软件分析

南京大学
计算机科学与技术系
程序设计语言与
静态分析研究组
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Static Program Analysis

Pointer Analysis

Nanjing University

Tian Tan

2021

Contents

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

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

Problem of CHA

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

interface Number {
    int get();
}
class Zero implements Number {
    public int get() { return 0; }
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class One implements Number {
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CHA:

- ? call targets

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CHA: based on **class hierarchy**
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Constant propagation

- x = ?

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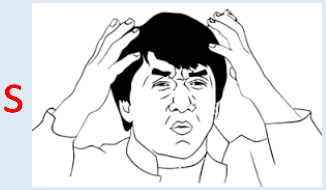
CHA: ~~based on~~ only considers **class hierarchy**

- 3 call targets
- 2 false positives



Constant propagation

- x = NAC   imprecise

Via Pointer Analysis

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void foo() {
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n points to new One

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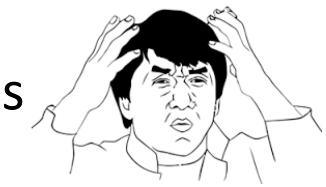

Constant propagation
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Pointer analysis: based on **points-to relation**
- 1 call target

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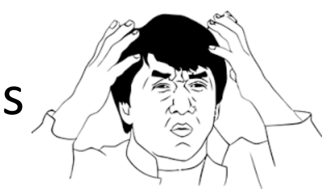

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Constant propagation

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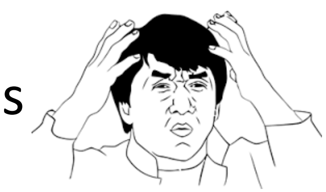

Constant propagation

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

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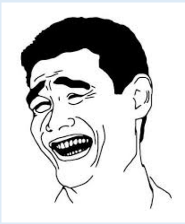

Constant propagation

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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, OOPSLA'21 …

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);
    B y = a.getB();
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class A {
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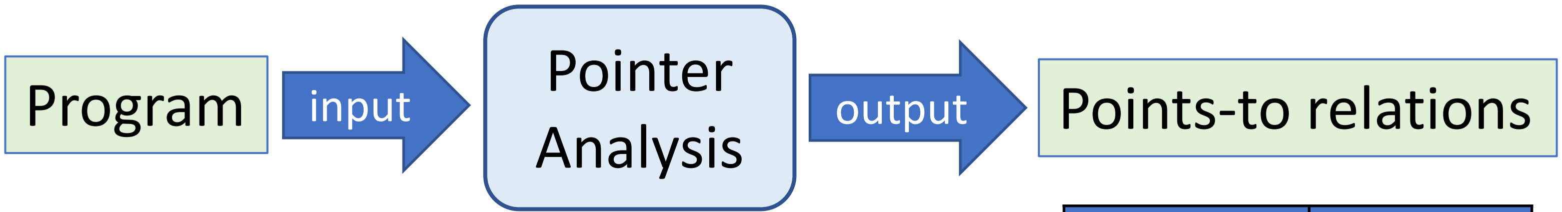


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Pointer Analysis and Alias Analysis

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 …

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

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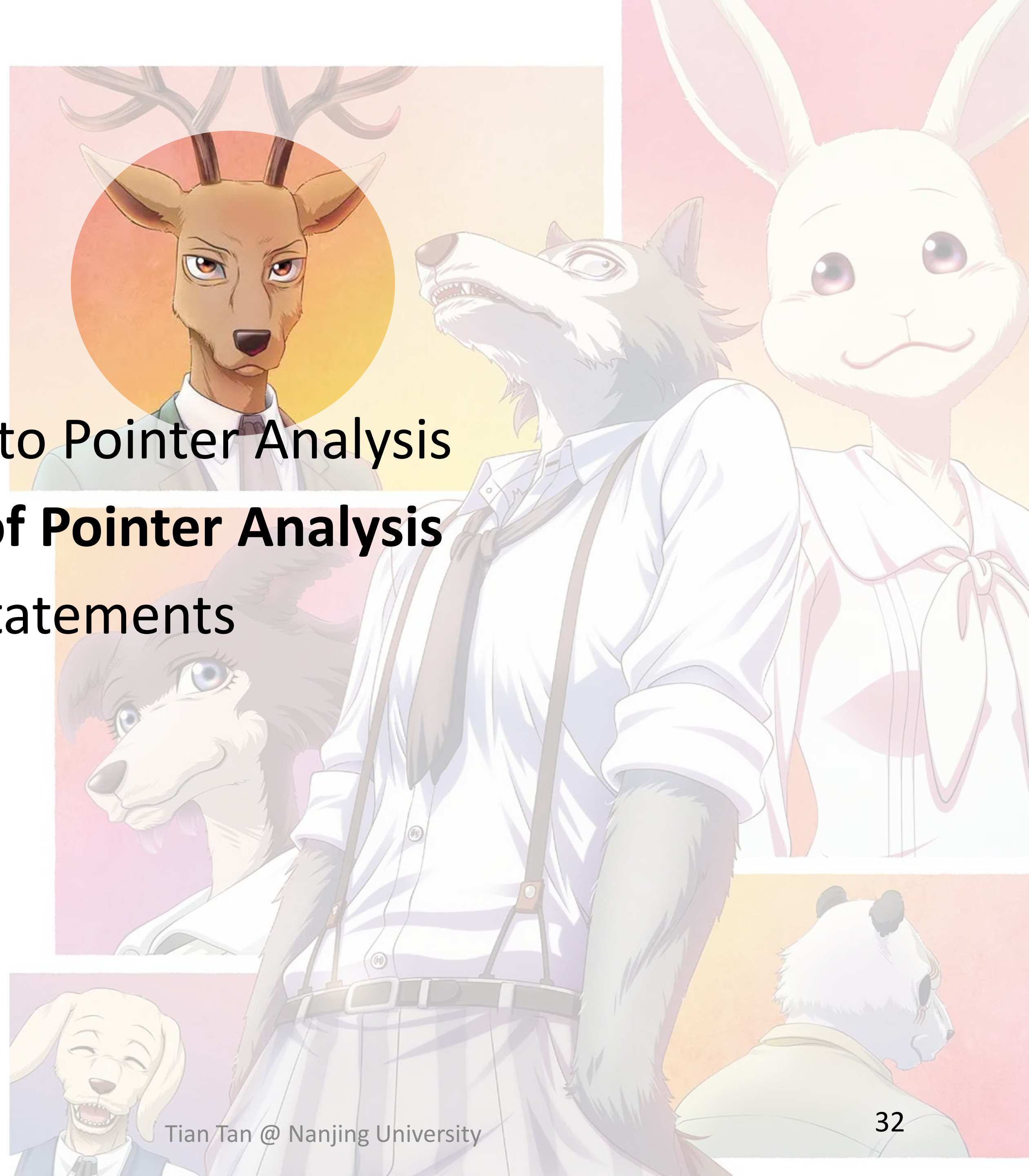

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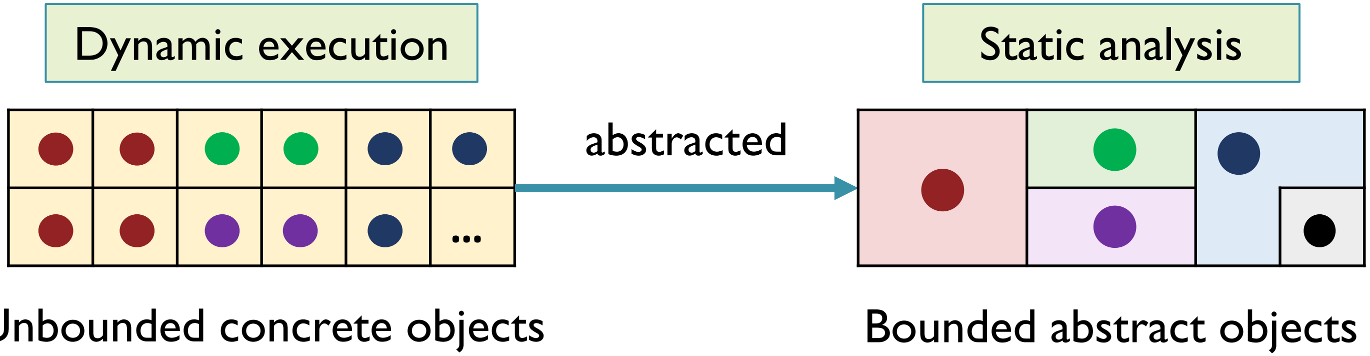

