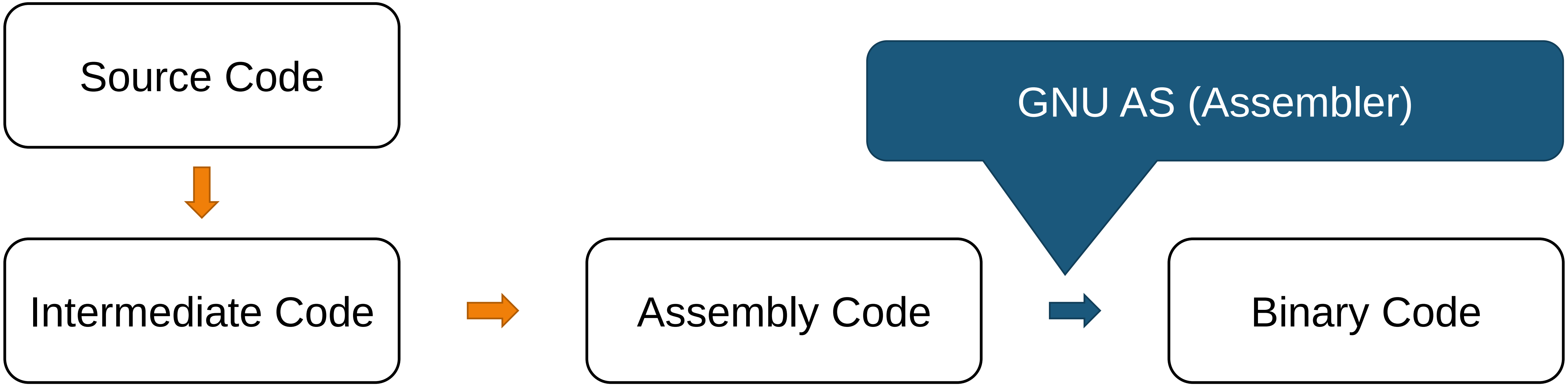
Lec 9: Control-flow Hijack

CS492E: Introduction to Software Security

Sang Kil Cha

Compilation



Source Code

Intermediate Code

Assembly Code

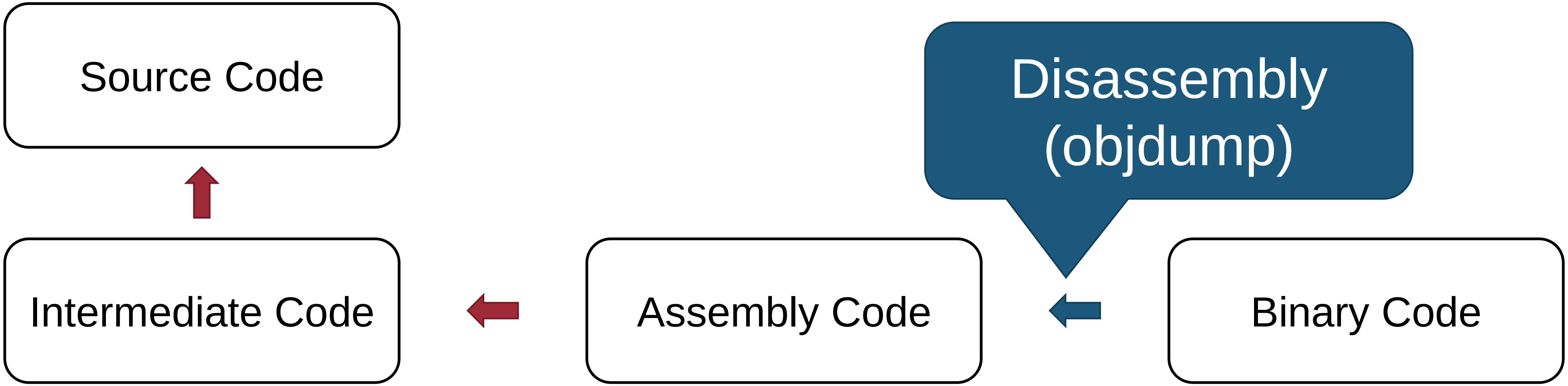
GNU AS (Assembler)

Binary Code

```
0:   push ebp
1:   mov ebp, esp
3:   sub esp, 0x18
…
```

```
0101010101101110110
0000010111111010100
0010101001010111010
```

Understanding Binary



```
0:   push ebp
1:   mov ebp, esp
3:   sub esp, 0x18
…
```

```
010101010110111011O
```

Disassembly is Difficult

- Indirect jumps
  - `jmp [eax]`
  - `call [eax]`

- Mixture of code and data

Example: Linear Sweep Disassembly

```
.intel_syntax noprefix
inc ebx
sub eax, ebx
call lbl
.ascii “hello world”
lbl:
pop eax
```

Try to assemble it and disassemble the resulting binary with objdump

Recursive Traversal Disassembly

- a.k.a. Recursive Descent Disassembly
- Follow control-flows starting from some entry points

Complex Constructs

- Shared basic blocks
- Overlapping instructions
- Inlined data
- Alignment data
- Tail call optimization
- Etc.

Software Bug

= an error in a program

Question

What kind of bugs are important for security?

For example, if you only have time for fixing one bug out of ten, which bug will you fix first?

