

Attacking the stack

Thanks to SysSec and Int. Secure Systems Labs
at Vienna University of Technology for some of these slides



Attacking the stack

We have seen how the stack works.

Now: let's see how we can abuse this.

We have already seen how **malicious code** can *deliberately* do “strange things”, and manipulate memory *anywhere* on the heap and stack.

Now: let's see how **benign, but buggy code** can be *manipulated* into doing strange things using **malicious input**

We'll use two techniques for this

1. **buffer overflows**
2. **format strings attacks**

Abusing the stack

Goals for an attacker

1. leaking data
2. corrupting data
3. corrupting program execution

This can be

3a) crashing

3b) doing something more interesting

In *CIA terminology*, such attacks result in breaking

1. confidentiality of data
2. integrity of data
3. integrity of program in execution (ie the “process”)
4. availability of data or the process
(if data is destroyed or program crashes)

Format string attacks

Format strings attacks

- Format strings were discovered (invented?) in 2000
- They provide a way for an attacker to leak or corrupt stack memory
- Not such a big problem as buffer overflows, as possibility of format string attacks are *easy to spot and remove*
- Still, a great example of how some harmless looking code can turn out to be vulnerable, and exploitable by an attacker who supplies malicious input

Leaking data

```
int main( int argc,  char** argv)
    int pincode = 1234;
    printf(argv[1]);
}
```

This program echoes the first program argument.

Aside on `main(int argc, char** argv)`

`argc` is the numbers of arguments, `argv` are the argument values.

`argv` has type is a `char**`, so

`*argv` has type `char*` (ie a string)

`**argv` has type `char`

and using pointer arithmetic

`argv[i]` has type `char*`, ie a strings

`argv[i][j]` has type `char`,

so effectively `argv` is an array of strings, or a 2-dimensional array of `char`'s

Note

- `argv[0]` is the name of the executable, so `argv[1]` is the first real argument
- `char** argv` can also be written as `char **argv`

format strings for printf

```
printf( "j is %i.\n" , j);  
    // %i to print integer value  
printf( "j is %x in hex.\n" , j);  
    // %x to print 4-byte hexadecimal value
```

"j is %i " is called a **format string**

Other printing functions, eg **snprintf**, also accept format strings.

Any guess what

```
printf("j is %x in hex");
```

does?

It will print the top 4 bytes of the stack

Leaking data with format string attack

```
int main( int argc,  char** argv)
    int pincode = 1234;
    printf(argv[1]);
}
```

This program may leak information from the stack when given *malicious input*, namely an argument that contains *special control characters*, which are *interpreted* by `printf`

Eg supplying `%x%x%x` as input will dump top 12 bytes of the stack

Leaking data from memory

```
printf( "j is %s.\n" , str);  
    // %s to print a string, ie a char*
```

Any guess what

```
printf("j is %s in hex");
```

does?

It will interpret the top of the stack as a pointer (an address) and will print the string allocated in memory at that address

Of course, there might not be a string allocated at that address, and `printf` simply prints whatever is in memory up to the next null terminator

Corrupting data with format string attack

```
int j;  
char* msg; ...  
printf( "how long is %s anyway %n" , msg, &j);
```

`%n` causes the number of characters printed to be **written** to `j`,
here it will write `20+length(msg)`

Any guess what

```
printf("how long is this %n");
```

does?

It interprets the top of the stack as an address, and writes a value there

Example malicious format strings

Interesting inputs for the string `str` to attack `printf(str)`

- `%x%x%x%x%x%x%x%x`

will print bytes from the top of the stack

- `%s`

will interpret the top bytes of the stack as an address `X`, and then prints the string starting at that address `A` in memory, ie. it dumps all memory from `A` up to the next null terminator

- `%n`

will interpret the top bytes of the stack as an address `X`, and then *writes* the number of characters output so far to that address

Example *really* malicious format strings

An attacker can try to control which address X is used for reading from memory using $\%s$ or for writing to memory using $\%n$ with specially crafted format strings of the form

- `\xEF\xCD\xCD\xAB %x %x . . . %x %s`

With the right number of $\%x$ characters, this will print the string located at address **ABCDCDEF**

