Made by Qingkai Shi
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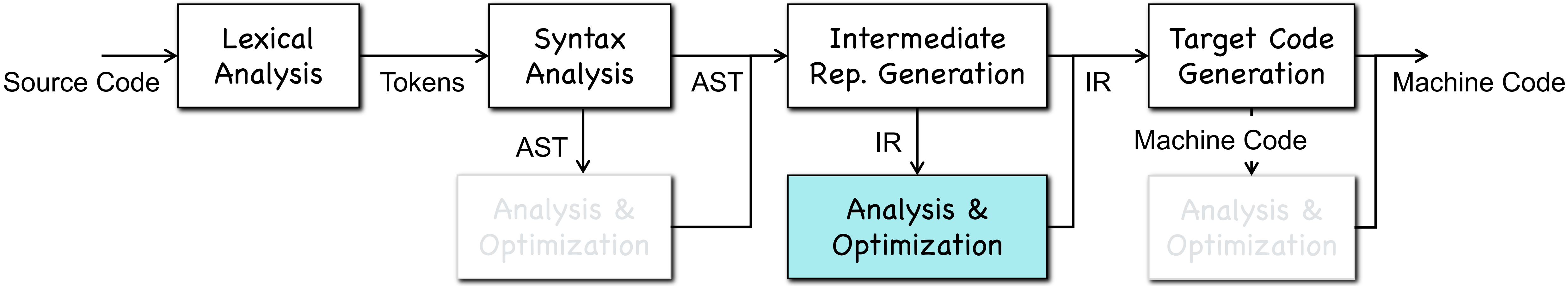
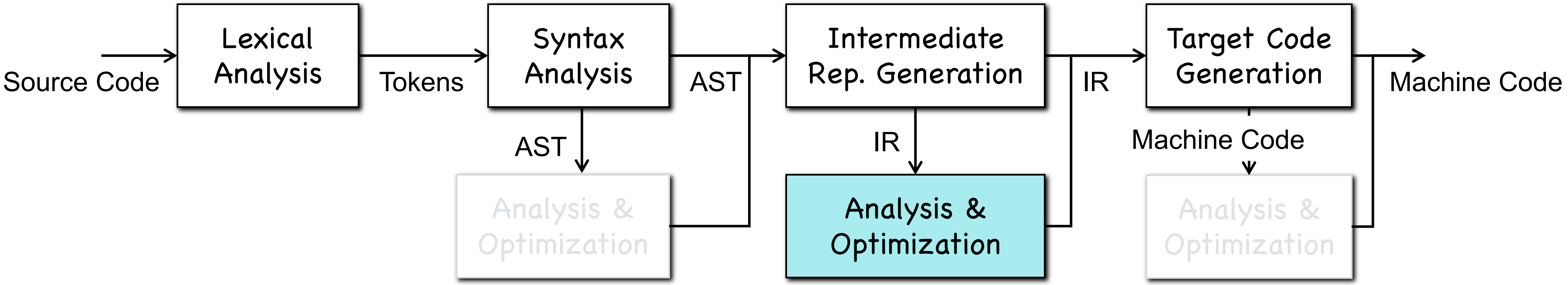
Chapter 12-2
Pointer Alias Analysis

Pointer Analysis



- Why pointer analysis?

Pointer Analysis



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*p = a; …; …; b = *q; // does b data-depend on a?
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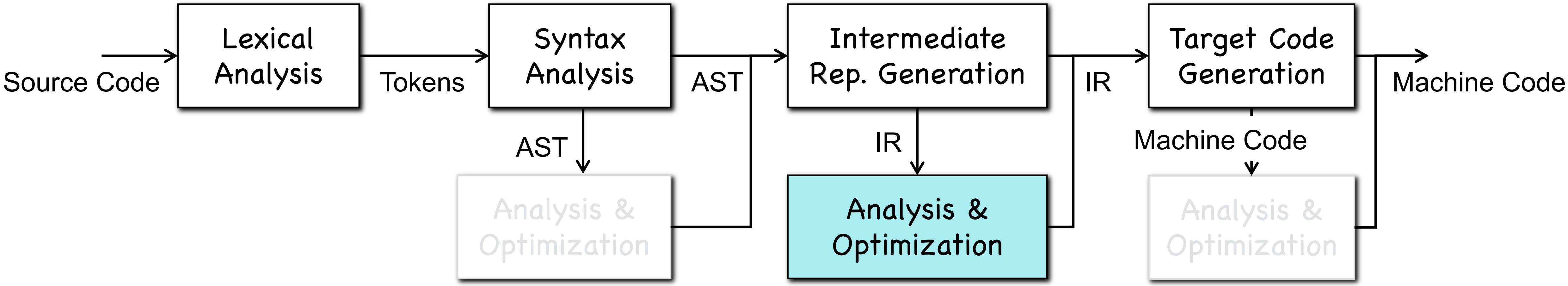

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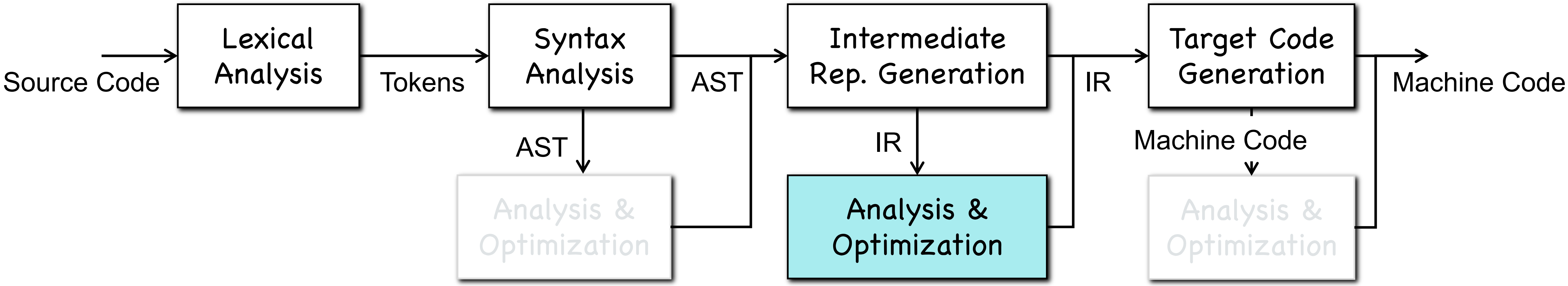

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- Flow-sensitivity
- Context-sensitivity
- Path-sensitivity
- Field-sensitivity

Why Pointer Alias Analysis?

- **Aliases**: two expressions that denote the same memory location
- Aliases are introduced by
  - references/pointers
  - function call
  - array indexing
  - C unions
  - …

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x = 3;
*p = 4;
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Constant Propagation

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```
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Constant Propagation

```
t = a + b;
*p = t
y = a + b; // is a + b available?
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Available Expression

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Constant Propagation

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Available Expression

- Error detection