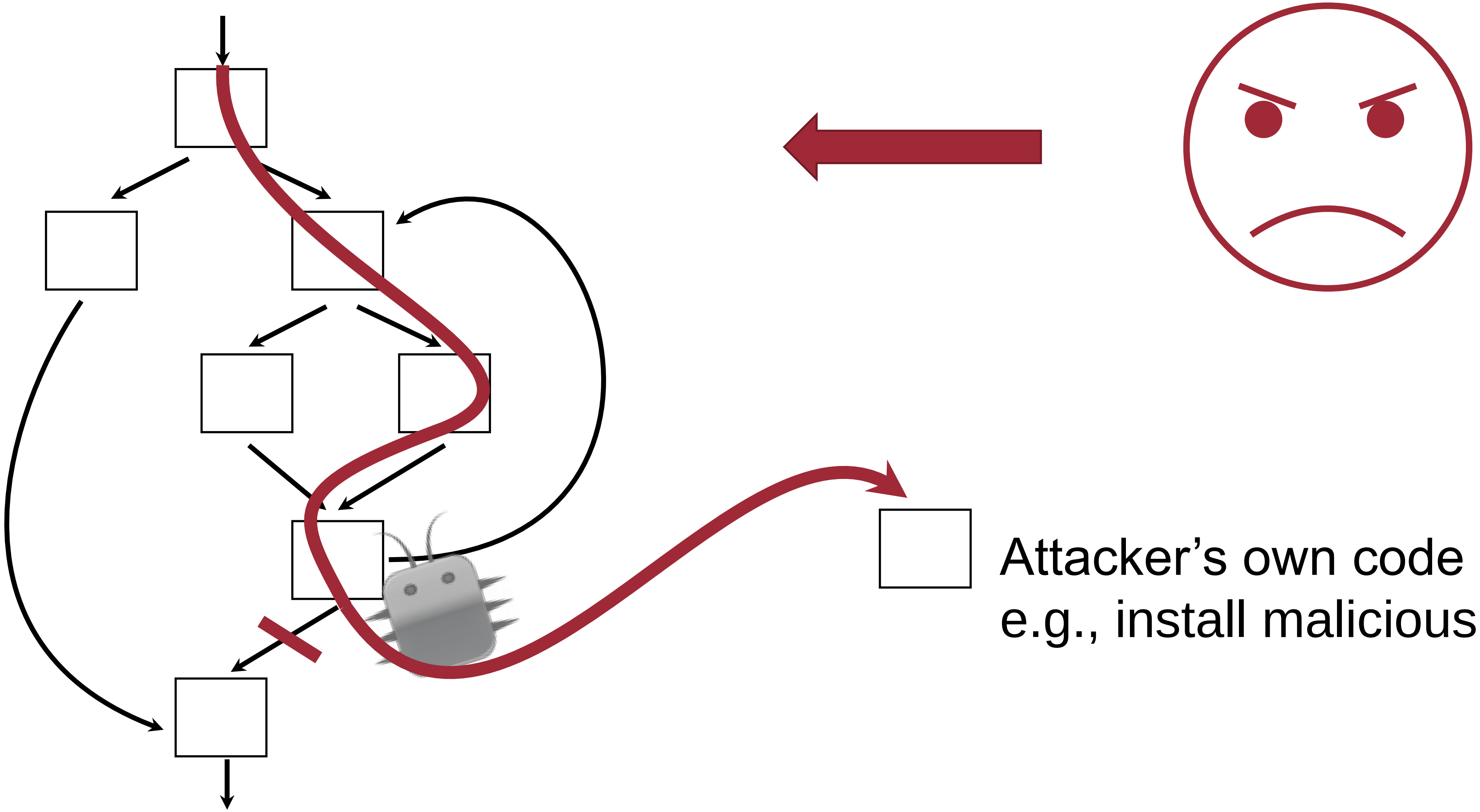
Exploitable Bug

We often call ***exploitable bugs*** as vulnerabilities.

Exploitation is the act of taking advantage of a bug to cause ***unintended behavior*** of the target program.

Some vulnerabilities allow an attacker to run any ***arbitrary code*** on victim’s machines without their consent.

Control Flow Hijack Exploit



Attacker’s own code
e.g., install malicious software

Classic Exploitation

Nov. 2, 1988

The first computer worm (called Morris Worm) was born.

Robert Tappan Morris

Creator of the worm
Cornell graduate
Tenured professor at MIT now

Image from www.[illegible]

Morris Worm

Exploited a ***buffer overflow*** vulnerability in `fingerd`

```
int main(int argc, char* argv[])
{
  char line[512];
  /* omitted … */
  gets(line); /* Buffer Overflow! */
  /* omitted … */
}
```

This single line allowed the Morris Worm to infect 10% of the Internet computers in 1988

Historic Exploitation

```
int main(int argc, char* argv[])
{
  char line[512];
  gets(line);
  printf(line);
  return 0;
}
```

```
$  gcc -m32 -mpreferred-stack-boundary=2 -O0 -fno-pic -no-pie -z execstack -o morris morris.c
```

Compiler Warning (ignore this for now):

```
morris.c:(.text+0x2a): warning: the `gets' function is dangerous and should not be used.
```

`gets(char *s)`

Reads a line from STDIN into the buffer pointed to by *s* until a terminating newline or EOF, which it replaces with a NULL byte (`‘\0’`)

Historic Exploitation

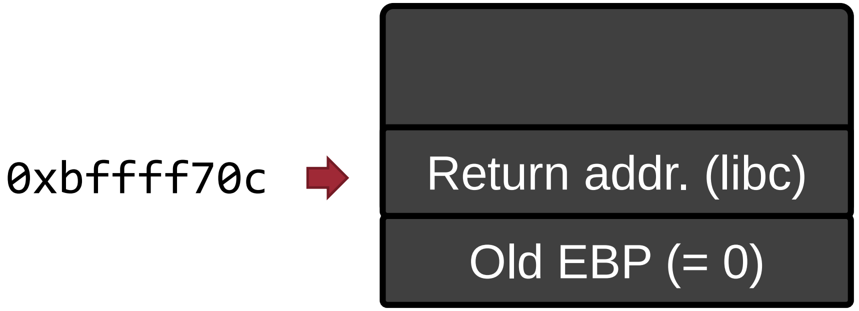
```
int main(int argc, char* argv[])
{
  char line[512];
  gets(line);
  return 0;
}
```

```
$ gcc -m32 -mpreferred-stack-boundary=2 -O0 -fno-pic -no-pie -z execstack -o morris morris.c
```

Compiler Warning (ignore this for now):
morris.c:(.text+0x2a): warning: the `gets' function is dangerous and should not be used.

```
080483fb <main>:
 80483fb:       55                      push   ebp
 80483fc:       89 e5                   mov    ebp,esp
 80483fe:       81 ec 00 02 00 00       sub    esp,0x200
 8048404:       8d 85 00 fe ff ff       lea    eax,[ebp-0x200]
 804840a:       50                      push   eax
 804840b:       e8 c0 fe ff ff          call   80482d0 <gets@plt>
 8048410:       83 c4 04                add    esp,0x4
 8048413:       b8 00 00 00 00          mov    eax,0x0
 8048418:       c9                      leave
 8048419:       c3                      ret
```

```
080483fb <main>:
 80483fb: push   ebp
 80483fc: mov    ebp,esp
 80483fe: sub    esp,0x200
 8048404: lea    eax,[ebp-0x200]
 804840a: push   eax
 804840b: call   80482d0 <gets@plt>
 8048410: add    esp,0x4
 8048413: mov    eax,0x0
 8048418: leave
 8048419: ret
```



