Program Analysis – Lecture 1

Introduction and Basics

Join the course on Ilias! See link on
http://software-lab.org/teaching/winter2019/pa/

Prof. Dr. Michael Pradel

Software Lab, University of Stuttgart

Winter 2019/2020

About Me: Michael Pradel

- **Since 9/2019: Full Professor at University of Stuttgart**
- **Before**
  - Studies at TU Dresden, ECP (Paris), and EPFL (Lausanne)
  - PhD at ETH Zurich, Switzerland
  - Postdoctoral researcher at UC Berkeley, USA
  - Assistant Professor at TU Darmstadt
  - Sabbatical at Facebook, Menlo Park, USA

About the Software Lab






- **My research group since 2014**
- **Focus: Tools and techniques for building reliable, efficient, and secure software**
  - Program testing and analysis
  - Machine learning, security
- **Thesis and job opportunities**

Plan for Today

- **Introduction**
  - What the course is about
  - Why it is interesting
  - How it can help you
- **Organization**
  - Course project
  - Mid-term and final exam
- **Foundations**
  - Grammars, ASTs, CFGs, etc.

Program Testing & Analysis

What you probably know:

- **Manual testing or semi-automated testing:**
  JUnit, Selenium, etc.
- **Manual ”analysis” of programs:**
  Code inspection, debugging, etc.

Focus of this course:

Automated testing and program analysis

Why Do We Need It?

- All software has bugs
- Bugs are hard to find
- Bugs cause serious harm

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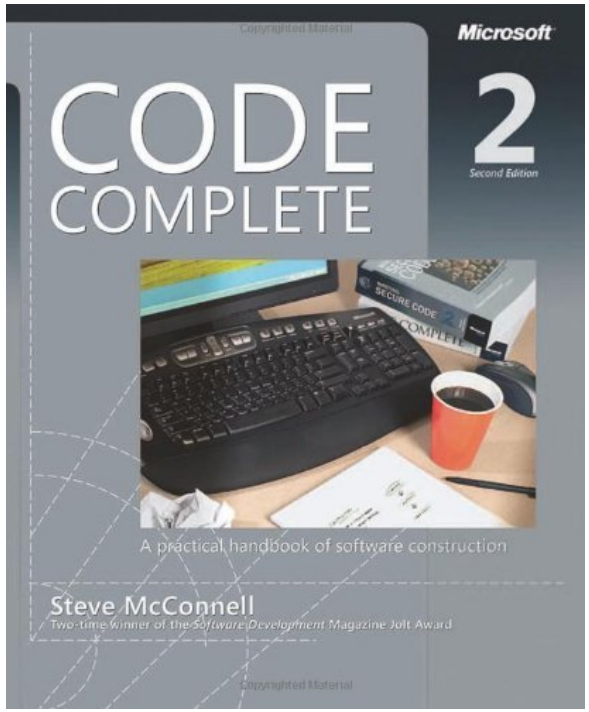

0.5-25/KLoC in delivered software

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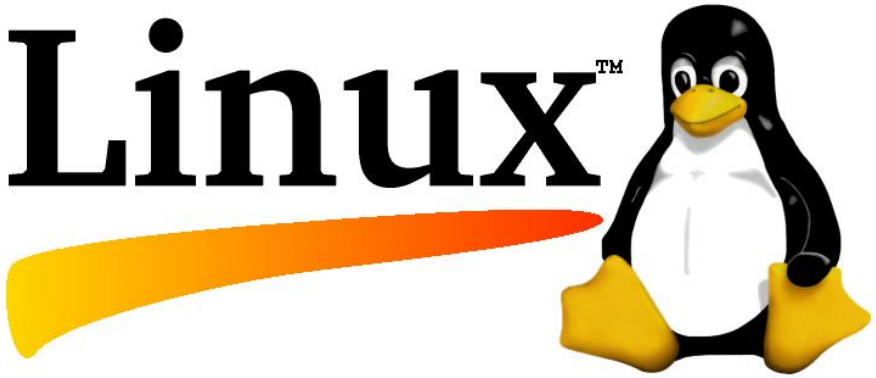

1.5 years to find a bug

[Palix2011]

Why Do We Need It?

- **All software has bugs**
- **Bugs are hard to find**
- **Bugs cause serious harm**

Ariane 5

Northeast blackout

Therac-25

What is Program Analysis?

