Static Program Analysis

Yue Li and Tian Tan

2020 Spring

Static Program Analysis

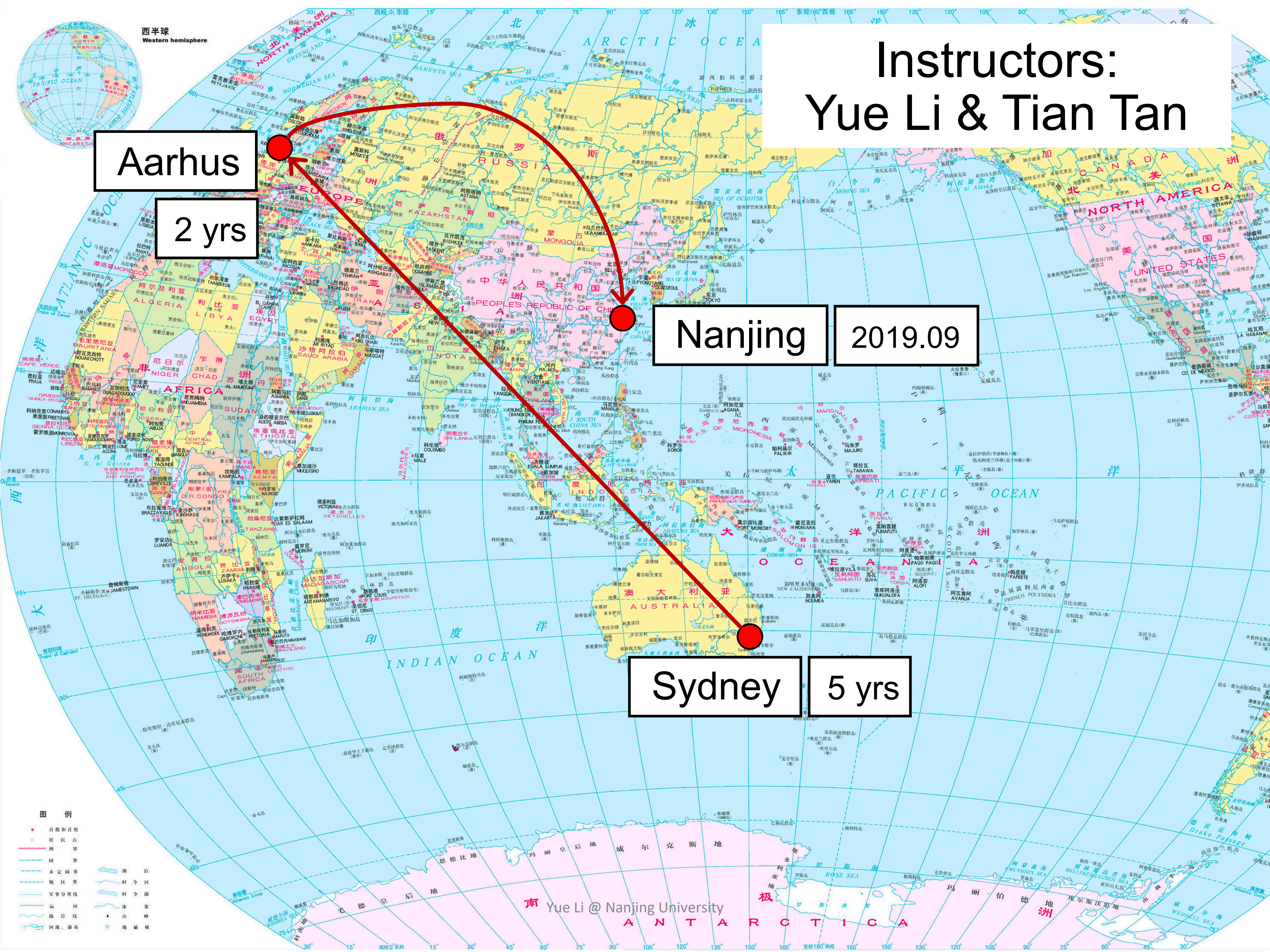
Introduction

Nanjing University

Yue Li

2020

Instructors: Yue Li & Tian Tan



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Programming Languages

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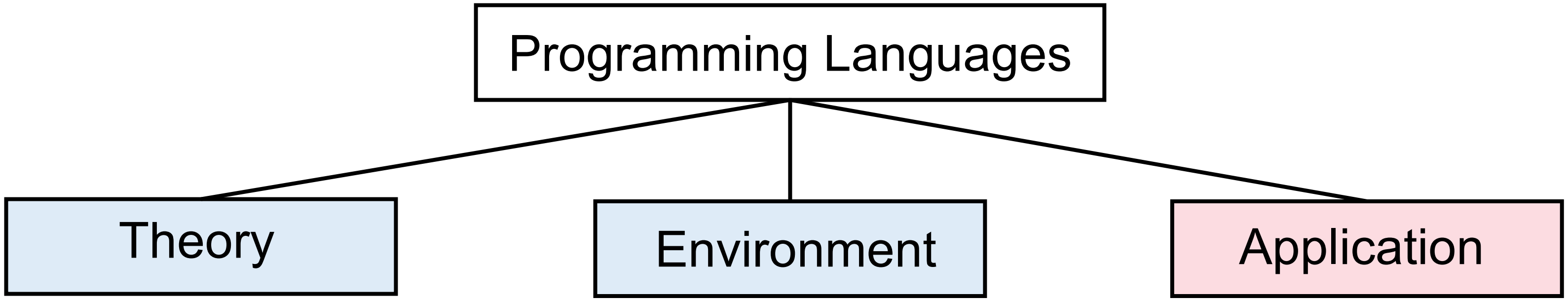

- Language design
- Type system
- Semantics and logics
- … …

- Compilers
- Runtime system
- … …

- Program analysis
- Program verification
- Program synthesis
- … …

Static Program Analysis (Static Analysis)

Programming Languages

Theory
- Language design
- Type system
- Semantics and logics
- … …

Environment
- Compilers
- Runtime system
- … …

Application
- Program analysis
- Program verification
- Program synthesis
- … …

Background: In the last decade, the language cores had few changes, but the programs became significantly larger and more complicated.

Challenge: How to ensure the reliability, security and other promises of large-scale and complex programs?

Why We Need Static Analysis?

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- Program Reliability

  Null pointer dereference, memory leak, etc.

  Examples

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  Dead code elimination, code motion, etc.

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  Examples

- Program Understanding

  IDE call hierarchy, type indication, etc.

  Examples

Market of Static Analysis

Academia

Programming Languages

Software Engineering

Systems

Security

… …

Any directions that rely on programs

Industries

Microsoft

ORACLE

HUAWEI

facebook

IBM Research

GRAMMATECH

Uber

Semmle™

SAMSUNG

Google

Sourcebrella

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book

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Static analysis people are urgently needed !

Static Analysis

Static analysis analyzes a program *P* to reason about its behaviors and determines whether it satisfies some properties before running *P*.