```
x.lock();
...
y.unlock(); // same object as x?
```

PART I: Pointer Alias Analysis

May/Must Pointer Alias Analysis

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May/Must Pointer Alias Analysis

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- May analysis – Must-not analysis
  - If a *may-analysis* says ‘no’, it means two expressions must not denote the same memory location.
  - Useful in compiler optimization.

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Available Expression

May/Must Pointer Alias Analysis

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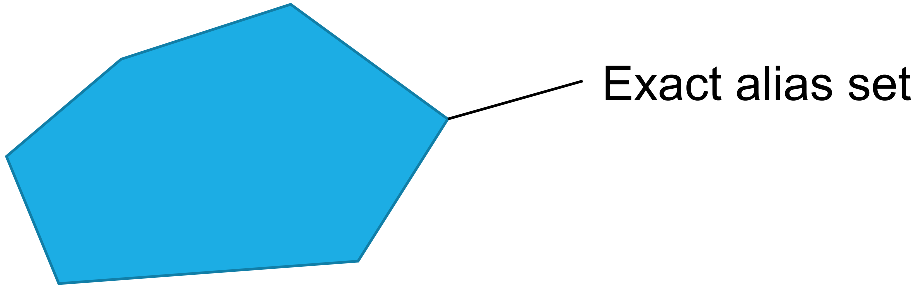

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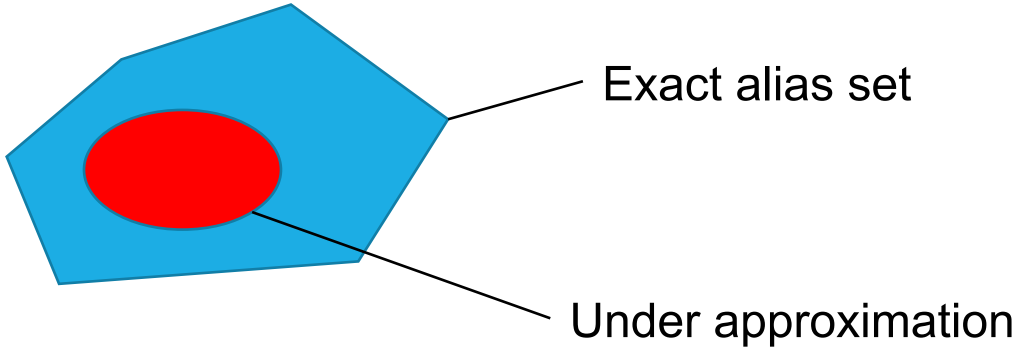

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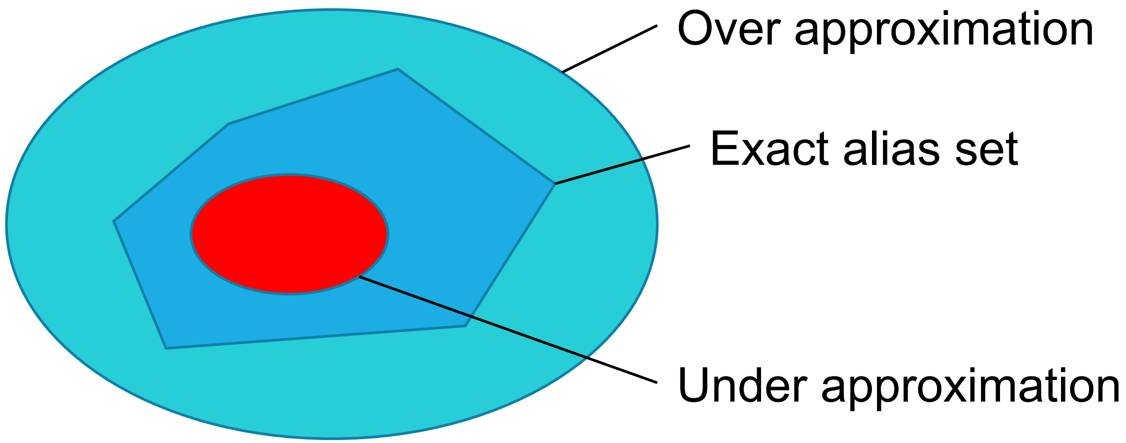

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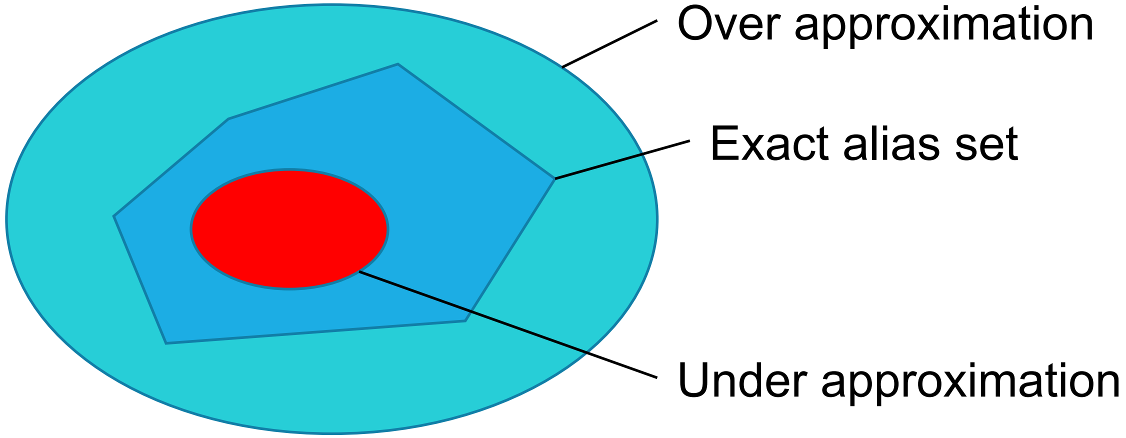

The simplest sound alias analysis is to return true for all may-alias queries

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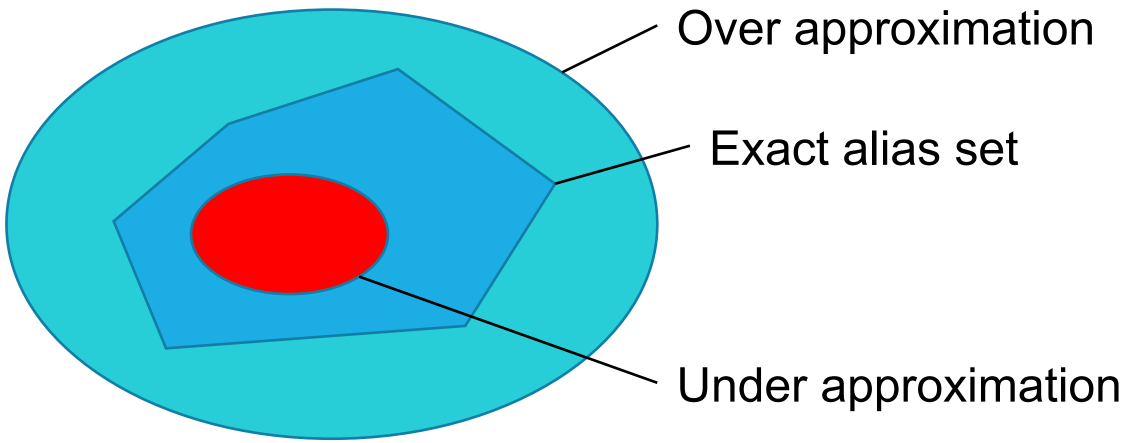

The simplest sound alias analysis is to return true for all may-alias queries

- Tradeoff between soundness and precision (i.e., completeness)

Flow-Sensitive Pointer Analysis

- Flow-sensitive pointer analysis computes **for each program point** what memory locations a pointer expression may refer to

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- There have been a few studies for flow-sensitive or even path-sensitive analysis

[1] Falcon: A Fused Approach to Path-Sensitive Data Dependence Analysis
Peisen Yao, Jinguo Zhou, Xiao Xiao, Qingkai Shi, Rongxin Wu, and Charles Zhang, PLDI 2024.

[2] Value-Flow-Based Demand-Driven Pointer Analysis for C and C++
Yulei Sui and Jingling Xue, IEEE Transactions on Software Engineering 2018.

Flow-Insensitive Pointer Analysis

- Flow-insensitive pointer analyses for whole program analyses

Andersen's Algorithm	**Steensgaard's Algorithm**
Presented by Andersen in 1994	Published in POPL 1996
Nearly cubic complexity	Almost linear, $O(n\alpha(n))$

A Small Pointer Language

- y = &x (address-taken)
- y = x (assignment)
- *y = x (store statement)
- y = *x (load statement)

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- y = &x (address-taken)
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- **pts(x)** --- the points-to set of x
  - pts(x) = { y, z } --- x may point to either y or z

Andersen’s Algorithm

Statement	Constraint	Shorthand
y = &x		
y = x		
*y = x		
y = *x		

Andersen's Algorithm

Statement	Constraint	Shorthand
y = &x	pts(y) ⊇ {x}	
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y = &x	$pts(y) \supseteq \{x\}$	
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Andersen's Algorithm

Inclusion-based pointer analysis

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➡

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pts(p) = { a, b };
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pts(p) = { a, b };
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Sound result!

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p  =  &a;
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*p =  q;
r  =  &c;
s  =  p;
t  =  *p;
*s =  r;
```

?

