Program Testing and Analysis: Introduction and Basics

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Prof. Dr. Michael Pradel

Software Lab, TU Darmstadt

About Me

- **Michael Pradel**
- **At TU Darmstadt since 2014**
- **Before joining TUDA**
  - Master-level studies in Dresden and Paris
  - Master thesis at EPFL, Switzerland
  - PhD at ETH Zurich, Switzerland
  - Postdoctoral researcher at UC Berkeley, USA

About the Software Lab





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

Plan for Today

- **Introduction**
  - What the course is about
  - Why it is interesting
  - How it can help you
- **Organization**
  - Course projects
  - Term paper
  - Mid-term and final exam
- **Foundations**
  - Grammars, ASTs, CFGs, CGs, PDGs, 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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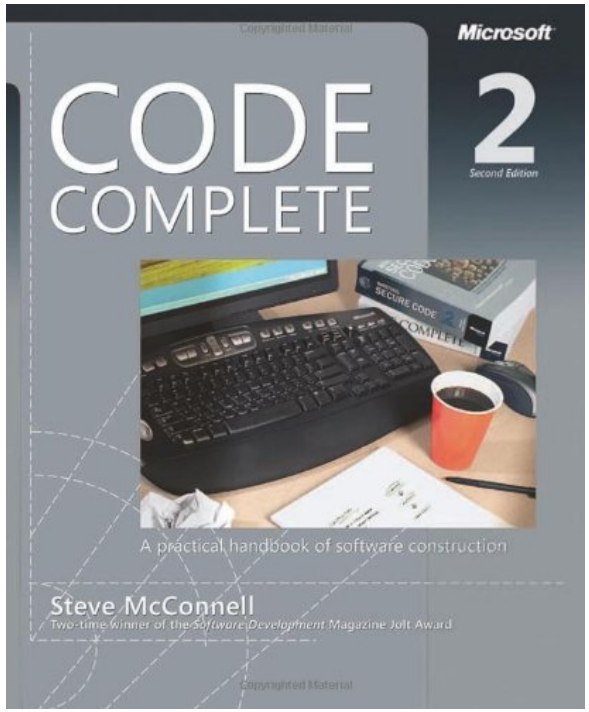

0.5-25/KLoC in delivered software

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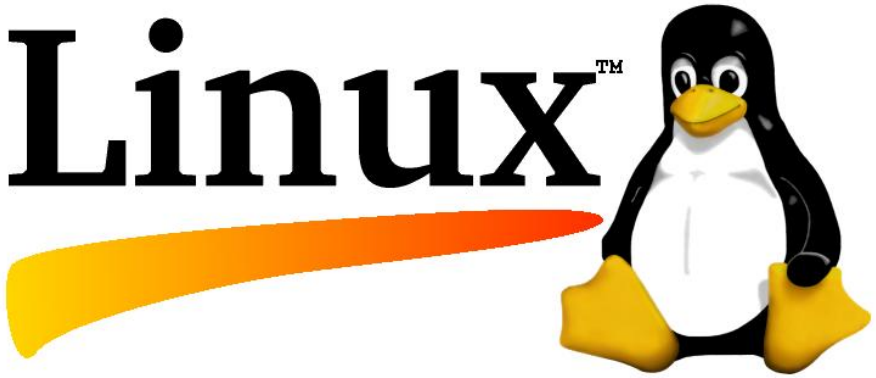

1.5 years to find a bug

[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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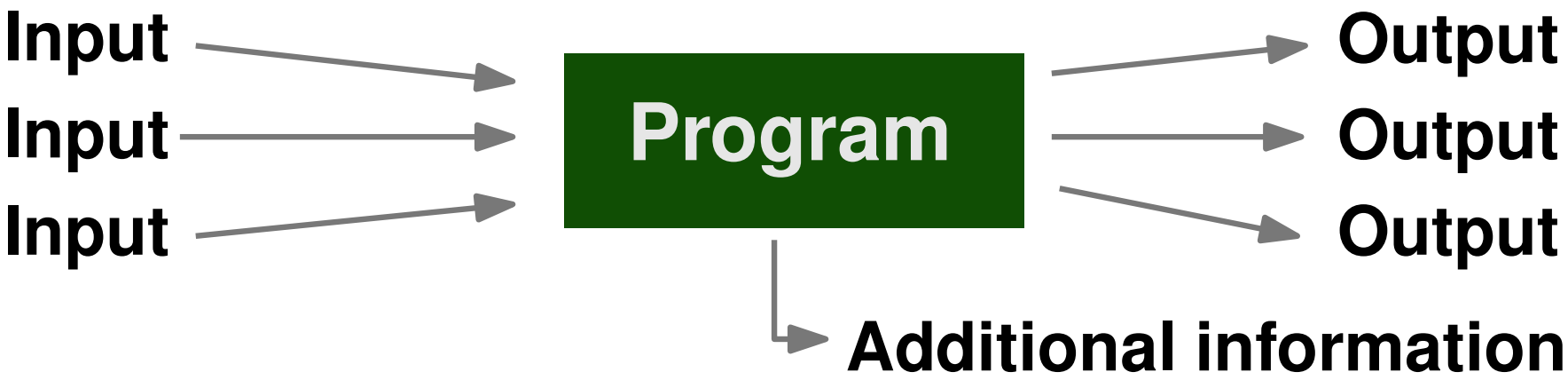

