Software Foundations of Security & Privacy
15316 Fall 2021
Lecture 1: Introduction

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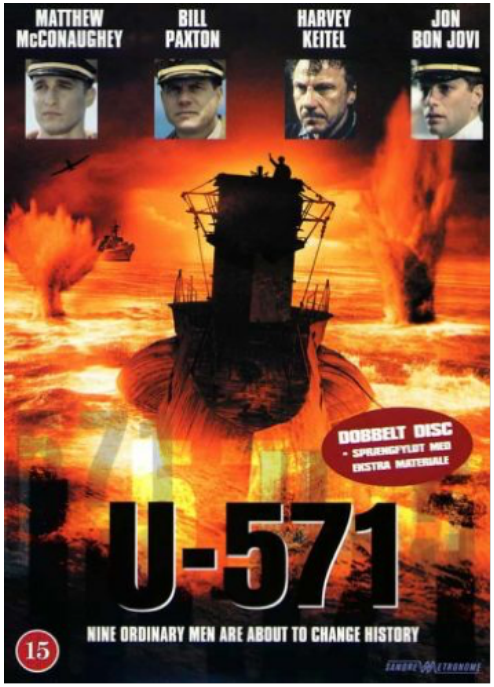
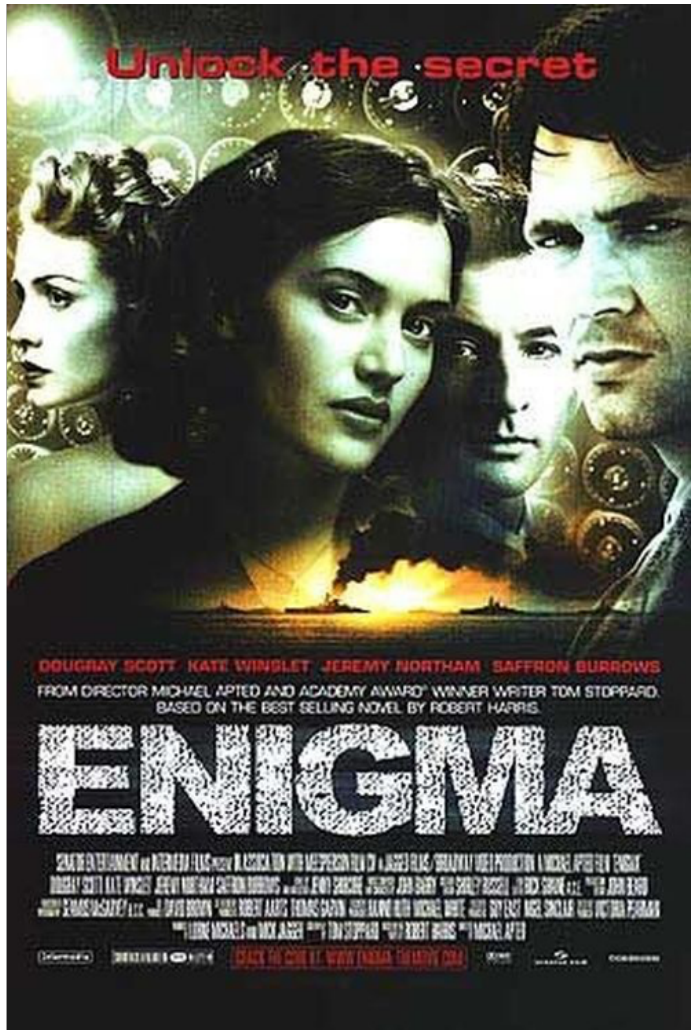
August 30, 2021

Themes and anti-themes

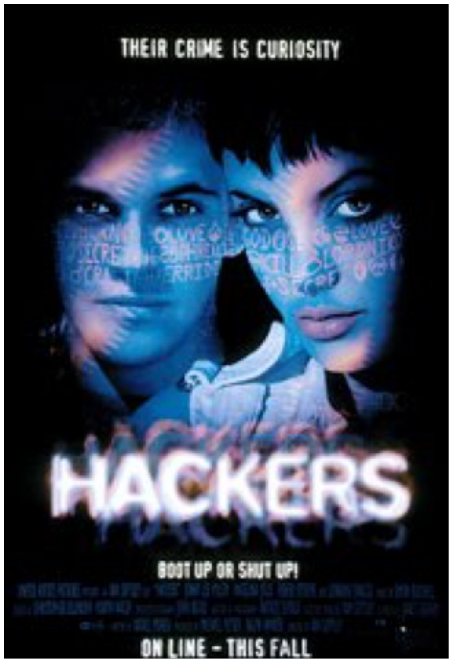
What is this course about?

