CS1632, LECTURE 20: Security Testing

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Writing Secure Software Is Difficult; So Is Testing It!

- **Heartbleed**: A defect in OpenSSL
  - Caused ~ 66% of servers connected to the Internet to be vulnerable
  - Allowed for untraceable eavesdropping on data in memory
  - Discovered in 2014, vulnerability introduced in 2012
- **Shellshock**: A defect in bash (default shell for OS X and most Linux)
  - Millions of attacks recorded in the days following discovery
  - Allowed arbitrary code execution stored in environment variables
  - Discovered in 2014, vulnerability introduced in 1989

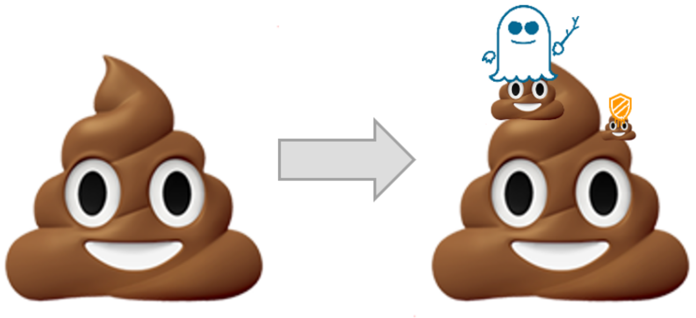
Even Testing Secure *Hardware* is Difficult

- **Spectre / Meltdown**: A vulnerability in CPU design
  - Impacts all CPUs in wide-use today (Intel, AMD, ARM, IBM …)
  - Allowed arbitrary access to private data in a process (Spectre)
  - Allowed arbitrary access to private data in an OS (Meltdown)
  - Discovered in 2017, vulnerability introduced in 1995
  - OS / Web Browser patches issued but some Spectre vulnerabilities still open

A Slide from a 2018 Hardware Design Conference

Risk in context

Because of software bugs, computer security was in a dire situation



Spectre doesn't change the magnitude of the risk, but adds to the mess

- Poor mitigation options (fixes -> new risks)

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* From ISCA 2018 Panel "**On the Implications of the Meltdown & Spectre Design Flaws**"

Why is it so Difficult?

1. Adversaries are actively seeking to defeat security
2. Information about security vulnerabilities spreads quickly
3. You need to protect all doors;
   They only need to find one they can open
4. Even minor vulnerabilities can have outsized consequences

History

- Security was not a big deal in the early computing world
  - Usually required physical access to a system to do anything
  - Few people had necessary skills even if they did
    (So called “security through obscurity”)

- Hacker culture 1960-80s exemplified in ITS Operating System
  - OS did not use passwords; anyone could use it and do anything
  - There was a flaw where clever users could crash the OS
    - Solution? A “crash” command was created that could be run by anyone
    - Crashing the OS was not challenging or fun anymore → nobody did it

History

- Now the stakes are much higher
  - "Estimating the Global Cost of Cyber Risk", RAND Corp., 2018 https://www.rand.org/pubs/research_reports/RR2299.html
  - Global cost of cyber crime: $799 billion to $22.5 trillion (1.1% to 32.4% of global GDP)

- And there are many more actors …

Actors in the Security Sphere

- White hat hackers (Ethical hackers)
    - Employed by companies to check their own systems, or by a security firm
    - Performs penetration testing and vulnerabilities testing for client
- Black hat hackers (Crackers)
    - Violates system security for personal gain or other malicious purpose
- Red hat hackers (Hacktivists)
    - Works to spread a political / ideological / religious message
- Organized crime (works in conjunction with black hat hackers)
- Nation states (e.g. Stuxnet, Equation Group)

The InfoSec (CIA) Triad

- No, it has nothing to do with *that* CIA
- CIA as in:
  - **C**onfidentiality
  - **I**ntegrity
  - **A**vailability
- A secure system needs to provide these qualities

Confidentiality

No unauthorized users may read data.

Integrity

No unauthorized users may write data.

Availability

System is available for authorized parties to read from and write to.

