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

Ruben Martins and Frank Pfenning
(slides ripped off from Matt Fredrikson)

February 2, 2021

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)

Ruben Martins
($\sim$ Part III)

Teaching Assistants

Jatin Arora
Aditi Gupta
Deepayan Patra

Something about me . . .

Learning objectives

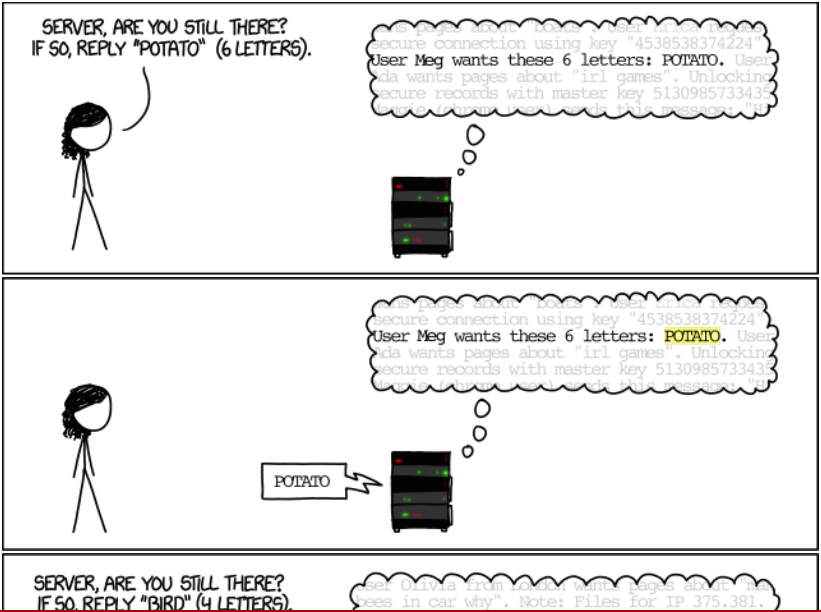
For this lecture

- 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 . . .

Bad code

- **April, 2014** OpenSSL announced critical vulnerability in their implementation of the Heartbeat Extension.
- "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



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.
}
```

Code matters

This is a correct binary search algorithm

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

Then `mid` $=$ (`low` $+$ `high`) / 2 becomes negative

- Best case: `ArrayIndexOutOfBoundsException`
- Worst case: undefined (that is, arbitrary) behavior

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

How do we fix it?

The culprit: `mid = (low + high) / 2`

Need to make sure we don't overflow at any point

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

The fix

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

    while (low < high) {
        int mid = low + (high - low) / 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.
}
```

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

How do we know if it's correct?

One solution: testing

- Probably incomplete $\longrightarrow$ uncertain answer
- Exhaustive testing not feasible

Another: code review

- Correctness definitely important, but not the only thing
- Humans are fallible, bugs are subtle
- What's the specification?

Better: prove correctness

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

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

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)) =
                Red(Blk(a,x,b),y,Blk(c,z,d))
  | balance (Blk(a,x,Red(b,y,Red(c,z,d)))) =
                Red(Blk(a,x,b),y,Blk(c,z,d))
  | balance (Blk(a,x,Red(Red(b,y,c),z,d))) =
                Red(Blk(a,x,b),y,Blk(c,z,d))
  | balance p = p
```

Different traditions and techniques

Functional programming: dependent types

- Proofs are expressed in programs (Agda)
- Proof tactics are expressed as programs (Coq)

Imperative programming: logical contracts

- Properties are expressed in contracts
- Reduce correctness to logical propositions (verification condition)
- Use automated theorem provers to prove VC

Why3 (this course) supports both!

- Functional and imperative code in WhyML
- Automated provers for VC (Z3, CVC, alt-ergo, ...)
- Interactive provers for VC (Coq)

We focus on automated proving

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

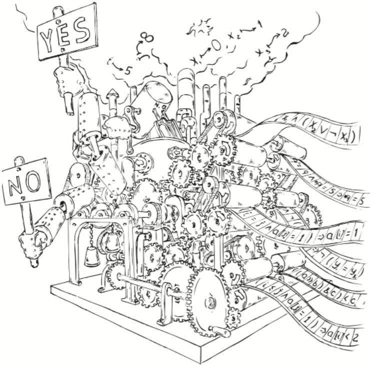


Image source: Daniel Kroening & Ofer Strichman, *Decision Procedures*

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
- Make you better programmers

Course outline

Part I: Reasoning about programs: from 122 and 150 to 414

- Gain intuitive understanding of language and methodology

Part II: From inform to formal reasoning

- Specifying meaning of programs
- Specifying meaning of propositions
- Formal reasoning and its justification

Part III: Mechanized reasoning

- Techniques for automated proving

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;
}
```

But . . .

Why3

Deductive verification platform

- Programming language (WhyML, derived from OCaml)
- Verification toolchain

Rich specification language

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

Programmer writes specification, partial annotations

Compiler proves correctness automatically!

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

Automated verifiers

Systems that prove that programs match their specifications

Problem is undecidable!

1. Require annotations
2. Relieve manual burden by inferring some annotations

Verifiers are complex systems

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

Basic idea:

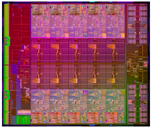
1. Translate programs into *proof obligations*
2. Encode proof obligations as satisfiability
3. Solve using a decision procedure

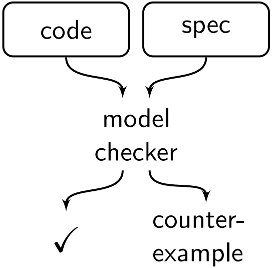
Model Checking

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

- Specifications written in *propositional temporal logic*
- Verification by exhaustive state space search
- Diagnostic counterexamples
- No proofs!
- **Downside**: "State explosion"

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





Model Checking

Clever ways of dealing with state explosion:

- Partial order reduction
- Bounded model checking
- Symbolic representations
- Abstraction & refinement

Now widely used for verification & bug-finding:

- Hardware, software, protocols, . . .
- Microsoft, Intel, Amazon, Google, NASA, . . .

Ed Clarke, 1945–2020
Turing Award, 2007
First developed this course!

Grading

Breakdown:

- 60% assignments (written + programming)
- 15% mini-project 1 ("midterm")
- 25% mini-project 2 ("final")
- no exams

7 assignments
done individually

2 mini-projects
pick from small menu
(still deliberating on pairing)

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

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 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

Most important criterion is **correctness**.

Full points when you provide the following

- Correct implementation
- Correct specification
- Correct contracts
- Sufficient contracts for verification

Partial credit depending on how many of these you achieve

Clarity & conciseness is necessary for partial credit!

Mini-Projects

Mini-projects are intended to build proficiency in:

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

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, on ohyay

Lecture Recordings: YouTube

Office Hours: on ohyay, schedule see web pages and course calendar

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!