- `\xEF\xCD\xCD\xAB %x %x . . . %x %n`

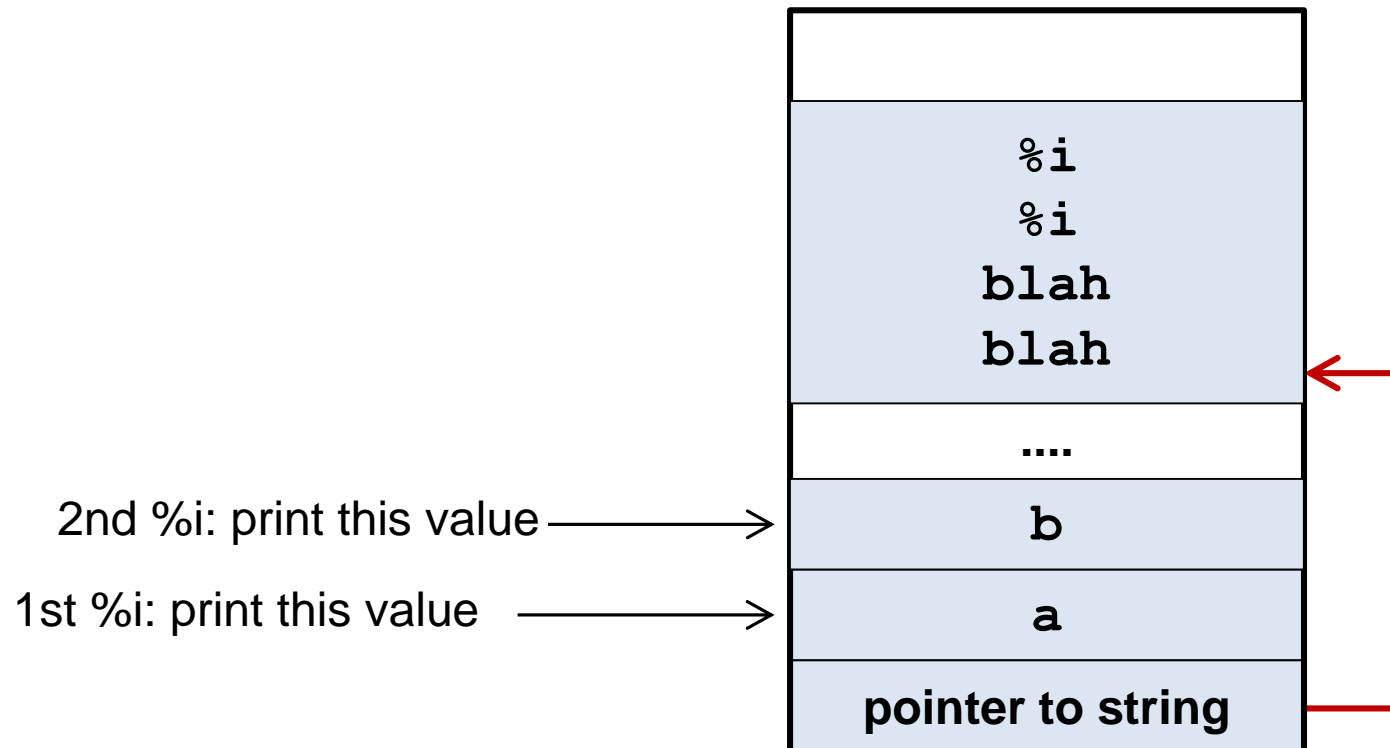
With the right number of $\%x$ characters, this will write the number of characters printed so far to location **ABCDCDEF**

The tricky things are inserting the right number of $\%x$, and choosing an interesting address

stack layout for printf

```
printf("blah blah %i %i", a, b)
```

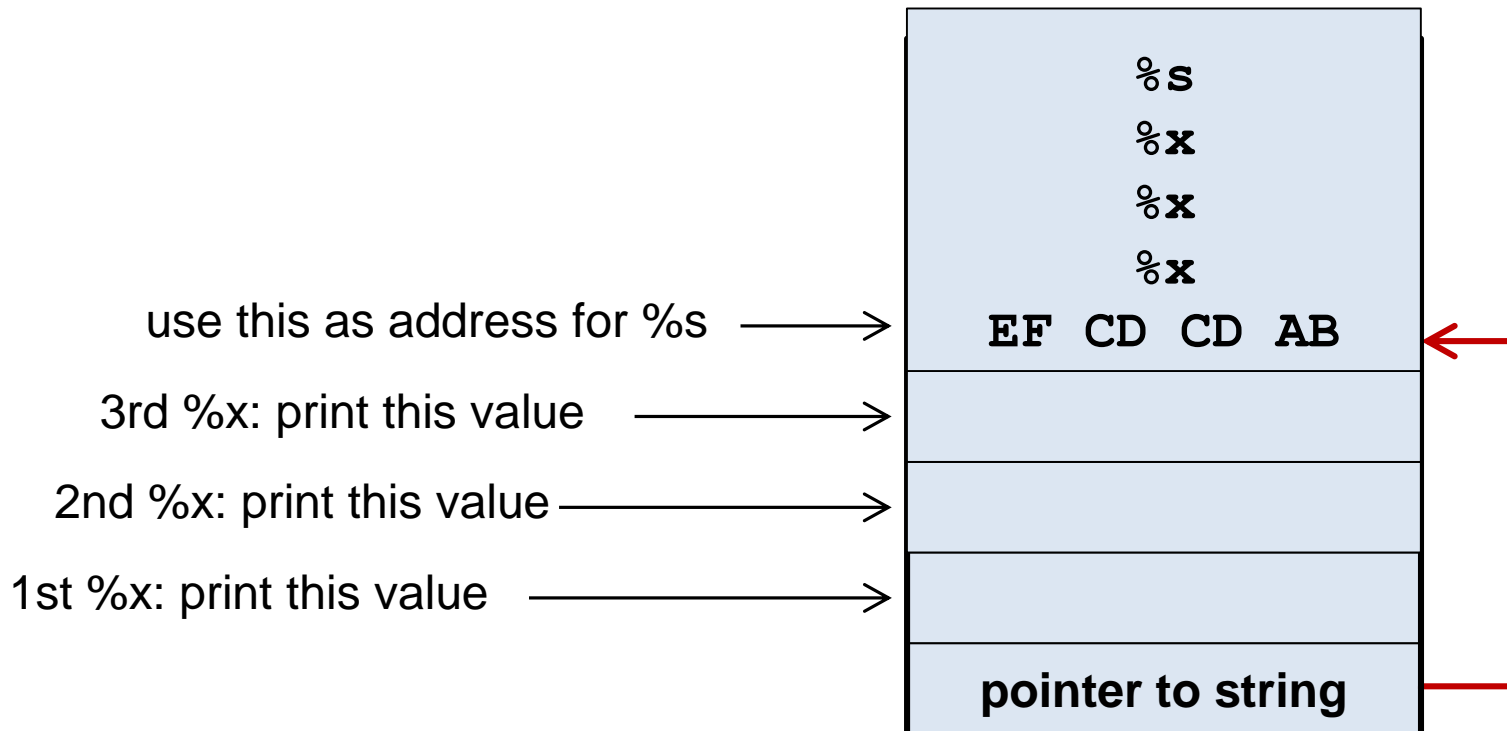
Recall: string is written upwards



stack layout for really malicious strings

```
printf ("\xEF\xCD\xCD\xAB %x %x ... %x %s");
```

