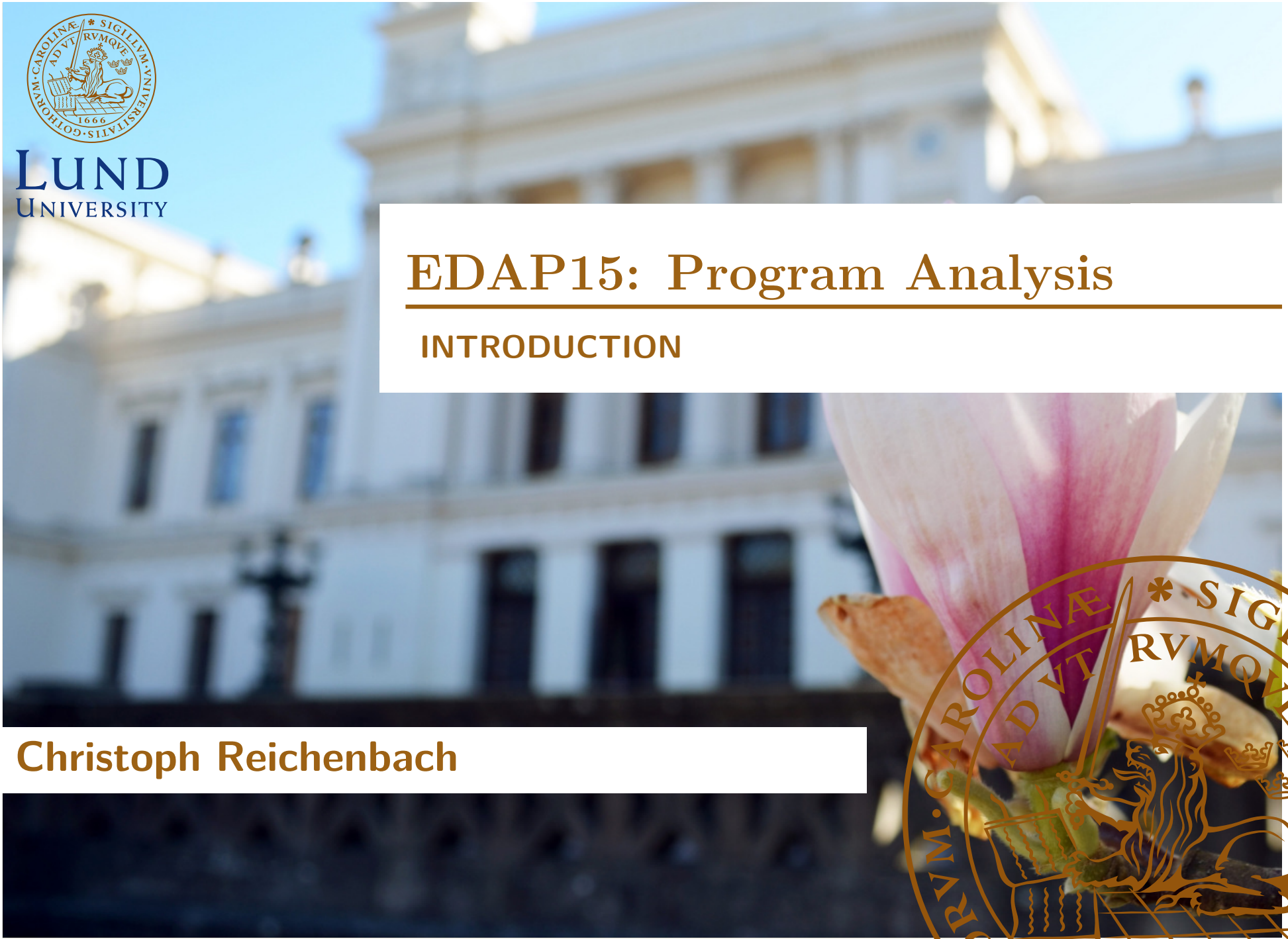


LUND UNIVERSITY

EDAP15: Program Analysis

INTRODUCTION

Christoph Reichenbach

Welcome!

- **EDAP15: Program Analysis**
- **Instructor**: Christoph Reichenbach
  `christoph.reichenbach@cs.lth.se`
- **Teaching Assistants**:
  - Alexandru Dura
  - Erik Präntare
- **Course Homepage**:
  `http://cs.lth.se/EDAP15`

Course Format

- **Moodle**: Sign up today!
- **Lectures**
  - In Person
  - Partially 'Flipped':
    - Check Moodle for videos to watch before lecture
- **Core material**
  - Lectures (*bring your questions!*)
  - Videos
- **Self-Study material**
  - Online Quizzes
  - Textbook (optional)
- **Questions**
  - *Ask in class*
    - Ask-and-Upvote system (or just raise your hand!)
  - Online forum
  - Office hours
- **Mandatory Activities**: Homework & Quizzes

Topics

- Concepts and techniques for understanding programs
  - Analysing program structure
  - Analysing program behaviour
- Practical concerns in program analysis

Language focus: Teal, a teaching language

- Concepts generalise to other mainstream languages:
  - Imperative
  - Object-Oriented

Goals

- **Understand**:
  - What is program analysis (not) good for?
  - What are strenghts and limitations of given analyses?
  - How do analyses influence each other?
  - How do programming language features influence analyses?
  - What are some of the most important analyses?
- **Be able to**:
  - Implement typical program analyses
  - Critically assess typical program analyses

Textbooks

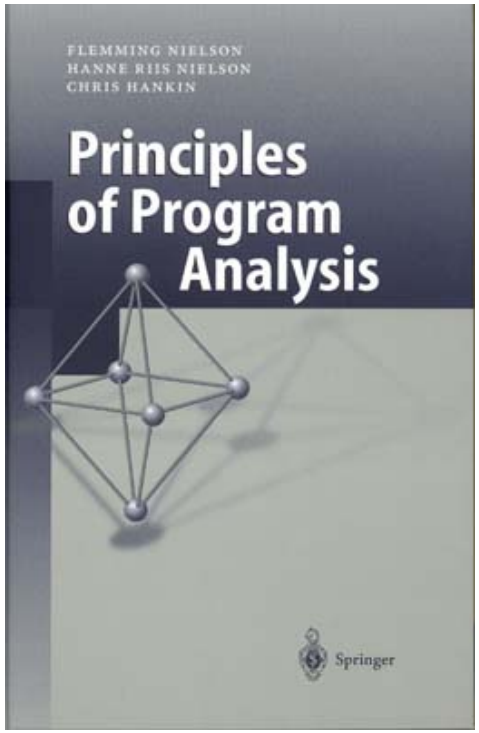
Static Program Analysis

Møller & Schwartzbach

- Optional
- PDF online from authors

Principles of Program Analysis

Nielson, Nielson & Hankin



- Very optional
- 3 copies in the library
- Theory-driven

How to Pass This Course

- **This Week**
  1. **today**: register in Moodle
  2. **2025-01-23, 14:00**: Find lab partner, register for lab slot
  3. **2025-01-27, 18:00**: Mandatory quizzes in Moodle (see below)
- **Every Week**
  1. Work on homework exercises
  2. Present homework solutions to TAs (labs)
  3. **Fri**: Lab slots (for help & presenting solutions)
  4. **Mon, 18:00**: Mandatory quizzes in Moodle
     - Score 70% to pass
     - Your best attempt counts
     - No limit on number of retries

Passing vs. Grades

- Passing these requirements gives you a grade of **3**
  - TAs must have approved all homework exercise solutions
- For higher grades (**4**, **5**):
  - Additional oral exam
  - Registration opens after course completion