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- Solving the set constraints via a dynamic transitive closure

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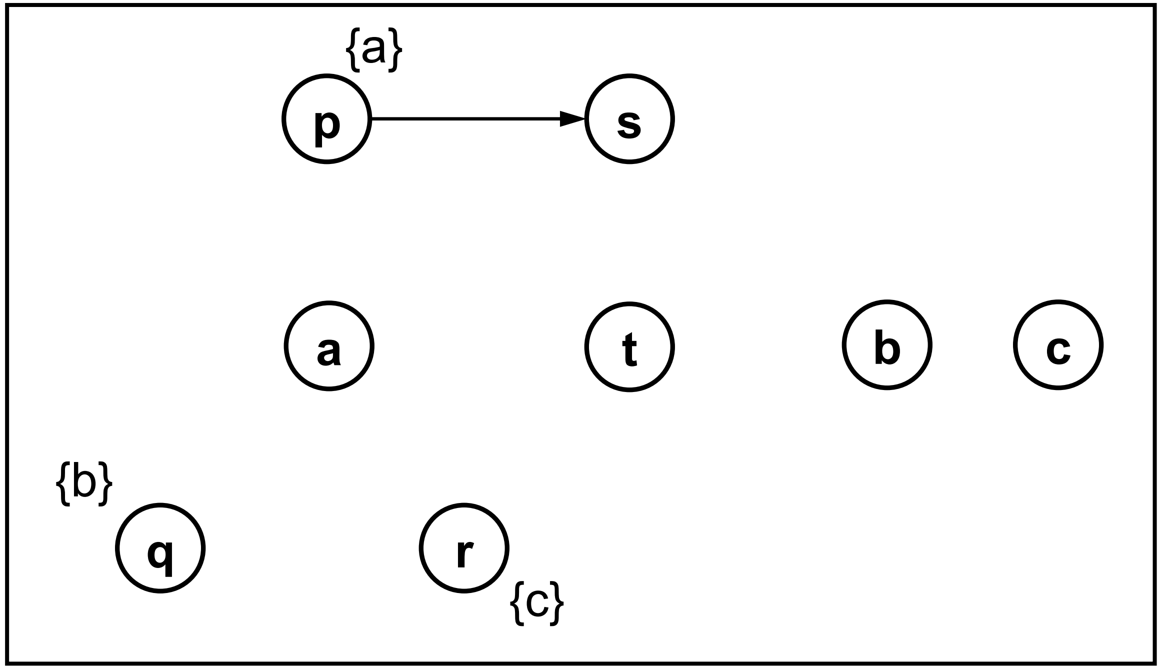

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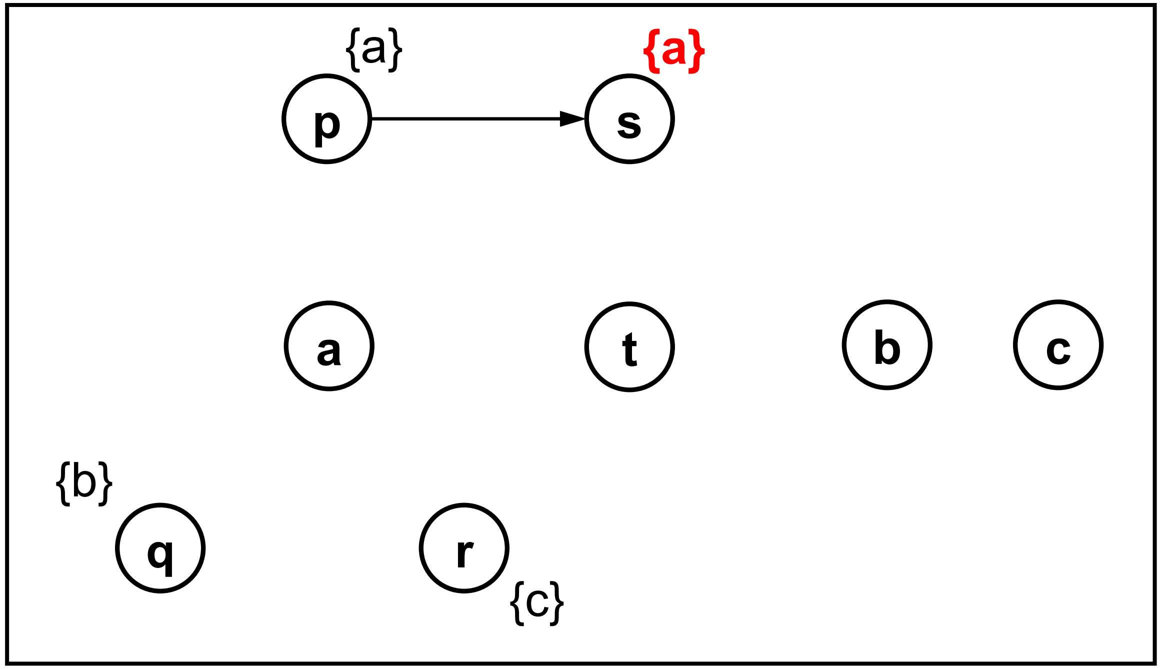

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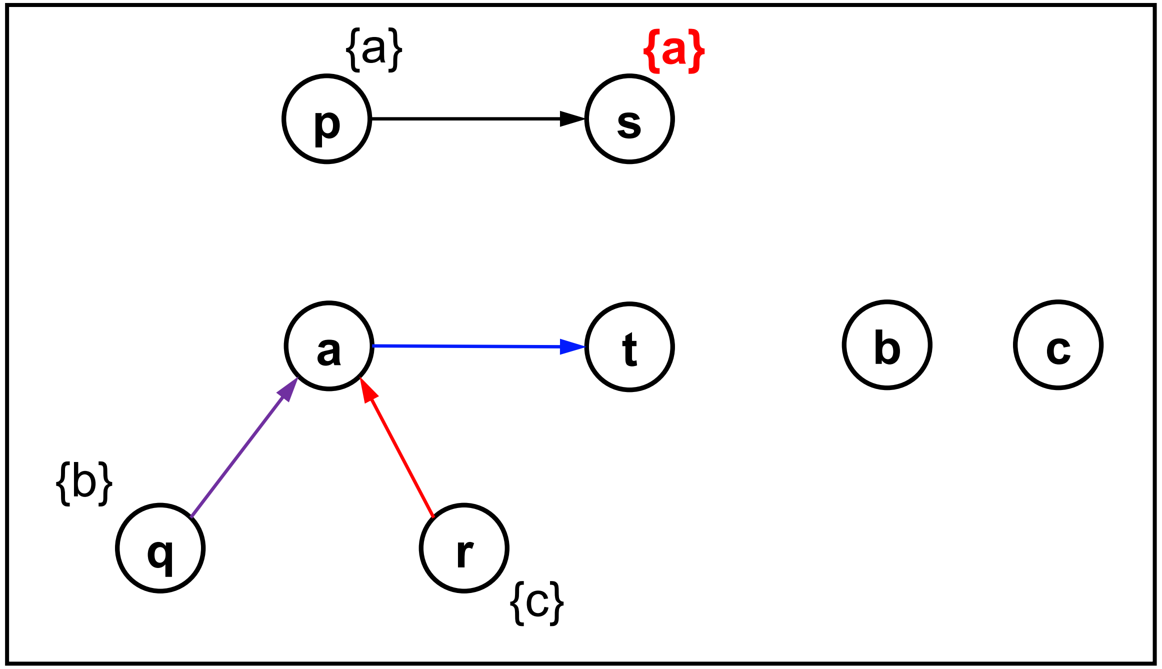