With the right number of %x characters, this will print the string located at address **ABCDCDEF**



buffer overflows

Buffer overflows

It is easy to make mistakes using arrays or strings

- when using array indices we can go outside the array bounds,

eg in

```
buffer[i]= c;
```

- when copying strings into arrays this can also happen

```
char buf[8];
```

```
sprintf(buf, "password");
```

```
// Does this fit?
```

```
// Not including the implicit null terminator!
```

Buffer overflows

```
void vulnerable(char *s) {
    char msg[10] = "hello";
    char buffer[10];
    strcpy(buffer, s); // copy s into buffer
}

void main( int argc, char** argv) {
    vulnerable(argv[1]);
    // argv[1] is first command line argument
}
```

What can go wrong here?

Buffer overflows to corrupt data or crash

By supplying a long argument, the **buffer** overflows, which can

- corrupt data
 - buffer** will overflow into other variables on the stack if it is too long
- crash the program

Why and when exactly does the program crash?

The buffer overrun corrupts administration on the stack, esp.

- the return address
- the stored frame pointer

Returning from the function **vulnerable** will cause a segmentation fault if these values point to places outside the correct data segment.

Buffer overflow to change a program

Can attacker do something more interesting than crashing?

Yes, supplying a value for ret which will do something interesting

recall: the stack

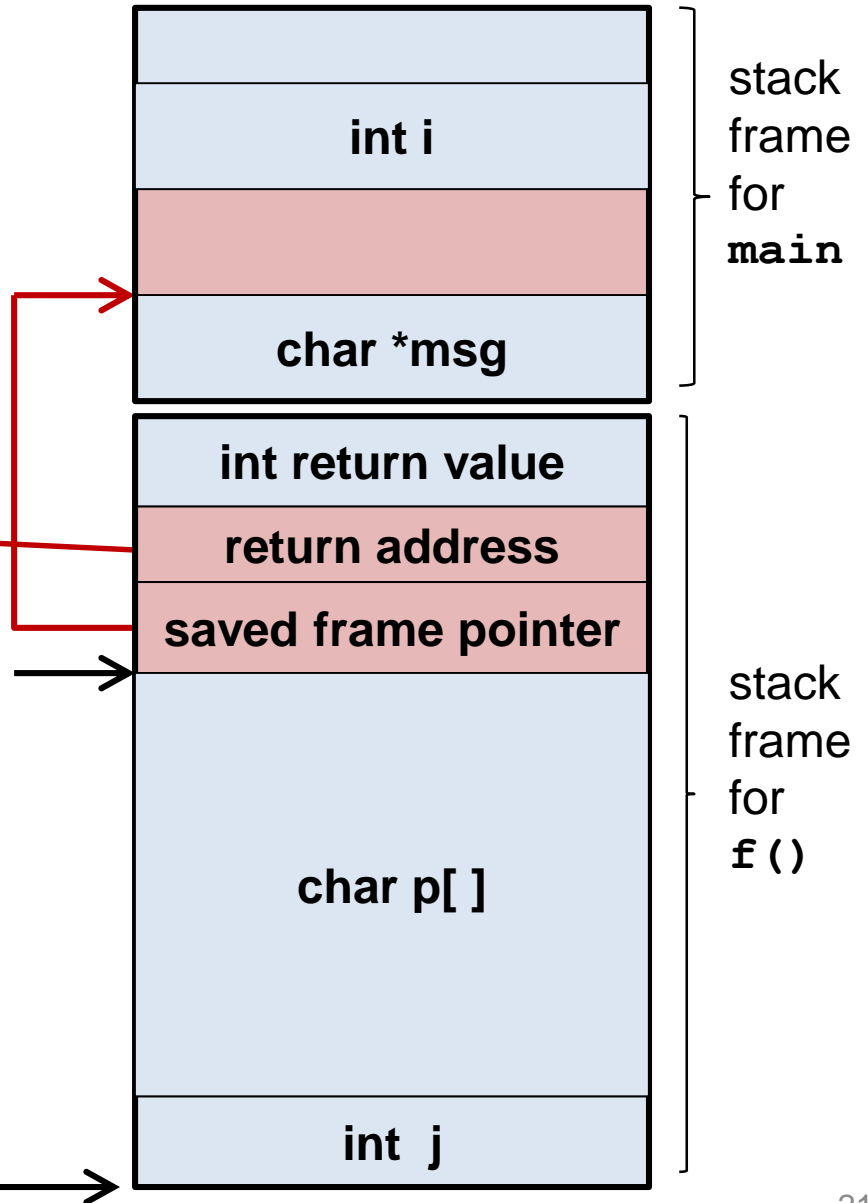
Stack during call to f

```
main(int i){  
    char *msg = "hello";  
    f();  
    print ("%i", i);  
}
```

```
int f(){  
    char p[20];  
    int j;  
    gets(p);  
    // NEVER USE gets!!  
    return 1;  
}
```