- **Automated analysis of program behavior, e.g., to**
  - find programming errors
  - optimize performance
  - find security vulnerabilities

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Static vs. Dynamic Analysis

Static

- Analyse source code, byte code, or binary
- Typically:
  - Consider all inputs
  - Overapproximate possible behavior

Dynamic

- Analyze program execution
- Typically:
  - Consider current input
  - Underapproximate possible behavior

Static vs. Dynamic Analysis

Static

- Analyse source code, byte code, or binary
- Typically:
  - Consider all inputs
  - Overapproximate possible behavior

E.g., compilers, lint-like tools

Dynamic

- Analyze program execution
- Typically:
  - Consider current input
  - Underapproximate possible behavior

E.g., automated testing, profilers

Example

```
// JavaScript
var r = Math.random(); // value in [0,1)
var out = "yes";
if (r < 0.5)
  out = "no";
if (r === 1)
  out = "maybe";
console.log(out);
```

Quiz: What are the possible outputs?

https://ilias3.uni-stuttgart.de/vote/KN2I

Example

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// JavaScript
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var out = "yes";
if (r < 0.5)
  out = "no";
if (r === 1)
  out = "maybe"; // infeasible path
console.log(out);
```

Overapproximation: ”yes”, ”no”, ”maybe”

- Consider all paths (that are feasible based on limited knowledge)

Example

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// JavaScript
var r = Math.random(); // value in [0,1)
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Underapproximation: ”yes”

- Execute the program once

Example

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```

Sound and complete: ”yes”, ”no”

- For this example: Can explore both feasible paths

Another Example

```
// JavaScript
var r = Math.random(); // value in [0,1)
var out = r * 2;
console.log(out);
```

Another Example

```
// JavaScript
var r = Math.random(); // value in [0,1)
var out = r * 2;
console.log(out);
```

Overapproximation: Any value

- Consider all paths (that are feasible based on limited knowledge about `random()`)

Another Example

```
// JavaScript
var r = Math.random(); // value in [0,1)
var out = r * 2;
console.log(out);
```

Underapproximation:

Some number in [0,2), e.g., 1.234

- Execute the program once

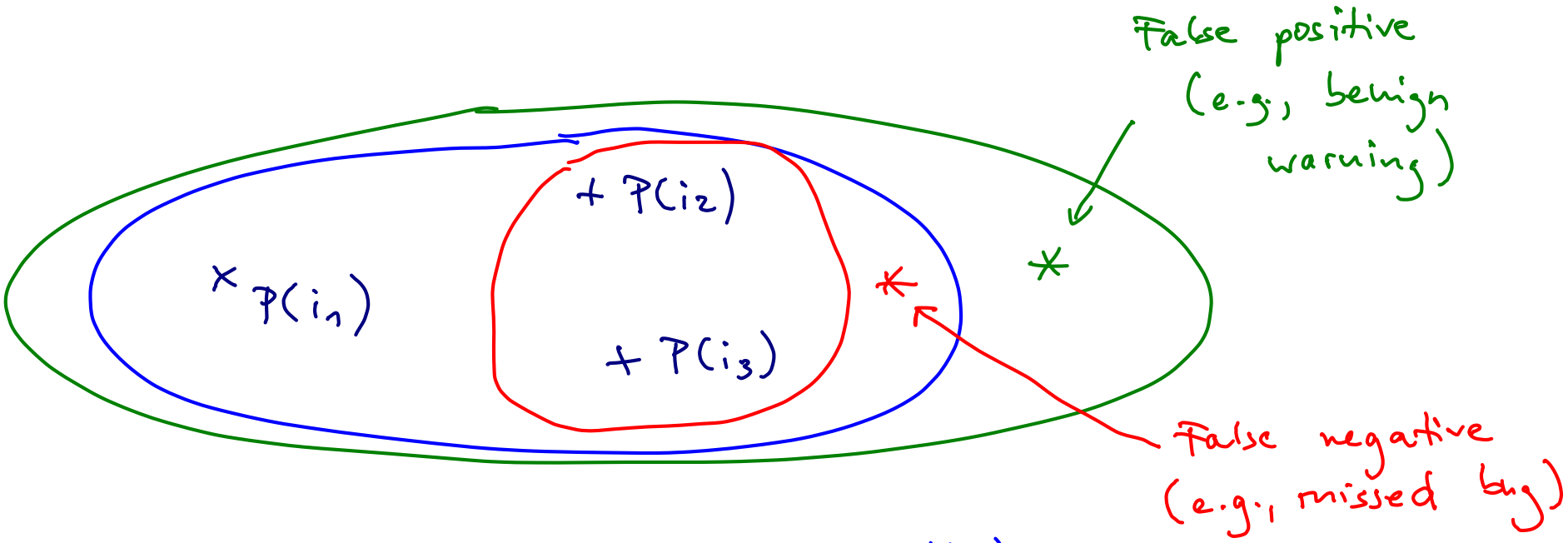
Another Example