Terminology: Kinds of Security Attacks

1. *Interruption* (attack on availability)
   - e.g. Pulling plug from network switch, DDoS
2. *Interception* (attack on confidentiality)
   - e.g. Eavesdropping, keylogger
3. *Modification* (attack on integrity)
   - Modifying or deleting data
4. *Fabrication* (attack on integrity)
   - Making up or inserting data

Terminology: Passive vs Active Attacks

- *Passive:* Do not modify system in any way
  - Eavesdropping
  - Monitoring
  - Traffic Analysis
- *Active:* Modify the system in some way
  - Fill up database with garbage data
  - Modify bank account information

Terminology: Vulnerability vs Exploit

- Vulnerability: identified weakness of a system
- Exploit: Mechanism for compromising a system using a vulnerability

Terminology: Kinds of Malicious Code

- **Malware** – General term for malicious code (includes all kinds below)
- **Bacteria** - program that consumes system resources (e.g. fork bomb)
- **Logic bomb** - code within a program which executes an unauthorized function
- **Trapdoor** - secret undocumented access to a system or app
- **Trojan horse** – program that pretends to be another program
- **Virus** - replicates itself WITH human intervention
- **Worm** - replicates itself WITHOUT human intervention
- **Zombie** – A computer or program being run by an unauthorized controller
- **Bot network** – collection of zombies controlled by master
- **Spyware** – surreptitiously monitors your actions
- **Adware** – Shows you more ads
- **DOS** (Denial of service) attacks (e.g. via LOIC)

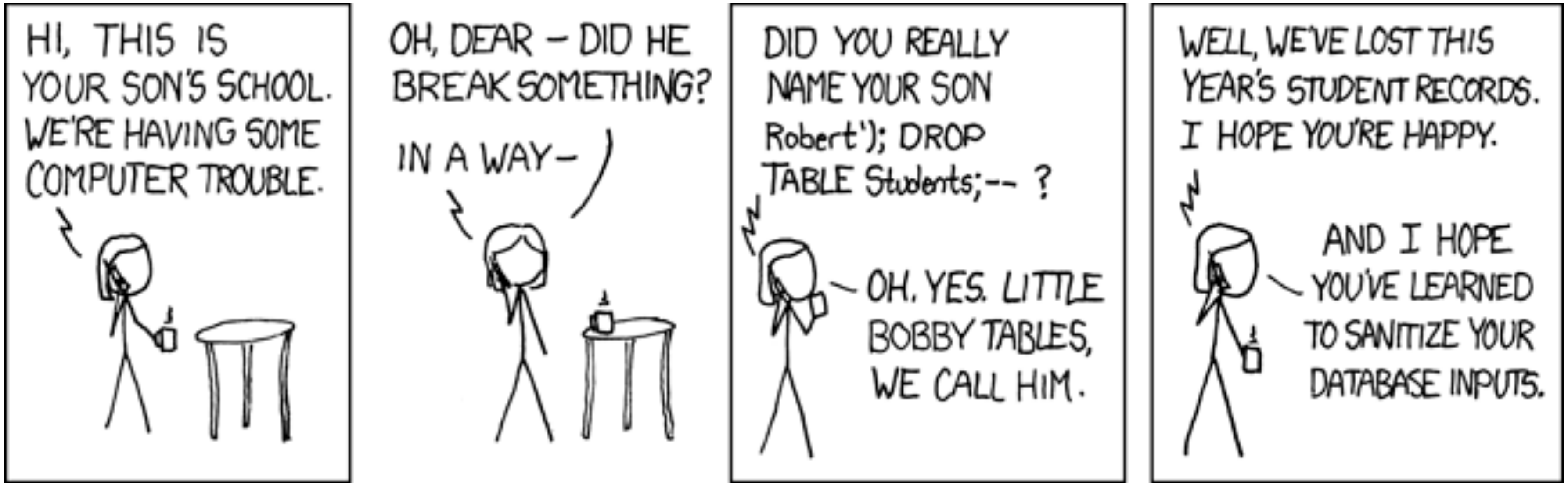
Protections

- Firewalls
- Operating System Permissions
- CDNs (Content Delivery Networks)
- Cryptography
- Well-written code
- User training

Common Attacks

- Injection Attacks
- Broken Authentication
- Cross-Site Scripting (XSS)
- Insecure Object References
- Security Misconfiguration
- Insecure Storage
- Buffer overruns
- Social Engineering