frame pointer

stack pointer

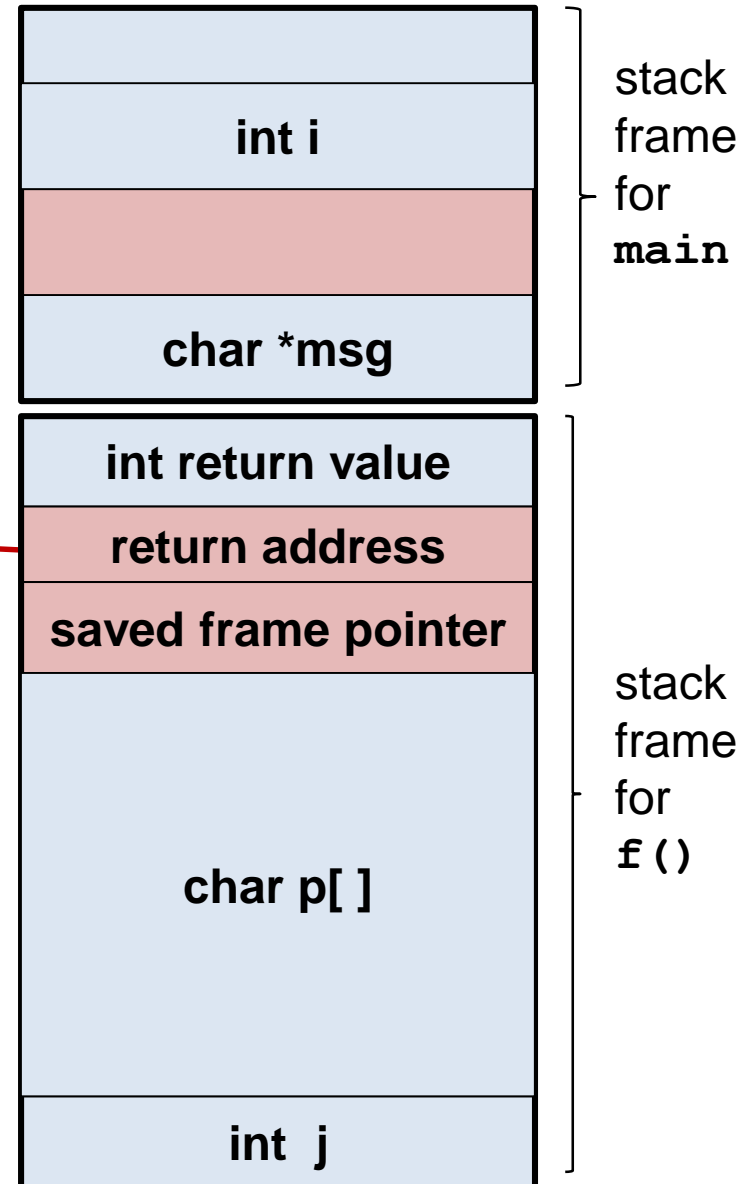


recall: the stack

Stack during call to f

```
main(int i){
    char *msg ="hello";
    f();
    print ("%i", i);
}

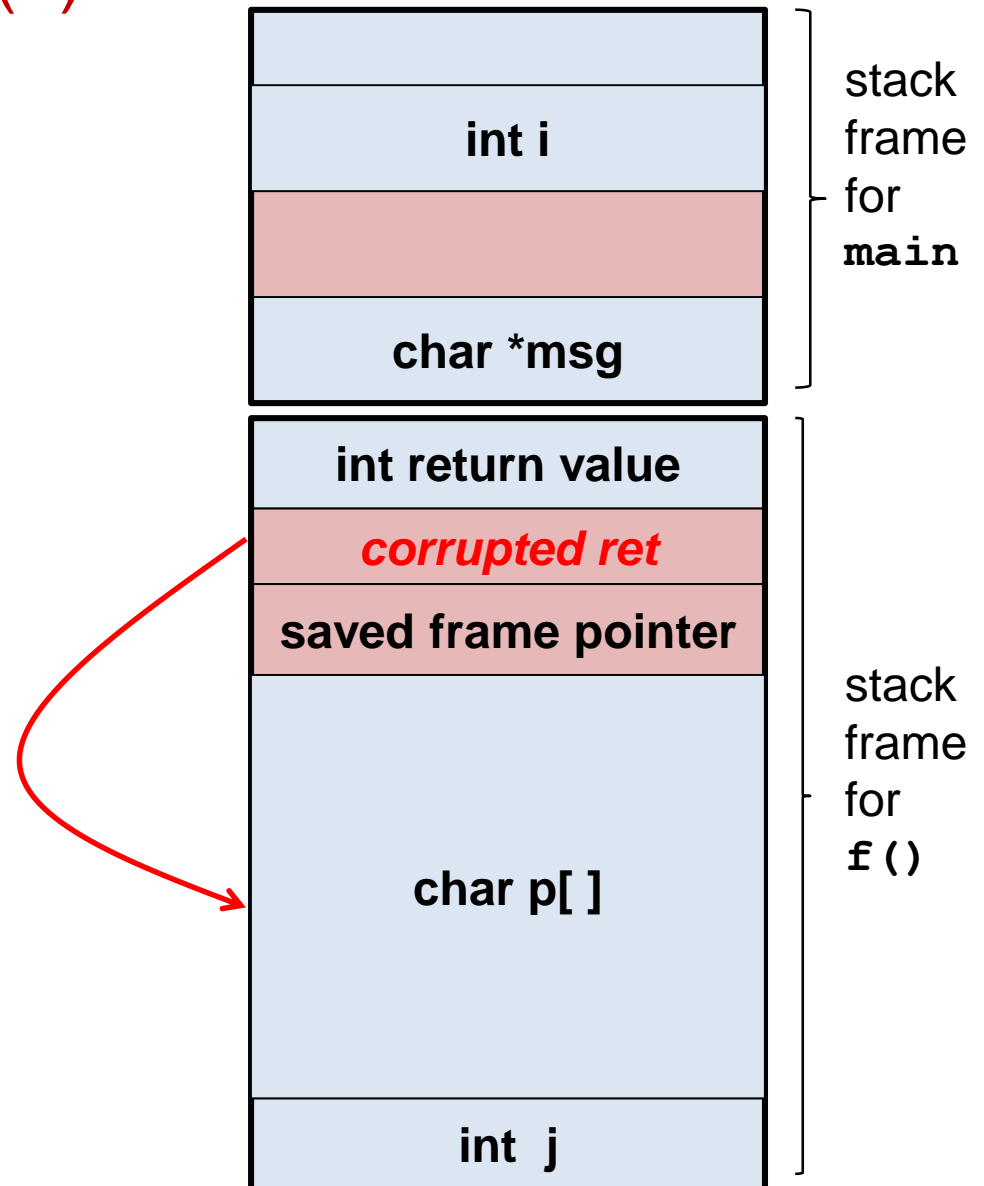
int f(){
    char p[20];
    int j;
    gets(p);
    // NEVER USE gets!!
    return 1;
}
```