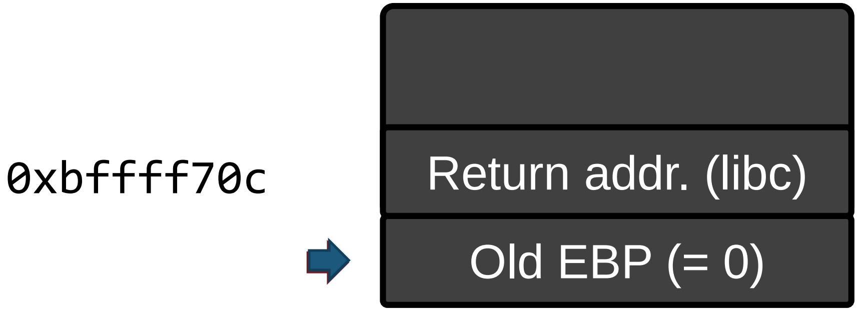
Execution Context

esp = 0xbffff70c

ebp = 0x0

eip = 0x80483fb

```
080483fb <main>:
 80483fb: push   ebp
 80483fc: mov    ebp,esp
 80483fe: sub    esp,0x200
 8048404: lea    eax,[ebp-0x200]
 804840a: push   eax
 804840b: call   80482d0 <gets@plt>
 8048410: add    esp,0x4
 8048413: mov    eax,0x0
 8048418: leave
 8048419: ret
```

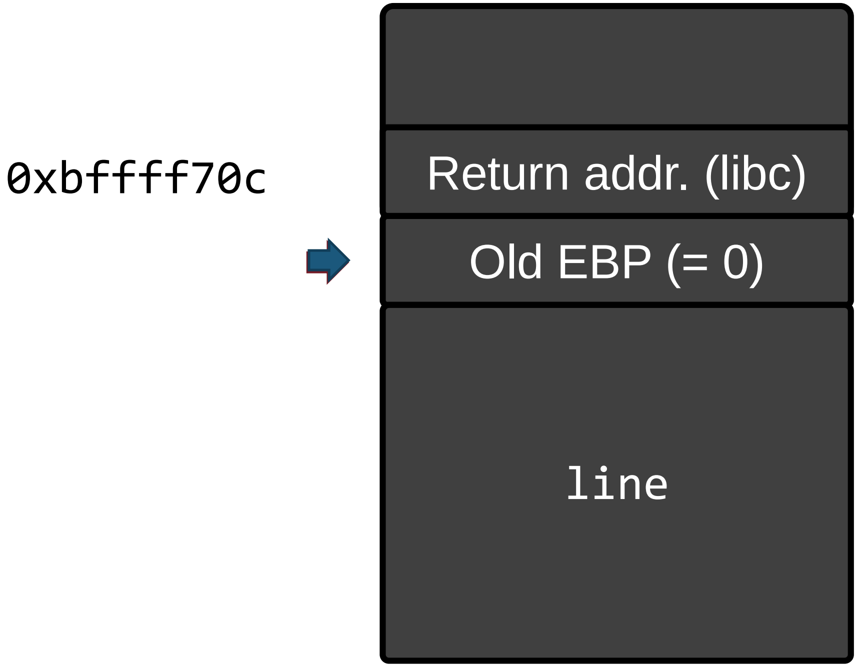


Execution Context

```
esp = 0xbffff708
ebp = 0x0
eip = 0x80483fc
```

```
080483fb <main>:
 80483fb: push   ebp
 80483fc: mov    ebp,esp
 80483fe: sub    esp,0x200
 8048404: lea    eax,[ebp-0x200]
 804840a: push   eax
 804840b: call   80482d0 <gets@plt>
 8048410: add    esp,0x4
 8048413: mov    eax,0x0
 8048418: leave
 8048419: ret
```

512 byte



0xbffff70c

Return addr. (libc)

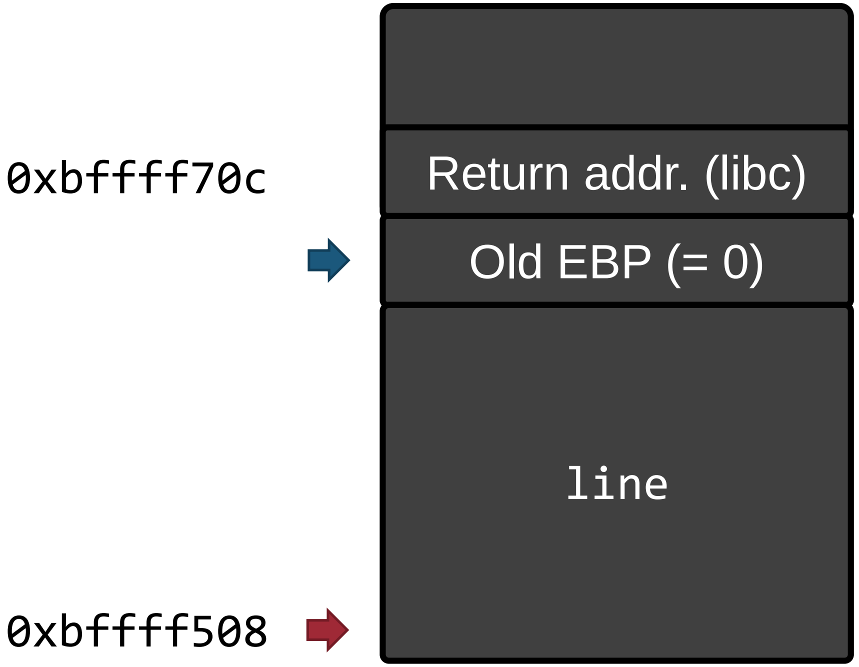
Old EBP (= 0)

line

Execution Context

```
esp = 0xbffff708
ebp = 0xbffff708
eip = 0x80483fe
```

```
080483fb <main>:
 80483fb: push   ebp
 80483fc: mov    ebp,esp
 80483fe: sub    esp,0x200
 8048404: lea    eax,[ebp-0x200]
 804840a: push   eax
 804840b: call   80482d0 <gets@plt>
 8048410: add    esp,0x4
 8048413: mov    eax,0x0
 8048418: leave
 8048419: ret
```