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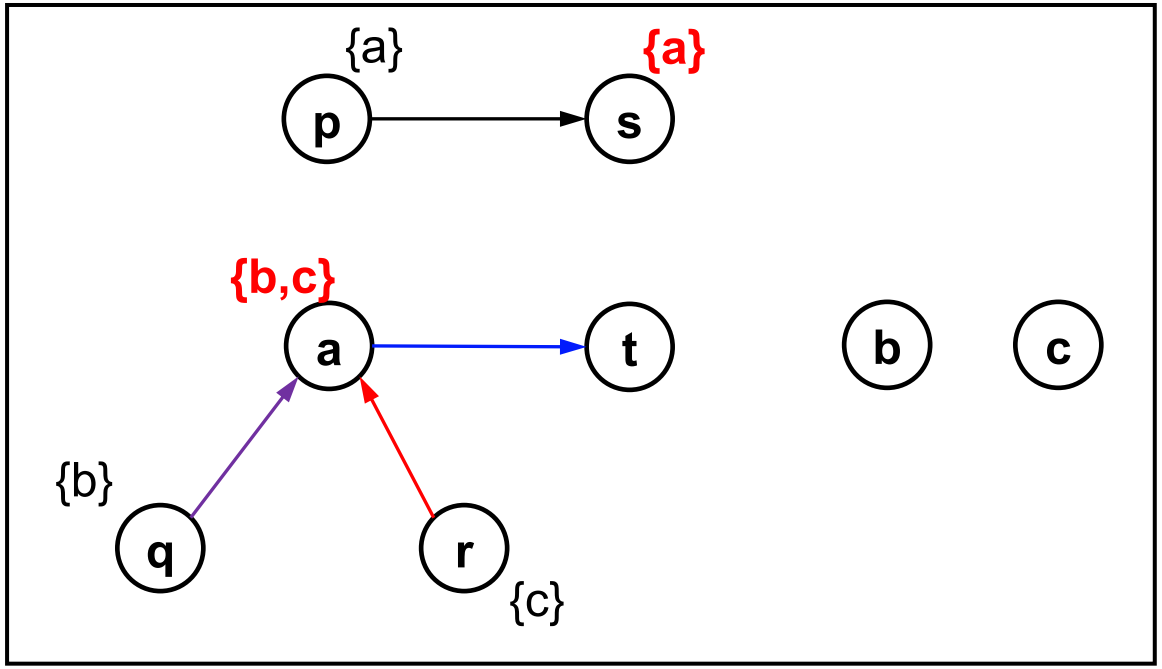