Injection Attacks



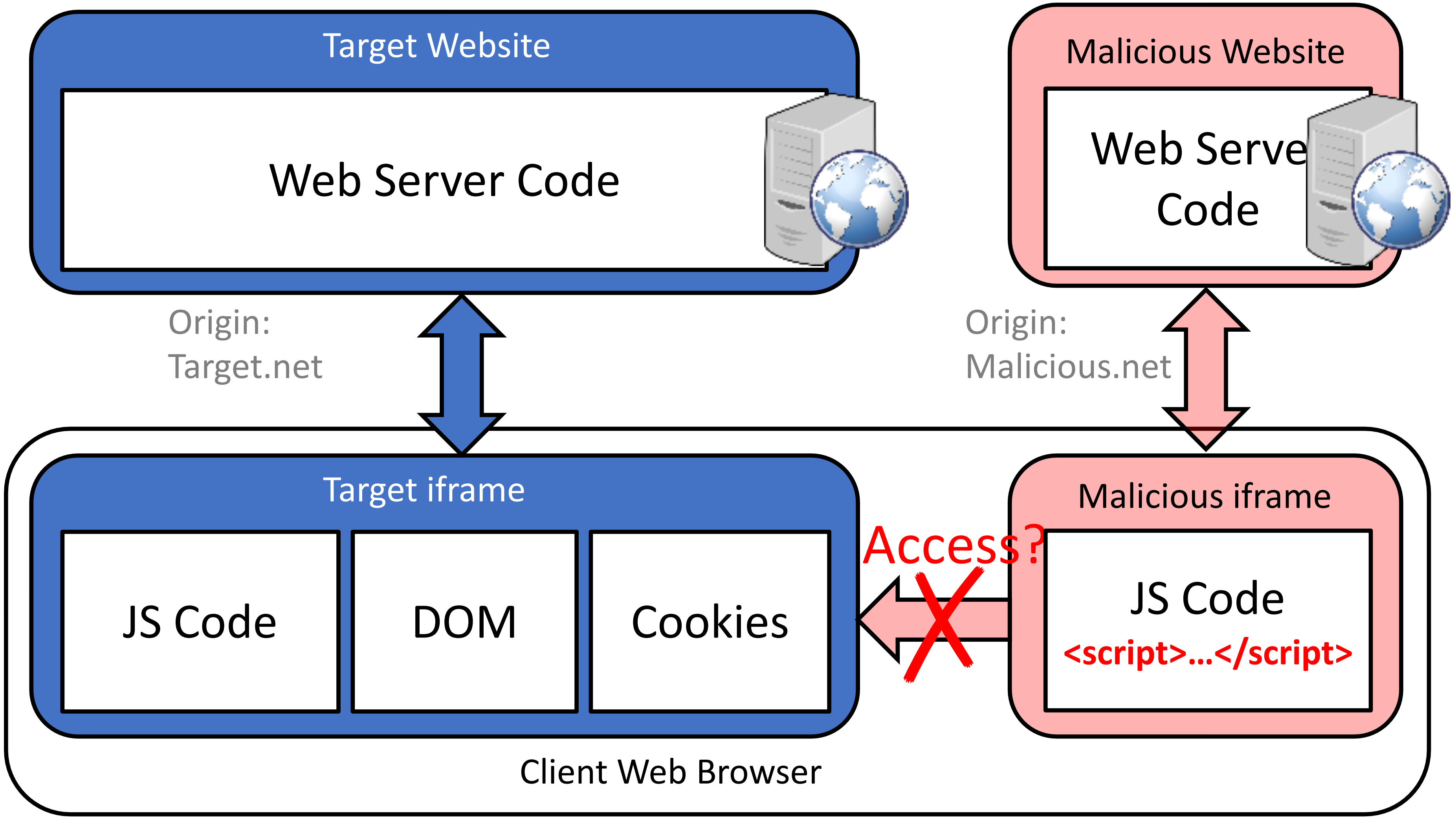
Broken Authentication

- One user pretends to be another
- How?
  - Guess or crack passwords
  - “Password reset”
  - Unencrypted session IDs
- Apple iCloud leak was suspected of being this
  - iCloud API allowed unlimited attempts – allowing a brute force attack
- Sarah Palin email hack was definitely this
  - All he needed to know, he learned from Wikipedia
  - Answered security questions, reset password