Execution Context

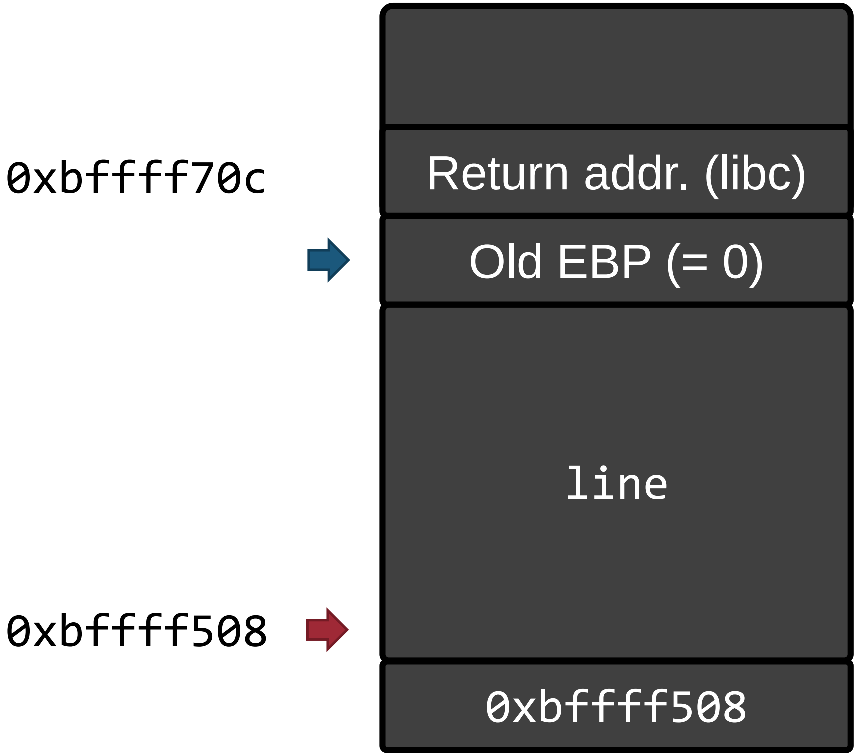
esp = 0xbffff508

ebp = 0xbffff708

eip = 0x8048404

eax = 0xbffff508

```
080483fb <main>:
 80483fb: push   ebp
 80483fc: mov    ebp,esp
 80483fe: sub    esp,0x200
 8048404: lea    eax,[ebp-0x200]
 804840a: push   eax
 804840b: call   80482d0 <gets@plt>
 8048410: add    esp,0x4
 8048413: mov    eax,0x0
 8048418: leave
 8048419: ret
```



Execution Context

esp = 0xbffff508

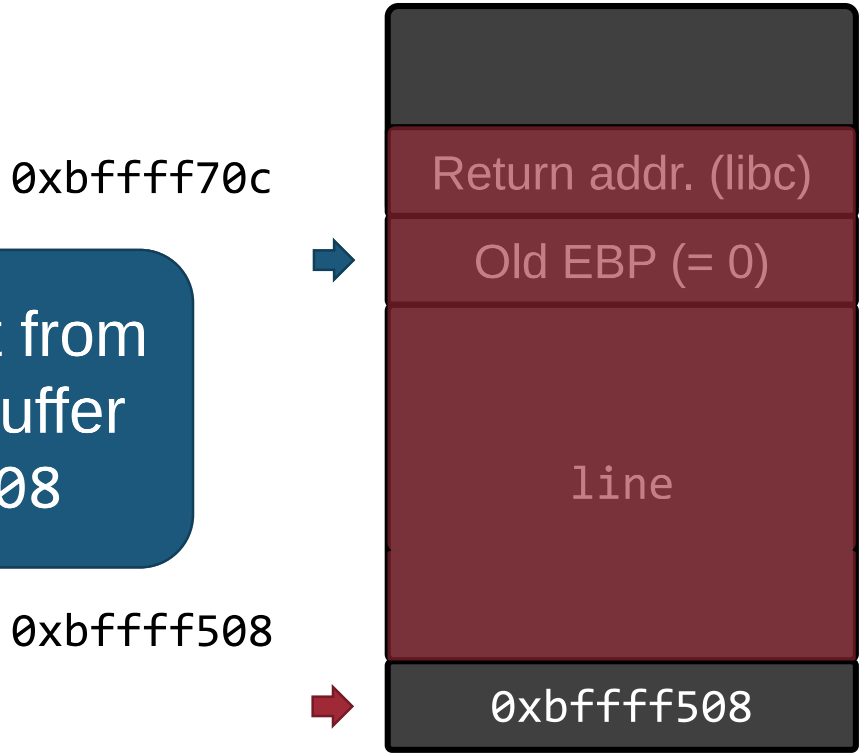
ebp = 0xbffff708

eip = 0x804840a

eax = 0xbffff508

```
080483fb <main>:
 80483fb: push   ebp
 80483fc: mov    ebp,esp
 80483fe: sub    esp,0x200
 8048404: lea    eax,[ebp-0x200]
 804840a: push   eax
 804840b: call   80482d0 <gets@plt>
 8048410: add    esp,0x4
 8048413: mov    eax,0x0
 8048418: leave
 8048419: ret
```