Heap Abstraction

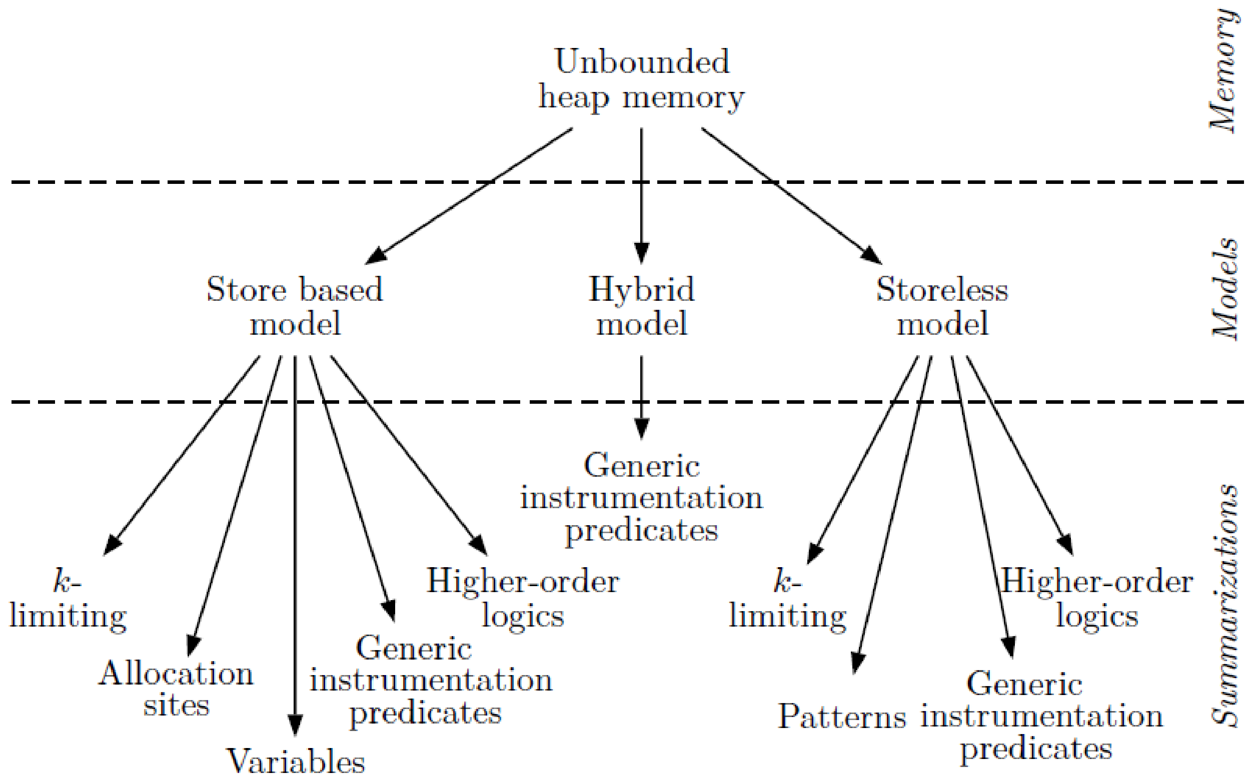

Figure 2. Heap memory can be modeled as storeless, store based, or hybrid. These models are summarized using allocation sites, k-limiting, patterns, variables, other generic instrumentation predicates, or higher-order logics.

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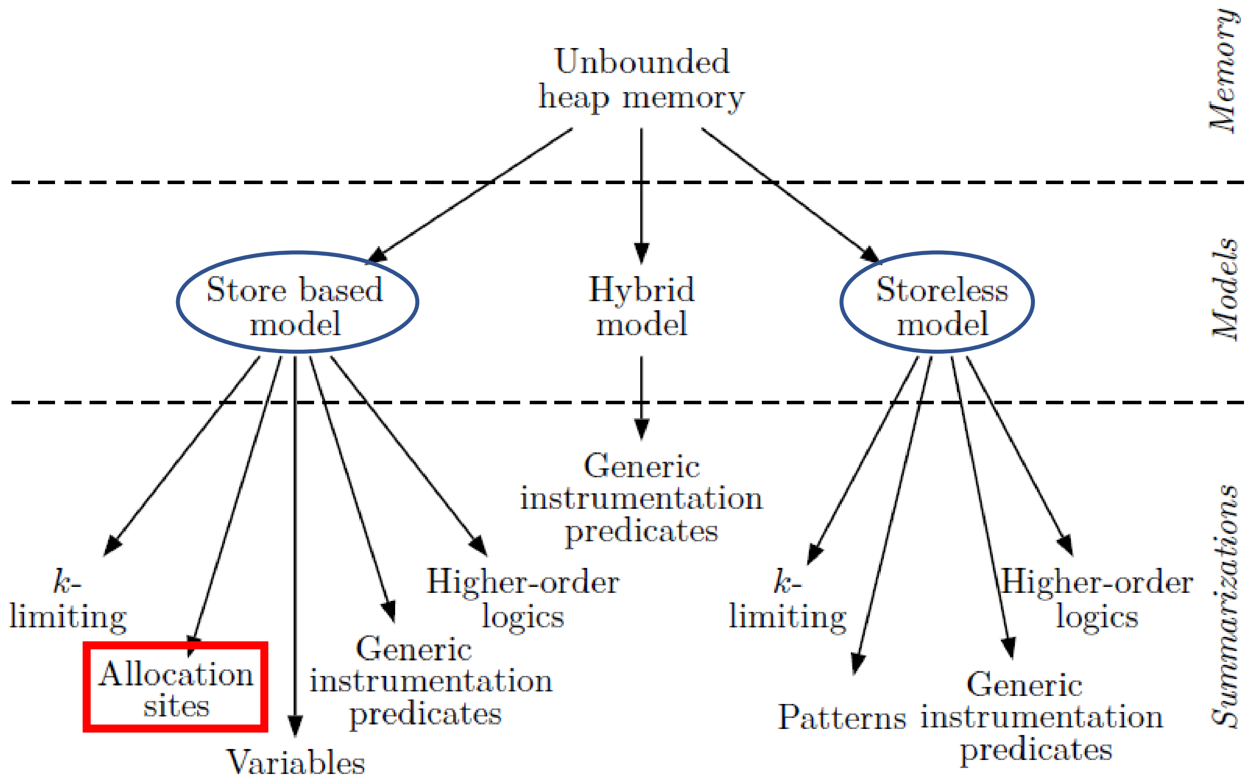

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Allocation-Site Abstraction

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    …
}
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o_2, iteration `i = 0`
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Dynamic execution

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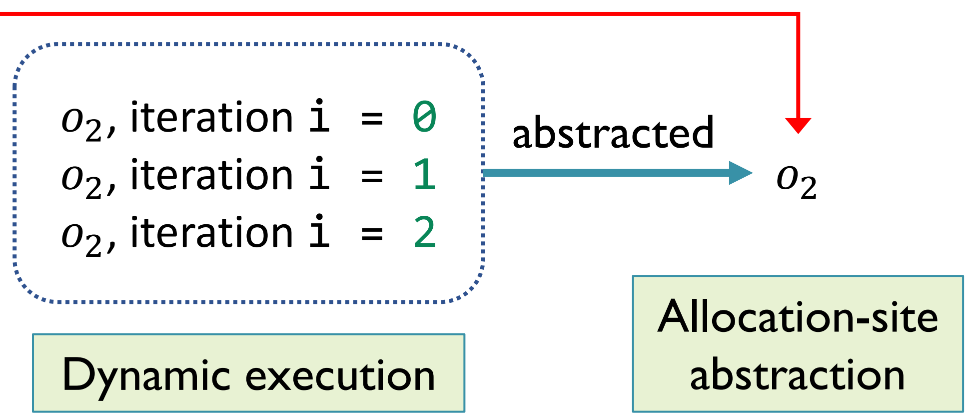

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Dynamic execution

abstracted → o_2

Allocation-site abstraction

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

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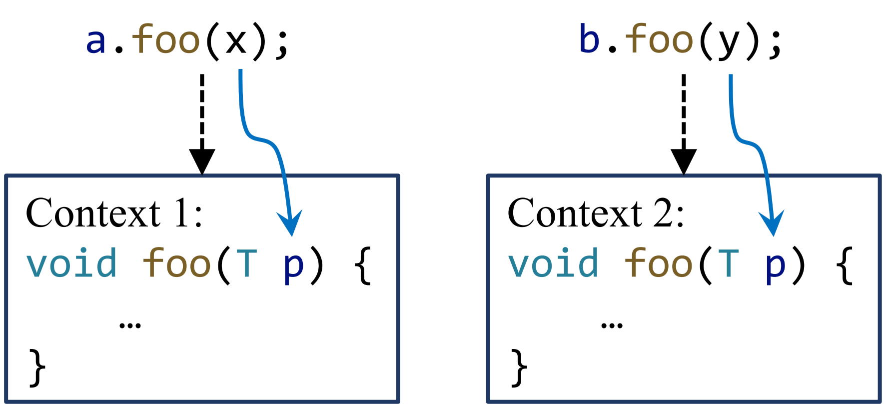