Cross-Site Scripting

- The most popular exploit for web apps for over a decade
- To fully understand, need to first understand Same Origin Policy
- Same Origin Policy (SOP): Web browser sandboxing architecture
  - A webpage can access data in another webpage only if from same URL origin
  - Your reddit.com webpage cannot access your onlinebanking.com webpage
  - Same rule applies for frames even if on same webpage
    (e.g. an advertisement in a frame cannot access data in rest of webpage)

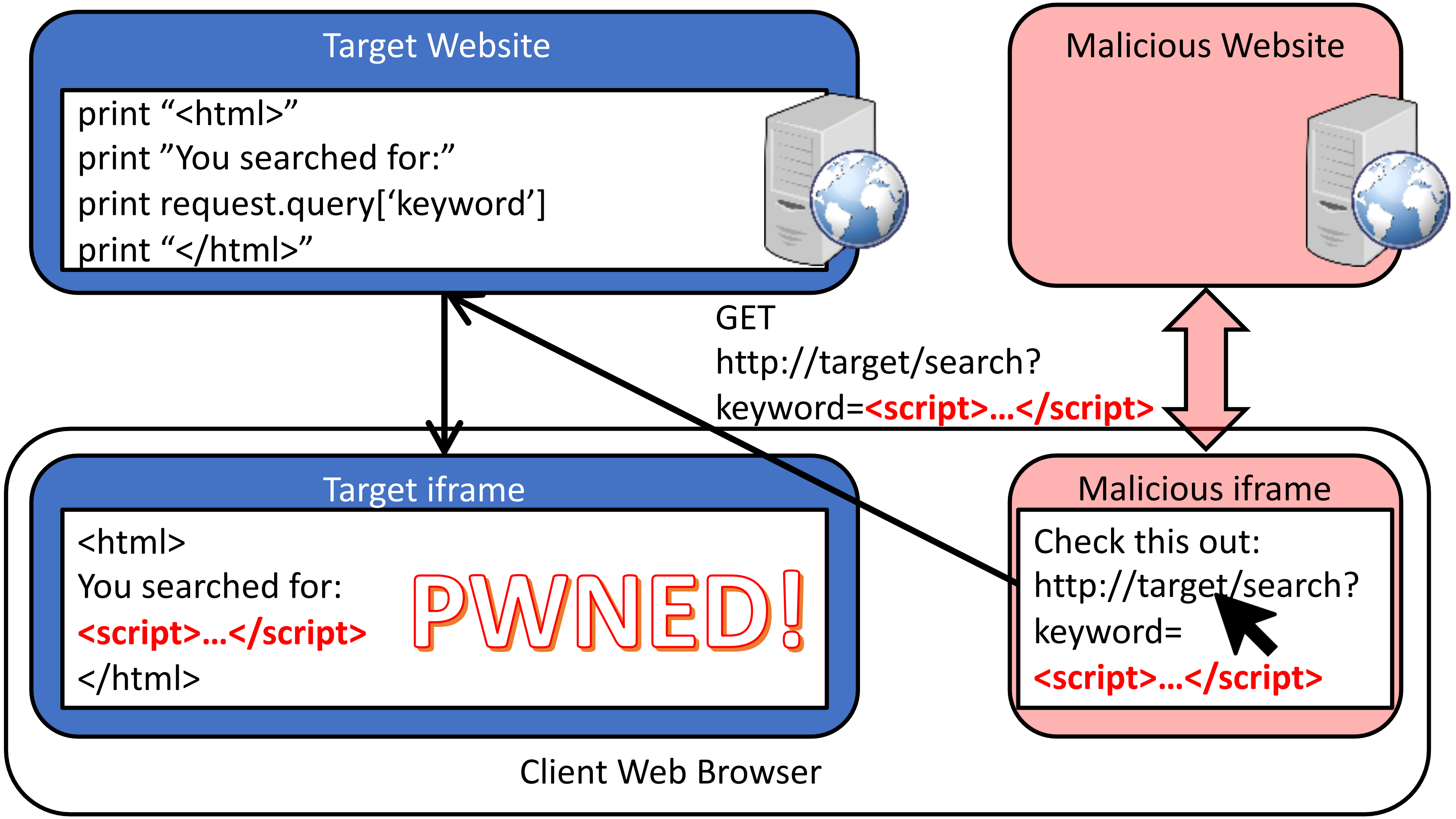
Browser Sandboxing – Same Origin Policy



Cross-Site Scripting

- Allows malicious website to execute (Java)script code
  - Across site boundaries
  - Ignoring SOP protections