```
// JavaScript
var r = Math.random(); // value in [0,1)
var out = r * 2;
console.log(out);
```

Sound and complete?

- Exploring all possible outputs:
  Practically impossible
- This is the case for most real-world programs

Program P, Input i, Behavior P(i)



All possible behaviors (what we want, ideally)

Underapproximation (e.g., testing, dynamic analysis)

Overapproximation (most static analyses)

Test Generation

- **Dynamic analysis:**
  Requires input to run the program
- **Test generation:**
  Creates inputs automatically
- **Examples**
  - Generate JUnit tests:
    Input = sequence of method calls
  - UI-level test generation:
    Input = sequence UI events
  - Fuzz-test a compiler: Input = program

How Does All This Help Me?

Improve the quality of your code

- Fewer bugs
- Better performance
- More secure software

Save time during manual testing

Become a better developer

- Get better understanding of program's behavior
- Avoid common pitfalls
- Learn to use and write tools

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  - Course project
  - Mid-term and final exam
- **Foundations**
  - Grammars, ASTs, CFGs, etc.

Organization

- **Two lecture slots per week**
  - But not all used: See course page
- **Weekly reading material**
- **Throughout the semester: Course project**
- **December 17: Mid-term exam**
- **End of semester: Final exam**

Grading

- **Two lecture slots per week**
  - But not all used: See course page
- **Weekly reading material**
- **Throughout the semester:**
  Course project → **40%**
- **December 17: Mid-term exam** → **10%**
- **End of semester: Final exam** → **50%**

A Friendly Warning

This is not going to be an easy course!

- Read regularly (otherwise, you won't be able to catch up)
- Work regularly on the course project

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... but the effort is worth it!

Programming Language

Most concepts taught in this course:
Language-independent

Most examples: JavaScript

- Very popular: client-side web applications, but also for server, mobile, and desktop applications
- Various interesting research challenges

Course project: Java and JavaScript

- Analysis written in Java
- Analysis of JavaScript code

Ilias

Platform for discussions, in-class quizzes, and sharing additional material

- Please register for the course
- Use it for all questions related to the course
- Messages sent to all students go via Ilias

Link to Ilias course on
software-lab.org/teaching/winter2019/pa/

Learning Material

There is no script or single book that covers everything

- Slides and hand-written nodes:
  Available after lecture