Copy user input from STDIN to the buffer at `0xbffff508`

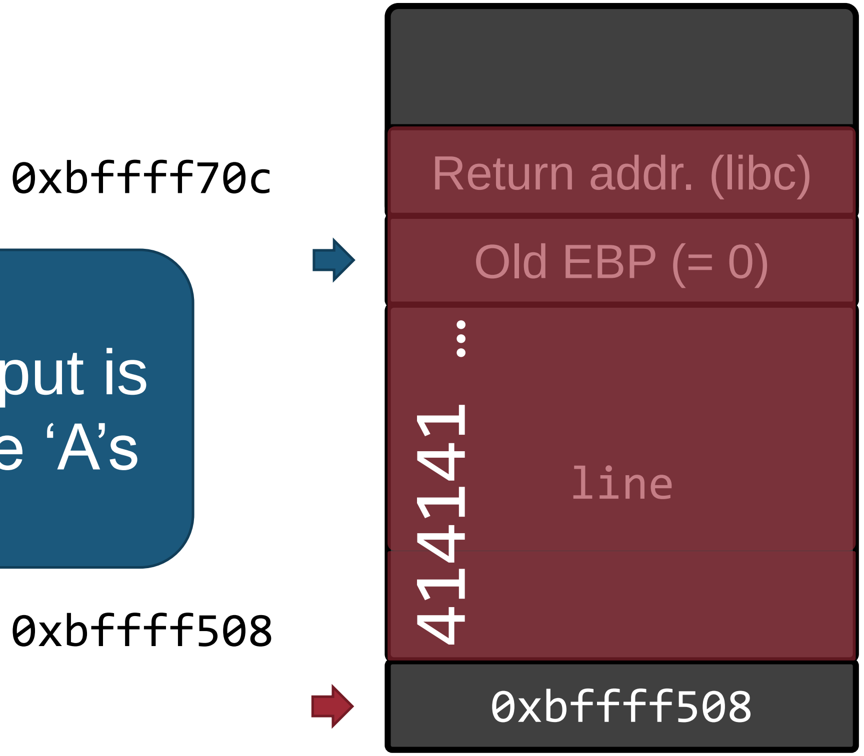


Execution Context

```
esp = 0xbffff504
ebp = 0xbffff708
eip = 0x804840b
eax = 0xbffff508
```

```
080483fb <main>:
 80483fb: push   ebp
 80483fc: mov    ebp,esp
 80483fe: sub    esp,0x200
 8048404: lea    eax,[ebp-0x200]
 804840a: push   eax
 804840b: call   80482d0 <gets@plt>
 8048410: add    esp,0x4
 8048413: mov    eax,0x0
 8048418: leave
 8048419: ret
```

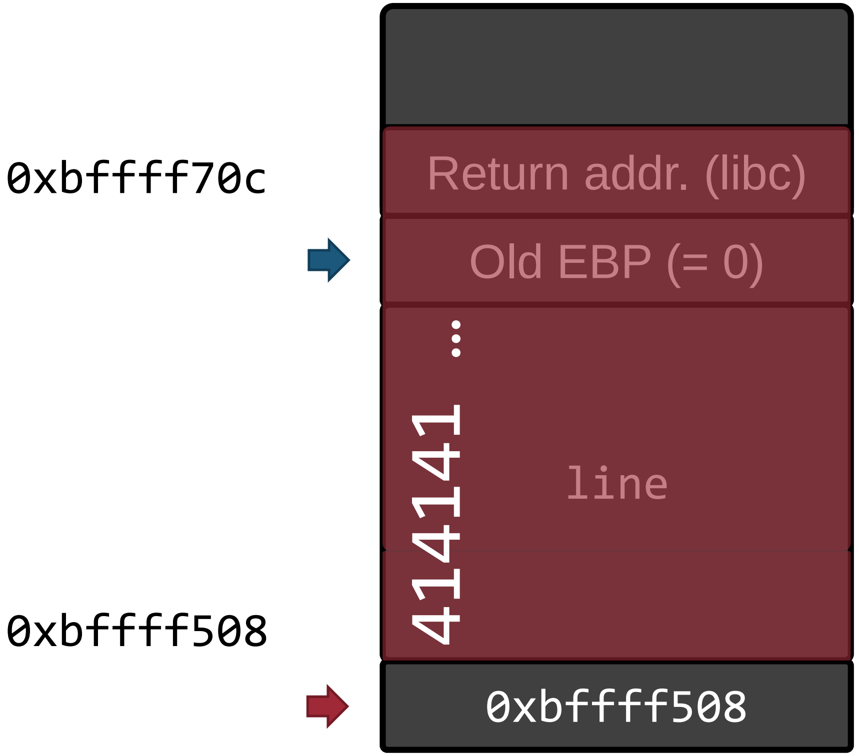
Assume user input is 520 consecutive ‘A’s



Execution Context

```
esp = 0xbffff504
ebp = 0xbffff708
eip = 0x804840b
eax = 0xbffff508
```

```
080483fb <main>:
 80483fb: push   ebp
 80483fc: mov    ebp,esp
 80483fe: sub    esp,0x200
 8048404: lea    eax,[ebp-0x200]
 804840a: push   eax
 804840b: call   80482d0 <gets@plt>
 8048410: add    esp,0x4
 8048413: mov    eax,0x0
 8048418: leave
 8048419: ret
```



0xbffff70c

Return addr. (libc)

Old EBP (= 0)