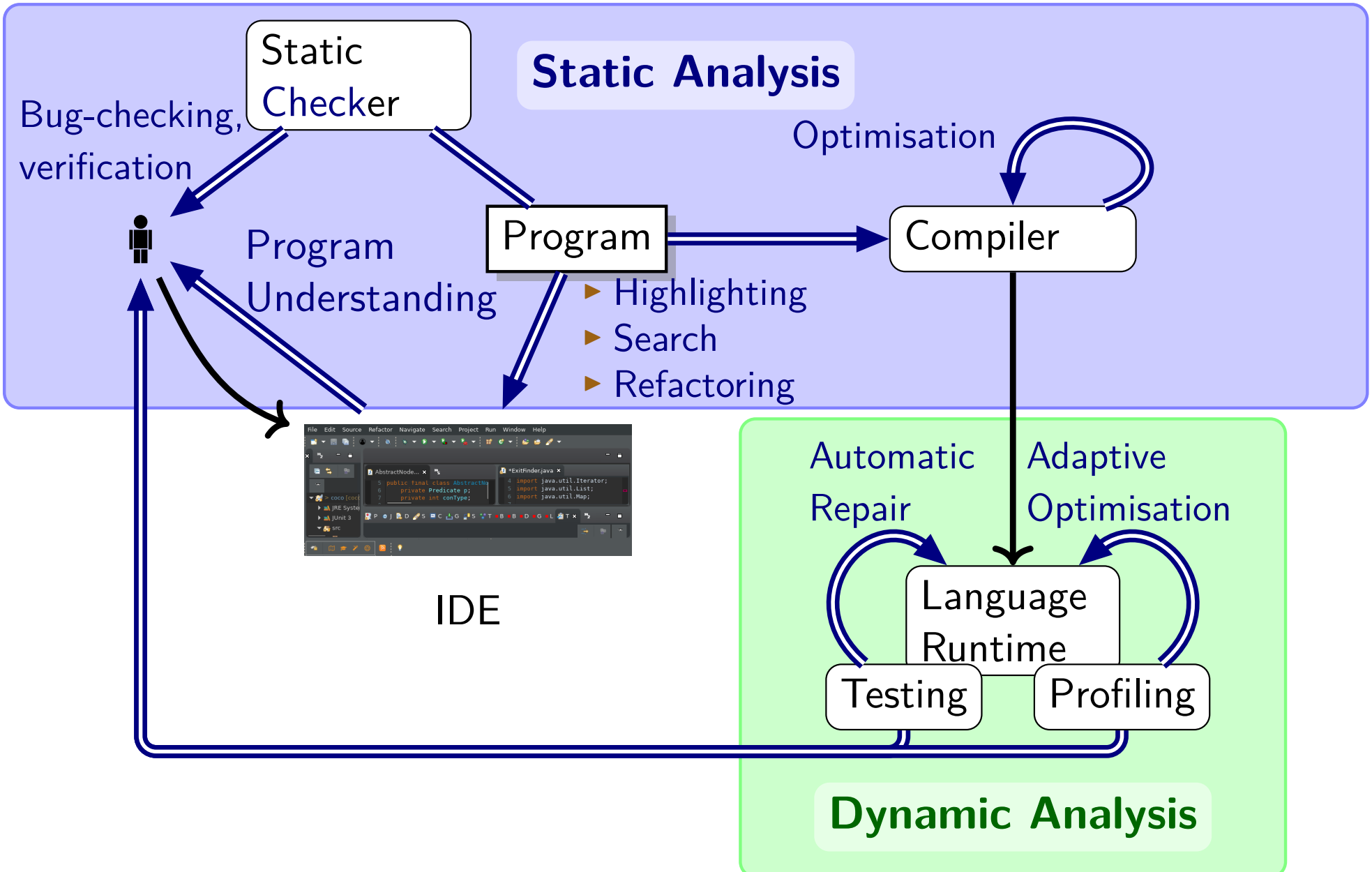
Homework Exercises

- **Lab Exercises**:
  - Lab 0: Group lab, W4 (**this** week!)
  - Lab 1: Group lab, W5–6
  - Labs 2–4: Solo labs, following weeks
- **To pass**:
  - Pass automatic tests
  - **Explain**(!) implementation and rationale to TA
- **Presenting to TAs**
  - You can present *once a week*
    Additional slots depend on TA capacity
  - During lab hours
- **Labs** for help with / presenting homework exercises
  - *Get started on on exercises before coming to lab*
  - Every Friday (7 weeks)
  - Current lab has priority (specifics will be on website)

Course Representative

- D-Sektionen is asking for:
  - *two course representatives*
  - Will meet with me in 3rd or 4th week of classes
  - To be selected *today*

Uses of Program Analysis



Categories of Program Analyses

	Manual / Interactive	Automatic
Static Analysis	▸ Interactive Theorem Provers	▸ (Most) Type Checkers ▸ Static Checkers (FindBugs, SonarQube, . . .) ▸ Compiler Optimisers
Dynamic Analysis ▸ Examines *behaviour* ▸ Sees interactions program $\leftrightarrow$ world	▸ Debuggers	▸ Unit Tests ▸ Benchmarks ▸ Profilers

Our Focus

Summary

- Program analyses are key components in *Software Tools*:
  - IDEs
  - Compilers
  - Bug and Vulnerability Checkers
  - Run-time systems

  ...
- Main Categories:
  - **Static Analysis**:
    Examine program structure
  - **Dynamic Analysis**:
    Examine program run-time behaviour
  - **Automatic Analysis**:
    "Black Box": Minimal user interaction
  - **Manual / Interactive Analysis**:
    User in the loop
    - Advanced manual analyses exploit automatic analysis

Examples of Program Analysis

Questions:

- 'Is the program well-formed?'

  ```
  gcc -c program.c
  javac Program.java
  ```

  At least for C, C++, Java; not so easy for JavaScript!
- 'Does my factorial function produce the right output for inputs in the range 0–5?'

Java

```
@Test // Unit Test
public void testFactorial() {
  int[] expected = new int[] { 1, 1, 2, 6, 24, 120 };
  for (int i = 0; i < expected.length; i++) {
      assertEquals(expected[i], factorial(i));
} }
```

Let's Analyse a Program!

- MISRA-C standard specifies:
  "*The library functions . . . ,* `gets`*, . . . shall not be used.*"
- Given some `program.c`:

```
user@host$ grep 'gets' program.c    # string search
     gets(input_buffer);
     /* The code below gets the system configuration */
     int failed_gets_counter = 0;
 user@host$
```

At least 2 of 3 resuls were wrong: "*False Positives*"

A First Challenge, Continued

```
user@host$ grep 'gets(' program.c
    gets(input_buffer);
user@host$
```

- More precise: no false positives!
- Will this catch *all* calls to `gets`?

C: program2.c

```c
#include <stdio.h>
void f(char* target_buffer) {
    char *(*dummy)(char*) = gets;
    dummy(target_buffer);
}
```

String search not smart enough: "*False Negative*"

A First Challenge, Continued Again

C: program2.c

```c
#include <stdio.h>
void f(char* target_buffer) {
    char *(*dummy)(char*) = gets;
    dummy(target_buffer);
}
```

```
user@host$ cc -c program.c -o program.o
user@host$ nm program.o
                 # check symbol table in compiled program
0000000000000000 T f
                 U gets          ⟵ Aha!
                 U _GLOBAL_OFFSET_TABLE_
 user@host$
```

Using a more powerful analysis yielded better results

A First Challenge, Solved?

C: program3.c

```
#include<stdio.h>
#include<dlfcn.h>
int f(char* target_buffer) {
    void* handle = dlopen("/lib/x86_64-linux-gnu/libc.so.6",
                          RTLD_LAZY);
    void* sym = dlsym(handle, "gets");
    void(*p)(char*) = sym;
    p(target_buffer);
    return 0;
}
```

- Dynamic library loading: `gets` will not show up in symbol table

Fancier program $\Longrightarrow$ harder analysis

Analysis vs. Property-of-Interest

- Distinguish:
  - **Property** of interest: $P(\varphi)$
    Examples:
    - All lines in φ that reference the 'gets' function
    - All type errors in φ
    - All lines in φ that take more than $1s$ of execution time
  - **Analysis** $\mathcal{A}(\varphi)$ that approximates $P(\varphi)$

$$P(\varphi) \approx \mathcal{A}(\varphi)$$

And How Good Is It?

- As we saw, program analyses may be incorrect
- We often describe them with *Information Retrieval* terminology:

r is...	$r \in \mathcal{A}(\varphi)$	$r \notin \mathcal{A}(\varphi)$
$r \in P(\varphi)$	**True Positive**	**False Negative**
$r \notin P(\varphi)$	**False Positive**	**True Negative**

- How well does $\mathcal{A}$ approximate $\mathcal{P}$?
  - Assume $\mathcal{A}(\varphi)$ returns $n = \#\mathcal{A}(\varphi)$ reports
    $n = \#\text{True Positives} + \#\text{False Positives}$ reports
  - Are the reports good?
    Precision $= \frac{\#\text{True Positives}}{n}$
  - Are the reports comprehensive?
    Recall $= \frac{\#\text{True Positives}}{\#\text{True Positives} + \#\text{False Negatives}}$
- #False Negatives (and thus **Recall**) is usually impossible to determine in program analysis

Summary

- Purpose of **Analysis** $\mathcal{A}$:
  - Compute **Property-of-interest** P
- Program Analysis is nontrivial
  - Programs can hide information that $\mathcal{A}$ wants
  - Analysis $\mathcal{A}$ can misunderstand parts of the program

Soundness and Completeness

Can we always build a $\mathcal{A}$ with $\mathcal{A}(\varphi) = P(\varphi)$?

- Connection to Mathematical Logic:
  - $\mathcal{A}$ is **sound** (with respect to P) iff:

$$\mathcal{A}(\varphi) \subseteq P(\varphi) \qquad \text{(Perfect Precision)}$$

  - $\mathcal{A}$ is **complete** (with respect to P) iff:

$$\mathcal{A}(\varphi) \supseteq P(\varphi) \qquad \text{(Perfect Recall)}$$

  - $\mathcal{A}(\varphi) = P(\varphi)$ iff $\mathcal{A}$ is both sound & complete

What if $P(\varphi)$ checks whether φ terminates?

The Bottom Line

"Everything interesting about the behaviour of programs is undecidable."