Static vs. Dynamic Analysis

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?

Example

```
// JavaScript
var r = Math.random(); // value in [0,1)
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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// JavaScript
var r = Math.random(); // value in [0,1)
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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

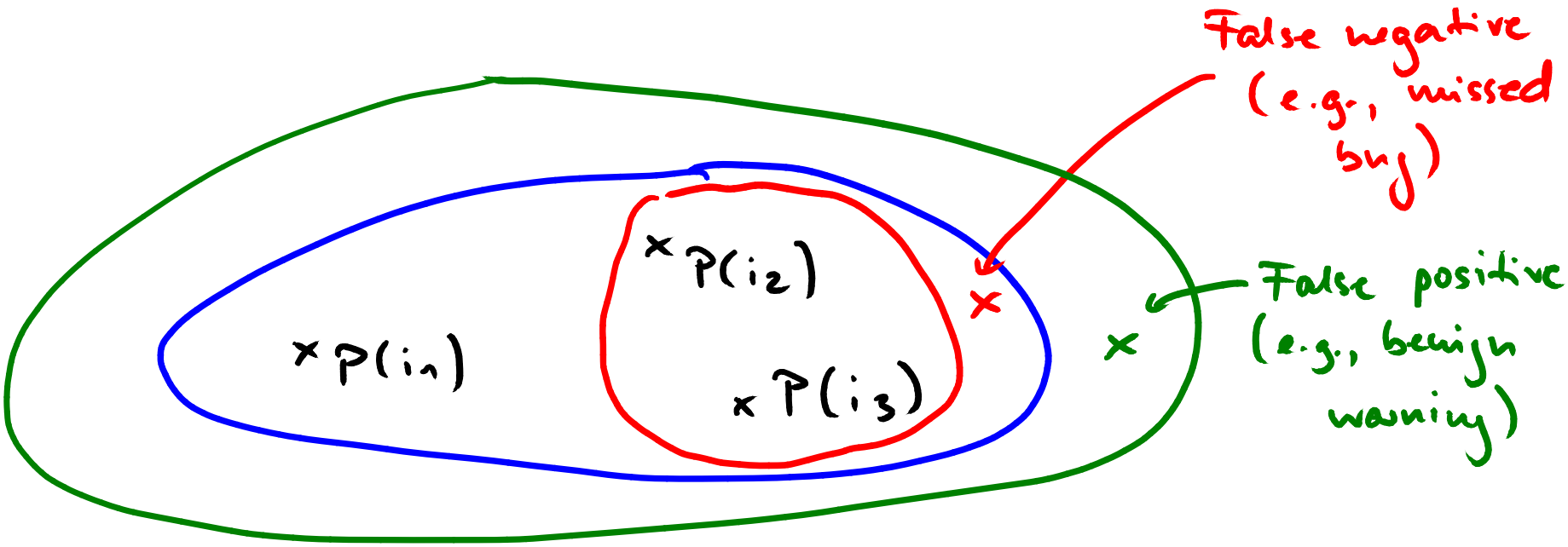
Another Example

```
// 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, dyn. analysis)

Overapproximation (e.g., 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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- **Foundations**
  - Grammars, ASTs, CFGs, CGs, PDGs, etc.