Corrupting the stack (1)

*What if we overrun p
to set return address
to point inside p ?*

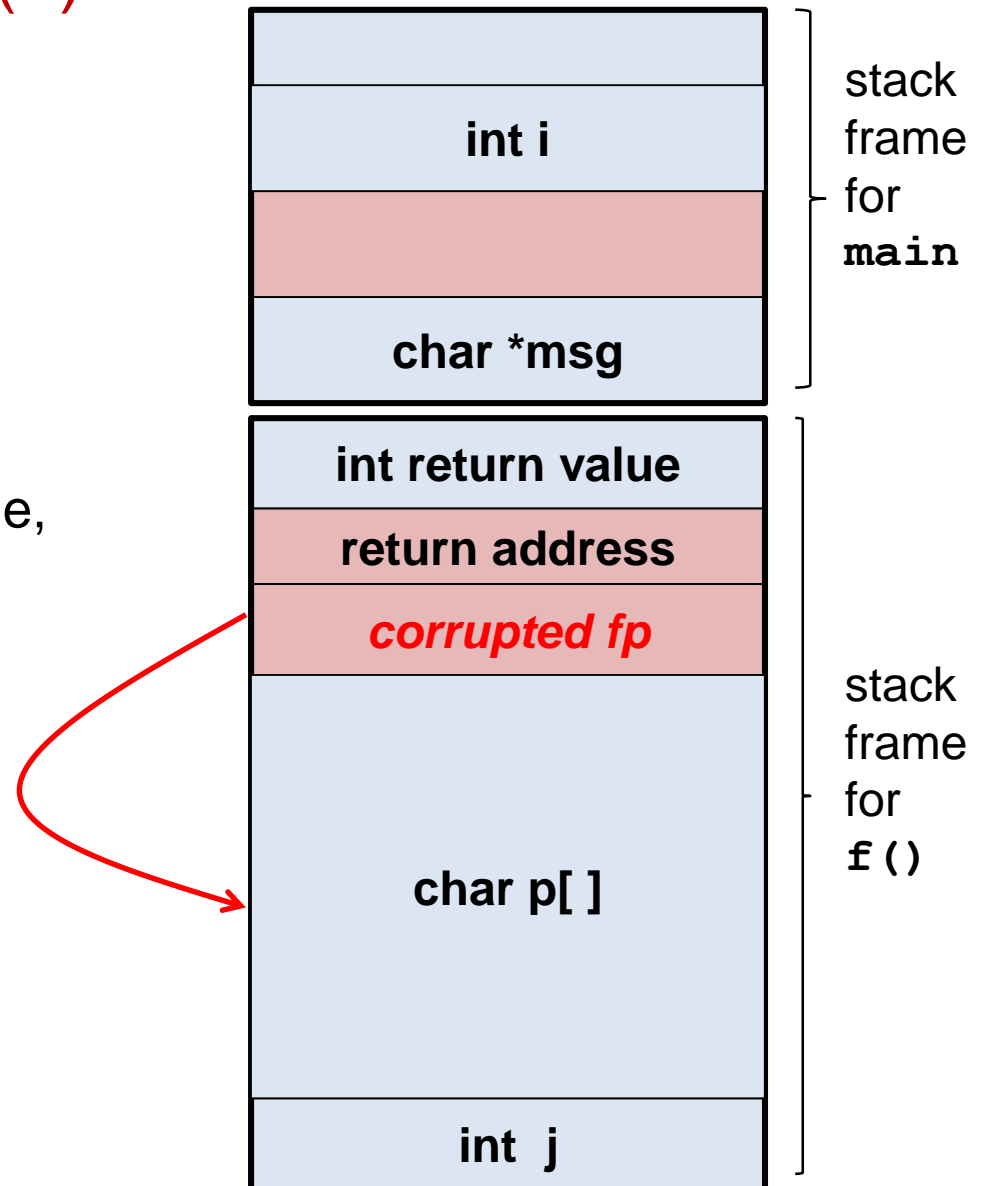
When f returns,
execution will resume
with what is written in p ,
interpreted as machine
code



Corrupting the stack (2)