- Does *P* contain any private information leaks?
- Does *P* dereference any null pointers?
- Are all the cast operations in *P* safe?
- Can *v1* and *v2* in *P* point to the same memory location?
- Will certain *assert* statements in *P* fail?
- Is this piece of code in *P* dead (so that it could be eliminated)?
- …

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Unfortunately, by **Rice's Theorem**, there is no such approach to determine whether P satisfies such non-trivial properties, i.e., giving ***exact answer***: Yes or No

Rice's Theorem

"Any non-trivial property of the behavior of programs in a r.e. language is undecidable."

r.e. (recursively enumerable) = recognizable by a Turing-machine

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~= interesting properties
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Perfect static analysis

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Perfect static analysis

AND
- Sound
- Complete

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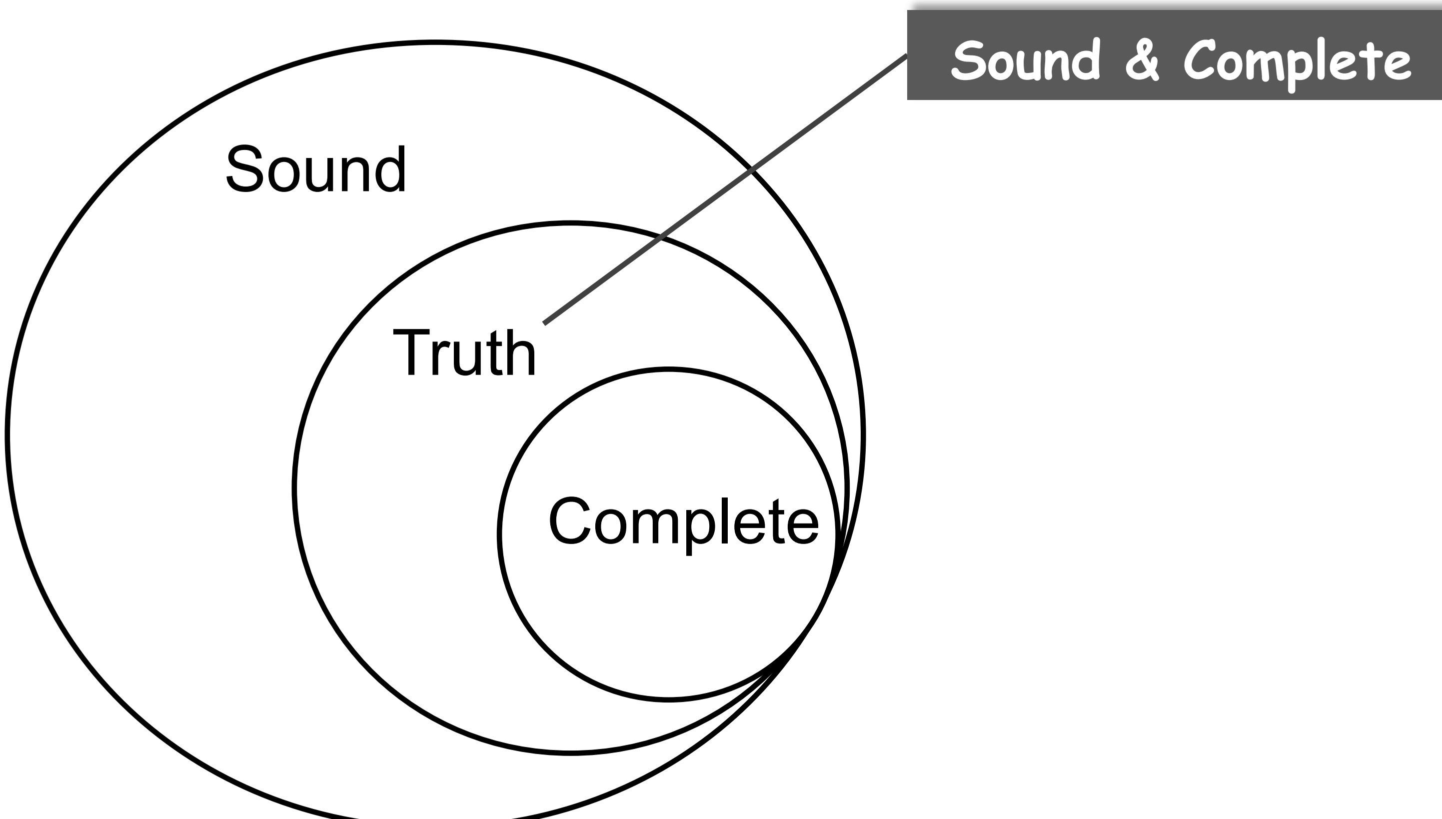

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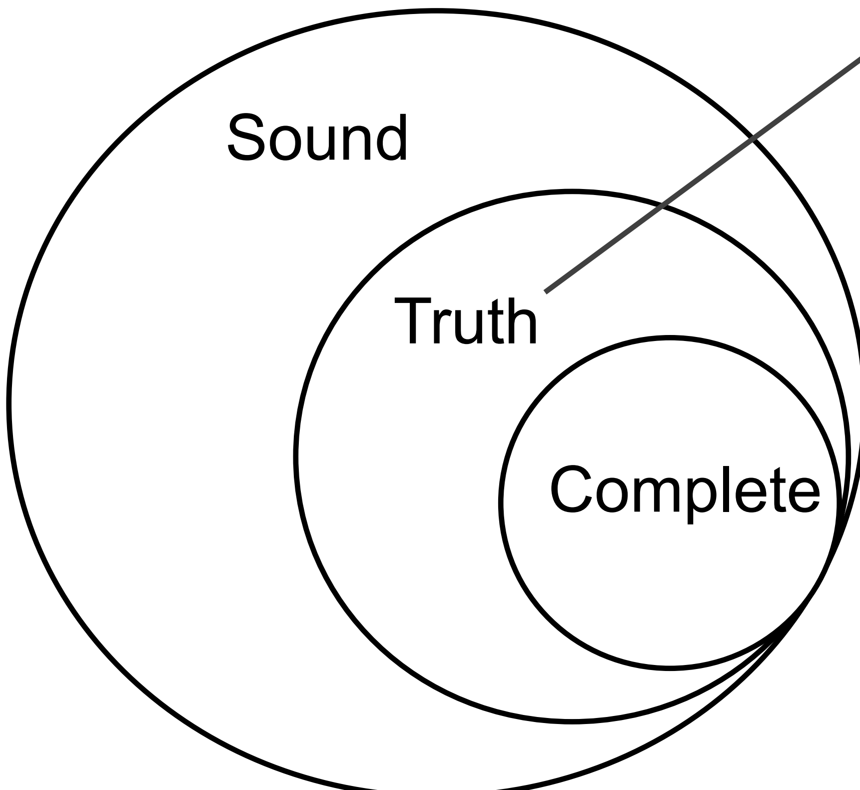
Rice