Cross Site Scripting



Insecure Object References

- Someone can access something by knowing where it is, despite not having proper security credentials
  - http://bank.com/?account=9844
  - http://bank.com/?account=9845

Security Misconfiguration

- You have proper security, it’s just not set up correctly!
- Default passwords
- IPS, packet filtering, etc. not running
- Insecure machine on secure network

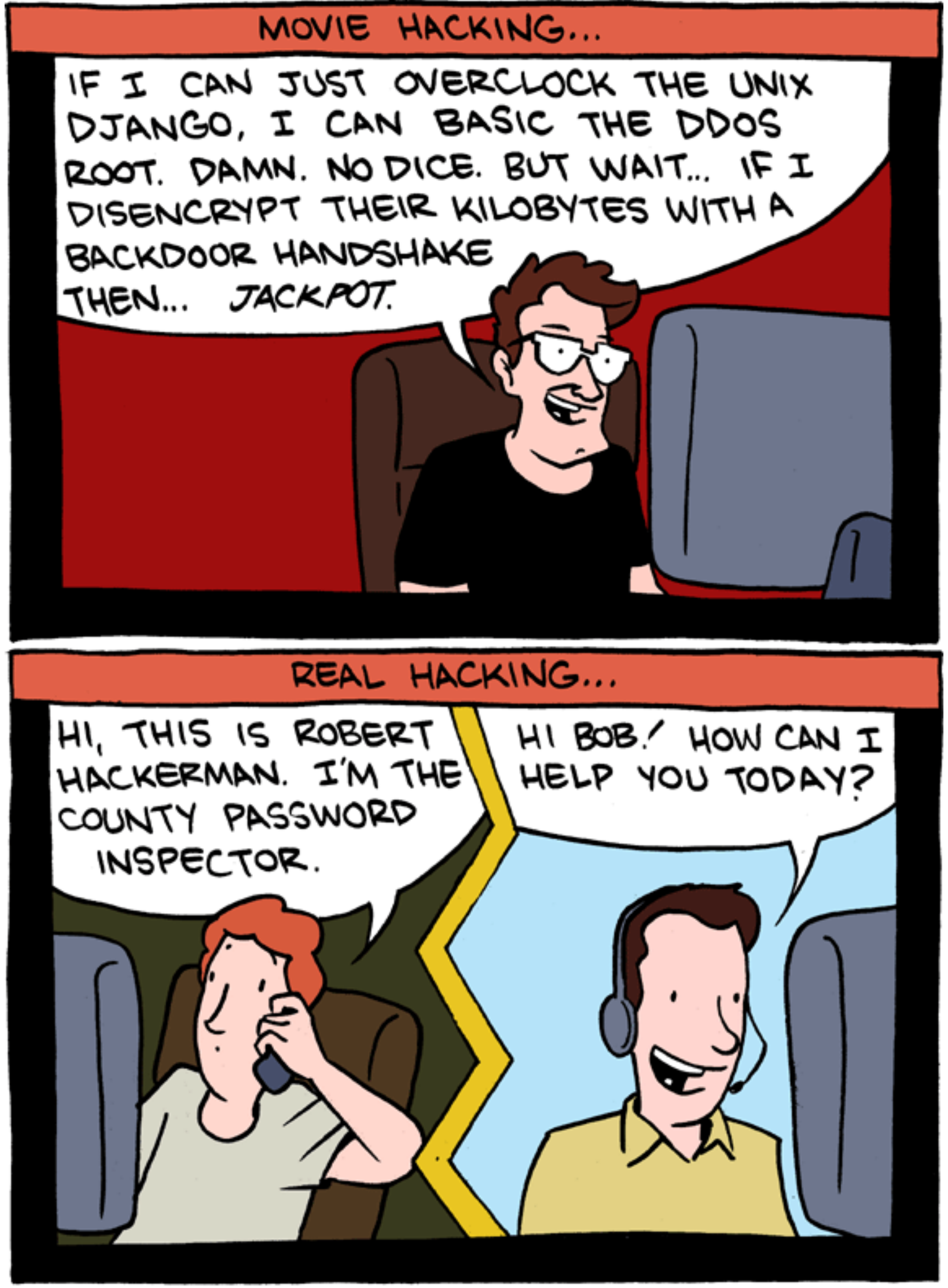
Insecure Storage

- Secure data is stored in an unsafe way
- Example: credit card numbers being stored in a /tmp or logging directory as part of logging all transactions
- Example: database being stored with incorrect file permissions, allowing the DB file to be copied wholesale

