Verification For Security: Introduction

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What is Algorithmic Verification?

Algorithms, Techniques and Tools to ensure that:

- Program's don't have bugs.
- Later: are secure in some sense.

But what does that *mean*? Stay tuned :)

Course Website

- Course website at: https://gleissen.github.io/vfs/
- Contains lecture slides, calendar, additional details

Goals

- **Deep dive** into:
  - The state of the art of program verification
  - Programming Languages (PL) techniques for security
  - Learn our way of thinking about these problems
  - Prepare for research in the area
  - Learn how to use this in practice
  - Make you a better programmer
  - Have fun!

Why should you care?

- Many success stories

  AWS, Airbus, Microsoft, NASA,

  Galois, Facebook, Google

- Verified crypto in google Chrome (Fiatcrypto)

- Verified Operating System (sel4, hi-star), compilers (compcert), processors (ARM/Intel), distributed systems (AWS), networks (AWS), enclaves, etc.

Turing Awards in PL / Verification

Dijkstra

Floyd

Hoare

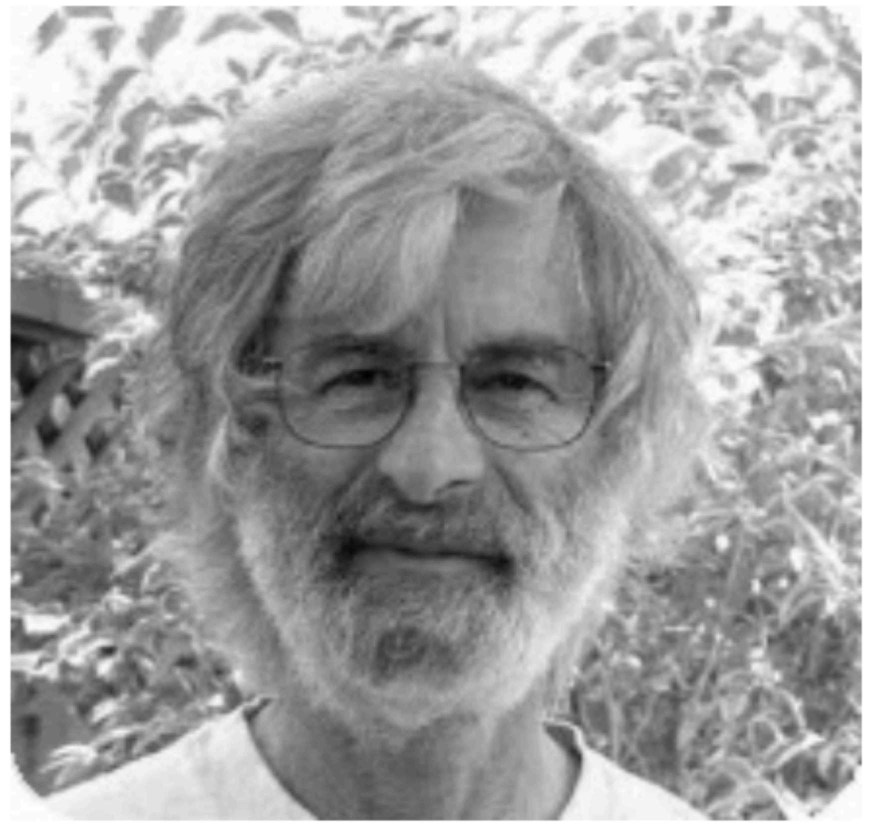
Milner

Pnueli

Clarke

Emerson

Sifakis



Lamport

Plan

Two parts:

- Algorithms for showing that programs are correct
- Later: Showing that programs are secure
- Not an easy course, but you will learn a lot

Plan

1. Propositional Logic / SAT
2. FO Logic / SMT
3. Floyd Hoare Logic / Proof Checking
4. Horn Clauses / Predicate Abstraction
5. Houdini / Abstract Interpretation

Verification Basics

Plan

1. Propositional Logic / SAT
2. FO Logic / SMT
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Verification Basics

6. Information Flow Types
7. Timing & Speculative Execution Attacks

Security

Evaluation

- 2 Practical Assignments (25%)
- Final Project (25%)
- Written Exam (50%)
- Must pass assignment and project with grade >=4
- Must pass the exam with grade >=5.5

Practical Assignments

- Implement an SMT solver & a program verifier in Haskell!
- Verify programs in a language called Nano
- 2 Assignments, about 2 weeks to complete for each
- Groups of 2

- We give you skeleton code, need to fill in main functions
- Pass all the tests, full points

Practical Assignments

- Late submissions: one malus point per day
- Exceptions for hardship
  - Need to be approved by study advisor

Practical Assignments

- Assignment 1: SAT & SMT Solver
- Assignment 2: Implement a Program Verifier
- Assignment 3: Pick your own Project

Practical Assignments

- You’ll need to know Haskell (quite well!)
- **Start reading the tutorial now!**
- http://learnyouahaskell.com/chapters
- Look at our monad tutorial here
- **Download GHC and start coding**

Project

- This is where you get to show us what you learned.
- The project needs to be written in Haskell
- Groups of 2, as before.
- First, 1 page proposal.
- Then, you'll implement the project and write up a report of up to three pages.
- List of project ideas on the website

Exam

- Check understanding of the material
- Shows individual contribution, as the rest of the course is pair projects.
- We'll release online Canvas quizzes that you can use to prepare for the exam.

