Program Testing and Analysis: Introduction and Foundations

Dr. Michael Pradel

Software Lab, TU Darmstadt

About Me

- **Michael Pradel**
- **At TU Darmstadt since 2014**
- **Before joining TUD**
  - 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**
- **Research on tools and techniques for building reliable, efficient, and secure software**
  - Program analysis
  - Test generation
  - Focus: JavaScript-based applications & Concurrency
- **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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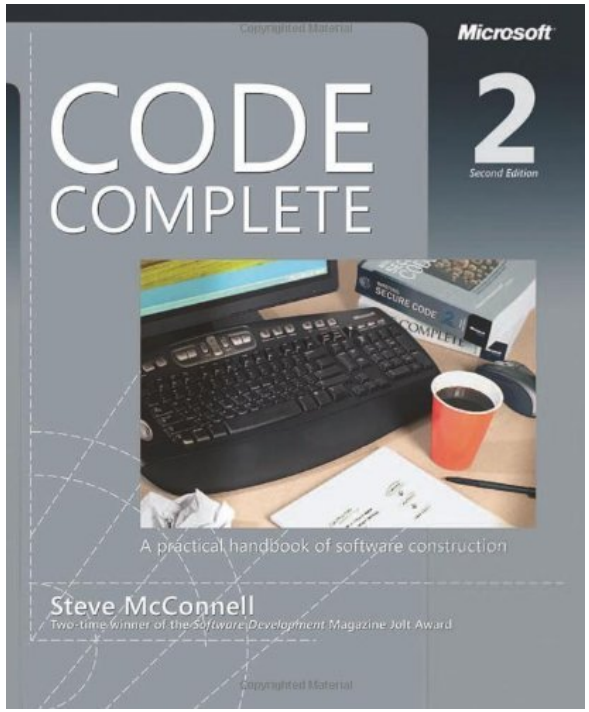

0.5-25/KLoC in delivered software

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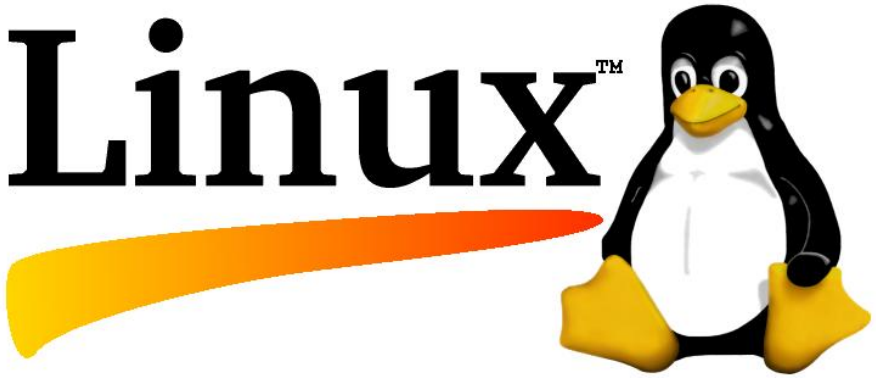

