will pick a specific system (e.g. gcc on Linux on x86)

Abstract model of the target platform

- Target platform consists of:
  - A byte-addressable memory (addresses MIN … MAX)
    - Could be either virtual memory (e.g., user-mode process) or physical memory (e.g., embedded code on a micro-processor)
  - A CPU with
    - Registers of word size (word = typically 4 or 8 bytes), including both general-purpose registers, as well as a program counter (PC), stack pointer (SP) and so forth
    - An instruction set with typical machine code instructions like
      - Arithmetic instructions
      - Memory access instructions
      - Branch and Call/return instructions
    - Instructions are stored in memory as sequence of bytes
      - Some processors have fixed instruction size, for others the size is variable

Mapping words in registers to memory

- We assume the processor is *little-endian*

0x107	0x07
0x106	0x06
0x105	0x05
0x104	0x04
0x103	0x03
0x102	0x02
0x101	0x01
0x100	0x00

Little-endian

0x104	0x07060504
0x100	0x03020100

Big-endian

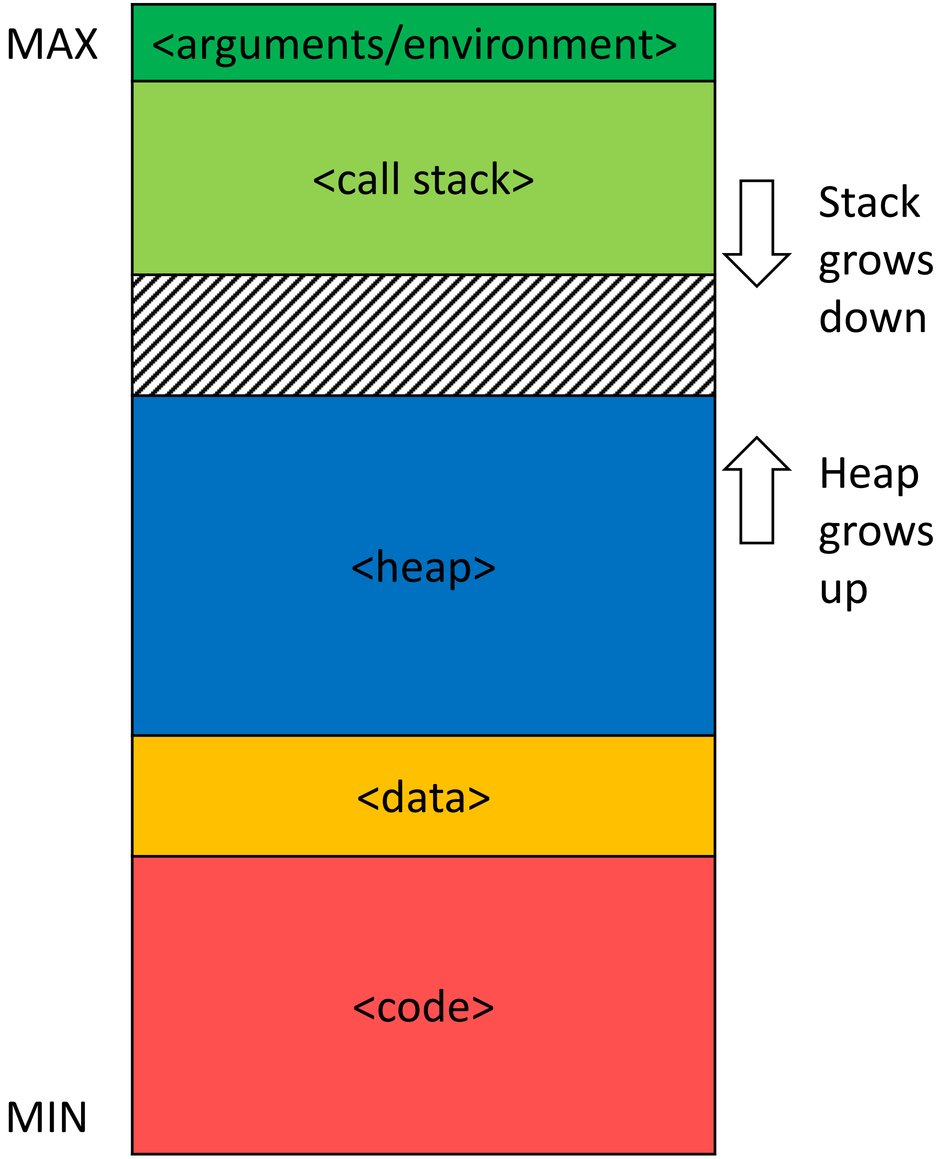
0x104	0x04050607
0x100	0x00010203

Source code model

- Simple C-like language
  - Types: char, int, void, pointers (e.g. char*, int**, …), arrays (e.g. char[10])
  - Local and global variables
    - Array variable is a pointer to the first element of the array
  - Statements and expressions:
    - Constants, variables, logical and arithmetic expressions, array indexing
    - If / while / sequencing / blocks / assignment / function calls
    - Library functions for I/O and memory management:
    - getchar(), putchar(),gets(), printf() + other typical C functions for I/O
    - malloc() and free()

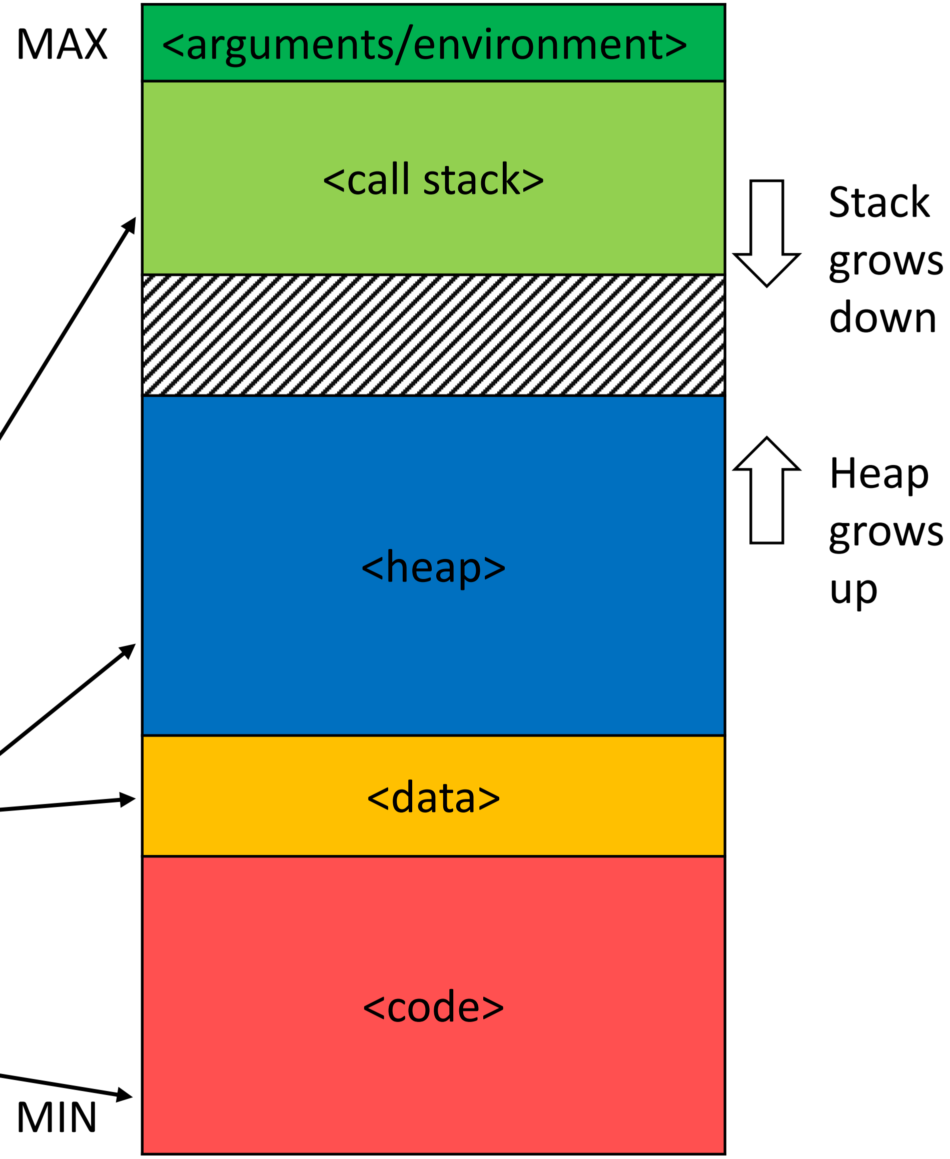
Compilation: overview

- Each function is compiled separately, and the resulting machine code is stored in a **code** section in memory
- Control-flow through the program is tracked by means of a **call stack**
- Variables used in the program are allocated in a number of ways:
  - Local variables are allocated on the call stack
  - Global variables are allocated in a dedicated **data** section in memory