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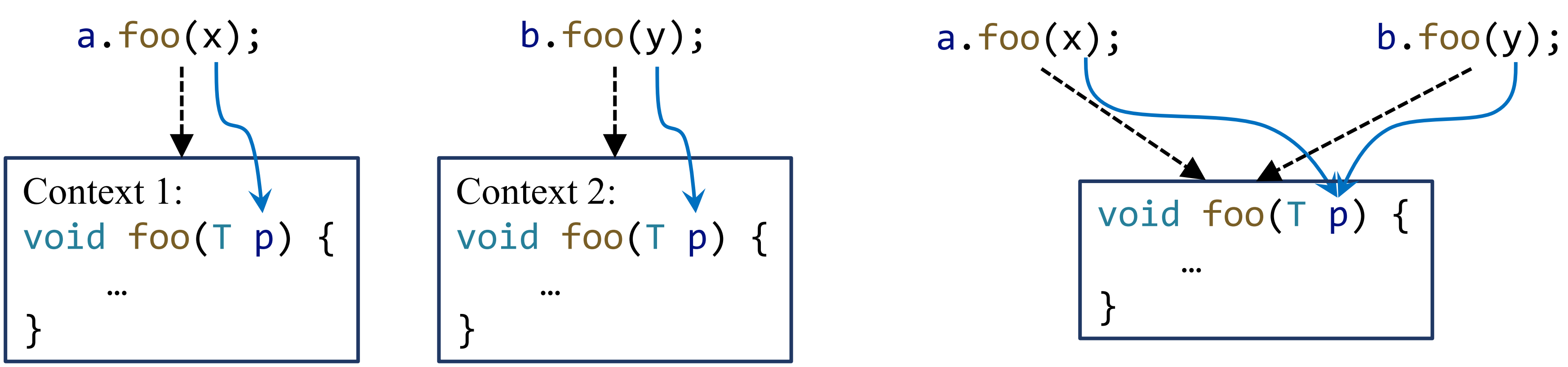

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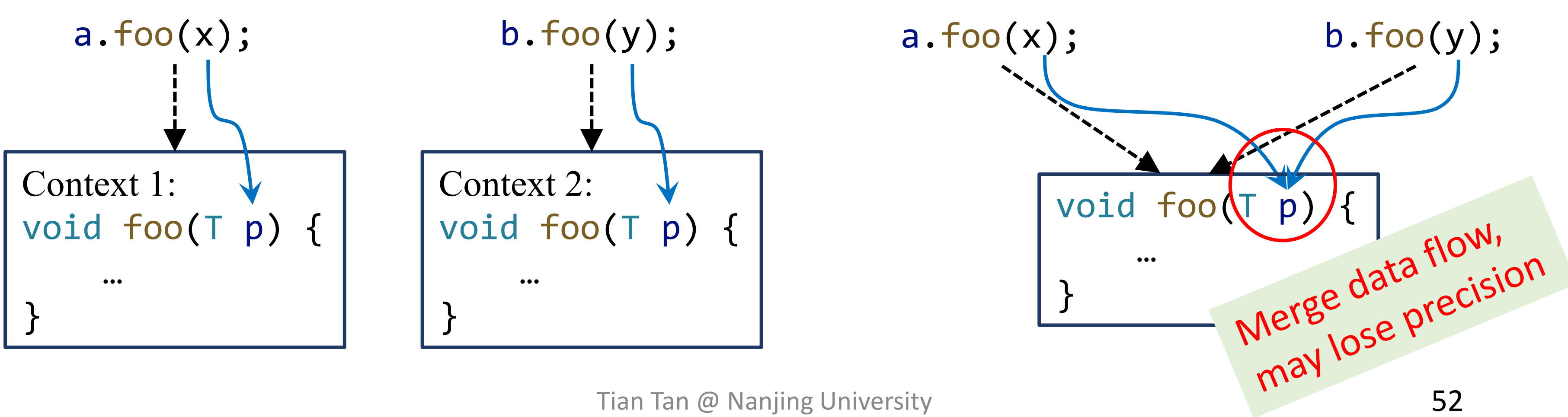

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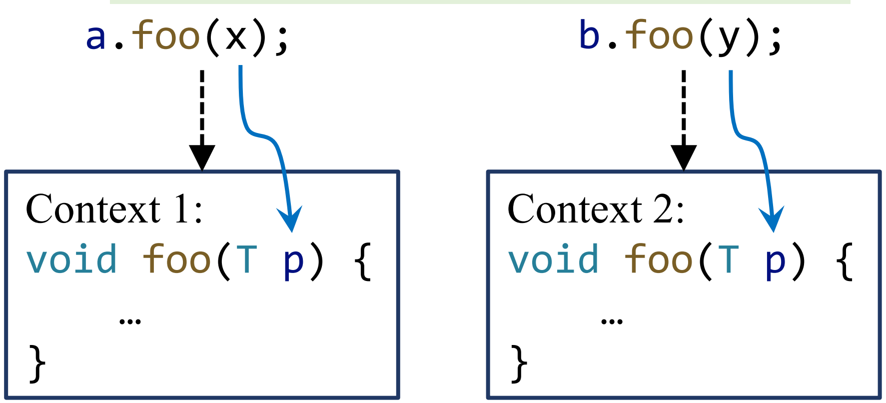
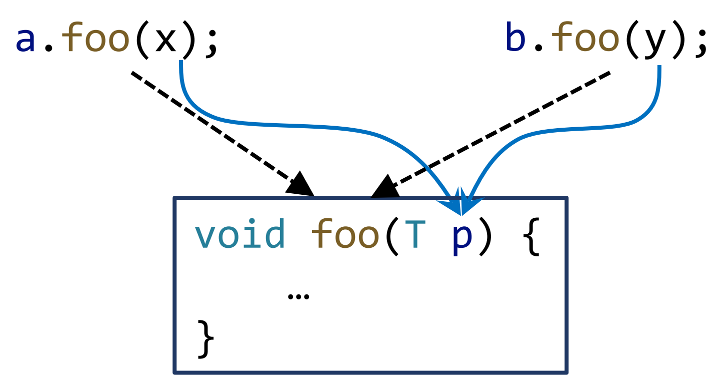
Very useful technique
Significantly improve precision
More details in **later lectures**

We start with **this**





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

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c $\rightarrow$ $\{o_1\}$

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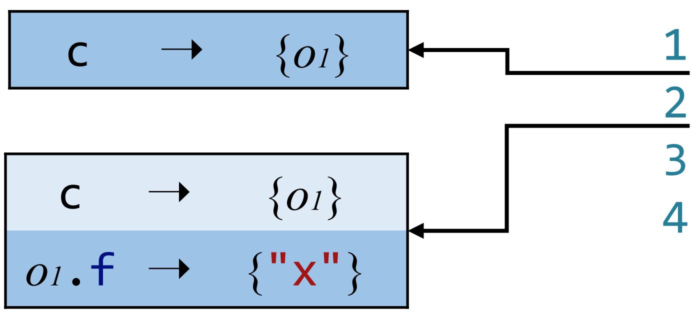


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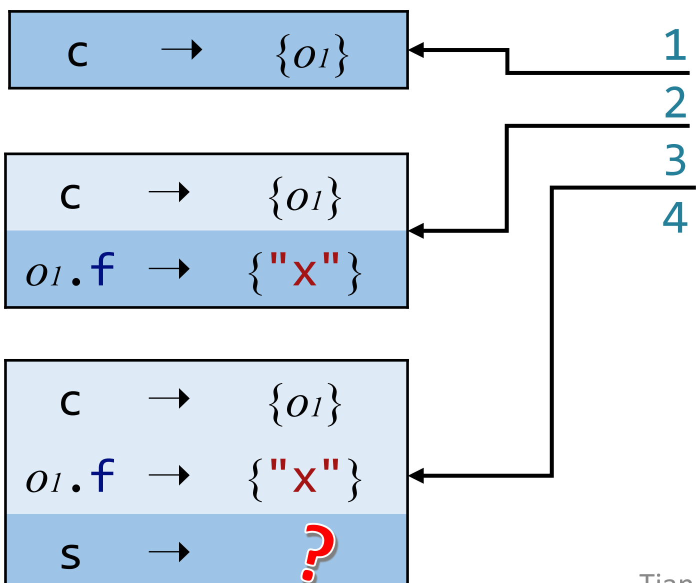


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Flow Sensitivity

How to model control flow?

