Static Program Analysis

Pointer Analysis

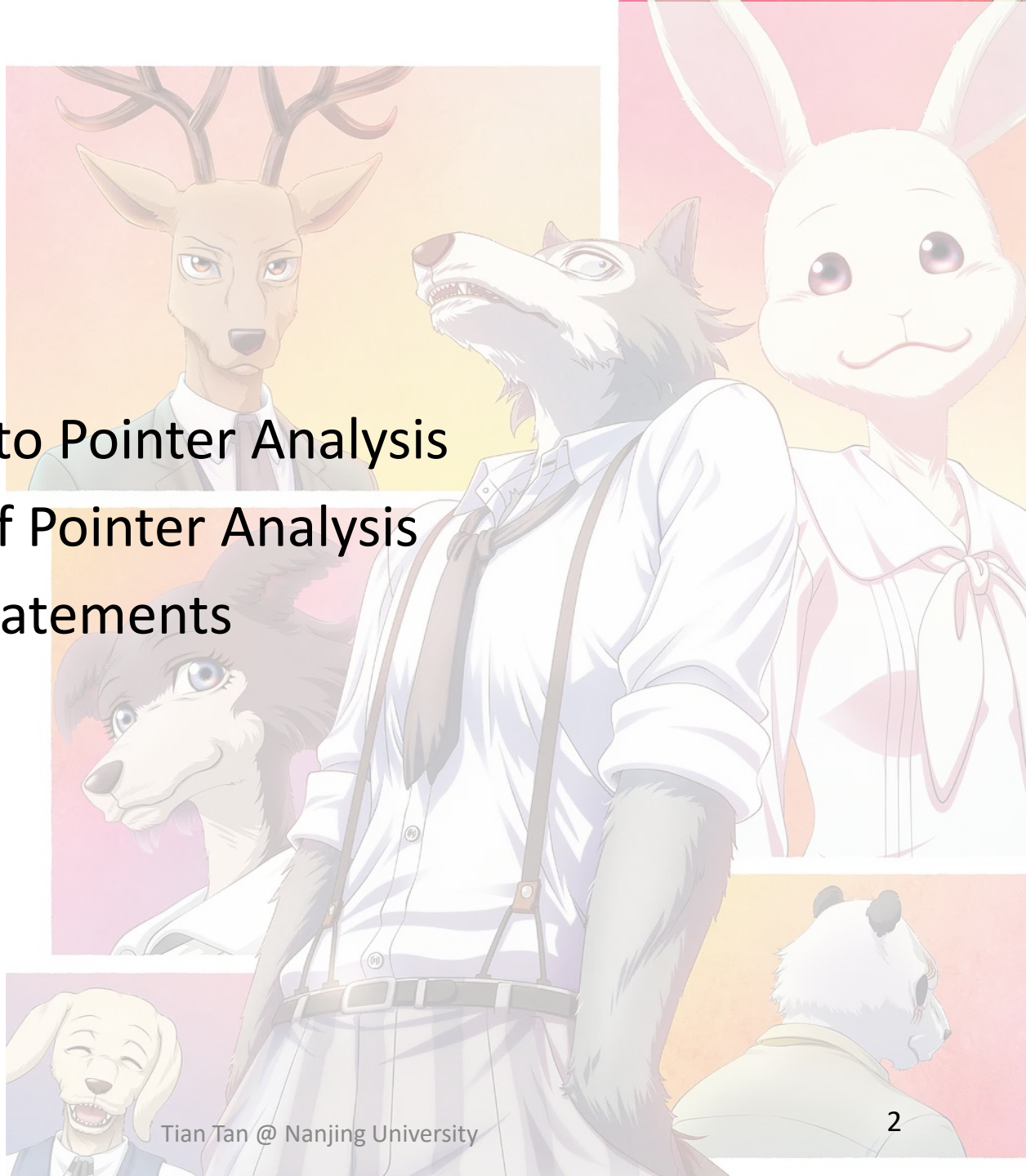
Nanjing University

Tian Tan

2020

Contents

1. Motivation
2. Introduction to Pointer Analysis
3. Key Factors of Pointer Analysis
4. Concerned Statements



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Problem of CHA

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void foo() {
    Number n = new One();
    int x = n.get();
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interface Number {
    int get();
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```

Problem of CHA

CHA:

- ? call targets

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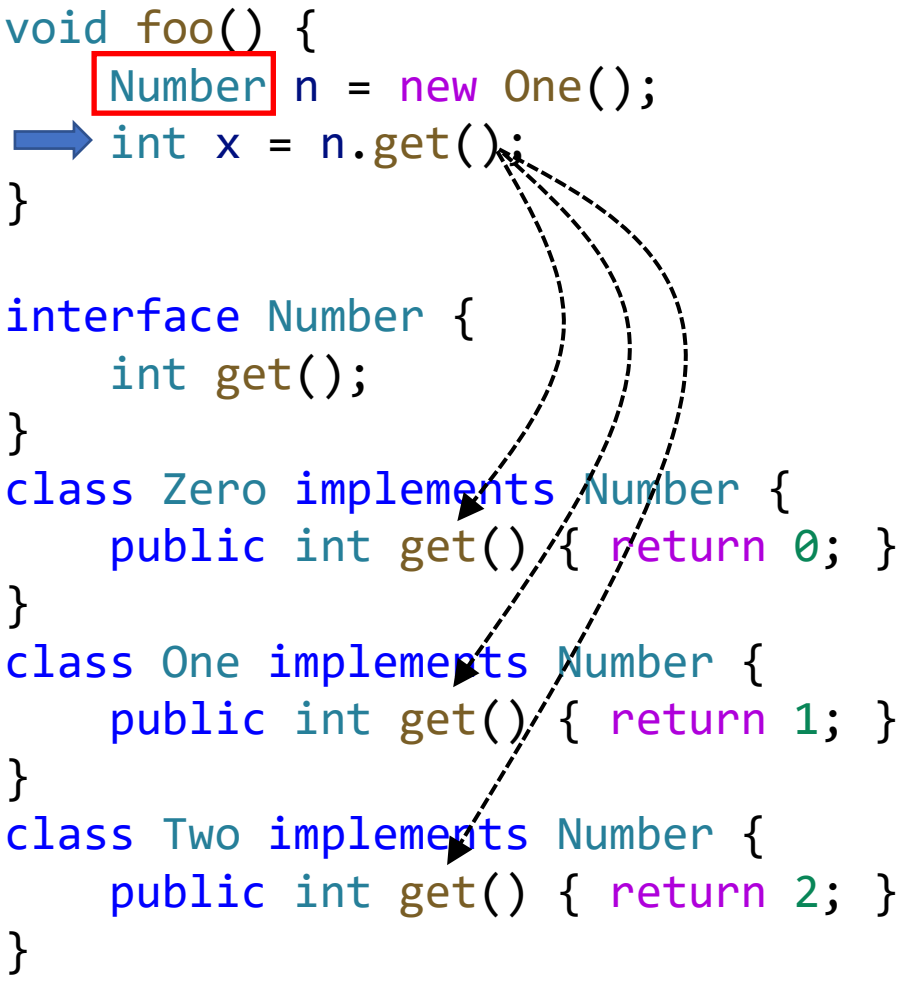
Problem of CHA

CHA: based on
class hierarchy
- 3 call targets



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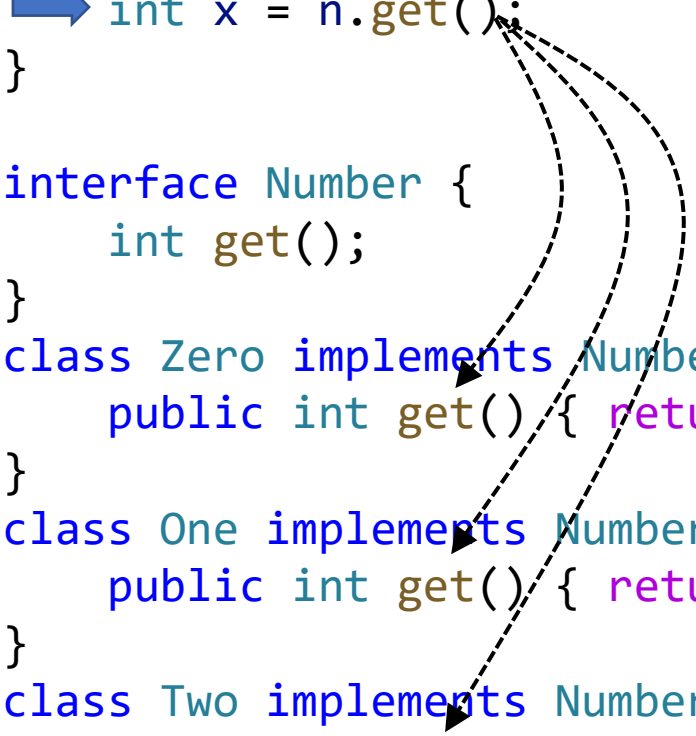

CHA: based on

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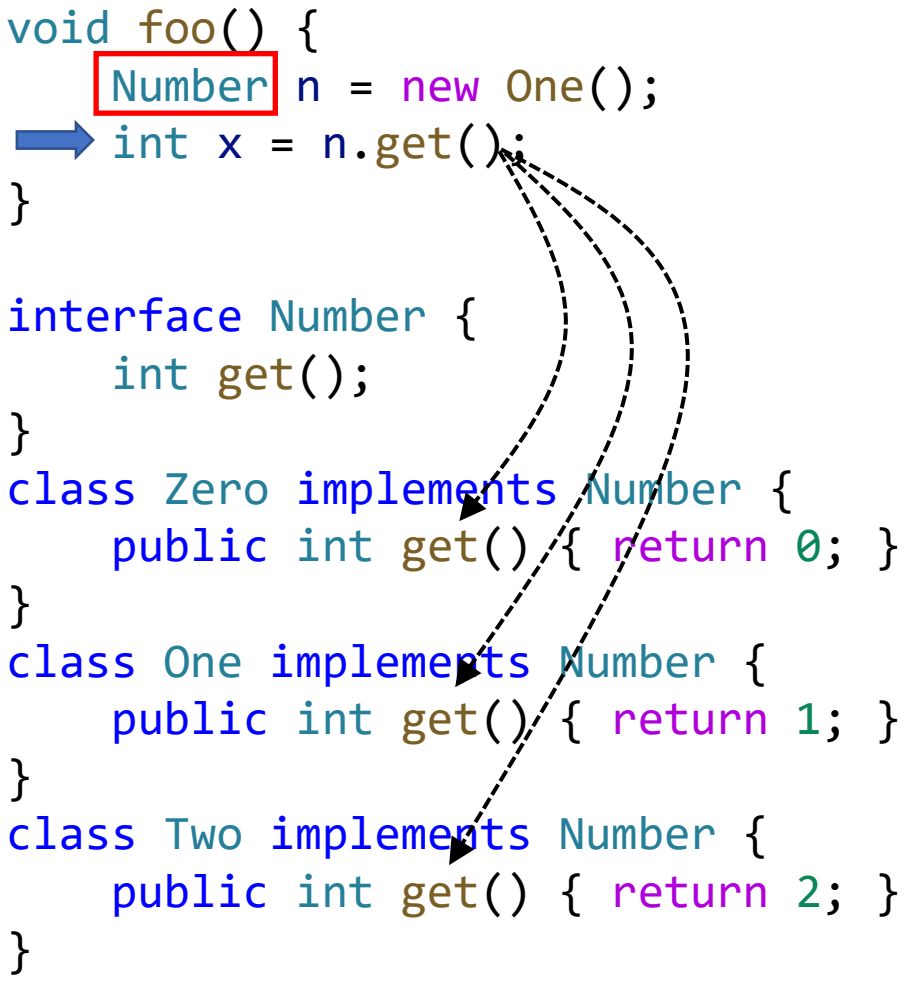
Constant propagation

- x = ?

Problem of CHA



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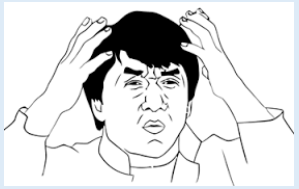
CHA: ~~based on~~ only considers **class hierarchy**

- 3 call targets
- 2 false positives



Constant propagation

- x = NAC imprecise

Via Pointer Analysis

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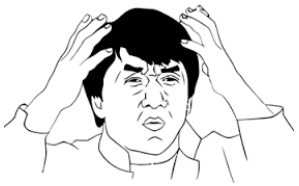

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Pointer analysis: based on **points-to relation**

- 1 call target

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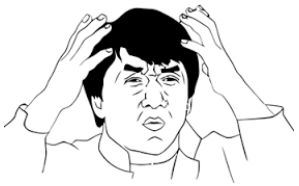

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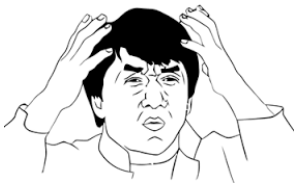

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Pointer analysis: based on **points-to relation**

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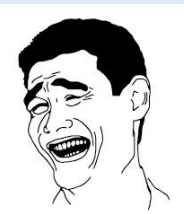