Buffer Overrun

- Reading or writing past the end of memory allocated for a buffer
- What heartbleed was – see heartbleed.c in sample_code directory

Social Engineering



For a More Comprehensive List …

- CWE (Common Weakness Enumeration) Top 25:
  - https://cwe.mitre.org/top25/archive/2019/2019_cwe_top25.html
  - By MITRE Corp. which maintains CVE (Common Vulnerabilities and Exposures) DB
- OWASP (Open Web Applications Security Project) Top 10 Project:
  - https://www.owasp.org/index.php/Category:OWASP_Top_Ten_Project
  - Top 10 security vulnerabilities for web applications over the years
- OWASP attacks page:
  - https://www.owasp.org/index.php/Category:Attack
  - Contains testing guides on how to test for those vulnerabilities

Pittsburgh – A Great City To Learn About Security!

- Many security researchers here at Pitt and CMU
  - LERSAIS at Pitt SCI – Laboratory for Education & Research on Security-Assured Information System
  - Pitt Cyber Institute
  - CyLab at CMU
- SEI (Software Engineering Institute)
- CERT (Computer Emergency Response Team)
- Many security engineering positions (esp. at banks)

Now Please Read Textbook Chapter 20

… and this ends all official lectures.

- Are you sad? Here are some extra slides for you:
  - Note: Slides following will not appear in the exam

- Monday (Dec. 2), we will have an exam review

Spectre & Its Root Causes

Paul Kocher
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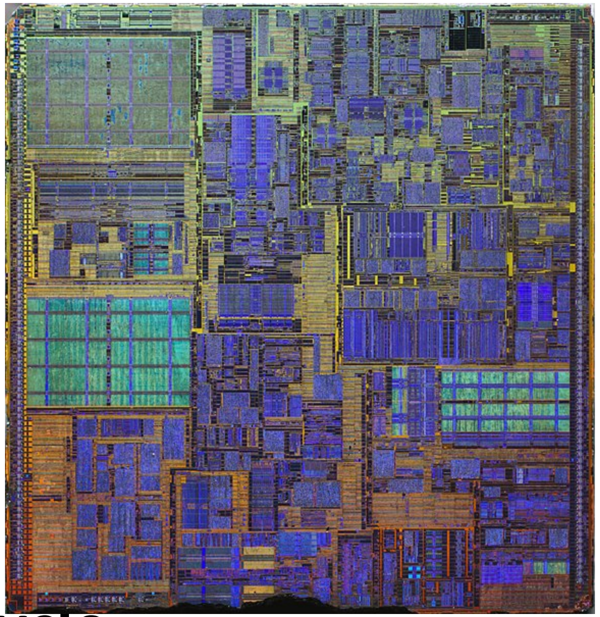
ISCA
June 4, 2018

If the surgery proves unnecessary, we'll revert your architectural state at no charge.