Sound & Complete

All possible true program behaviors



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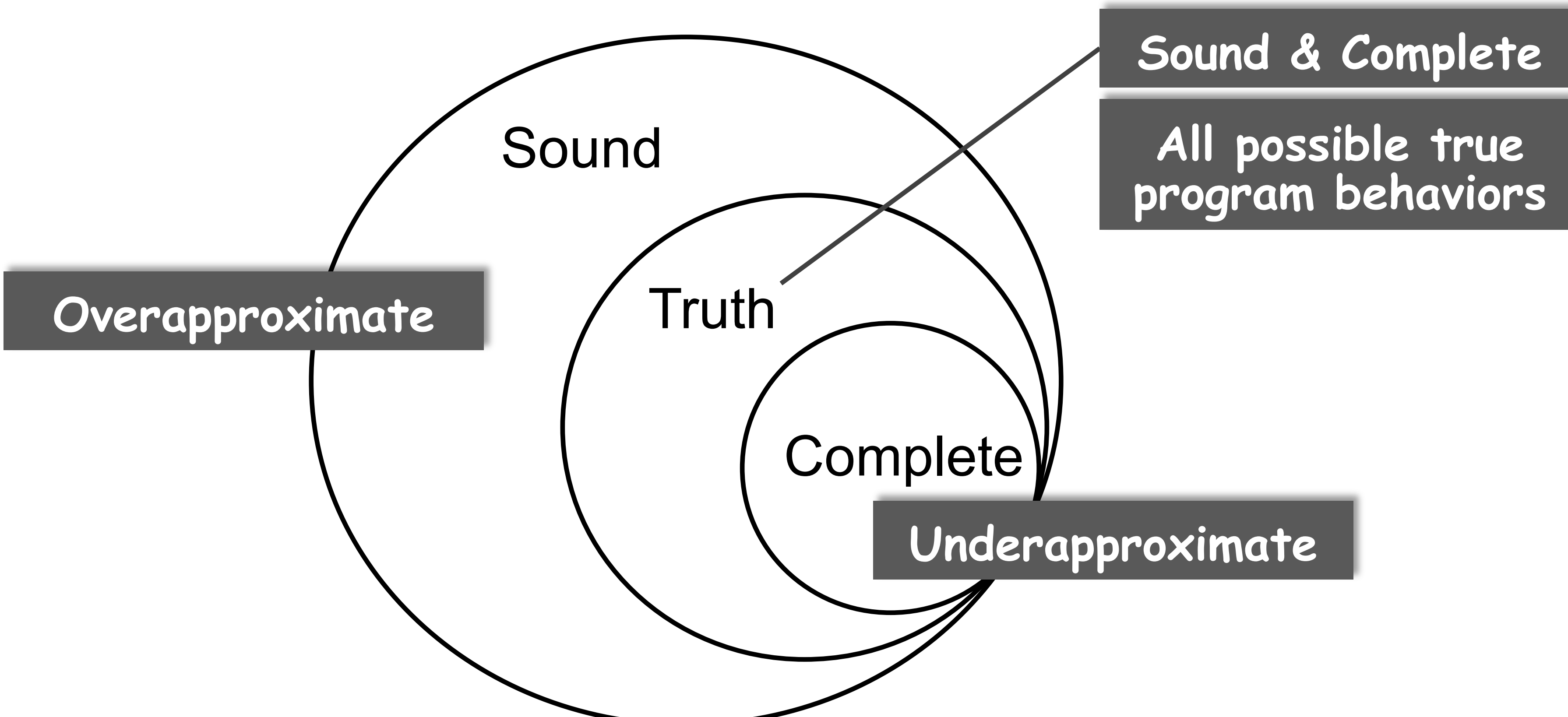

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Rice

Sound & Complete

All possible true ... am behaviors

Sound

NO perfect static analysis!

The end of story ???

Complete

Underapproximate

Perfect static analysis

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Useful static analysis

OR

- Compromise soundness (false negatives)
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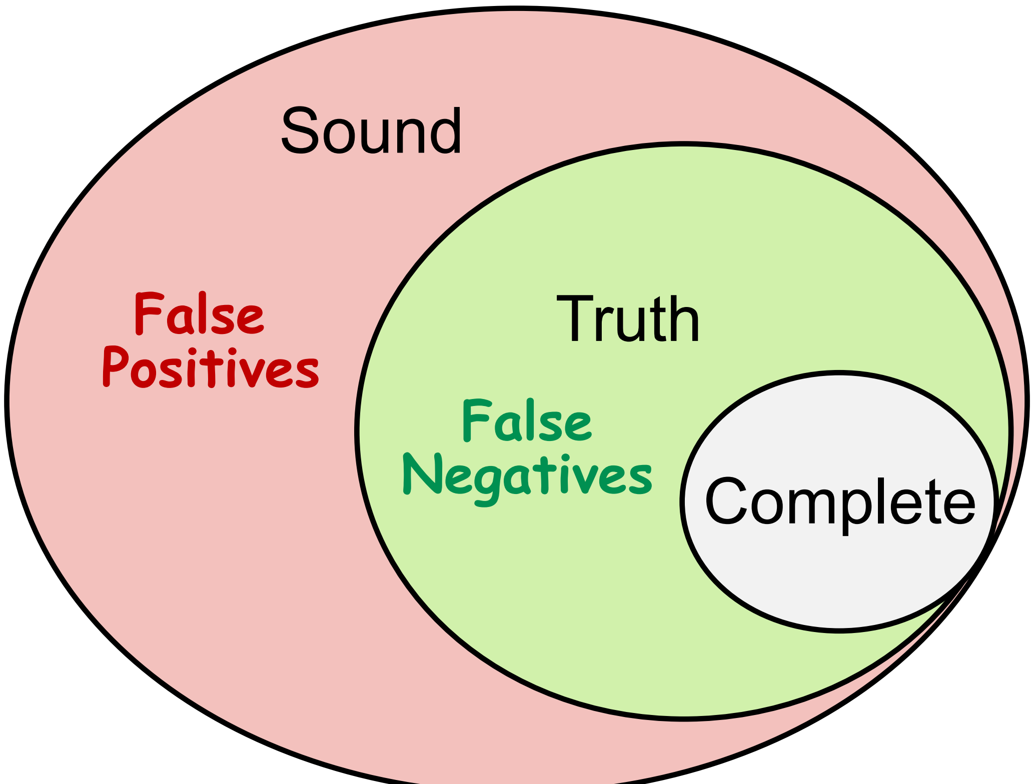