Constant propagation

- x = 1 precise

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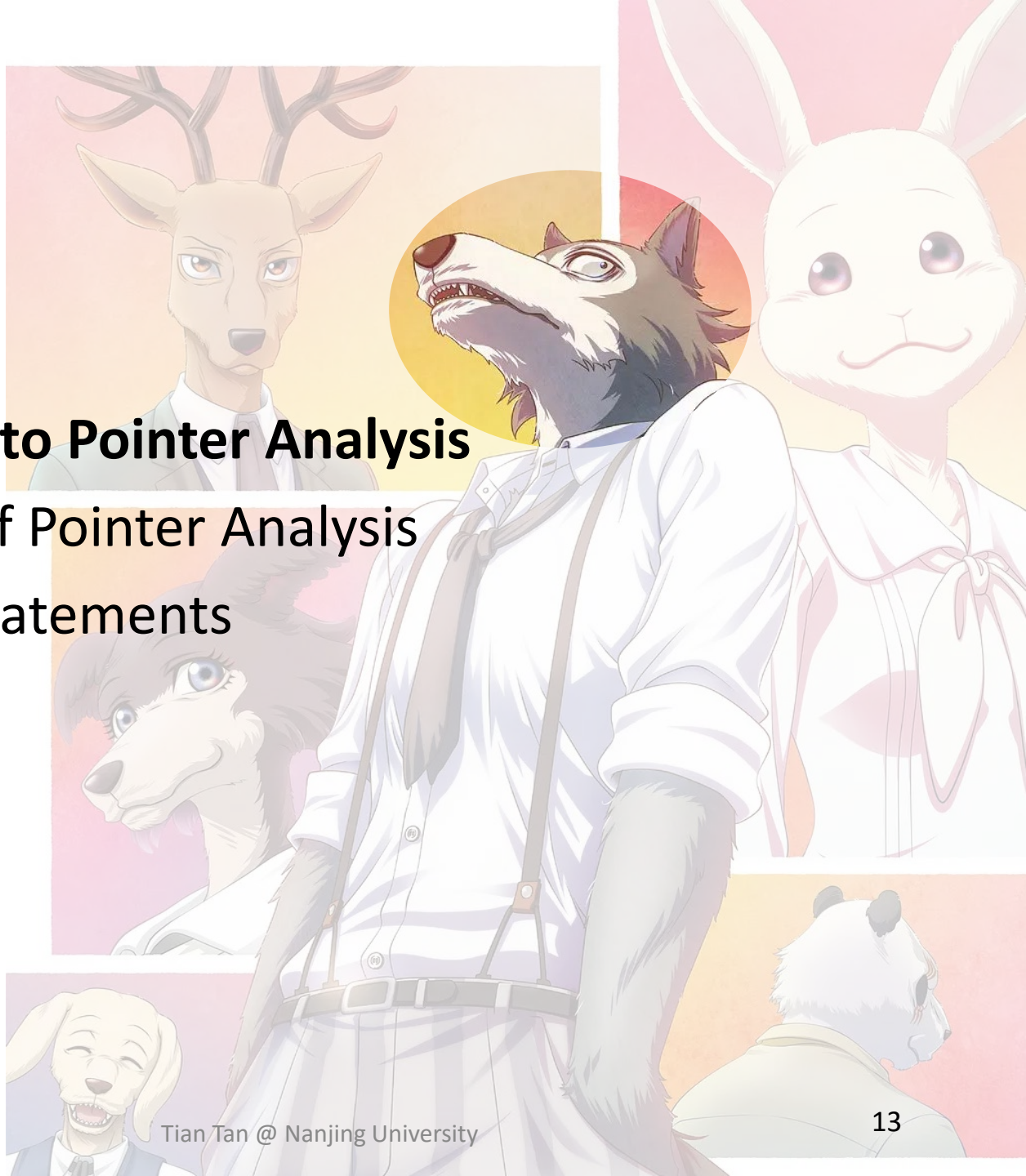

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A research area with 40+ years of history

- William E. Weihl, "*Interprocedural Data Flow Analysis in the Presence of Pointers, Procedure Variables, and Label Variables*". POPL 1980.

Still an active area today

- OOPSLA'18, FSE'18, TOPLAS'19, OOPSLA'19, TOPLAS'20, …

Example

"Which objects a pointer can point to?"

