Bug Catching: Automated Program Verification
15414/15614 Spring 2021
Lecture 1: Introduction

Matt Fredrikson and Frank Pfenning

January 18, 2022

Ohyay

- Refresh the page if a technical issue arises
- Communicate via chat, questions, or with emojis
- Or via raise your hand boxes
  - Click on a box
  - Unmute yourself
  - Speak ...
  - Click box again to disappear
- Breakout rooms
- Office hours
- Help Desk!

Course staff

Instructors

Frank Pfenning
($\sim$ Parts I & II)

Matt Fredrikson
($\sim$ Part III)

Teaching Assistants

May Li
Warwick Marangos
Long Pham
Victor Song

Learning objectives

For this lecture

- What is this course about?
- What are the learning objectives for the course?
- How does it fit into the curriculum?
- How does the course work?
- Remember . . .

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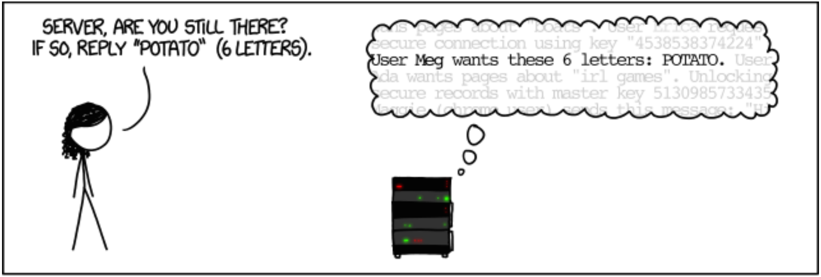
- "The Heartbleed bug allows anyone on the Internet to read the memory of the systems protected by the vulnerable versions of the OpenSSL software."
- "...this allows attackers to eavesdrop on communications, steal data directly from the services and users and to impersonate services and users."

Heartbleed, explained



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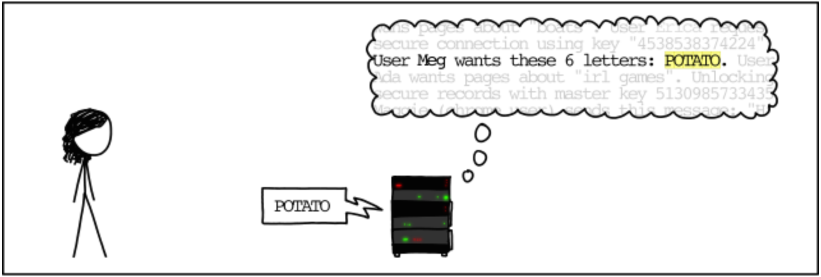

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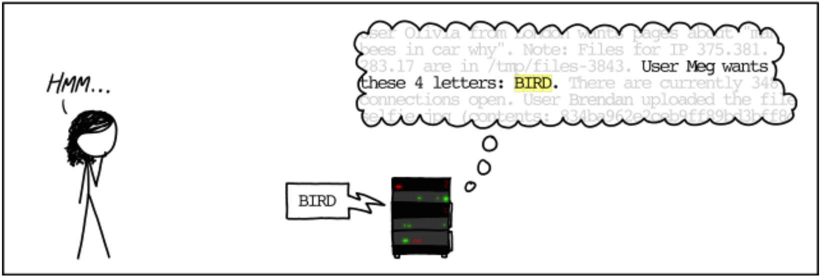

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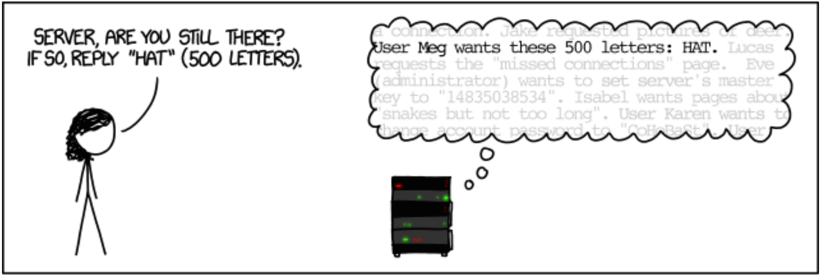