Organization

- **Weekly lectures**
- **Weekly reading material**
- **Throughout the semester:**
  - Course project
  - Term paper
- **December 22: Mid-term exam**
- **March 20: Final exam**

Grading

- **Weekly lectures**
- **Weekly reading material**
- **Throughout the semester:**
  - Course project → **33%**
  - Term paper → **33%**
- **December 22: Mid-term exam** → **+10%**
- **March 20: Final exam** → **33%**

Grading

- **Weekly lectures**
- **Weekly reading material**

relevant for

- **Throughout the semester:**
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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
- Schedule enough time to work on the term paper

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... but the effort is worth it!

Programming Language

Most concepts taught in this course:
Language-independent

Most course projects and examples:
JavaScript (specifically: ECMAScript 6)

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

Piazza

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

- Please register and enroll for the class
- Use it for all questions related to the course
- Starting from next week, messages sent to all students go via Piazza (not TUCaN!)

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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

- **Independent research project**
- **Design, implement, and evaluate a program analysis and/or test generator**
- **Teams of 2 students**
  - In principle: Individual grades
  - Typically: One team, one grade

Course Project: Tools

Based on existing frameworks and tools

- Jalangi: Dynamic analysis framework
- Esprima & Escodegen: ASTs, parsing, code generation
- Google Closure compiler: Static analysis of JavaScript
- Soot: Static analysis framework for Java

Course Project: Organization

Timeline

- Nov 10: Register teams and preferred projects
- Throughout the semester:
  Up to three meetings with mentor
- Feb 12–16: Presentation of results
- Feb 25: Final submission

Project proposals will be available via Piazza

Course Project: Deliverables

1) Implementation and results

- Source code and everything needed to reproduce the results

2) Report

- 10 pages maximum, English
- Written like a scientific paper

Due on Feb 25, 2018

Term Paper

Write a scientific article that summarizes and compares three existing papers

- Topic & papers: Based on lecture content
- Individual work
- 6 pages maximum, English
- Peer reviewing

Term Paper

Write a scientific article that summarizes and compares three existing papers

- Topic & papers: Based on lecture content
- Individual work
- 6 pages maximum, English
- Peer reviewing

Grading: 75% final paper + 25% reviews

Term Paper: Some Advice

- **Don’t waste space on basics**
- **Examples are your secret weapon**
- **Most important part:**
  Comparison of the three papers
- **Bad English distracts from good content**
- **Revise, revise, revise**

Term Paper: Rules

- **No verbatim copying of text (exception: quotes)**
- **You may copy *some* figures (e.g., result graphs) and refer to the source**
- **You must use your own example(s)**

Term Paper: Reviews

- **Imitates peer reviewing process**
- **Each student reviews three term papers**
- **Revise your term paper after getting reviews**
  - Grade will be for final term paper

- **Plain text format**
- **About 1 page, English**

Reviews: Some Advice

- **Be constructive**
- **Be polite**
- **Your reviews contribute to your grade, not to the reviewee's grade**

Term Paper: Organization

Timeline

- Nov 10: Register with preferred topics
- Jan 12: Submit paper for peer review
- Jan 26: Reviews due
- Feb 25: Final version of paper due

Exams

Mid-term exam (written)

- Recommended but not mandatory
- Can improve overall grade up to 10%
- On Dec 22 in the lecture slot

Final exam (written)

- Mar 20, 2018

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Mid-term exam (written)

- Recommended but not mandatory
- Can improve overall grade up to 10%
- On Dec 22 in the lecture slot

Final exam (written)

- Mar 20, 2018

For both:

- Open book: Bring books, papers, etc.
- Corollary: Will test your understanding, not your memory!