This is not a course about encryption...

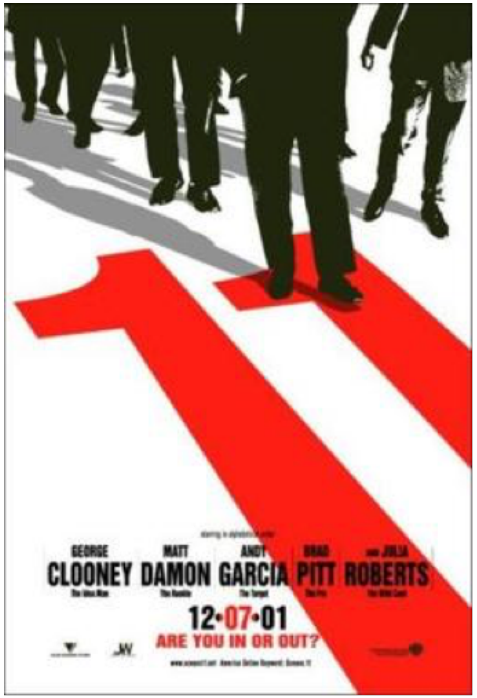


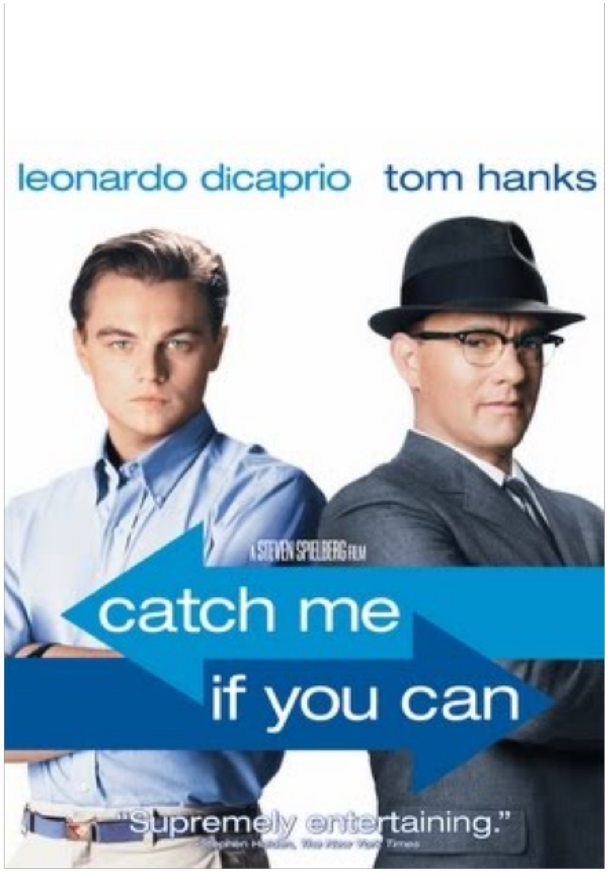


Not a course about hacking...



Not a course about social engineering...