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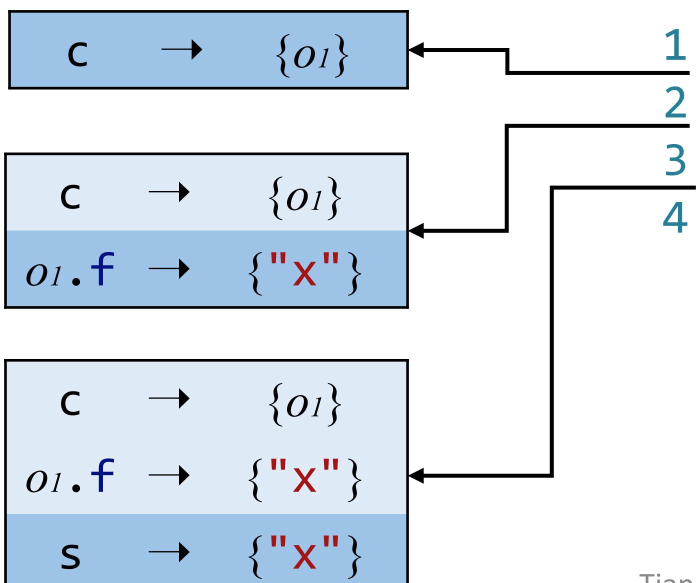


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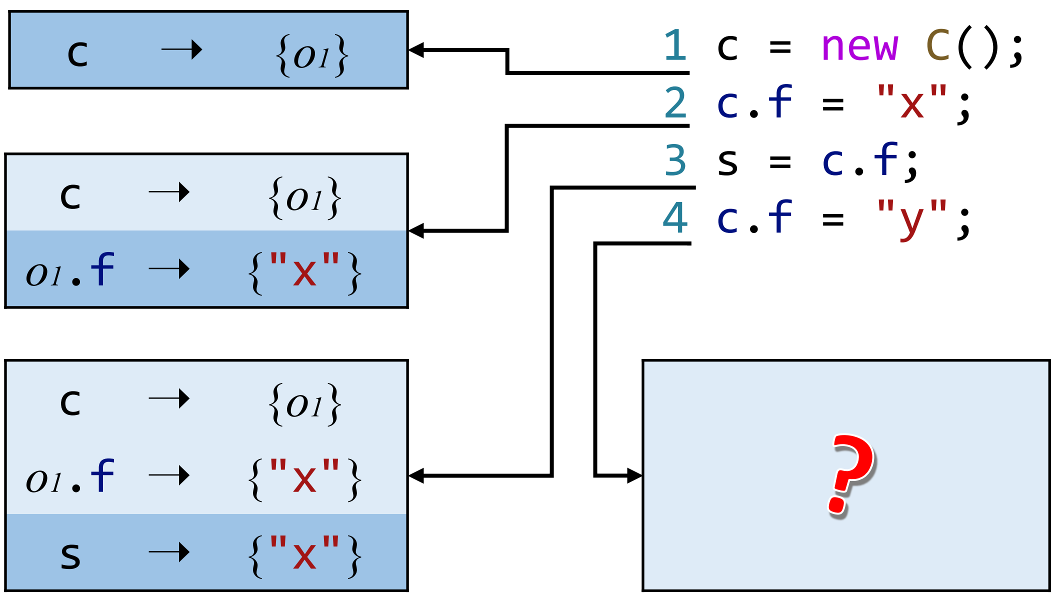

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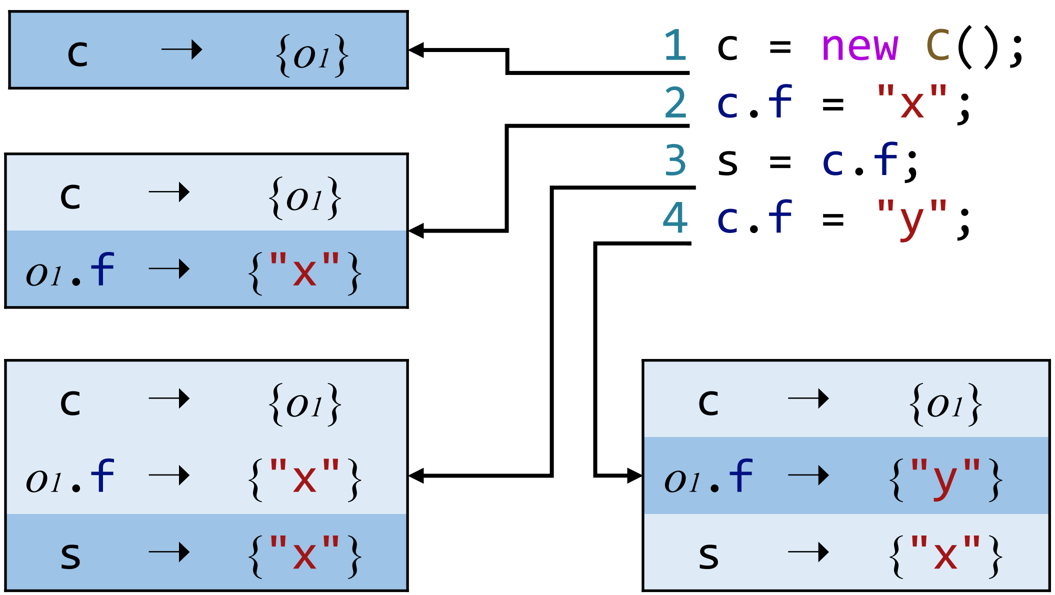

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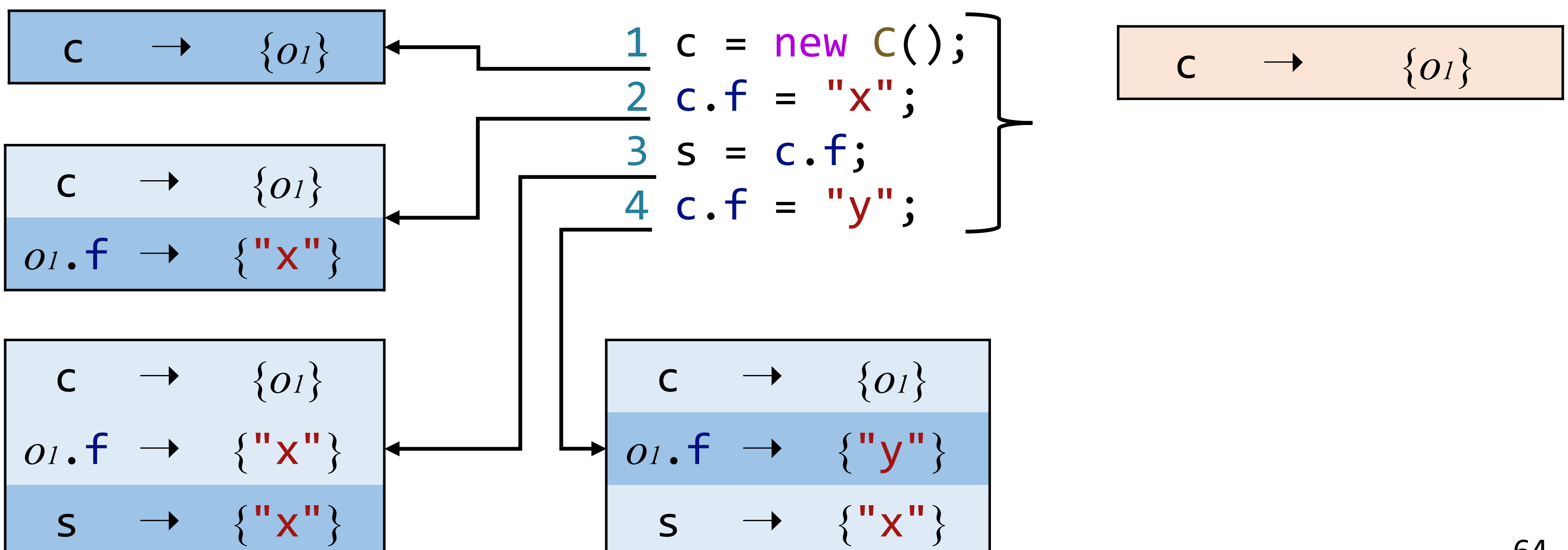