Useful static analysis

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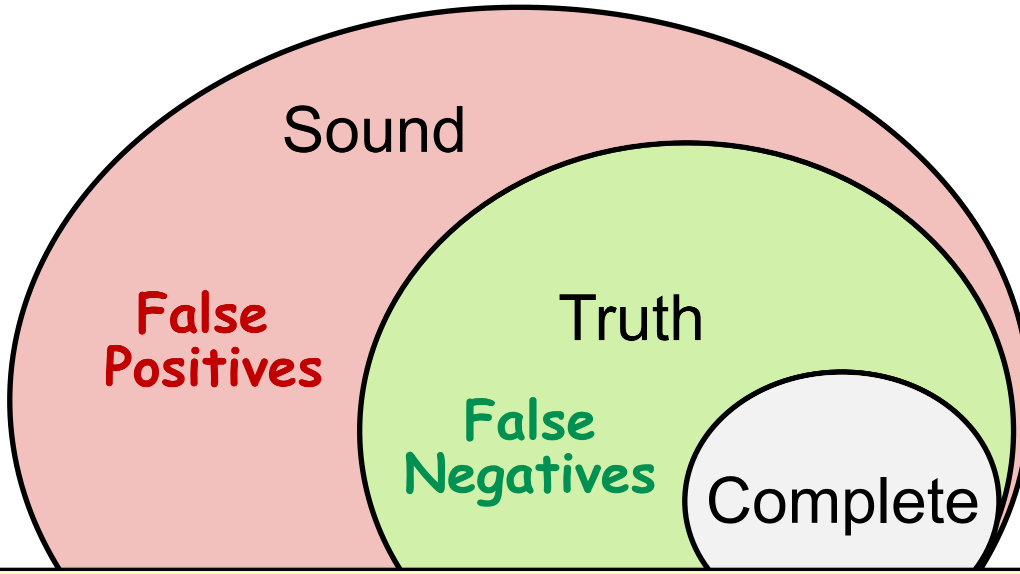

Mostly compromising completeness:
Sound but not fully-precise static analysis

Necessity of Soundness

- Soundness is critical to a collection of important (static-analysis) applications such as *compiler optimization* and *program verification.*

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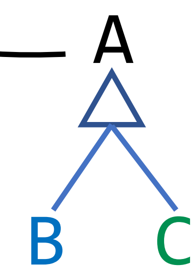
Unsound

"Safe Cast": wrong conclusion

```
B b = new B();
a.fld = b;
```

```
C c = new C();
a.fld = c;
```

```
B b' = (B) a.fld;
```



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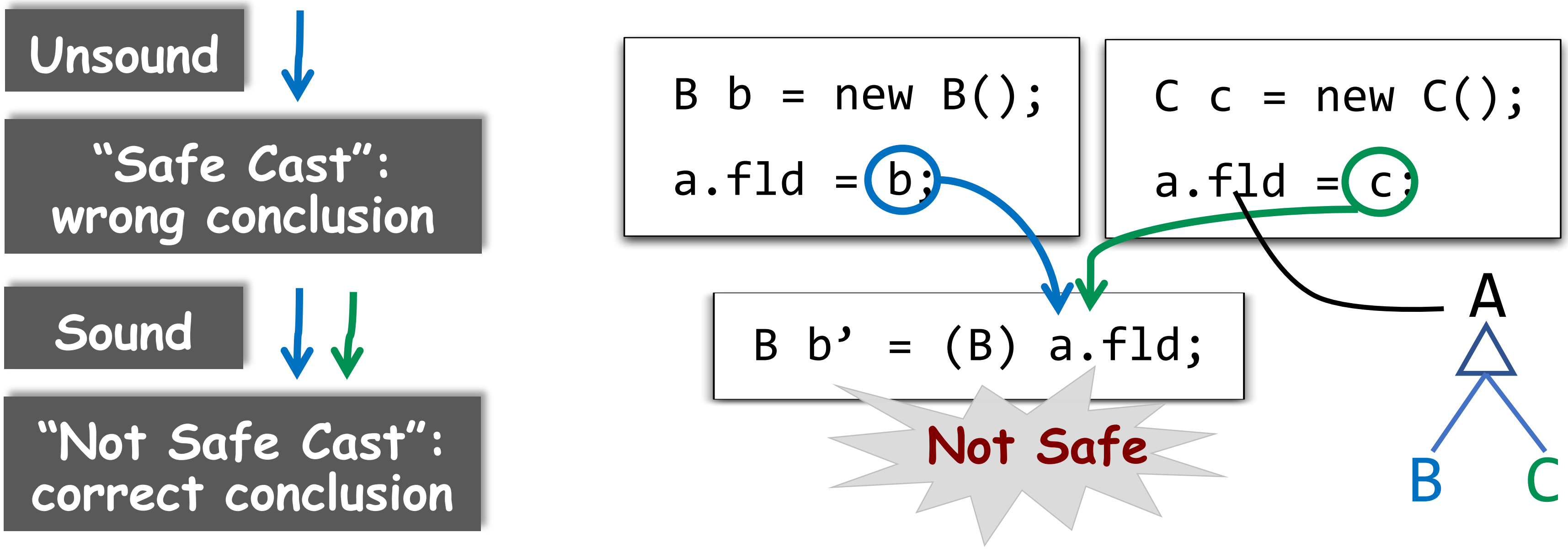

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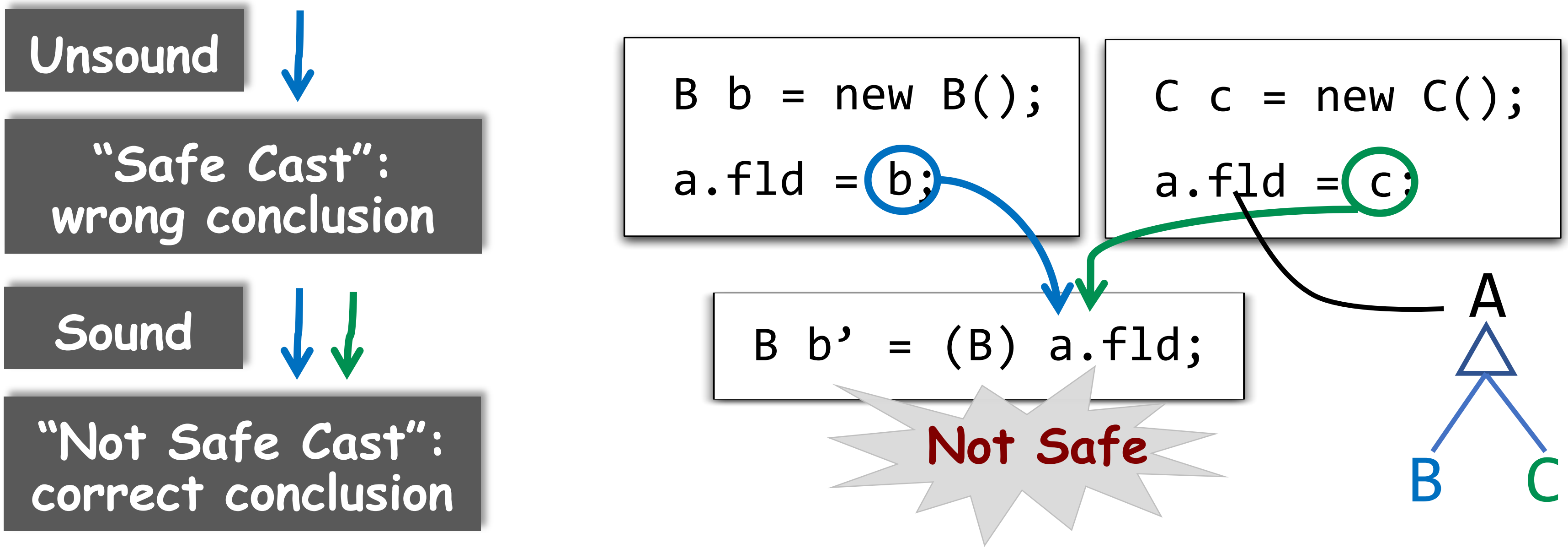

- Soundness is also preferable to other (static-analysis) applications for which soundness is not demanded, e.g., *bug detection*, as better soundness implies more bugs could be found.