  - Dynamic allocation is handled by a memory management library that manages a **heap**
    - malloc(), free(), …
- Pointers are represented as integer addresses, supporting pointer arithmetic
- Arrays are represented as pointers, indexing is similar to pointer arithmetic



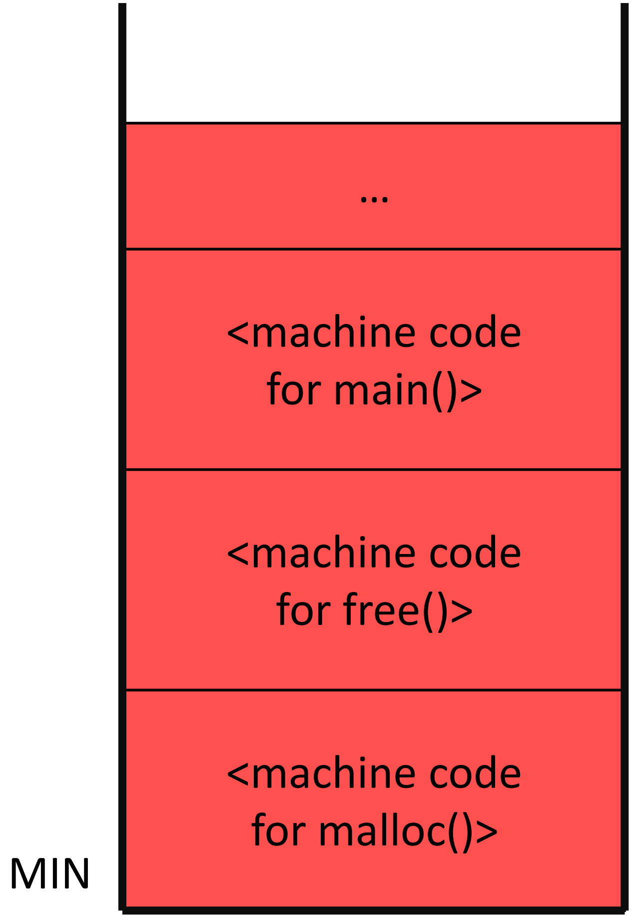
Example

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

int g = 12;

int main() {
        int l = 13;
        int *d = malloc(100);
        printf("Address of g    : %8lx\n", (size_t)&g);
        printf("Address of l    : %8lx\n", (size_t)&l);
        printf("Address of *d   : %8lx\n", (size_t) d);
        printf("Address of main: %8lx\n", (size_t)&main);
}
```



Compilation: the code section

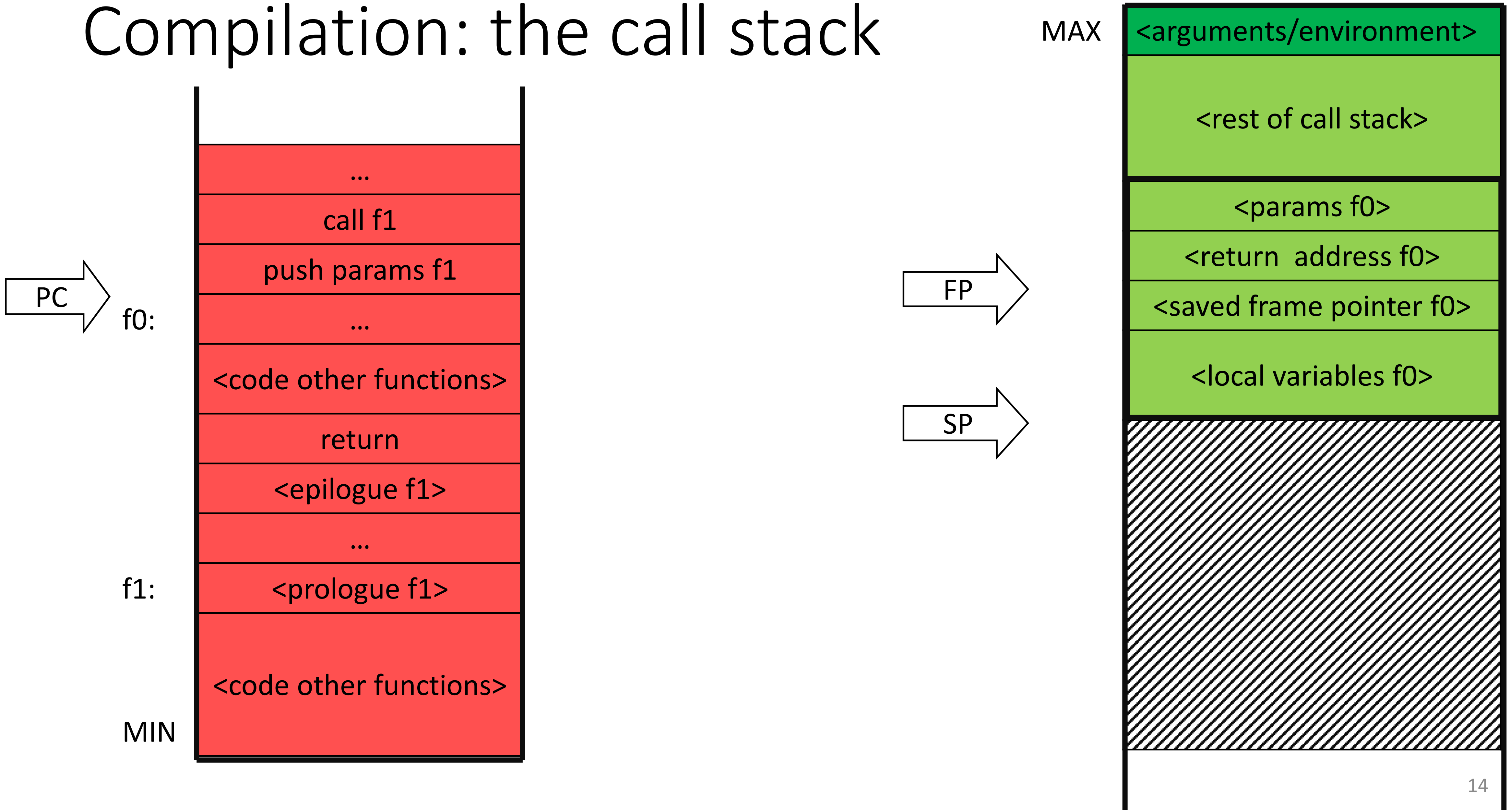
- Code for every function is compiled separately
  - Prologue: allocates space for activation record
  - Code for the body
  - Epilogue: put result in designated register, clear space for activation record
- We make abstraction of shared dynamically loaded libraries



Compilation: the call stack

- The stack used at run time to track function calls and returns
  - Per call, *an activation record* or *stack frame* is pushed on the stack, containing:
    - Actual parameters, return address, automatically allocated local variables, …
  - On return of a call, the corresponding stack frame is popped from the stack

Compilation: the call stack



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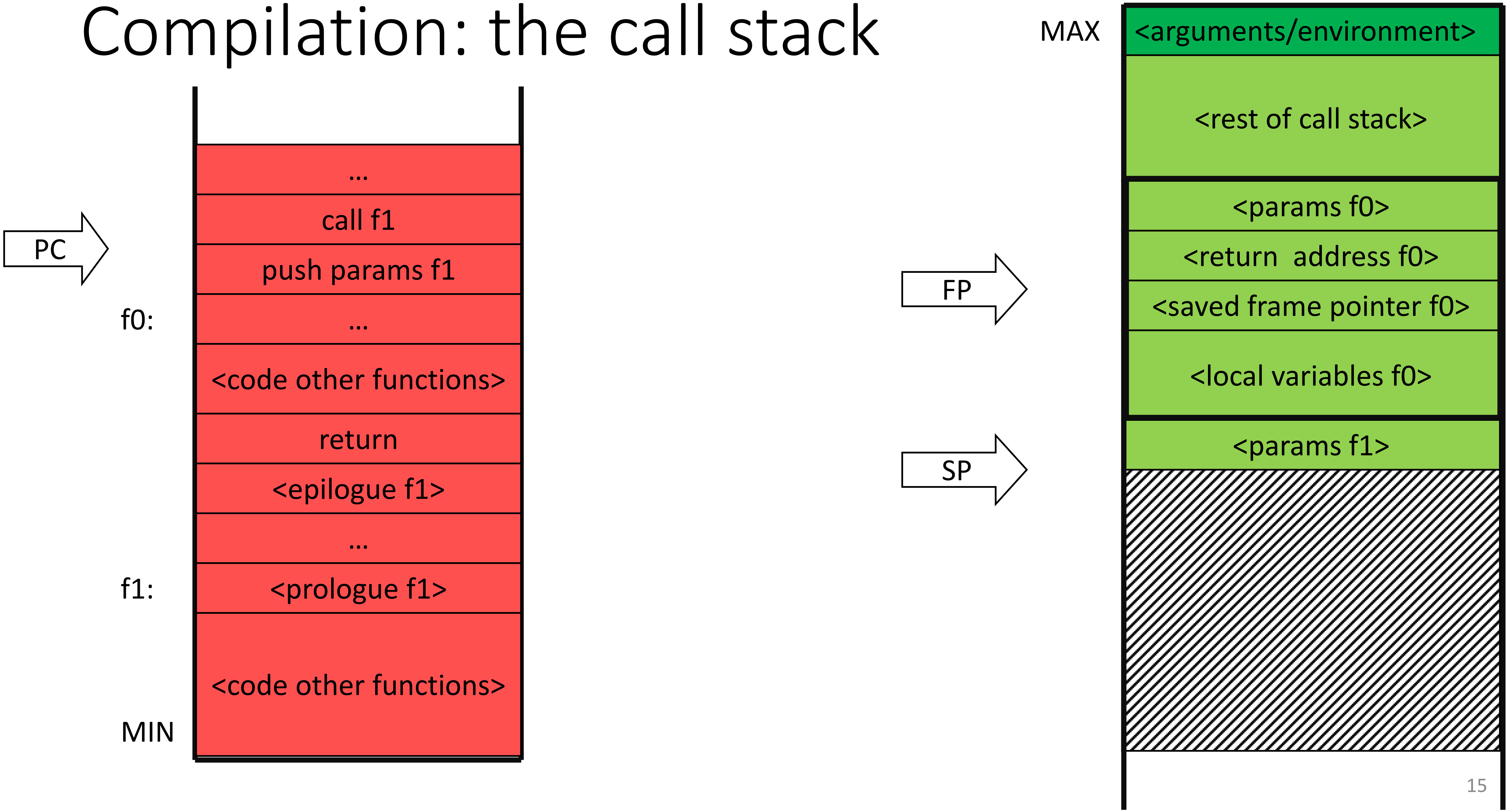

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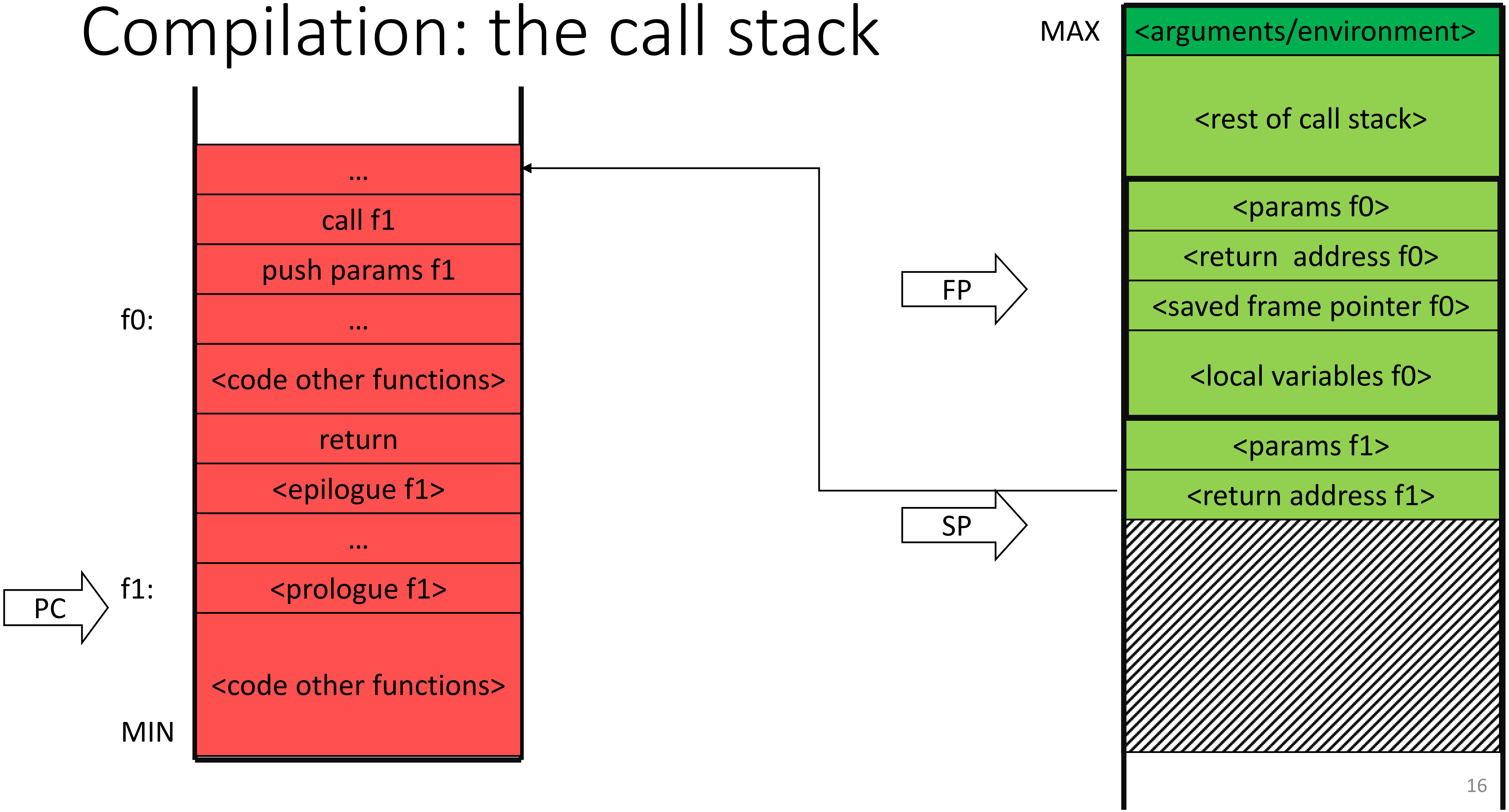

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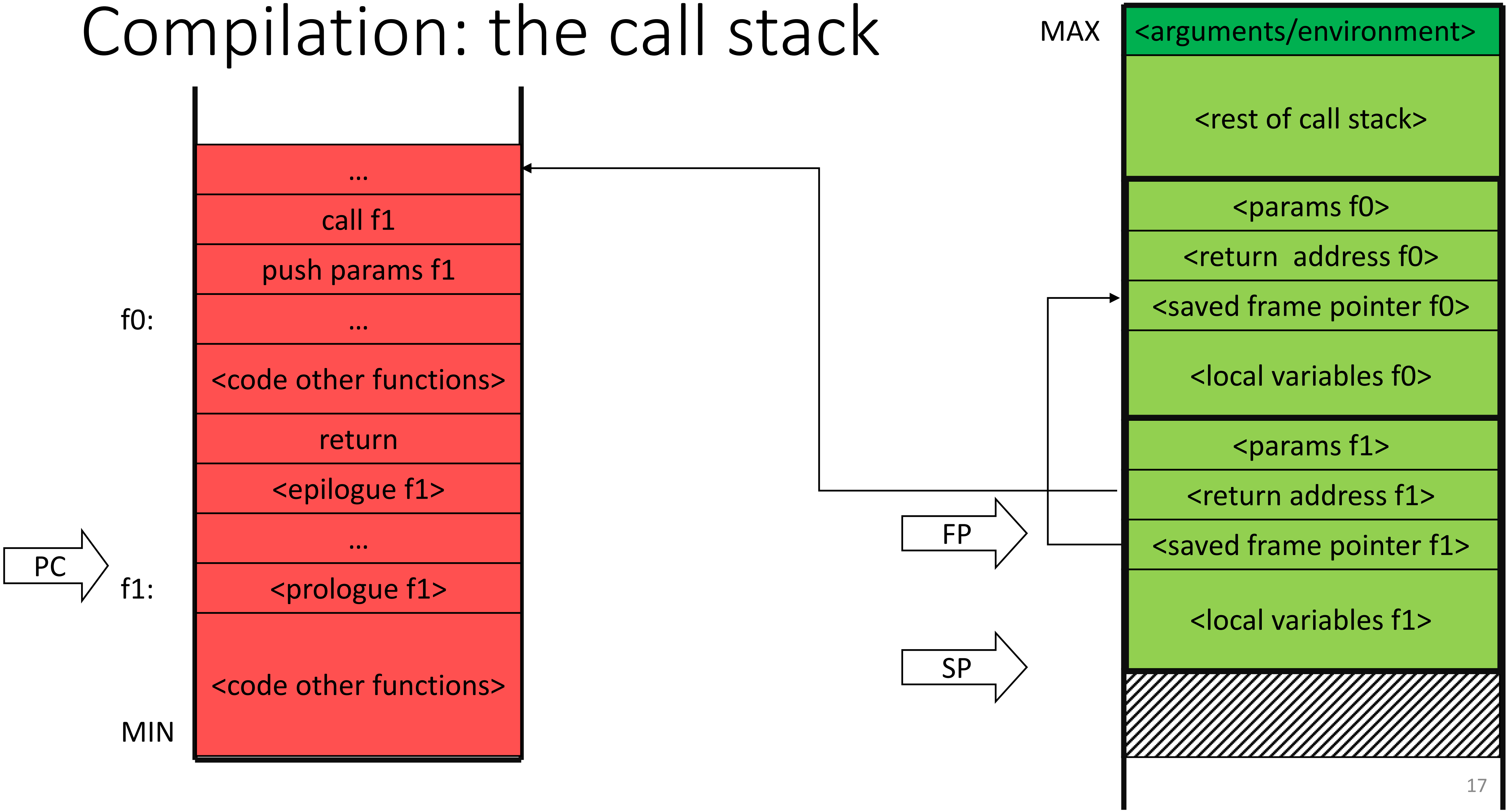

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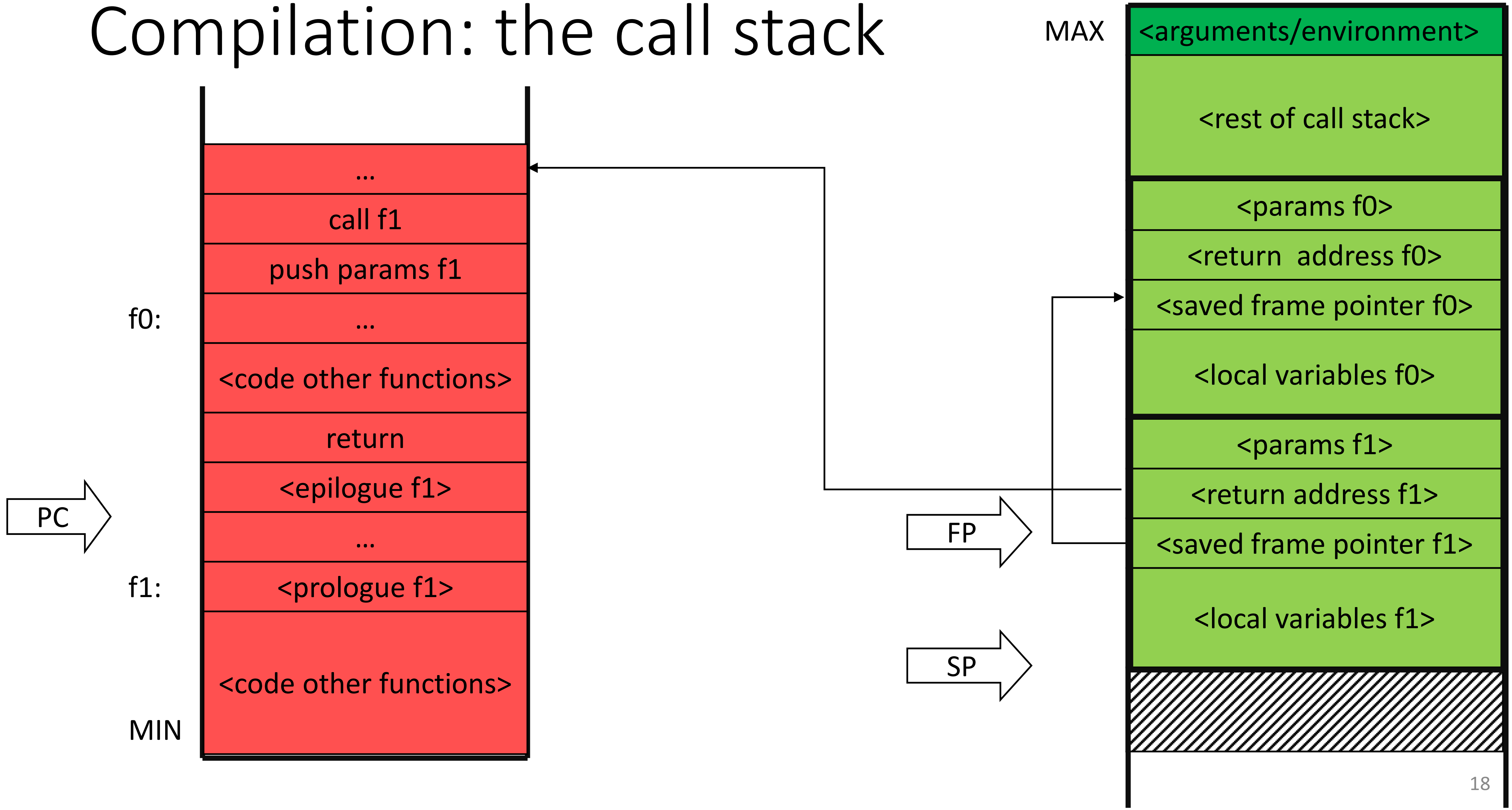
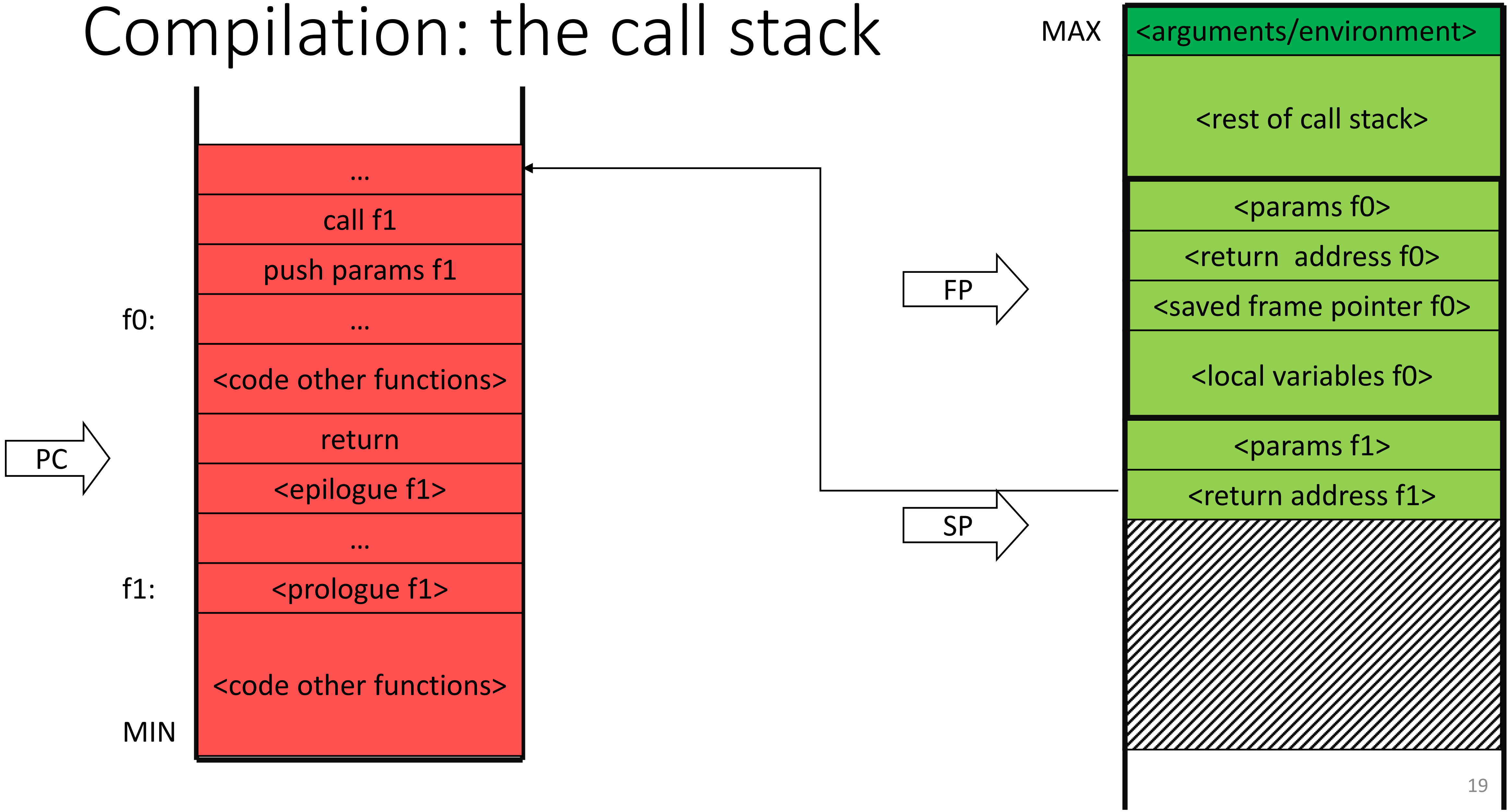
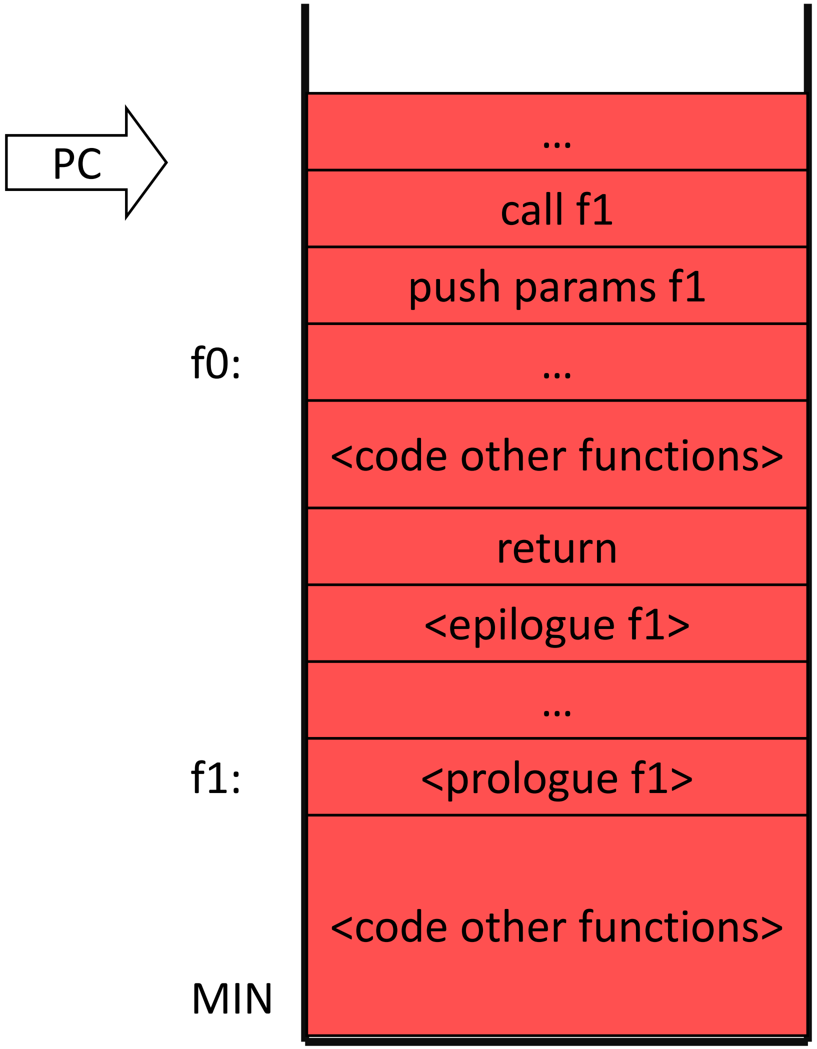
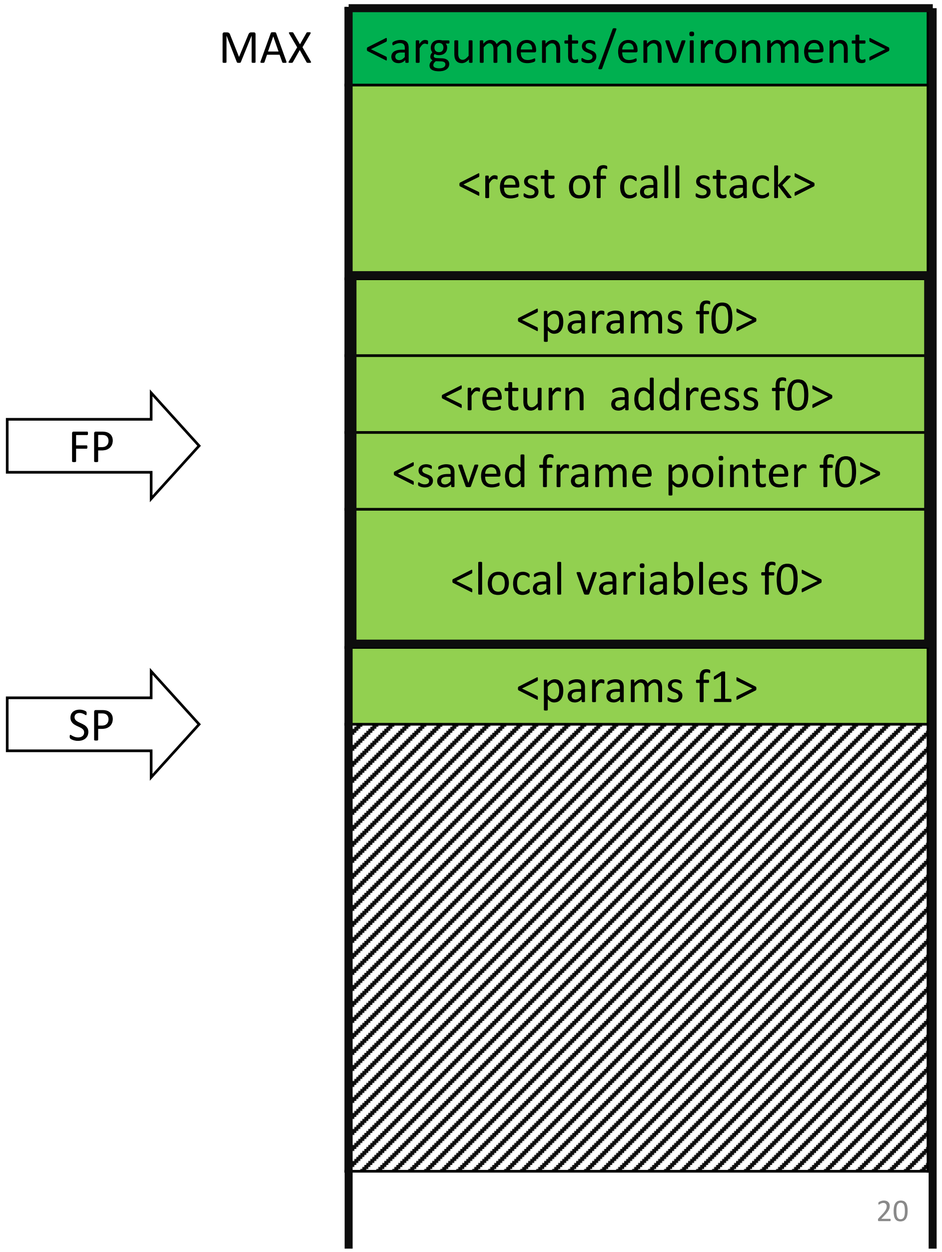


Compilation: the call stack



Compilation: the call stack





Putting it all together for gcc on 32-bit x86 linux …

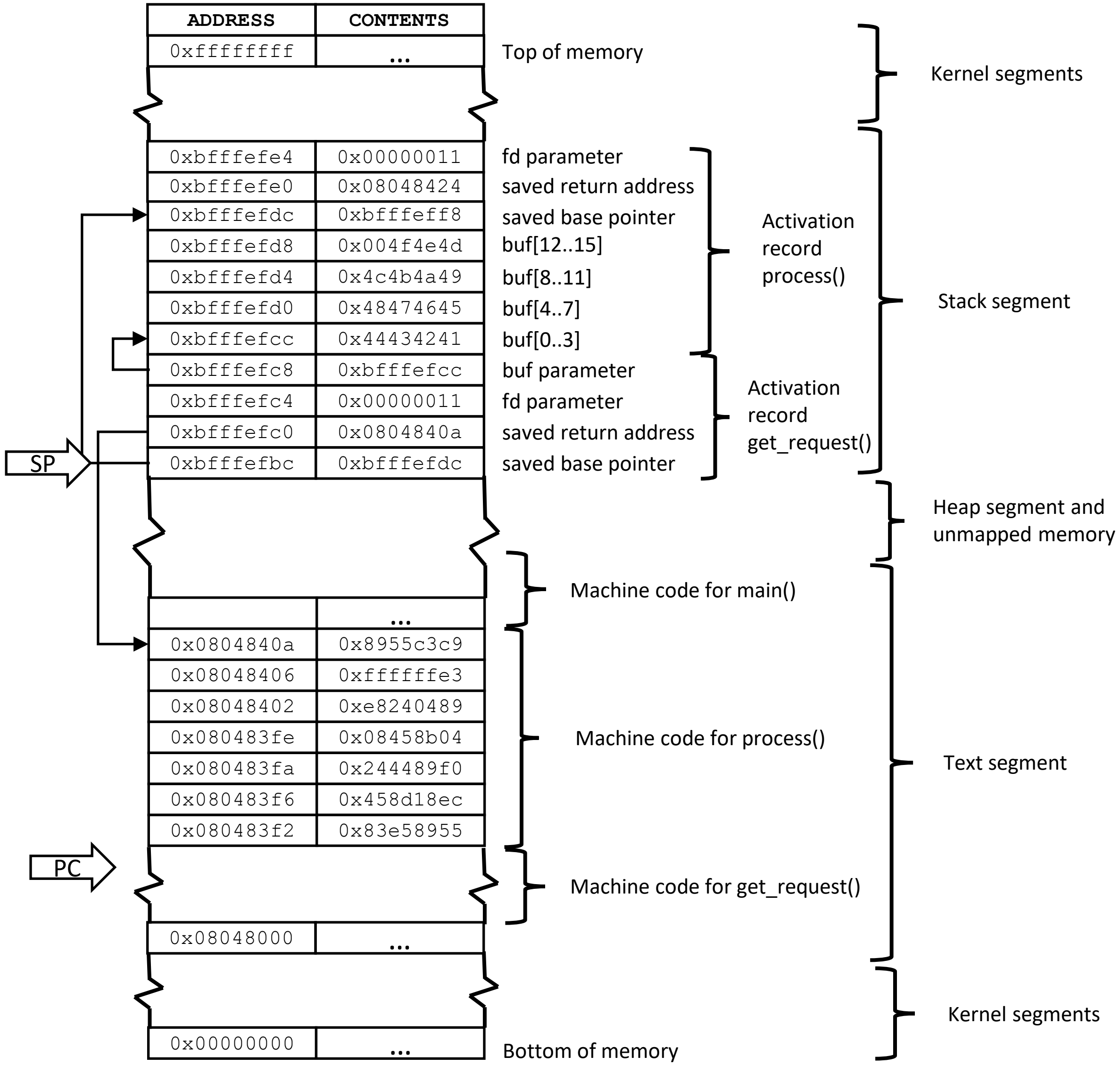
```c
void get_request(int fd, char buf[]) {
  read(fd,buf,16);
}