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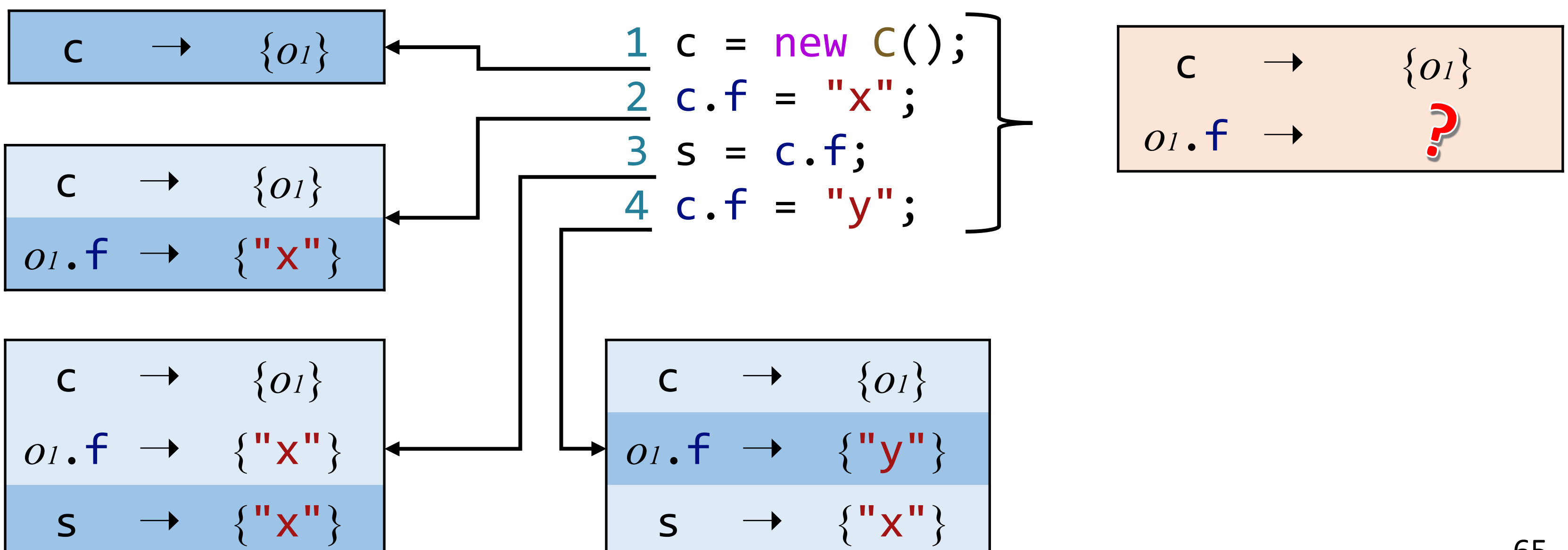

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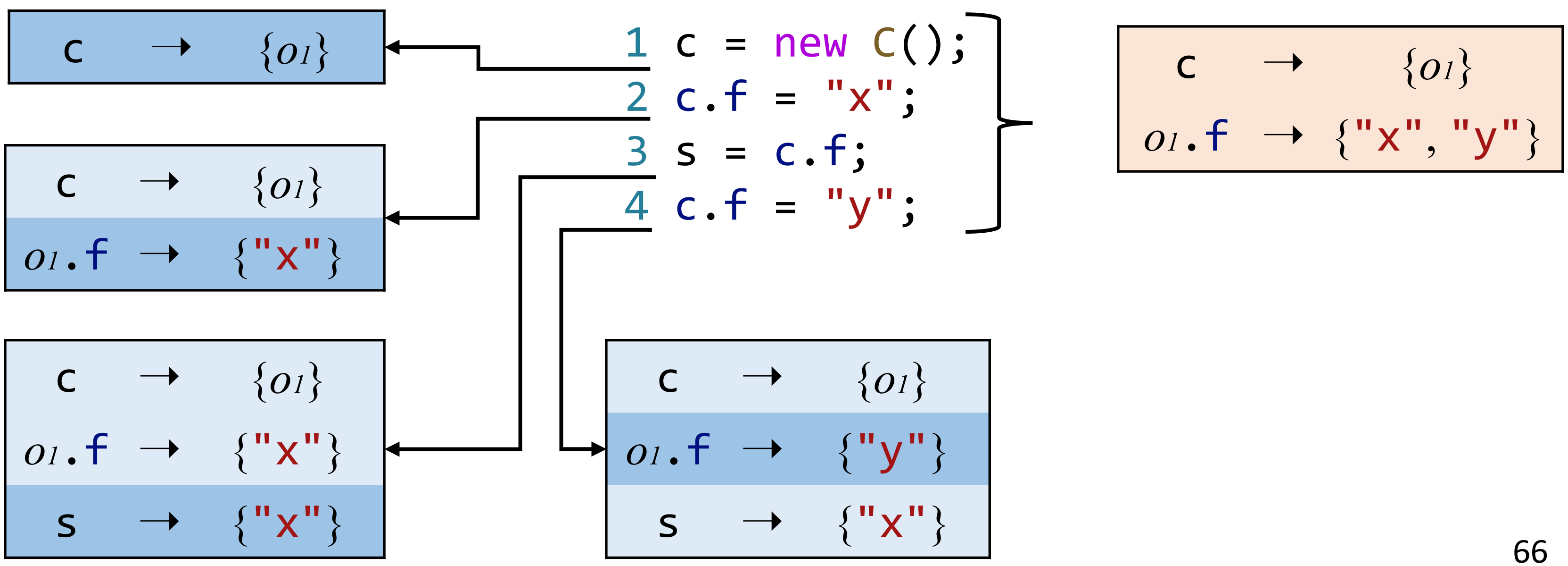

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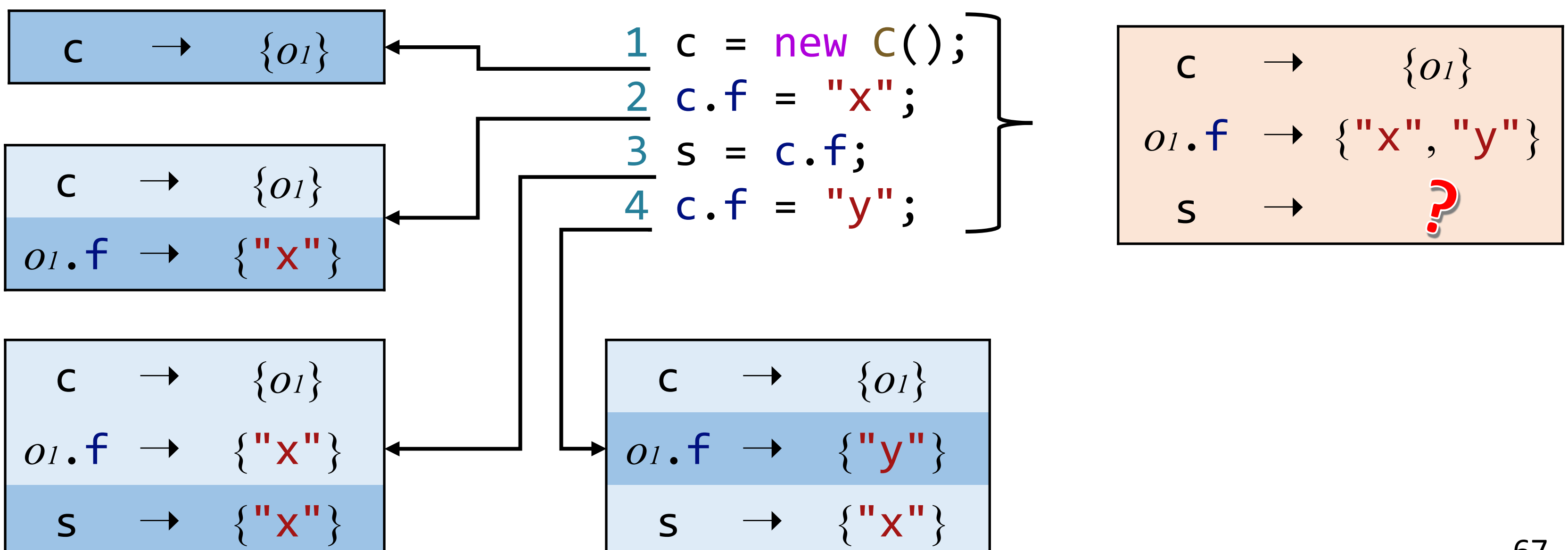