Program

Points-to relations

```
void foo() {
    A a = new A();
    B x = new B();
    a.setB(x);
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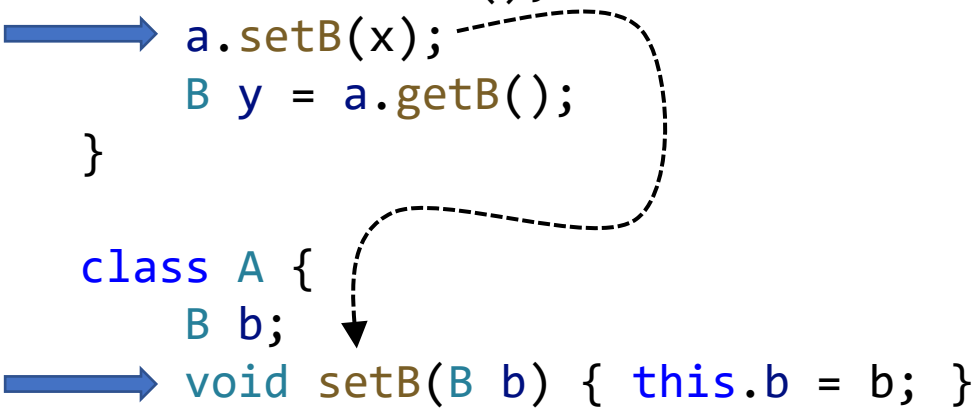

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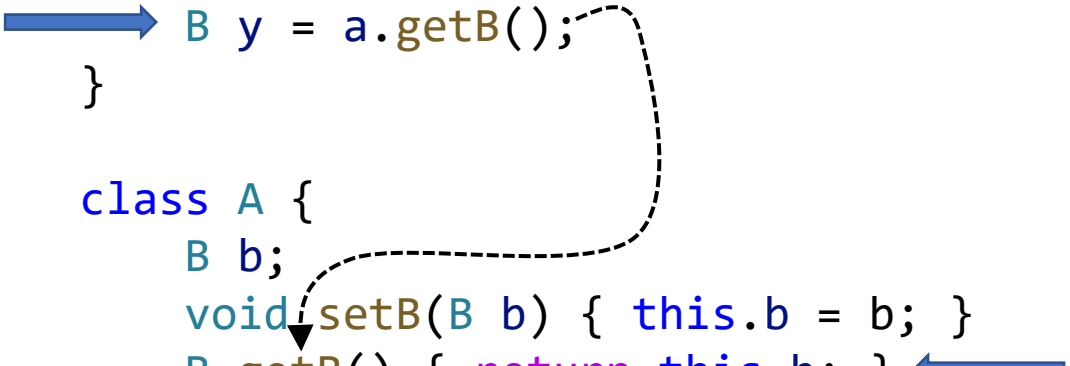

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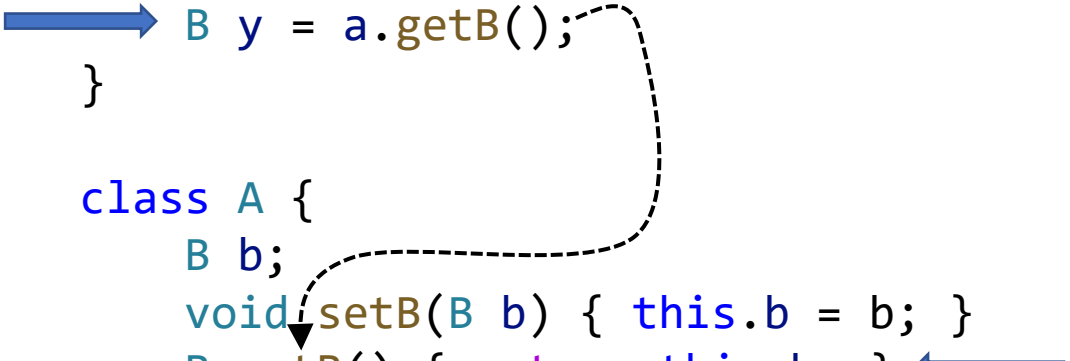

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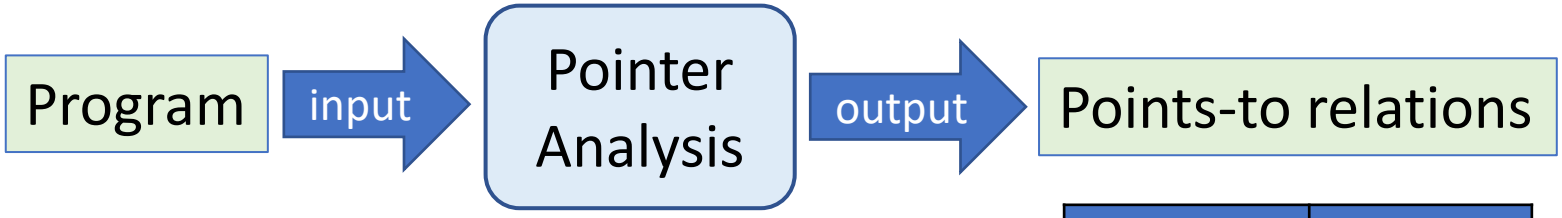


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Pointer Analysis and Alias Analysis

Two closely related but different concepts

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Alias information can be derived from points-to relations

Applications of Pointer Analysis

- Fundamental information
  - Call graph, aliases, …
- Compiler optimization
  - Virtual call inlining, …
- Bug detection
  - Null pointer detection, …
- Security analysis
  - Information flow analysis,
- And many more …

*"Pointer analysis is one of the **most fundamental** static program analyses, on which **virtually all others are built**."**

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*Pointer Analysis - Report from Dagstuhl Seminar 13162. 2013.

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- Multiple factors affect the precision and efficiency of the system

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Heap abstraction	How to model heap memory?	• Allocation-site • Storeless
Context sensitivity	How to model calling contexts?	• Context-sensitive • Context-insensitive
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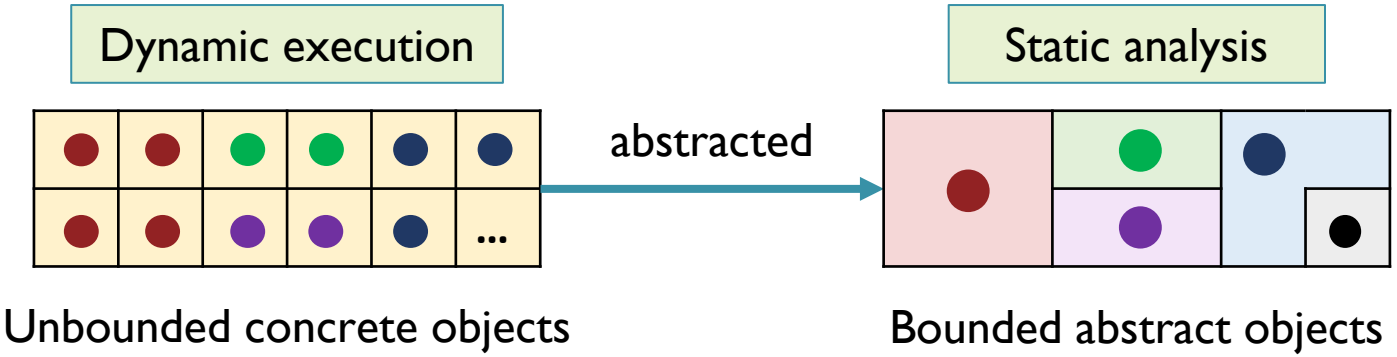

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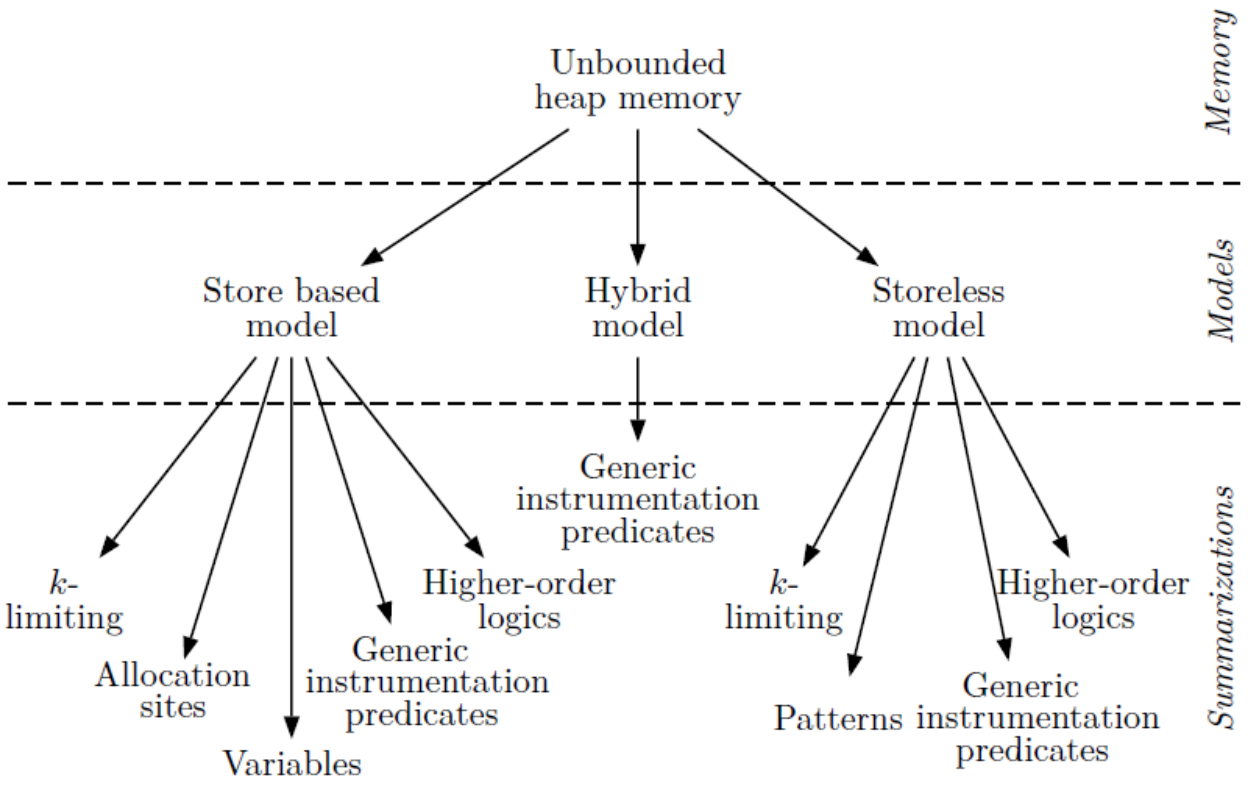