Static Analysis — Bird's Eye View

```
if(input)
  x = 1;
else
  x = 0;
→ x = ?
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   Sound, precise, expensive

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Static Analysis: ensure (or get close to) soundness, while making good trade-offs between analysis precision and analysis speed.

For most static analyses
(may analysis)

Two Words to Conclude Static Analysis

Abstraction + **Over-approximation**

Static Analysis — An Example

Determine the sign (+, -, or 0) of all the variables of a given program.

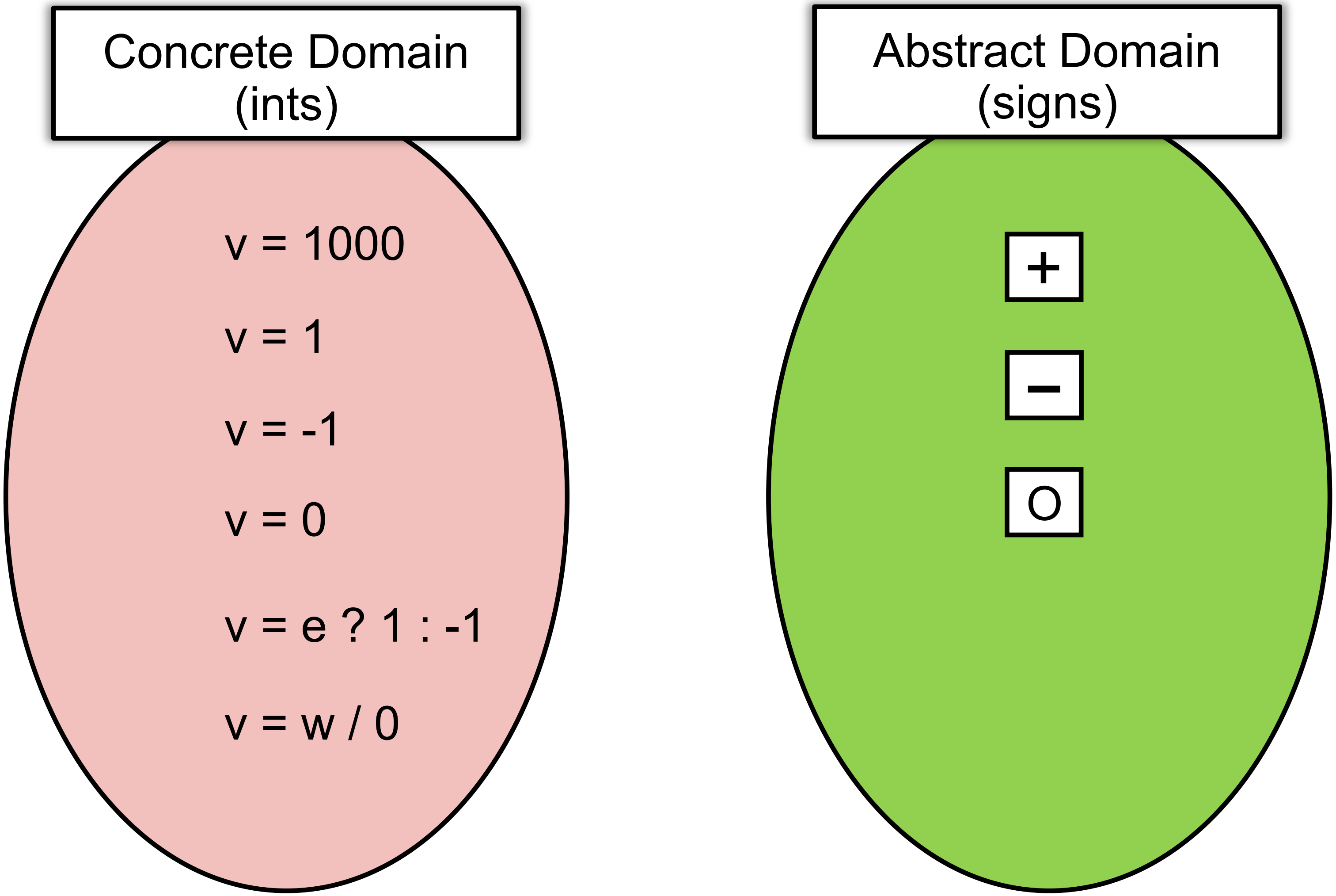
- Abstraction
- Over-approximation
  - Transfer functions
  - Control flows

To check divided by zero error

To check negative array indices

Abstraction

Determine the sign (+, -, or 0) of all the variables of a given program.



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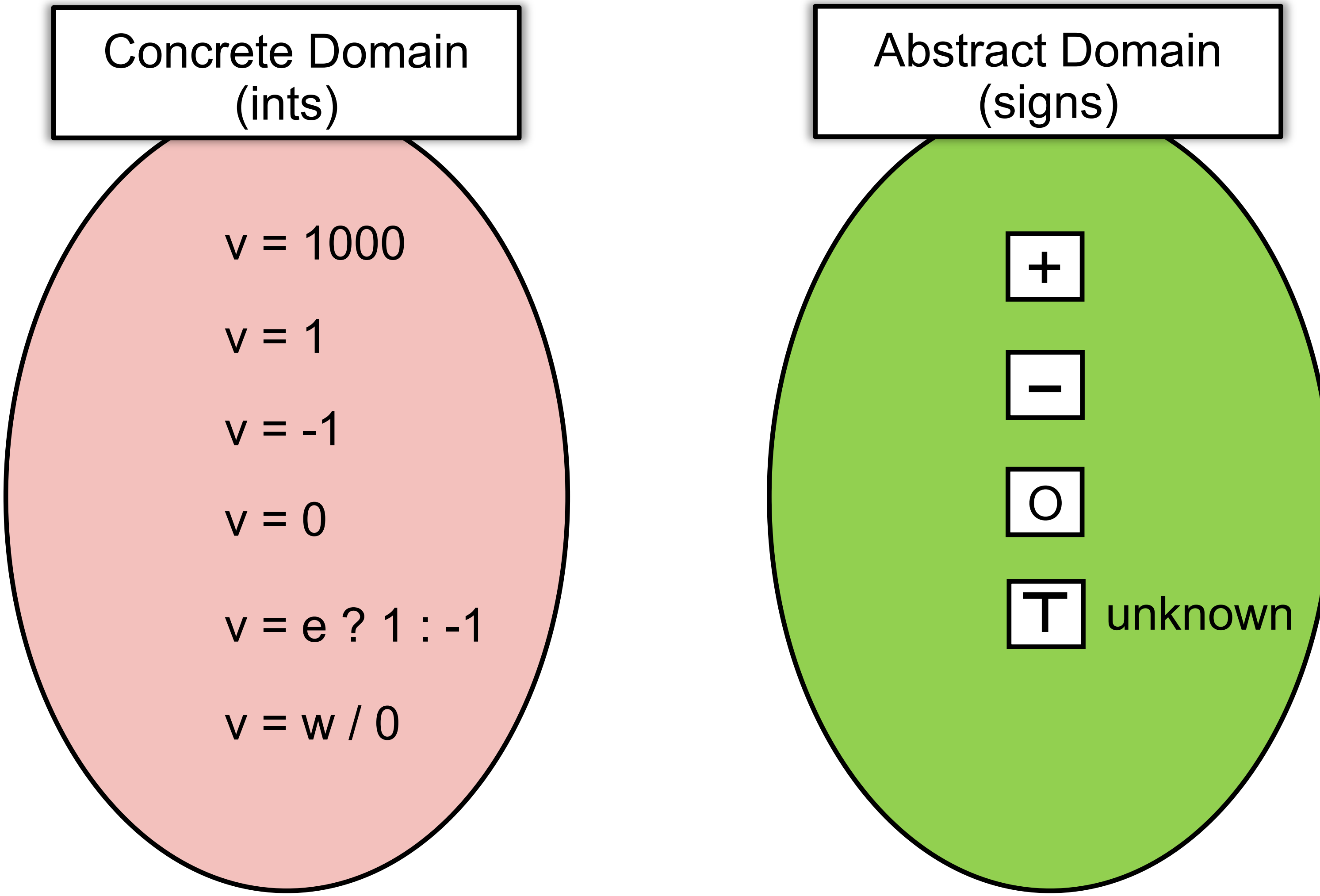

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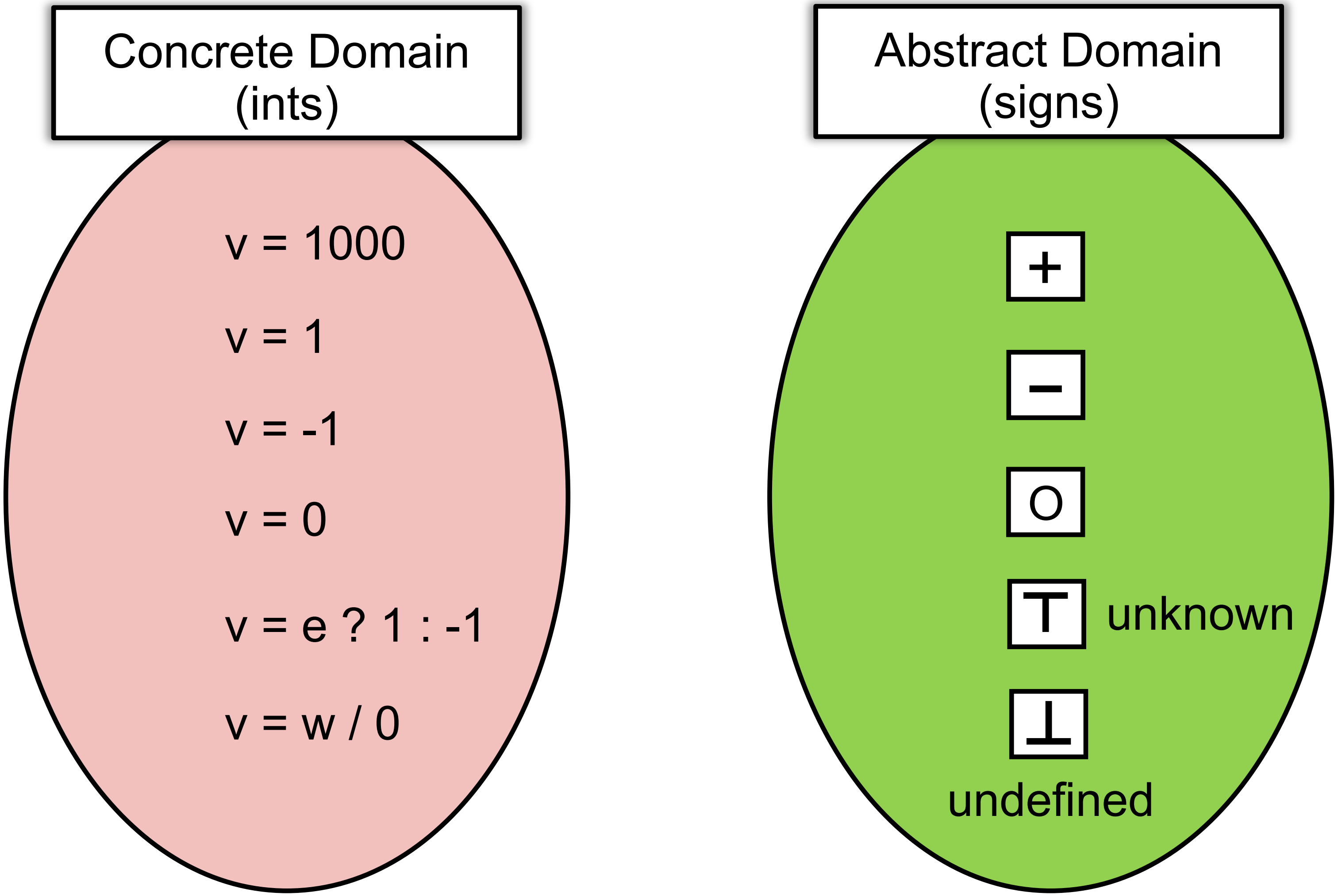

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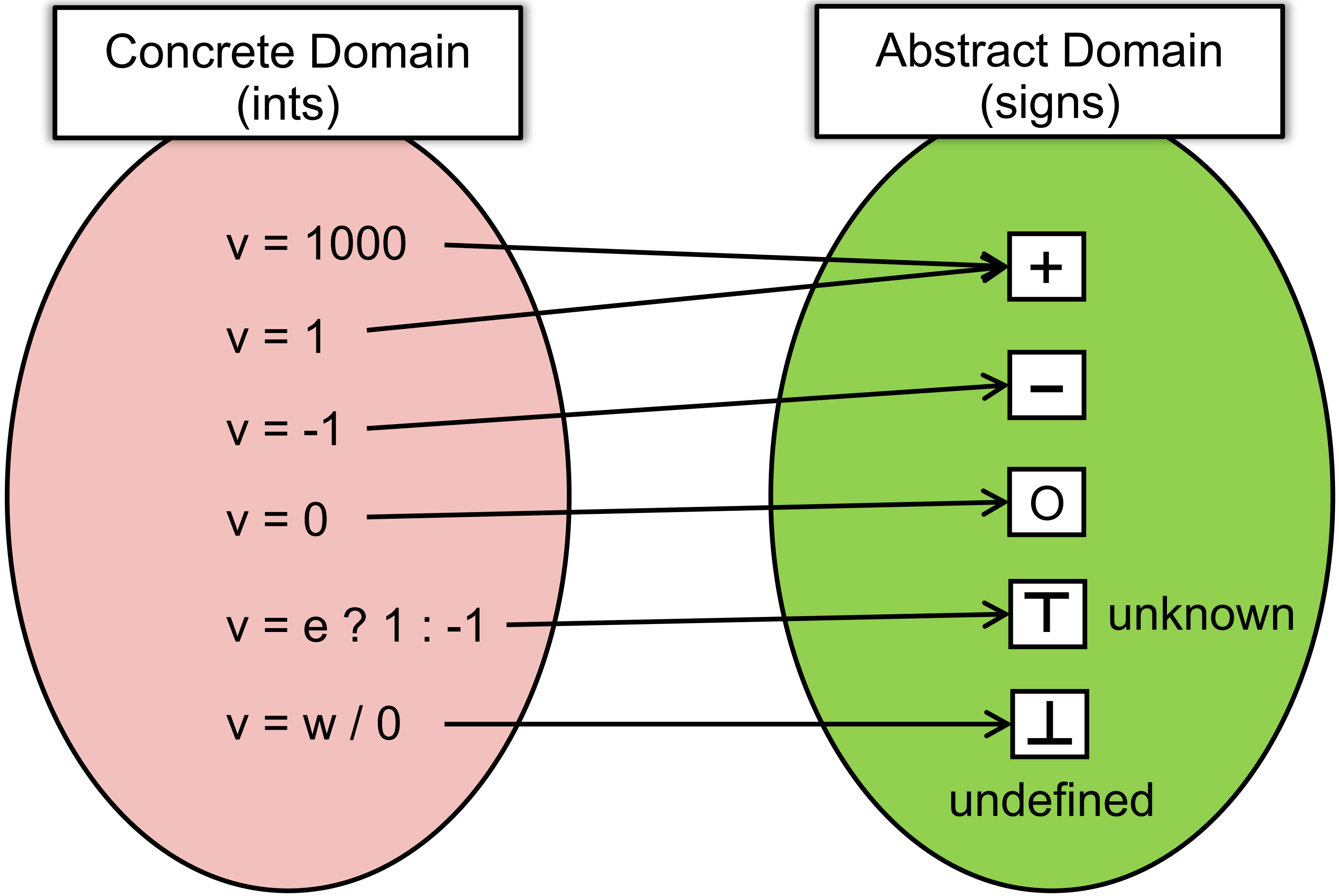

Over-approximation: Transfer Functions