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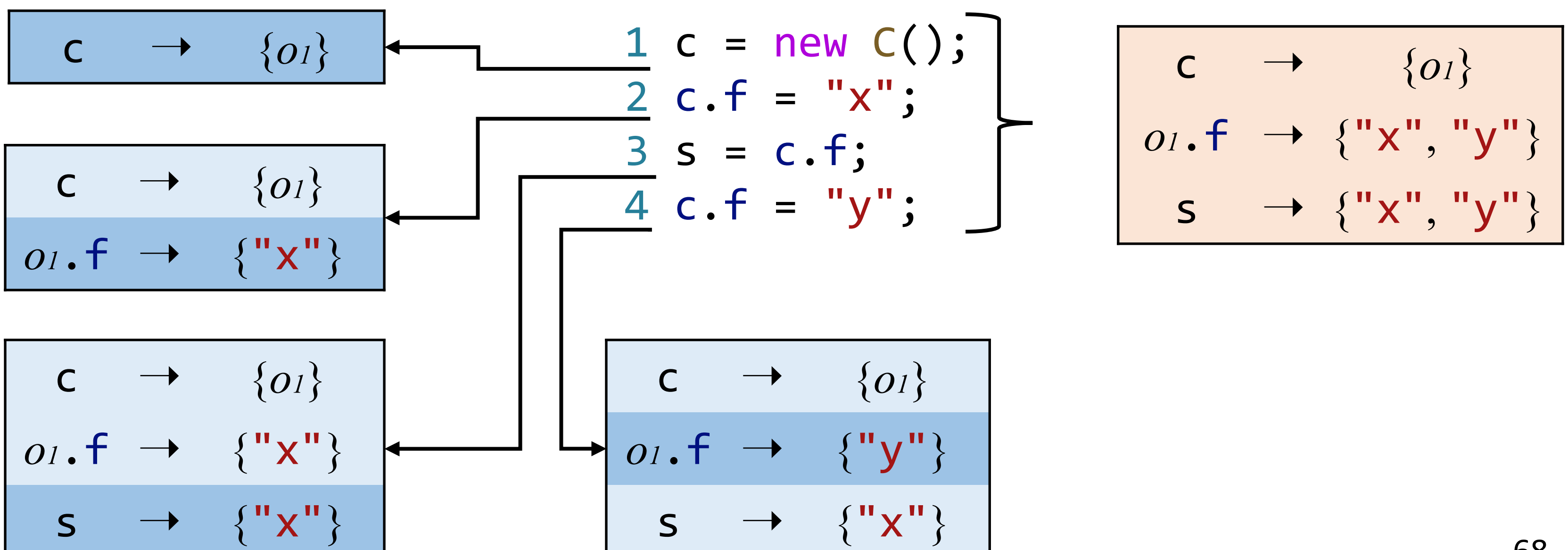

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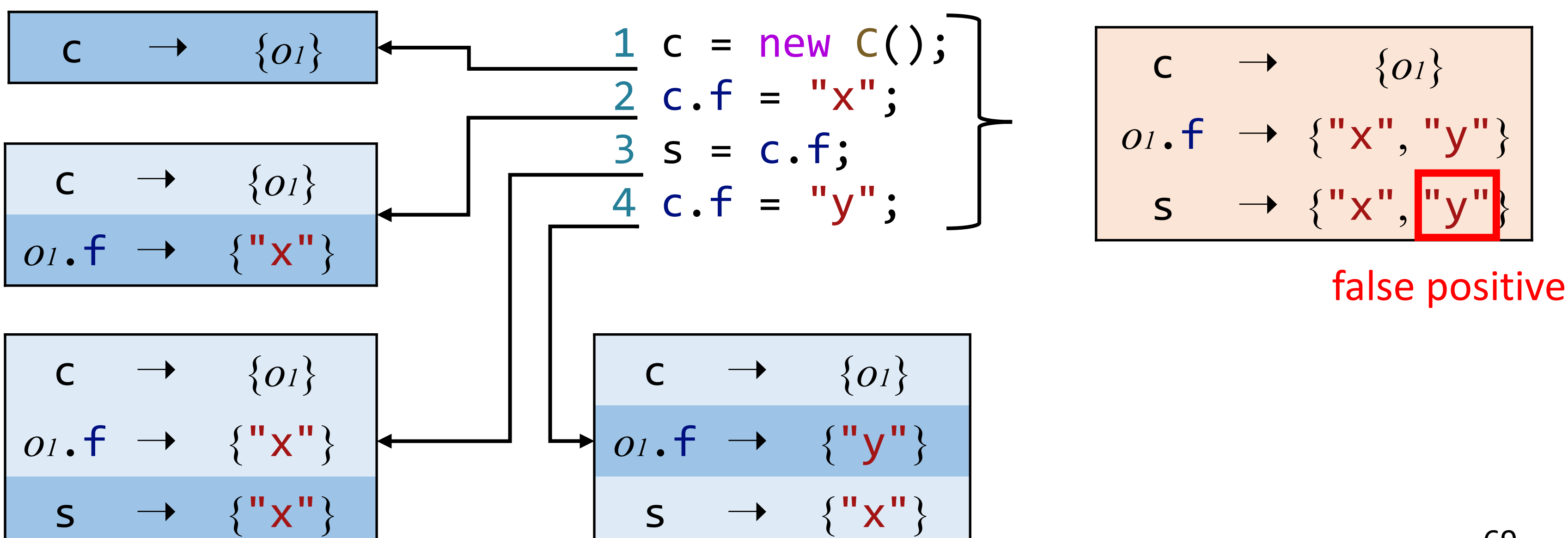

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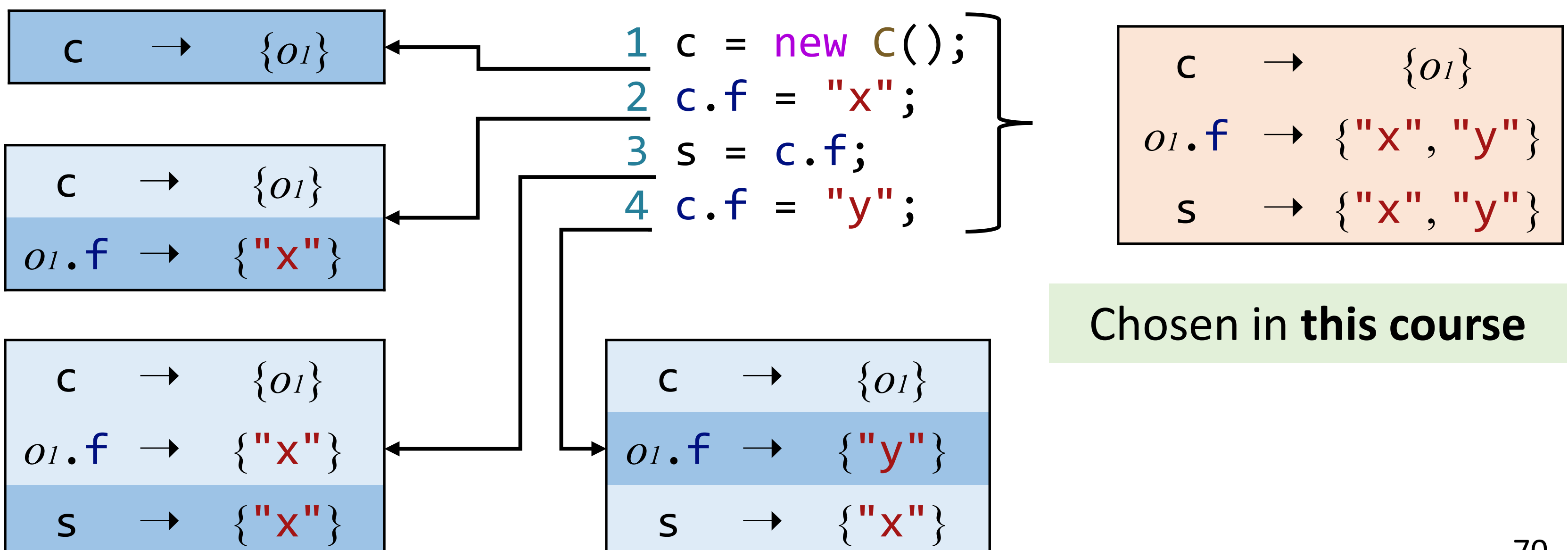

Key Factors in Pointer Analysis

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

Factor	Problem	Choice
Heap abstraction	How to model heap memory?	• Allocation-site • Storeless
Context sensitivity	How to model calling contexts?	• Context-sensitive • Context-insensitive
Flow sensitivity	How to model control flow?	• Flow-sensitive • Flow-insensitive
Analysis scope	Which parts of program should be analyzed?	• Whole-program • Demand-driven

Analysis Scope

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

Analysis Scope

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

```
x = new A();
y = x;
…
z = new T();
z.bar();
```

Analysis Scope

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)
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x	$\rightarrow$	$\{o_1\}$
y	$\rightarrow$	$\{o_1\}$
z	$\rightarrow$	$\{o_4\}$

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

What points-to information do we need?

Client: call graph construction
Site of interest: line 5

Analysis Scope

Which parts of program should be analyzed?