Academic Integrity

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

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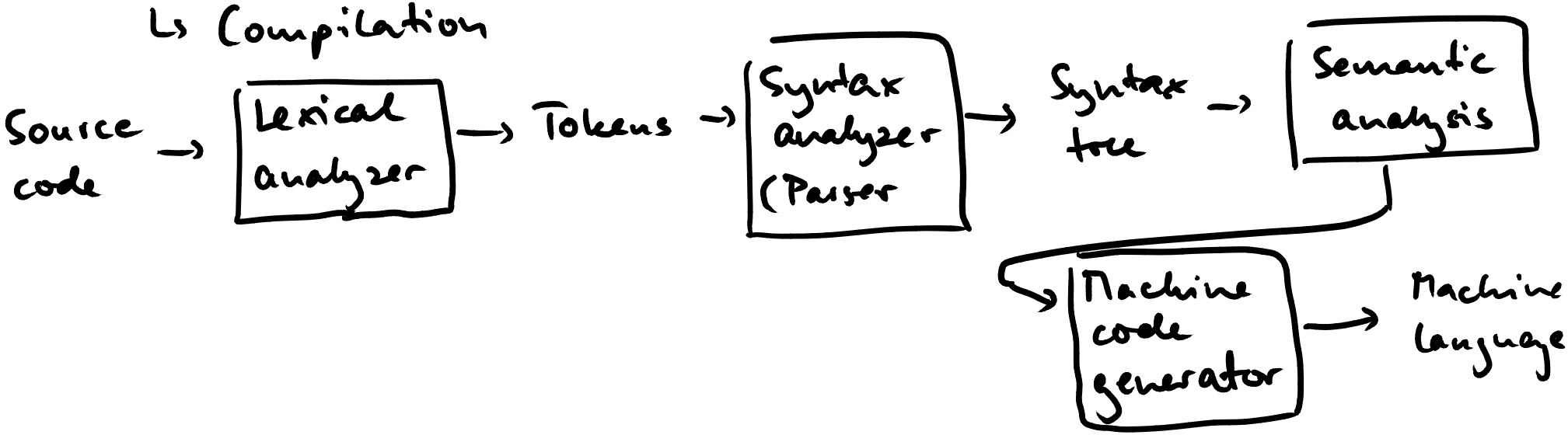
1) Programming Languages

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

a) Implementation

↳ Compilation



b) Interpretation

c) Hybrid

↳ e.g. Java, JavaScript

2) Syntax

a) Grammar → which programs are syntactically correct

4 parts: terminals Σ, non-terminals N, production P
initial symbol $S \in N$

Example: Arithmetic expression

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

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

$S = Exp$

P :
$Exp \to Num \mid Exp\ Op\ Exp$
$Op \to + \mid -$
$Num \to Digit \mid Digit\ Num$
$Digit \to 0 \mid 1 \mid \dots \mid 9$

What is part of the language?

A) 12-2 ✓

B) 2+(12-4)