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```

```
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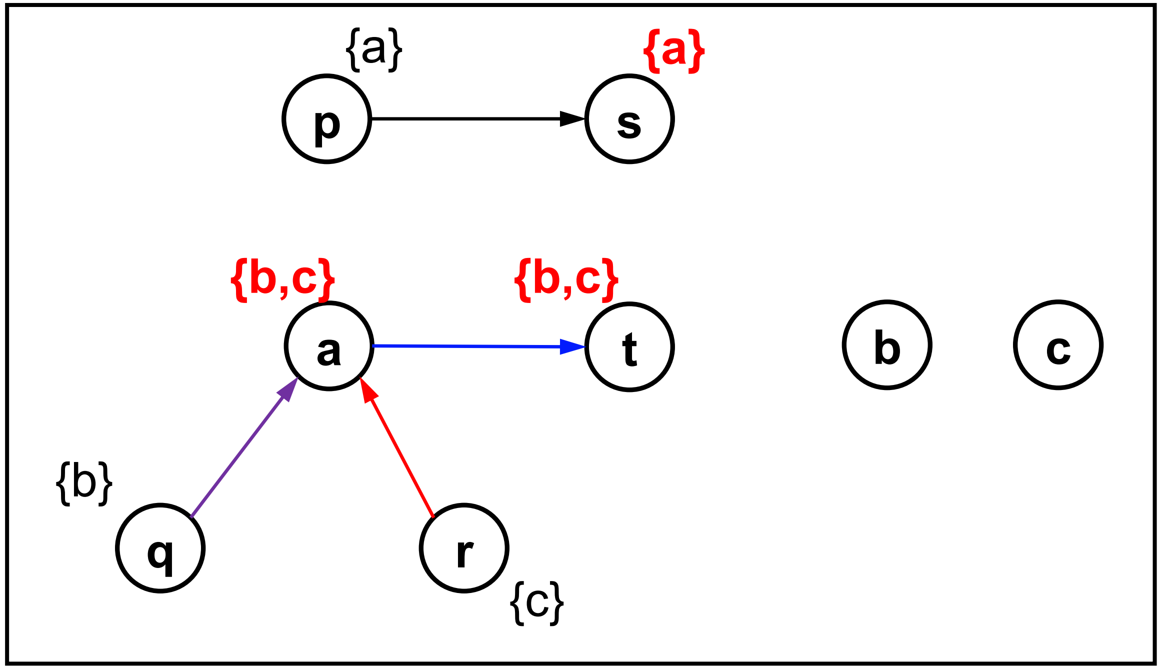

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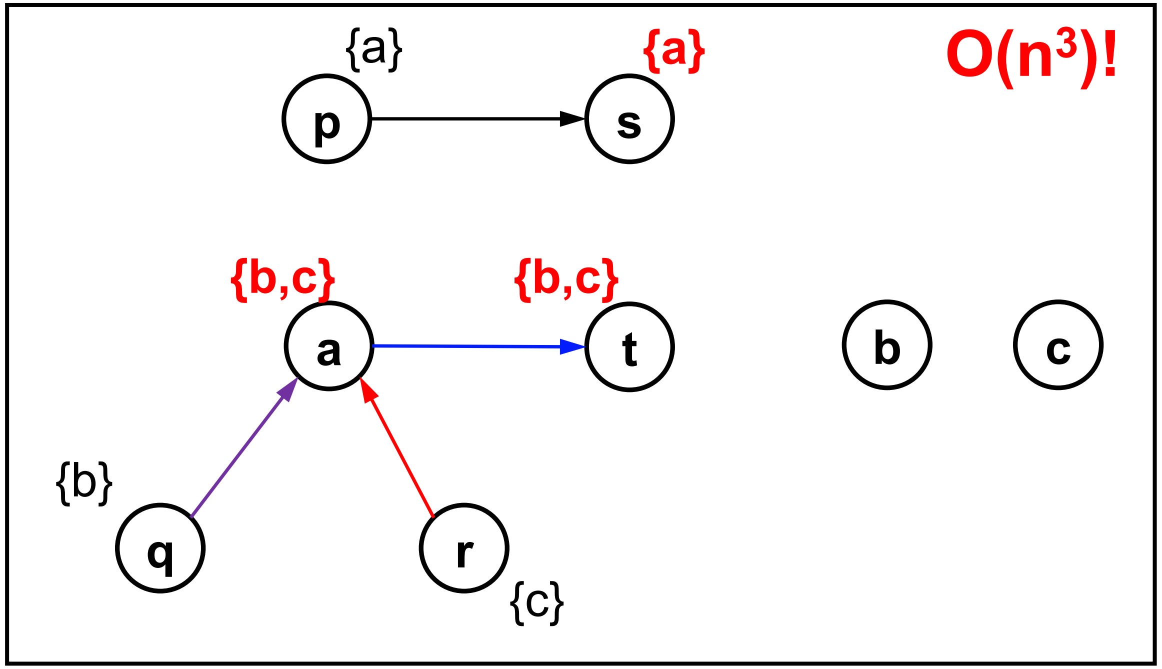

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s  = p;
t  = *p;
*s = r;
```

```
...
...
pts(*p) ⊇ pts(q)
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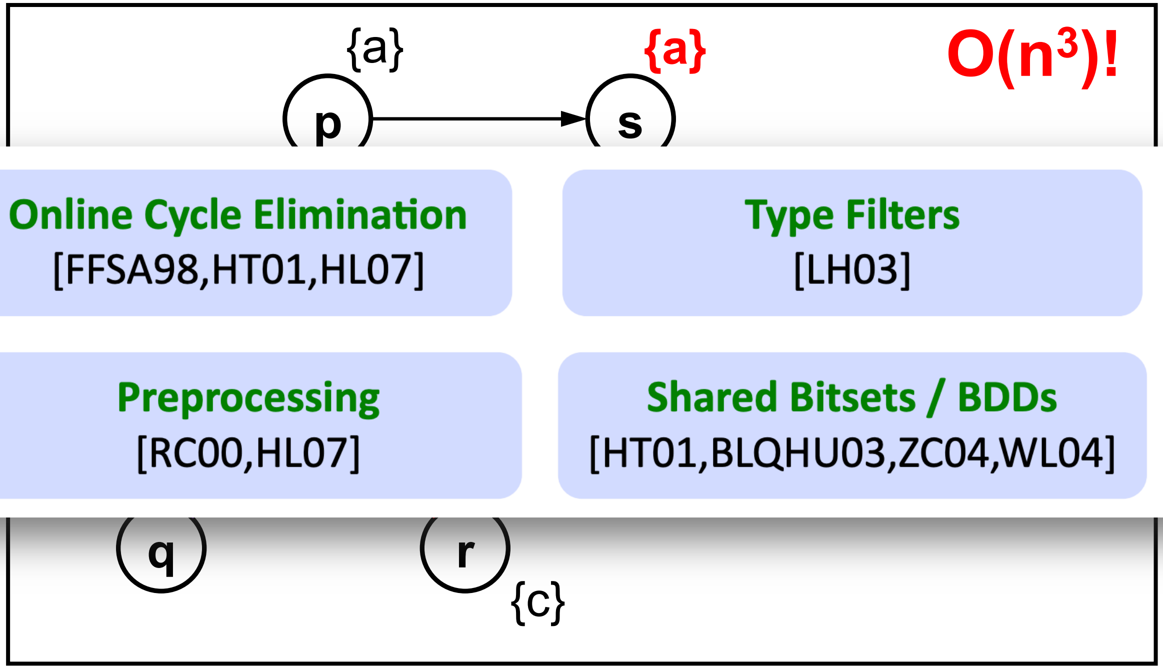

Online Cycle Elimination
[FFSA98,HT01,HL07]

Type Filters
[LH03]

Preprocessing
[RC00,HL07]

Shared Bitsets / BDDs
[HT01,BLQHU03,ZC04,WL04]

Steensgaard's Algorithm

Inclusion-based pointer analysis (Andersen's Algorithm)

Statement	Constraint	Shorthand
y = &x	pts(y) ⊇ {x}	
y = x	pts(y) ⊇ pts(x)	
*y = x	∀ v ∊ pts(y): pts(v) ⊇ pts(x)	pts(*y) ⊇ pts(x)
y = *x	∀ v ∊ pts(x): pts(y) ⊇ pts(v)	pts(y) ⊇ pts(*x)

Steensgaard’s Algorithm

Inclusion-based pointer analysis (Andersen’s Algorithm)

Statement	Constraint	Shorthand