Plagiarism

- Please don't do it! It's bad for everyone
- Don't copy & don't share solutions
- We will check automatically & manually
- There are no existing solutions, the assignments are new

Office Hours

- We have a practical session on Friday
- This will be used as office hours for asking questions about lecture, programming assignments and the project

Getting the most out of this course

- Take what I say as a starting point and read more!
- I will add links to further reading & other similar courses
- Google: "topic site:edu slides” to find more material
- Think about how & why things work
- Would they still work if we changed x,y?
- Ask questions!
- Use the canvas message board liberally (but don’t share code)!

Questions? … let’s start!

Let’s start!

1. Propositional Logic / SAT
2. FO Logic / SMT
3. Floyd Hoare Logic / Proof Checking
4. Horn Clauses / Predicate Abstraction
5. Houdini / Abstract Interpretation

Verification Basics

Logic

- Why are we talking about logic?
- Logic is the *Calculus of Computation*!
- May seem abstract now (*what's up with all these symbols?*) …
- … but much/all of program analysis can be boiled down to logic.
- Think of logic as a language for **asking questions** about programs!

Decision Procedures

- Efficient Algorithms to **answer questions** about programs
- Easily enough to teach one or many courses
- We will only scratch the surface to give a feel
- Good resource: Calculus of Computation
    - https://community.wvu.edu/~krsubramani/courses/backupcourses/dm2Spr2013/coursetext/CalcofComp.pdf

Propositional Logic

- You probably already know this, but good to recap
- A logic is a **language**, described by:
  - Syntax of its formulas (variables, connectives, ...)
  - Semantics of formulas (when is a formula *satisfied*, or *valid*)

Propositional Logic: Syntax

Atom:	truth symbols	$\top$ (true), $\bot$ (false)
	propositional variables	$p, q, r, p_1, p_2, \ldots$
Literal:	an atom α or its negation $\neg\, \alpha$	

Formula: A literal, or application of a **logical connective** to formula F, F_1, F_2, …

$\neg\, F$	"not"	negation
$F_1 \wedge F_2$	"and"	conjunction
$F_1 \vee F_2$	"or"	discjunction

Propositional Logic: Syntax

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$F_1 \vee F_2$	"or" F_1	discjunction

We can define additional connectives in terms of these basic ones:

$F_1 \rightarrow F_2$	"implies"	$\neg F_1 \vee F_2$
$F_1 \leftrightarrow F_2$	"if and only if"	$(F_1 \rightarrow F_2) \wedge (F_2 \rightarrow F_1)$

Propositional Logic: Semantics

- A logic is a **language**, described by:
  - Syntax of its formulas (predicates, connectives, ...)
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Propositional Logic: Semantics

An interpretation **I** maps propositional formulas to truth values

$$I : \{p \rightarrow \top,\ q \rightarrow \bot,\ r \rightarrow \bot, \cdots\}$$

We can **evaluate** a formula F **under I** by substituting each p for **I**(p)

We write $I \models F$, if F evaluates to $\top$ under I, we call I a **satisfying interpretation or model**

We write $I \not\models F$, if F evaluates to $\bot$ under I, I is a **falsifying interpretation or counter-model**

Propositional Logic: Semantics

We can **evaluate** a formula F **under I** by substituting each p for **I**(p)

We can make this more precise through an **inductive definition**

Base case

$I \models \top \qquad I \not\models \bot$

$I \models p, \quad \text{if} \quad I(p) = \top$

$I \not\models p, \quad \text{if} \quad I(p) = \bot$

Inductive Case

$I \models \neg F, \quad \text{if} \quad I \not\models F$

$I \models F_1 \wedge F_2, \quad \text{if} \quad I \models F_1 \text{ and } I \models F_2$

$I \models F_1 \vee F_2, \quad \text{if} \quad I \models F_1 \text{ or } I \models F_2$

What about $\rightarrow$, $\leftrightarrow$? Already defined.

Propositional Logic: Semantics

Example

Consider formula $F \triangleq (\neg p \lor q)$ and interpretation $I \triangleq \{p \mapsto \top, q \mapsto \bot\}$

Quiz: Which of the following is true?

a) $I \models F$ b) $I \not\models F$

What about formula $(p \land q) \rightarrow (\neg p \lor q)$?

Propositional Logic: Semantics

Satisfiability and Validity

F is <u>satisfiable</u>, iff *there exists* an interpretation I such that $I \models F$

F is <u>valid</u>, iff *for all* interpretations I, $I \models F$

F is <u>contingent</u>, iff it is satisfiable but not valid

Duality between satisfiability and validity:

F is <u>valid</u>, iff $\neg F$ is <u>satisfiable</u>

Thus: If we can decide whether a formula is satisfiable, we can also check if it is valid

Propositional Logic: Semantics

Example

Quiz: Are these formulas sat, unsat, or valid?