Whole-program	Demand-driven
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Chosen in **this course**

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Client: call graph construction
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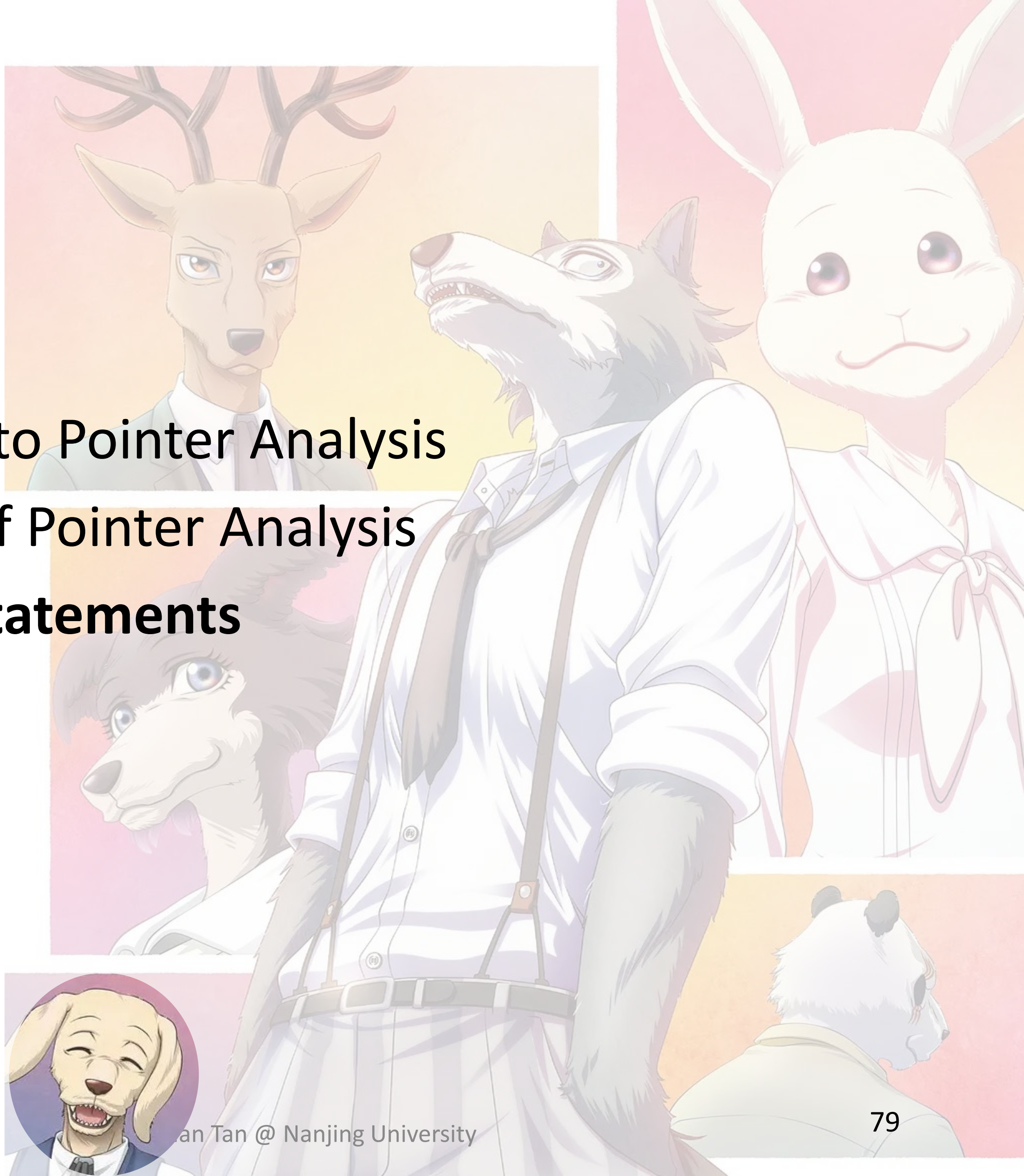
Pointer Analysis in This Course

Factor	Problem	Choice
Heap abstraction	How to model heap memory?	• Allocation-site • Storeless
Context sensitivity	How to model calling contexts?	• Context-sensitive • Context-insensitive
Flow sensitivity	How to model control flow?	• Flow-sensitive • Flow-insensitive
Analysis scope	Which parts of program should be analyzed?	• Whole-program • Demand-driven

Contents



What Do We Analyze?

- Modern languages typically have many kinds of statements
  - if-else
  - switch-case
  - for/while/do-while
  - break/continue
  - …

What Do We Analyze?

- Modern languages typically have many kinds of statements
  - ~~if-else~~
  - ~~switch-case~~
  - ~~for/while/do-while~~
  - ~~break/continue~~
  - …

Do not directly affect pointers
Ignored in pointer analysis

- We only focus on **pointer-affecting statements**

Pointers in Java

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

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Pointers in Java

- Local variable: `x`
- Static field: `C.f` ⟸ Sometimes referred as global variable
- Instance field: `x.f`
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Pointers in Java

- Local variable: `x`
- Static field: `C.f`
- Instance field: `x.f` ⟵ 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, …)`

Pointer-Affecting Statements

New	`x = new T()`
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Call	`r = x.k(a, …)`