void process(int fd) {
  char buf[16];
  get_request(fd,buf);
  // Process the request (code not shown)
}
void main() {
  int fd;
  // Initialize server, wait for a connection
  // Accept connection, with file descriptor fd
  // Finally, process the request:
  process(fd);
}
```

(a) Program source code

```
55              push  %ebp               ; save base pointer
89 e5           mov   %esp,%ebp          ; set new base pointer
83 ec 18        sub   $0x18,%esp         ; allocate stack record
8d 45 f0        lea   -0x10(%ebp),%eax   ; put buf in %eax
89 44 24 04     mov   %eax,0x4(%esp)     ; and push on the stack
8b 45 08        mov   0x8(%ebp),%eax     ; put fd parameter in %eax
89 04 24        mov   %eax,(%esp)        ; and push on the stack
e8 e3 ff ff ff  call  0x80483ed          ; call get_request
c9              leave                    ; deallocate stack frame
c3              ret                      ; return
```

(b) Machine code for process() function



(c) Run-time machine state on entering get_request()

Memory management vulnerabilities

- C-like languages offer mutable variables that can be allocated, deallocated and accessed in a number of ways:
  - Automatic, static or dynamic allocation and deallocation
  - Access through pointers and array indexing
- These memory management and access operations should be used correctly, e.g.:
  - Access arrays within bounds
  - Do not access memory after it has been deallocated
- For performance, compilers do not detect invalid memory accesses
  - Instead, behavior of the program becomes **undefined**
  - A program that can perform such an invalid access has a **memory management vulnerability**

Overview

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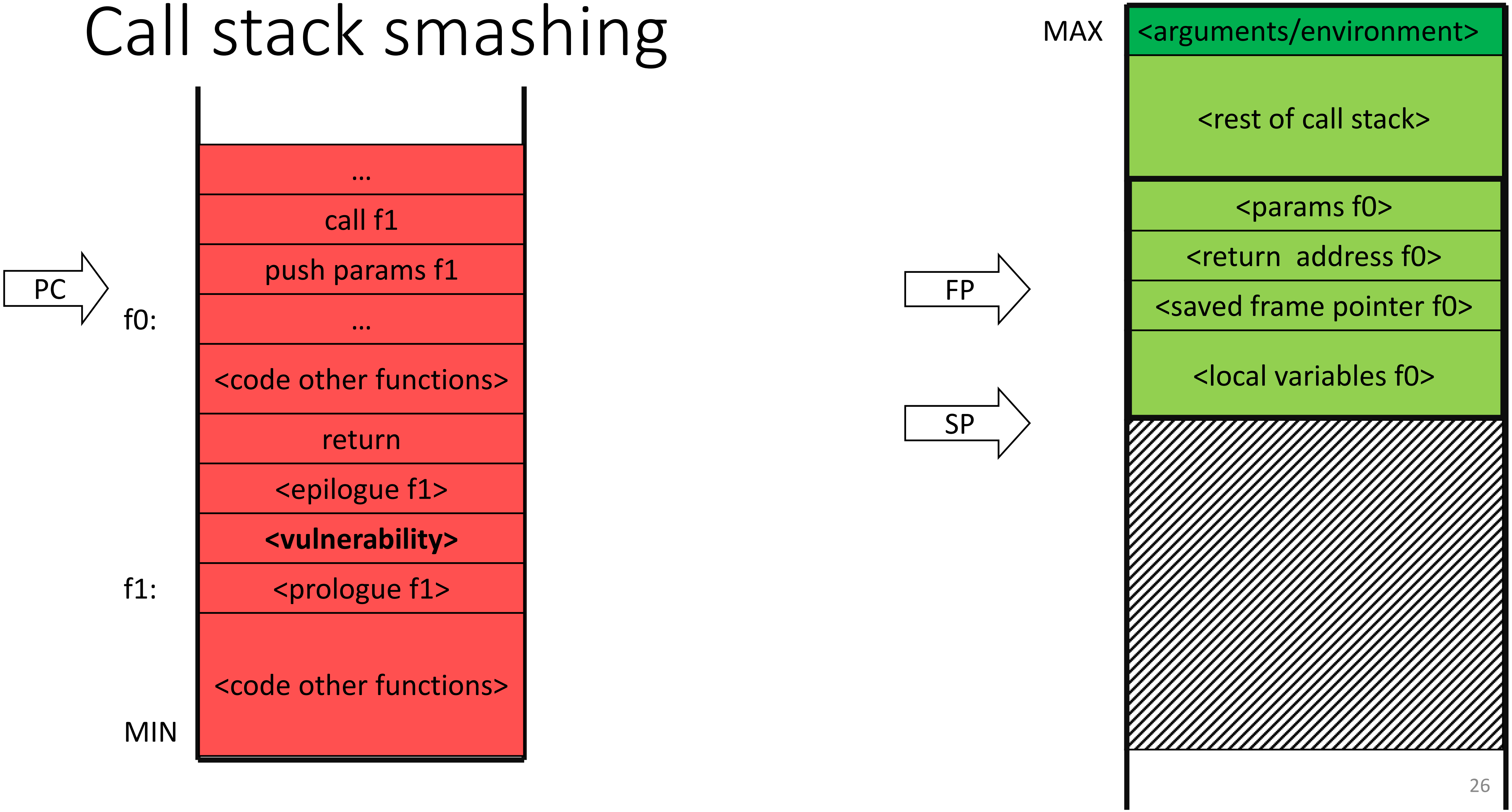
Introduction: attack scenarios

- The key idea underlying exploitation of programs with memory management vulnerabilities is:
  - Feed the program input that triggers the vulnerability, i.e., causes an invalid memory access
    - Hence, further behavior is undefined according to the language specification
  - Use knowledge and understanding of this particular implementation of the language to make sure that what happens is useful to the attacker
    - Leak data
    - Tamper with data or the execution of the program

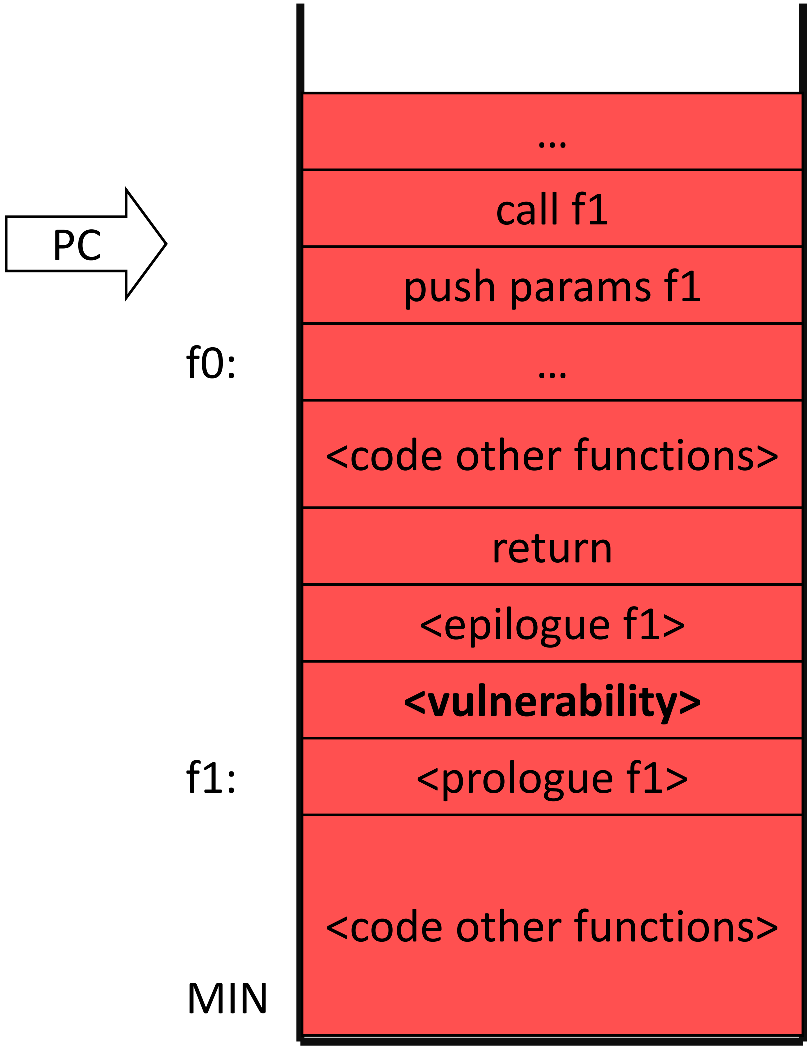
Attack scenario 1: call stack smashing

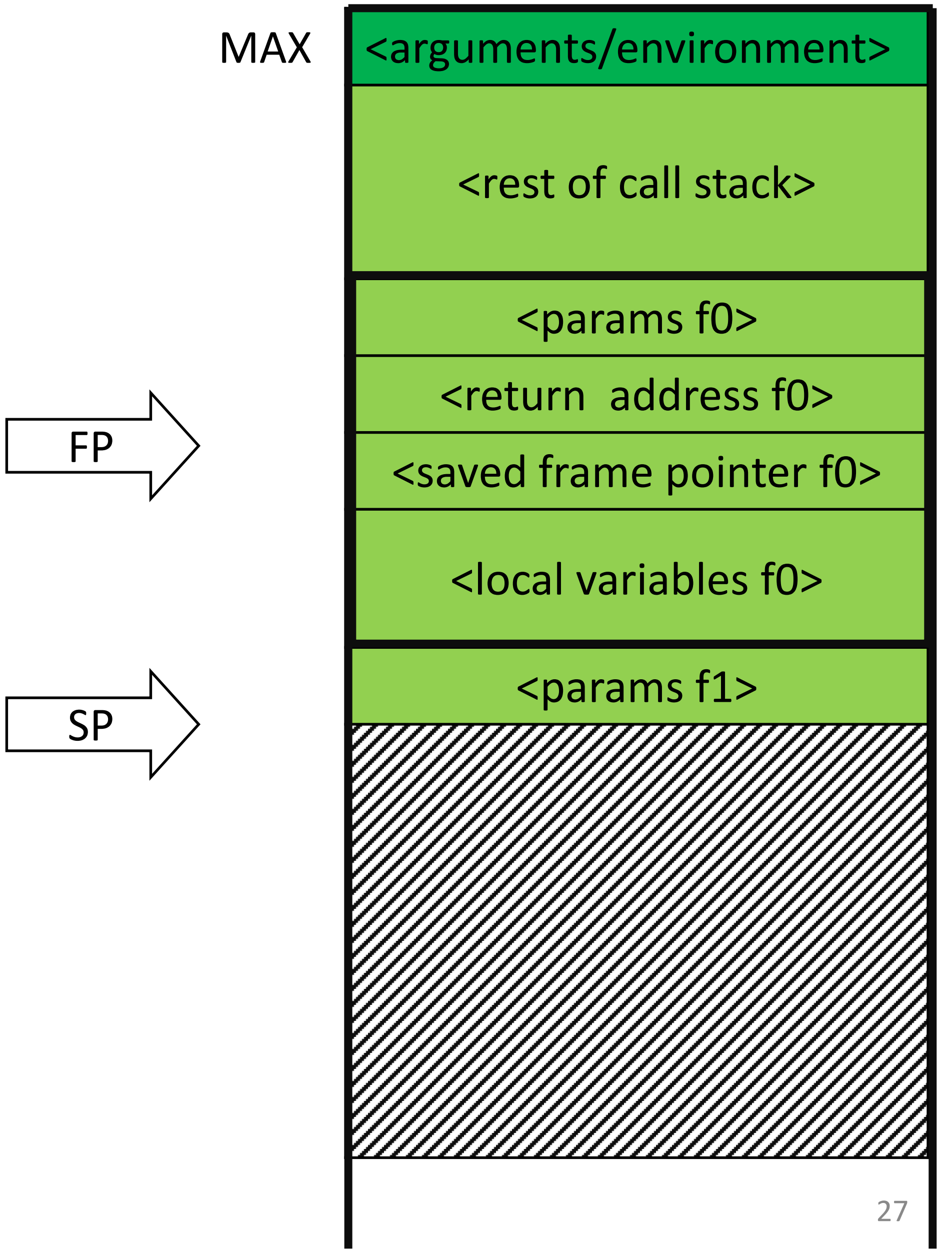
- The stack used at run time to track function calls and returns
  - Per call, *an activation record* or *stack frame* is pushed on the stack, containing:
    - Actual parameters, return address, automatically allocated local variables, …
  - On return of a call, the corresponding stack frame is popped from the stack
- As a consequence, if a local array (buffer) variable can be overflowed, there are interesting memory locations to overwrite nearby
  - The simplest attack is to overwrite the return address so that it points to attacker-chosen code (**shellcode**)

Call stack smashing



Call stack smashing





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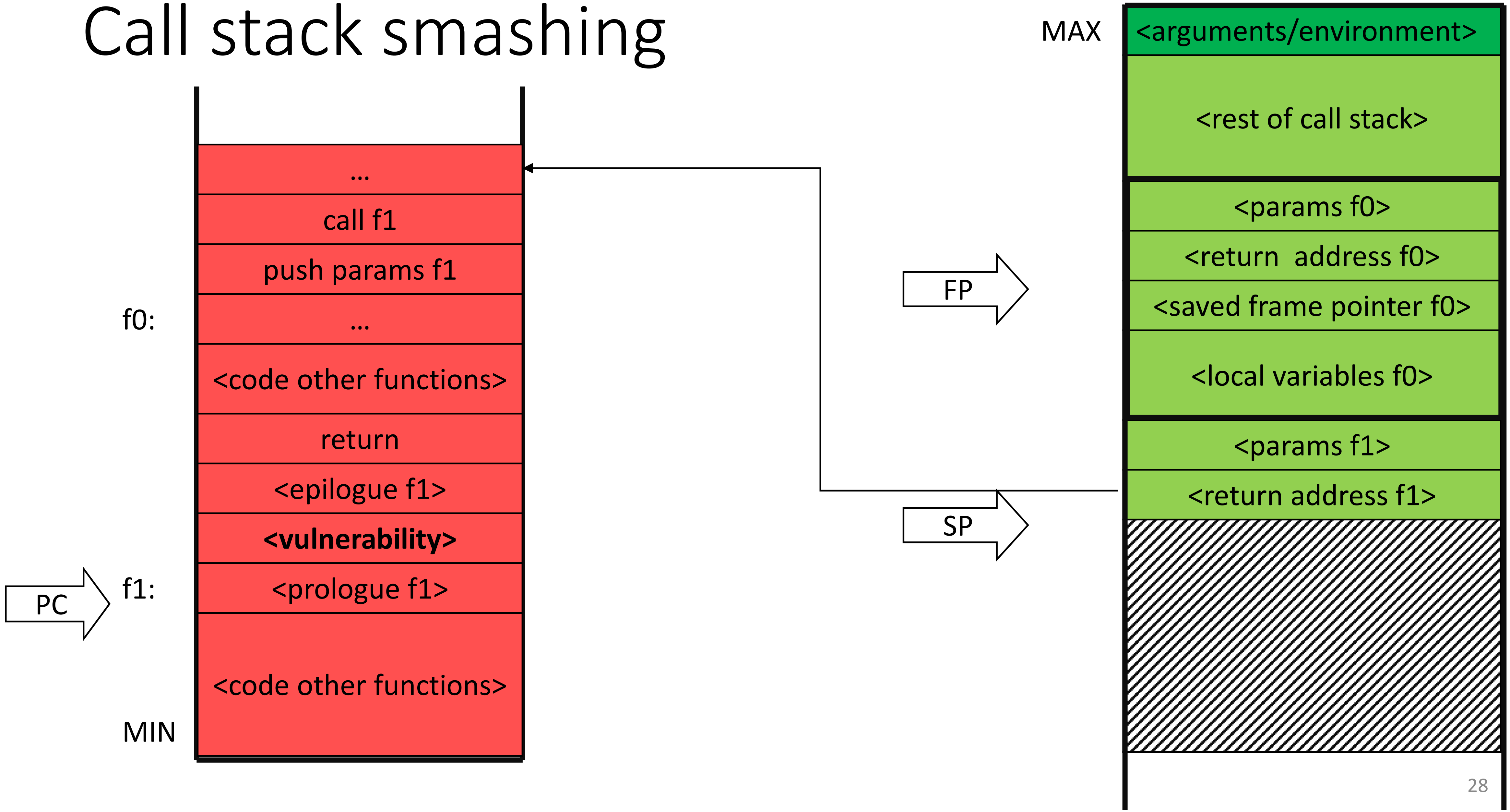

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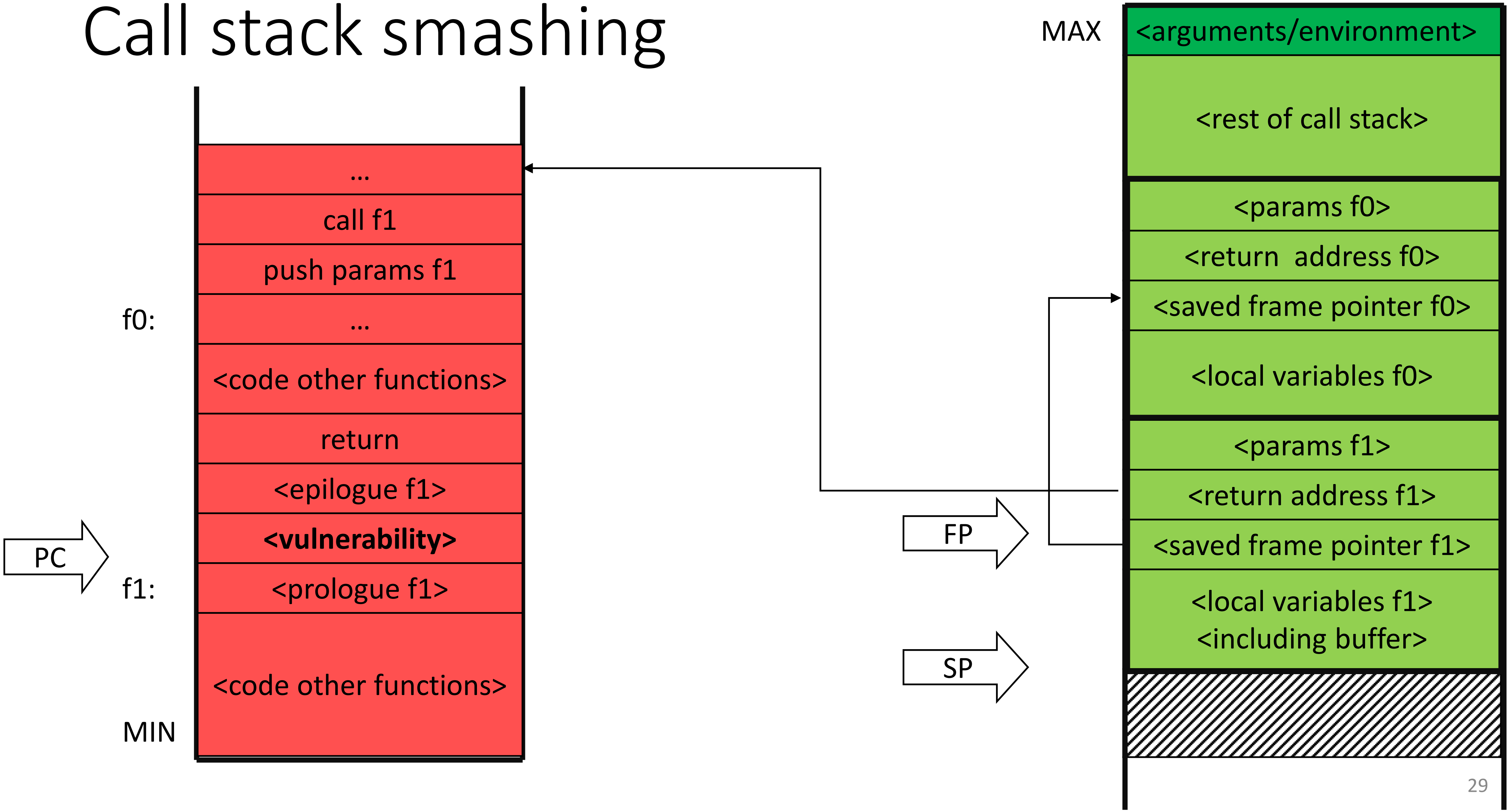

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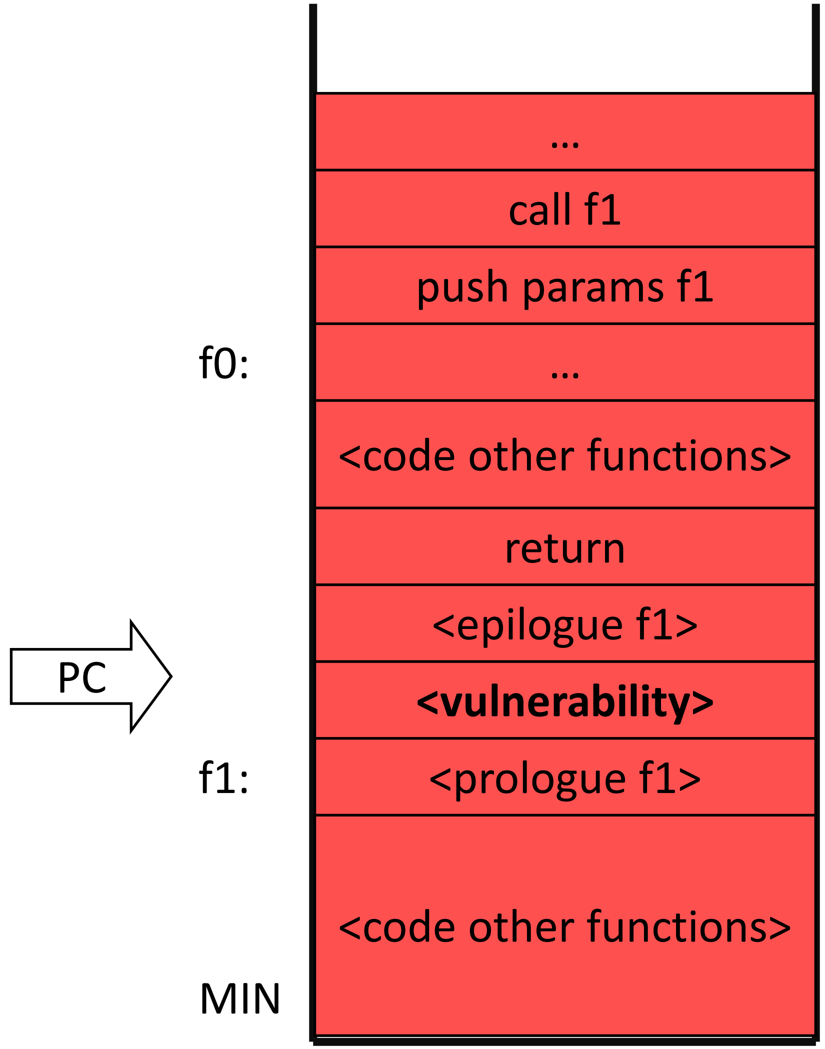

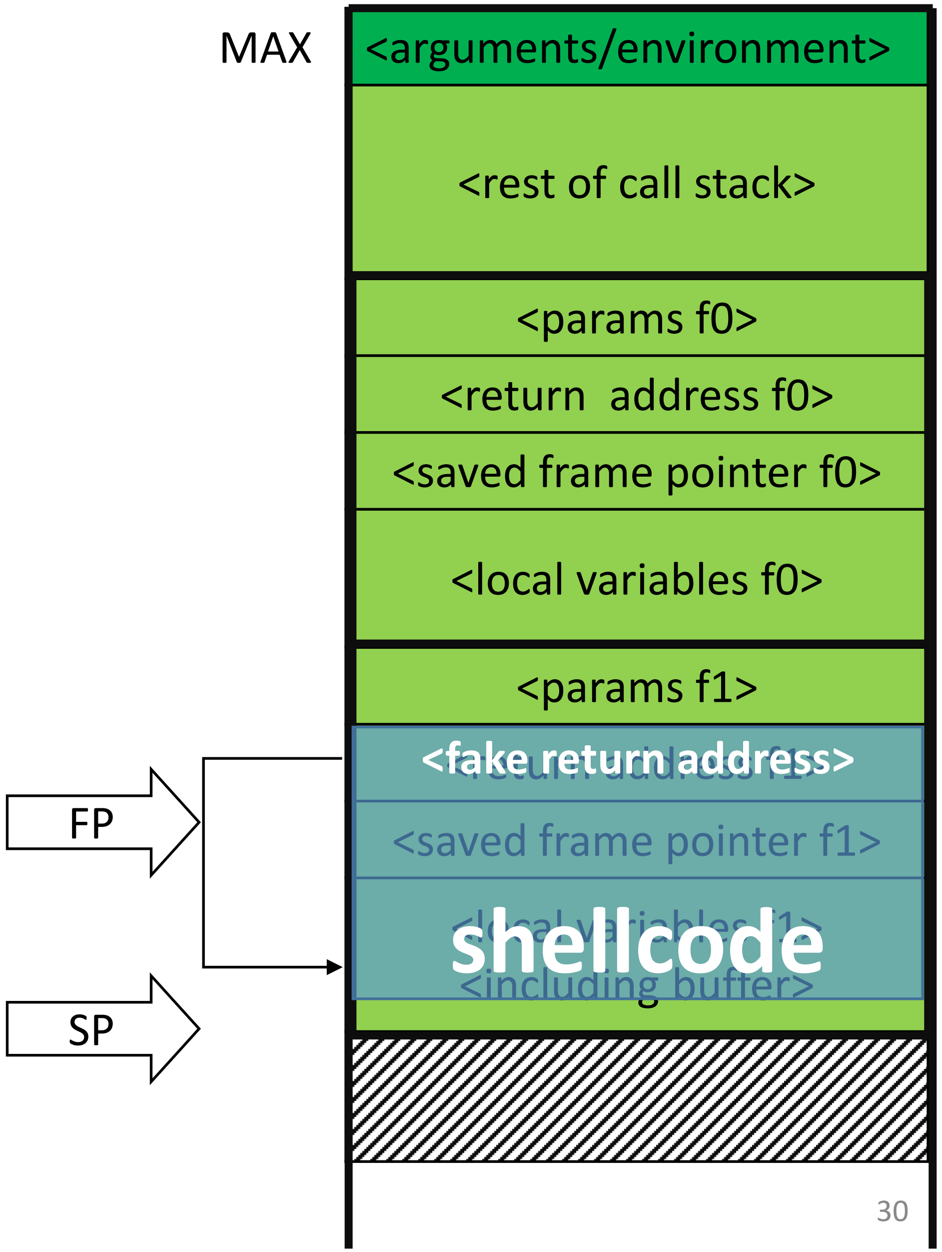

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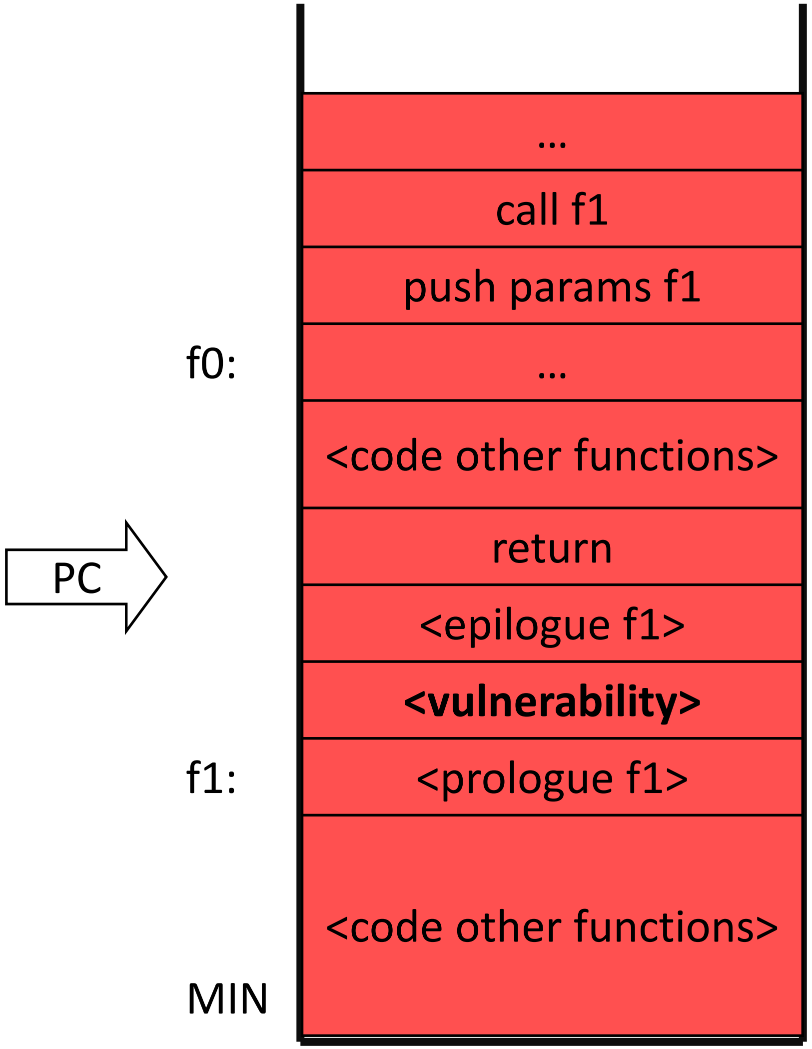

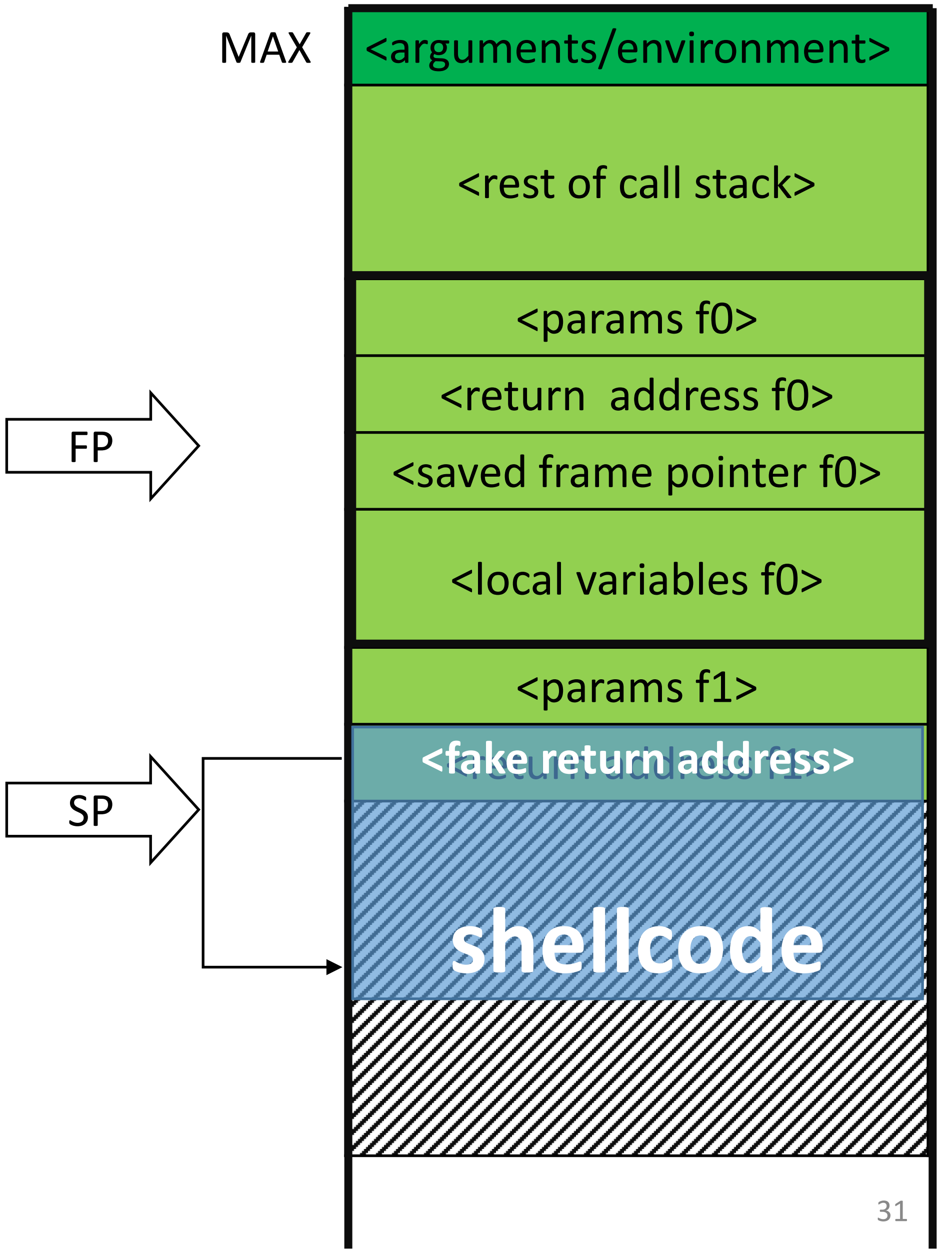

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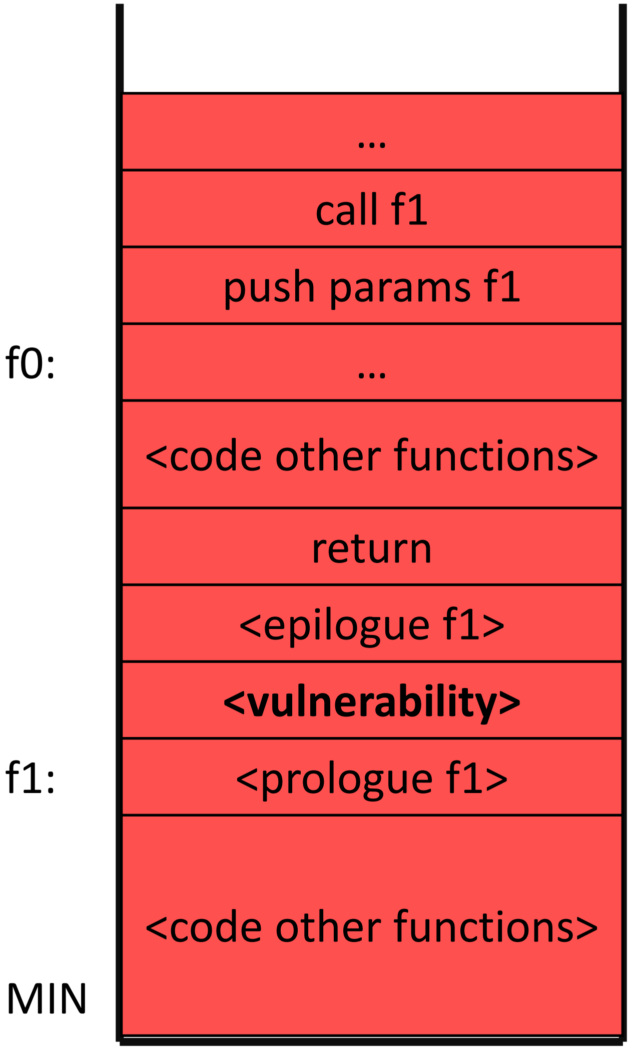
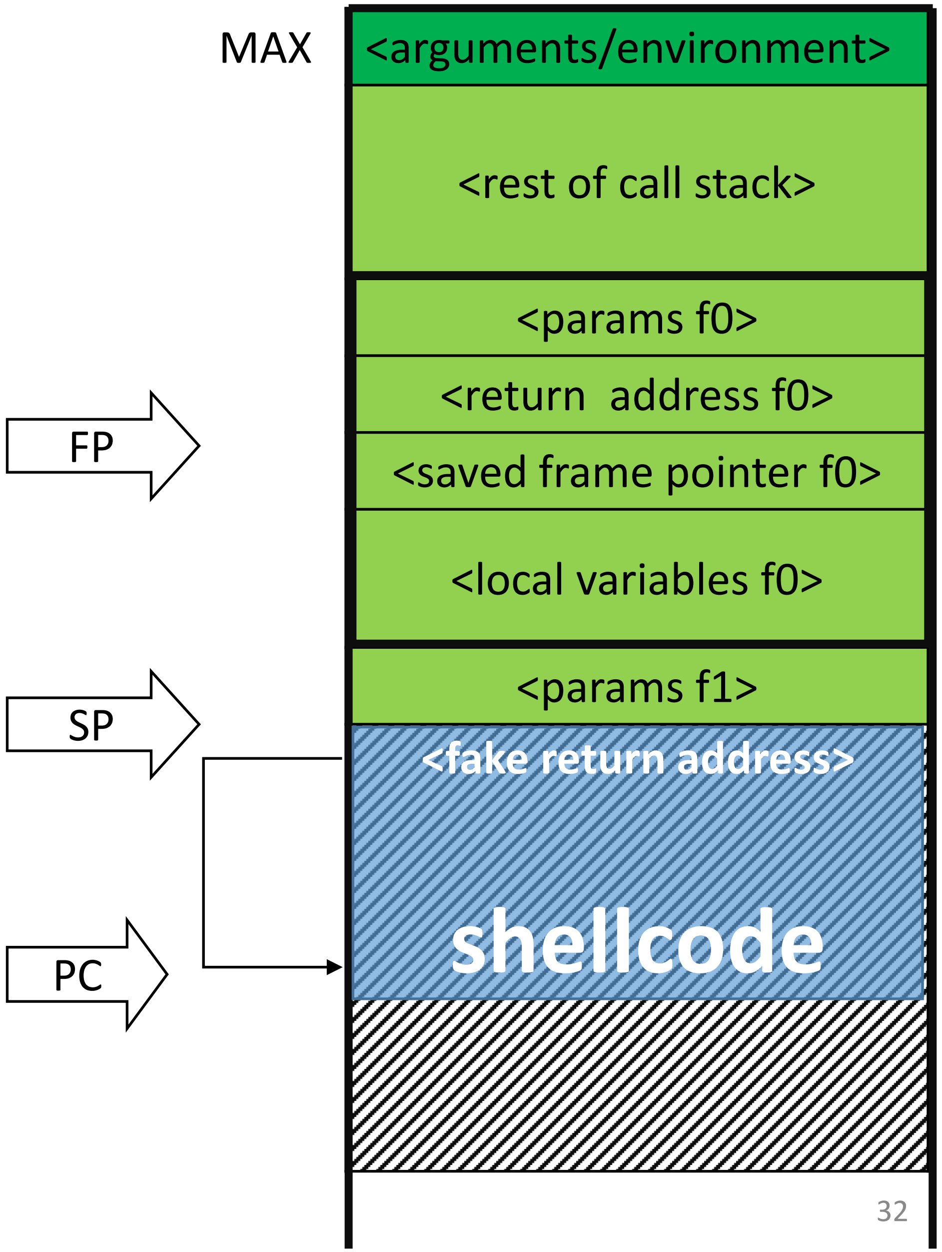




A concrete attack

- Very simple shell code:

machine code opcode bytes	assembly-language version of the machine code
`0xcd 0x2e`	`int 0x2e` ; system call to the operating system
`0xeb 0xfe`	`L: jmp L` ; a very short, direct infinite loop

- Keeping in mind little-endianness, this shell code appears as the 4-byte word `0xfeeb2ecd`

A concrete attack

- Vulnerable code:

```
int is_file_foobar( char* one, char* two )
{
    // must have strlen(one) + strlen(two) < MAX_LEN
    char tmp[MAX_LEN];
    strcpy( tmp, one );
    strcat( tmp, two );
    return strcmp( tmp, "file://foobar" );
}
```

Snapshot of the stack before the return

```
 address     content
0x0012ff5c 0x00353037 ; argument two pointer
0x0012ff58 0x0035302f ; argument one pointer
0x0012ff54 0x00401263 ; return address
0x0012ff50 0x0012ff7c ; saved base pointer
0x0012ff4c 0x00000072 ; tmp continues 'r' '\0' '\0' '\0'
0x0012ff48 0x61626f6f ; tmp continues 'o' 'o' 'b' 'a'
0x0012ff44 0x662f2f3a ; tmp continues ':' '/' '/' 'f'
0x0012ff40 0x656c6966 ; tmp array:     'f' 'i' 'l' 'e'
```

Snapshot of the stack before the return

address	content	
0x0012ff5c	0x00353037	; argument two pointer
0x0012ff58	0x0035302f	; argument one pointer
0x0012ff54	0x00401263	; return address
0x0012ff50	0x0012ff7c	; saved base pointer
0x0012ff4c	0x00000072	; tmp continues 'r' '\0' '\0' '\0'
0x0012ff48	0x61626f6f	; tmp continues 'o' 'o' 'b' 'a'
0x0012ff44	0x662f2f3a	; tmp continues ':' '/' '/' 'f'
0x0012ff40	0x656c6966	; tmp array: 'f' 'i' 'l' 'e'

Snapshot of the stack before the return

address	content		
0x0012ff5c	0x00353037	; argument two pointer	
0x0012ff58	0x0035302f	; argument one pointer	
0x0012ff54	0x0012ff4c	; return address	\x4c\xff\x12\x00
0x0012ff50	0x66666666	; saved base poi	'f' 'f' 'f' 'f'
0x0012ff4c	0xfeeb2ecd	; tmp continues	\xcd\x2e\xeb\xfe
0x0012ff48	0x66666666	; tmp continues	'f' 'f' 'f' 'f'
0x0012ff44	0x66 2f2f3a	; tmp continues	':' '/' '/' 'f'
0x0012ff40	0x656c6966	; tmp array:	'f' 'i' 'l' 'e'

Call stack smashing

- Lots of details to get right before it works:
  - No nulls in (character-)strings
  - Filling in the correct return address:
    - Fake return address must be precisely positioned
    - Attacker might not know the address of his own string
  - Other overwritten data must not be used before return from function
  - …
- More information in
  - “Smashing the stack for fun and profit” by Aleph One

Attack scenario 2: overwriting a function pointer on the heap

- If a program contains a buffer overflow vulnerability for a buffer allocated on the heap, there is no return address nearby
- So attacking a heap based vulnerability requires the attacker to overwrite other code pointers
- We look at an example where we overwrite a function pointer

Concrete attack: overwriting a function pointer

- Example vulnerable program:

```
typedef struct _vulnerable_struct {
    char buff[MAX_LEN];
    int (*cmp)(char*,char*);
} vulnerable;

int is_file_foobar_using_heap( vulnerable* s, char* one, char* two ) {
    // must have strlen(one) + strlen(two) < MAX_LEN
    strcpy( s->buff, one );
    strcat( s->buff, two );
    return s->cmp( s->buff, "file://foobar" );
}
```

This defines the type: vulnerable

This struct can be allocated anywhere, most likely on the heap

Concrete attack: overwriting a function pointer

	buff (char array at start of the struct)				cmp
address:	0x00353068	0x0035306c	0x00353070	0x00353074	0x00353078
content:	0x656c6966	0x662f2f3a	0x61626f6f	0x00000072	0x004013ce

(a) A structure holding "file://foobar" and a pointer to the `strcmp` function.

	buff (char array at start of the struct)				cmp
address:	0x00353068	0x0035306c	0x00353070	0x00353074	0x00353078
content:	0x656c6966	0x612f2f3a	0x61666473	0x61666473	0x00666473

(b) After a buffer overflow caused by the inputs "file://" and "asdfasdfasdf".

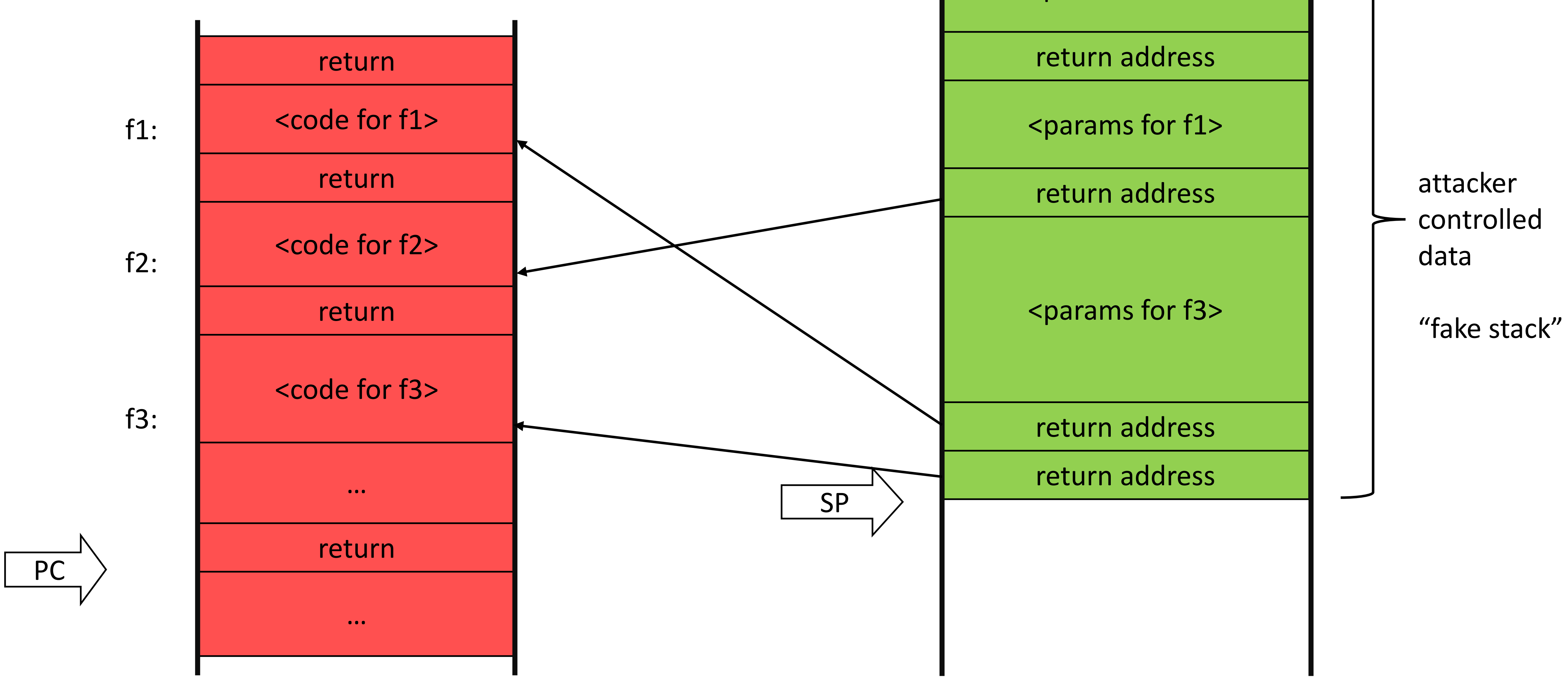
	buff (char array at start of the struct)				cmp
address:	0x00353068	0x0035306c	0x00353070	0x00353074	0x00353078
content:	0xfeeb2ecd	0x11111111	0x11111111	0x11111111	0x00353068

(c) After a malicious buffer overflow caused by attacker-chosen inputs.

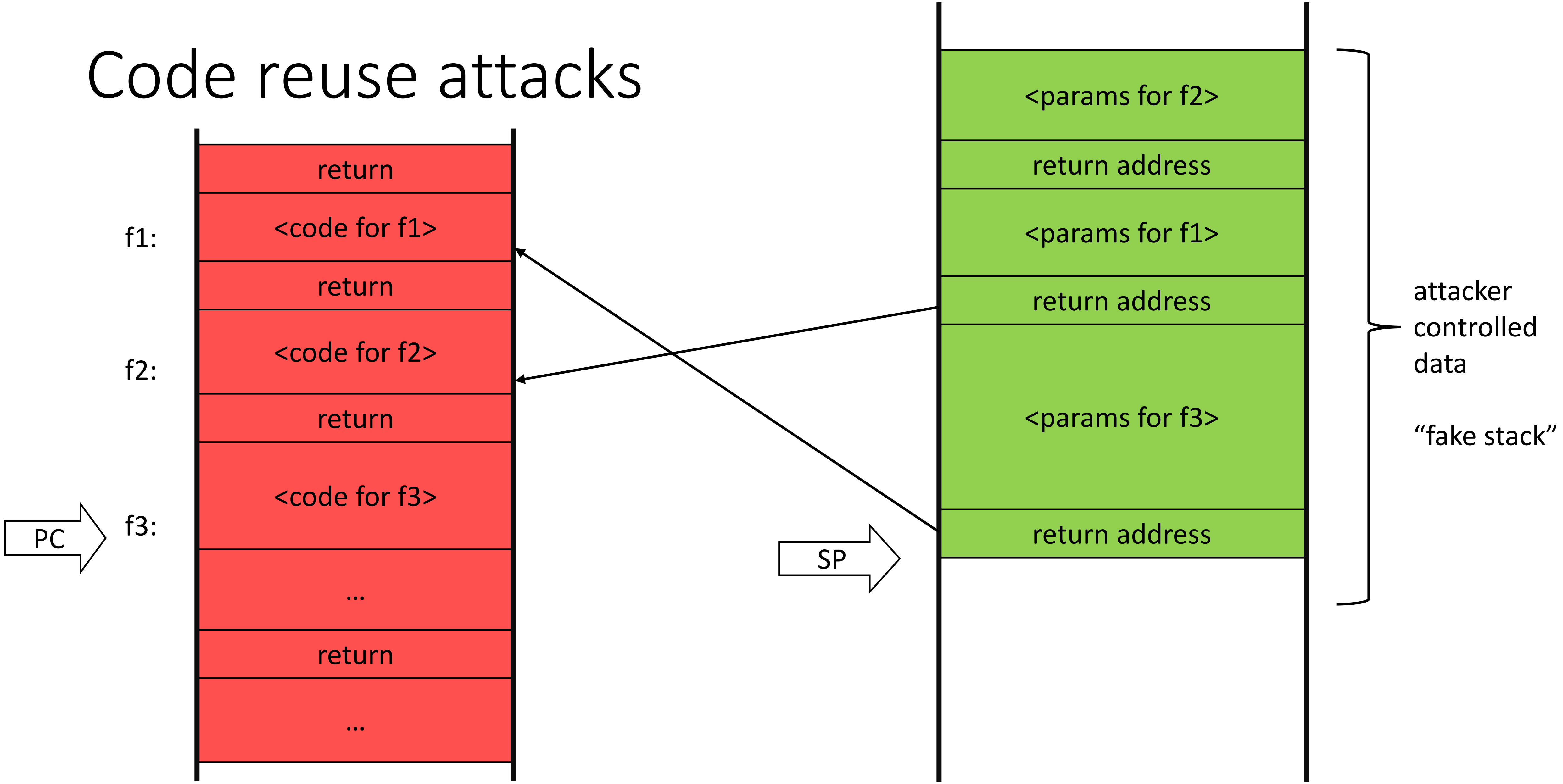
Attack scenario 3: code reuse attacks

- *Direct code injection*, where an attacker injects code as data is not always feasible
  - E.g. When certain countermeasures are active
- *Indirect code injection* or *code reuse* attacks will control execution of the program by reusing fractions of the existing code
- The crux of the attack is to find a way to execute (a chain of) code fractions under the control of the attacker
  - One way of achieving this is by controlling the stack pointer

Code reuse attacks



Code reuse attacks



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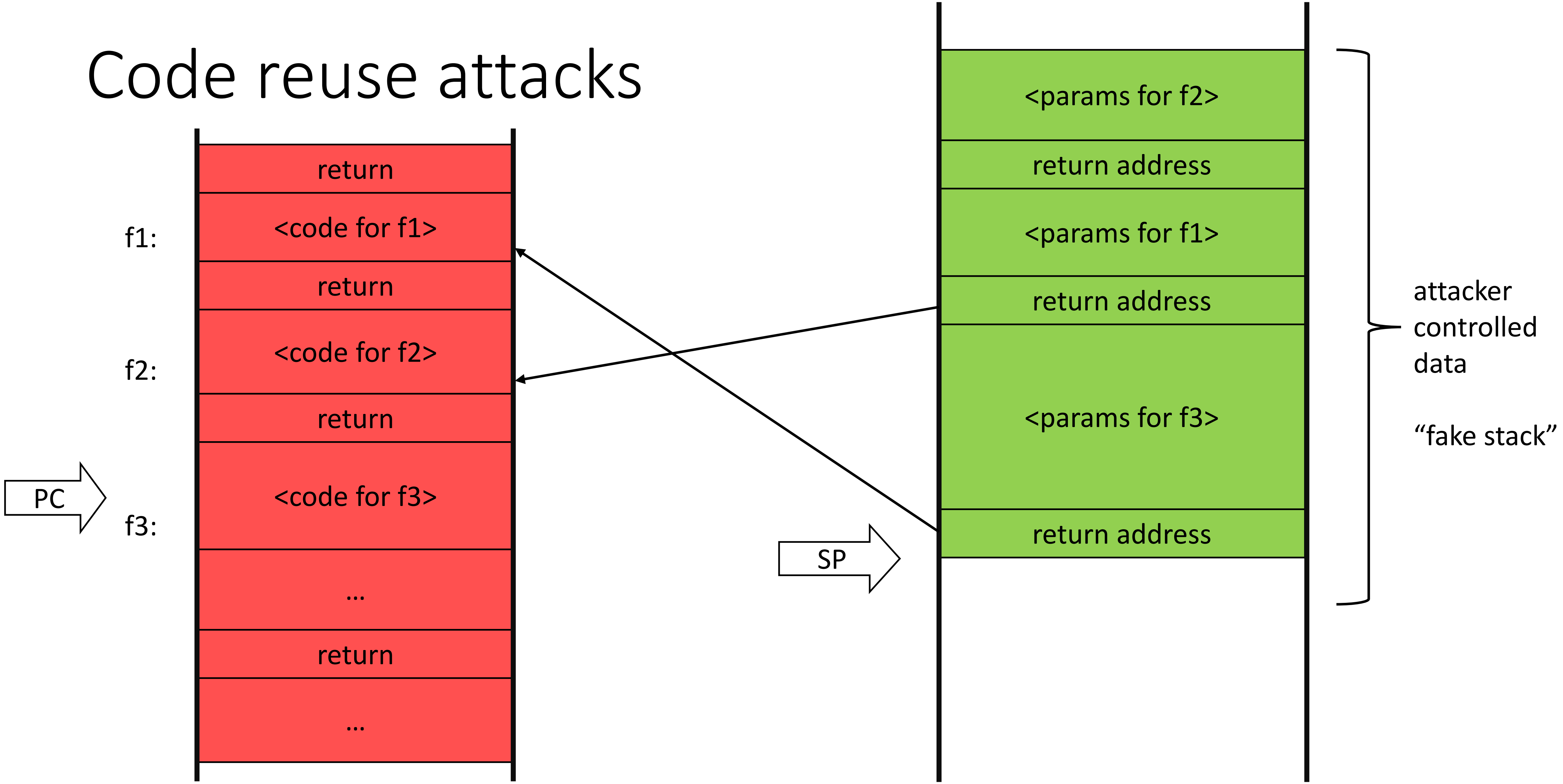

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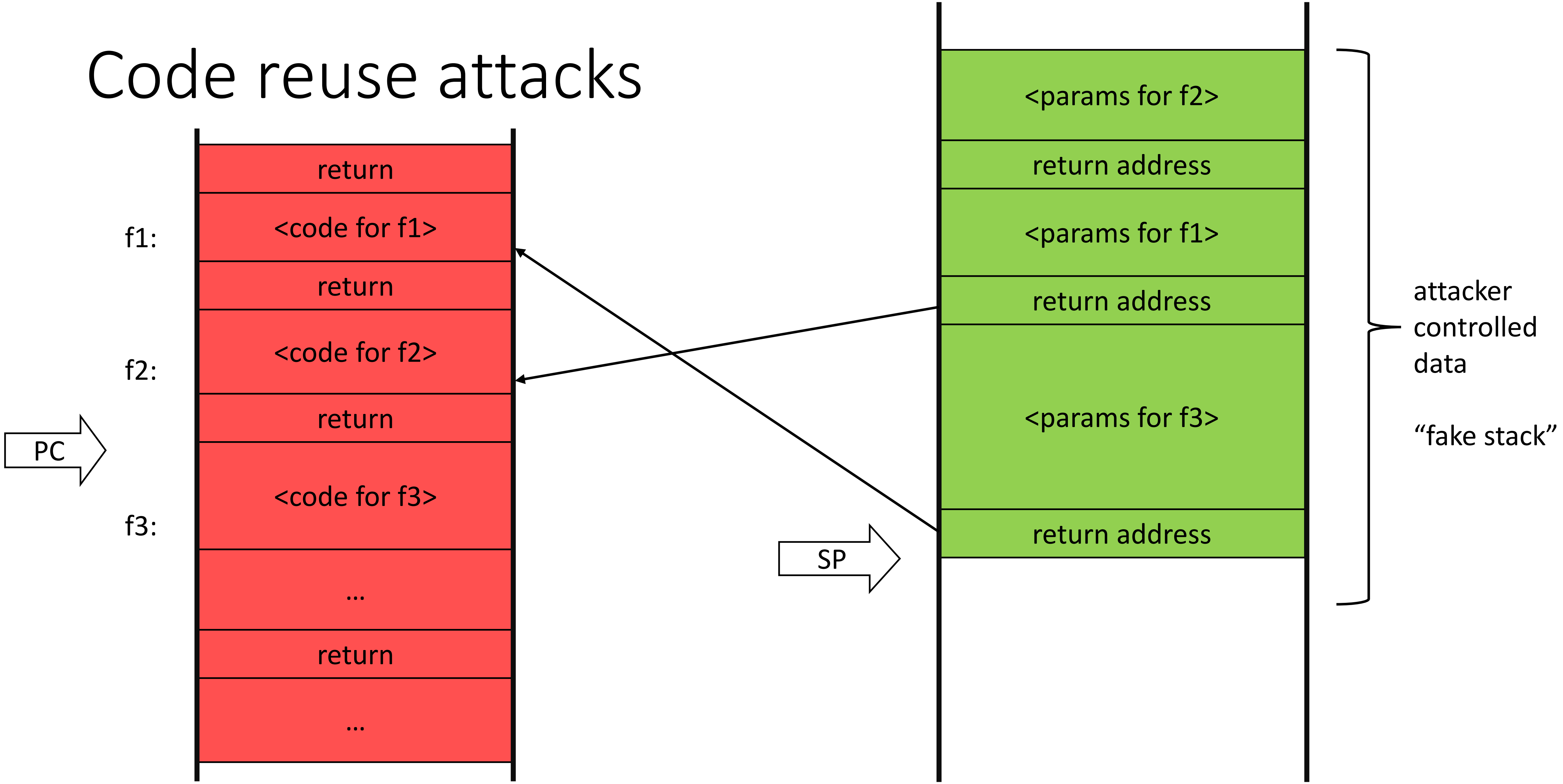

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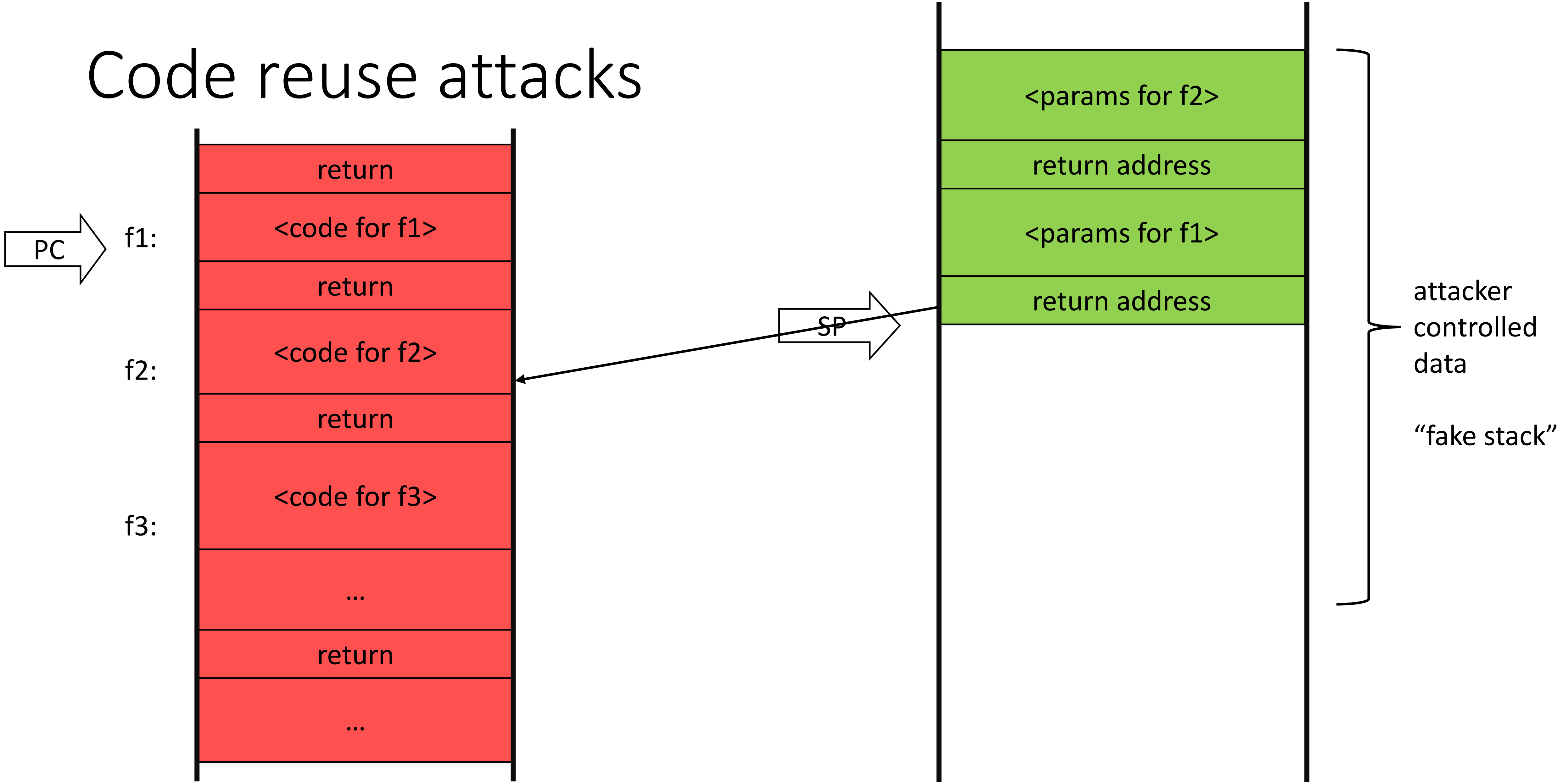

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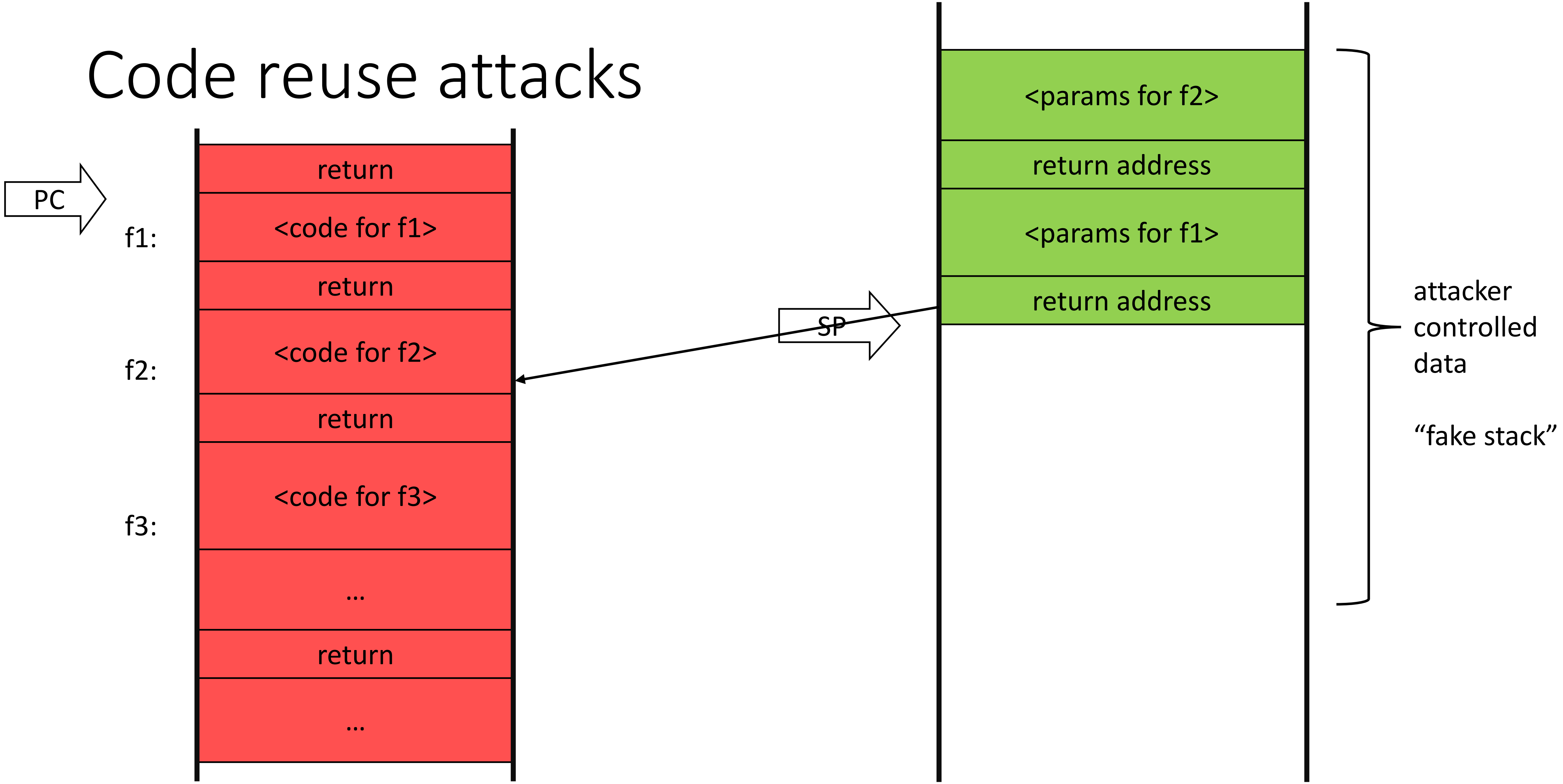

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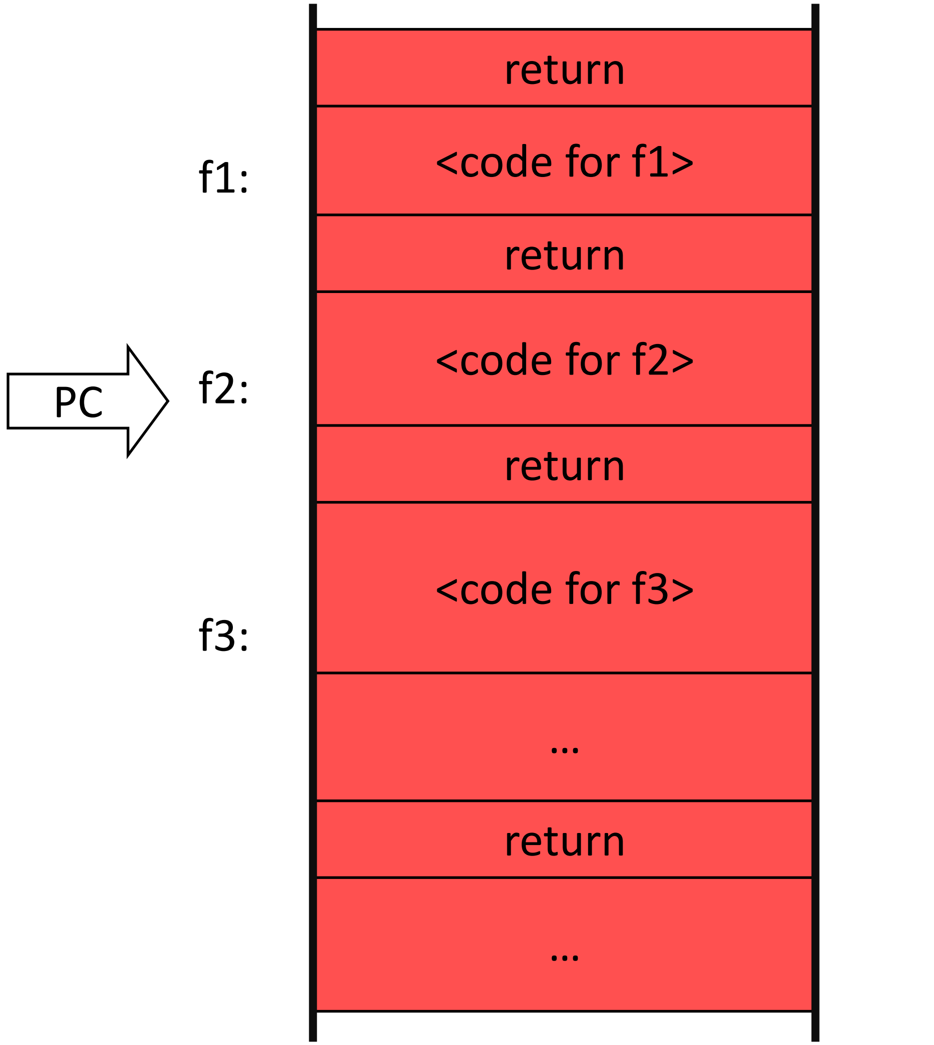
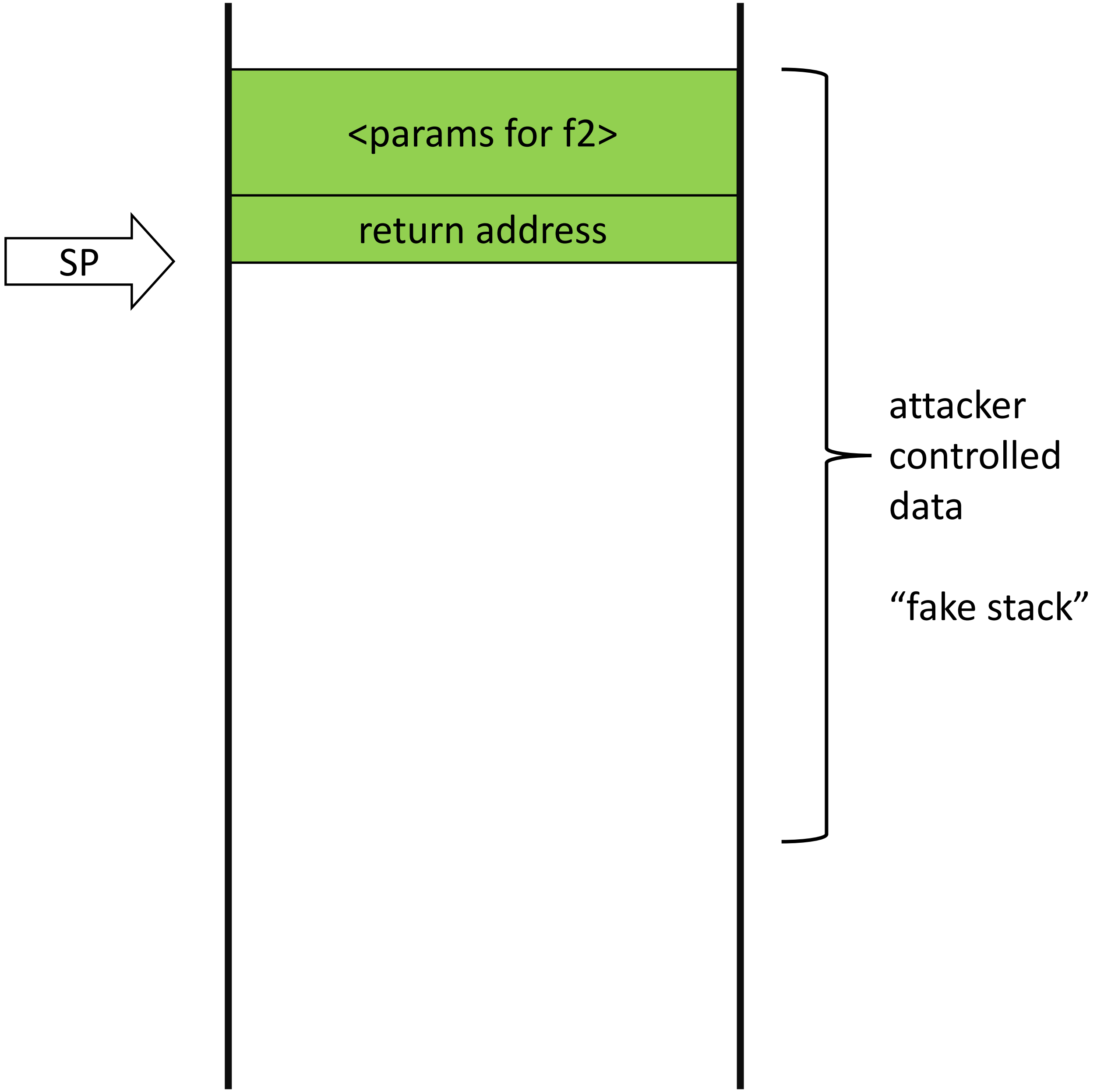
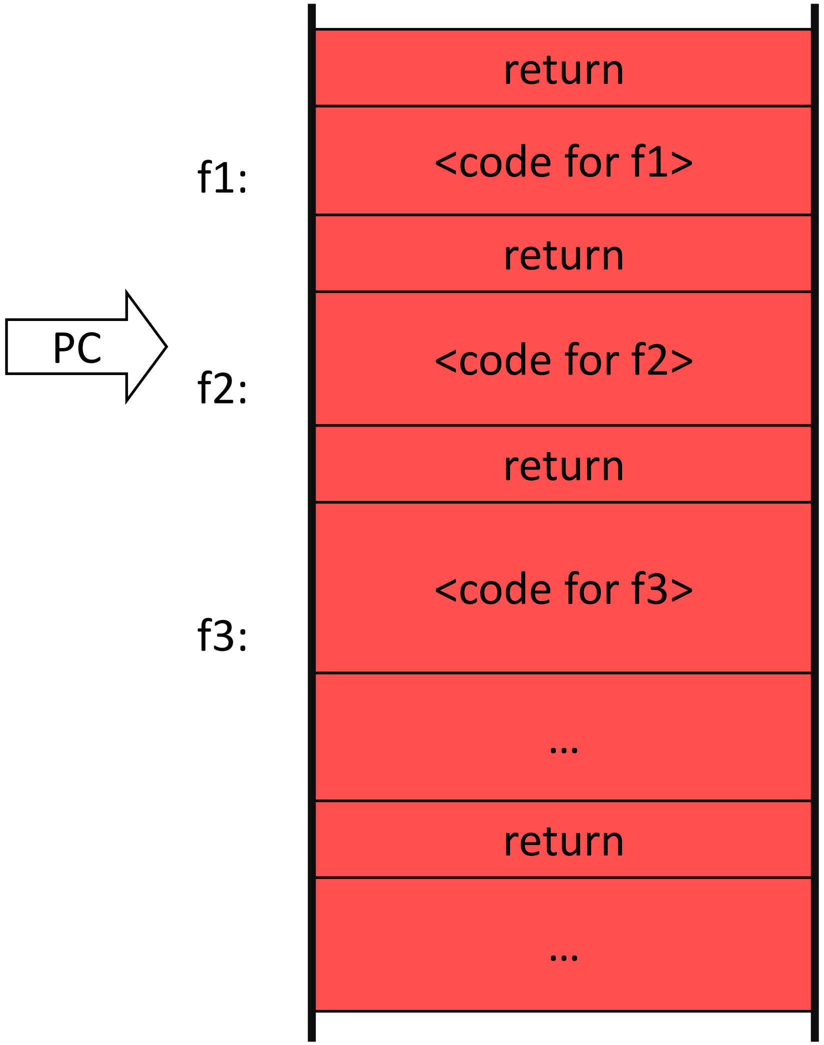
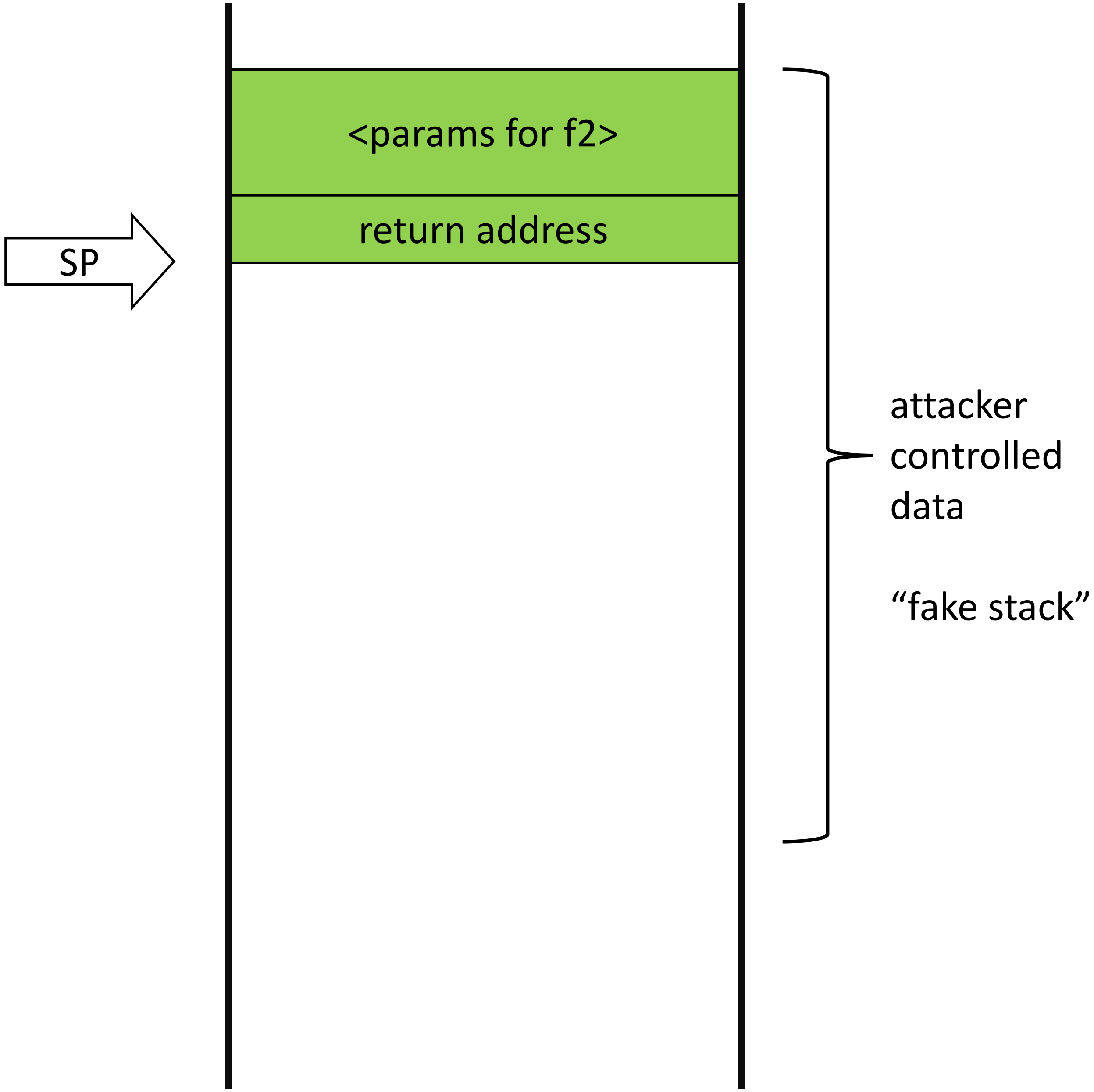




Code reuse attacks





A concrete attack

- What do we need to make this work?
    - Inject the fake stack
        - Easy: this is just data we can put in a buffer
    - Make the stack pointer point to the fake stack right before a return instruction is executed
        - We will show an example where this is done by jumping to a *trampoline*
    - Then we make the stack execute existing functions to do a direct code injection
        - But we could do other useful stuff without direct code injection

Vulnerable program