Figure 2. Heap memory can be modeled as storeless, store based, or hybrid. These models are summarized using allocation sites, k-limiting, patterns, variables, other generic instrumentation predicates, or higher-order logics.

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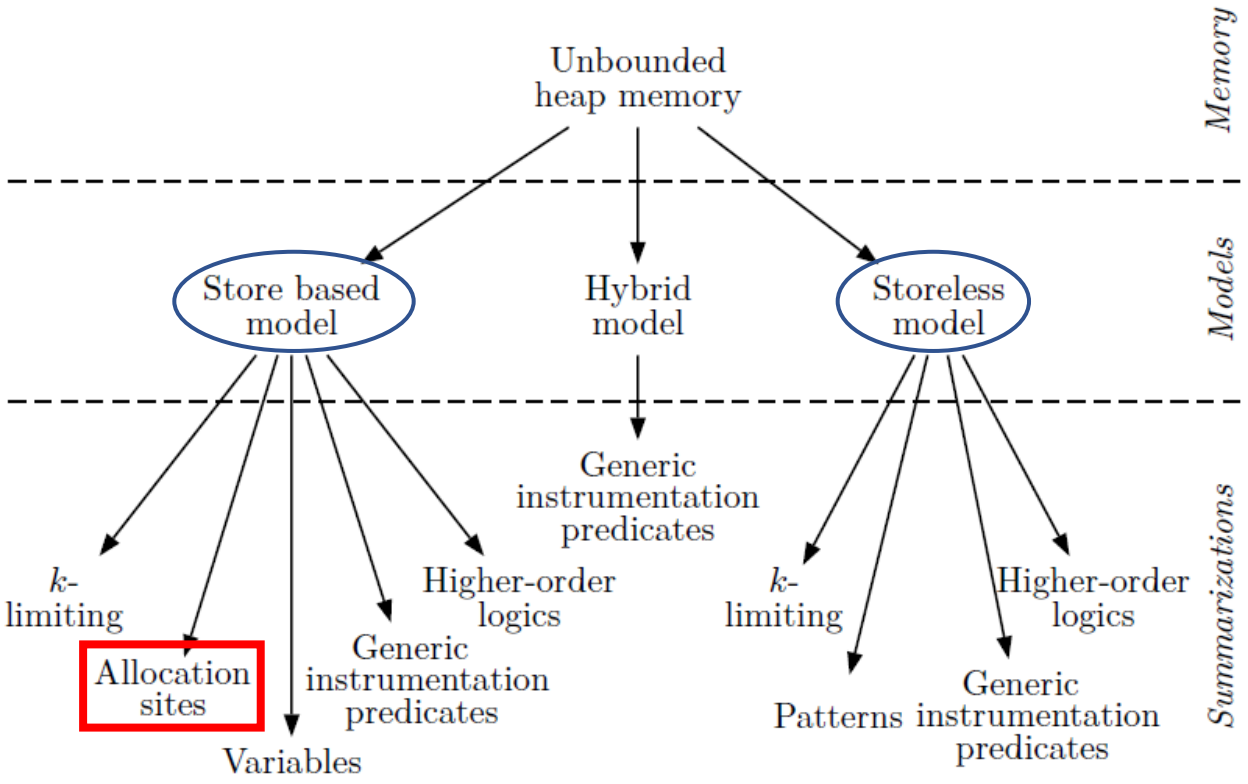

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The most commonly-used heap abstraction

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o_2, iteration `i = 0`
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Dynamic execution

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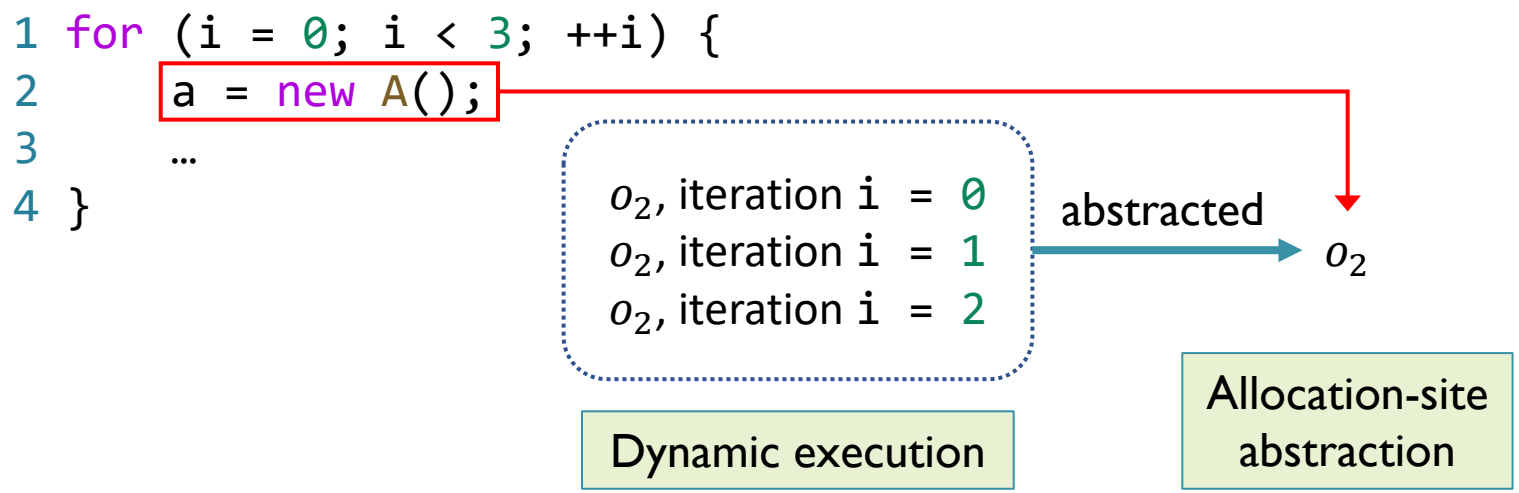

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o_2, iteration `i = 1`
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abstracted → o_2

Dynamic execution

Allocation-site abstraction

The number of allocation sites in a program is bounded, thus the abstract objects must be finite.

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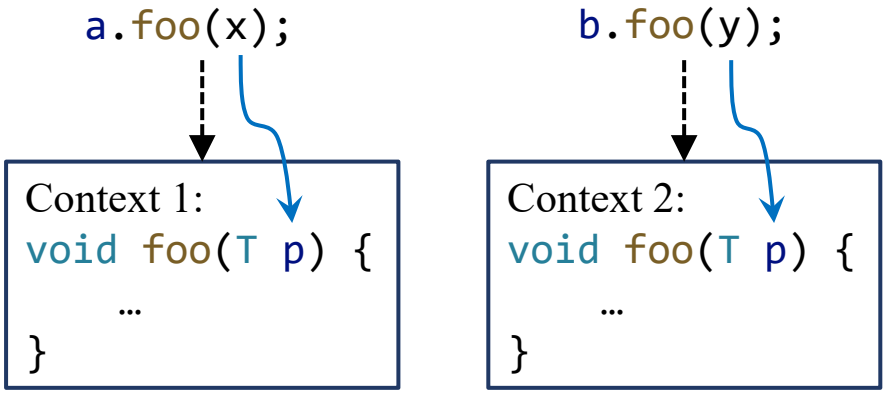

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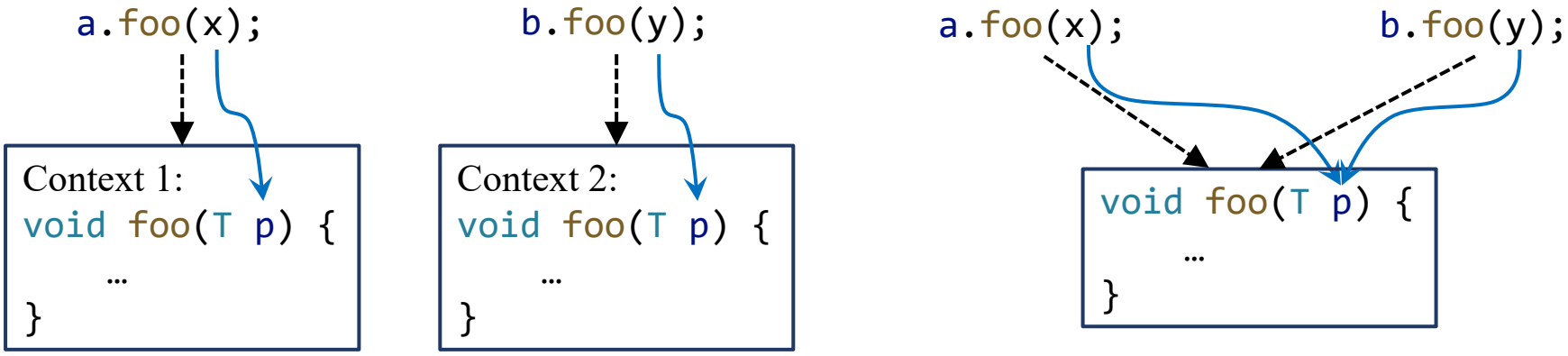

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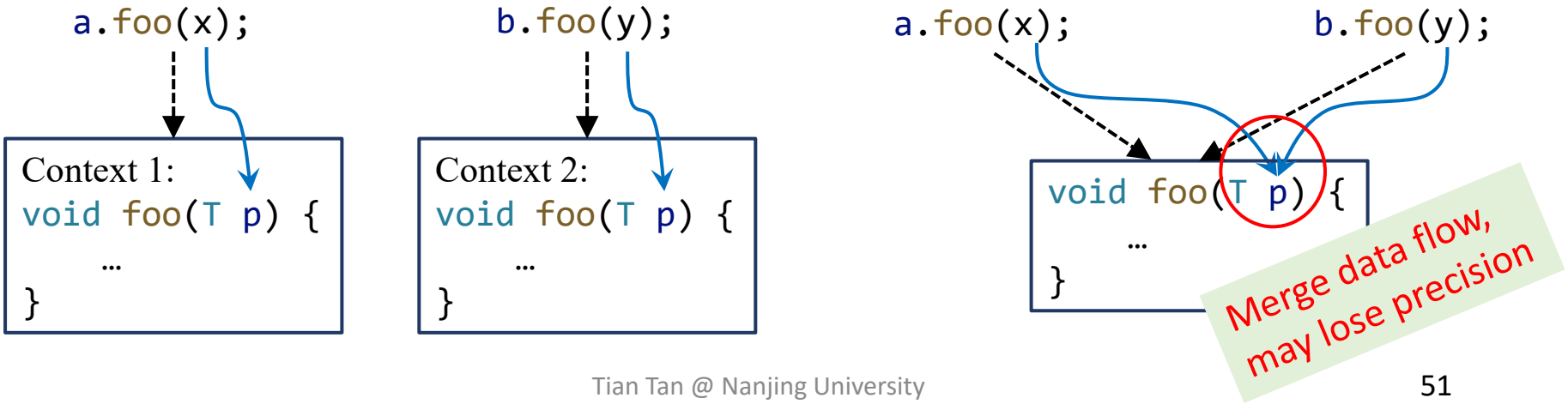

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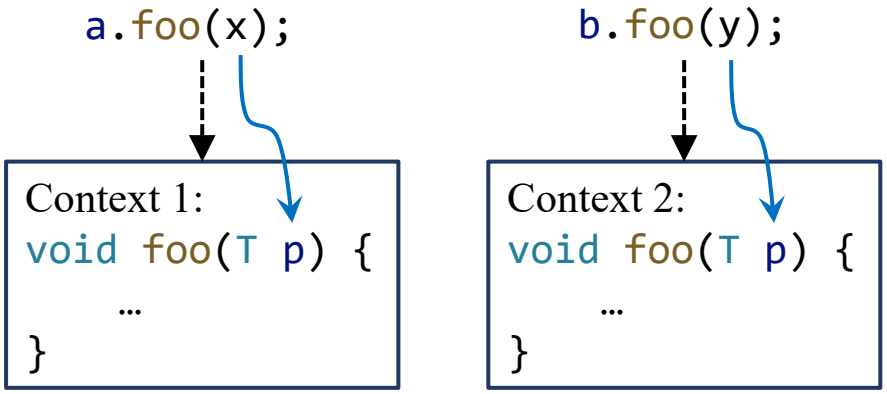
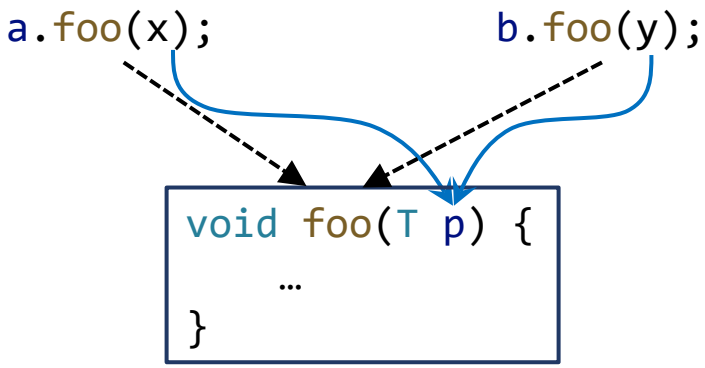
Very useful technique
Significantly improve precision
More details in **later lectures**

We start with **this**





Key Factors in Pointer Analysis

- Pointer analysis is a complex system
- Multiple factors affect the precision and efficiency of the system

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So far, all data-flow analyses we have learnt are flow-sensitive