*What if we overrun `p`
to set save frame pointer
to point inside `p`?*

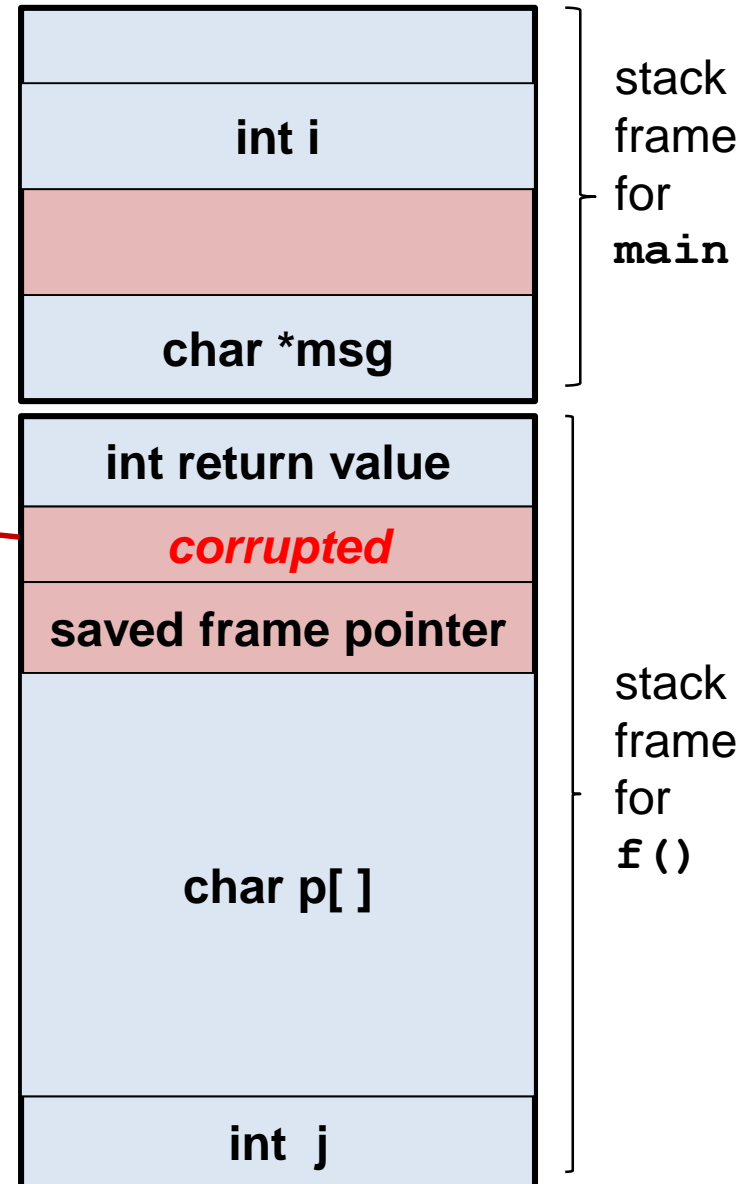
When `f` returns,
execution of `main` will resume,
but interpreting wrong part
of the stack as stack frame
for `main`



Corrupting the stack (3)

What if we overrun p
and to set return address
to point to some existing code,
say inside a function $g()$?

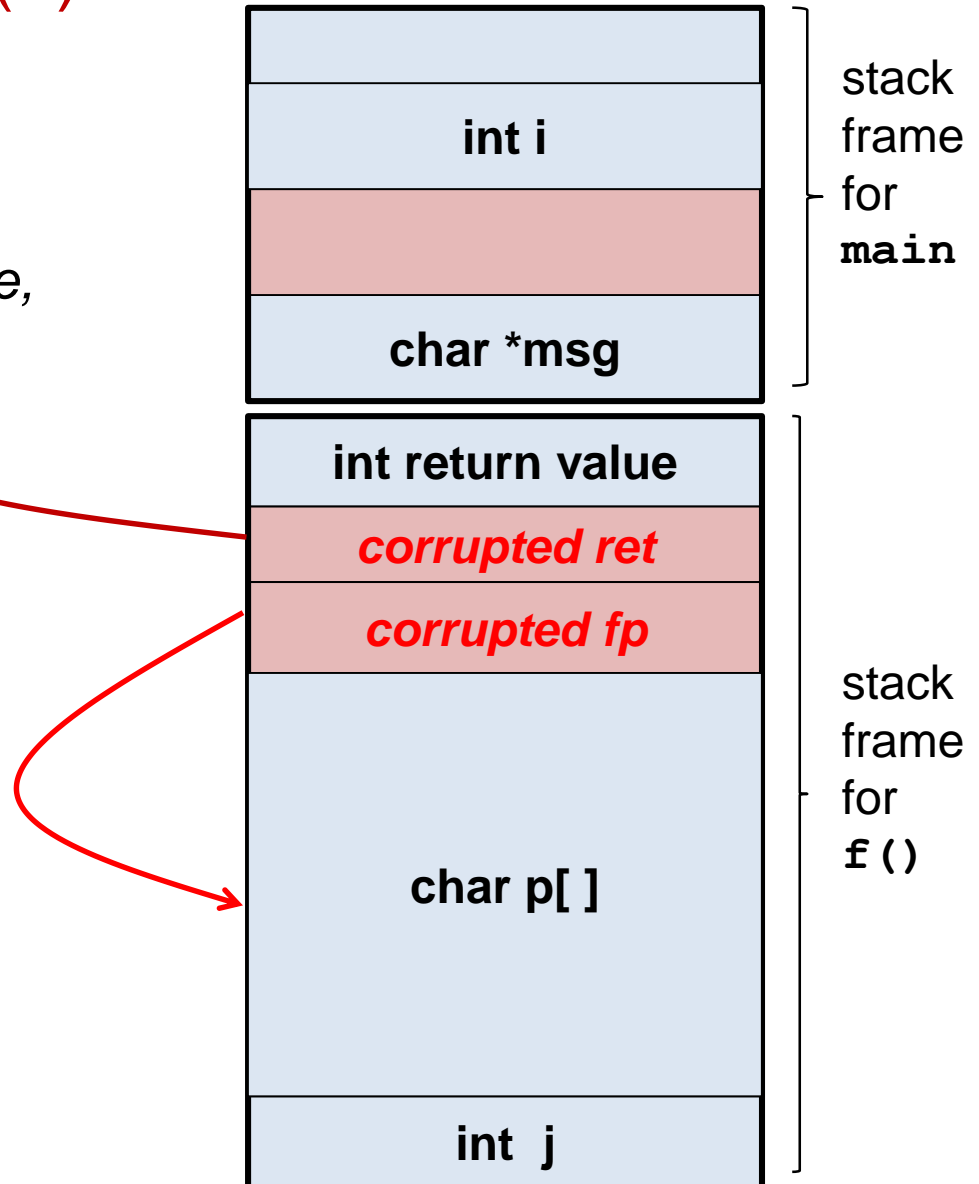
When f returns,
execution will resume
with executing g instead
of $main$ and
interpreting $main$'s frame
as a stack frame for g



Corrupting the stack (4)

What if we overrun p
and to set return address
to point to some existing code,
say inside a function $g()$,
and to set save frame
pointer to point inside p ?