1.5 years to find a bug

[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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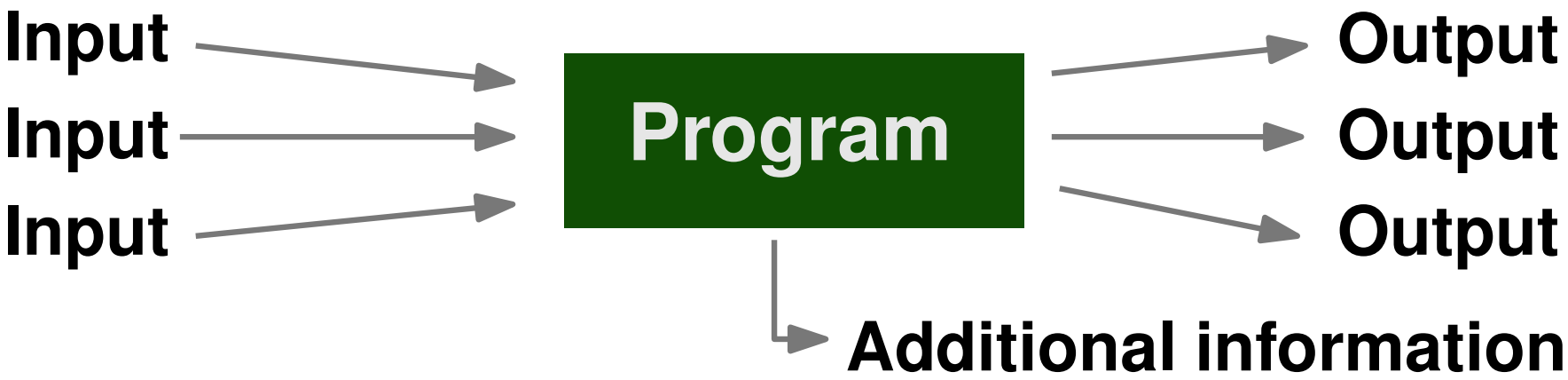

Static vs. Dynamic Analysis

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

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// 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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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)
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```