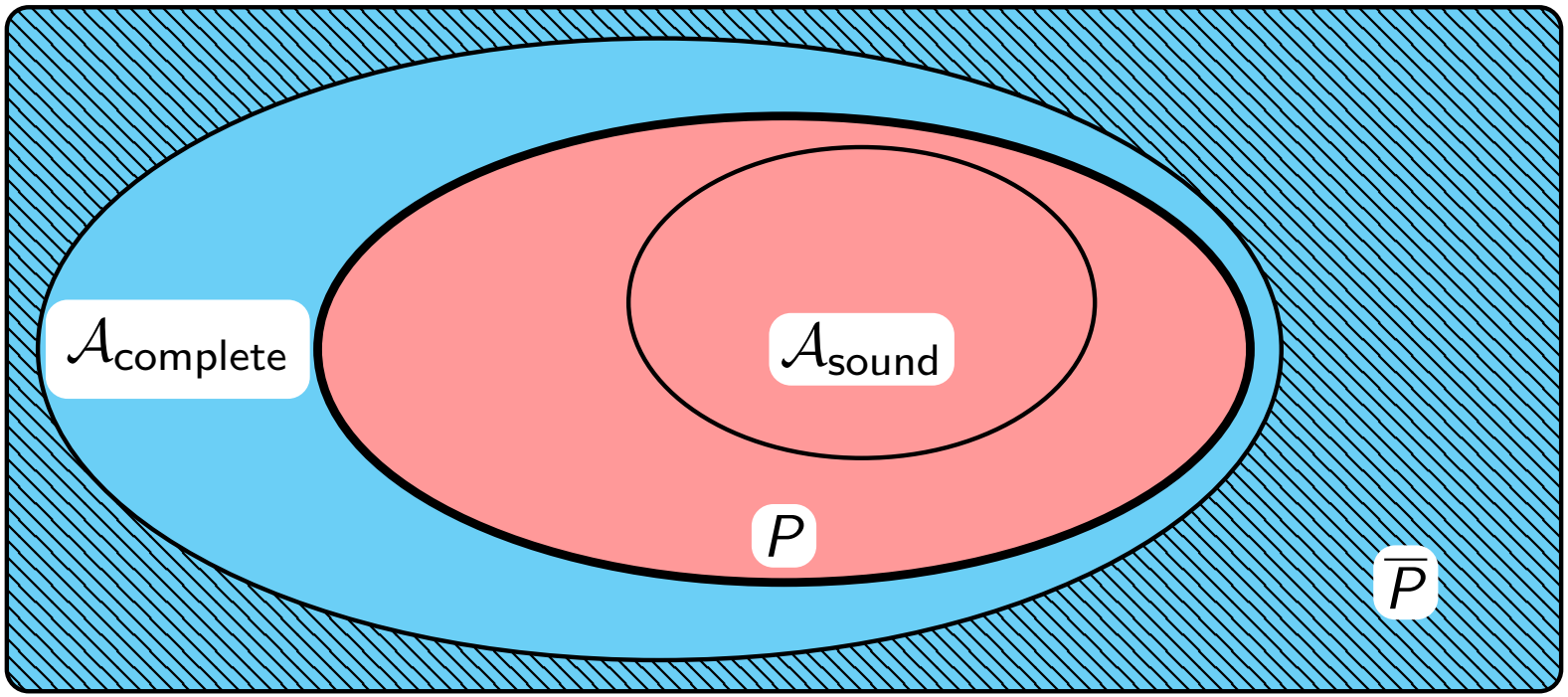
— Anders Møller, paraphrasing H.G. Rice [1953]

We must choose:

- **Soundness**
- **Completeness**
- **Decidability**

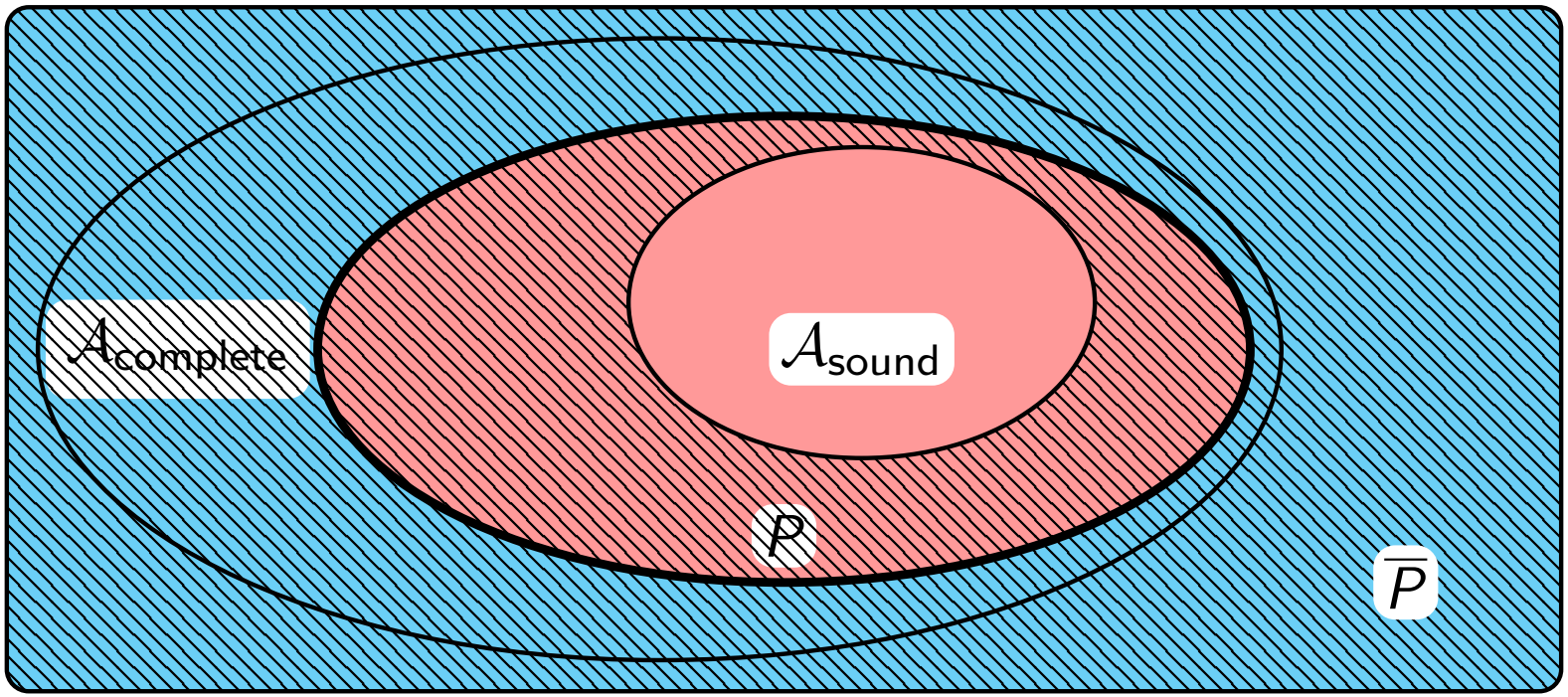
. . . pick any two.

Soundness and Completeness: Caveat



- *Beware*: "sound" and "complete" be confusing:
  - Example: $P(\varphi)$ is "φ has a bug"
  - If you now want to check $\overline{P}$, the *negation* of P:
    - $\overline{P}(\varphi)$ is "φ does not have a bug"
    - $\overline{\mathcal{A}_{\text{complete}}}$ (= run $\mathcal{A}_{\text{complete}}$ and invert output) is *sound wrt* $\overline{P}$