When f returns,
execution will resume
with executing g instead
of $main$ and
interpreting stack starting
at p as a stack frame for g



Buffer overflow to change a program

Can attacker do something more interesting than crashing?

Yes, supplying a value for ret which will do something interesting

There are two possibilities for the attacker:

1. jumping to his own attack code (aka shell code)

The attacker writes some **program code** into a buffer, and sets the return address to point to this code

2. jumping to some existing code, but with malicious stack frame

The attacker writes a **fake stack frame** into a buffer, and sets the return address to point to some existing code, and sets the saved frame pointer to point to this fake stack frame

NB lots of tricky details to get right!

pros & cons of where to jump

1. Jumping to own attack code (the original form of buffer overflow)

CON: the attacker needs to know the address of the buffer

CON: the memory page containing the buffer must be executable;
on many modern systems the stack is not executable

2. Jumping to existing function inside the program with a manipulated stack frame

PRO: does not require an executable stack or access to executable memory somewhere else

CON: need to find the right code, and

one or more fake frames must be put on the stack

Often attacker will jump to functions in standard libc library, in so-called [return-to-libc](#) attack.

Both require the attacker to control the content of some buffers and corrupt the return address and frame pointer on the stack.

Other options on where to jump include using environment variables.

Shell code

Shell code

- If attacker manipulates the return address on the stack to jump to his own code, he needs some interesting code to jump to
- This code is known as **shell code**. It is sequence of machine instructions that is executed when the attack is successful.
 - Traditionally, the goal was to spawn a shell, hence the name “shell code”
- The actual attack will involve
 1. somehow getting this shell code somewhere in memory
 2. overwriting the return address on the stack to this place where the shell code is
- The attacker can then do practically *anything*, within the rights & permissions of the program that was attacked.

How to spawn a shell

```
void main(int argc, char **argv) {  
    char *name[2];  
    name[0] = "/bin/sh";  
    name[1] = NULL;  
  
    execve(name[0], name, NULL);  
}
```

How to spawn a shell

```
void main(int argc, char **argv) {  
    char *name[2];  
    name[0] = "/bin/sh";  
    name[1] = NULL;  
  
    execve(name[0], name, NULL);  
}
```

```
(gdb) disas execve  
    . . . .  
    mov     0x8(%ebp), %ebx  
    mov     0xc(%ebp), %ecx  
    mov     0x10(%ebp), %edx  
    mov     $0xb, %eax  
    int     $0x80  
    . . . .
```


How to spawn a shell

```
int execve(char *file, char *argv[], char *env[])
```

```
(gdb) disas execve
```

```
....
```

```
mov    0x8(%ebp), %ebx
```

```
mov    0xc(%ebp), %ecx
```

```
mov    0x10(%ebp), %edx
```

```
mov    $0xb, %eax
```

```
int    $0x80
```

```
....
```

copy **file* to ebx

copy **argv[]* to ecx

copy **env[]* to edx

put the syscall number in
eax

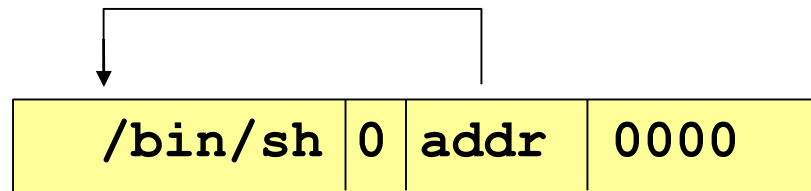
(execve is 0xb)

invoke the syscall

How to spawn a shell

Three parameters are needed

- ***file**: put the zero-terminated string `\bin\sh` somewhere in memory
- ***argv[]**: put somewhere in memory the address of the string `\bin\sh` followed by NULL (0x00000000)
- ***env[]**: put somewhere in memory a NULL



The address problem: where am I?

- How can we put in memory the address of the string `\bin\sh` if we do not even know where the position of the shellcode is?
- Solution...
 - the CALL instruction puts the return address on the stack
 - if we put a CALL instruction just before the string `\bin\sh`, when it is executed it will push the address of the string onto the stack

The Shellcode (almost ready)

```
jmp      0x26          # 2 bytes
popl    %esi          # 1 byte
movl    %esi,0x8(%esi) # 3 bytes
movb    $0x0,0x7(%esi) # 4 bytes
movl    $0x0,0xc(%esi) # 7 bytes
movl    $0xb,%eax     # 5 bytes
movl    %esi,%ebx     # 2 bytes
leal    0x8(%esi),%ecx # 3 bytes
leal    0xc(%esi),%edx # 3 bytes
int     $0x80         # 2 bytes
movl    $0x1,%eax     # 5 bytes
movl    $0x0,%ebx     # 5 bytes
int     $0x80         # 2 bytes
call    -0x2b         # 5 bytes
.string \"/bin/sh\"   # 8 bytes
```

setup
execve()
exit()
setup

The zeroes problem

The shellcode is usually copied into a string buffer

```
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\x89xec\x5d\xc3";
```

- Problem: the null byte `\x00` is the string terminator character which will stop any copying
- Solution: substitute any instruction containing zeros, with an alternative instruction

```
mov 0x0, reg --> xor reg, reg
mov 0x1, reg --> xor reg, reg
                    inc reg
```

The zeroes problem

- Some tools provide this functionality automatically:
e.g., **msfencode** (metasploit framework)