⋮

414141

line

0xbffff508

0xbffff508

Execution Context

esp = 0xbffff504

ebp = 0xbffff708

eip = 0x8048410

```
080483fb <main>:
 80483fb: push   ebp
 80483fc: mov    ebp,esp
 80483fe: sub    esp,0x200
 8048404: lea    eax,[ebp-0x200]
 804840a: push   eax
 804840b: call   80482d0 <gets@plt>
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 8048413: mov    eax,0x0
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 8048419: ret
```
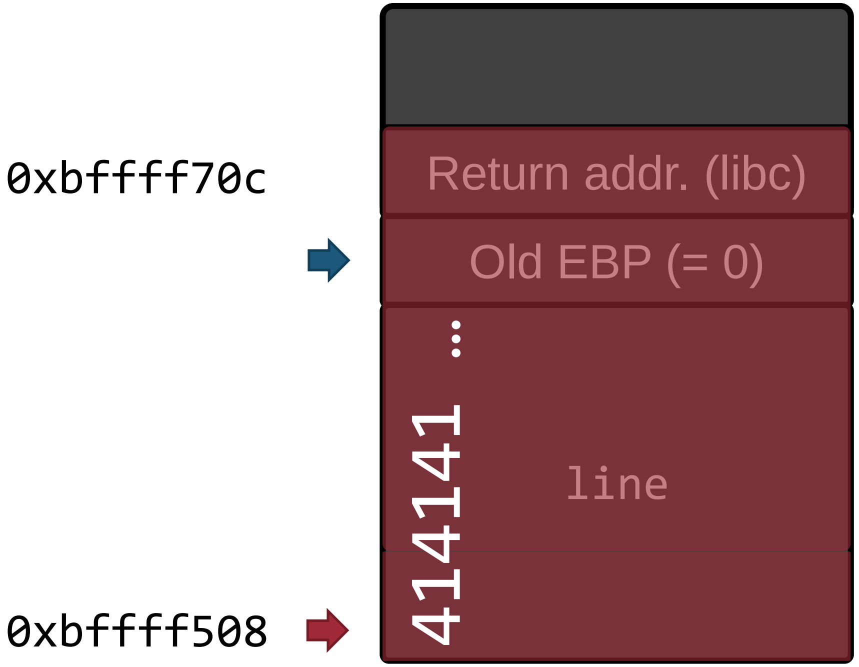
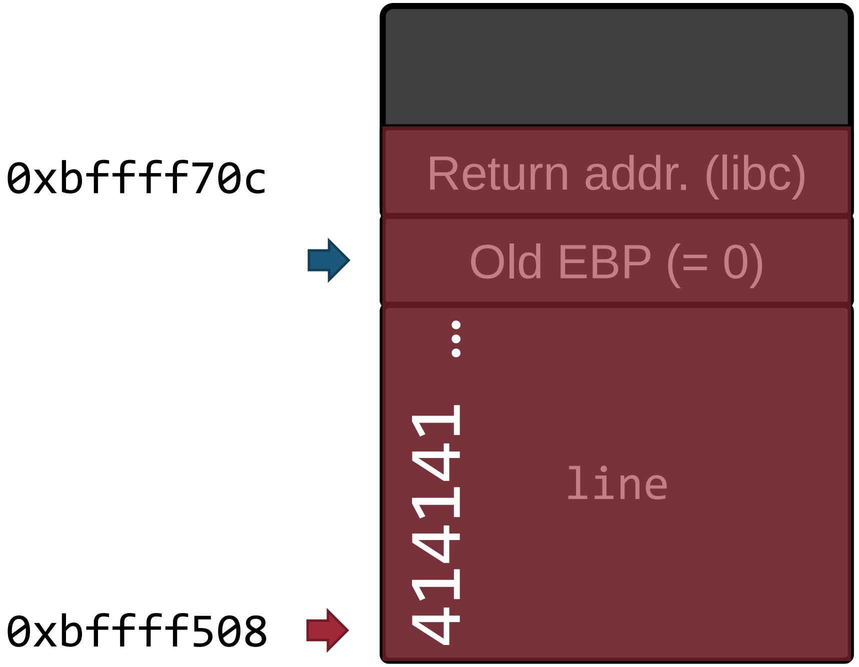



Execution Context

```
esp = 0xbffff508
ebp = 0xbffff708
eip = 0x8048413
eax = 0x0
```

```
080483fb <main>:
 80483fb: push   ebp
 80483fc: mov    ebp,esp
 80483fe: sub    esp,0x200
 8048404: lea    eax,[ebp-0x200]
 804840a: push   eax
 804840b: call   80482d0 <gets@plt>
 8048410: add    esp,0x4
 8048413: mov    eax,0x0
 8048418: leave
 8048419: ret
```

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



Execution Context

```
esp = 0xbffff508
ebp = 0xbffff708
eip = 0x8048418
eax = 0x0
```

```
080483fb <main>:
 80483fb: push   ebp
 80483fc: mov    ebp,esp
 80483fe: sub    esp,0x200
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 804840a: push   eax
 804840b: call   80482d0 <gets@plt>
 8048410: add    esp,0x4
 8048413: mov    eax,0x0
 8048418: leave
 8048419: ret
```
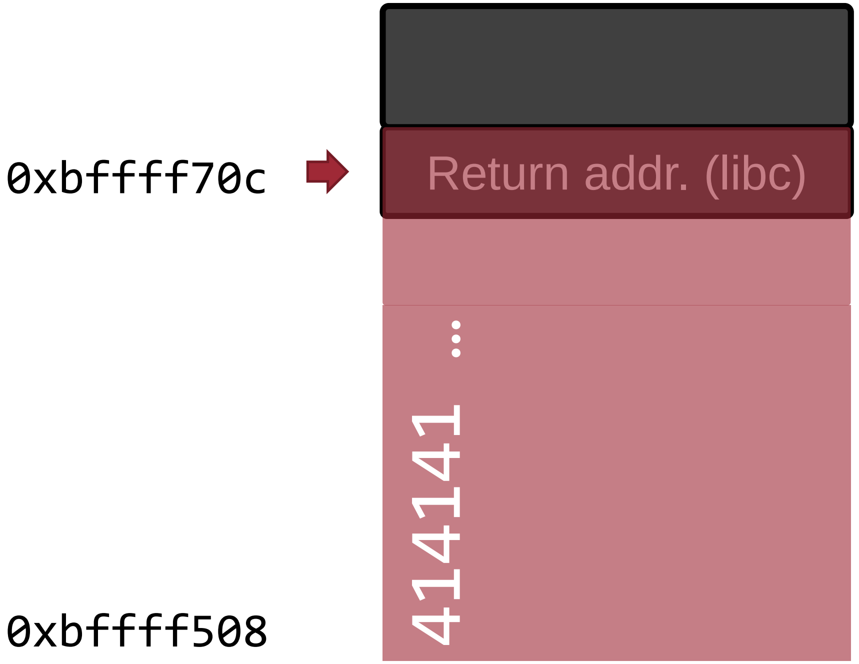