```c
int median( int* data, int len, void* cmp )
{
    // must have 0 < len <= MAX_INTS
    int tmp[MAX_INTS];
    memcpy( tmp, data, len*sizeof(int) ); // copy the input integers
    qsort( tmp, len, sizeof(int), cmp ); // sort the local copy
    return tmp[len/2]; // median is in the middle
}
```

The trampoline

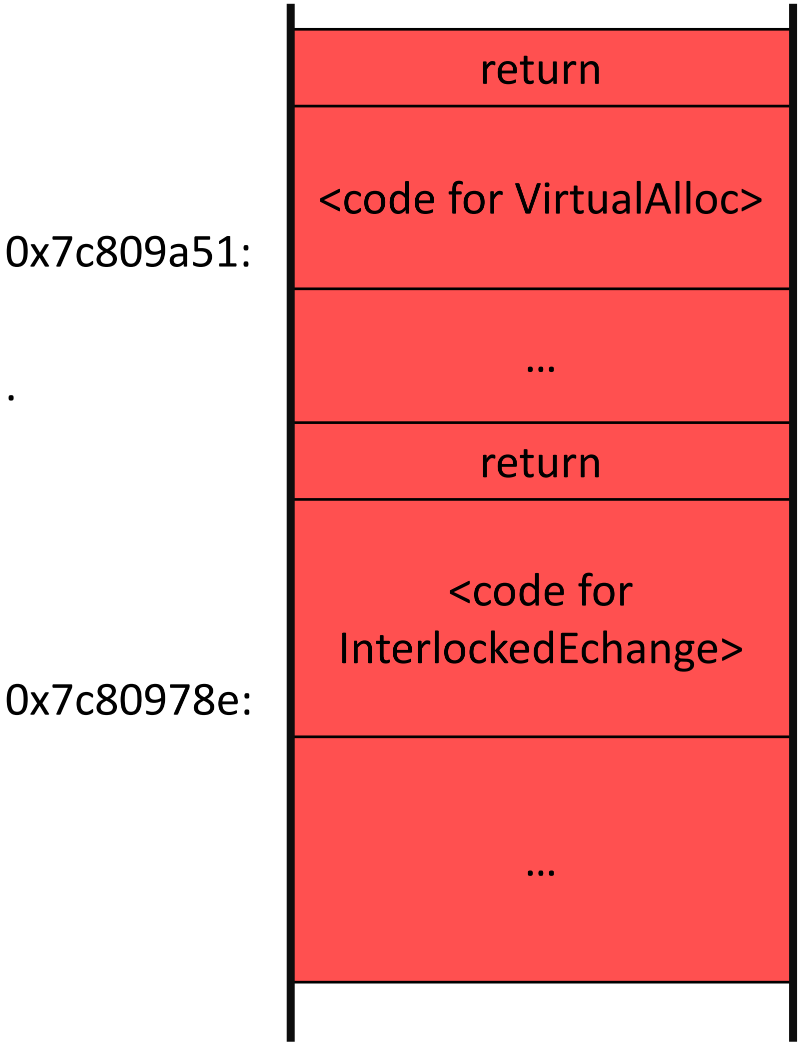
Assembly code of qsort:

```
...
push    edi             ; push second argument to be compared onto the stack
push    ebx             ; push the first argument onto the stack
call    [esp+comp_fp]   ; call comparison function, indirectly through a pointer
add     esp, 8          ; remove the two arguments from the stack
test    eax, eax        ; check the comparison result
jle     label_lessthan  ; branch on that result
...
```

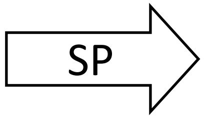
Trampoline code

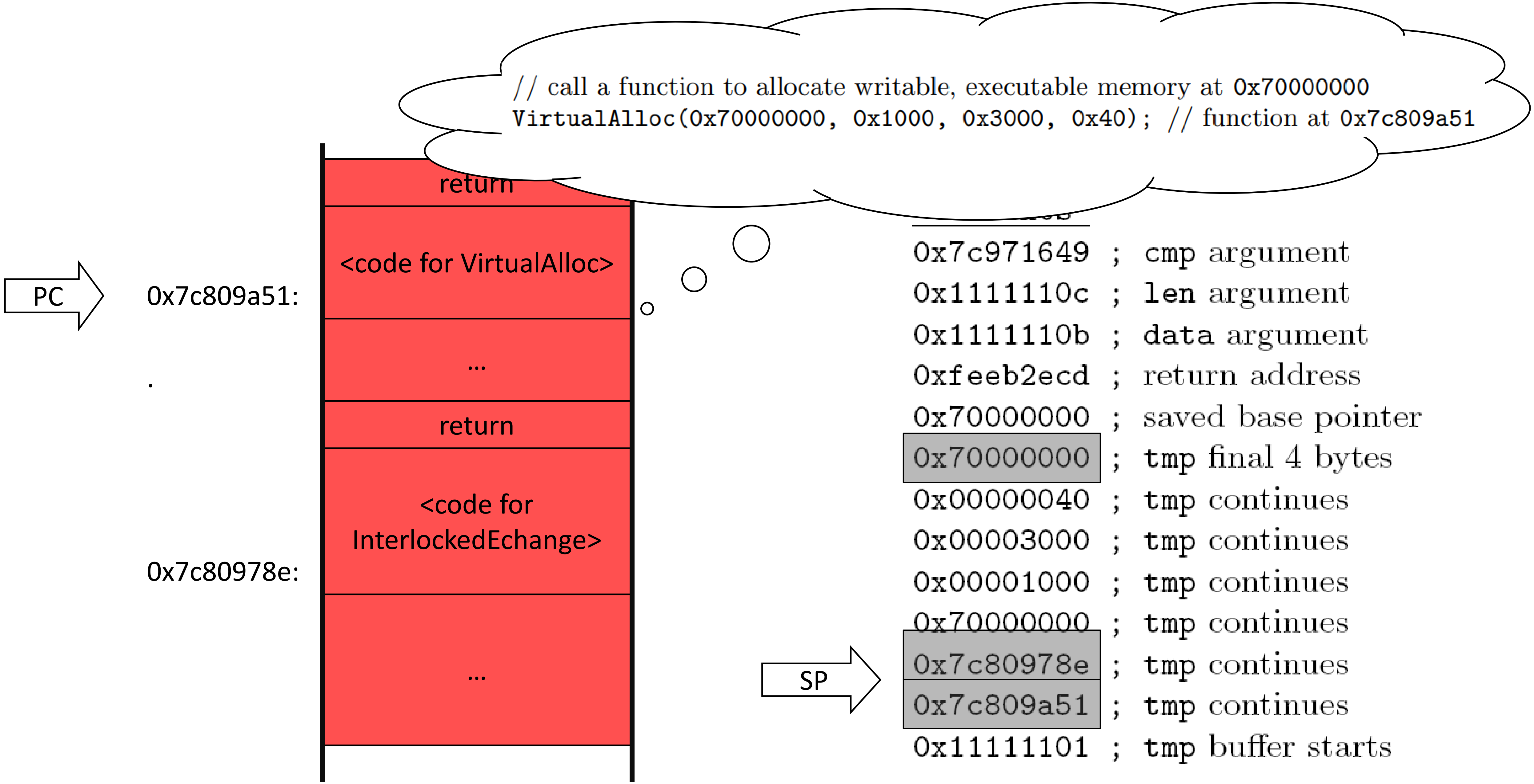
address	machine code opcode bytes	assembly-language version of the machine code
0x7c971649	0x8b 0xe3	mov esp, ebx ; change the stack location to ebx
0x7c97164b	0x5b	pop ebx ; pop ebx from the new stack
0x7c97164c	0xc3	ret ; return based on the new stack

stack address	normal stack contents	benign overflow contents	malicious overflow contents	
0x0012ff38	0x004013e0	0x1111110d	0x7c971649	; cmp argument
0x0012ff34	0x00000001	0x1111110c	0x1111110c	; len argument
0x0012ff30	0x00353050	0x1111110b	0x1111110b	; data argument
0x0012ff2c	0x00401528	0x1111110a	0xfeeb2ecd	; return address
0x0012ff28	0x0012ff4c	0x11111109	0x70000000	; saved base pointer
0x0012ff24	0x00000000	0x11111108	0x70000000	; tmp final 4 bytes
0x0012ff20	0x00000000	0x11111107	0x00000040	; tmp continues
0x0012ff1c	0x00000000	0x11111106	0x00003000	; tmp continues
0x0012ff18	0x00000000	0x11111105	0x00001000	; tmp continues
0x0012ff14	0x00000000	0x11111104	0x70000000	; tmp continues
0x0012ff10	0x00000000	0x11111103	0x7c80978e	; tmp continues
0x0012ff0c	0x00000000	0x11111102	0x7c809a51	; tmp continues
0x0012ff08	0x00000000	0x11111101	0x11111101	; tmp buffer starts
0x0012ff04	0x00000004	0x00000040	0x00000040	; memcpy length argument
0x0012ff00	0x00353050	0x00353050	0x00353050	; memcpy source argument
0x0012fefc	0x0012ff08	0x0012ff08	0x0012ff08	; memcpy destination arg.

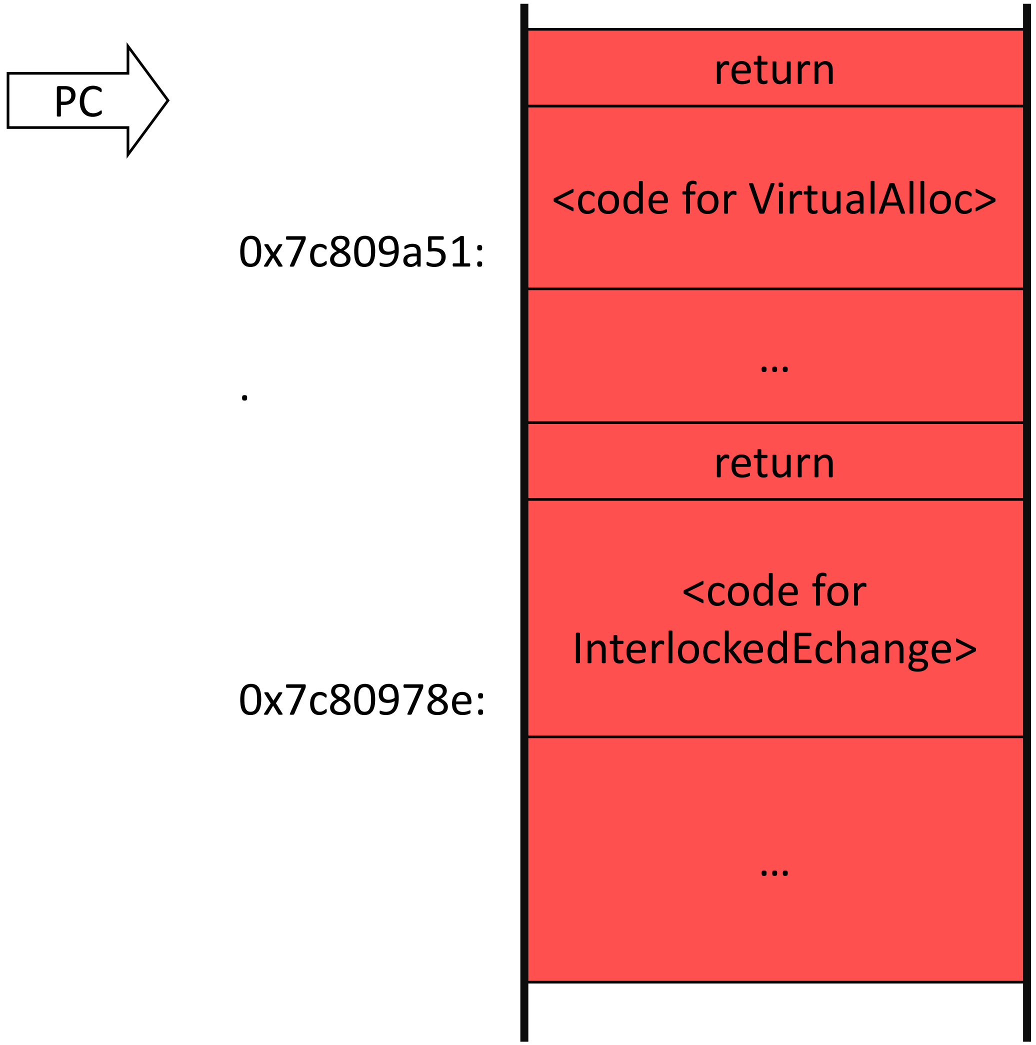


malicious overflow contents		
0x7c971649	;	cmp argument
0x1111110c	;	len argument
0x1111110b	;	data argument
0xfeeb2ecd	;	return address
0x70000000	;	saved base pointer
0x70000000	;	tmp final 4 bytes
0x00000040	;	tmp continues
0x00003000	;	tmp continues
0x00001000	;	tmp continues
0x70000000	;	tmp continues
0x7c80978e	;	tmp continues
0x7c809a51	;	tmp continues
0x11111101	;	tmp buffer starts

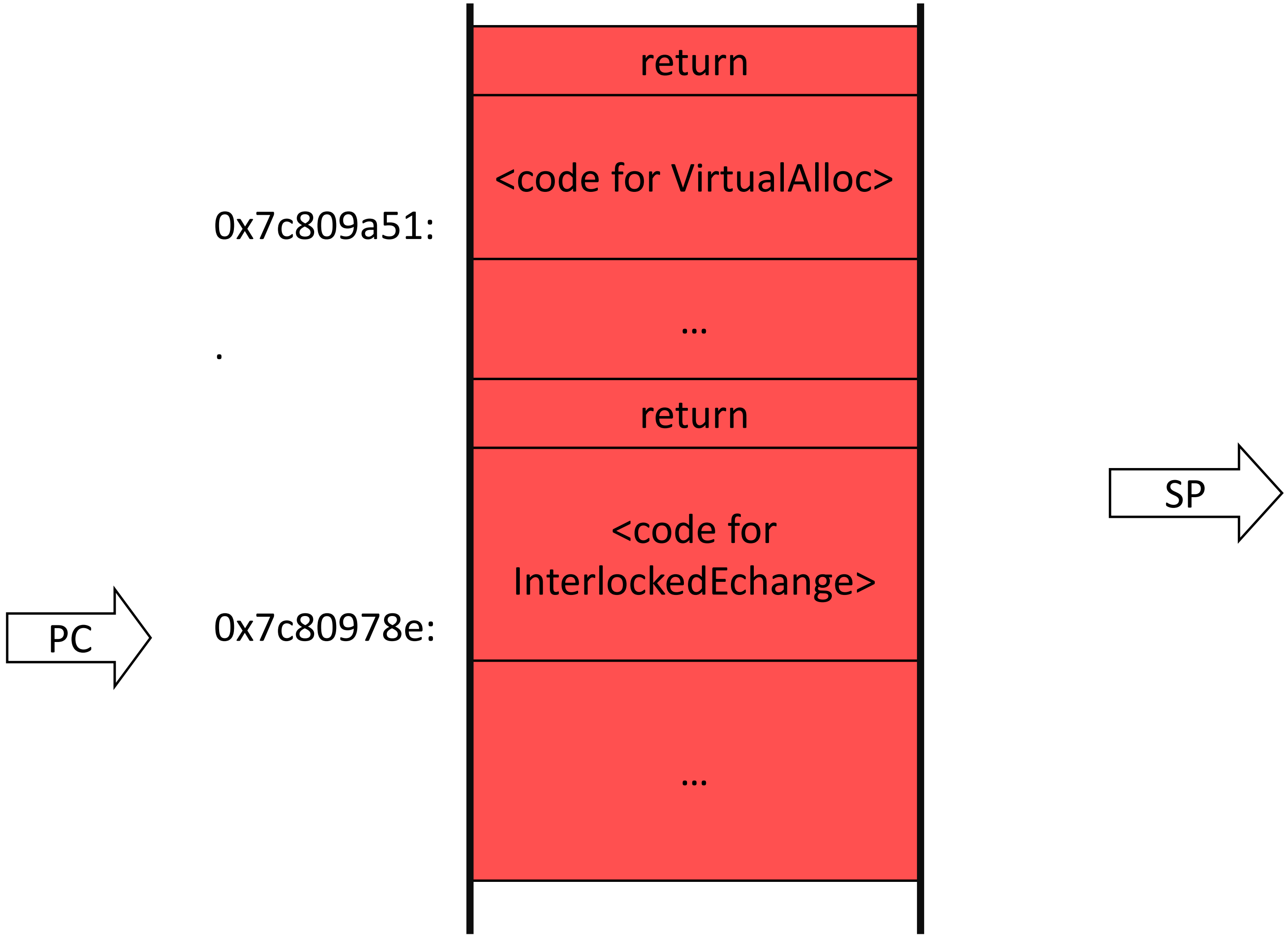




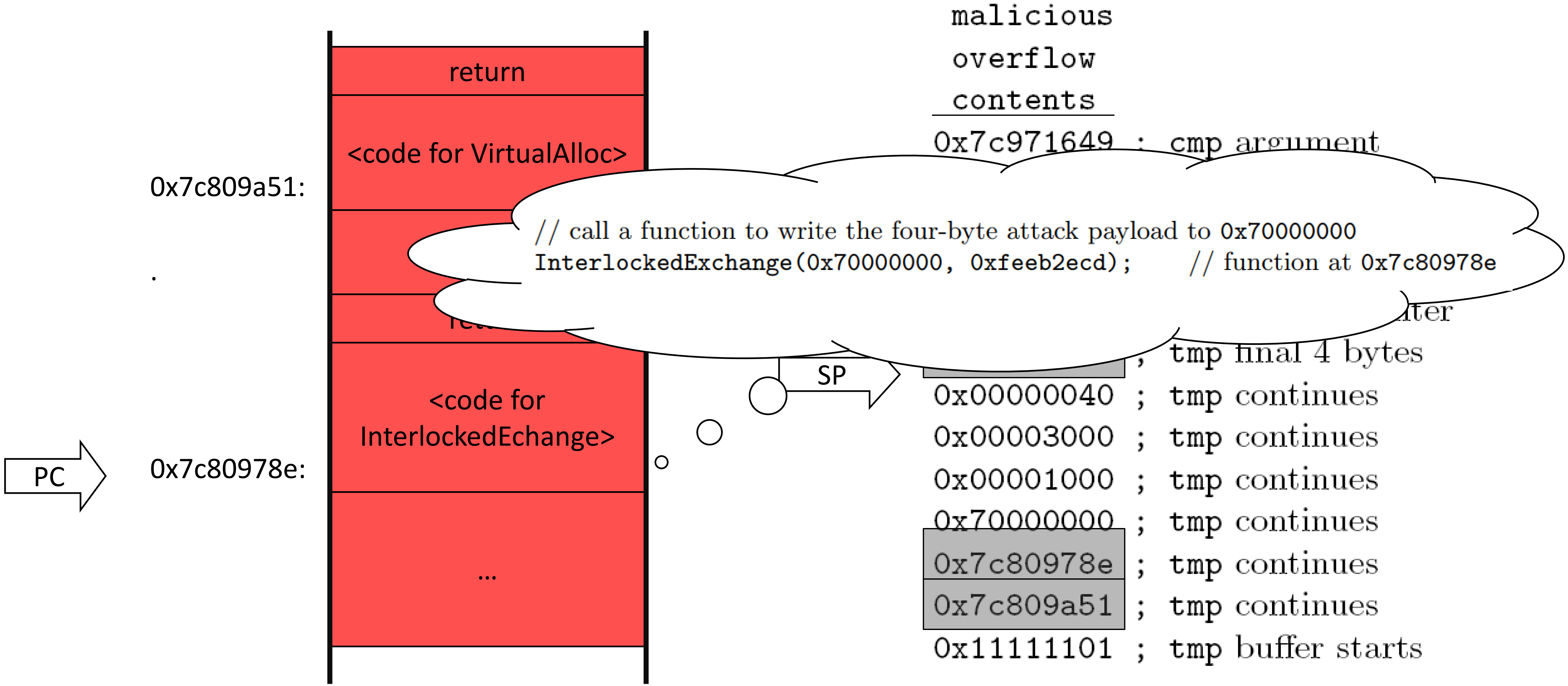
// call a function to allocate writable, executable memory at 0x70000000
VirtualAlloc(0x70000000, 0x1000, 0x3000, 0x40); // function at 0x7c809a51
PC
0x7c809a51:
return
<code for VirtualAlloc>
…
return
<code for InterlockedEchange>
…
0x7c80978e:
SP
0x7c971649 ; cmp argument
0x1111110c ; len argument
0x1111110b ; data argument
0xfeeb2ecd ; return address
0x70000000 ; saved base pointer
0x70000000 ; tmp final 4 bytes
0x00000040 ; tmp continues
0x00003000 ; tmp continues
0x00001000 ; tmp continues
0x70000000 ; tmp continues
0x7c80978e ; tmp continues
0x7c809a51 ; tmp continues
0x11111101 ; tmp buffer starts



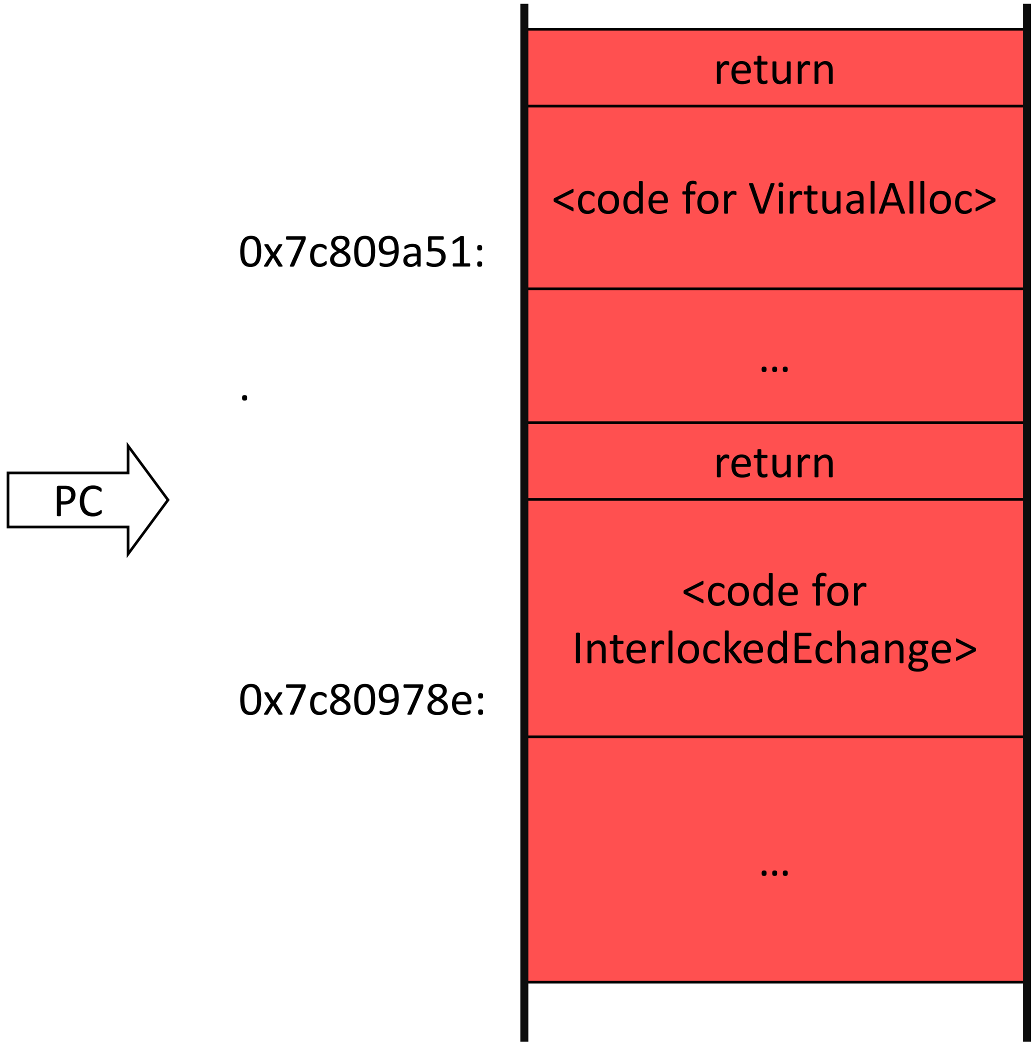
	malicious overflow contents	
	0x7c971649	; cmp argument
	0x1111110c	; len argument
	0x1111110b	; data argument
	0xfeeb2ecd	; return address
	0x70000000	; saved base pointer
	0x70000000	; tmp final 4 bytes
	0x00000040	; tmp continues
	0x00003000	; tmp continues
	0x00001000	; tmp continues
	0x70000000	; tmp continues
SP	0x7c80978e	; tmp continues
	0x7c809a51	; tmp continues
	0x11111101	; tmp buffer starts

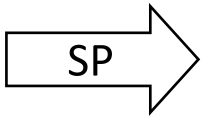