1. $(p \land q) \rightarrow \neg p$
2. $(p \land q) \rightarrow (p \lor \neg q)$
3. $(p \rightarrow (q \rightarrow r)) \land \neg((p \land q) \rightarrow r)$

Deciding Satisfiability

- Logic: **asking questions** about programs
- But how to answer?
- We want to decide whether a formula is satisfiable
- Let’s look at two simple methods first:
  - Enumerating interpretations (aka truth tables)
  - Semantic Arguments (deductive proofs)

Deciding Satisfiability: Truth Table

- Let's look at the following formula $F \triangleq (p \land q) \rightarrow (p \lor \neg q)$
- We can enumerate its interpretations via a truth table

Deciding Satisfiability: Truth Table

- Let's look at another example $F \triangleq (p \lor q) \rightarrow (p \land q)$

For n propositional variables, there are 2^n interpretations: <u>impractical</u>

Deciding Satisfiability: Semantic Argument

Try to prove validity of formula F through a proof by contradiction

- Assume F is not valid, i.e., there exists I s.t., $I \not\models F$
- Apply proof rules to derive $\perp$ along every branch (what's that?)
- If we succeed, F is valid

Deciding Satisfiability: Semantic Argument

Proof Rules

<u>neg</u>

$$\frac{I \models \neg F}{I \not\models F} \qquad \frac{I \not\models \neg F}{I \models F}$$

<u>conj</u>

$$\frac{I \models F_1 \land F_2}{I \models F_1 \quad I \models F_2} \qquad \frac{I \not\models F_1 \land F_2}{I \not\models F_1 \ \underline{\text{or}} \ I \not\models F_2}$$

<u>disj</u>

$$\frac{I \models F_1 \lor F_2}{I \models F_1 \ \underline{\text{or}} \ I \models F_2} \qquad \frac{I \not\models F_1 \lor F_2}{I \not\models F_1 \quad I \not\models F_2}$$

<u>imp</u>

$$\frac{I \models F_1 \rightarrow F_2}{I \models \neg F_1 \ \underline{\text{or}} \ I \models F_2} \qquad \frac{I \not\models F_1 \rightarrow F_2}{I \models F_1 \quad I \not\models F_2}$$

<u>contr</u>

$$\frac{I \models F \quad I \not\models F}{I \models \bot}$$

neg
$$\frac{I \models \neg F}{I \not\models F} \qquad \frac{I \not\models \neg F}{I \models F}$$

conj
$$\frac{I \models F_1 \land F_2}{I \models F_1 \quad I \models F_2} \qquad \frac{I \not\models F_1 \land F_2}{I \not\models F_1 \ \underline{\text{or}}\ I \not\models F_2}$$

disj
$$\frac{I \models F_1 \lor F_2}{I \models F_1 \ \underline{\text{or}}\ I \models F_2} \qquad \frac{I \not\models F_1 \lor F_2}{I \not\models F_1 \quad I \not\models F_2}$$

imp
$$\frac{I \models F_1 \rightarrow F_2}{I \models \neg F_1 \ \underline{\text{or}}\ I \models F_2} \qquad \frac{I \not\models F_1 \rightarrow F_2}{I \models F_1 \quad I \not\models F_2}$$

contr
$$\frac{I \models F \quad I \not\models F}{I \models \bot}$$

Let's prove that $F \triangleq (p \land q) \rightarrow (p \lor \neg q)$ is valid

neg

$$\frac{I \vDash \neg F}{I \nvDash F} \qquad \frac{I \nvDash \neg F}{I \vDash F}$$

conj

$$\frac{I \vDash F_1 \wedge F_2}{I \vDash F_1 \quad I \vDash F_2} \qquad \frac{I \nvDash F_1 \wedge F_2}{I \nvDash F_1 \ \underline{\text{or}}\ I \nvDash F_2}$$

disj

$$\frac{I \vDash F_1 \vee F_2}{I \vDash F_1 \ \underline{\text{or}}\ I \vDash F_2} \qquad \frac{I \nvDash F_1 \vee F_2}{I \nvDash F_1 \quad I \nvDash F_2}$$

imp

$$\frac{I \vDash F_1 \rightarrow F_2}{I \vDash \neg F_1 \ \underline{\text{or}}\ I \vDash F_2} \qquad \frac{I \nvDash F_1 \rightarrow F_2}{I \vDash F_1 \quad I \nvDash F_2}$$

contr

$$\frac{I \vDash F \quad I \nvDash F}{I \vDash \bot}$$

Let's do $F \triangleq (p \rightarrow q) \wedge (q \rightarrow r) \rightarrow (p \rightarrow r)$

Where are we?

- Propositional Logic Syntax & Semantics
- Naive ways of checking satisfiability
- Next lecture: checking sat efficiently
- Bigger picture:
  - Logic is the language of computation
  - Propositional logic is too restricted
  - Next, first order logic (too expressive) & undecidable
  - Goldilocks solution SMT: propositional logic + theories