y = &x	$pts(y) \supseteq \{x\}$	
y = x	$pts(y) \supseteq pts(x)$	
*y = x	$\forall\ v \in pts(y)$: $pts(v) \supseteq pts(x)$	$pts(*y) \supseteq pts(x)$
y = *x	$\forall\ v \in pts(x)$: $pts(y) \supseteq pts(v)$	$pts(y) \supseteq pts(*x)$

Unification-based pointer analysis (Steensgaard’s Algorithm)

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y = &x	$pts(y) \supseteq \{x\}$	
y = x	$pts(y) = pts(x)$	
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y = *x	$\forall\ v \in pts(x)$: $pts(y) = pts(v)$	$pts(y) = pts(*x)$

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- **Points-to graph**: x → y means y ∊ pts(x).

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Steensgaard's algorithm: One node, one out-going edge!

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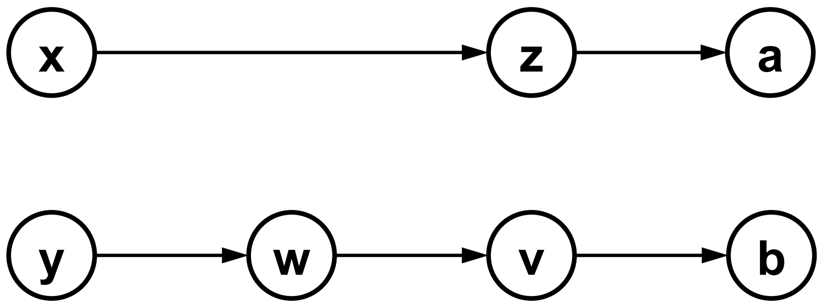

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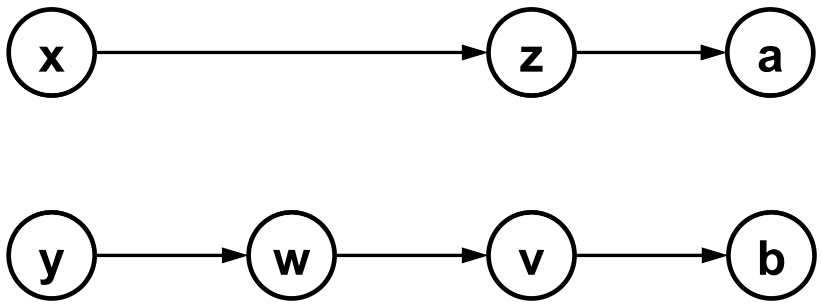

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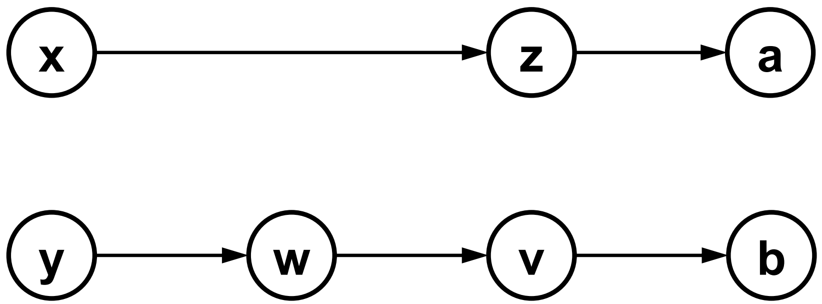