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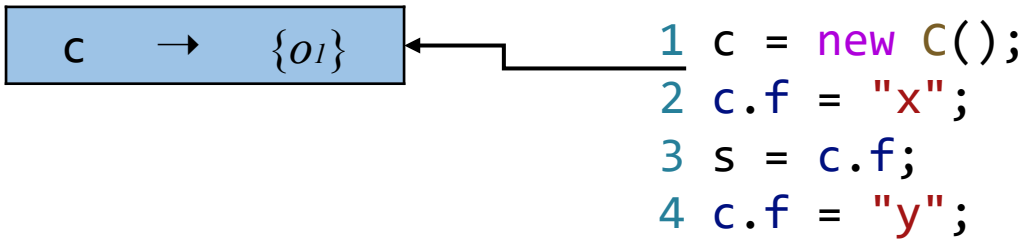

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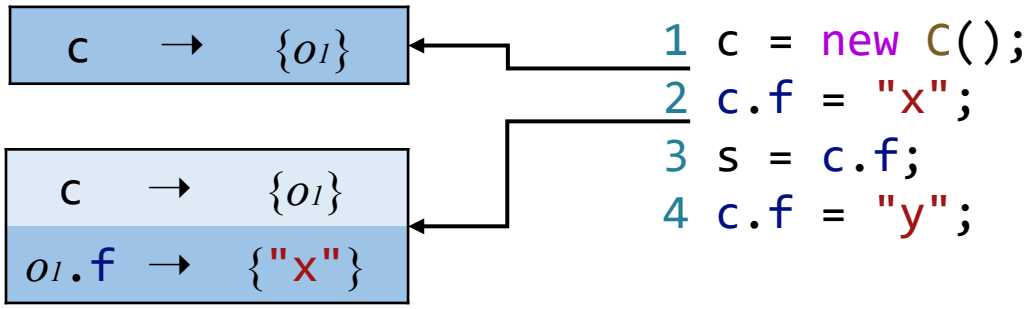

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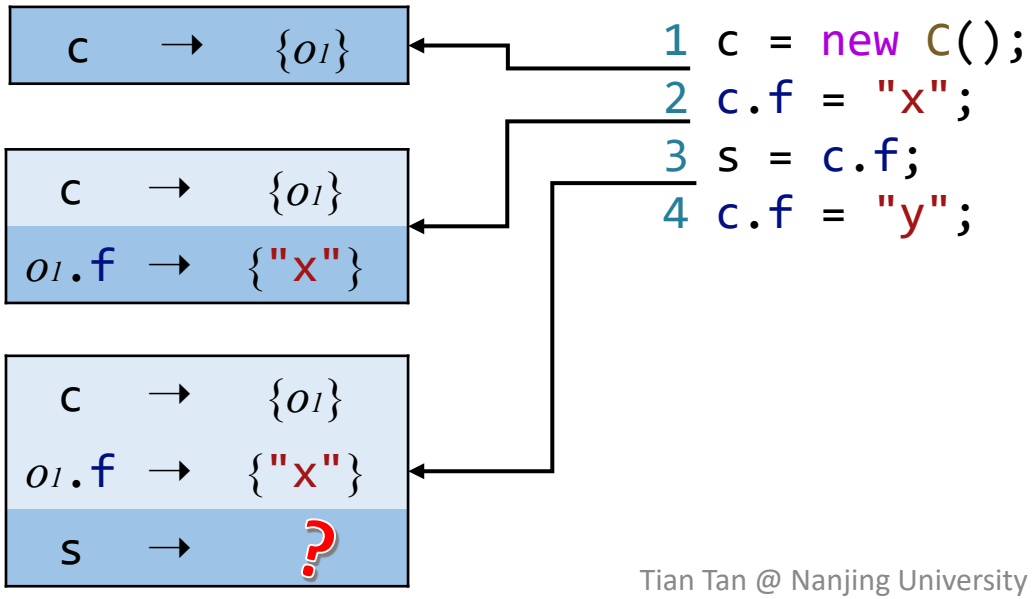

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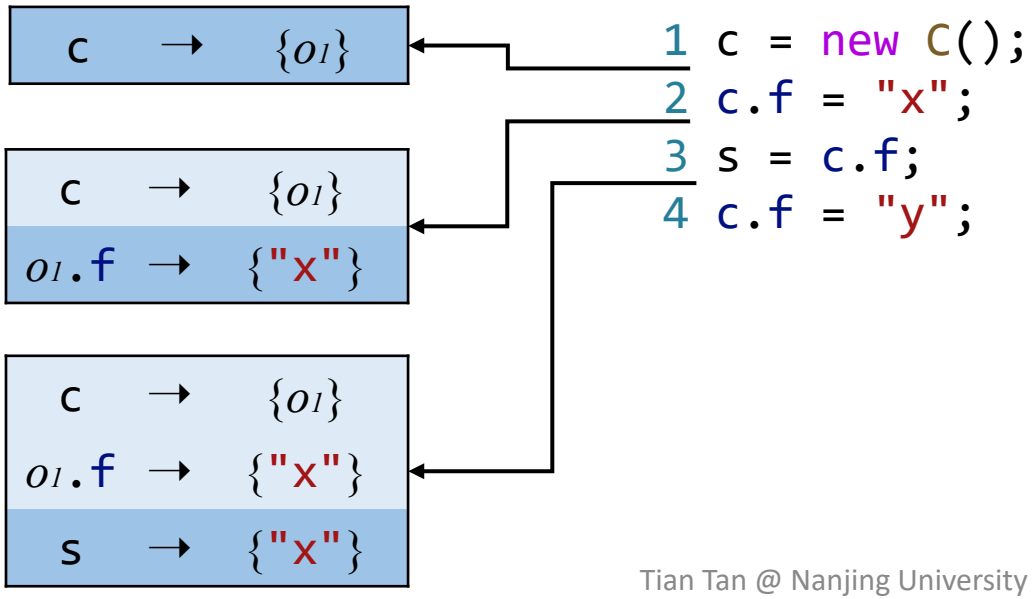

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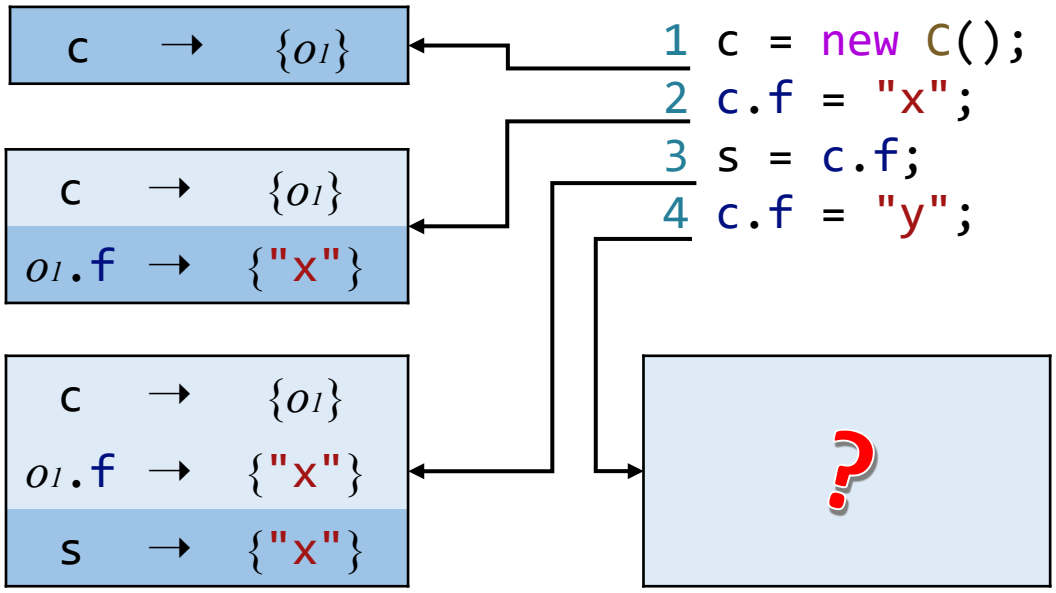

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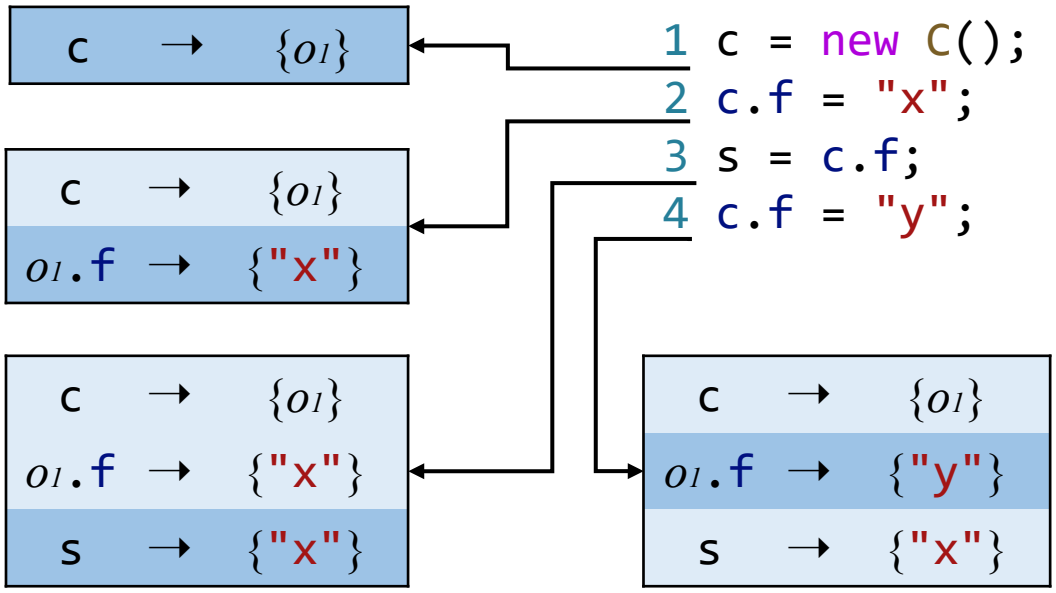

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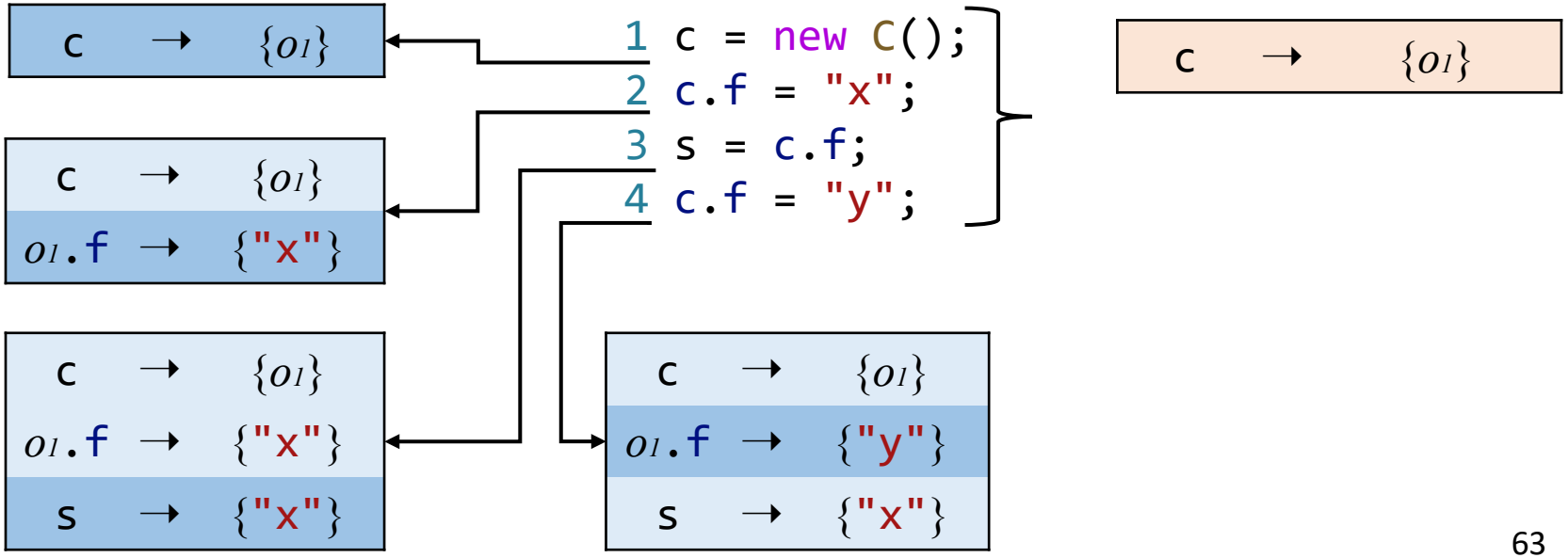

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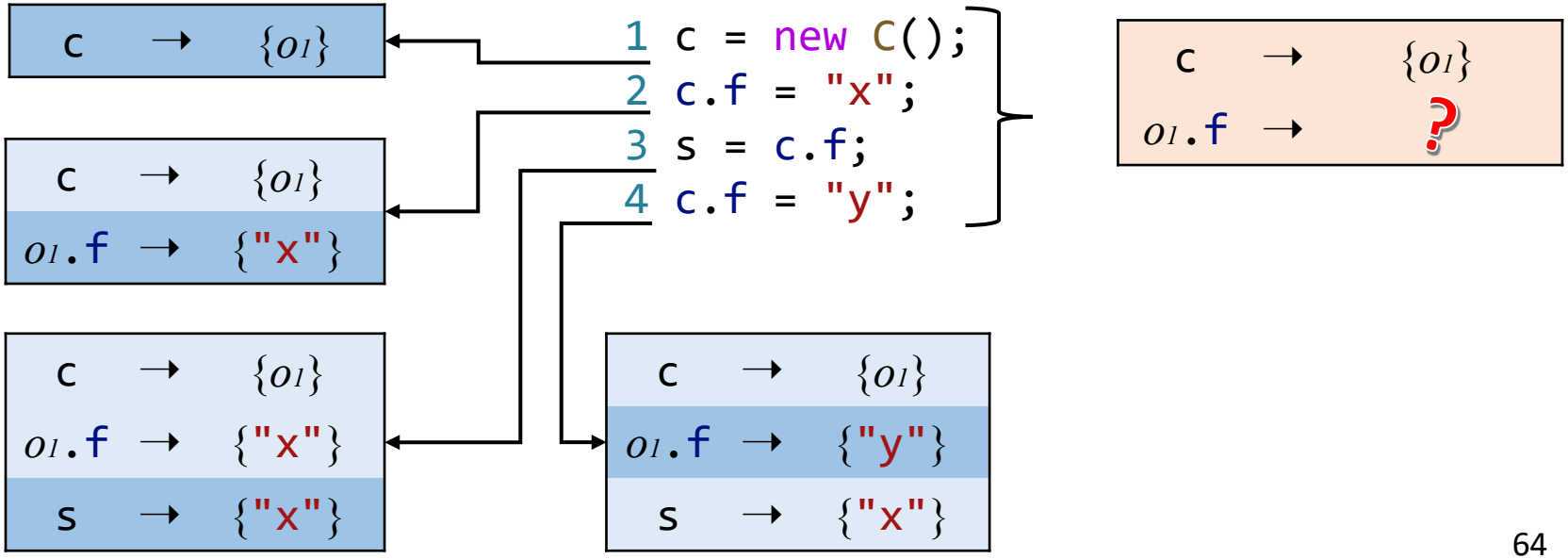

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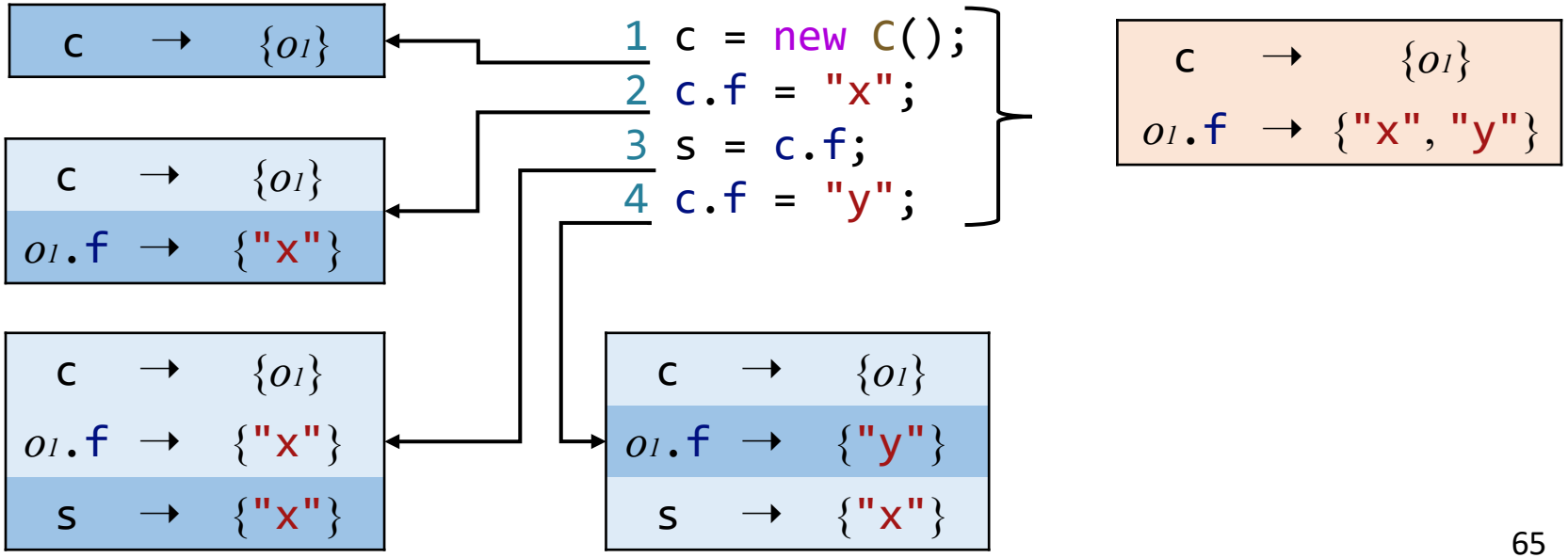

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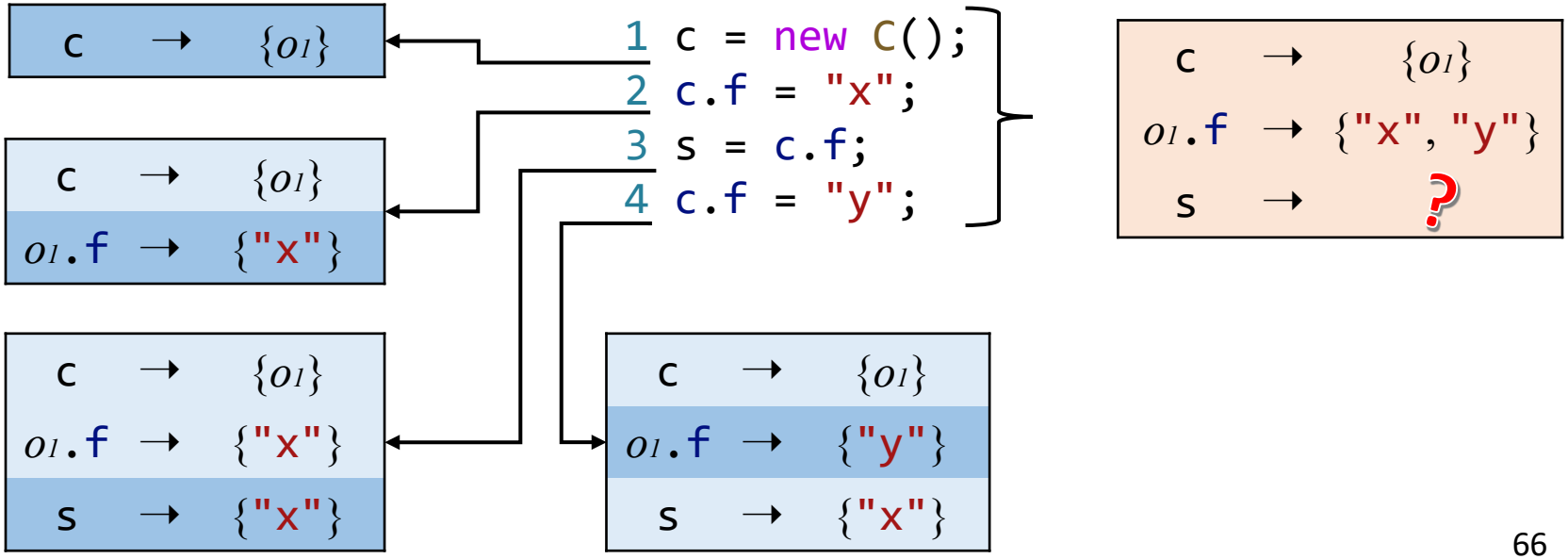

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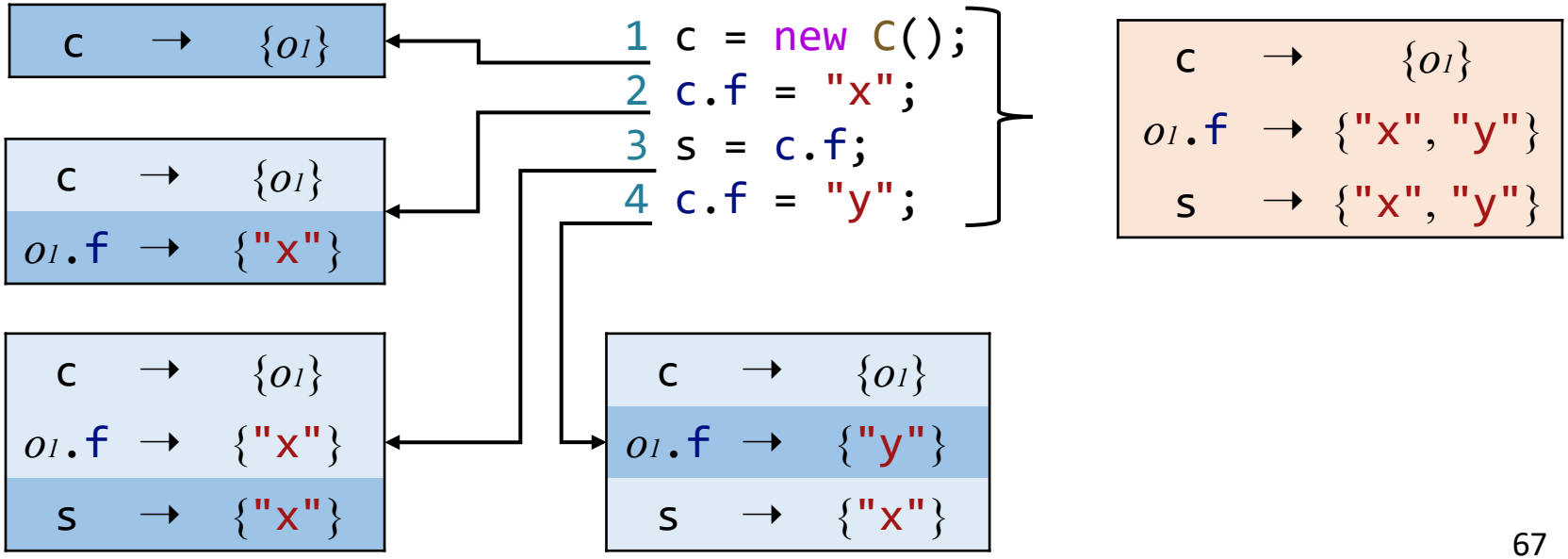

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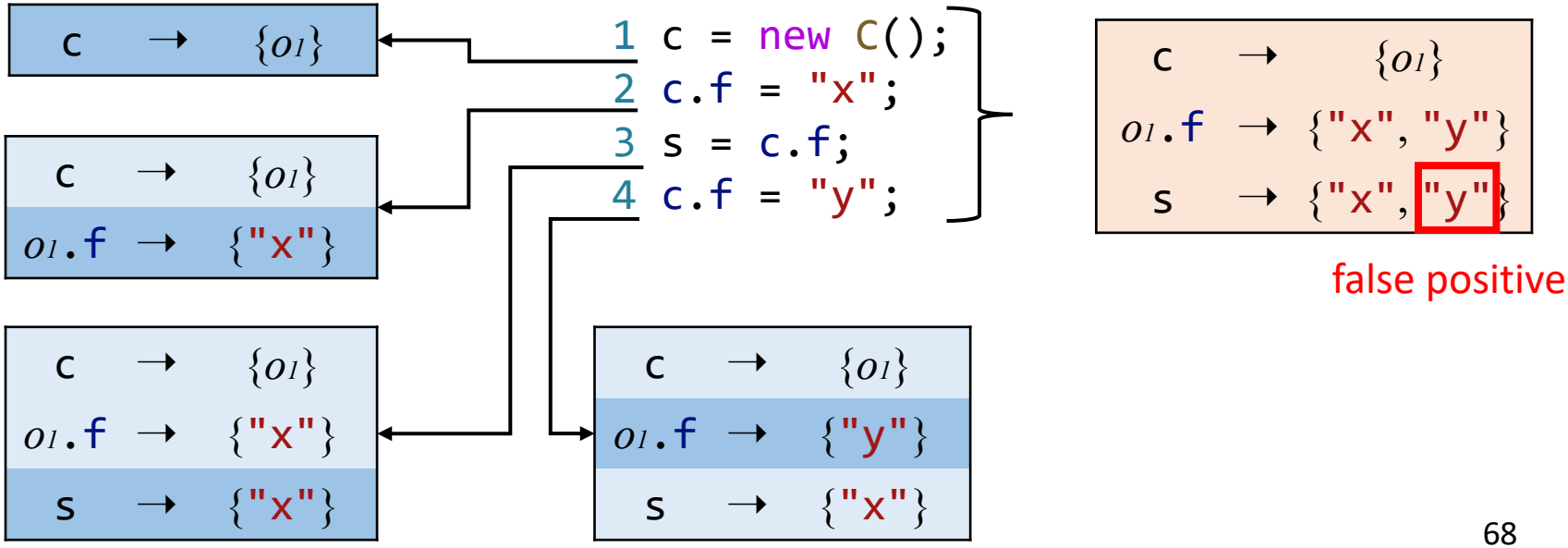

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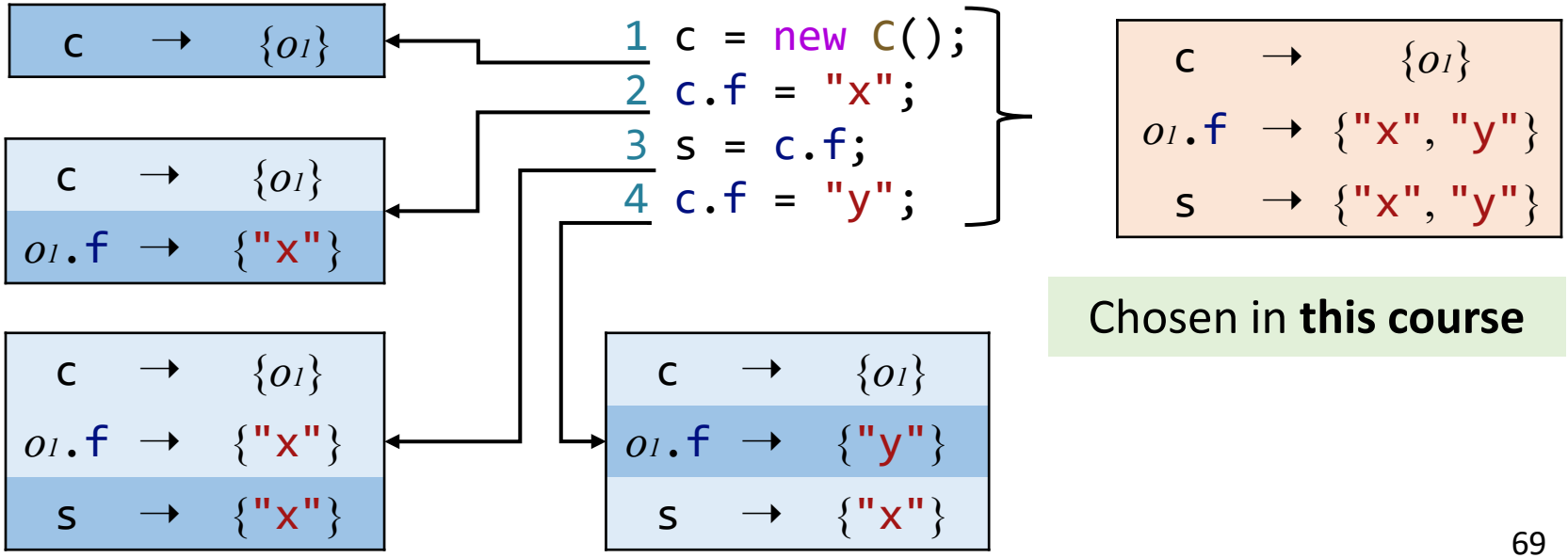

Chosen in **this course**

Key Factors in Pointer Analysis

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Which parts of program should be analyzed?

Whole-program	Demand-driven
Compute points-to information for all pointers in the program	Only compute points-to information for the pointers that may affect specific sites of interest (on demand)
Provide information for all possible clients	Provide information for specific clients

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2 y = x;
3 …
4 z = new T();
5 z.bar();
```