```
malicious
overflow
contents
0x7c971649 ; cmp argument
0x1111110c ; len argument
0x1111110b ; data argument
0xfeeb2ecd ; return address
0x70000000 ; saved base pointer
0x70000000 ; tmp final 4 bytes
0x00000040 ; tmp continues
0x00003000 ; tmp continues
0x00001000 ; tmp continues
0x70000000 ; tmp continues
0x7c80978e ; tmp continues
0x7c809a51 ; tmp continues
0x11111101 ; tmp buffer starts
```

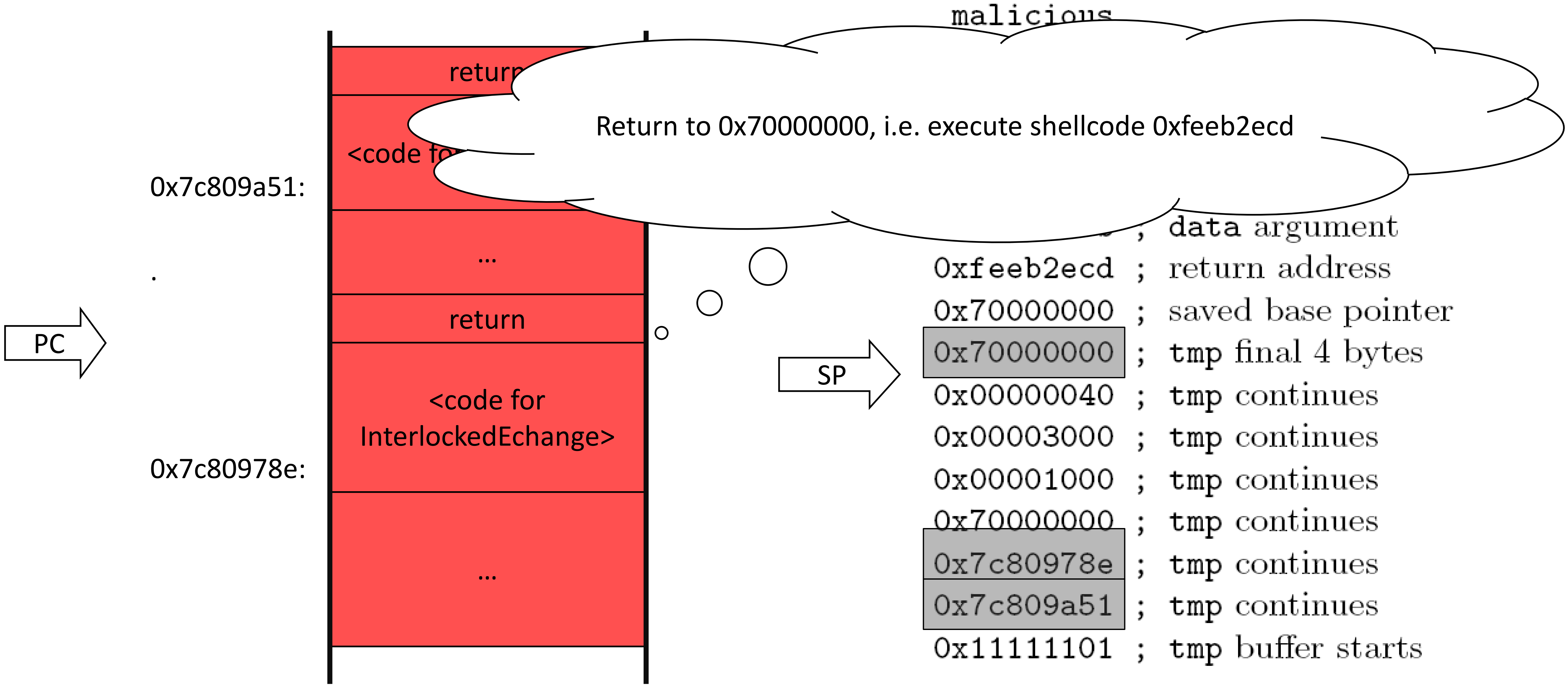


return
<code for VirtualAlloc>
0x7c809a51:
<code for InterlockedEchange>
0x7c80978e:
PC
...
SP
malicious overflow contents
0x7c971649 ; cmp argument
// call a function to write the four-byte attack payload to 0x70000000
InterlockedExchange(0x70000000, 0xfeeb2ecd); // function at 0x7c80978e
; tmp final 4 bytes
0x00000040 ; tmp continues
0x00003000 ; tmp continues
0x00001000 ; tmp continues
0x70000000 ; tmp continues
0x7c80978e ; tmp continues
0x7c809a51 ; tmp continues
0x11111101 ; tmp buffer starts






```
malicious
overflow
contents
0x7c971649 ; cmp argument
0x1111110c ; len argument
0x1111110b ; data argument
0xfeeb2ecd ; return address
0x70000000 ; saved base pointer
0x70000000 ; tmp final 4 bytes
0x00000040 ; tmp continues
0x00003000 ; tmp continues
0x00001000 ; tmp continues
0x70000000 ; tmp continues
0x7c80978e ; tmp continues
0x7c809a51 ; tmp continues
0x11111101 ; tmp buffer starts
```



malicious
Return to 0x70000000, i.e. execute shellcode 0xfeeb2ecd
return
<code fo
0x7c809a51:
...
.
PC
return
<code for InterlockedEchange>
0x7c80978e:
...
SP
; data argument
0xfeeb2ecd ; return address
0x70000000 ; saved base pointer
0x70000000 ; tmp final 4 bytes
0x00000040 ; tmp continues
0x00003000 ; tmp continues
0x00001000 ; tmp continues
0x70000000 ; tmp continues
0x7c80978e ; tmp continues
0x7c809a51 ; tmp continues
0x11111101 ; tmp buffer starts

Modern variant: Return-Oriented-Programming (ROP)

- Key idea:
  - Instead of using the stack to “return into” functions, use it to chain “gadgets”
  - A *gadget* is a small piece of machine code ending in return
  - By finding a Turing-complete set of gadgets, one can “compile” arbitrary code into a fake stack calling these gadgets

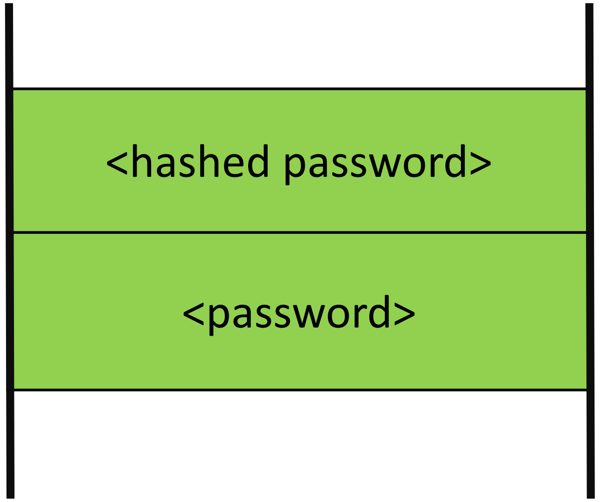
Attack scenario 4: Data-only attacks

- *Data-only attacks* proceed by changing only data of the program under attack
- Depending on the program under attack, this can result in interesting exploits
- We discuss two examples:
  - The unix password attack
  - Overwriting the environment table

Unix password attack

- Old implementations of login program looked like this:

Stack

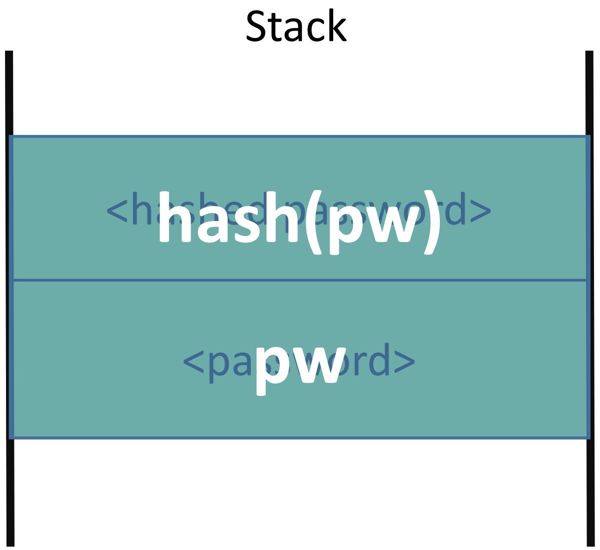


Password check in login program:

1. Read loginname
2. Lookup hashed password
3. Read password
4. Check if
   hashed password = hash (password)

Unix password attack

- Old implementations of login program looked like this:



Password check in login program:

1. Read loginname
2. Lookup hashed password
3. Read password
4. Check if
   hashed password = hash (password)

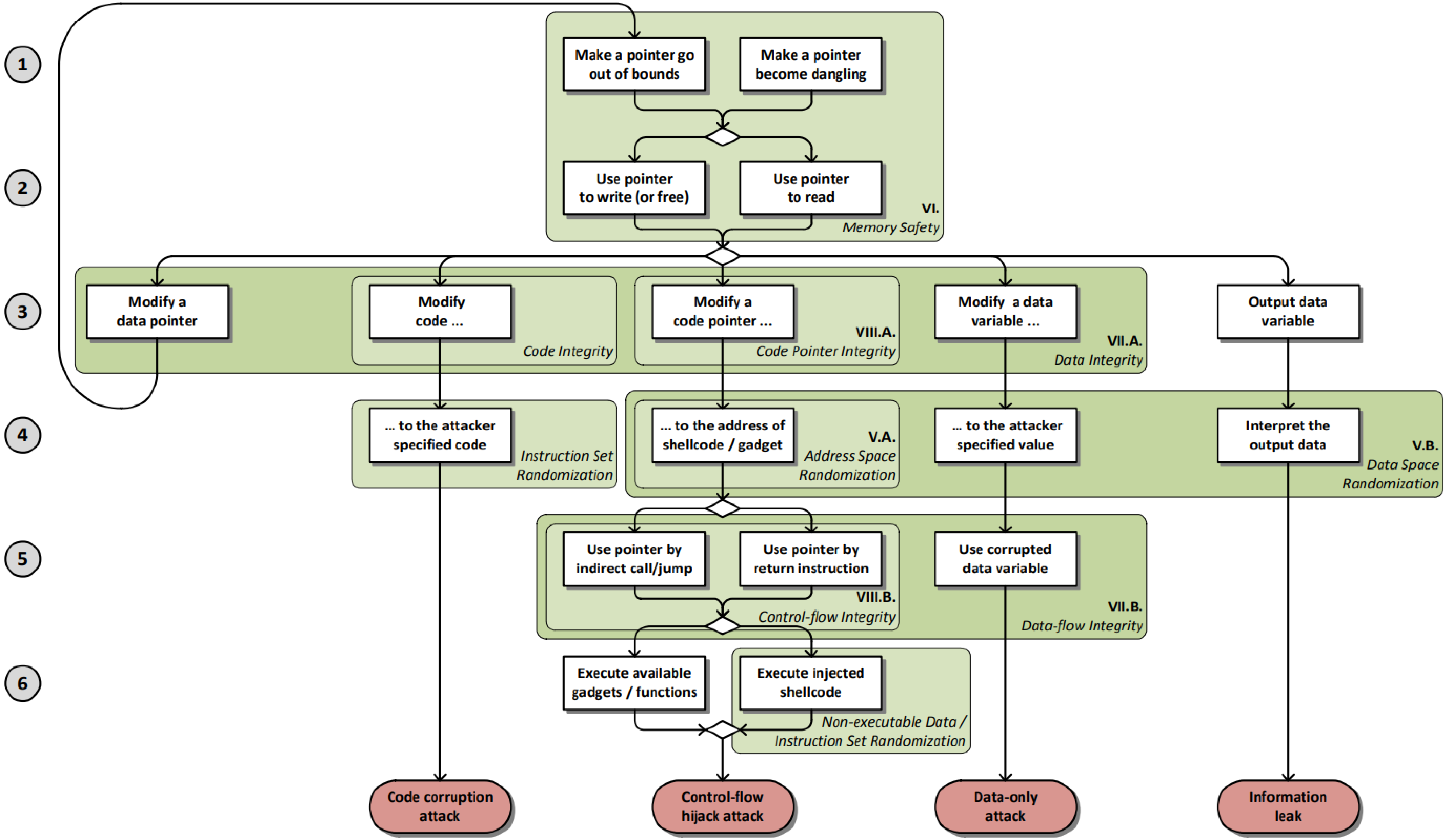
- Hence, typing in a password of the form pw ++ hash(pw) always succeeds

Overwriting the environment table

```
void run_command_with_argument( pairs* data, int offset, int value )
{
    // must have offset be a valid index into data
    char cmd[MAX_LEN];
    data[offset].argument = value;
    {
        char valuestring[MAX_LEN];
        itoa( value, valuestring, 10 );
        strcpy( cmd, getenv("SAFECOMMAND") );
        strcat( cmd, " " );
        strcat( cmd, valuestring );
    }
    data[offset].result = system( cmd );
}
```

Other attack scenarios

- We have discussed 4 attack scenarios:
  - Call stack smashing
  - Function pointer overwrite
  - Code-reuse attacks like return-oriented-programming
  - Data-only attacks
- Other variations exist and attacks can also be combined
- A structured overview of attacks is in:
  - Laszlo Szekeres, Mathias Payer, Tao Wei, Dawn Song: *SoK: Eternal War in Memory*. IEEE Symposium on Security and Privacy 2013.


1
2
3
4
5
6
Make a pointer go out of bounds
Make a pointer become dangling
Use pointer to write (or free)
Use pointer to read
VI.
Memory Safety
Modify a data pointer
Modify code ...
Code Integrity
Modify a code pointer ...
VIII.A.
Code Pointer Integrity
Modify a data variable ...
VII.A.
Data Integrity
Output data variable
... to the attacker specified code
Instruction Set Randomization
... to the address of shellcode / gadget
V.A.
Address Space Randomization
... to the attacker specified value
Interpret the output data
V.B.
Data Space Randomization
Use pointer by indirect call/jump
Use pointer by return instruction
VIII.B.
Control-flow Integrity
Use corrupted data variable
VII.B.
Data-flow Integrity
Execute available gadgets / functions
Execute injected shellcode
Non-executable Data / Instruction Set Randomization
Code corruption attack
Control-flow hijack attack
Data-only attack
Information leak

Overview

- System model
- Attack scenarios
- Mitigating attacks
- Avoiding vulnerabilities
- Conclusions

Mitigating attacks

- The first line of defense developed against the attacks we discussed builds in countermeasures in compiler/operating system/hardware to make attacks harder
- We discuss the widely deployed mitigations
- But all these defenses are *partial* – they just make it harder to develop an effective attack
- We will illustrate that by means of a running example taken from the SYSSEC 10K Challenge (http://10kstudents.eu/material/)

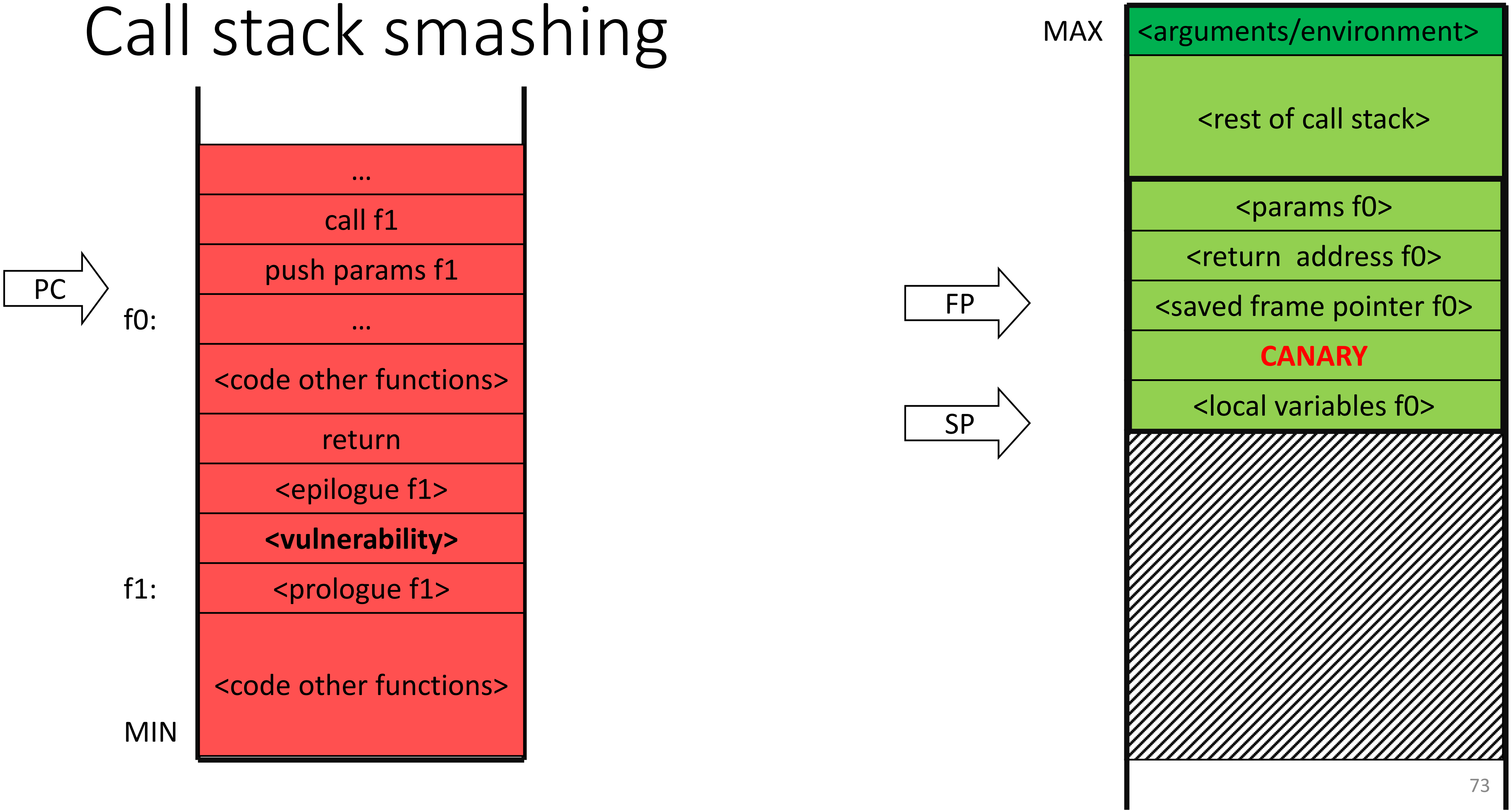
```c
char gWelcome[] = "Welcome to our system!";
void echo (int fd) {
  int len;
  char name[64],reply[128];

  len = strlen(gWelcome);
  memcpy(reply, gWelcome, len); /* copy the welcome string to reply */
  write_to_socket(fd, "Type your name:");
  read(fd,name,128);

  /* copy the name into the reply buffer (starting at offset len so
   * that we do not overwrite the welcome message) */
  memcpy(reply+len, name, 64);

 write(fd, reply, len + 64); /* send full welcome message to client */
  return;
}