- In static analysis, transfer functions define how to evaluate different program statements on abstract values.

- Transfer functions are defined according to “analysis problem” and the “semantics” of different program statements.

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$$\boxed{\mathrm{O}} + \boxed{\mathrm{O}} = \boxed{\mathrm{O}}$$

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y = -1;
z = 0;
a = x + y;
b = z / y;
c = a / b;
p = arr[y];
q = arr[a];
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1

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$c = \boxed{\bot}$ Divided by zero

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$x = \boxed{+}$

$y = \boxed{-}$

$z = \boxed{0}$

$a = \boxed{\top}$

$b = \boxed{0}$

$c = \boxed{\bot}$ Divided by zero

$p = \boxed{\bot}$

$q = \boxed{\bot}$ negative array index

$\boxed{+} + \boxed{+} = \boxed{+}$

$\boxed{-} + \boxed{-} = \boxed{-}$

$\boxed{0} + \boxed{0} = \boxed{0}$

$\boxed{+} + \boxed{-} = \boxed{\top}$

$\boxed{+} / \boxed{+} = \boxed{+}$

$\boxed{-} / \boxed{-} = \boxed{+}$

$\boxed{\top} / \boxed{0} = \boxed{\bot}$

$\boxed{+} / \boxed{-} = \boxed{-}$

$\boxed{0} / \boxed{-} = \boxed{0}$

… …