Soundness and Completeness: Caveat



- *Beware*: "sound" and "complete" be confusing:
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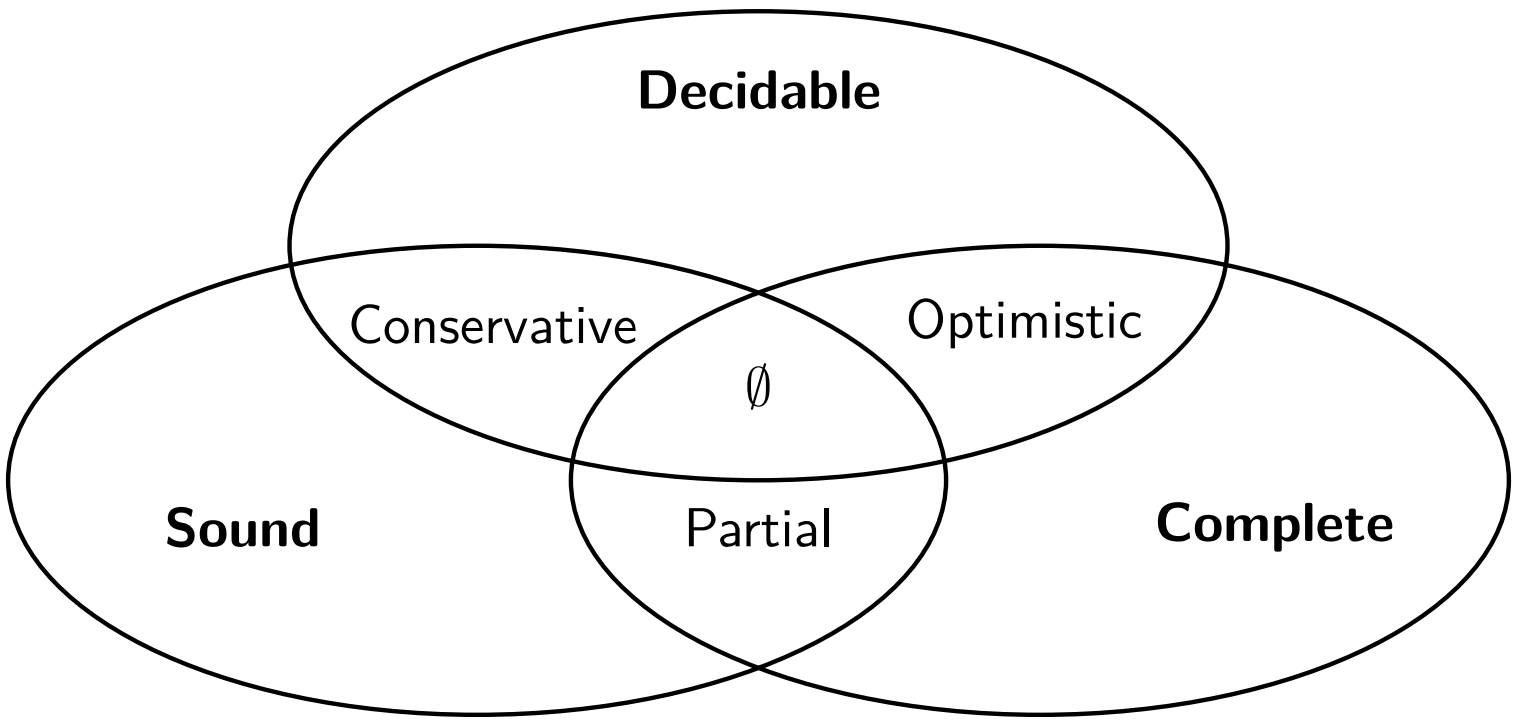
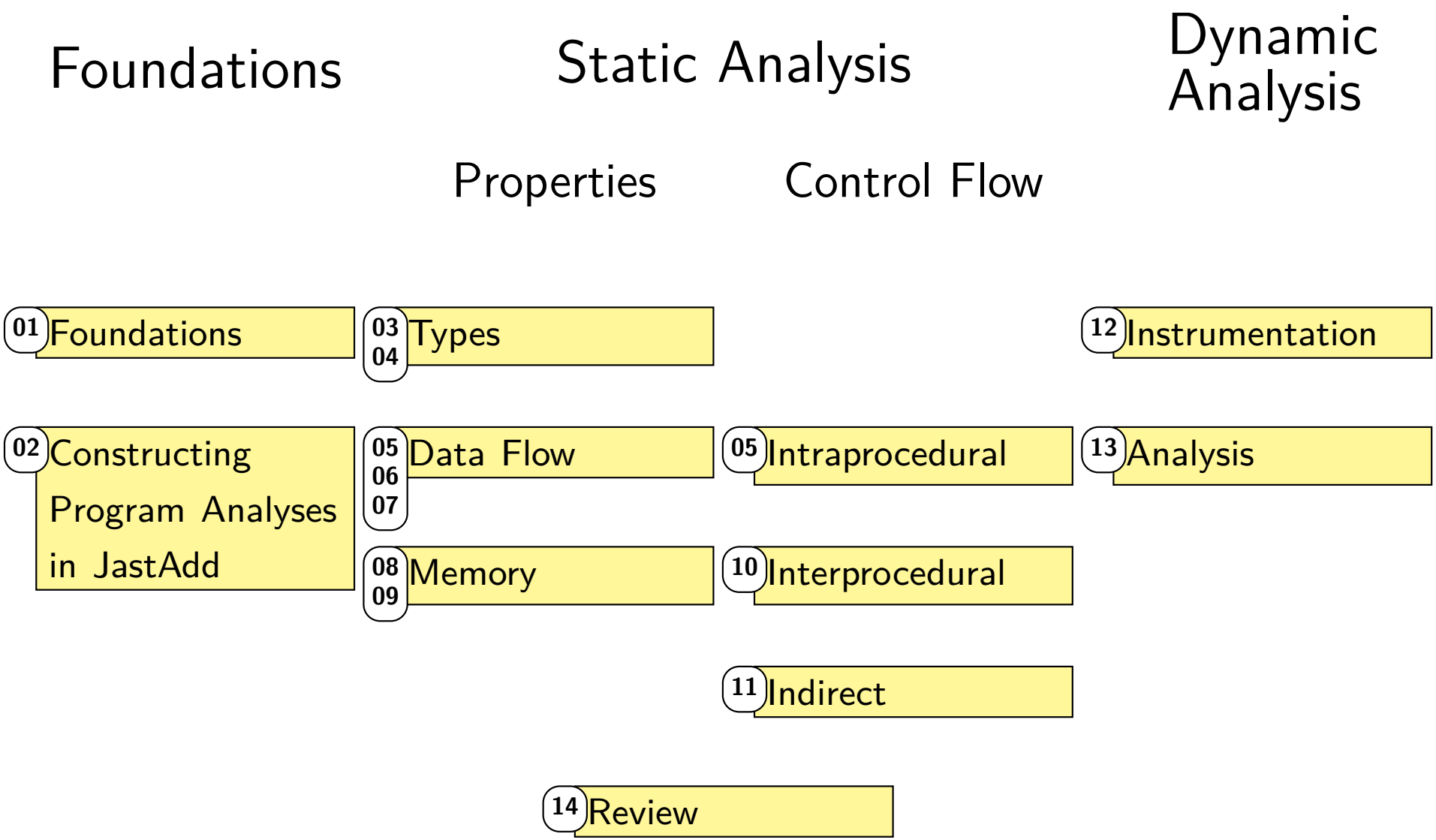
    - $\overline{P}(\varphi)$ is "φ does not have a bug"
    - $\overline{\mathcal{A}_{\text{complete}}}$ (= run $\mathcal{A}_{\text{complete}}$ and invert output) is *sound wrt* $\overline{P}$
    - $\overline{\mathcal{A}_{\text{sound}}}$ is *complete wrt* $\overline{P}$

Summary

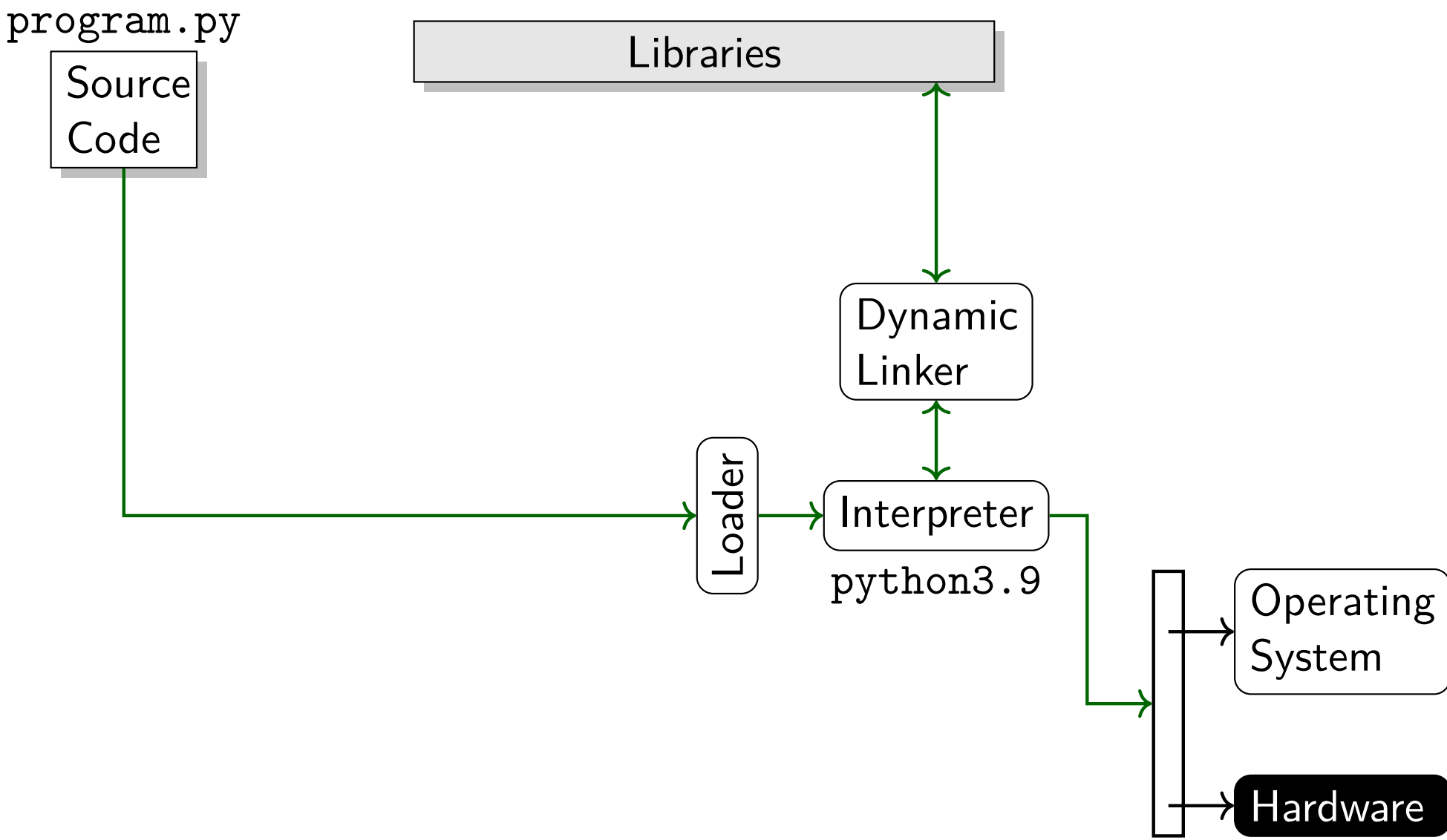
- Given property P and analysis $\mathcal{A}$:
  - $\mathcal{A}$ is **sound** if it triggers only on P
    $P =$ "program has bug": $\mathcal{A}$ reports *only* bugs
  - $\mathcal{A}$ is **complete** if it always triggeres on P
    $P =$ "program has bug": $\mathcal{A}$ reports *all* bugs
- If P is nontrivial (i.e., depends on behaviour):