C) 11*4

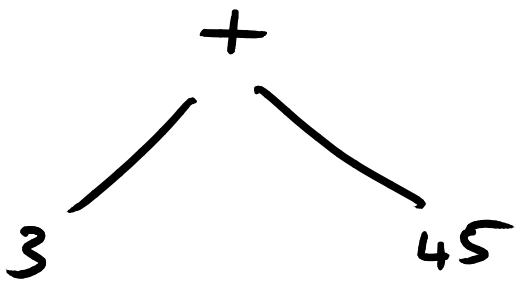
D) 123456790 ✓

b) Abstract Syntax Trees

- abstract grammar
- e.g., $E \rightarrow n \mid O_p\,(E, E)$

  $O_p \rightarrow + \mid -$

- terminals = tokens
- e.g., 3 + 45



3) Control flow graphs

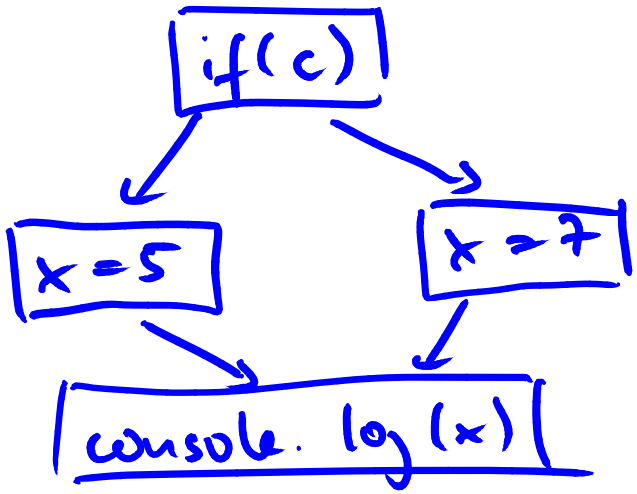
↳ Models flow of control of program

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

E.. possible transfers of control

Ex. 1

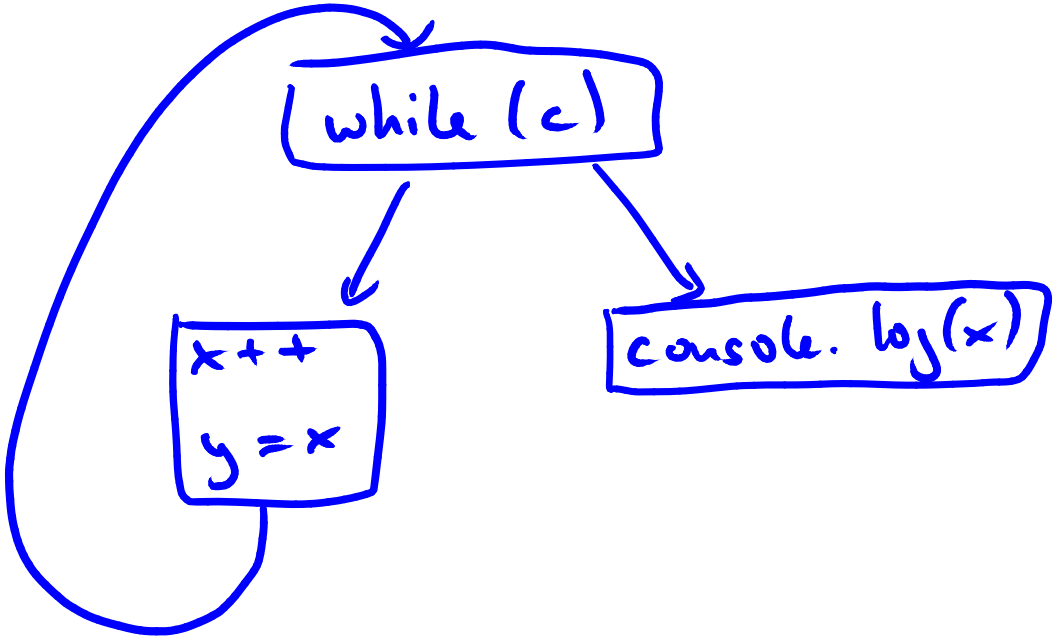
```
if (c)
    x = 5
else
    x = 7
console.log(x)
```



Ex. 2

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

Edges & # nodes of control flow graph?



3 + 3

4) Data Dependence Graph

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

$G = (N, E)$ where N .. operations

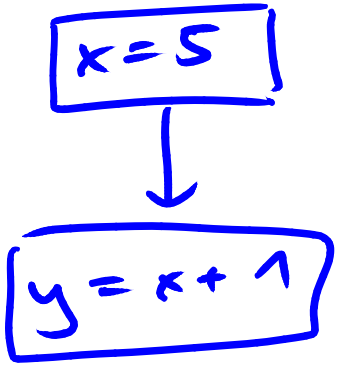
E .. possible def-use relations

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

Ex. 1

$x = 5$

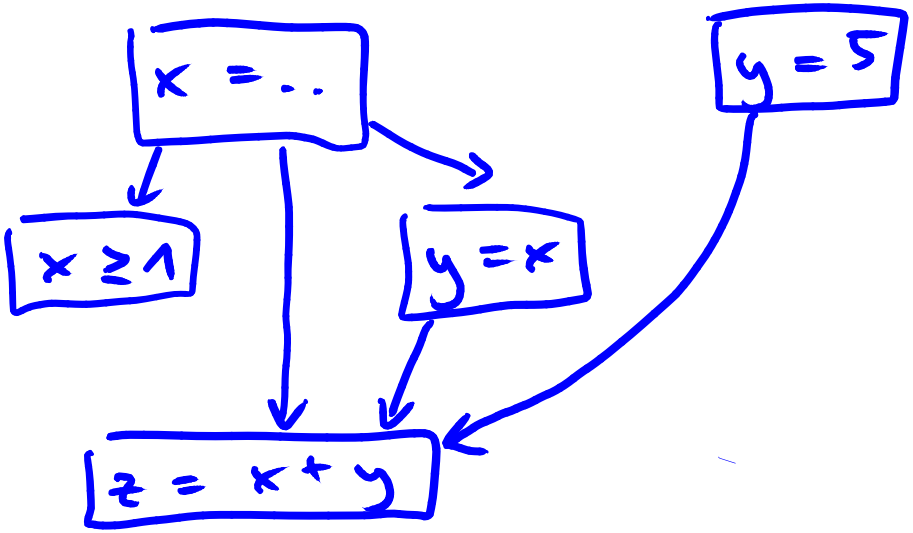
$y = x + 1$



Ex. 2

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

Edges and # nodes in data dep. graph?



Outlook

- Operational semantics
- Manual testing
- Random and fuzz testing
- Symbolic and concolic testing
- Testing concurrent programs
- Program slicing
- Information flow analysis
- Specification mining
- Performance profiling
- Path profiling