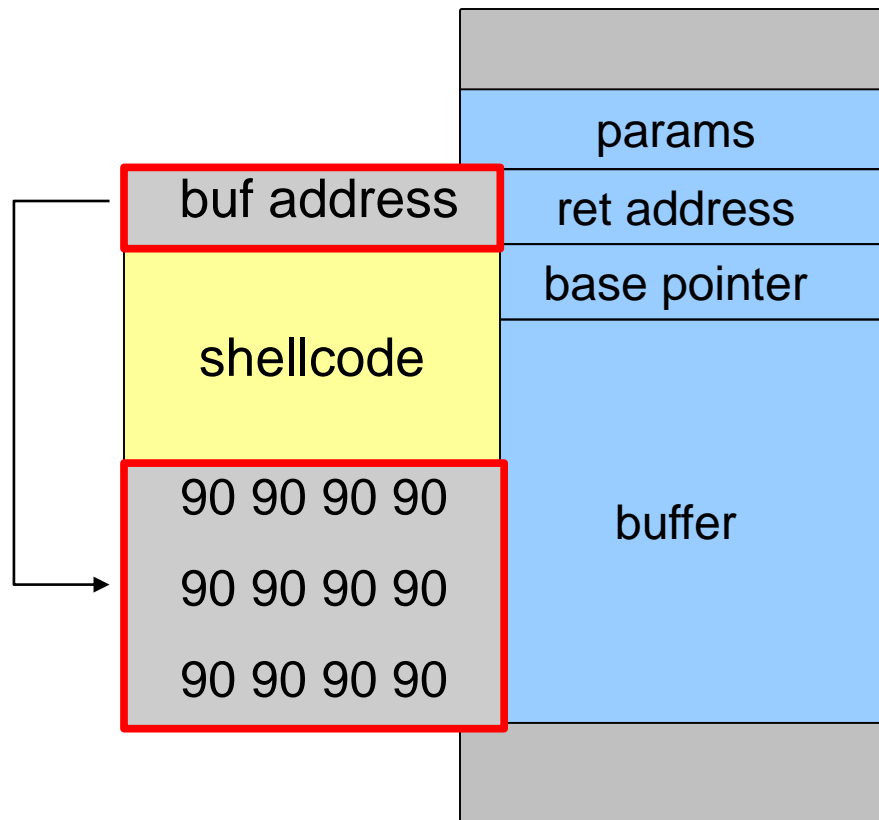
Jumping into the buffer

- The buffer that we are overflowing is usually a good place to put the code (shellcode) that we want to execute
- The buffer is somewhere on the stack, but in most cases the exact address is unknown
 - the address must be precise: jumping one byte before or after would just make the application crash
 - on the local system it is possible to calculate the address with a debugger, but it is very unlikely to be the same address on a different machine
 - any change to the environment variables affects the stack position

Solution 1: the NOP sled

- A sled is a “landing area” that is put in front of the shellcode
- Must be created in a way such that wherever the program jump into it..
 - .. it always finds a valid instruction
 - .. it always reaches the end of the sled and the beginning of the shellcode
- The simplest sled is a sequence of no operation (NOP) instructions
 - Single byte instruction (0x90) that does not do anything
- It mitigates the problem of finding the exact address to the buffer by increasing the size of the target area

Assembling the malicious buffer



Solution 2: jump using a register

- Find a register that points to the buffer (or somewhere into it)
 - ESP
 - EAX (return value of a function call)
- Locate an instruction that jumps/calls using that register
 - can also be in one of the libraries
 - does not even need to be a real instruction, just look for the right sequence of bytes
- Overwrite the return address with the address of that instruction

Recap

Recap

An attacker feeding **malicious input to insecure code** can

1. leak data
2. corrupt data
3. change program execution entirely

This can happen due to **buffer overflows** or **format string attacks**

When using buffer overflows to change program behaviour an attacker can

1. inject his own code or
2. jump to existing code with a fake stack frame

More general trends

Format string problems are easy to fix,

eg replacing `printf(msg)`

by `printf("%s", msg)`

(for all functions of the `*printf` family!)

and are then no longer a threat.

Still, they are a representative of many examples where some small feature in one function can be a source of security vulnerabilities

- Such vulnerabilities typically involve *special characters* which are *interpreted* in a special way at runtime
- Note that this means that such characters are effectively more like *program code* than just *data*

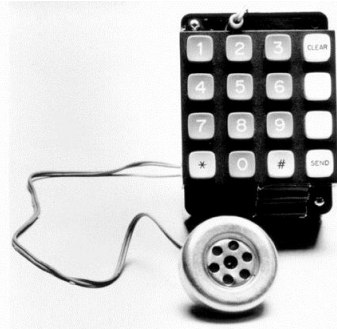
pre-history of hacking

In 1950s, Joe Engressia showed the telephone network could be hacked by **phone phreaking**:
ie. whistling at right frequencies



<http://www.youtube.com/watch?v=vVZm7I1CTBs>

In 1970s, before founding Apple together with Steve Jobs, Steve Wozniak sold Blue Boxes for phone phreaking at university



Common theme: mixing channels

The root cause of phone phreaking & buffer overflows is the same!

- signals to control the telephone switchboards (*beeps at certain frequencies*) are sent over the same channel as untrusted user data (*the phone calls*)
- data to control execution (*return addresses*) are stored in the same places as untrusted user data (*user input*)

These *attack vectors* give the attacker control over the phone network and the computer, respectively

Common theme: mixing channels

Moral of the story:

- **Don't mix data and code!**

Here **data** is **phone call** or **user input**,

code is **control beeps** or **return addresses**

- **History repeats itself!**

Not just phone phreaking & stack overflow,

but also XSS, SQL injection, OS command injection, ...