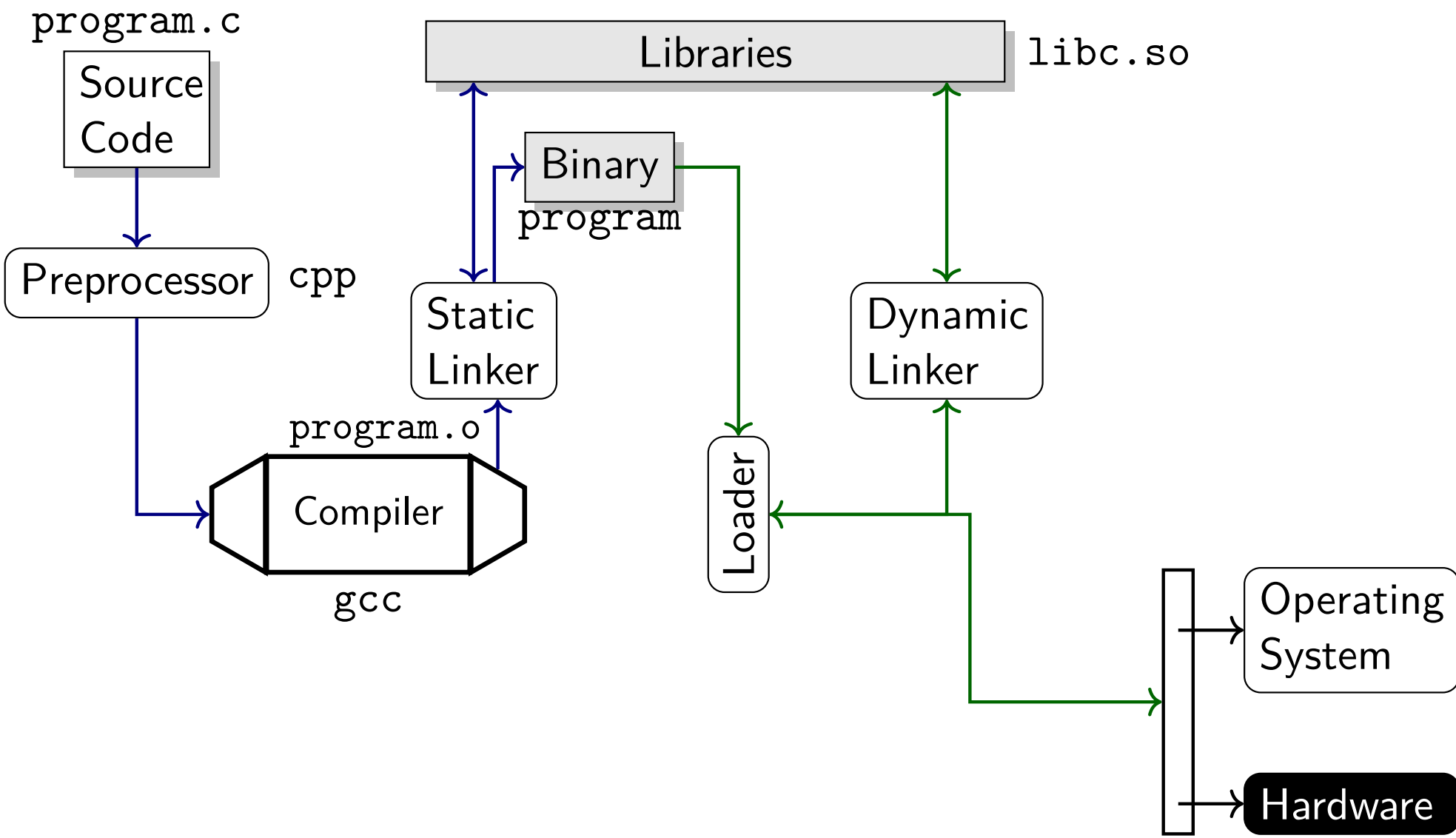
Lecture Overview



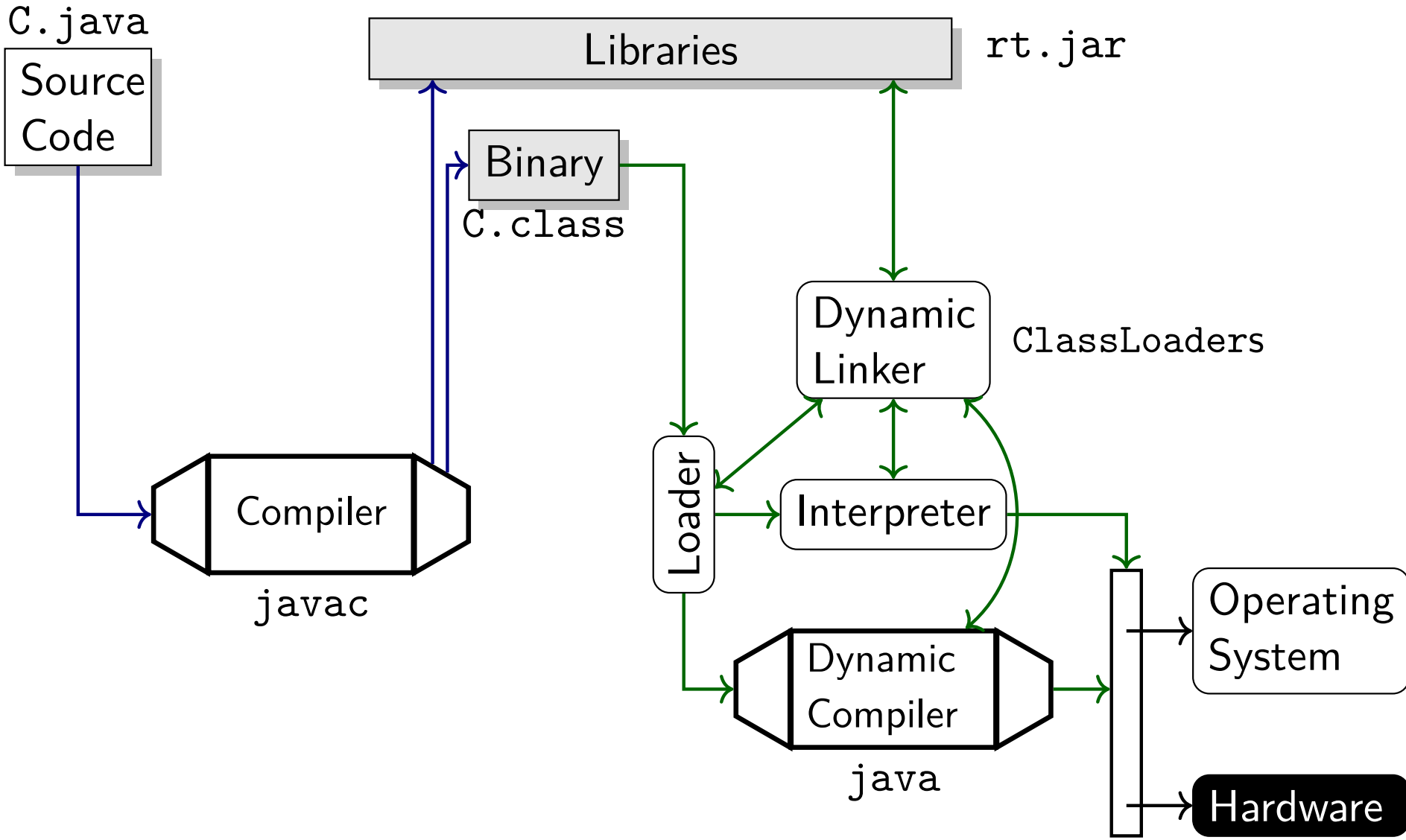
Program Execution Pipeline



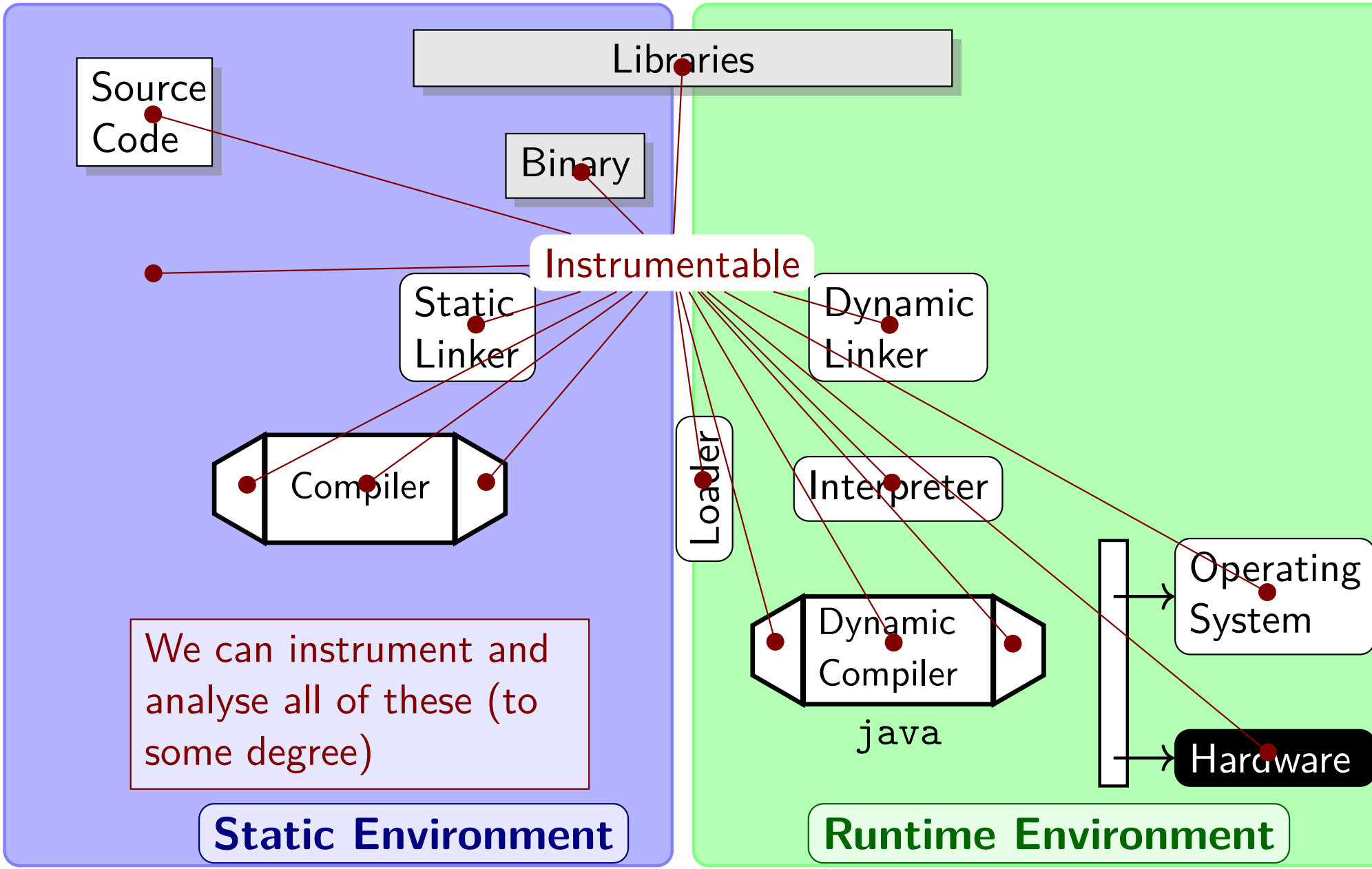
Program Execution Pipeline



Program Execution Pipeline



Program Execution Pipeline



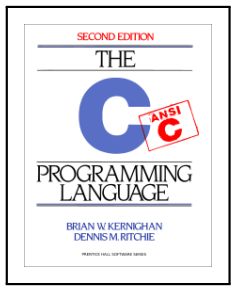
Static vs. Dynamic Program Analyses

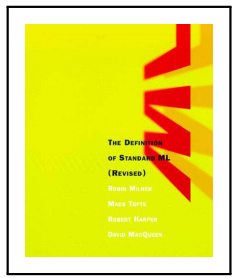
	Static Analysis	Dynamic Analysis
Principle	Analyse program structure	Analyse program execution
Input	Independent	Depends on input
Hardware/OS	Independent	Depends on hardware and OS
Perspective	Sees everything	Sees that which actually happens
Completeness (bug-finding)	Possible	Must try all possible inputs. . .
Soundness (bug-finding)	Possible	Always, for free