void server(int socketfd) {
  while(1) echo(socketfd);
}
```


Source: http://10kstudents.eu/material/

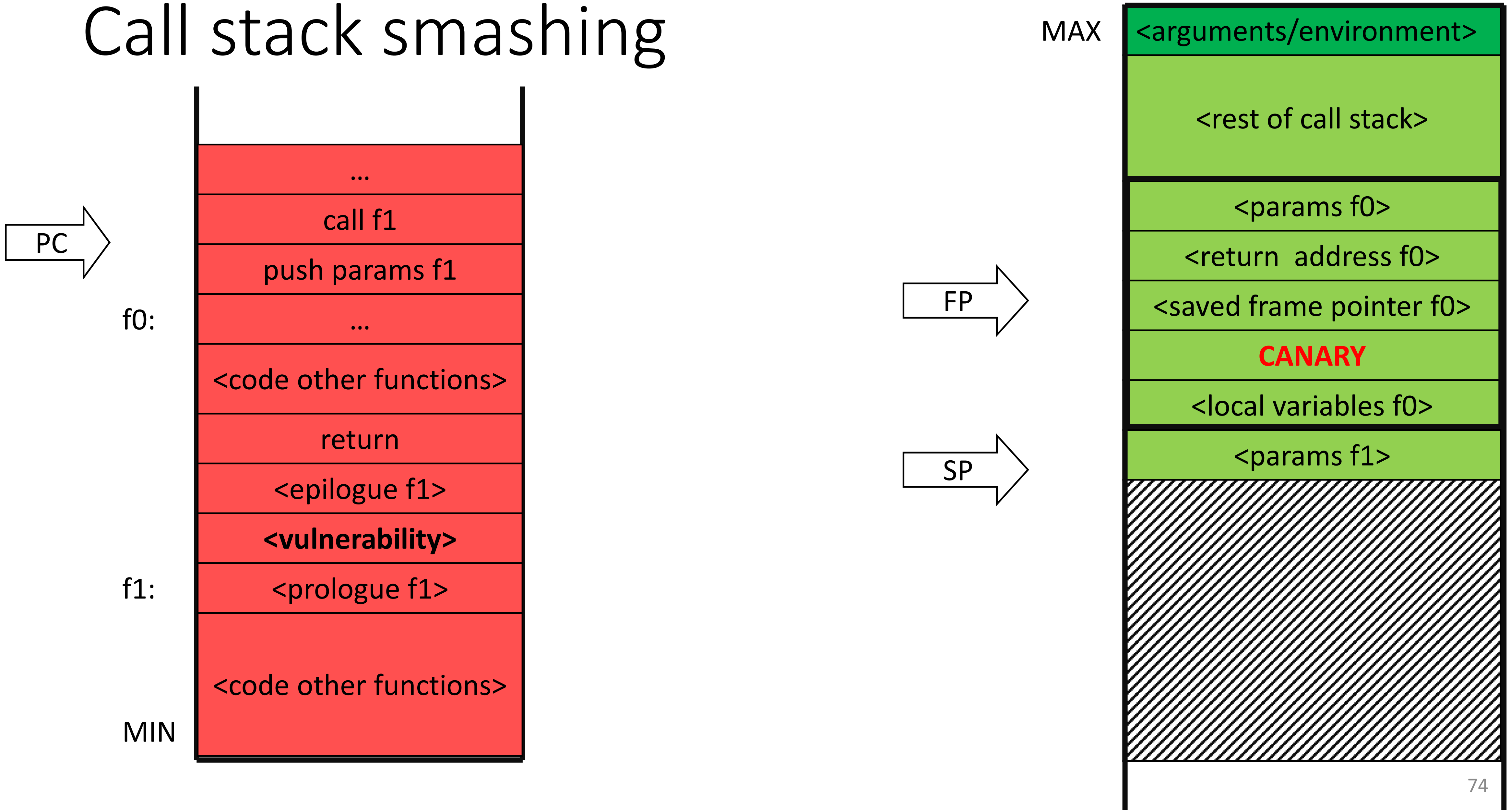
Mitigation 1: Stack canaries

- Basic idea
  - Insert a value in a stack frame right before the stored base pointer/return address
  - Verify on return from a function that this value was not modified
- The inserted value is called a *canary*, after the coal mine canaries

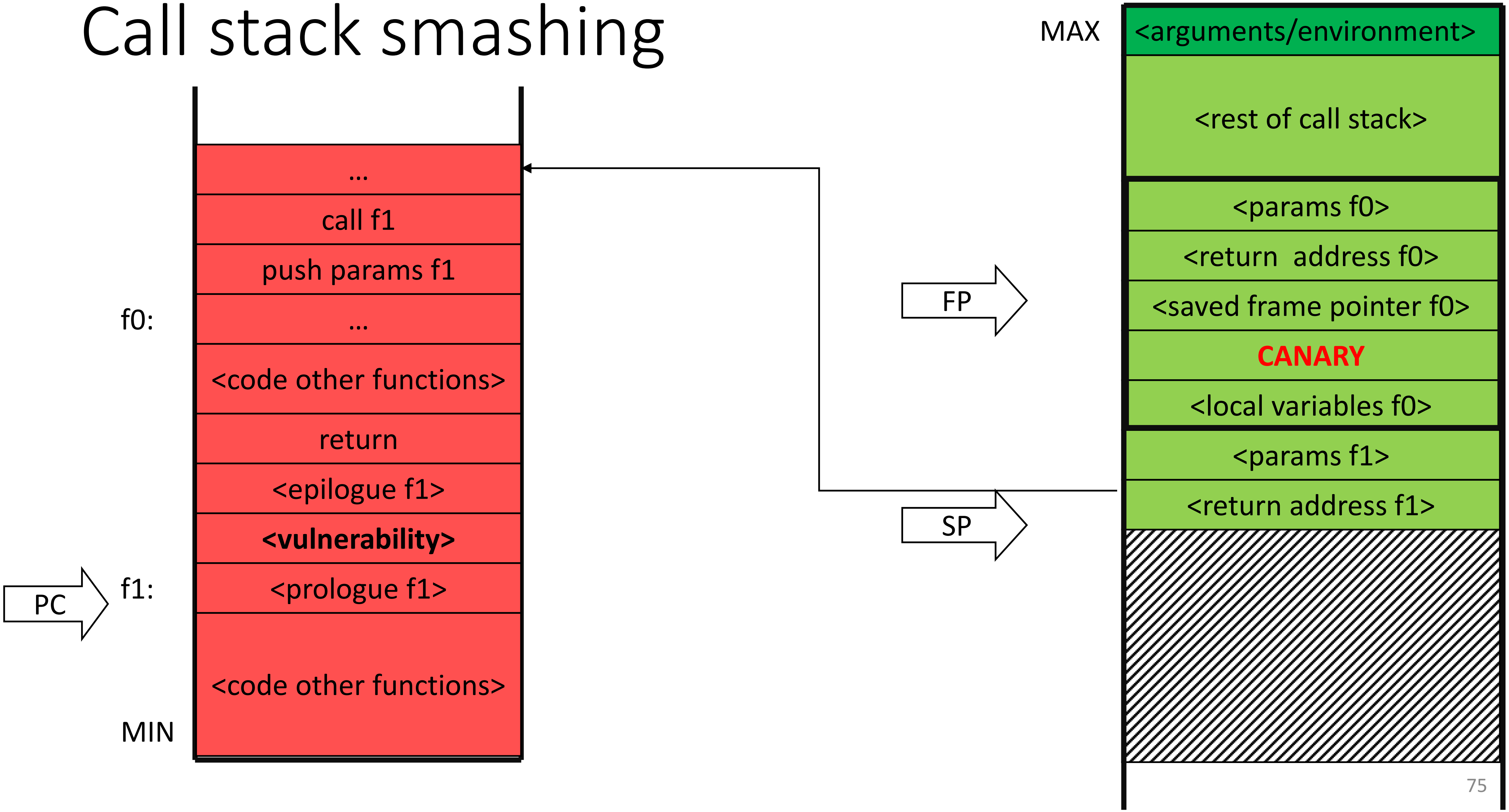
Call stack smashing



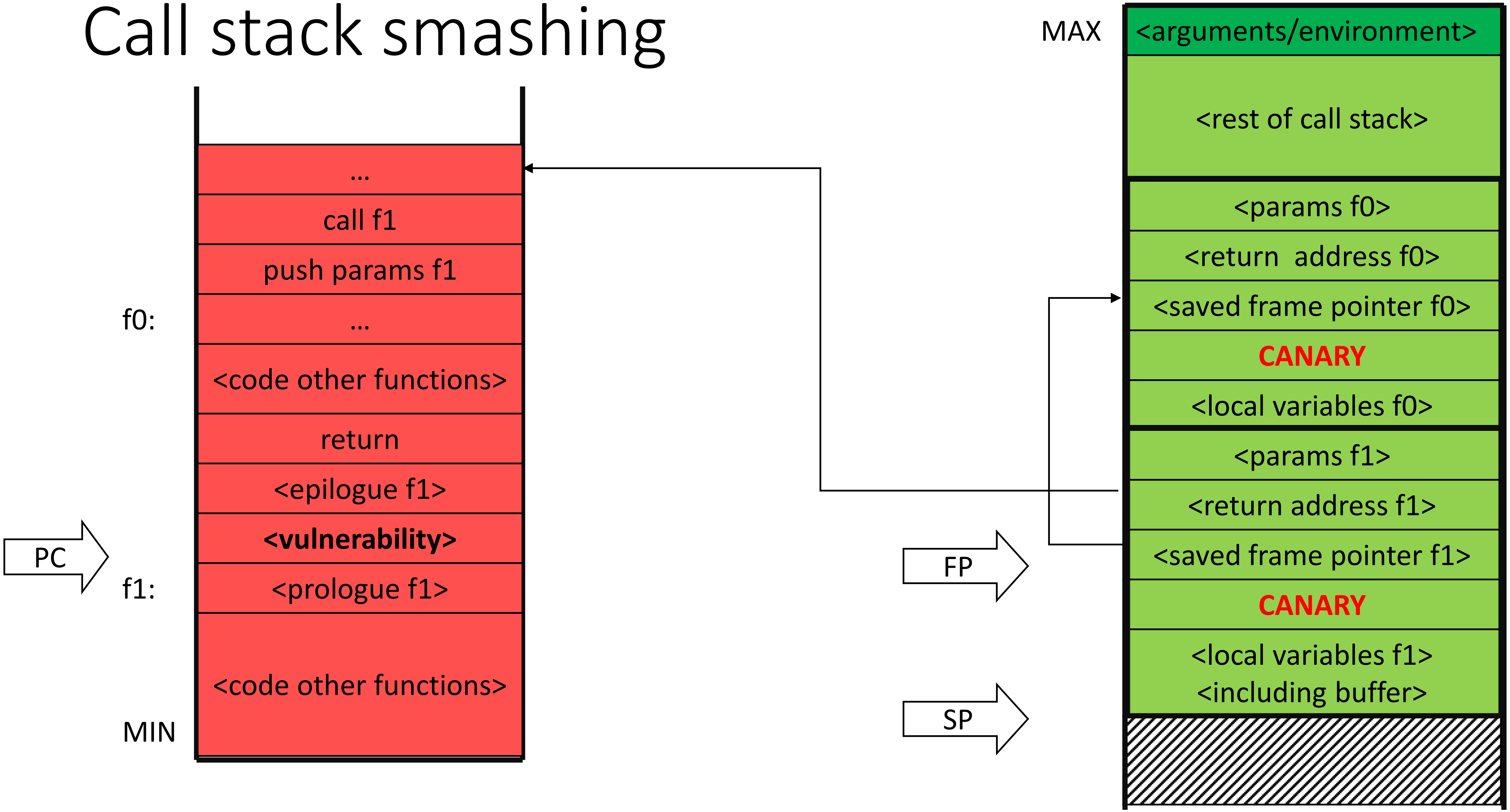
Call stack smashing



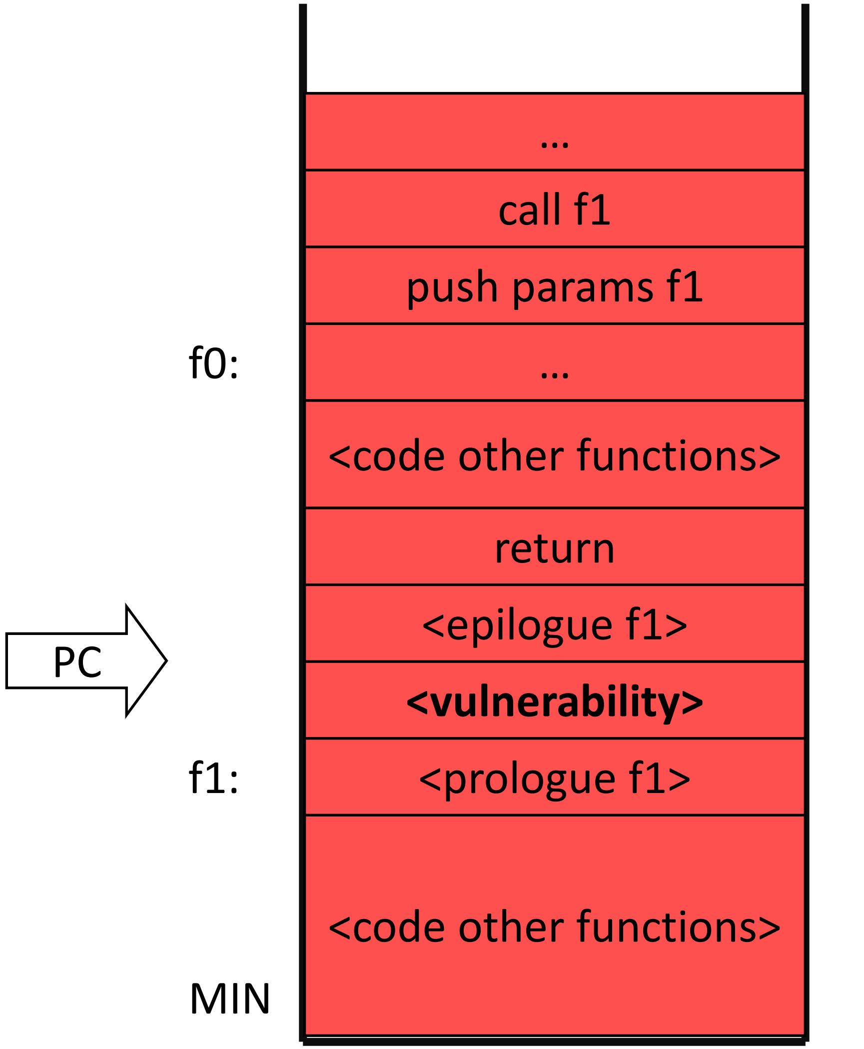
Call stack smashing

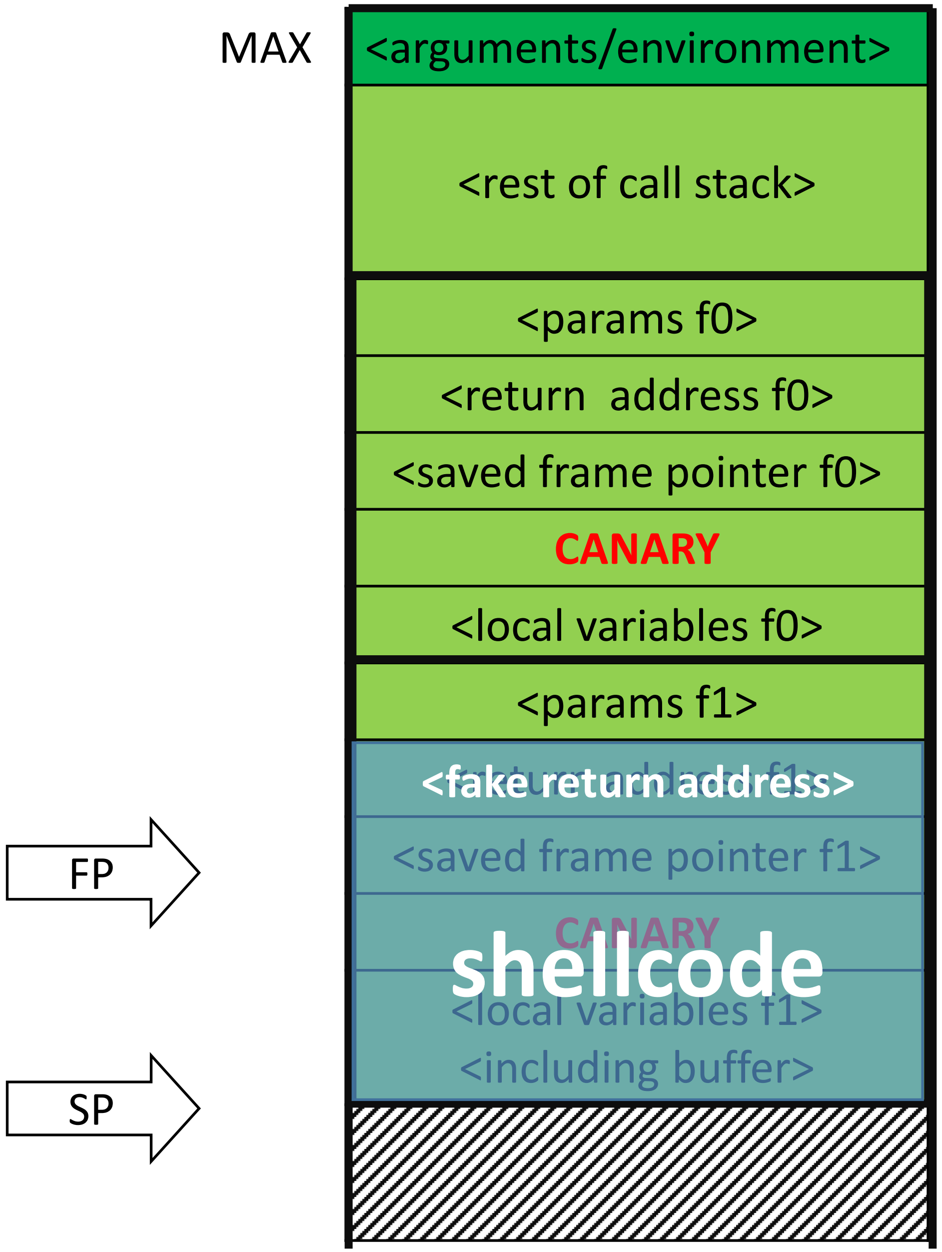


Call stack smashing

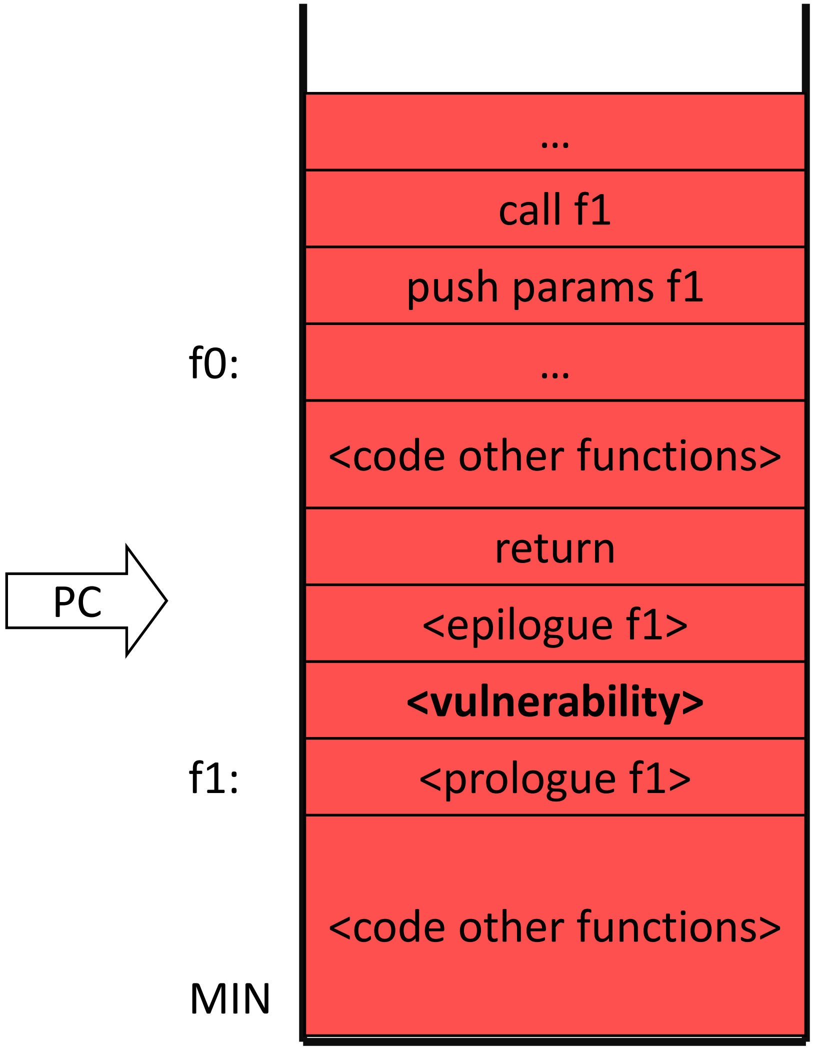


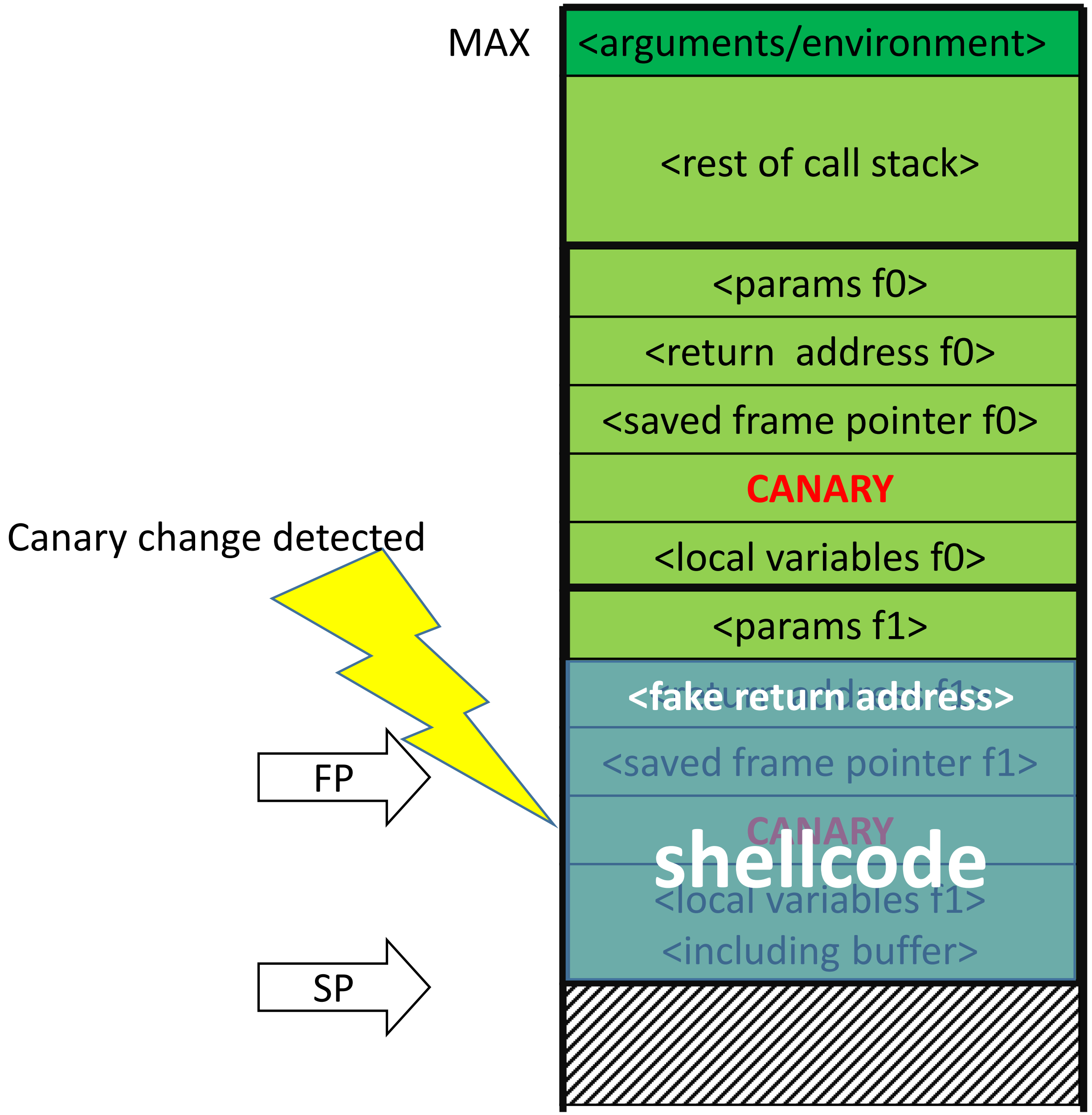
Call stack smashing





Call stack smashing





```c
char gWelcome[] = "Welcome to our system!";
void echo (int fd) {
  int len;
  char name[64],reply[128];

  len = strlen(gWelcome);
  memcpy(reply, gWelcome, len); /* copy the welcome string to reply */
  write_to_socket(fd, "Type your name:");
  read(fd,name,128);

  /* copy the name into the reply buffer (starting at offset len so
   * that we do not overwrite the welcome message) */
  memcpy(reply+len, name, 64);

 write(fd, reply, len + 64); /* send full welcome message to client */
  return;
}

void server(int socketfd) {
  while(1) echo(socketfd);
}
```


Source: http://10kstudents.eu/material/

Mitigation 2: Non-executable data

- Direct code injection attacks at some point execute data
- Most programs never need to do this
- Hence, a simple countermeasure is to mark data memory (stack, heap, ...) as non-executable, and code memory as non-writable
- This counters direct code injection and code corruption, but not code-reuse or data-only attacks
- In addition, this countermeasure may break certain legacy applications

```c
char gWelcome[] = "Welcome to our system!";
void echo (int fd) {
  int len;
  char name[64],reply[128];

  len = strlen(gWelcome);
  memcpy(reply, gWelcome, len); /* copy the welcome string to reply */
  write_to_socket(fd, "Type your name:");
  read(fd,name,128);

  /* copy the name into the reply buffer (starting at offset len so
   * that we do not overwrite the welcome message) */
  memcpy(reply+len, name, 64);

 write(fd, reply, len + 64); /* send full welcome message to client */
  return;
}

void server(int socketfd) {
  while(1) echo(socketfd);
}
```


Source: http://10kstudents.eu/material/

Mitigation 3: Address Space Layout Randomization

- Most attacks rely on precise knowledge of run time memory addresses
- Introducing artificial variation in these addresses significantly raises the bar for attackers
- Such adress space layout randomization (ASLR) is a cheap and effective countermeasure

Example

```c
int median( int* data, int len, void* cmp )
{
    // must have 0 < len <= MAX_INTS
    int tmp[MAX_INTS];
    memcpy( tmp, data, len*sizeof(int) ); // copy the input integers
    qsort( tmp, len, sizeof(int), cmp ); // sort the local copy
    return tmp[len/2]; // median is in the middle
}
```

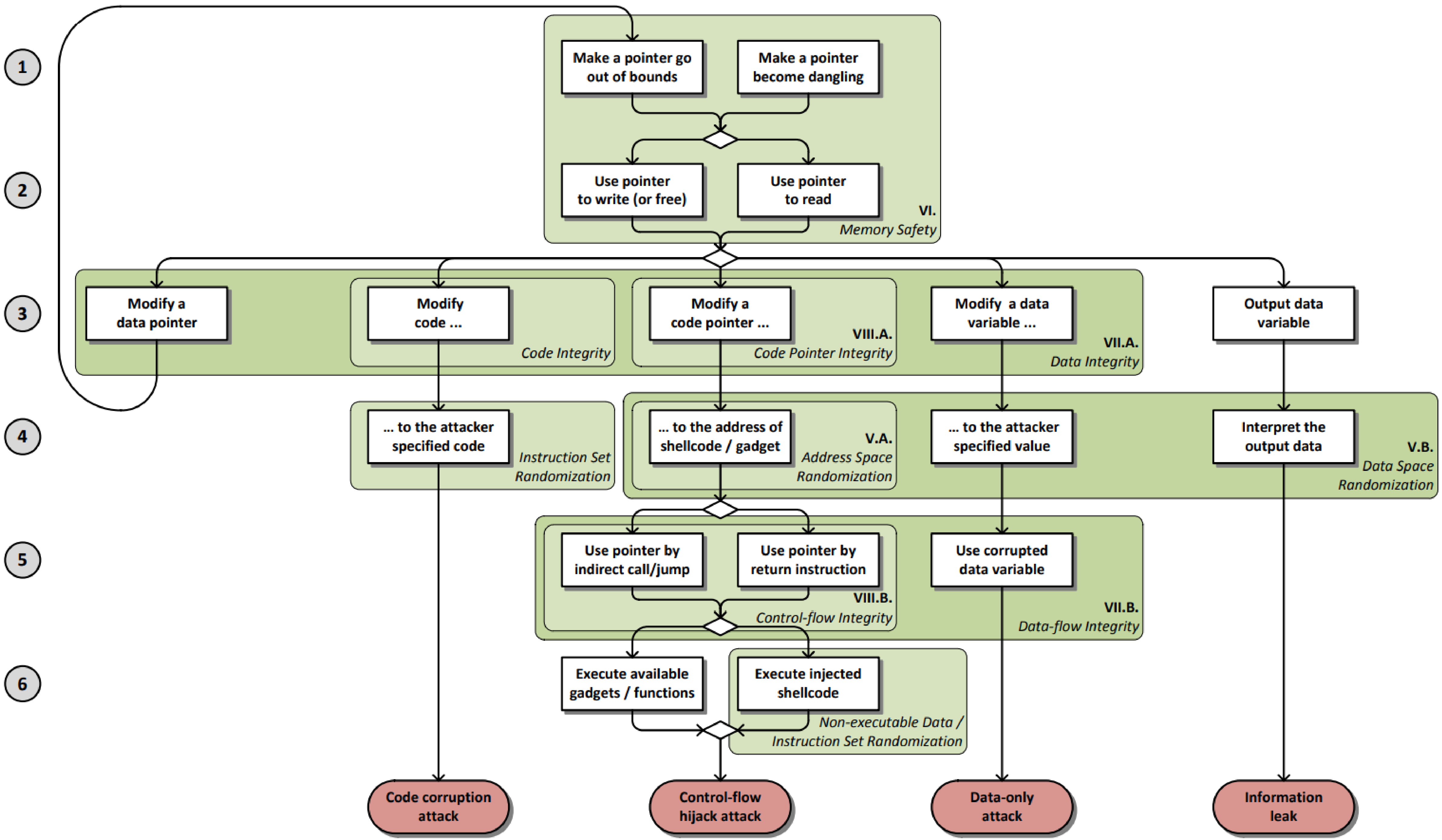
stack one		stack two		
address	contents	address	contents	
0x0022feac	0x008a13e0	0x0013f750	0x00b113e0	; cmp argument
0x0022fea8	0x00000001	0x0013f74c	0x00000001	; len argument
0x0022fea4	0x00a91147	0x0013f748	0x00191147	; data argument
0x0022fea0	0x008a1528	0x0013f744	0x00b11528	; return address
0x0022fe9c	0x0022fec8	0x0013f740	0x0013f76c	; saved base pointer
0x0022fe98	0x00000000	0x0013f73c	0x00000000	; tmp final 4 bytes
0x0022fe94	0x00000000	0x0013f738	0x00000000	; tmp continues
0x0022fe90	0x00000000	0x0013f734	0x00000000	; tmp continues
0x0022fe8c	0x00000000	0x0013f730	0x00000000	; tmp continues
0x0022fe88	0x00000000	0x0013f72c	0x00000000	; tmp continues
0x0022fe84	0x00000000	0x0013f728	0x00000000	; tmp continues
0x0022fe80	0x00000000	0x0013f724	0x00000000	; tmp continues
0x0022fe7c	0x00000000	0x0013f720	0x00000000	; tmp buffer starts
0x0022fe78	0x00000004	0x0013f71c	0x00000004	; memcpy length argument
0x0022fe74	0x00a91147	0x0013f718	0x00191147	; memcpy source argument
0x0022fe70	0x0022fe8c	0x0013f714	0x0013f730	; memcpy destination arg.

```c
char gWelcome[] = "Welcome to our system!";
void echo (int fd) {
  int len;
  char name[64],reply[128];

  len = strlen(gWelcome);
  memcpy(reply, gWelcome, len); /* copy the welcome string to reply */
  write_to_socket(fd, "Type your name:");
  read(fd,name,128);

  /* copy the name into the reply buffer (starting at offset len so
   * that we do not overwrite the welcome message) */
  memcpy(reply+len, name, 64);

 write(fd, reply, len + 64); /* send full welcome message to client */
  return;
}

void server(int socketfd) {
  while(1) echo(socketfd);
}
```


Source: http://10kstudents.eu/material/

Other mitigations

- A wide variety of other such mitigations have been investigated
- Again, a good overview is provided by:
    - Laszlo Szekeres, Mathias Payer, Tao Wei, Dawn Song: *SoK: Eternal War in Memory*. IEEE Symposium on Security and Privacy 2013.
- But the general belief is that these automatic, efficient "mitigate-the-exploit" approaches are just stop-gap measures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Data Integrity
Output data variable
... to the attacker specified code
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... to the address of shellcode / gadget
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Data-flow Integrity
Execute available gadgets / functions
Execute injected shellcode
Non-executable Data / Instruction Set Randomization
Code corruption attack
Control-flow hijack attack
Data-only attack
Information leak

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Low-level vulnerabilities

- A C program can only be attacked using the techniques we discussed if it has a *memory management vulnerability*, a bug that can lead to an incorrect memory access
- These vulnerabilities come in a number of forms:
  - Spatial vulnerability: access allocated memory out of bounds
  - Temporal vulnerability: access memory after it has been freed.
  - Pointer forging: an invalid construction of a pointer, for instance through casting
  - Incorrect call of a function that supports a variable number of arguments, for instance the printf() family of functions

Spatial vulnerabilities

- Programming languages can offer various mechanisms to index into allocated memory regions:
  - Array indexing a[i]
  - Field access in structs, unions or objects
  - Pointer arithmetic, where a pointer “walks” over an allocated region of memory
    - E.g. `for( ; *src != ’\0’; ++src, ++tgt ) *tgt = *src;`
- Each of these mechanisms can lead to spatial memory vulnerabilities

Temporal vulnerabilities

- How long are pointers valid?