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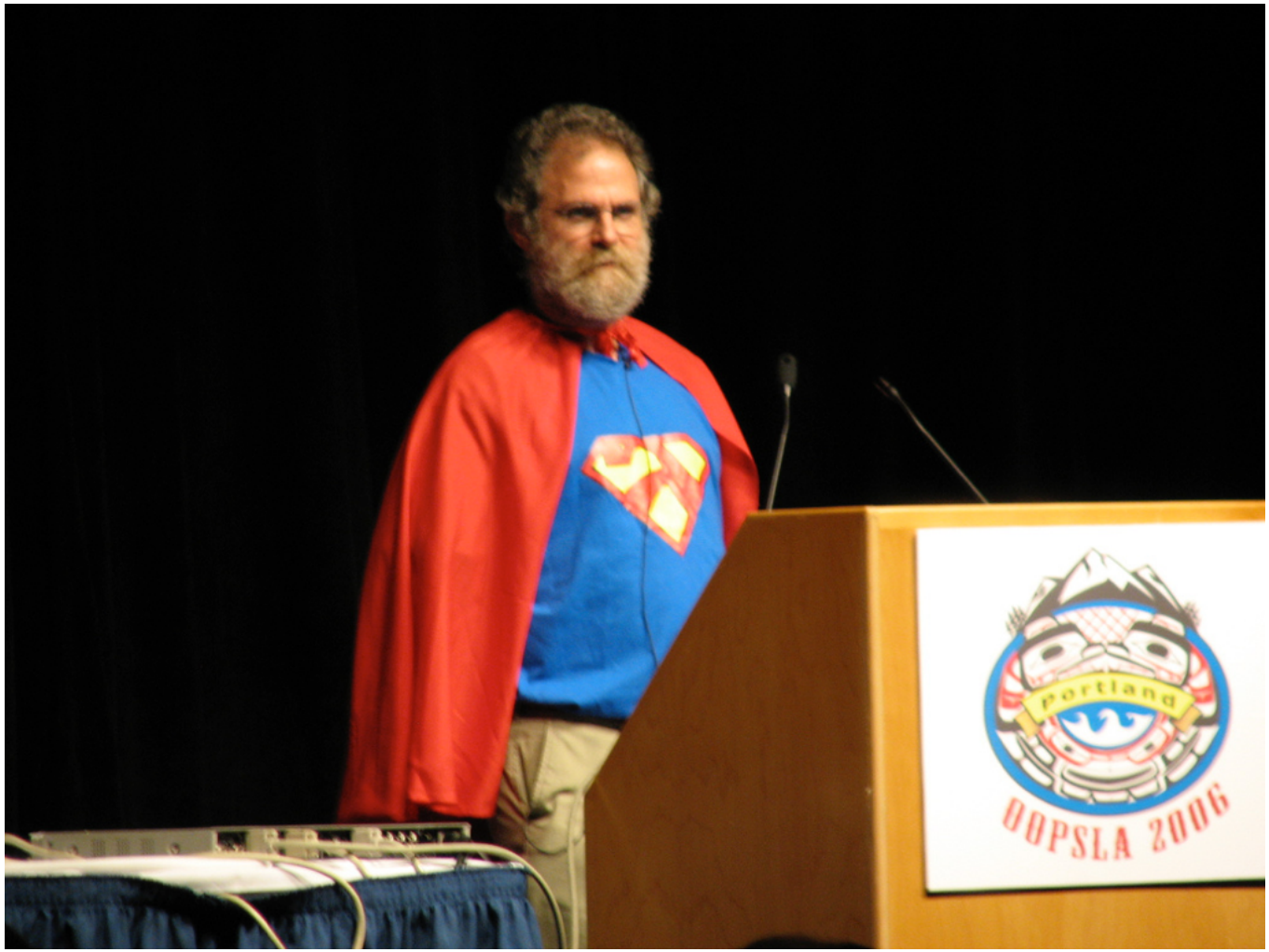

How logic and languages will save us (and make software secure)

Falling sky

Project Zero

News and updates from the Project Zero team at Google

Wednesday, January 3, 2018

Reading privileged memory with a side-channel

Posted by Jann Horn, Project Zero

Spectre & Meltdown

What's the big deal?

Spectre & Meltdown

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- "Efficiently" leak information via mis-speculated execution
- Read arbitrary virtual memory regions (including kernel)
- Bypass explicit bounds checks
- Violate browser sandboxing
- ...?

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- ...?