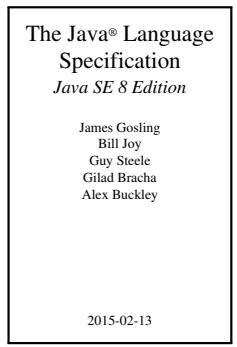
Summary

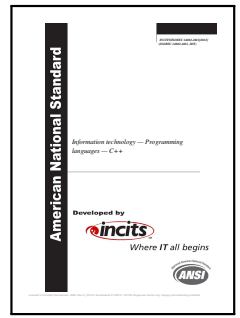
- **Preprocessor**: Transforms source code before compilation
- **Static compiler**: Tranlates source code into executable (machine or intermediate) code
- **Interpreter**: Step-by-step execution of source or intermediate code
- **Dynamic (JIT) compiler**: Translates code into machine-executable code
- **Loader**: System tool that ensures that OS starts executing another program
- **Linker**: System tool that connects references between programs and libraries
  - **Static linker**: Before running
  - **Dynamic linker**: While running
- **Machine code**: Code that is executable by a machine
- **Static Analysis**: Analyse program without executing it
- **Dynamic Analysis**: Analyse program execution

Defining Language Behaviour









- Many languages have multiple *language implementations*
- Language behaviour defined in *language specification*:
  - **Static Semantics**:
    Behaviour in static environment
  - **Dynamic Semantics**:
    Behaviour in runtime environment

Static vs. Dynamic Semantics

- Static semantics:
  - Identifier binding (C, Java)
  - Type checking (C, Java)
  - Other well-formedness constraints (C, Java)

Static Environment

- Dynamic semantics:
  - Execution, evaluation, control flow
  - Identifier binding (Python, JavaScript)
  - Type checking (Python, JavaScript, *Java*)
  - Dynamic dispatch (Java, Python, JavaScript)

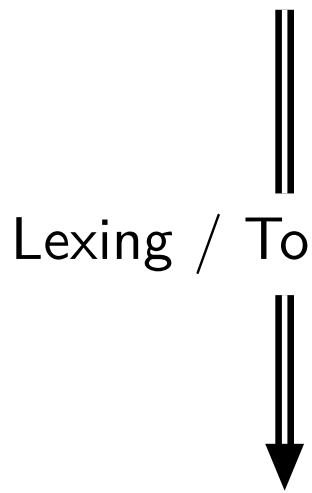
Runtime Environment

Static Analysis

Analysing Program Structure

Java lexing

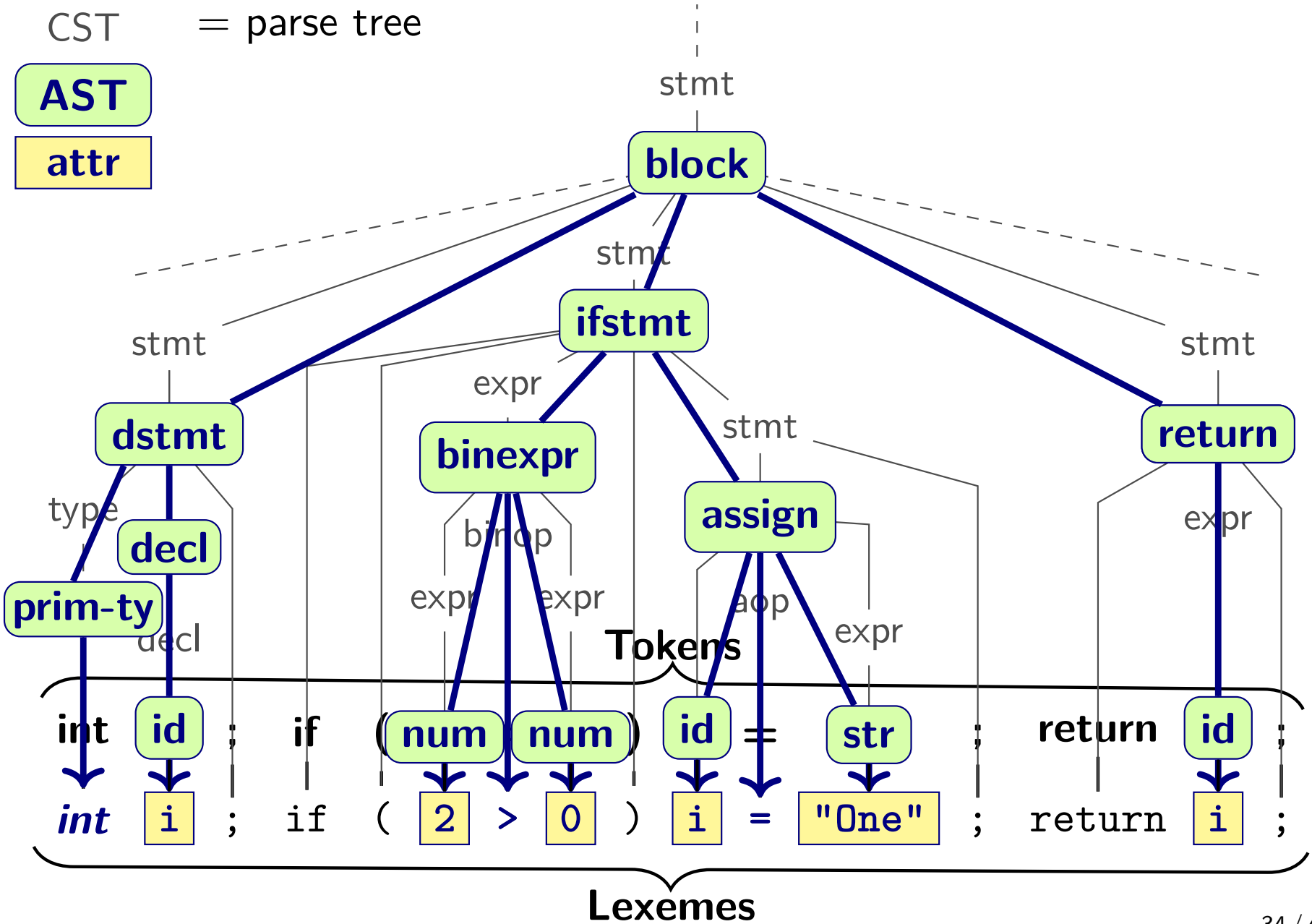
```
int i;
if (2 > 0) {
  i = "One";
}
return i;
```