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);
```

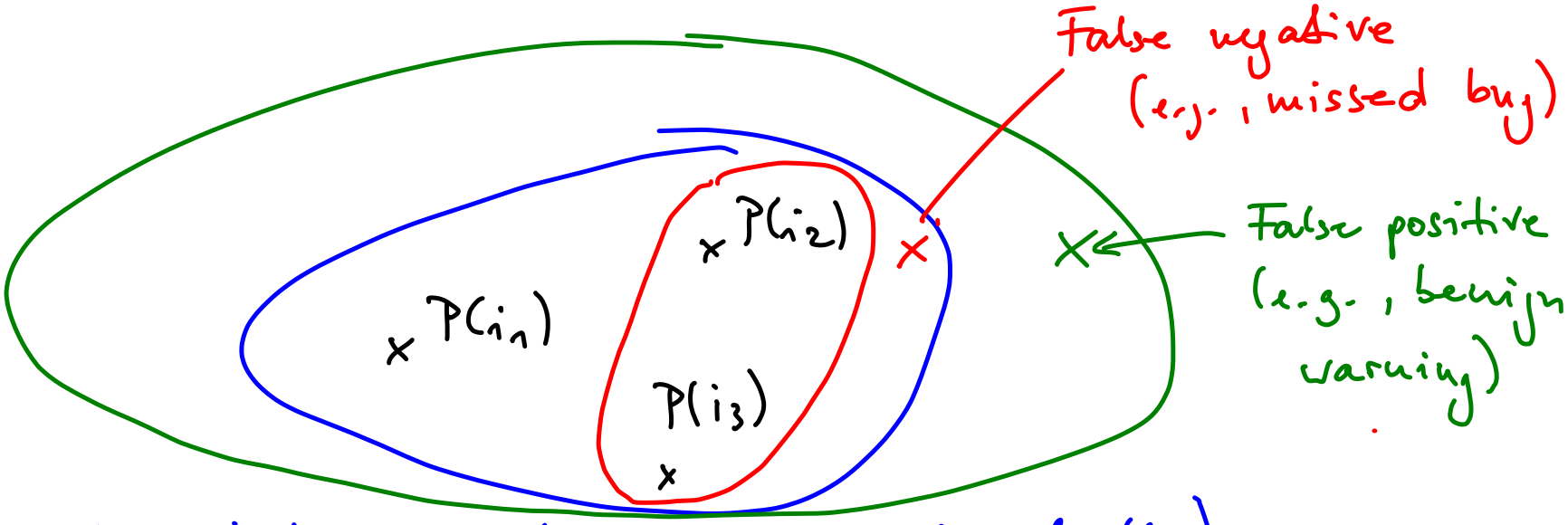
Sound and complete?

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

Over- vs. Underapproximation

Handwritten notes...

Program P, Input i, Behavior P(i)



All possible behavior (what we want, ideally)

Underapproximation (e.g. testing, dyn. a.) ⇒ False negative

Overapproximation (e.g., most static a.) ⇒ False pos.

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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Organization

- **Weekly lectures**
- **Weekly reading material**
- **Throughout the semester:**
  - Course project
  - Term paper
- **End of November: Mid-term exam**
- **End of semester: Final exam**

Grading

- **Weekly lectures**
- **Weekly reading material**
- **Throughout the semester:**
  - Course project → **33%**
  - Term paper → **33%**
- **End of November: Mid-term exam → +10%**
- **End of semester: Final exam → 33%**

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relevant for

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- **End of November: Mid-term exam** → **+10%**
- **End of semester: Final exam** → **33%**

Must pass all three to pass the course

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

Programming Language

Most concepts taught in this course:
Language-independent

Course projects and most examples:
JavaScript (specifically: ECMAScript 5)

- 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 for all questions related to the course
- Starting from next week, messages sent to all students go via Piazza (not TUCaN!)

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 or 3 students**
  - One team, one grade

Course Project: Tools

Based on existing frameworks and tools

- Jalangi: Dynamic analysis framework