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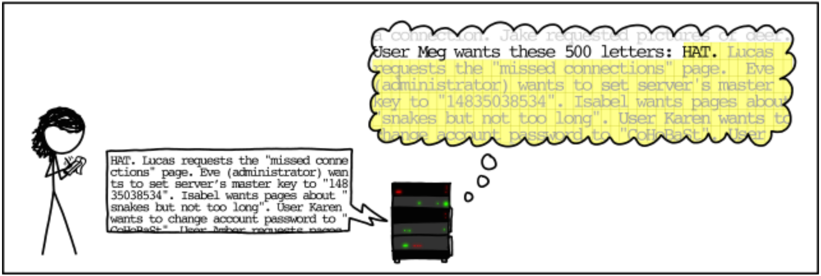

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Algorithms vs. code

```
int binarySearch(int key, int[] a, int n) {
    int low = 0;
    int high = n;

    while (low < high) {
        int mid = (low + high) / 2;

        if(a[mid] == key) return mid; // key found
        else if(a[mid] < key) {
            low = mid + 1;
        } else {
            high = mid;
        }
    }
    return -1;  // key not found.
}
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Code matters

This is a correct binary search algorithm

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But what if `low` $+$ `high` $> 2^{31} - 1$?

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Algorithm may be correct—but we run code, not algorithms.

How do we fix it?

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Solution: `mid = low + (high - low)/2`

The fix

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int binarySearch(int key, int[] a, int n)
//@requires 0 <= n && n <= \length(a);
/*@ensures (\result == -1 && !is_in(key, A, 0, n))
  @      || (0 <= \result && \result < n
  @          && A[\result] == key); @*/
{
    int low = 0;
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The fix

```
int binarySearch(int key, int[] a, int n)
//@requires 0 <= n && n <= \length(a);
//@requires is_sorted(a, 0, n);
/*@ensures (\result == -1 && !is_in(key, A, 0, n))
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- Humans are fallible, bugs are subtle
- What's the specification?

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Better: prove correctness

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$$\mathit{Specification} \Longleftrightarrow \mathit{Implementation}$$

- Specification must be precise (many subtleties)
- Meaning of code must be well-defined (many subtleties)
- Reasoning must be sound (many subtleties)

Functional programming

Functional programming

Correctness and proof is not limited to imperative programs!

```
(* balance : rbt -> rbt
 * balance T ==> R
 * REQUIRES T ordered, bh(T) def,
 *   either T is r/b
 *   or T is black; and at most one child is almost r/b
 * ENSURES R is r/b, bh(T) = bh(R), R ordered,
 *   set(T) = set(R)
 *)
fun balance (Blk(Red(Red(a,x,b),y,c),z,d)) =
            Red(Blk(a,x,b),y,Blk(c,z,d))
  | balance (Blk(Red(a,x,Red(b,y,c)),z,d)) =
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            Red(Blk(a,x,b),y,Blk(c,z,d))
  | balance p = p
```

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Functional programming: dependent types

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- Interactive provers for VC (Coq)

We focus on automated proving

Algorithmic approaches

Formal proofs are tedious

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- Fill in low-level details
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This is what you will learn!

- Make use of these methods
- How (and when) they work

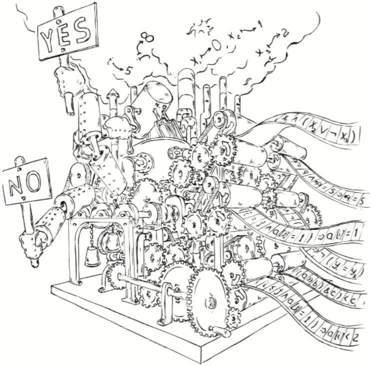

Image source: Daniel Kroening & Ofer Strichman, *Decision Procedures*

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- Make you better programmers

Course outline

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Part III: Mechanized reasoning

- Techniques for automated proving

Reasoning about correctness

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Functional Correctness

- Specification
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Systematic proof techniques

- Derived from semantics
- Exhaustive proof rules
- Automatable*

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When it works! (It's not quite like a type-checker ...)