Lexing / Tokenisation


```
int i ; if ( 2 > 0 ) i = "One" ; return i ;
```

Java lexing & parsing



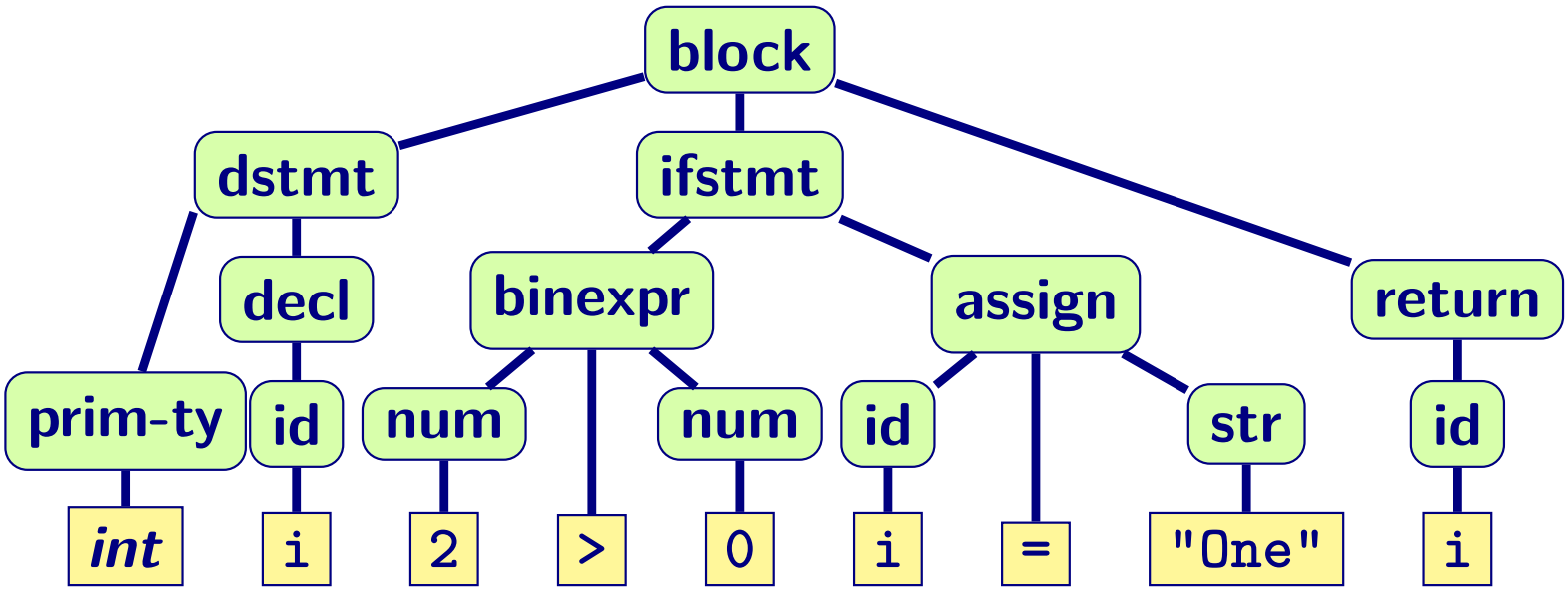
Parsing in general

*Translate text files into **meaningful** in-memory structures*

- CST = Concrete Syntax Tree
  - Full "parse", cf. language BNF grammar
  - Not usually materialised in memory
- AST = Abstract Syntax Tree
  - Standard in-memory representation
  - Avoids syntactic sugar from CST, preserves important nonterminals as **AST nodes**
  - Converts useful tokens into intrinsic attributes
- The AST is the most common **Intermediate Representation** (IR) of program code
  - Effective for frontend analyses
  - Other IRs focus e.g. on optimisations in the backend

Program analysis starts on the AST

In-Memory Representation



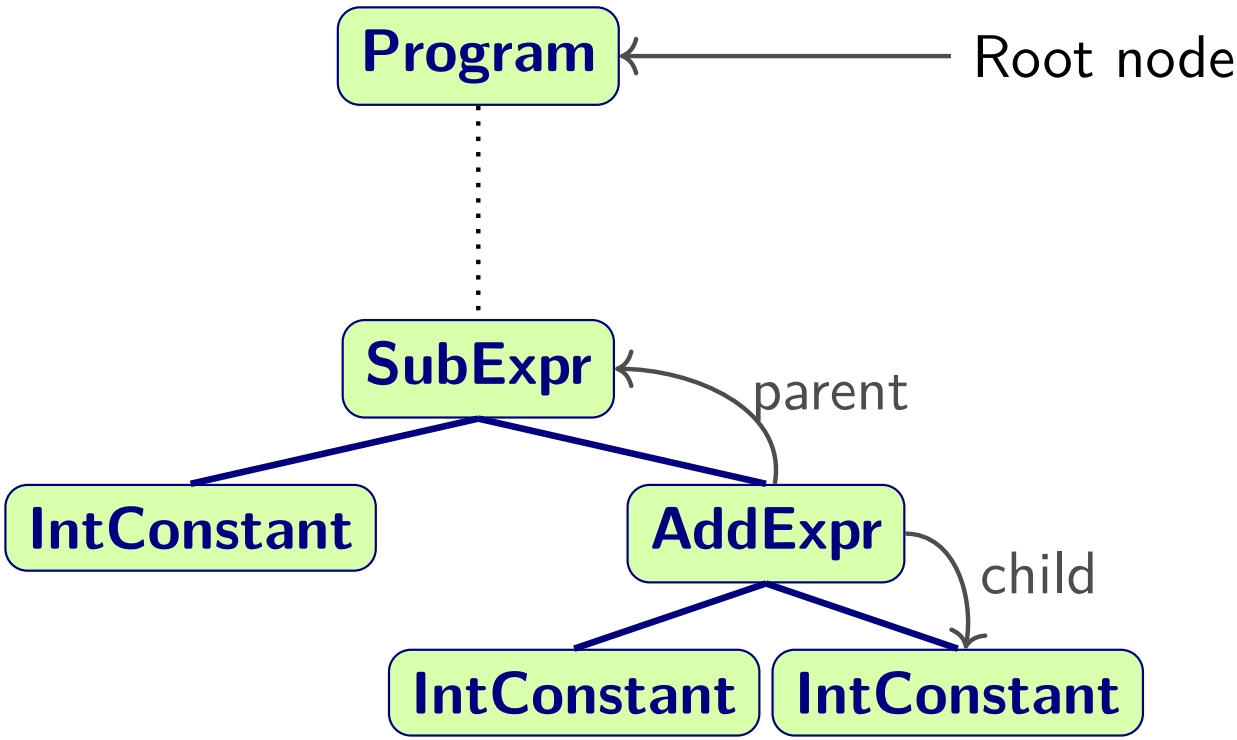
Typical in-memory representations for this AST:

- Algebraic values (functional)
- Records (imperative)
- Objects (object-oriented)

Summary

- Static program analysis operates on an **Intermediate Program Representation** (IR)
  - Our main IR: **Abstract Syntax Trees** (ASTs)
  - Other IRs can speed up / simplify certain tasks (more later)
- ASTs constructed by *Compiler Frontend*:
  - Scanning/lexing/tokenising
  - Parsing
  - Translation from parse tree into AST
  - Not covered in this course; see **EDAN65: Compiler Construction** for details

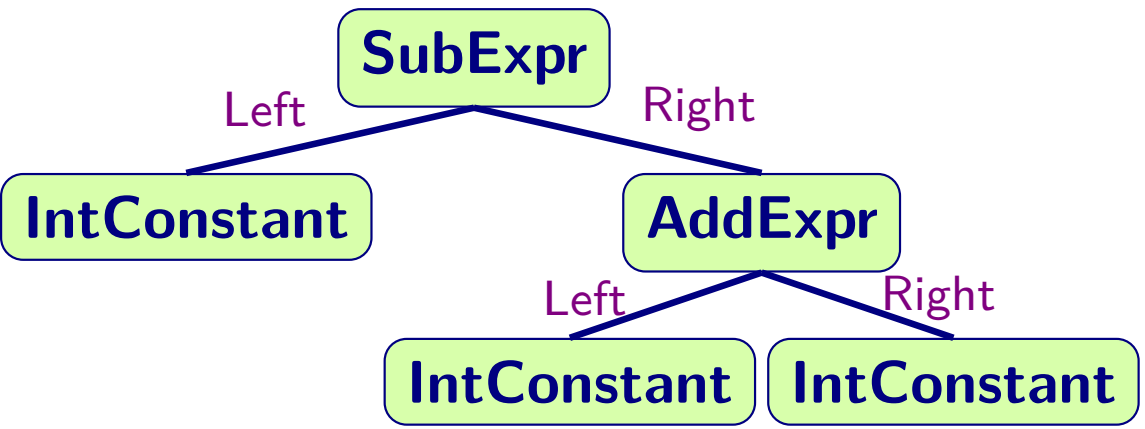
The AST as Data Structure

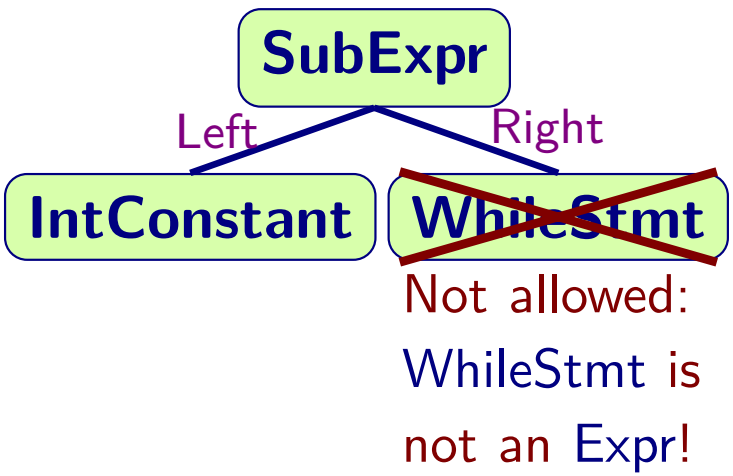


Structure of the AST

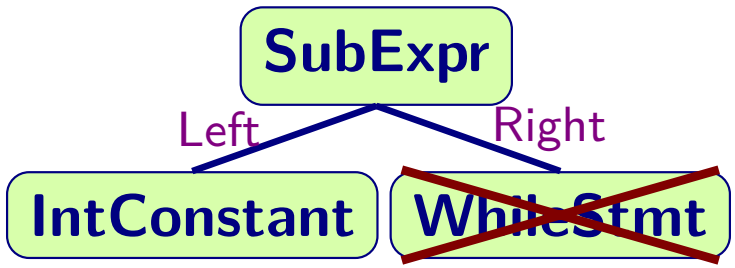
Abstract Grammar

```
Program ::= ...; // start symbol

abstract Expr;
IntConstant :  Expr ::= <Value:int>;

AddExpr :  Expr ::= Left:Expr Right:Expr;
SubExpr :  Expr ::= Left:Expr Right:Expr;

abstract Stmt;
WhileStmt :  Stmt ::= Cond:Expr Body:Stmt;
```





Restricting AST Structure

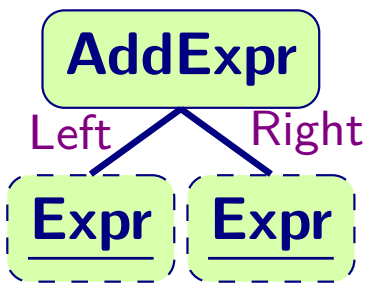


- Intuition:
  - SubExpr wants to subtract values from each other
  - WhileStmt does not compute a value
- Parser and type system guarantee that such nonsensical combinations don't occur
  - Otherwise program analyses would have to check for them