"Every Intel processor that implements out-of-order execution is potentially affected"

Timing channels

```
1  struct array {
2   unsigned long length;
3   unsigned char data[];
4  };
5  struct array *arr1 = ...; /* small array */
6  struct array *arr2 = ...; /* array of size 0x400 */
7  unsigned long untrusted_offset = network_read(...);
8  unsigned char value = arr1->data[untrusted_offset];
9  unsigned long index2 = ((value&1)*0x100)+0x200;
10 unsigned char value2 = arr2->data[index2];
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```

Step 1. Read some data from an arbitrary memory location

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Step 2. Isolate a bit of data from the read

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Step 2. Isolate a bit of data from the read

- `index2` is `0x200` if bit is 0
- Otherwise, `index2` is `0x300`

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```

Step 3. Read from a location dependent on extracted bit

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Step 4. Time reads to `arr2->data[0x200]`, `arr2->data[0x300]`

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- If `0x200` takes less time, then extracted bit was 0
- Otherwise, the extracted bit was 1

This last step is a result of the processor's data cache!

Progress

At this point, the attacker has accomplished:

1. Read an arbitrary bit of memory
2. Exfiltrate value of bit by timing cache hits & misses

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2. Exfiltrate value of bit by timing cache hits & misses

Keeping track of assumptions:

1. Code doesn't check bounds on memory access
2. Code reads memory using untrusted, attacker-controlled index `untrusted_offset`
3. Targeted memory location won't cause segfault

Defensive programming: bounds checks

```
1  struct array {
2   unsigned long length;
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5  struct array *arr1 = ...; /* small array */
6  struct array *arr2 = ...; /* array of size 0x400 */
7  unsigned long untrusted_offset = network_read(...);
8  if (untrusted_offset < arr1->length) {
9   unsigned char value = arr1->data[untrusted_offset];
10  unsigned long index2 = ((value&1)*0x100)+0x200;
11  if (index2 < arr2->length) {
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Speculative execution

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- If `arr1->length` is not in cache, 100 cycles until it fetches
- Processor may begin executing inside branch anyway...
- If condition is false, results are rolled back like a transaction
- But not the cache!

Speculative cache leaks

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Attacker-controlled reads make measureable changes to the processor cache

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Keeping track of necessary assumptions:

1. ~~Process code doesn't check bounds on memory access~~
2. **Code reads memory using untrusted, attacker-controlled index** `untrusted_offset`
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Packet filters in Linux, BSD provided by usermode processes

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- Filters are bytecode-interpreted or JIT-compiled, run *in kernel*
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Google's Project Zero team showed how to create JITted eBPF bytecode that opens a side-channel vulnerability

- Upshot: unprivileged processes can read all kernel memory
- Proof of concept demonstrated 2000 bytes/second