Addicted to speed



Public domain image of Pentium 4 die by Ritzchens Fritz

Performance goal

- Lowest time to reach the result same as running program <u>in-order</u>

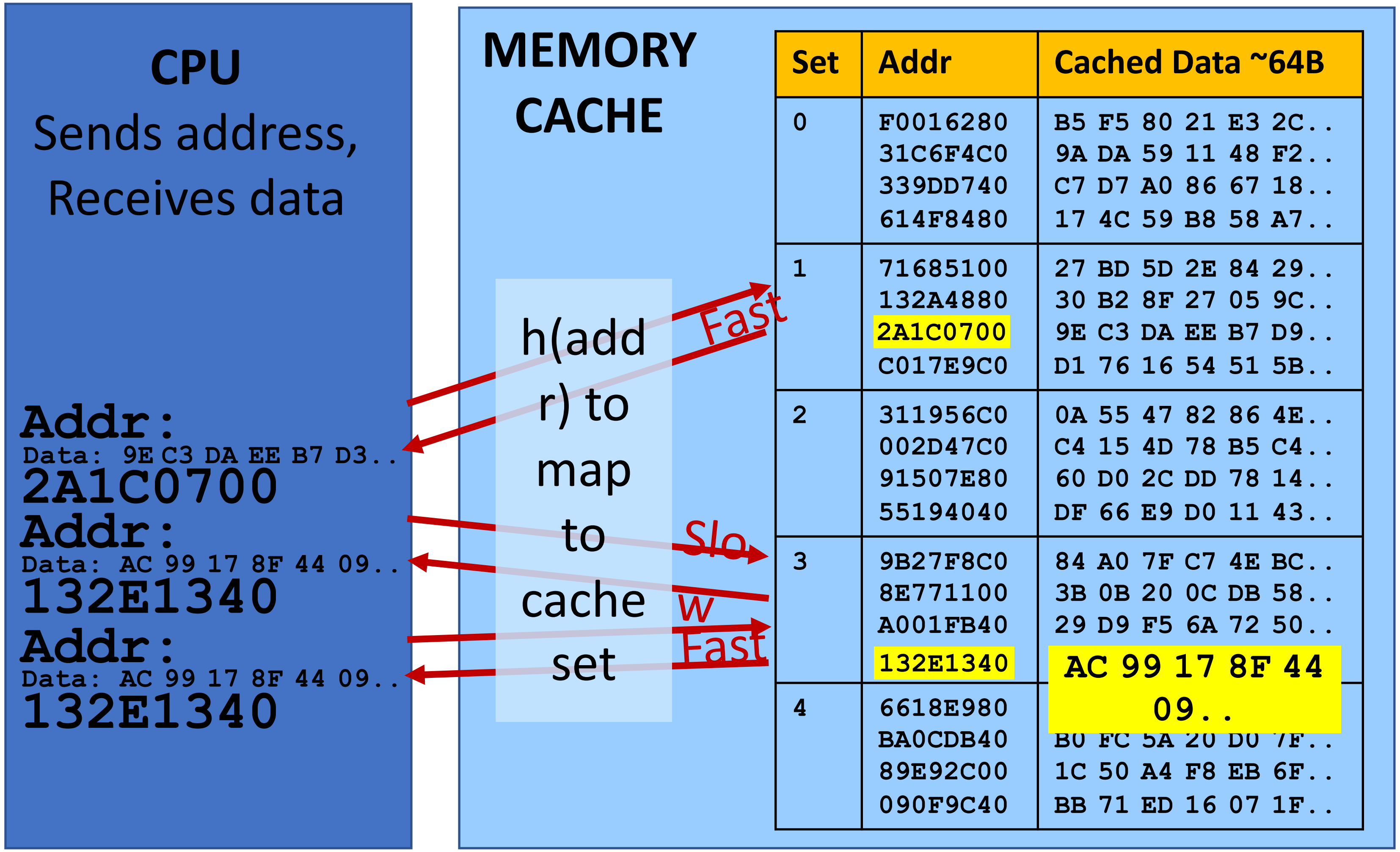
Single-thread speed gains require getting <u>**more done per clock cycle**</u>

- Memory latency is slow and not improving much
- Clock rates are maxed out: Pentium 4 reached 3.8 GHz in 2004

- How to do more per clock?
  - Reducing memory delays → Caches
  - Working during delays → Speculative execution

Memory caches for dummies

- Caches hold local (fast) copy of recently-accessed 64-byte chunks of memory



Set	Addr	Cached Data ~64B
0	F0016280 31C6F4C0 339DD740 614F8480	B5 F5 80 21 E3 2C.. 9A DA 59 11 48 F2.. C7 D7 A0 86 67 18.. 17 4C 59 B8 58 A7..
1	71685100 132A4880 2A1C0700 C017E9C0	27 BD 5D 2E 84 29.. 30 B2 8F 27 05 9C.. 9E C3 DA EE B7 D9.. D1 76 16 54 51 5B..
2	311956C0 002D47C0 91507E80 55194040	0A 55 47 82 86 4E.. C4 15 4D 78 B5 C4.. 60 D0 2C DD 78 14.. DF 66 E9 D0 11 43..
3	9B27F8C0 8E771100 A001FB40 132E1340	84 A0 7F C7 4E BC.. 3B 0B 20 0C DB 58.. 29 D9 F5 6A 72 50.. AC 99 17 8F 44 09..
4	6618E980 BA0CDB40 89E92C00 090F9C40	B0 FC 5A 20 D0 7F.. 1C 50 A4 F8 EB 6F.. BB 71 ED 16 07 1F..