Automated verifiers

Systems that prove that programs match their specifications

Basic idea:

1. Translate programs into *proof obligations*
2. Encode proof obligations as satisfiability
3. Solve using a decision procedure

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Verifiers are complex systems

- We'll deep-dive into selected components
- Understand "big picture" for the rest

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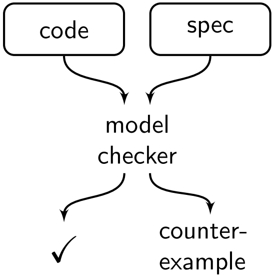
Model Checking

Fully-automatic techniques for finding bugs (or proving their absence)

- Specifications written in *propositional temporal logic*
- Verification by exhaustive state space search
- Diagnostic counterexamples



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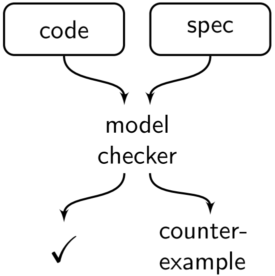

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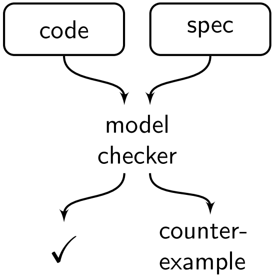

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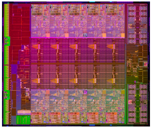
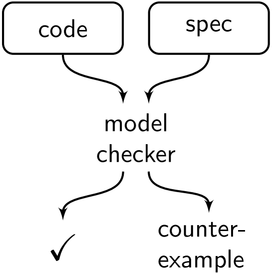
10^{70} atoms 10^{500000} states





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First developed this course!

Grading

Breakdown:

- 50% assignments
  (written + programming)
- 15% mini-project 1
- 15% mini-project 2
- 20% final exam

6 assignments
done individually

2 mini-projects
pick from small menu
can work with a partner

Participation:

- Come to lecture
- Answer questions
  (in class and on Piazza!)
- Contribute to discussion

Written parts of assignments

Written homeworks focus on theory and fundamental skills

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Grades are based on:

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- How you present your reasoning

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Strive for **clarity & conciseness**

- Show each step of your reasoning
- State your assumptions
- Answers without these $\longrightarrow$ no points

Programming parts of assignments

For the programming, you will:

- Implement some functionality (data structure or algorithm)
- Specify correctness for that functionality
- Use Why3 to prove it correct

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Partial credit depending on how many of these you achieve

Clarity & conciseness is necessary for partial credit!

Mini-Projects

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- Applying course principles to practice
- Making effective use of automated tools
- **Writing useful & correct code**

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Gradual progression to sophistication:

1. Familiarize yourself with Why3
2. Implement and prove something
3. Work with more complex data structures
4. Implement and prove something really interesting
5. Optimize your implementation, still verified

Late Policy

Late days

- 5 late days to use throughout the semester
- No more than 2 late days on any assignment
- Late days do not apply to mini-projects!

Logistics

Website: `http://www.cs.cmu.edu/~15414`

Course staff contact: Piazza

Lecture: Tuesdays & Thursdays, 12:20-1:40pm

- First two weeks on ohyay
- Afterwards: HH B131

Lecture Recordings (when remote): YouTube

Office Hours: TBD, schedule on website and course calendar soon

Assignments: Gradescope

Let's prove something!

- Will sort you into breakout rooms
- Figure out mystery function does and how to prove it
- Will recall you to lecture hall
- Let's live-code!