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What points-to information do we need ?

Client: call graph construction
Site of interest: line 5

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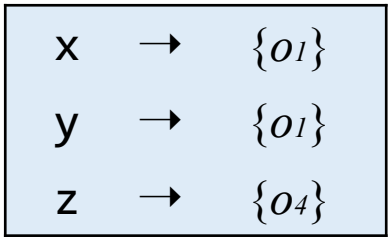


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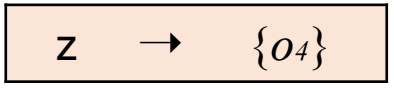

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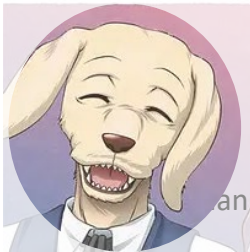
1. Motivation
2. Introduction to Pointer Analysis
3. Key Factors of Pointer Analysis
4. **Concerned Statements**



What Do We Analyze?

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  - if-else
  - switch-case
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What Do We Analyze?

- Modern languages typically have many kinds of statements
  - ~~if-else~~
  - ~~switch-case~~
  - ~~for/while/do-while~~
  - ~~break/continue~~
  - …
- We only focus on **pointer-affecting statements**

Do not directly affect pointers
Ignored in pointer analysis

Pointers in Java

- Local variable: `x`
- Static field: `C.f`
- Instance field: `x.f`
- Array element: `array[i]`

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Sometimes referred as global variable

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Modeled as an object (pointed by x) with a field `f`

- Array element: `array[i]`

Pointers in Java

- Local variable: `x`
- Static field: `C.f`
- Instance field: `x.f`
- Array element: `array[i]`

Ignore indexes. Modeled as an object (pointed by `array`) with a single field, say `arr`, which may point to any value stored in `array`

```
array = new String[10];
array[0] = "x";
array[1] = "y";
s = array[0];
```

Real code

```
array = new String[];
array.arr = "x";
array.arr = "y";
s = array.arr;
```

Perspective of pointer analysis

Pointers in Java

- Local variable: `x`
- Static field: `C.f`
- Instance field: `x.f`
- Array element: `array[i]`

Pointer-Affecting Statements

New	`x = new T()`
Assign	`x = y`
Store	`x.f = y`
Load	`y = x.f`
Call	`r = x.k(a, …)`

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Complex memory-accesses will be converted to three-address code by introducing temporary variables

```
x.f.g.h = y;
```

```
t1 = x.f
t2 = t1.g
t2.h = y;
```

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The X You Need To Understand in This Lecture

- What is pointer analysis?
- Understand the key factors of pointer analysis
- Understand what we analyze in pointer analysis

Static Program Analysis

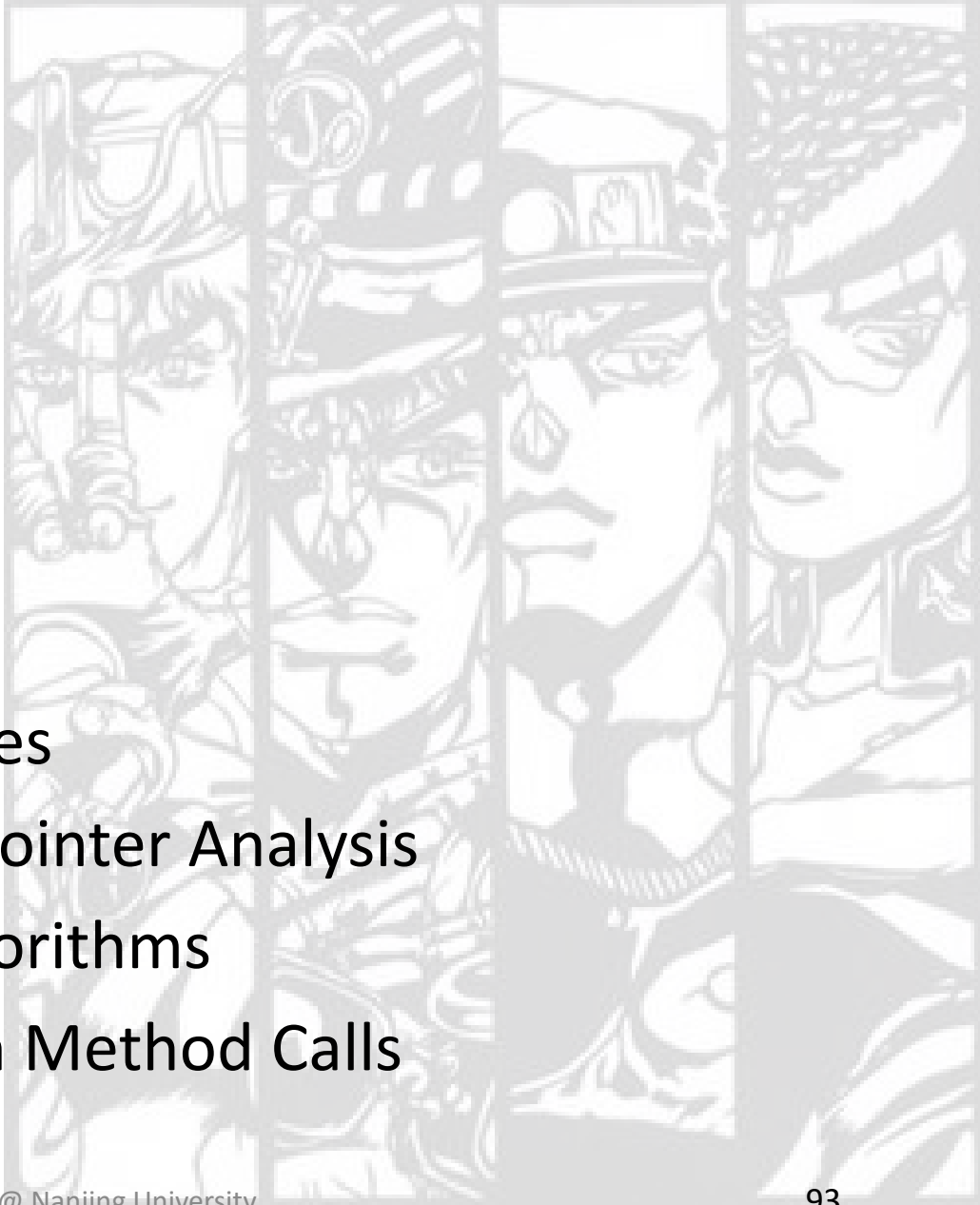
Pointer Analysis Foundations (I)

Nanjing University

Tian Tan

2020

Contents



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2. How to Implement Pointer Analysis
3. Pointer Analysis: Algorithms
4. Pointer Analysis with Method Calls

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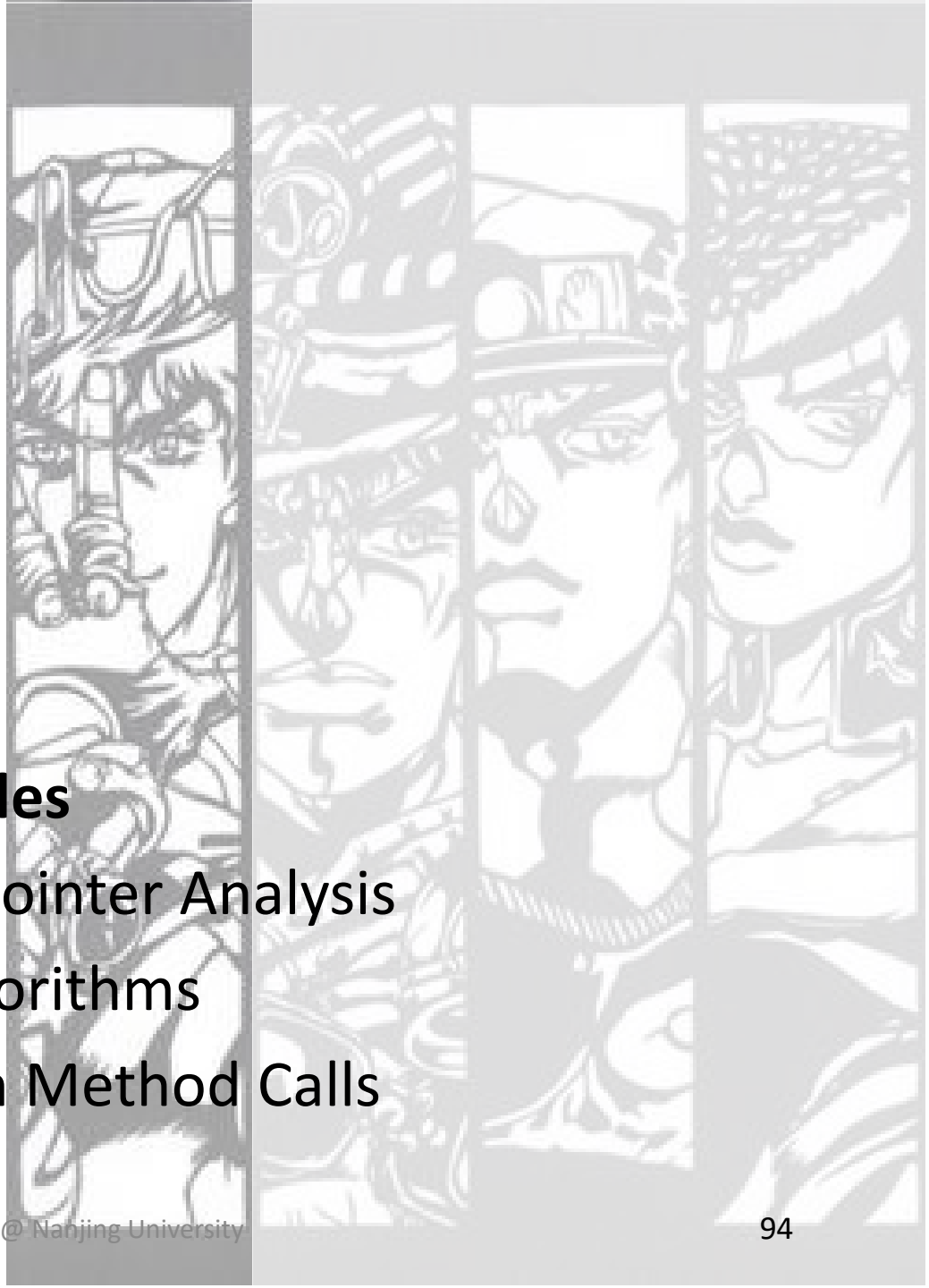

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Pointer-Affecting Statements

New	`x = new T()`
Assign	`x = y`
Store	`x.f = y`
Load	`y = x.f`
Call	`r = x.k(a, …)`

First focus on these statements
(suppose the program has just one method)

Will come back to this in
pointer analysis with method calls

Domain and Notations

Variables:	$x, y \in \mathrm{V}$
Fields:	$f, g \in \mathrm{F}$
Objects:	$o_i, o_j \in \mathrm{O}$
Instance fields:	$o_i.f, o_j.g \in \mathrm{O} \times \mathrm{F}$
Pointers:	$\mathrm{Pointer} = \mathrm{V} \cup (\mathrm{O} \times \mathrm{F})$
Points-to relations:	$pt : \mathrm{Pointer} \rightarrow \mathcal{P}(\mathrm{O})$

- $\mathcal{P}(\mathrm{O})$ denotes the powerset of O
- $pt(p)$ denotes the points-to set of p

Rules

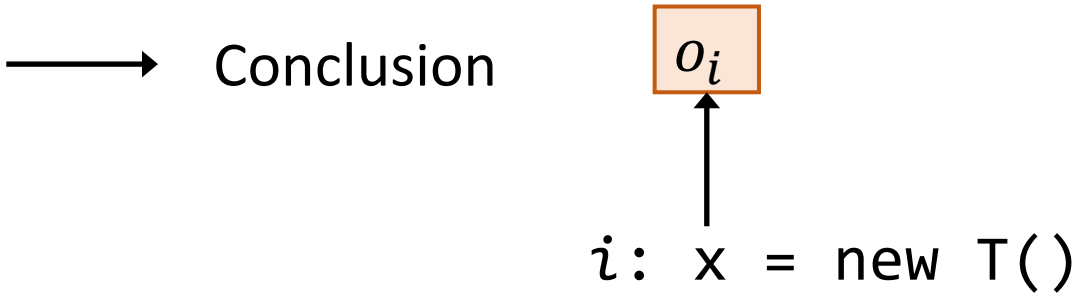
Kind	Statement	Rule
New	`i: x = new T()`	$\dfrac{}{o_i \in pt(x)}$
Assign	`x = y`	$\dfrac{o_i \in pt(y)}{o_i \in pt(x)}$
Store	`x.f = y`	$\dfrac{o_i \in pt(x),\ o_j \in pt(y)}{o_j \in pt(o_i.f)}$
Load	`y = x.f`	$\dfrac{o_i \in pt(x),\ o_j \in pt(o_i.f)}{o_j \in pt(y)}$

Rules

Kind	Statement	Rule
New	`i: x = new T()`	$\dfrac{}{o_i \in pt(x)}$ ← unconditional
Assign	`x = y`	$\dfrac{o_i \in pt(y)}{o_i \in pt(x)}$ ← premises ← conclusion
Store	`x.f = y`	$\dfrac{o_i \in pt(x),\ o_j \in pt(y)}{o_j \in pt(o_i.f)}$
Load	`y = x.f`	$\dfrac{o_i \in pt(x),\ o_j \in pt(o_i.f)}{o_j \in pt(y)}$