- Pointers to papers, book chapters, and web resources

Course Project

- **Design, implement, and evaluate a program analysis based on an existing framework**
  - Data flow analysis of JavaScript code
  - Based on Google Closure compiler
- **Individual, independent project**
  - Mentor available for questions

Course Project: Timeline

- **Project published on November 4**
- **Due on February 7**
  - Implementation and results
  - Report
- **Week of February 10 to 14**
  - Presentation of projects

Academic Integrity

- **Work you submit must be your own**
- **Unauthorized group efforts and any form of plagiarism are considered academic dishonesty and will be punished**
- **Allowed to discuss the problem with your peers, but not to reuse any part of an existing solution**

Exams

Mid-term exam (written)

- Recommended but not mandatory
- 10% of final grade, but mostly to help you learn
- On Dec 17 in the lecture slot

Final exam (written)

- End of semester

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For both: Open book exam

- Bring books, papers, etc.
- No electronic devices
- Will test your understanding, not your memory!

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- **Introduction**
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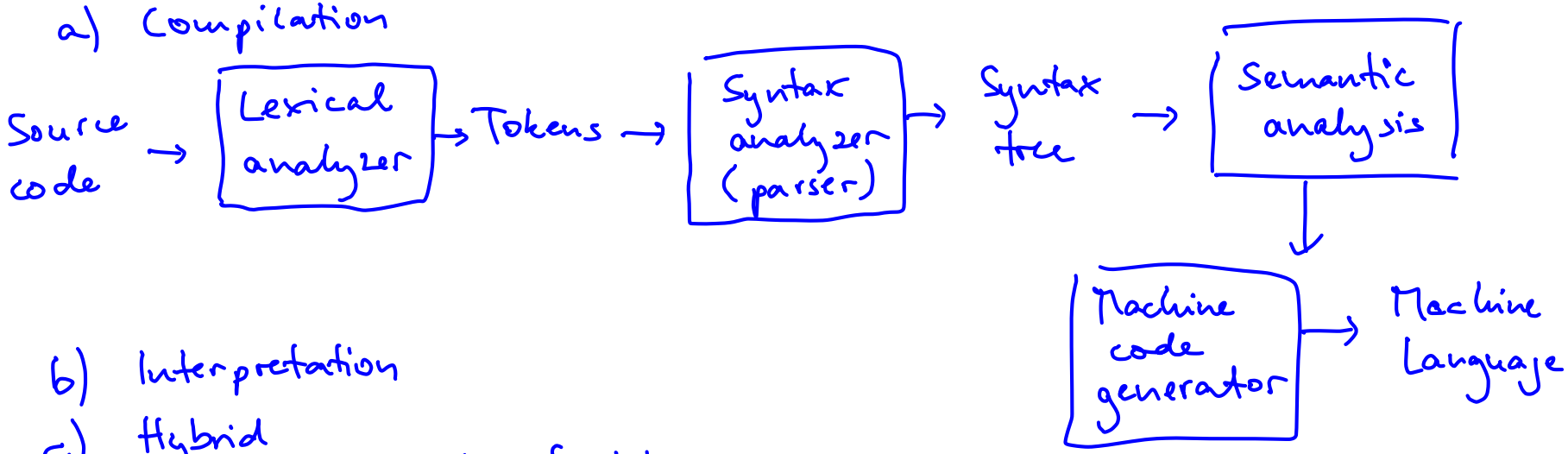
- **Organization**
  - Course projects
  - Term paper
  - Mid-term and final exam
- **Foundations** ←
  - Grammars, ASTs, CFGs, CGs, PDGs, etc.

Programming languages

↳ syntax (= form)
semantics (= meaning)
implementation (= execution)

Implementation

a) Compilation



b) Interpretation

c) Hybrid
↳ e.g., Java, JavaScript

Syntax

a) Grammar → which programs are syntactically correct

4 parts: terminals Σ, non-terminals N, productions P,
initial symbol $s \in N$

Example: Arithmetic expressions

$\Sigma = \{0, 1, 2, \ldots, 9, +, -\}$

$N = \{Exp, Num, Op, Digit\}$

$S = Exp$

P: $Exp \to Num \mid Exp\ Op\ Exp$

$Op \to + \mid -$

$Num \to Digit \mid Digit\ Num$

$Digit \to 0 \mid 1 \mid \ldots \mid 9$

What is part of this language?

A) 12-2

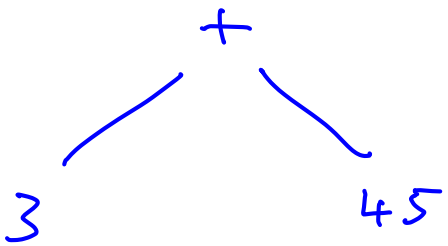
B) 2+(12-4)

C) 11*4

D) 1234567890

b) Abstract Syntax Trees

- abstract grammar
- e.g., $E \rightarrow n \mid Op(E, E)$
  $Op \rightarrow + \mid -$
- terminals = tokens
- e.g., 3+45



3) Control flow graphs

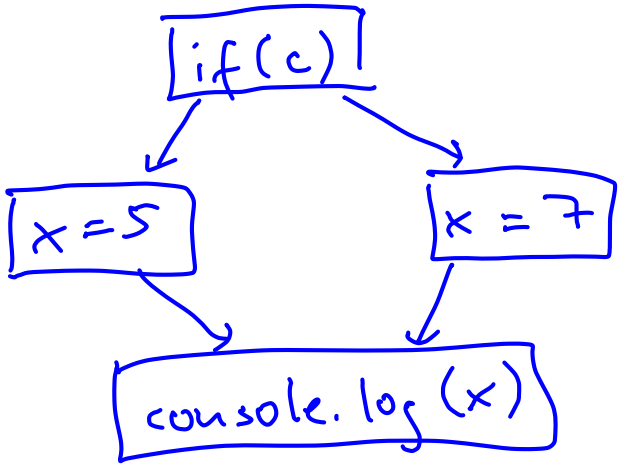
↳ Models flow of control through program

$G = (N, E)$ where N .. basic block (sequence of operations executed together)

E .. possible transfers of control

Ex. 1

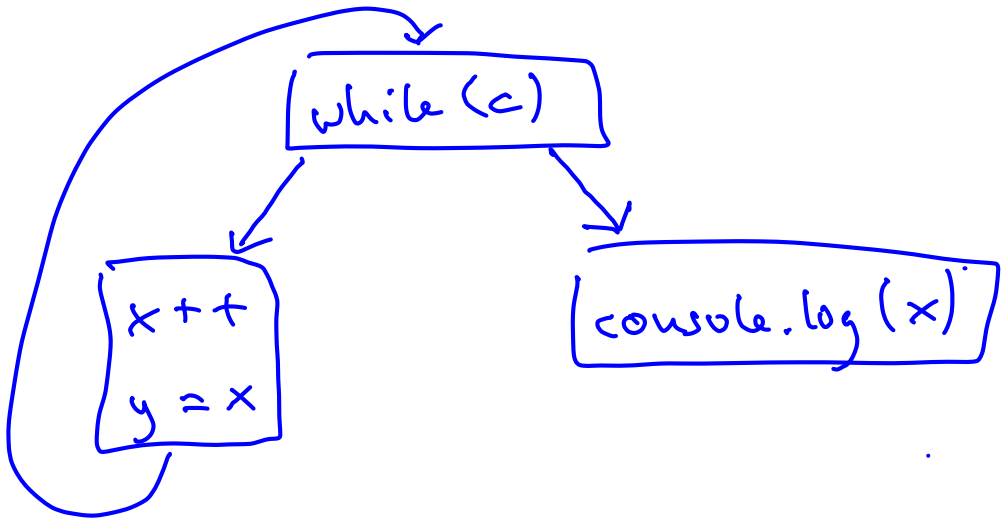
```
if (c)
    x = 5
else
    x = 7
console.log(x)
```



Ex. 2:

```
while (c) {
    x++;
    y = x;
}
console.log(x);
```

Edges & # nodes in the CFG?



3 + 3

4) Data Dependence Graph

↳ Model flow of data from "definitions" to "use"

$G = (N, E)$ where N .. operations
E .. possible def-use relations

$e = (n_1, n_2)$ means: n_2 may use data defined at n_1

Ex. 1

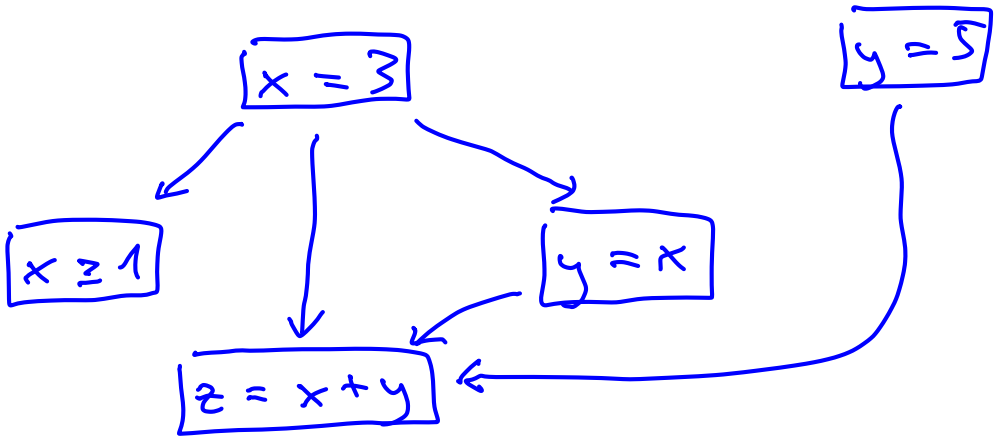
$x = 5$
$y = x + 1$

$$\boxed{x = 5} \rightarrow \boxed{y = x + 1}$$

Ex. 2

```
x = 3
y = 5
if (x ≥ 1)
    y = x
z = x + y
```

Edges & # nodes in data dep. graph?



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