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;
```

Pointer-Affecting Statements

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

- Static call `C.foo()`
- Special call `super.foo()/x.<init>()/this.privateFoo()`
- Virtual call `x.foo()`

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New	x = new T()
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- Static call C.foo()
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- Virtual call x.foo() focus

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

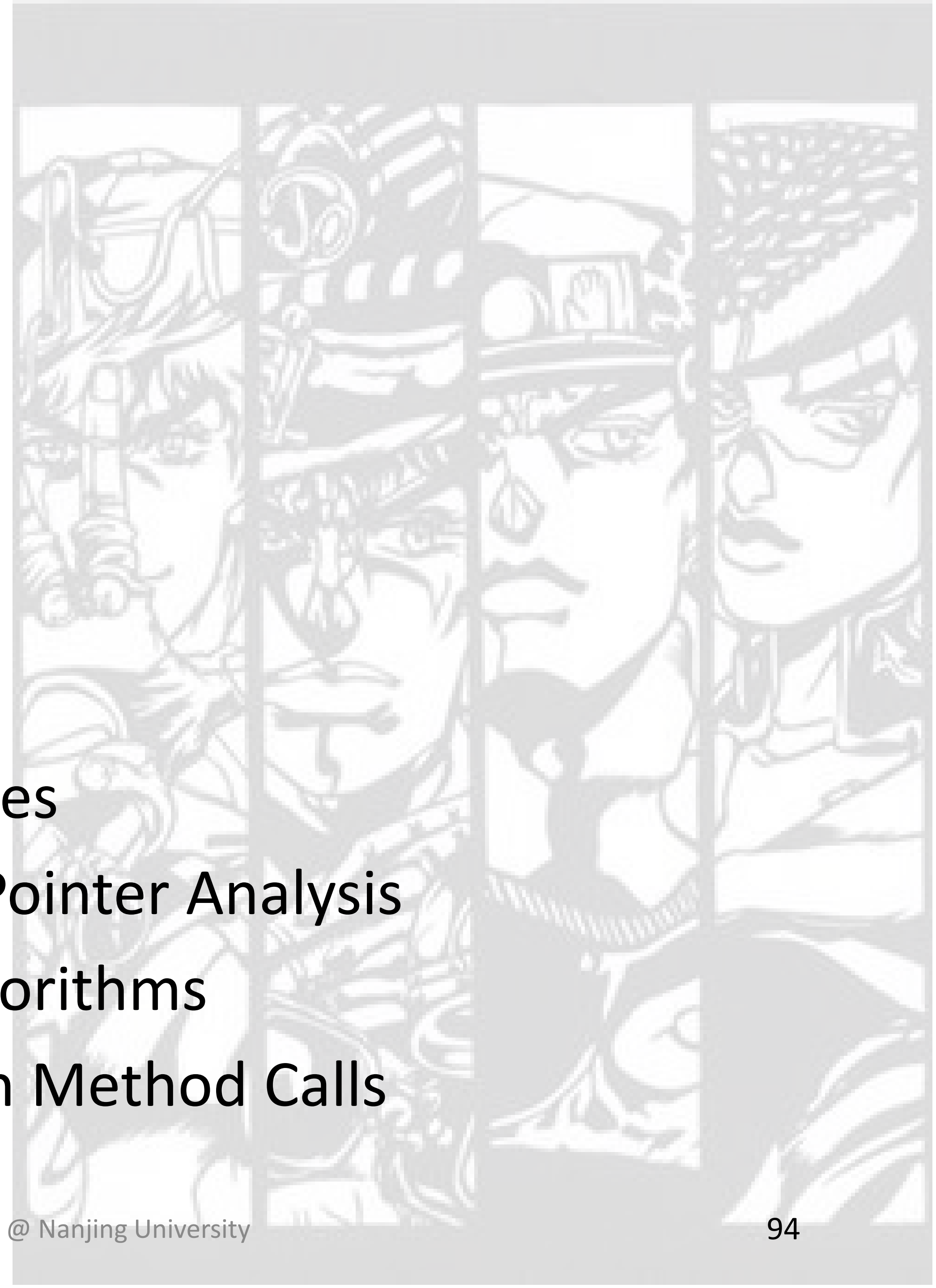
Pointer Analysis
Foundations (I)

Nanjing University

Tian Tan

2020

Contents



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

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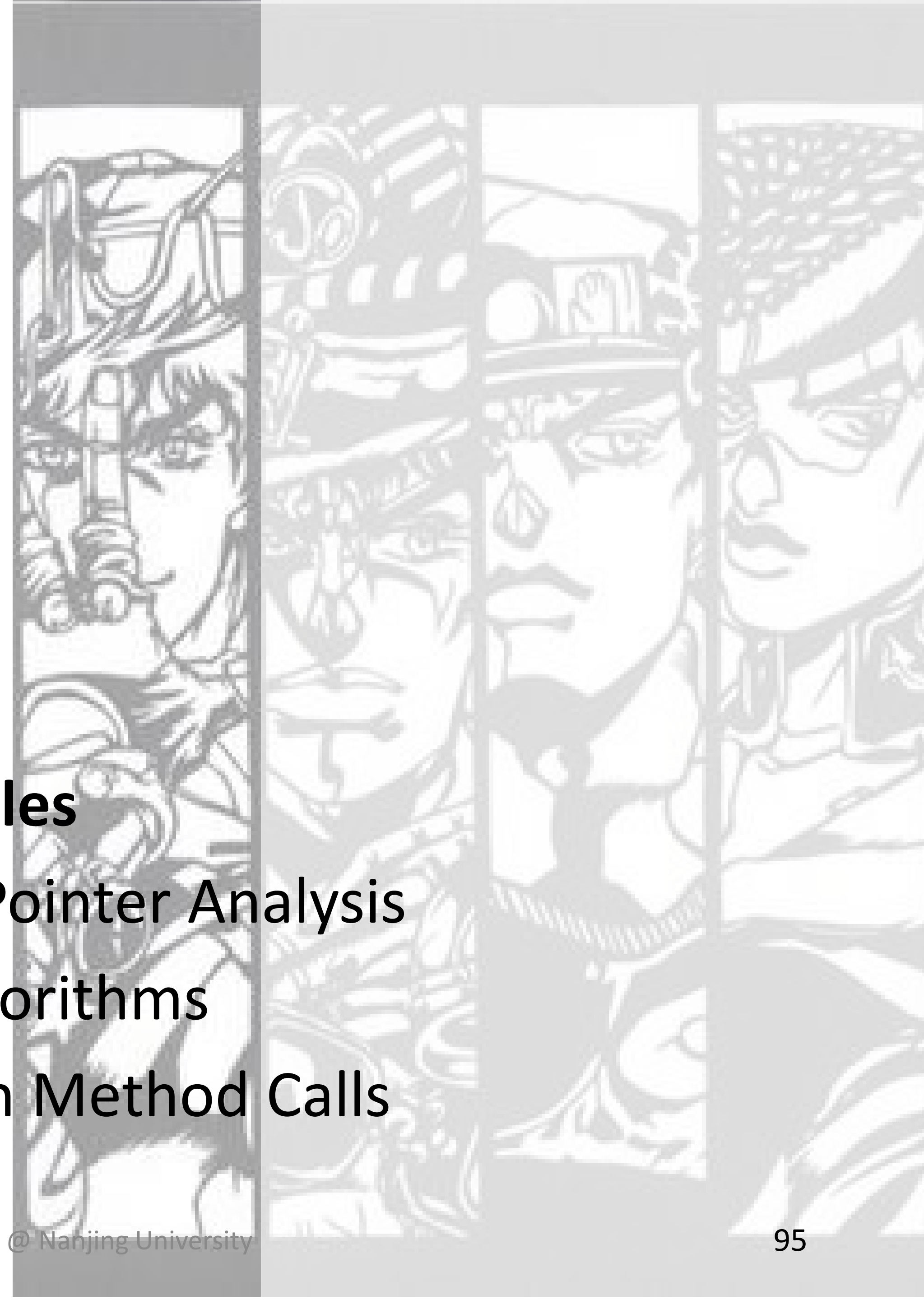

1. **Pointer Analysis: Rules**
2. How to Implement Pointer Analysis
3. Pointer Analysis: Algorithms
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Pointer-Affecting Statements

New	`x = new T()`	First focus on these statements (suppose the program has just one method)
Assign	`x = y`	
Store	`x.f = y`	
Load	`y = x.f`	
Call	`r = x.k(a, …)`	← 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()`	$\frac{}{o_i \in pt(x)}$ ← unconditional
Assign	`x = y`	$\frac{o_i \in pt(y)}{o_i \in pt(x)}$ ← premises ← conclusion
Store	`x.f = y`	$\frac{o_i \in pt(x),\ o_j \in pt(y)}{o_j \in pt(o_i.f)}$
Load	`y = x.f`	$\frac{o_i \in pt(x),\ o_j \in pt(o_i.f)}{o_j \in pt(y)}$

Rule: New

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

⟶ Conclusion

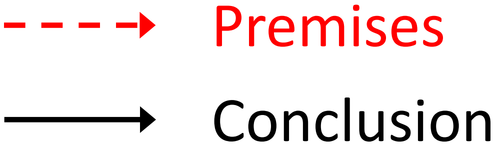
o_i

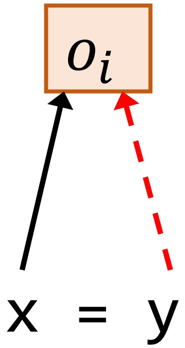
↑

```
i: x = new T()
```

Rule: Assign

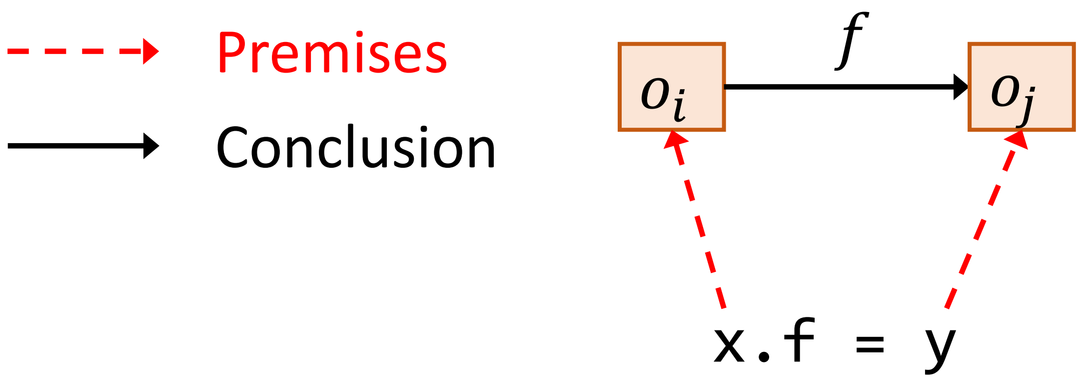
$$\frac{o_i \in pt(y)}{o_i \in pt(x)}$$





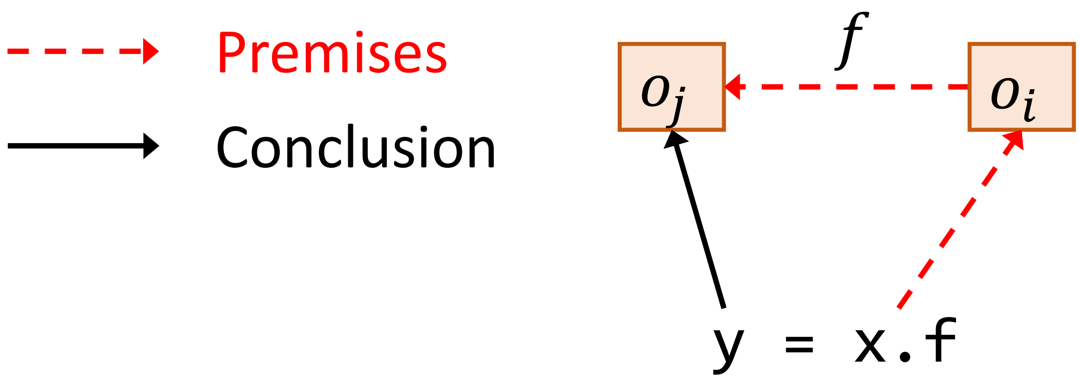
Rule: Store

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



Rule: Load

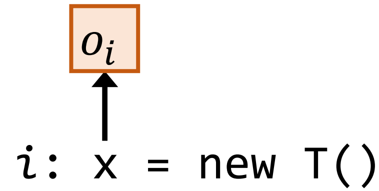
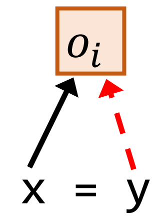
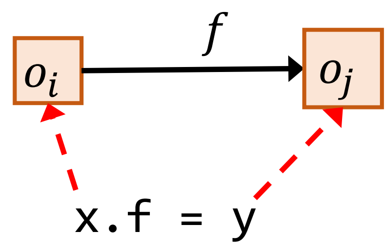
$$\frac{o_i \in pt(x),\ o_j \in pt(o_i.f)}{o_j \in pt(y)}$$



Rules

Premises

Conclusion

Kind	Rule	Illustration
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	$\dfrac{o_i \in pt(x),\ o_j \in pt(o_i.f)}{o_j \in pt(y)}$