Rule: New

$$\frac{}{o_i \in pt(x)}$$

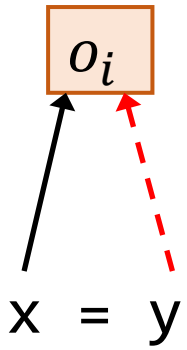


Rule: Assign

$$\frac{o_i \in pt(y)}{o_i \in pt(x)}$$

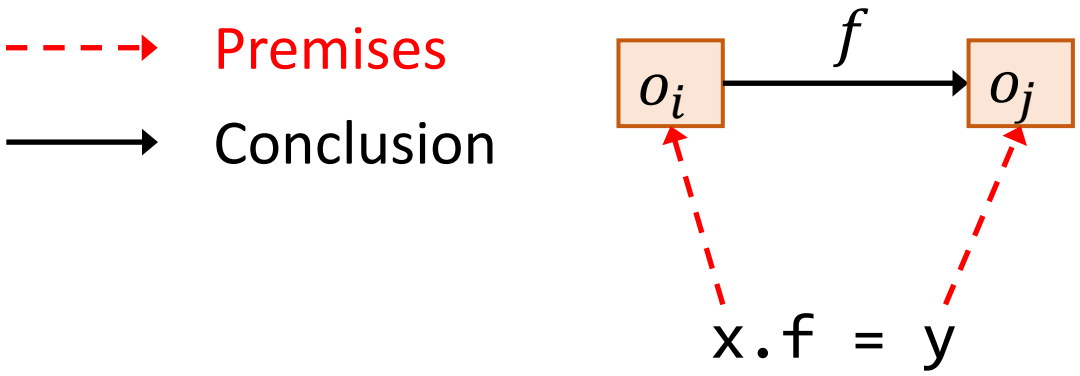
Premises

Conclusion



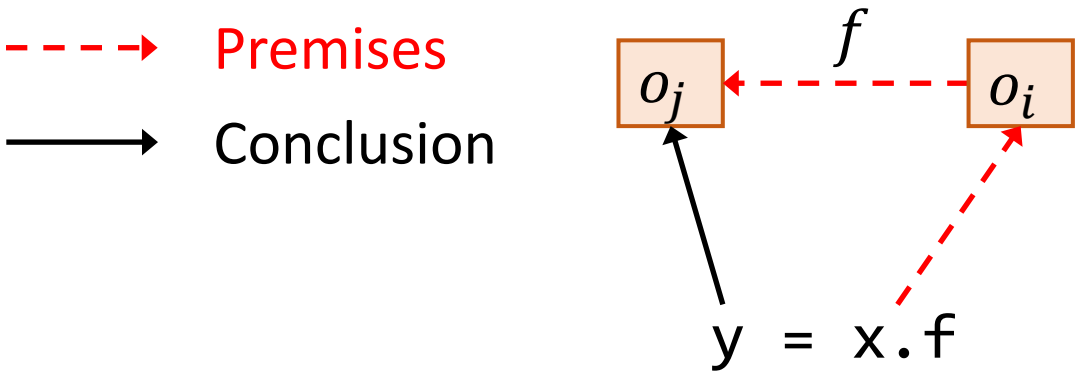
Rule: Store

$$\frac{o_i \in pt(x),\ o_j \in pt(y)}{o_j \in pt(o_i.f)}$$



Rule: Load

$$\frac{o_i \in pt(x),\ o_j \in pt(o_i.f)}{o_j \in pt(y)}$$



Rules

Premises

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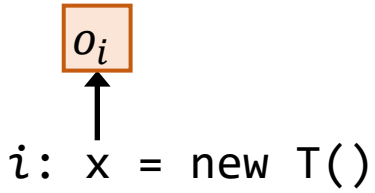
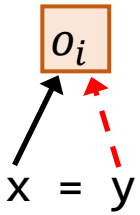
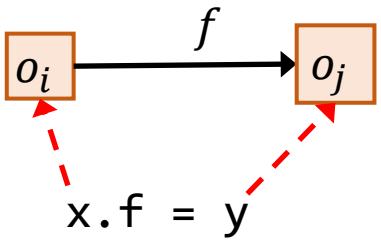
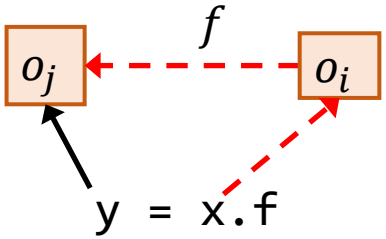
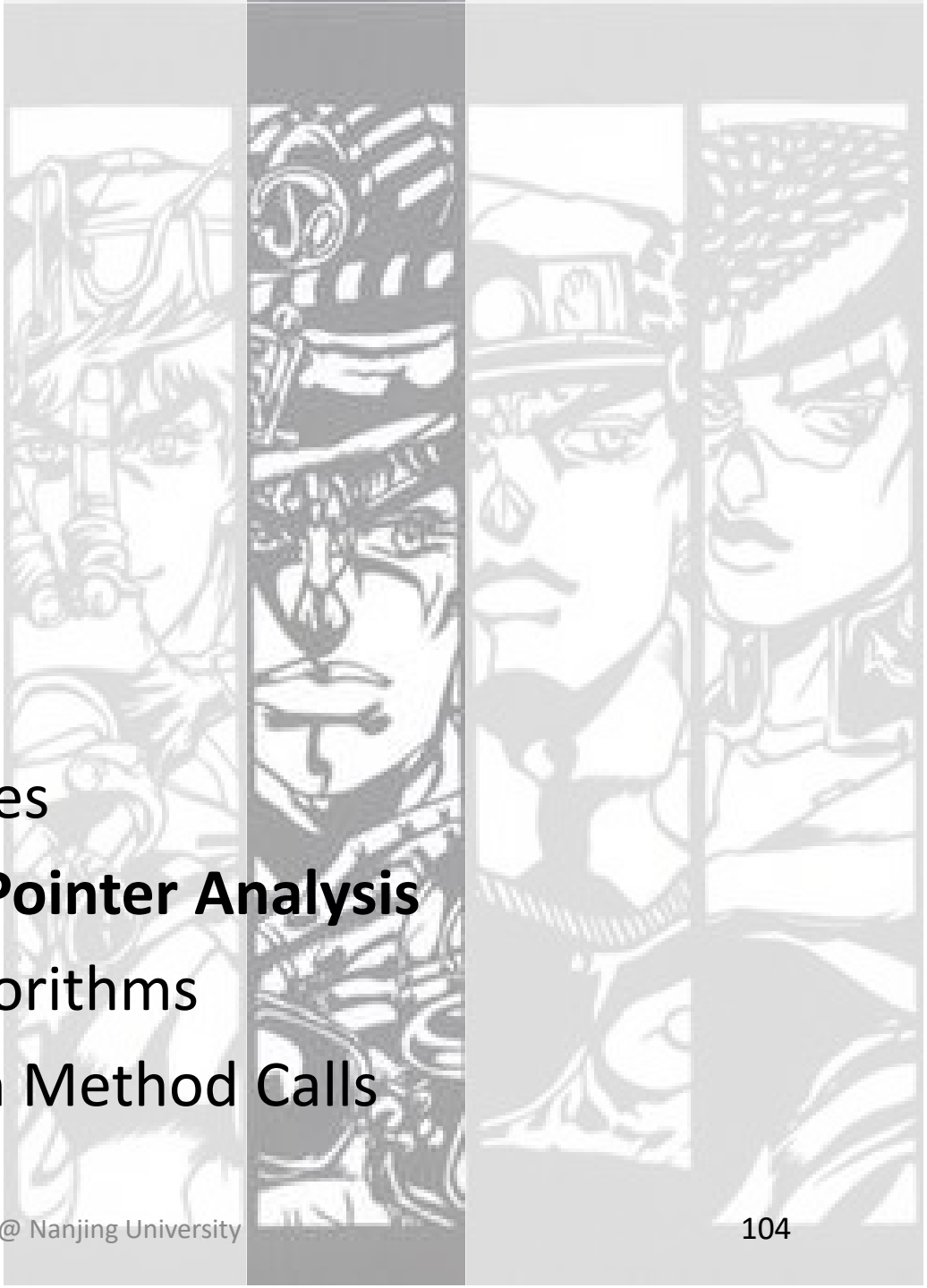
New	$\dfrac{}{o_i \in pt(x)}$	
Assign	$\dfrac{o_i \in pt(y)}{o_i \in pt(x)}$	
Store	$\dfrac{o_i \in pt(x),\ o_j \in pt(y)}{o_j \in pt(o_i.f)}$	
Load	$\dfrac{o_i \in pt(x),\ o_j \in pt(o_i.f)}{o_j \in pt(y)}$	

Contents



1. Pointer Analysis: Rules
2. **How to Implement Pointer Analysis**
3. Pointer Analysis: Algorithms
4. Pointer Analysis with Method Calls

Our Pointer Analysis Algorithms

- A complete whole-program pointer analysis
- Carefully designed for understandability
- Easy to follow and implement

How to Implement Pointer Analysis?

- Essentially, pointer analysis is to **propagate** points-to information among pointers (variables & fields)

Kind	Statement	Rule
New	`i: x = new T()`	$\dfrac{}{o_i \in pt(x)}$
Assign	`x = y`	$\dfrac{o_i \in pt(\boldsymbol{y})}{o_i \in pt(\boldsymbol{x})}$
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Pointer analysis as solving a system of inclusion constraints for pointers

Referred as *Andersen-style analysis**

∗ Lars Ole Andersen, 1994. "*Program Analysis and Specialization for the C Programming Language*". Ph.D. Thesis. University of Copenhagen.

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Solution

- We use a **graph** to connect related pointers
- When $pt(x)$ changes, propagate the changed part to x's **successors**

Key to implementation: when $pt(x)$ is **changed**, **propagate** the **changed part** to the **related pointers** of x

Pointer Flow Graph (PFG)

Pointer flow graph of a program is a *directed graph* that expresses how objects flow among the pointers in the program.

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- Nodes: $\text{Pointer} = \text{V} \cup (\text{O} \times \text{F})$

  A node n represents *a variable* or *a field of an abstract object*

- Edges: $\text{Pointer} \times \text{Pointer}$

  An edge $x \rightarrow y$ means that the objects pointed by pointer x *may flow to* (and also be pointed to by) pointer y

Pointer Flow Graph: Edges

- PFG edges are added according to the statements of the program and the corresponding rules

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New	`i: x = new T()`	$\overline{o_i \in pt(x)}$
Assign	`x = y`	$\dfrac{o_i \in pt(\boldsymbol{y})}{o_i \in pt(\boldsymbol{x})}$
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Pointer Flow Graph: Edges

- PFG edges are added according to the statements of the program and the corresponding rules

Kind	Statement	Rule	PFG Edge
New	`i: x = new T()`	$\overline{o_i \in pt(x)}$	N/A
Assign	`x = y`	$\dfrac{o_i \in pt(\boldsymbol{y})}{o_i \in pt(\boldsymbol{x})}$	$x \leftarrow y$
Store	`x.f = y`	$\dfrac{o_i \in pt(x),\ o_j \in pt(\boldsymbol{y})}{o_j \in pt(\boldsymbol{o_i.f})}$	$o_i.f \leftarrow y$
Load	`y = x.f`	$\dfrac{o_i \in pt(x),\ o_j \in pt(\boldsymbol{o_i.f})}{o_j \in pt(\boldsymbol{y})}$	$y \leftarrow o_i.f$

Pointer Flow Graph: An Example

Program

$(o_i \in pt(c), o_i \in pt(d))$

```
a = b;     ①
c.f = a;   ②
d = c;     ③
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e = d.f;   ⑤
```

Pointer flow graph

- Variable node 

- Instance field node 

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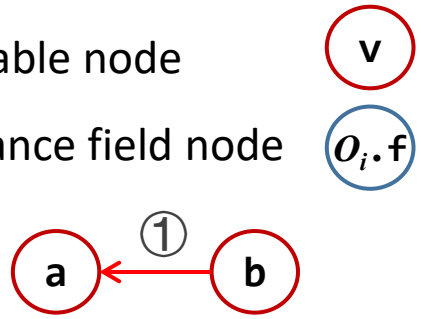

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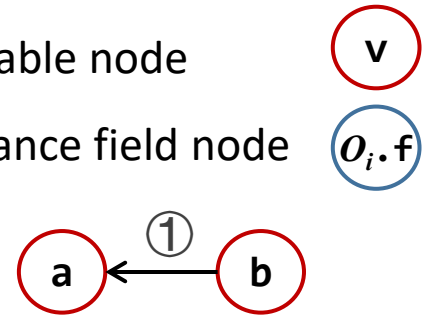

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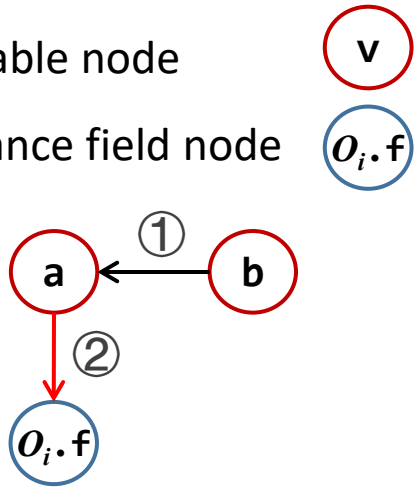

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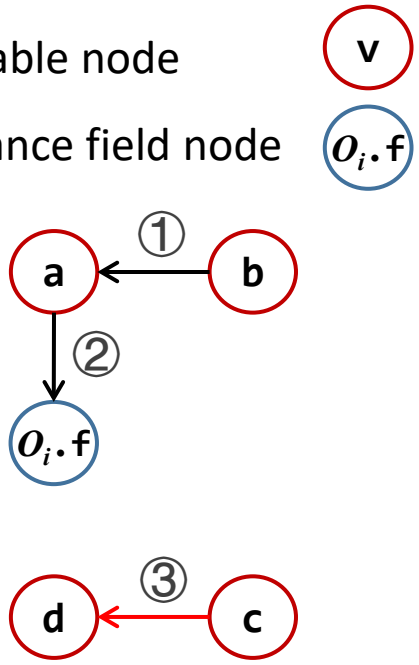

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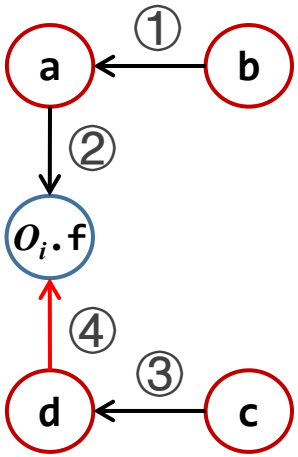
Pointer flow graph

- Variable node **v**
- Instance field node $o_i.f$



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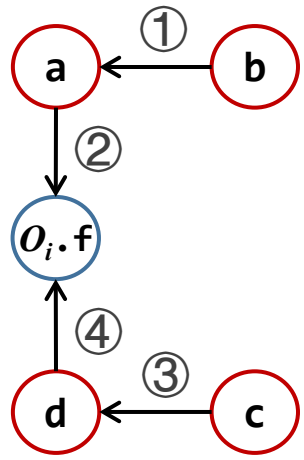