Javascript Interpreters

```
1 if (index < simpleByteArray.length) {
2   index = simpleByteArray[index | 0];
3   index = (((index * 4096)|0) & (TABLE1_BYTES-1))|0;
4   localJunk ^= probeTable[index|0]|0;
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This script causes V8 to JIT-compile vulnerable bytecode

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- HTML5 *Web Workers* feature can open new thread, repeatedly decrement shared memory value for precise timing

Upshot: Untrusted websites can read memory of other sites (passwords, CC #'s, emails, …), extension data, browser settings, …

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2. Disable the cache *(way more expensive!)*

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But there are mitigations

1. Disable speculative execution *(expensive!)*
2. Disable the cache *(way more expensive!)*
3. Serialize around sensitive accesses *(how?)*
4. Don't index arrays on untrusted values *(hard?)*

Ongoing research: provable side-channel security

Vale: Verifying High-Performance Cryptographic Assembly Code

Barry Bond*, Chris Hawblitzel*, Manos Kapritsos†, K. Rustan M. Leino*, Jacob R. Lorch*,
Bryan Parno‡, Ashay Rane§, Srinath Setty*, Laure Thompson¶

* Microsoft Research † University of Michigan ‡ Carnegie Mellon University
§ The University of Texas at Austin ¶ Cornell University

Verifying and Synthesizing Constant-Resource Implementations with Types

Van Chan Ngo Mario Dehesa-Azuara Matthew Fredrikson Jan Hoffmann
Carnegie Mellon University, Pittsburgh, Pennsylvania 15213
Email: channgo@cmu.edu, mdehazu@gmail.com, mfredrik@cs.cmu.edu, jhoffmann@cmu.edu

Verifying Constant-Time Implementations

José Bacelar Almeida
HASLab - INESC TEC & Univ. Minho

Manuel Barbosa
HASLab - INESC TEC & DCC FCUP

Gilles Barthe
IMDEA Software Institute

François Dupressoir
IMDEA Software Institute

Michael Emmi
Bell Labs, Nokia

Spectre & Meltdown: Takeaways

Security problems can be subtle and challenging

- Speculative execution isn't exactly new...

Spectre & Meltdown: Takeaways

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Spectre & Meltdown: Takeaways

Security problems can be subtle and challenging

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This course will teach you how to deal with hard security problems

- Understand the general principles behind vulnerabilities
- Learn about properties, policies that mitigate them
- Evaluate the tradeoffs of different security mechanisms
- Write code that is secure by design

Writing secure code

We'll deal with two core ingredients throughout the semester

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A way to specify software behaviors that are secure, i.e. *policies*

- Who can see what data, and when? Who can we trust?
- Under what circumstances can a program execute?
- ...and what do we expect of its outputs?
- How should information flow through a system?

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- Under what circumstances can a program execute?
- ...and what do we expect of its outputs?
- How should information flow through a system?

A way to ensure that software adheres to policy, i.e. *enforcement*

- With **provable guarantees**, not ad-hoc arguments
- Ideally, without trusting developers or users

What logic & languages gives us

Precise ways to write down policies

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Rigorous ways to enforce policies

- Type checking, formal verification for *static*
- Runtime monitors, instrumentation for *dynamic*

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- Type checking, formal verification for *static*
- Runtime monitors, instrumentation for *dynamic*

Rigorous means: we can *prove* that code follows policy

Formalism & security

Why is proving things important?

Formalism & security

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Proof requires formalism

Formalism & security

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Proof requires formalism

Formal policies make assumptions and provisions explicit:

- These define our goals, the attacker's capabilities
- For security, formality means *no surprises*!

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- For security, formality means *no surprises*!

Focus on provable claims of security

- Use math to exhaust the relevant space of attacks
- Rely on formalism to make it clear what remains unknown

Course topics

Some of the topics that we will cover include:

- Policy models: safety, information flow, statistical privacy
- Runtime policy enforcement, reference monitoring
- Security type systems
- Isolation (SFI, CFI, hardware protections)
- Privacy for individual users
- Trusted computing, authorization logic
- Web app security & best practices
- Side channel vulnerabilities and defenses
- ...

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3. Understand the role of key principles like least privilege, small trusted computing base, and complete mediation in formulating effective defenses
4. Be able to use formal proof and deductive systems to reason about the security of software systems

Logistics

Website: `https://15316-cmu.github.io`

Course staff contact:
`15-316-course-staff@lists.andrew.cmu.edu`
Lecture: Tuesdays & Thursdays, 8:35-9:55

Matt Fredrikson

- Location: CIC 2126
- Office Hours: **answer Piazza poll on good times**

Grading

Breakdown:

- 35% written homework
- 35% labs
- 20% final exam
- 10% in-class quizzes

Written homework most weeks

2 lab assignments

$\sim$10 quizzes

Closed-book final exam

Drop lowest homework & quiz grade

Written homework (35% of grade)

Written homeworks focus on theory and fundamental skills

Handed out Monday morning, due Sunday evening

Grades are based on:

- Correctness of your answer
- How you present your reasoning

Strive for **clarity & conciseness**

- Show each step of your reasoning
- State your assumptions
- Answers without well-explained reasoning may not be counted

Labs (35% of grade)

Extend HTTP server to serve answers to data queries

Incrementally add functionality while maintaining security

Grades are based on:

- Whether you implemented correct functionality
- Robustness to relevant attacks

Partial credit depending on:

- How close your impl. is to the functional spec
- How many attacks your security measures prevent

Exam and quizzes (10% + 20% of grade)

In-class quizzes every 1-2 weeks

- Handed out at start of lecture
- Covers material from current & most recent lectures
- 10-15 minutes at end of lecture to complete

Final exam

- Cumulative
- May use up to 2 pages of hand-written notes
- Formula sheet provided with exam

What to do before Thursday

1. Make sure that you are enrolled in the Gradescope, Canvas, Piazza sections for this course
   - Canvas: `https://canvas.cmu.edu/courses/25525`
   - Gradescope entry code: **KYGB73**
   - Piazza signup link: `https://piazza.com/class/ksue23cg9723zj`
2. Answer the Piazza poll about office hours time slots
3. Read the syllabus carefully, ask questions