```
    x = 10;
    y = -1;
    z = 0;
    a = x + y;
    b = z / y;
(1) c = a / b;
(2) p = arr[y];
(3) q = arr[a];
```

$x = \boxed{+}$

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1 2 **Static analysis is useful**

$\boxed{+} + \boxed{+} = \boxed{+}$

$\boxed{-} + \boxed{-} = \boxed{-}$

$\boxed{0} + \boxed{0} = \boxed{0}$

$\boxed{+} + \boxed{-} = \boxed{\top}$

$\boxed{+} / \boxed{+} = \boxed{+}$

$\boxed{-} / \boxed{-} = \boxed{+}$

$\boxed{\top} / \boxed{0} = \boxed{\bot}$

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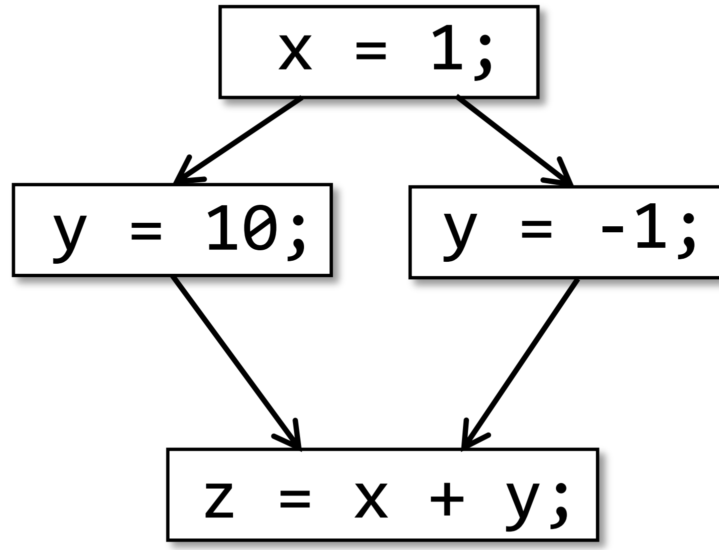
1 2 **Static analysis is useful**

3 **But (over-approximated) static analysis produces false positives**

Over-approximation: Control Flows