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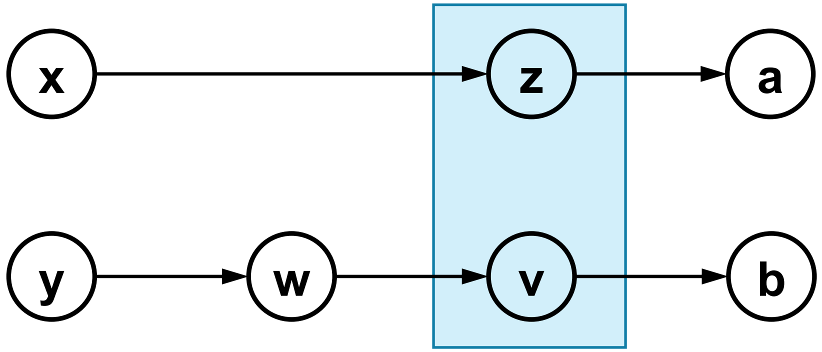

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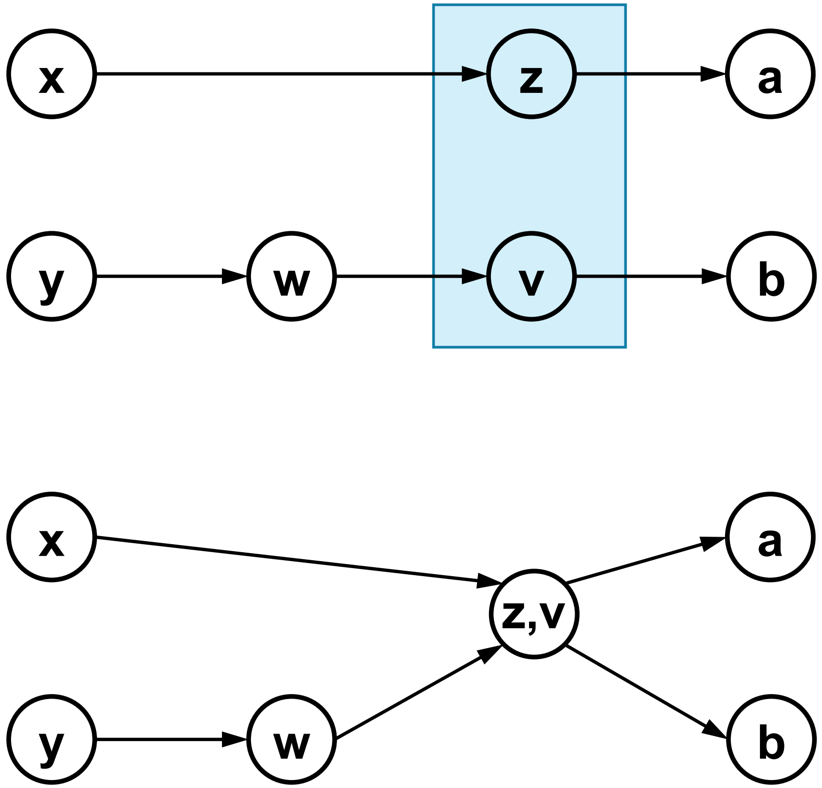

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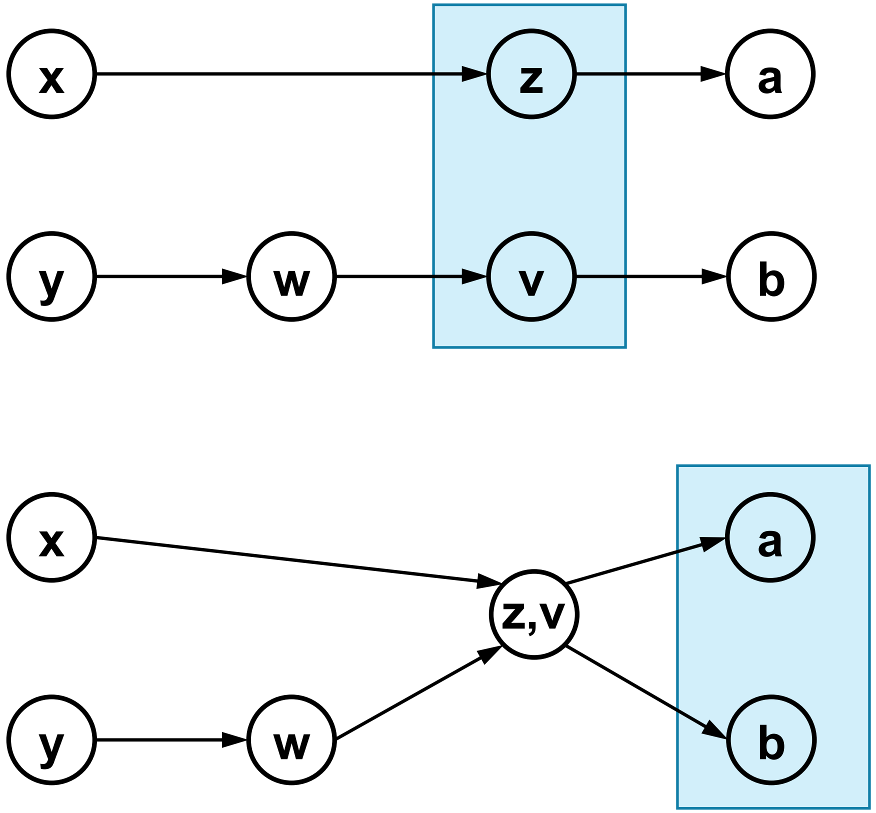

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⇦ x = *y

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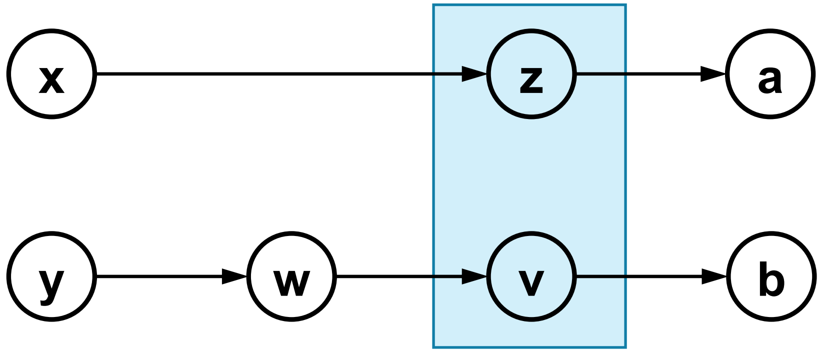

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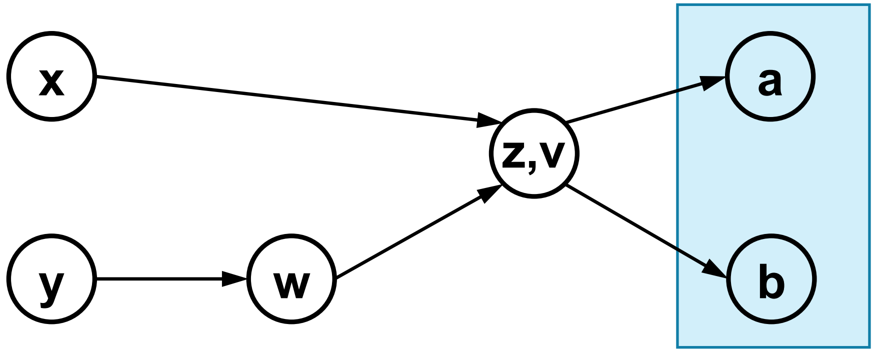

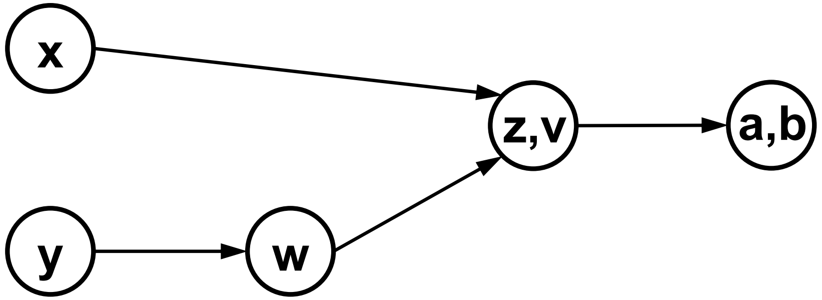

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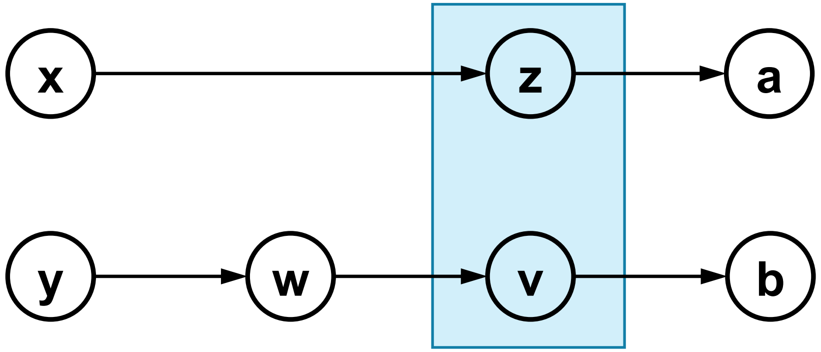

Steensgaard’s algorithm: One node, one out-going edge!

x = *y

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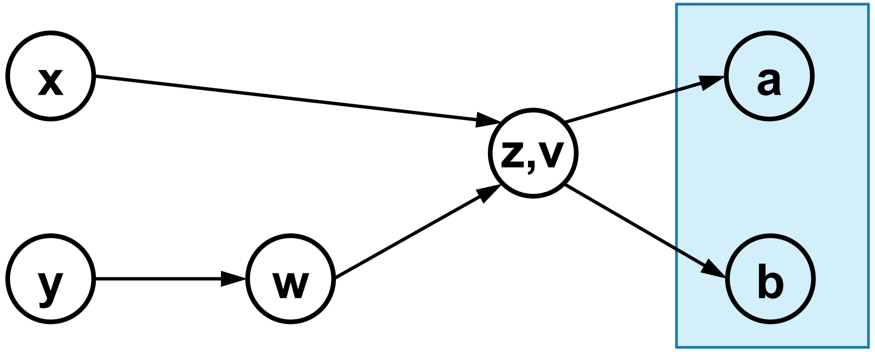
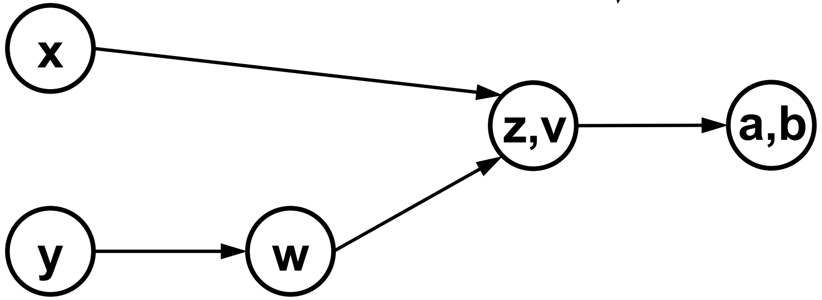
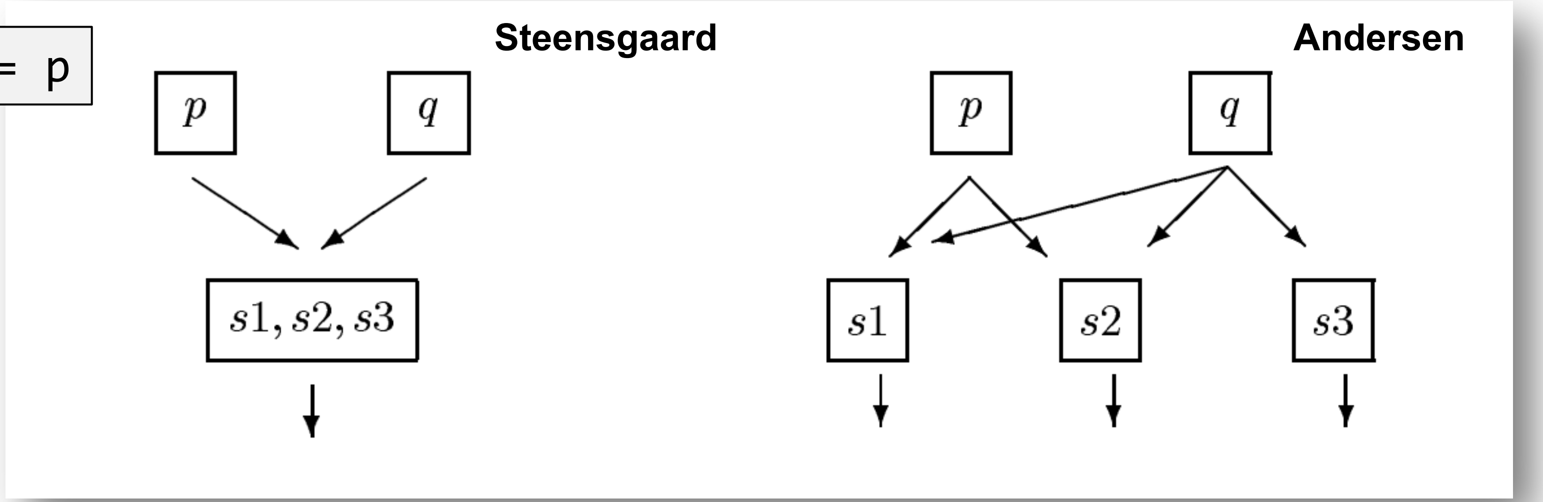
Disjoint-Set
Union-Find





Steensgaard’s Algorithm