pop eip



Control Hijacked!

```
41414141 : ???
```

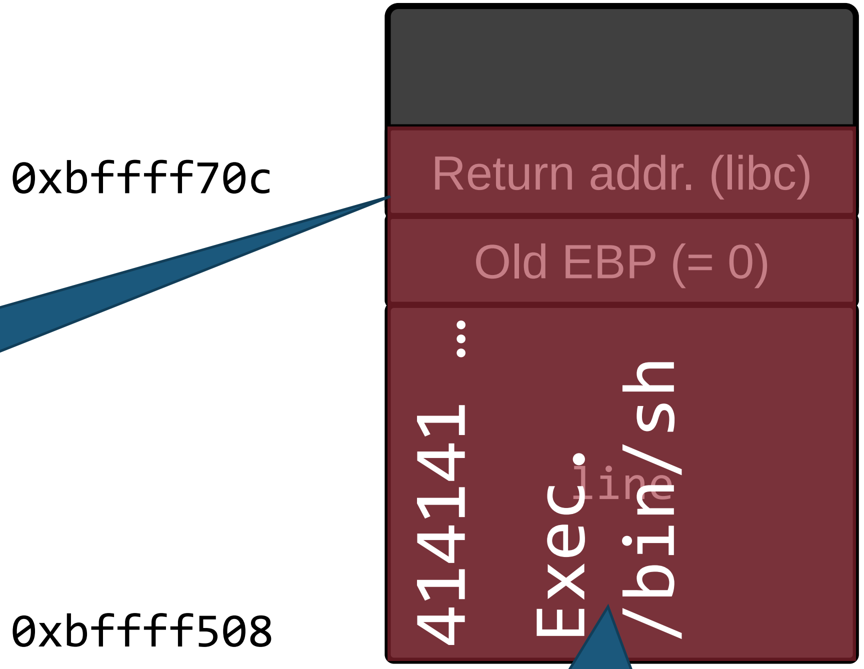
Execution Context

esp = 0xbffff70c
ebp = 0x41414141
eip = 0x8048419
eax = 0x0

So Far …

- We hijacked the control of the program (= We can jump to anywhere!)
- But, where do we jump to?
- We want to inject some code to run!

```
080483fb <main>:
 80483fb: push   ebp
 80483fc: mov    ebp,esp
 80483fe: sub    esp,0x200
 8048404: lea    eax,[ebp-0x200]
 804840a: push   eax
 804840b: call   80482d0 <gets@plt>
 8048410: add    esp,0x4
 8048413: mov    ea
 8048418: leave
 8048419: ret
```



Make this `0xbffff508`

Put some arbitrary code here

This is so-called the ***return-to-stack*** exploit.

Executing *Shellcode*

- Small piece of code that is used as the payload

- Shellcode can run any arbitrary logic
  - Download /etc/passwd
  - Install malicious software (malware)
  - …

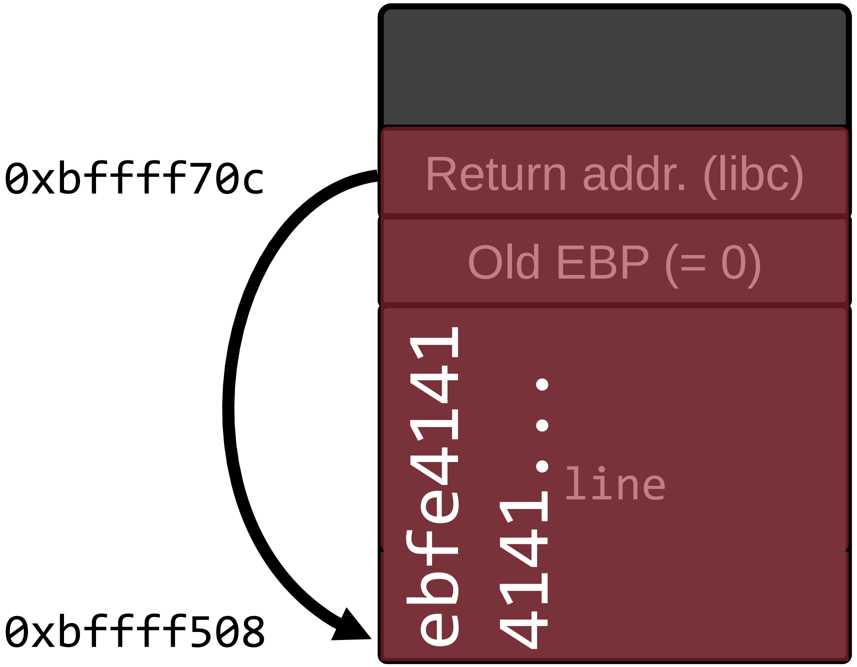
- But typically executing `/bin/sh` is enough
  - This is the most powerful attack: we can run arbitrary commands
  - You can also achieve this with relatively ***small amount of code***
  - This is the reason why we call it as shellcode (code that typically runs shell)

Write an Infinite Loop Shellcode

```
.intel_syntax noprefix

loop:
jmp loop
```

Final Exploitation

- Fill the buffer with our shellcode (31 bytes)
- The rest of the buffer (481 bytes = 512-31) can be filled with any characters
- The old ebp can be filled with any characters (4 bytes)
- The return address should point to the shellcode (`0xbffff508`)



Caveat

We assume that we know the exact address of the buffer.

This is very difficult even without modern defenses such as ASLR.

Practice: Same Machine w/ or w/o GDB

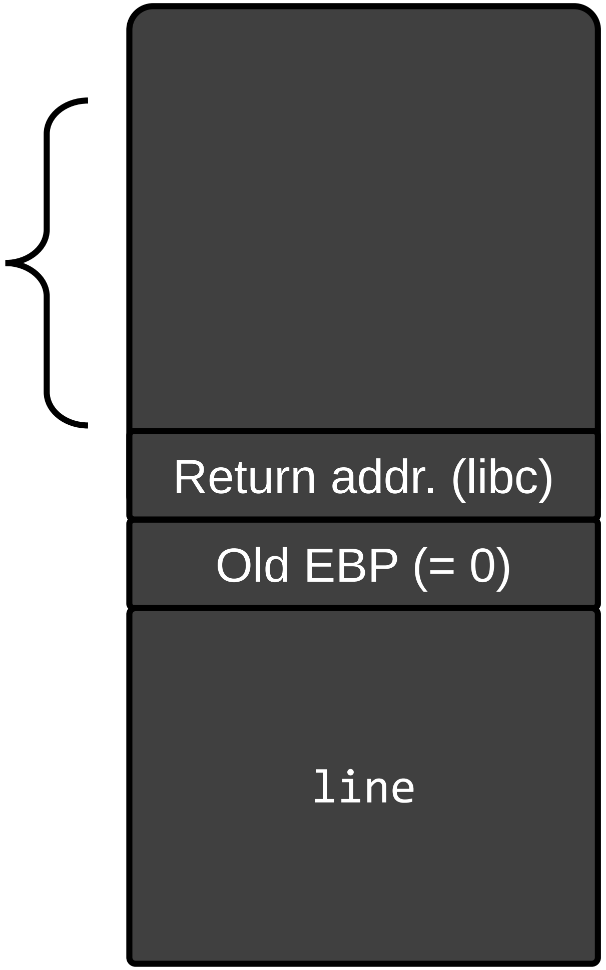
GDB reference:
http://www.yolinux.com/TUTORIALS/GDB-Commands.html