```
x = 1;
if(input)
  y = 10;
else
  y = -1;
z = x + y;
```



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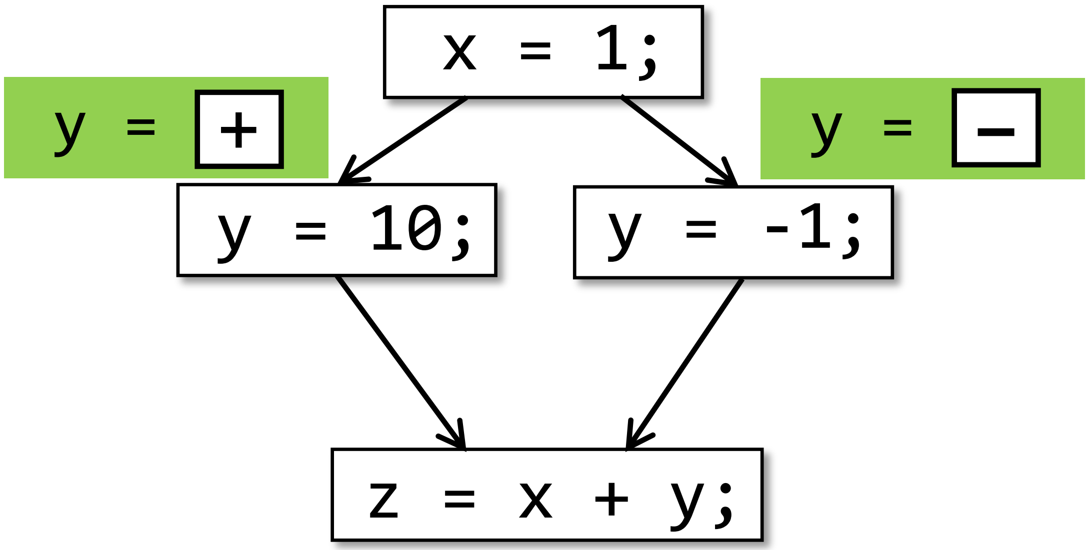

Over-approximation: Control Flows

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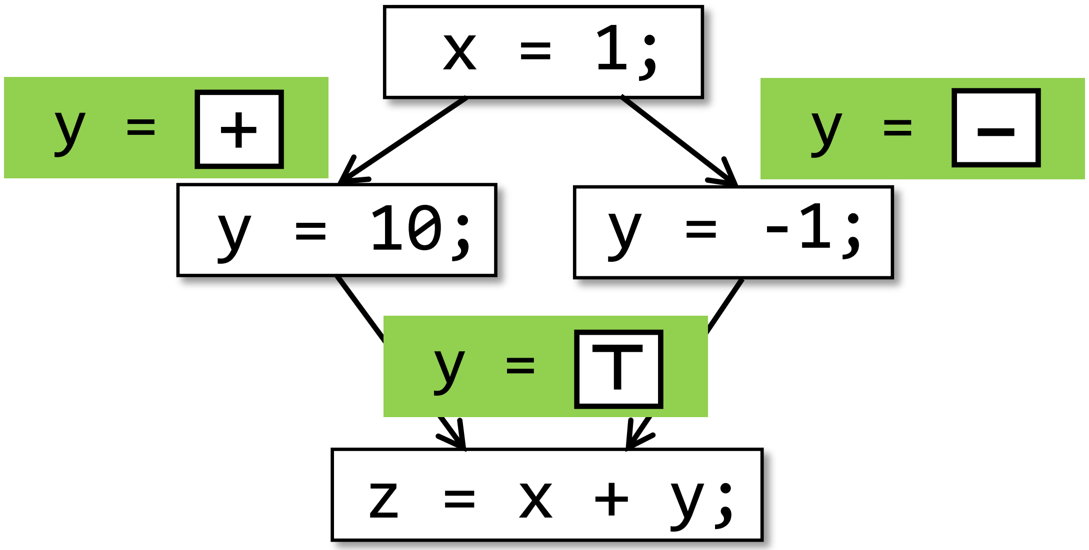

Over-approximation: Control Flows

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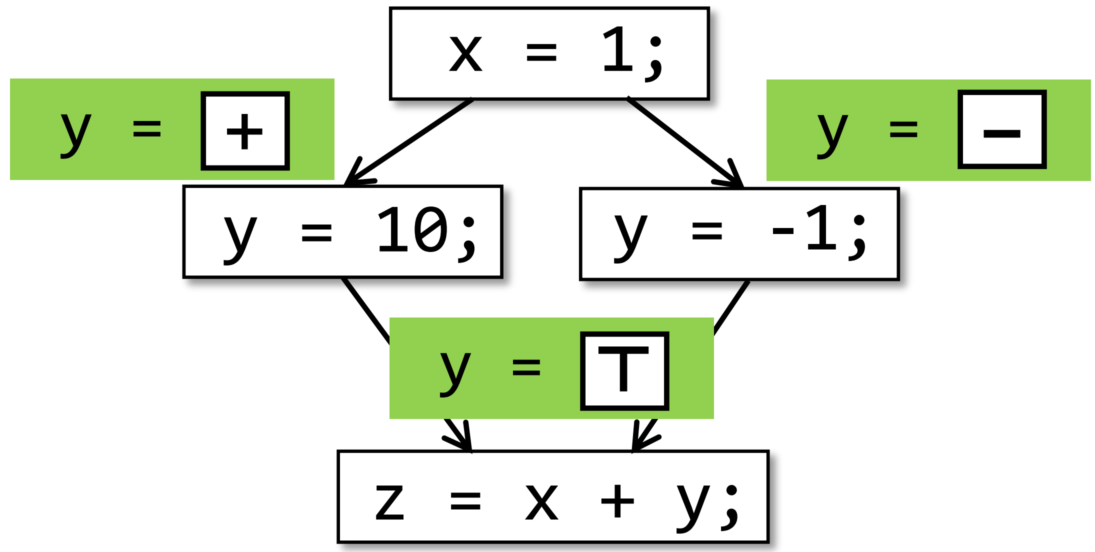

As it's impossible to enumerate all paths in practice, flow merging (as a way of over-approximation) is taken for granted in most static analyses.

Teaching Plan (Tentative)

1. Introduction
2. Intermediate Representation
3. Data Flow Analysis – Applications (I)
4. Data Flow Analysis – Applications (II)
5. Data Flow Analysis – Foundations (I)
6. Data Flow Analysis – Foundations (II)
7. Inter-procedural Analysis
8. Pointer Analysis
9. Pointer Analysis – Foundations (I)
10. Pointer Analysis – Foundations (II)
11. Pointer Analysis – Context Sensitivity
12. Static Analysis for Security
13. CFL-Reachability and IFDS
14. Soundness and Soundiness
15. Abstract Interpretation
16. Course Summary

Evaluation Criteria

- Coding Assignments 50%
- Final Exam 50%

Coding Assignments (Tentative)

- Assignment 1: Constant Propagation (CP, 10 points)
  - Statically compute and propagate constant values in program
  - Intra-procedural analysis

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  - b =true; if (b) { … } else { /* dead code */ }

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- Assignment 5: Context-Sensitive Pointer Analysis (CSPTA, 6 points)
  - Build a call graph via C.S. pointer analysis (more precise than PTA)
  - Enable more precise inter-procedural constant propagation

The X You Need To Understand in This Lecture

- What are the differences between static analysis and (dynamic) testing?
- Understand soundness, completeness, false negatives, and false positives.
- Why soundness is ~~usually~~ required by static analysis?
- How to understand abstraction and over-approximation?

Our PASCAL Research Group @Nanjing University

PASCAL

Programming LAnguages and StatiC AnaLysis Group

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The **PASCAL Research Group** is affiliated with Institute of Computer Software and Department of Computer Science and Technology at Nanjing University. We develop effective static program analysis techniques and tools for solving the problems in programming languages, software engineering, system and security.

News

October 15, 2019
Yue Li and Tian Tan start the **PASCAL Research Group** at Nanjing University!

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Hao Ling
Undergraduate, 2016 —

Shengyuan Yang
Undergraduate, 2017 —

Tian Tan
Assistant Research Professor

Weiyu Ye
Ph.D., 2017 — (co-supervised with Prof. Xiaoxing Ma)

Yue Li
Associate Professor

Yuying Yuan
Undergraduate, 2017 —


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