Bug Catching: Automated Program Verification
15414/15614 Spring 2020
Lecture 1: Introduction

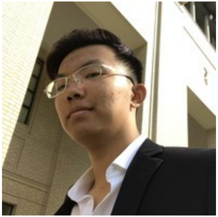
Matt Fredrikson

January 14, 2020

Course Staff

Matt Fredrikson
Instructor

Di Wang
TA



Ryan Chen
TA

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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

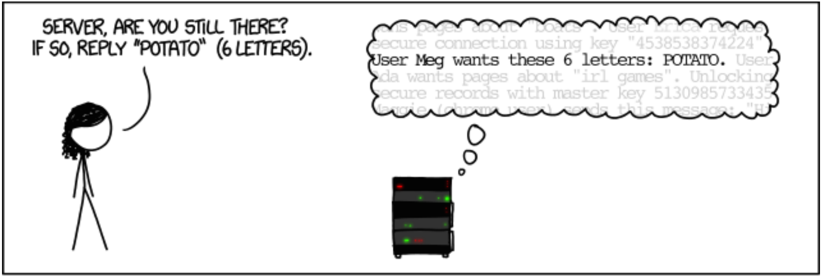

Image source: Randall Munroe, xkcd.com

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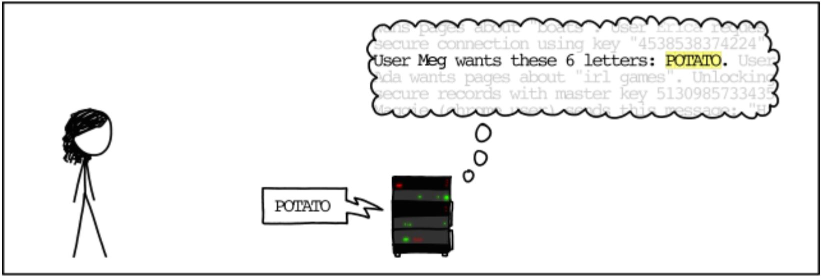

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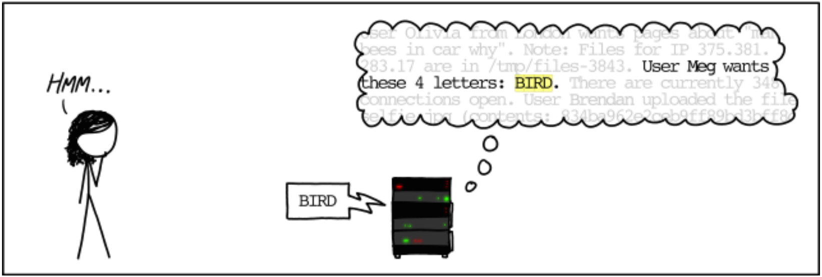

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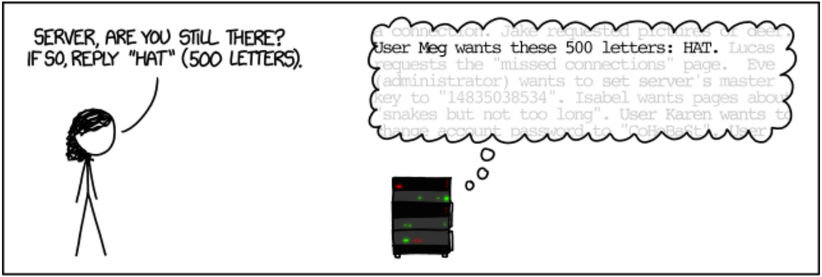

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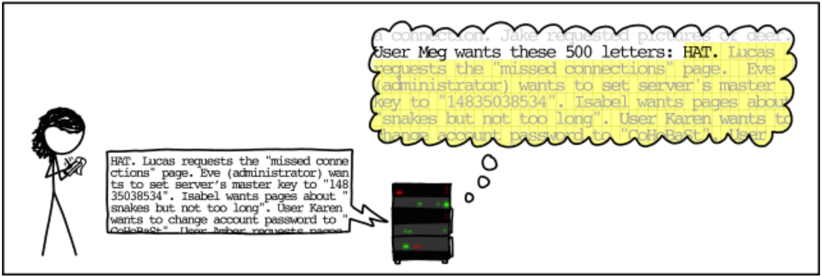

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Algorithms vs. code

```
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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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`

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The fix

```
int binarySearch(int key, int[] a, int n)
//@requires 0 <= n && n <= \length(A);
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The fix

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

       if(a[mid] == key) return mid; // key found
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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))
  @      || (0 <= \result, \result < n
  @           && A[\result] == key); @*/
{
   int low = 0;
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       int mid = low + (high - low) / 2;

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

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$$\textit{Specification} \Longleftrightarrow \textit{Implementation}$$

- Specification must be precise
- Meaning of code must be well-defined
- Reasoning must be sound

Algorithmic Approaches

Formal proofs are tedious

Automatic methods can:

- Check our work
- Fill in low-level details
- Give diagnostic info
- Verify everything for us

This is what you will learn!