```
int global;

int *f(int param) {
    int local;
    int *p1 = &global;
    int *p2 = &param;
    int *p3 = &local;
    int *p4 = malloc(sizeof(int));
    return p1; // or p2, or p3 or p4?
}
```

Example temporal vulnerability

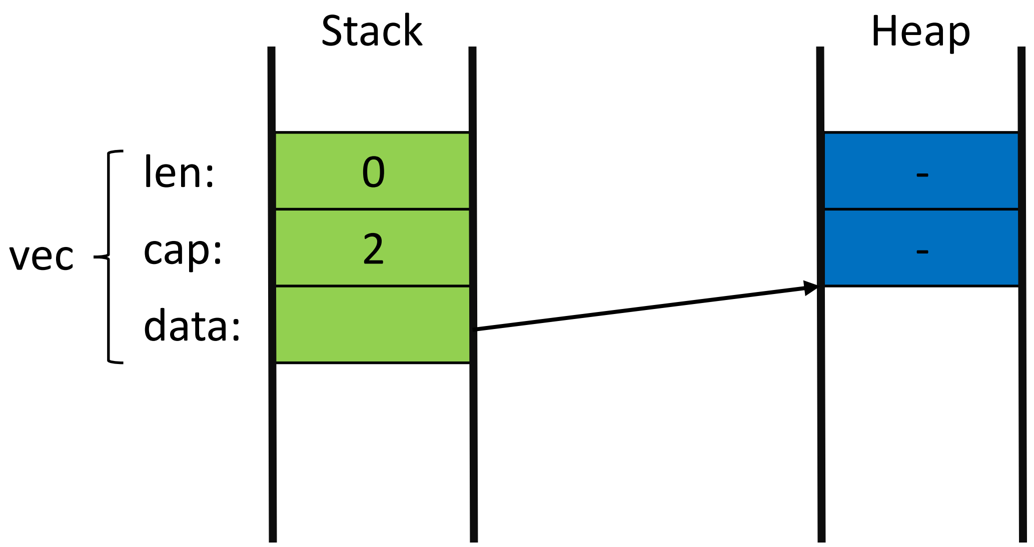
```c
typedef struct {
    int len;
    int cap;
    int *data;
} vec;
vec newvec() {
    vec v;
    v.len = 0;
    v.cap = 2;
    v.data = malloc(2 * sizeof(int));
    return v;
}
void push(vec* v, int i) {
    if (v->len >= v->cap) {
        v->cap *= 2;
        int *new = malloc(v->cap * sizeof(int));
        memcpy(new,v->data, v->len *sizeof(int));
        free(v->data);
        v->data = new;
    }
    v->data[v->len++] = i;
}
```

```c
void printvec(vec v) {
    int i;
    for (int i = 0; i< v.len; i++) {
        printf("%d\n",v.data[i]);
    }
}
int* get(vec* v, int i) {
    return v->data + i;
}
void main() {
    vec v = newvec();
    int i;
    push(&v,0);
    printvec(v);
    int* i0 = get(&v,0);
    *i0 = 10;
    printvec(v);
    for (i=1; i< 4; i++) push(&v,i);
    printvec(v);
    *i0 = 20;
    printvec(v);
}
```

Example temporal vulnerability

```
void main() {
    vec v = newvec();
    int i;
    push(&v,0);
    printvec(v);
    int* i0 = get(&v,0);
    *i0 = 10;
    printvec(v);
    for (i=1; i< 4; i++) push(&v,i);
    printvec(v);
    *i0 = 20;
    printvec(v);
}
```

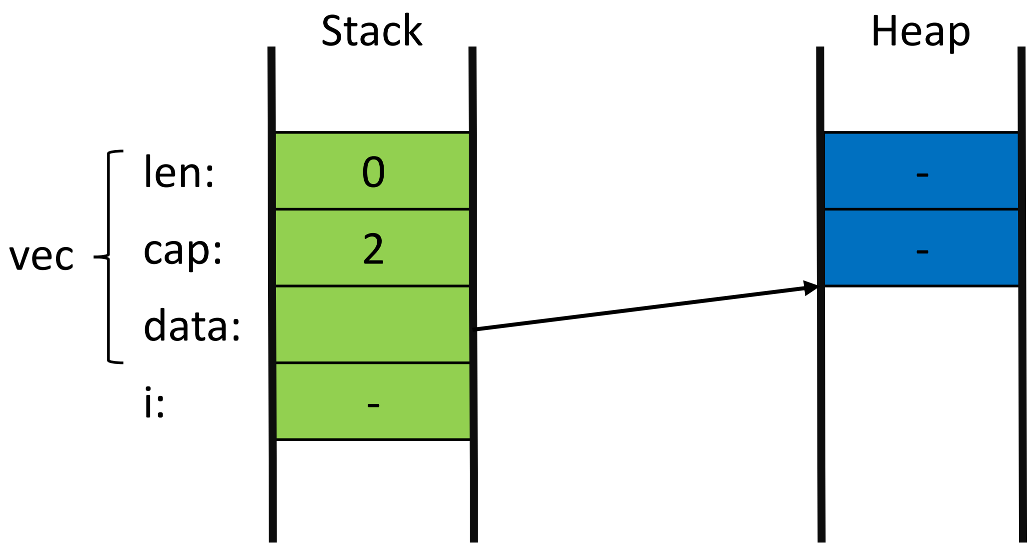
Output:



Example temporal vulnerability

```
void main() {
    vec v = newvec();
    int i;
    push(&v,0);
    printvec(v);
    int* i0 = get(&v,0);
    *i0 = 10;
    printvec(v);
    for (i=1; i< 4; i++) push(&v,i);
    printvec(v);
    *i0 = 20;
    printvec(v);
}
```

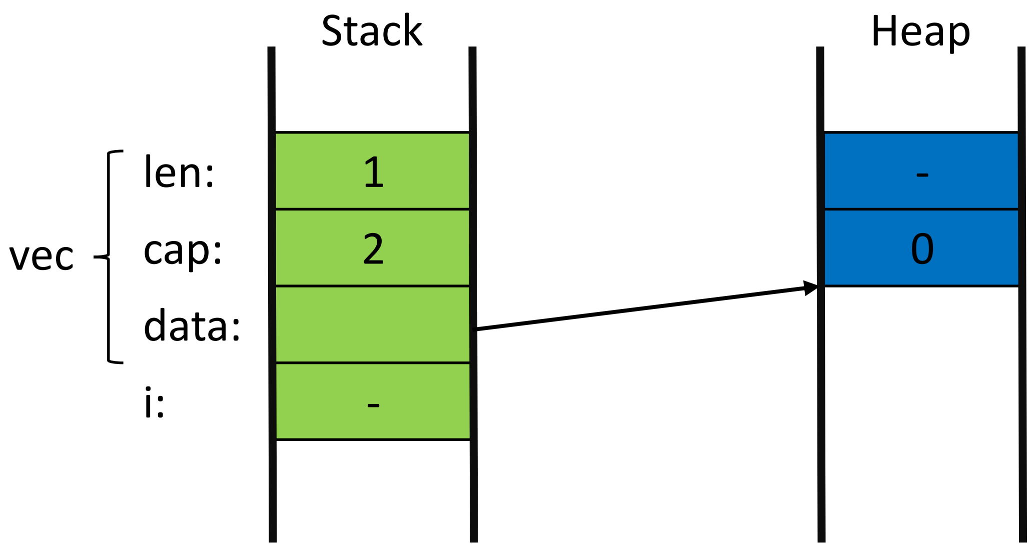
Output:



Example temporal vulnerability

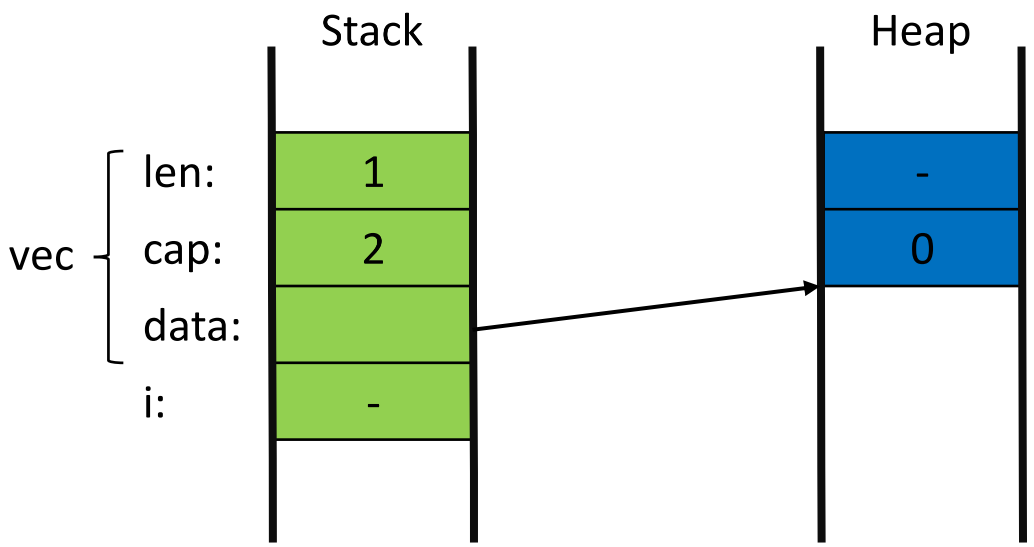
```
void main() {
    vec v = newvec();
    int i;
    push(&v,0);
    printvec(v);
    int* i0 = get(&v,0);
    *i0 = 10;
    printvec(v);
    for (i=1; i< 4; i++) push(&v,i);
    printvec(v);
    *i0 = 20;
    printvec(v);
}
```

Output:



Example temporal vulnerability

```
void main() {
    vec v = newvec();
    int i;
    push(&v,0);
    printvec(v);
    int* i0 = get(&v,0);
    *i0 = 10;
    printvec(v);
    for (i=1; i< 4; i++) push(&v,i);
    printvec(v);
    *i0 = 20;
    printvec(v);
}
```

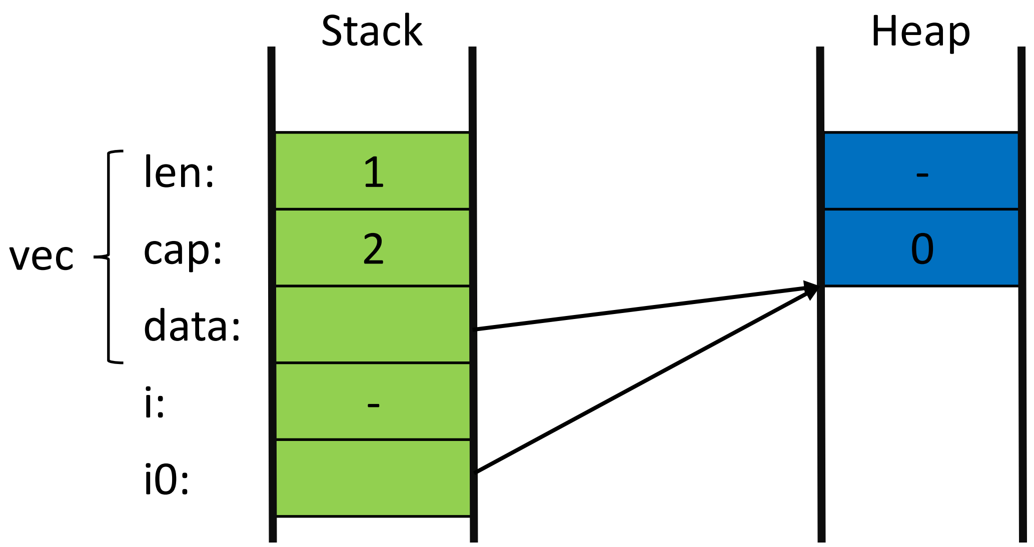


Output:
0

Example temporal vulnerability

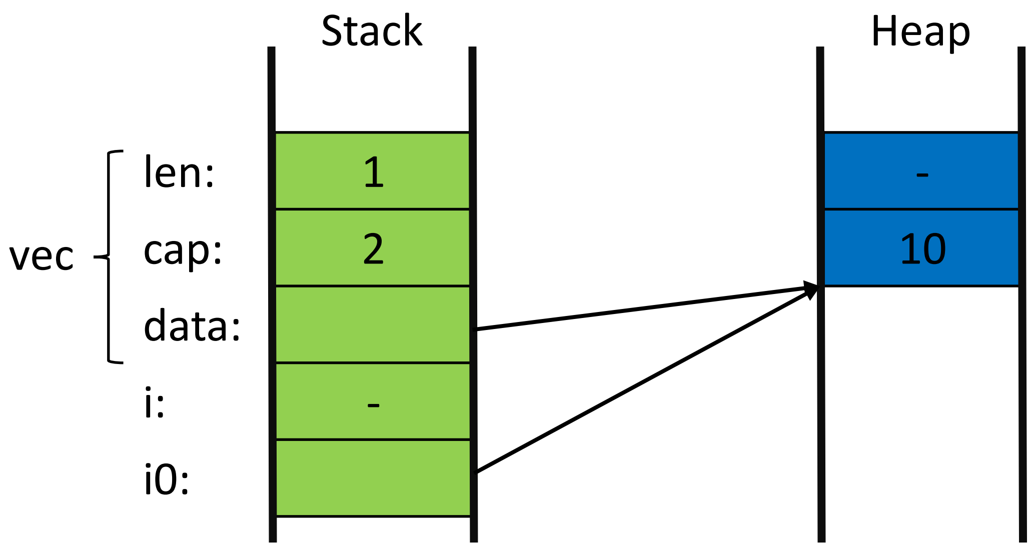
```
void main() {
    vec v = newvec();
    int i;
    push(&v,0);
    printvec(v);
    int* i0 = get(&v,0);
    *i0 = 10;
    printvec(v);
    for (i=1; i< 4; i++) push(&v,i);
    printvec(v);
    *i0 = 20;
    printvec(v);
}
```

Output:
0



Example temporal vulnerability

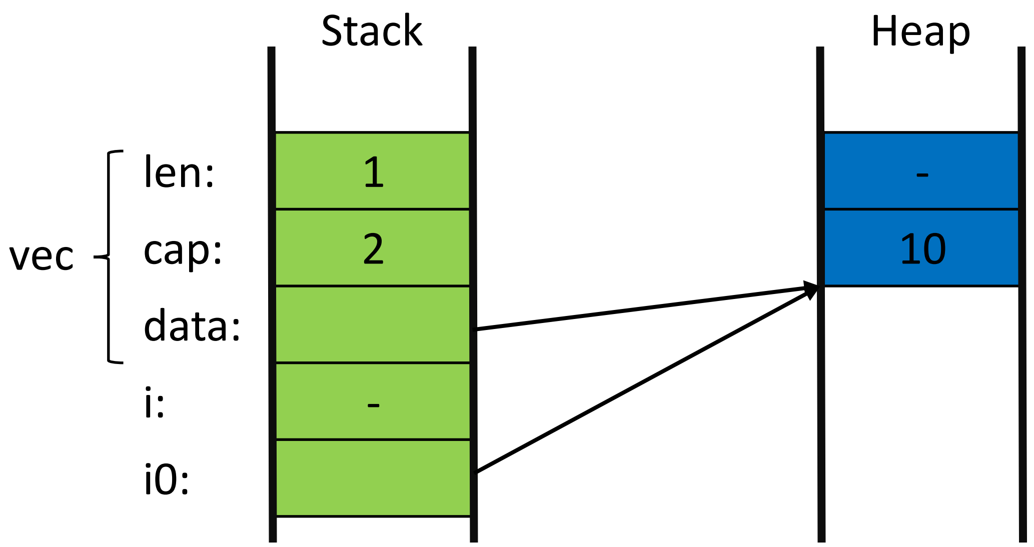
```
void main() {
    vec v = newvec();
    int i;
    push(&v,0);
    printvec(v);
    int* i0 = get(&v,0);
    *i0 = 10;
    printvec(v);
    for (i=1; i< 4; i++) push(&v,i);
    printvec(v);
    *i0 = 20;
    printvec(v);
}
```



Output:
0

Example temporal vulnerability

```
void main() {
    vec v = newvec();
    int i;
    push(&v,0);
    printvec(v);
    int* i0 = get(&v,0);
    *i0 = 10;
    printvec(v);
    for (i=1; i< 4; i++) push(&v,i);
    printvec(v);
    *i0 = 20;
    printvec(v);
}
```

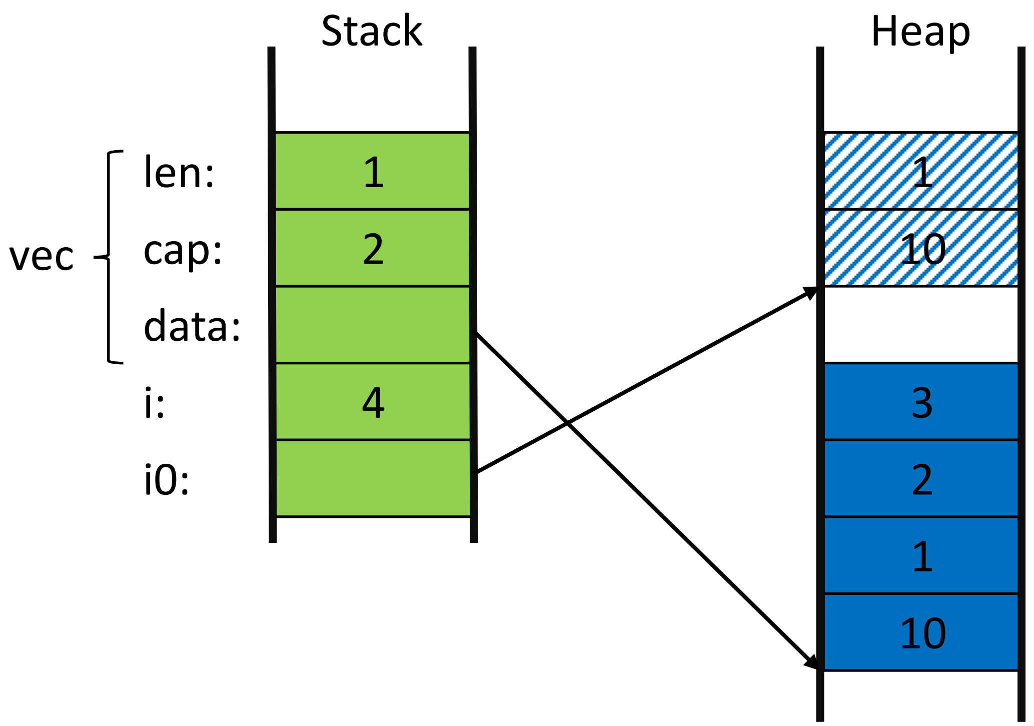


Output:
0
10

Example temporal vulnerability

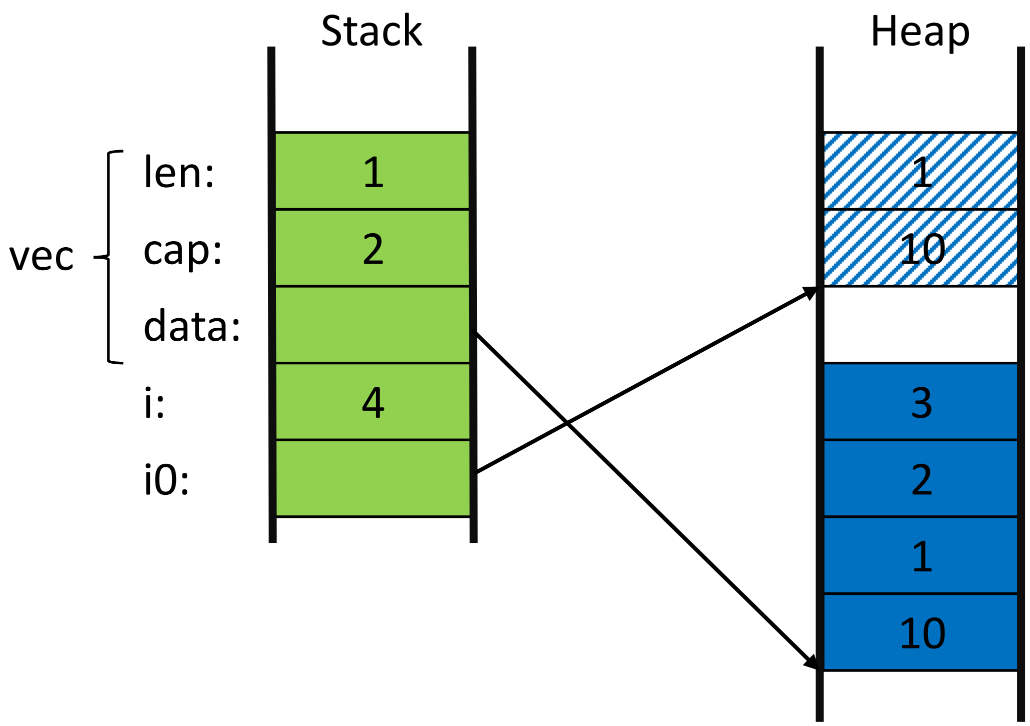
```
void main() {
    vec v = newvec();
    int i;
    push(&v,0);
    printvec(v);
    int* i0 = get(&v,0);
    *i0 = 10;
    printvec(v);
    for (i=1; i< 4; i++) push(&v,i);
    printvec(v);
    *i0 = 20;
    printvec(v);
}
```

Output:
0
10



Example temporal vulnerability

```
void main() {
    vec v = newvec();
    int i;
    push(&v,0);
    printvec(v);
    int* i0 = get(&v,0);
    *i0 = 10;
    printvec(v);
    for (i=1; i< 4; i++) push(&v,i);
    printvec(v);
    *i0 = 20;
    printvec(v);
}
```



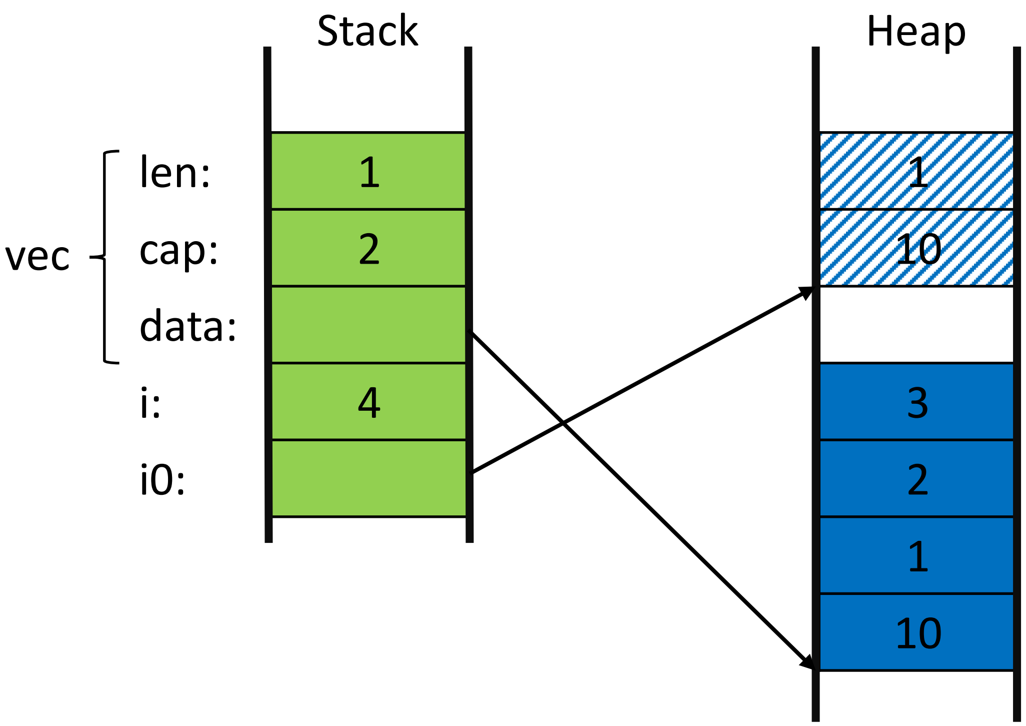
Output:
0
10
10
1
2
3

Example temporal vulnerability

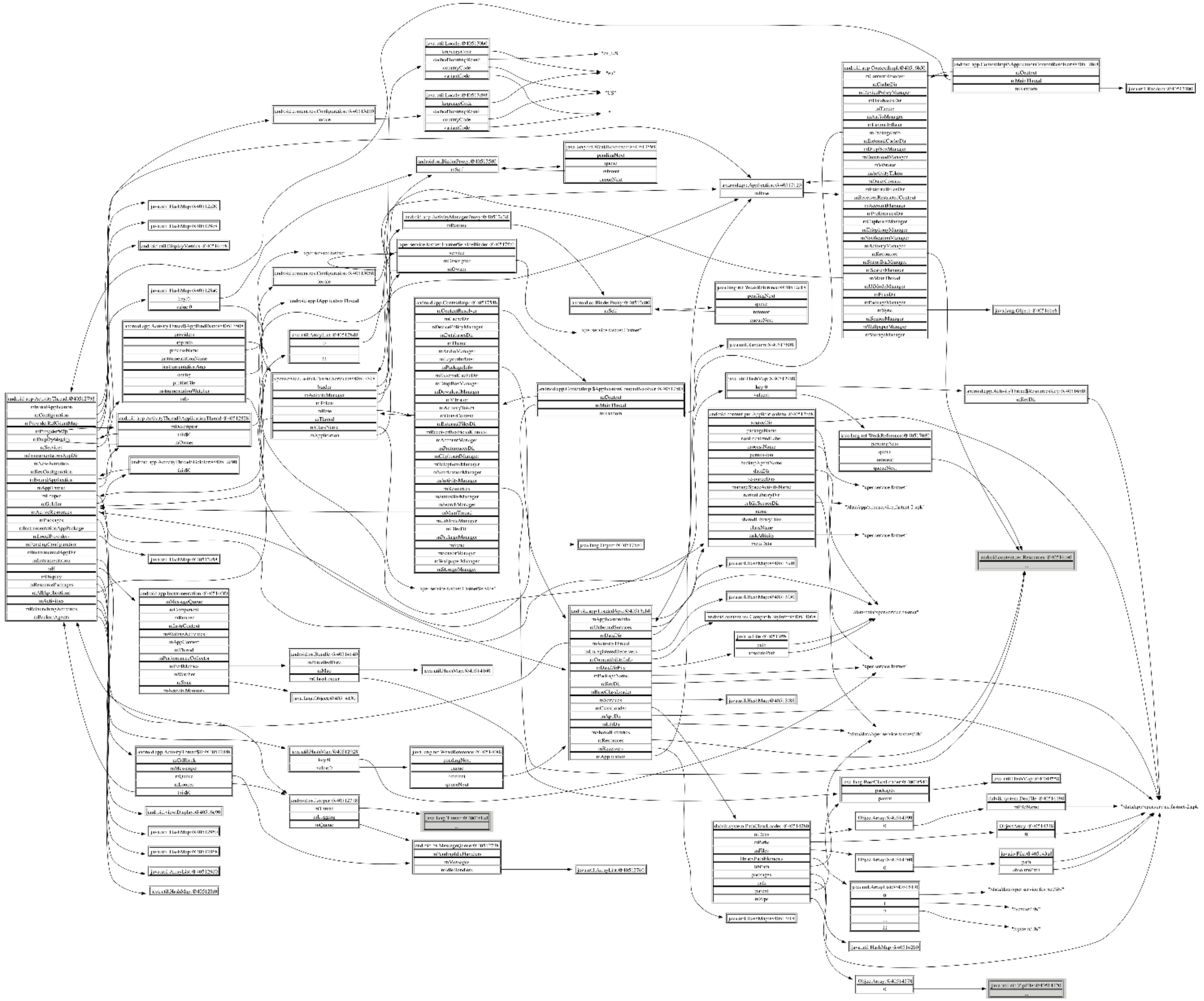
```
void main() {
    vec v = newvec();
    int i;
    push(&v,0);
    printvec(v);
    int* i0 = get(&v,0);
    *i0 = 10;
    printvec(v);
    for (i=1; i< 4; i++) push(&v,i);
    printvec(v);
    *i0 = 20;
    printvec(v);
}
```

Output:
0
10
10
1
2
3

Temporal memory error



Real heap is more complicated …



Avoiding such vulnerabilities

- Preventing introduction
  - Coding guidelines
  - Use of safe languages
- Detecting
  - Code review
  - Static analysis
    - Simple “grep”-like tools that detect unsafe functions
    - Advanced heuristic tools that have false positives and false negatives
    - Sound tools that require significant programmer effort to annotate the program
  - Testing
    - Fuzz testing
    - Directed fuzz-testing / symbolic execution
    - Run-time memory safety checkers
      - E.g. AddressSanitizer

Overview

- System model
- Attack scenarios
- Mitigating attacks
- Avoiding vulnerabilities
- Conclusions

Conclusions

- The security of software in C-like languages has been the subject of decades of *attacker-defender race*
- The desire to maintain C's performance and backward compatibility have made rigorous solutions to the problem of memory management vulnerabilities hard
- But some promising solutions are on the horizon
  - Hardware support for safe compilation of C
  - New systems programming languages with better safety guarantees
- Reading material:
  - Mandatory: Erlingsson, Younan, Piessens, *Low-level software security by example*
    - https://lirias.kuleuven.be/retrieve/110131
  - Recommended: Szekeres, Payer, Wei, Song, *SoK: Eternal War in Memory*
    - https://people.eecs.berkeley.edu/~dawnsong/papers/Oakland13-SoK-CR.pdf