To see how to enable Intel syntax in GDB:
Add the following to ~/.gdbinit file
(`set disassembly-flavor intel`)

Why Different?

The key problem is ***Environment Variables***

- GDB puts extra environment variables
- Each machine has different environment variables



Making Exploit Robust

- NOP sled (= NOP slide)

  - 0x90 represents an 1-byte instruction NO-OP (= `xchg eax, eax`)

- Store a payload in an environment variable
  - We can control the size of the buffer (= we can put a larger NOP sled)
  - Works only for local exploitation

Off-by-One Error

Subtle Error

```
#include <stdio.h>
#include <string.h>
#define BUFSIZE  (512)
void printer(char* str)
{
  char buf[BUFSIZE];
  strcpy(buf, str);
  printf("%s\n", buf);
}
int main(int argc, char* argv[])
{
  if ( argc < 2 || strlen(argv[1]) > BUFSIZE ) return -1;
  printer(argv[1]);
  return 0;
}
```

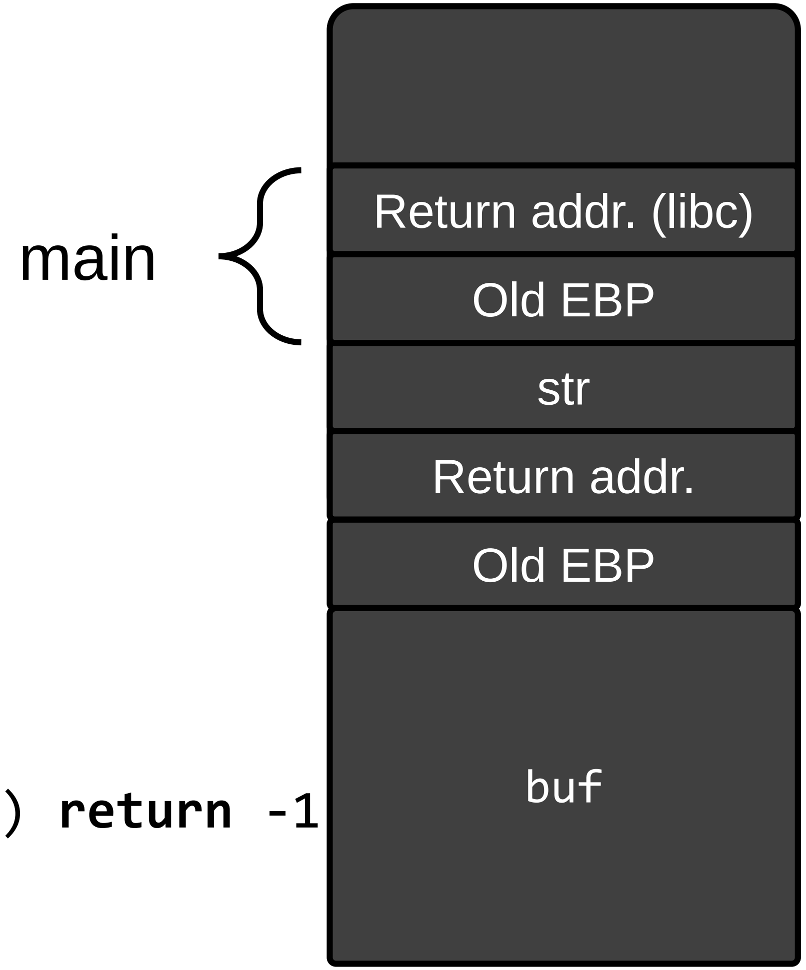
We can just overwrite 1 byte NULL beyond the size of the buffer (buf)

But, some off-by-one bugs are exploitable!

Exercise: Can you draw the stack diagram?

```c
#include <stdio.h>
#include <string.h>
#define BUFSIZE  (512)
void printer(char* str)
{
  char buf[BUFSIZE];
  strcpy(buf, str);
  printf("%s\n", buf);
}
int main(int argc, char* argv[])
{
  if ( argc < 2 || strlen(argv[1]) > BUFSIZE ) return -1;
  printer(argv[1]);
  return 0;
}
```

```
#include <stdio.h>
#include <string.h>
#define BUFSIZE  (512)
void printer(char* str)
{
  char buf[BUFSIZE];
  strcpy(buf, str);
  printf("%s\n", buf);
}
int main(int argc, char* argv[])
{
  if ( argc < 2 || strlen(argv[1]) > BUFSIZE ) return -1
  printer(argv[1]);
  return 0;
}
```



main

Return addr. (libc)

Old EBP

str

Return addr.

Old EBP

buf

Lots of Defenses and Attacks Since 1988

- Data execution prevention
- Code reuse attacks
- Canary
- Address space layout randomization
- and many more …

Future lectures

Recommended Readings

- Smashing the Stack for Fun and Profit, Phrack 1996 by Aleph One
  http://phrack.org/issues/49/14.html
- x86 Calling Conventions
  https://en.wikipedia.org/wiki/X86_calling_conventions

Summary

- Only some bugs are exploitable.
- Some exploits allow an attacker to hijack the control flow of the target program and to run any arbitrary code.
- Return-to-stack exploit puts a shellcode in to a stack buffer and jumps to it by overwriting the return address.
- We can make return-to-stack exploit robust by using NOP sleds.

Questions?