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

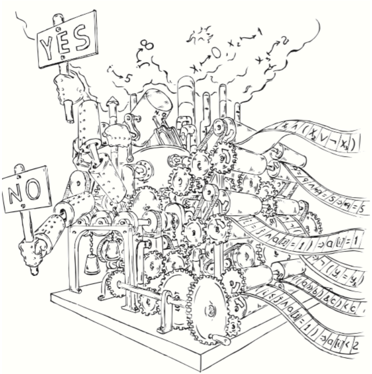

Image source: Daniel Kroening & Ofer Strichman, *Decision Procedures*

Course objectives

- Identify and formalize program correctness
- Understand language semantics
- Apply mathematical reasoning to program correctness
- Learn how to write correct software, from beginning to end
- Use automated tools that assist verifying your code
- Understand how verification tools work

Reasoning about correctness

Functional Correctness

- Specification
- Proof

Specify behavior with logic

- Declarative
- Precise

Systematic proof techniques

- Derived from semantics
- Exhaustive proof rules
- Automatable*

```
int[] array_copy(int[] A, int n)
//@requires 0 <= n && n <= \length(A);
//@ensures \length(\result) == n;
{
  int[] B = alloc_array(int, n);

  for (int i = 0; i < n; i++)
  //@loop_invariant 0 <= i;
  {
    B[i] = A[i];
  }

  return B;
}
```

Why3

Deductive verification platform

- Programming language
- Verification toolchain

Rich specification language

- Pre- and post-conditions, assertions
- Pure mathematical functions
- Termination metrics

Programmer writes specification, partial annotations

Compiler proves correctness automatically!

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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Problem is undecidable!

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Automated Verifiers

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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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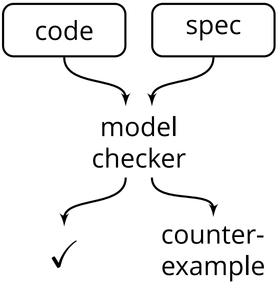
Model Checking

***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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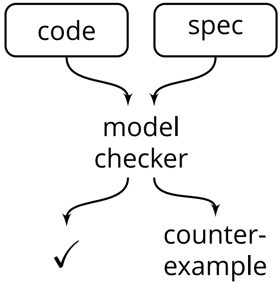

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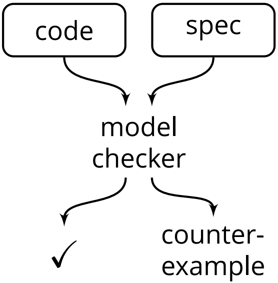

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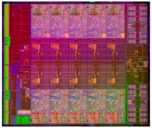
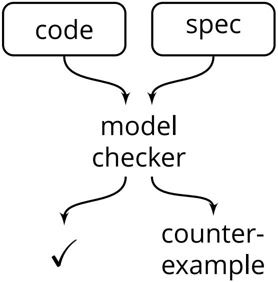
10^{70} atoms 10^{500000} states





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Now widely used for verification & bug-finding:

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Ed Clarke
Turing Award, 2007

Grading

Breakdown:

- 40% labs
- 25% written homework
- 30% exams (15% each, midterm and final)
- 5% participation

5 labs

Weekly written homework

In-class exams, closed-book

Participation:

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

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- Implement some functionality
- Specify correctness for that functionality
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Full points when you provide the following

- Correct implementation
- Correct specification
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- Sufficient annotations for verification

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Partial credit depending on how many of these you achieve

Clarity & conciseness is necessary for partial credit!

Labs

Labs are intended to build proficiency in:

- Writing good specifications
- 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

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Strive for **clarity & conciseness**

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

Late Policy

No late days on written homework

- Not intended to be time-intensive
- 20% deduction for each day past deadline

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Regrades

- No push-button regrades
- Discuss suspected error with us in person
- We will regrade the entire assignment

Logistics

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

Course staff contact: Piazza or
`15414-staff@lists.andrew.cmu.edu`
Lecture: Tuesdays & Thursdays, 12:00-1:20pm GHC 4307

Matt Fredrikson

- Location: CIC 2126
- Office Hours: Thursdays 4pm

Di Wang, Ryan Chen

- Office Hours: TBD