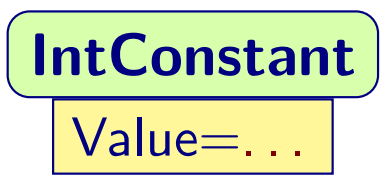
Abstract Grammars

- Grammar specifies all permissible tree constructions
- Consists of *production rules*:
  - *Production* (AddExpr): Name of the language construct
  - *Nonterminal* (Expr): Category ('supertype') for production
  - *Components* (Left:Expr): Child nodes
    - Nonterminal components: child nodes
    - Terminal components: intrinsic attributes

```
AddExpr :  Expr ::= Left:Expr Right:Expr;
```




```
IntConstant :  Expr ::= <Value:int>;
```



Summary

- Permissible structure of the AST is governed by the *Abstract Grammar*
- The grammar is specified in terms of *Production Rules*
  - Production rules describe the *components* of one Production
  - Each Production belongs to one Nonterminal
  - Standard notation: Backus-Naur Form (BNF)
  - Exact BNF syntax varies between tools; we will use JastAdd's variant
- Structure is enforced by parser and type system

$\Rightarrow$ Simplifies analysis construction

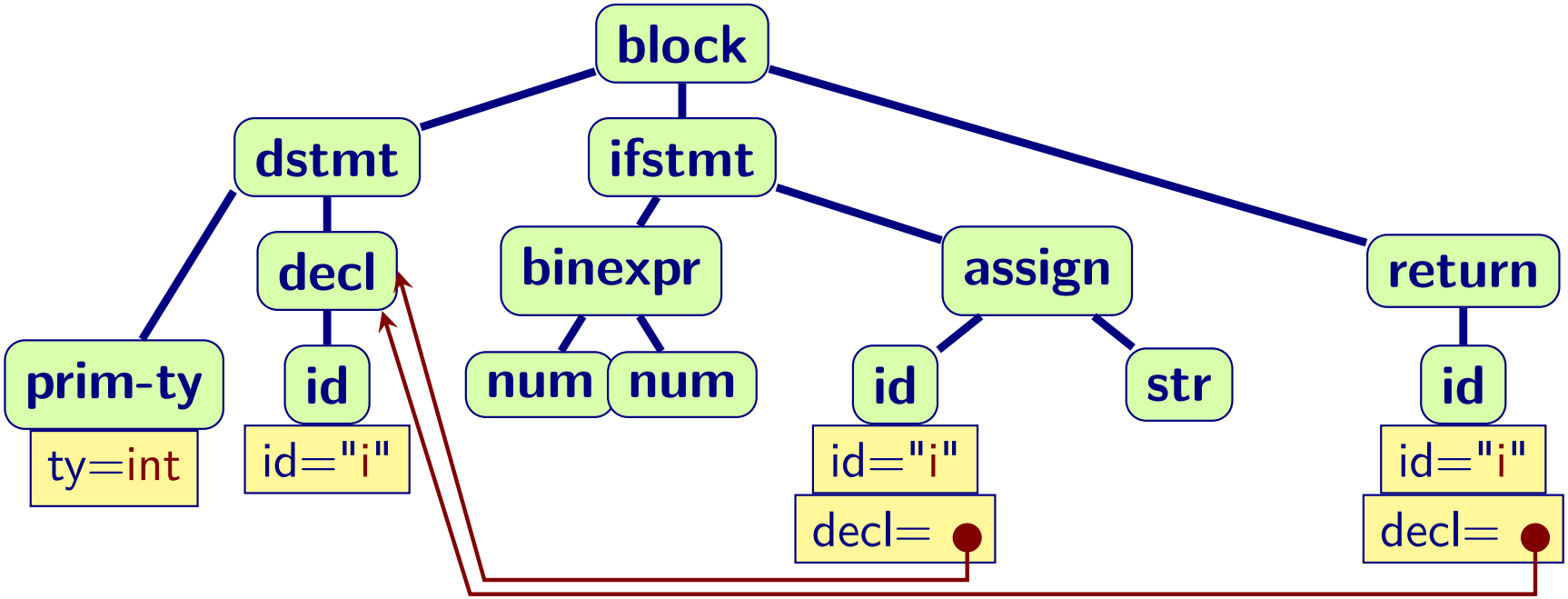
- Common nonterminals:
  - Expr: computes a value
  - Stmt: triggers a side effect or controls the order of side effects
  - Decl: declares or defines a variable/function/...

Some Basic Analyses

- *Name Analysis*:
  - Which name *use* binds to which *declaration*?
- *Type Analysis*:
  - What are the types of all expressions?
- *Static Correctness Checks*:
  - Are there type errors?
  - Is a variable unused?
  - Are we initialising all variables?

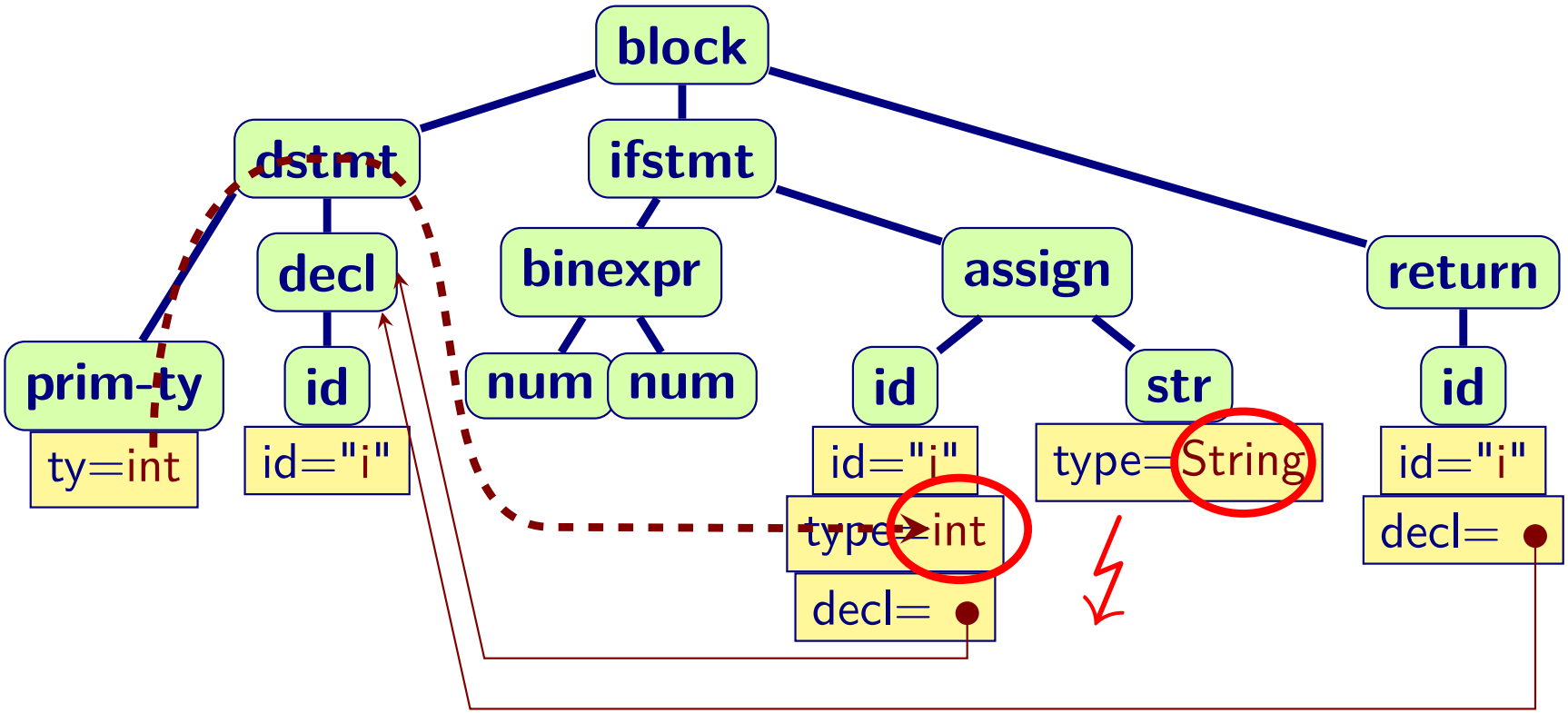
  ...

Example: Name Analysis



- For each **id**, compute the corresponding **decl**
- In AST-based IR: keep reference to
- Check that we found a **decl** node (otherwise **Error**)

Example: Type Analysis



- Check that all types are compatible with their operators
- Must first compute types
- **assign** node: type error!
  Trying to assign String to int variable

Summary

- Program analysis on AST:
  - Enrich AST nodes with additional information
  - Name Analysis: references to declarations
  - Type Analysis: types (computed, propagated)
  - Analyses often need to use results of earlier analyses
- Lecture 2 will introduce systematic strategies for computing such information

Moving Forward

- **How do we *build* static program analyses?**
  - Avoid building from scratch: many frameworks available
  - Re-use where you can
  - **This course**: JastAdd: Next lecture (Flipped!)
- **How do we *design* program analyses?**
  - Theoretical frameworks:
    - **Type Inference**
    - **Dataflow analysis**
    - Abstract interpretation

      ...
  - Language Definition:
    - **Static Semantics**:
      Compile-time/load-time behaviour
    - **Dynamic Semantics**:
      Run-time behaviour

Outlook

- **Remember**:
  - Join Moodle *today*
  - Form groups by Wednesday, 18:00
- Continuing on static program analysis:
  - Type Analysis
  - Data Flow Analysis
  - Heap Analysis
- **Next Lecture**: Thursday, same time & place:
  - Topic: Building Program Analyses with *Reference Attribute Grammars* in *JastAdd*
  - **Flipped Classroom lecture**
    - Watch videos beforehand
    - Bring questions
    - We will discuss material from the videos *based on your questions*

`http://cs.lth.se/EDAP15`