Reads change system state:

- Next read to newly-cached location is faster
- Next read to evicted

Speculative execution

Instead of idling, CPUs can *guess* likely program path and do speculative execution

- Example:

```
if (uncached_value_usually_1 == 1)
    foo()
```

- Branch predictor: if() will probably be 'true' (based on prior history)
- CPU starts foo() speculatively -- but doesn't commit changes
- When value arrives from memory, if() can be evaluated definitively -- check if guess was correct:
  - Correct: Commit speculative work – performance gain
  - Incorrect: Discard speculative work

Violates software security requirement that the CPUs runs instructions correctly.

Regular execution

Set up the conditions so the processor will make a desired mistake

Fetch the sensitive data from the covert channel

Erroneous speculative execution

Mistake leaks sensitive data into a covert channel (e.g. state of the cache)

Conditional branch (Variant 1) attack

```
if (x < array1_size)
   y = array2[array1[x]*4096];
```

Assume code in kernel API, where unsigned int `x` comes from untrusted caller

Execution <u>without</u> speculation is safe

- CPU will not evaluate `array2[array1[x]*4096]` unless `x < array1_size`

What about with speculative execution?

Conditional branch (Variant 1) attack

```
if (x < array1_size)
    y = array2[array1[x]*4096];
```

Before attack:

- Train branch predictor to expect if() is true (e.g. call with `x` < `array1_size`)
- Evict `array1_size` and `array2[]` from cache

Memory & Cache Status

`array1_size = 00000008`

Memory at `array1` base address:

8 bytes of data (value doesn't matter)

[... lots of memory up to `array1` base+N...]

09 `F1 98 CC 90...` (something secret)

`array2[ 0*4096]`
`array2[ 1*4096]`
`array2[ 2*4096]`
`array2[ 3*4096]`
`array2[ 4*4096]`
`array2[ 5*4096]`
`array2[ 6*4096]`
...

Contents don't matter

only care about cache ***status***

Uncached Cached

Conditional branch (Variant 1) attack

```
if (x < array1_size)
    y = array2[array1[x]*4096];
```

Attacker calls victim with `x`=N (where N > 8)

- Speculative exec while waiting for `array1_size`
  - Predict that if() is true
  - Read address (`array1` base + `x`) w/ out-of-bounds `x`
  - Read returns secret byte = **09** (fast – in cache)
  - Request memory at (`array2` base + **09***4096)
  - Brings `array2[09*4096]` into the cache
  - Realize if() is false: discard speculative work
- Finish operation & return to caller

Attacker measures read time for `array2[i*4096]`

- Read for `i=09` is fast (cached), revealing secret byte
- Repeat with many `x` (eg ~10KB/s)

Memory & Cache Status

`array1_size = 00000008`

Memory at `array1` base address:

8 bytes of data (value doesn't matter)

[... lots of memory up to `array1` base+N...]

09 `F1 98 CC 90...` (something secret)

```
array2[ 0*4096]
array2[ 1*4096]
array2[ 2*4096]
array2[ 3*4096]
array2[ 4*4096]
array2[ 5*4096]
...
array2[ 6*4096]
```

Contents don't matter

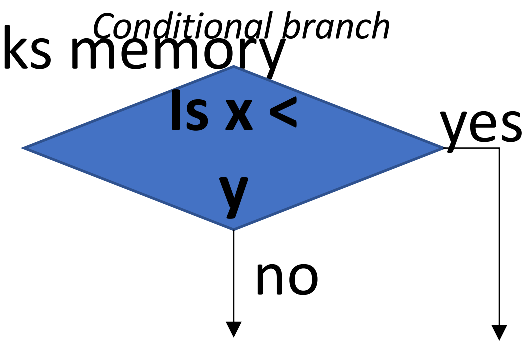
only care about cache ***status***

Uncached Cached

Indirect branches (Variant 2)

Can go anywhere instantly (“jmp [rax]”)

- Poison predictor so victim speculative executes a ‘gadget’ that leaks memory



- Attack steps
    - **<u>Poison</u>** branch predictor/BTB so speculative execution will go to gadget
    - **<u>Evict</u>** from the cache or do other setup to encourage speculative execution
    - **<u>Execute</u>** victim so it runs gadget speculatively
    - **<u>Read</u>** sensitive data from covert channel
    - **<u>Repeat</u>**