- WebAppWalker: UI-level test generation framework
- Esprima & Escodegen: ASTs, parsing, code generation

Course Project: Organization

Timeline

- Oct 19: Register teams and preferred projects
- Week of Oct 26–30: Meeting with mentor
- Week of Dec 1–4: Meeting with mentor
- Week of Jan 18–22: Meeting with mentor
- Feb 8: Presentation of results
- Feb 19: Final submission

(There are office hours for additional meetings.)

Project proposals will be available via Piazza

Course Project: Deliverables

1) Implementation and results

- Source code and everything needed to reproduce the results
- Packaged as VM image

2) Report

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

Due on Feb 19

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

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Grading: $\frac{2}{3}\cdot$ final paper + $\frac{1}{3}\cdot$ 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 figures (e.g., result graphs)**
- **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 2: Register with preferred topics
- Jan 11: Submit paper for peer review
- Feb 1: Reviews due
- Feb 19: Final version of paper due

Exams

Mid-term exam (written)

- Advisable but not mandatory
- Can improve overall grade up to 10%
- Last week of November

Final exam (written)

- After the last lecture (exact date TBD)

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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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Foundations

Hand-written notes ...

1) Programming Langs.

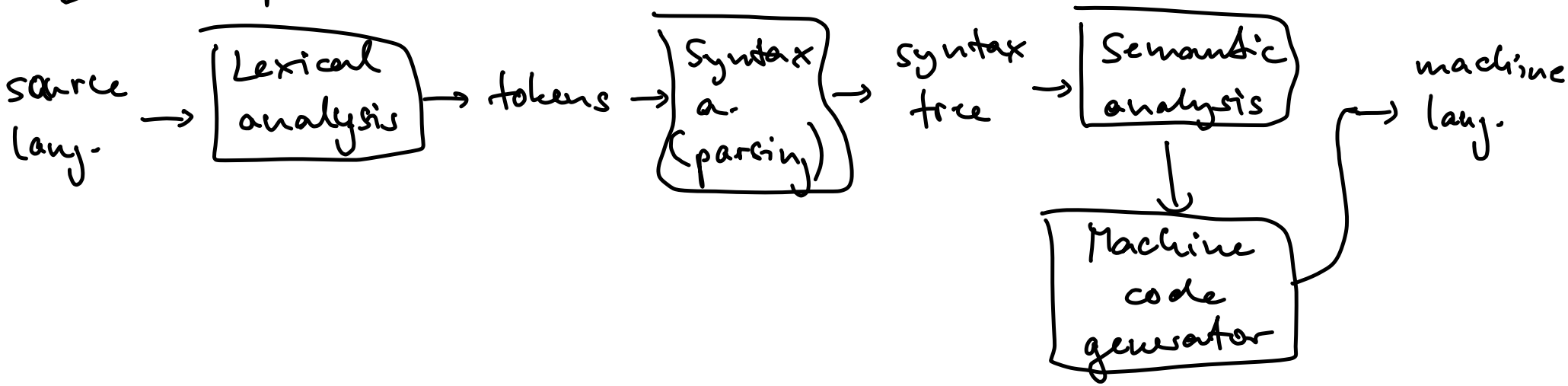
→ Paradigms:
- Imperative, e.g., C
- Functional, e.g., Haskell
- Object-oriented, e.g., Java
- Logic, e.g., Prolog

} our focus

→ Components:
- syntax (= form)
- semantics (= meaning)
- implementation (= execution)