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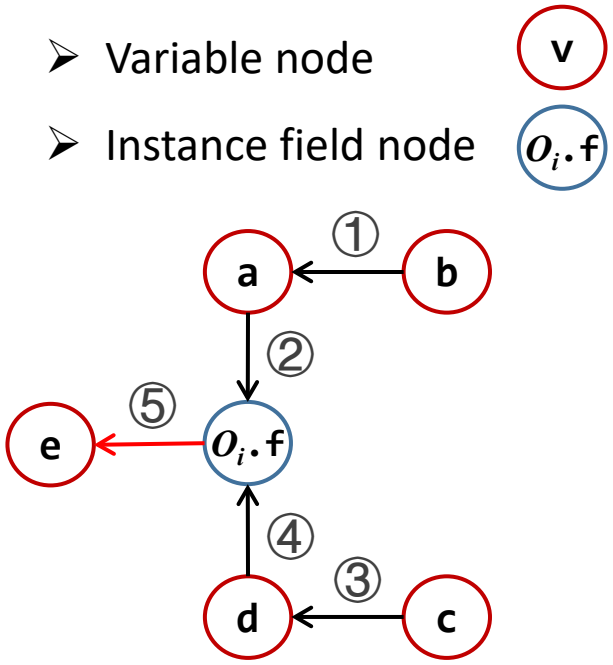

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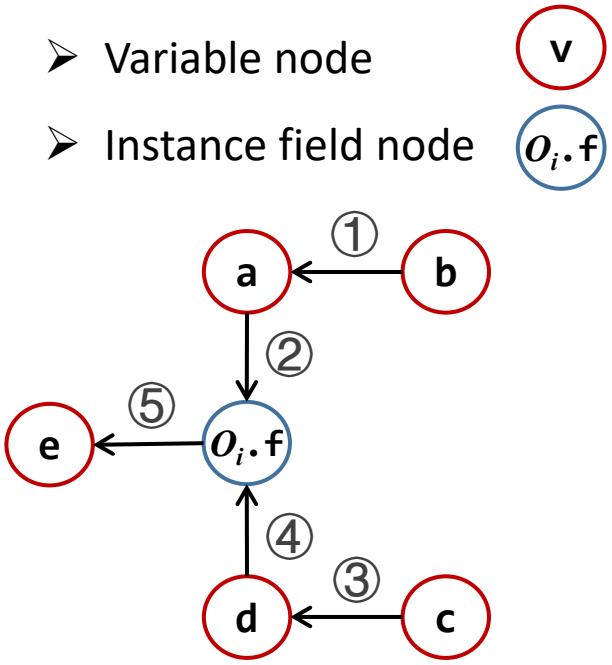

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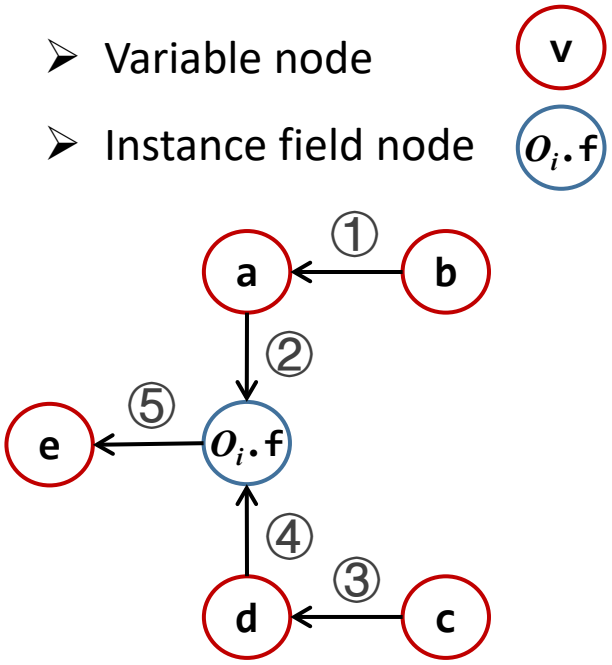

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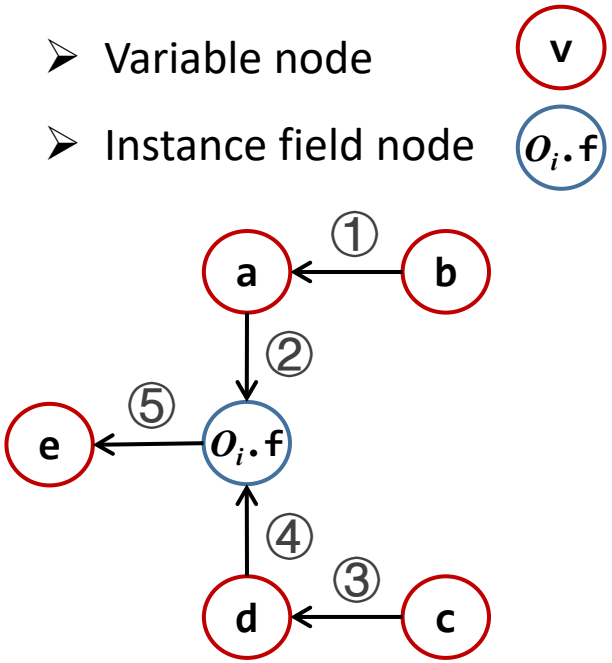

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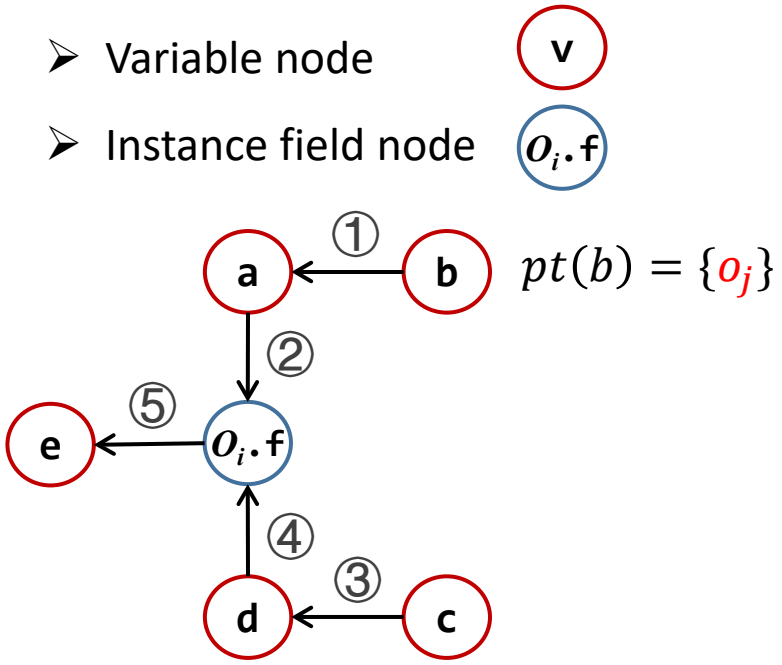

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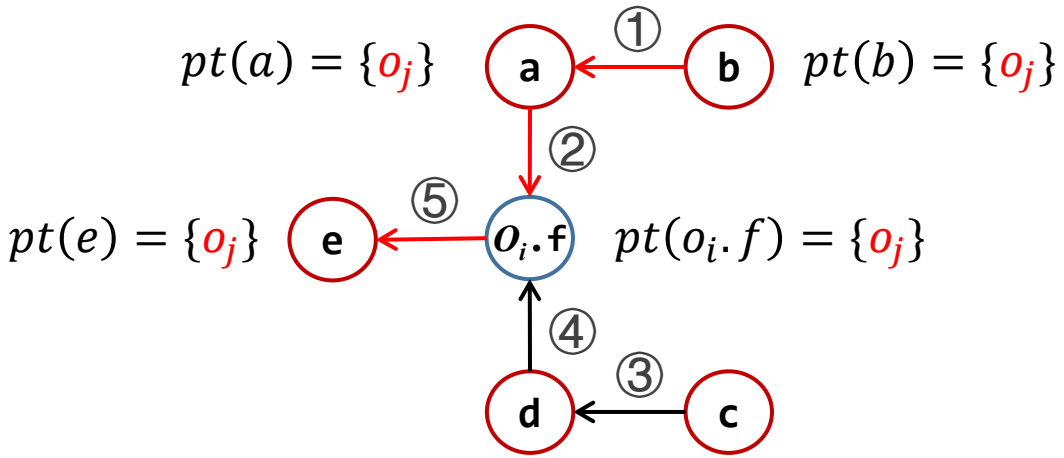

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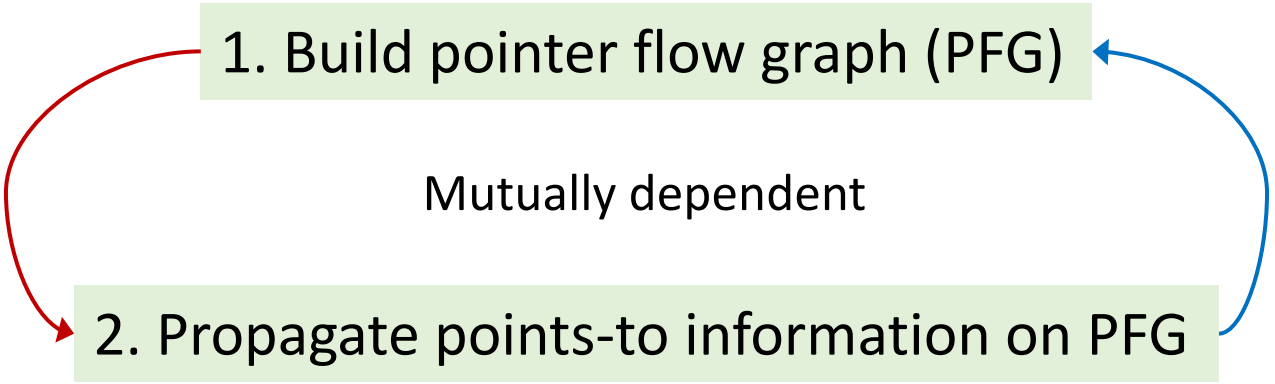
Implementing Pointer Analysis

1. Build pointer flow graph (PFG)

2. Propagate points-to information on PFG

Implementing Pointer Analysis



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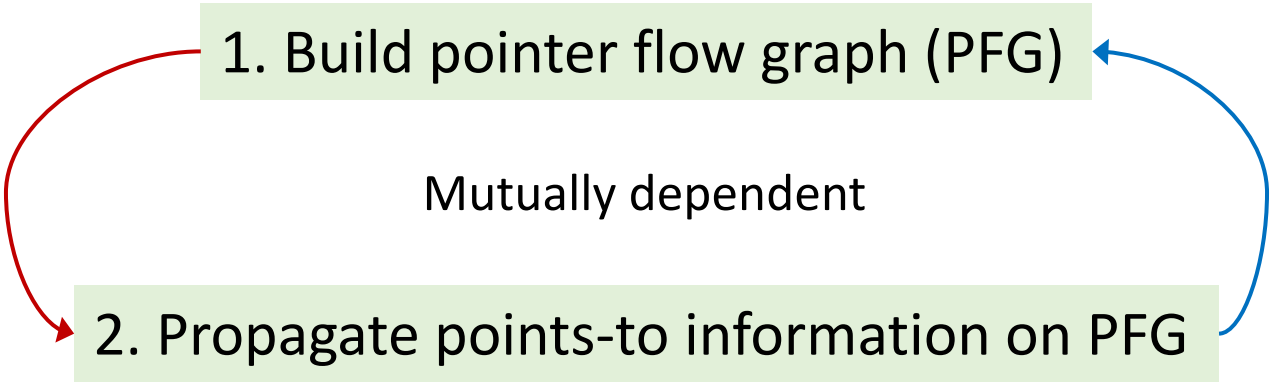

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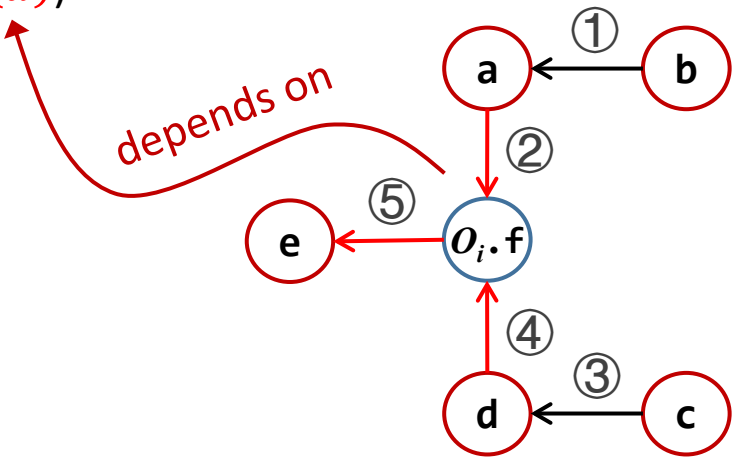
Pointer flow graph



Implementing Pointer Analysis

1. Build pointer flow graph (PFG)

Mutually dependent

2. Propagate points-to information on PFG

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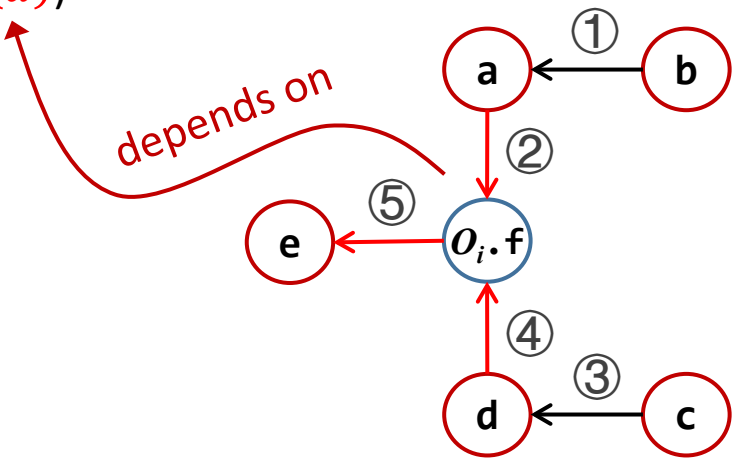
Pointer flow graph



PFG is dynamically **updated** during pointer analysis