2) Lang. Implementation

a) Compilation



b) Interpretation

c) Hybrid implementation

Example 1: Java

- compile to bytecode
- interpreted by VM
- (optionally), compiled to machine code → JIT

Example 2: JavaScript

- interpret source code
- JIT compilation

3) 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

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

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

$S = Exp$

P:

$Exp \longrightarrow Num \mid Exp\ Op\ Exp$

$Op \longrightarrow + \mid -$

$Num \longrightarrow Digit \mid Digit\ Num$

$Digit \longrightarrow 0 \mid 1 \mid \dots \mid 9$

What is part of lang.?

A) 12−2

B) 2+(12−4)

C) 11 * 4

D) 1234567890

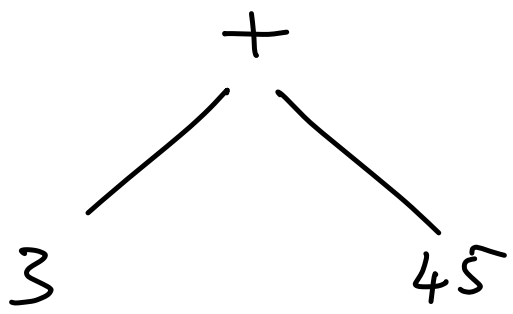
b) Abstract Syntax Trees

- abstract grammar for example:

$$E \rightarrow n \mid Op(E, E)$$

$$Op \rightarrow + \mid -$$

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



4) Control flow graphs → models flow of control of program

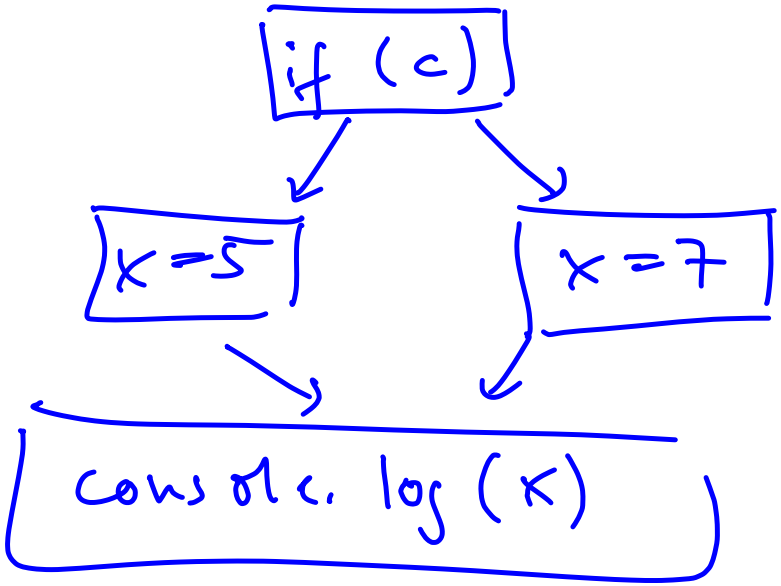
$G = (N, E)$ where N .. basic blocks = seqn. of operations executed together

E .. possible transfer of control

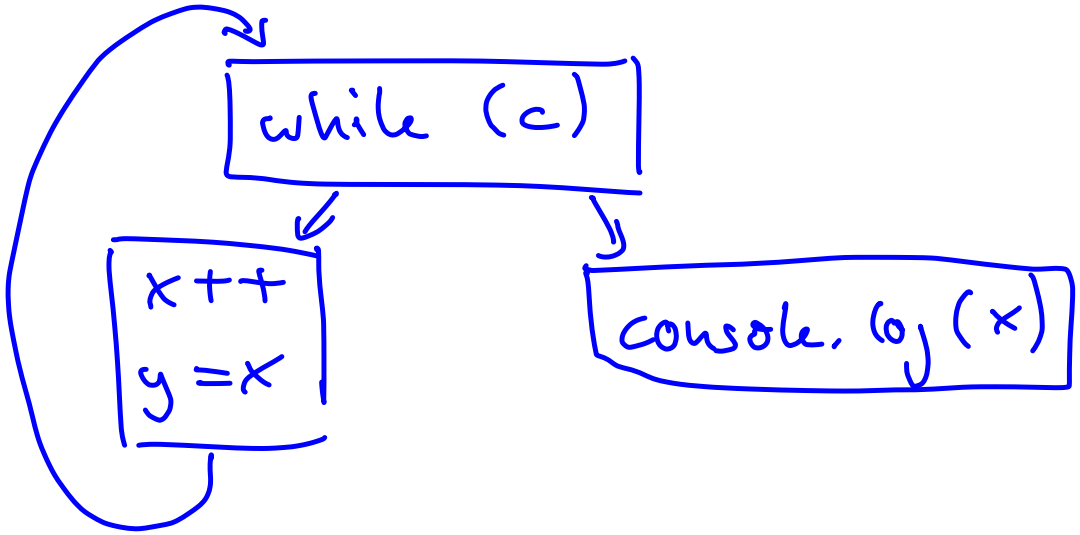
$e = (n_1, n_2) \in E$ means that n_2 may execute after n_1

Ex 1:

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



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



5) Data Dependence Graph → models flows of values from "definition" to "use"

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

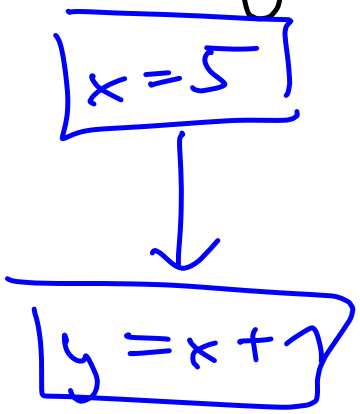
E.. possible def-use relations

$e = (n_1, n_2) \in E$ means that n_2 may use data defined in n_1

Ex. 1

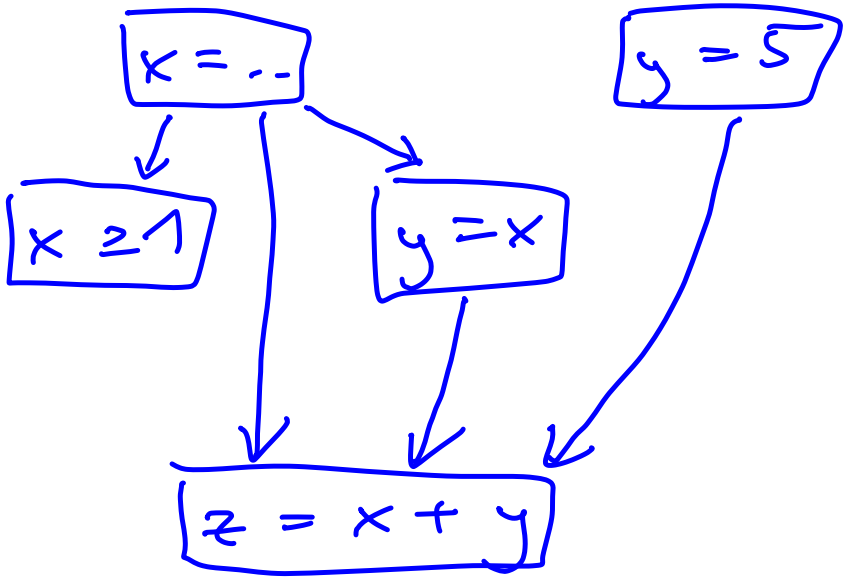
$x = 5$

$y = x + 1$



Ex. 2:

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



Outlook

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