```
q = p
```



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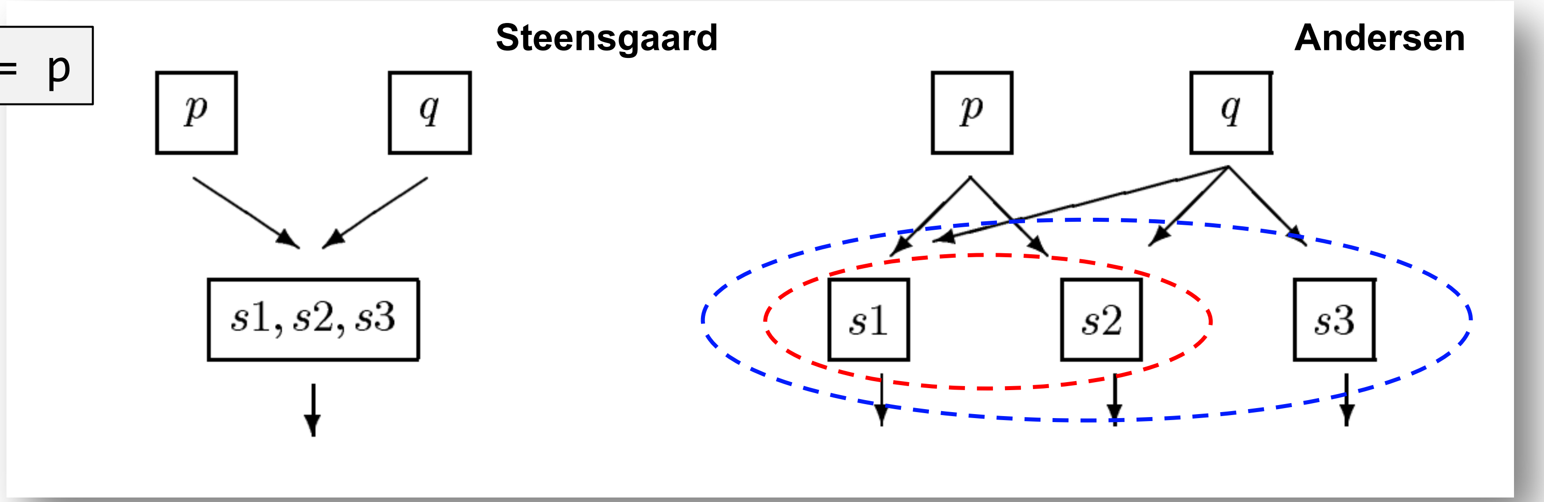

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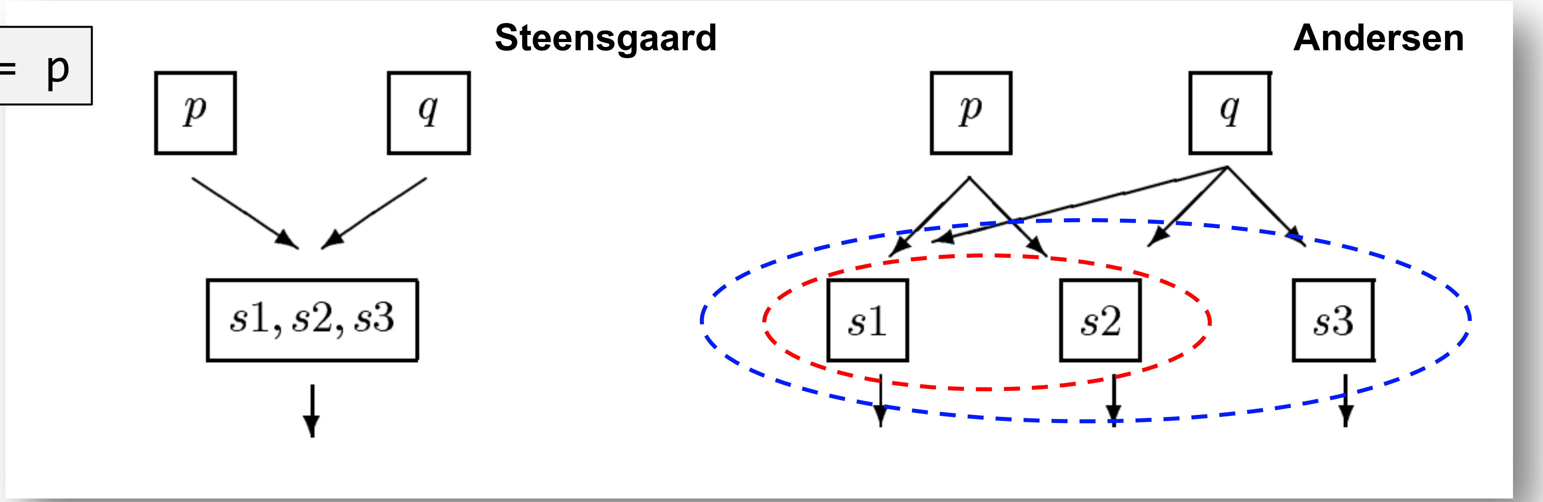
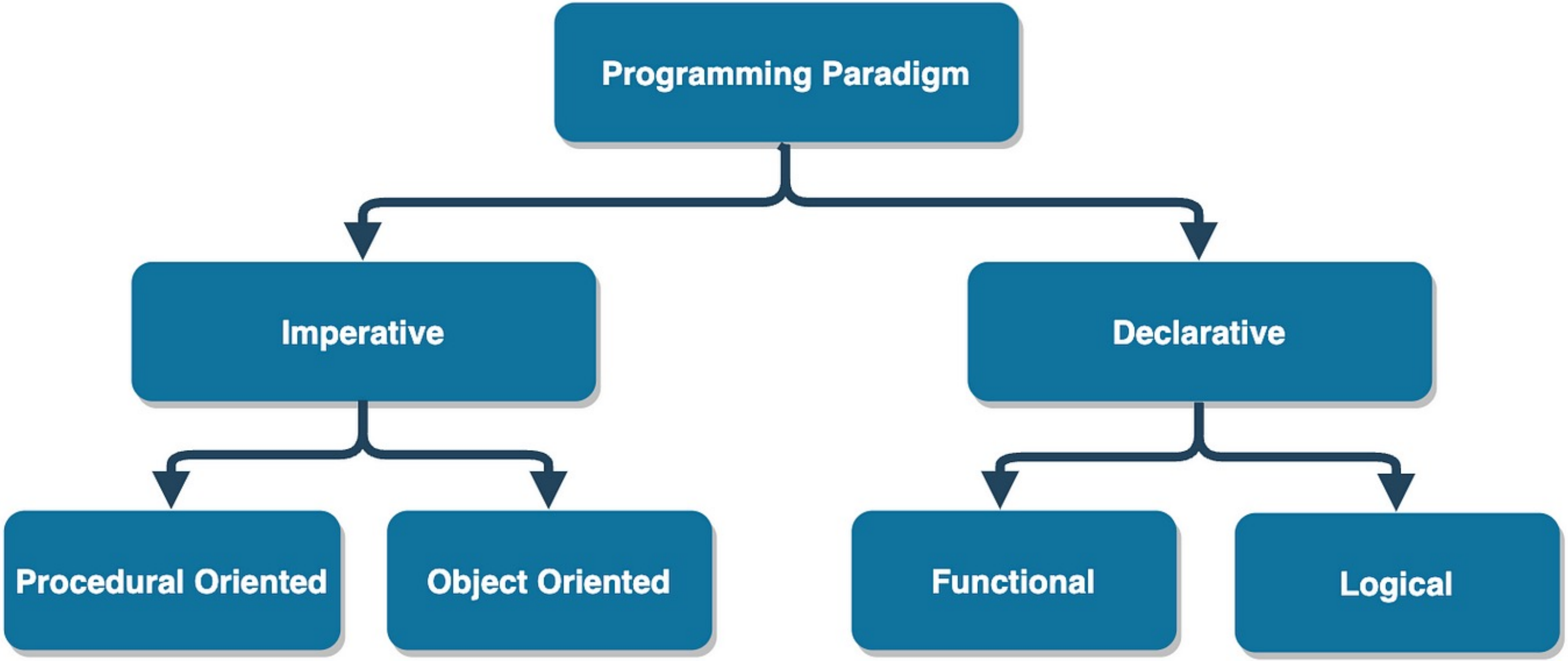


Steensgaard	Andersen
Sound	Sound
Almost linear (more efficient)	Nearly cubic
Unification-based (less precise)	Inclusion-based

PART IV: Datalog-Based DFA

Recap: Programming Paradigm



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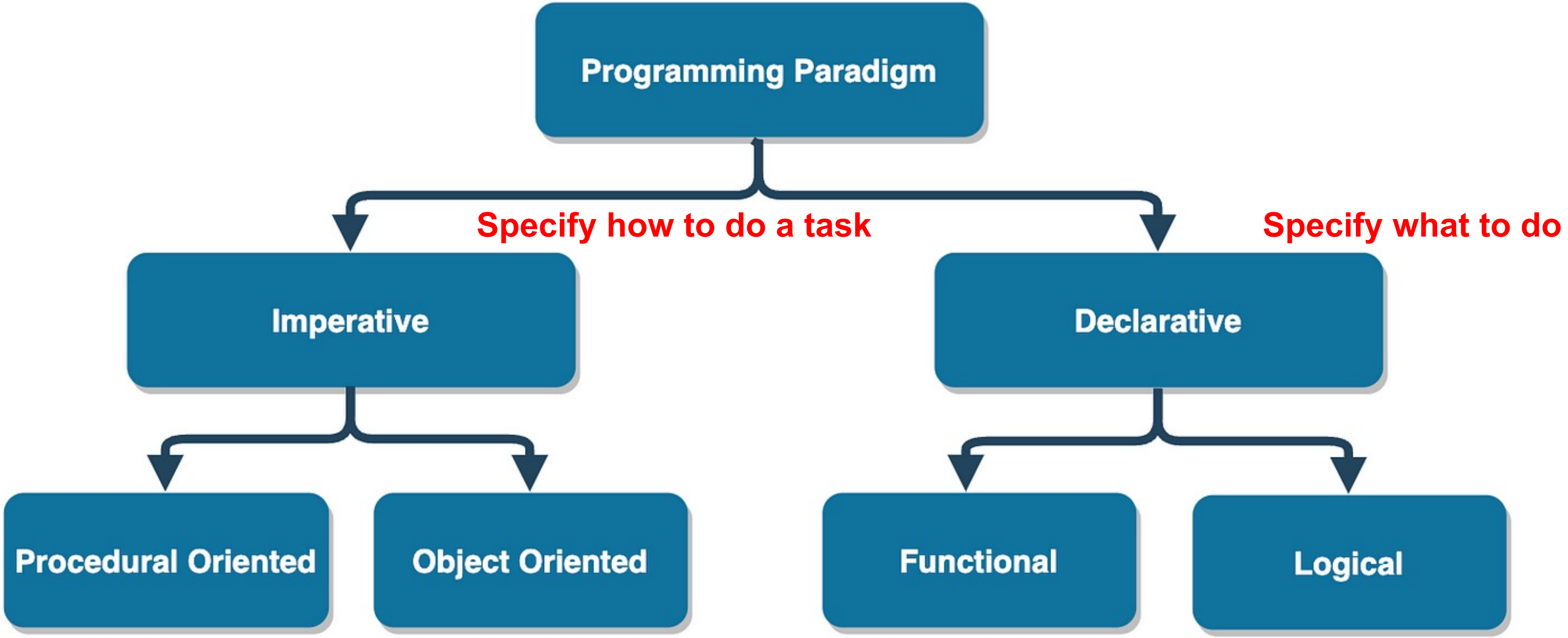

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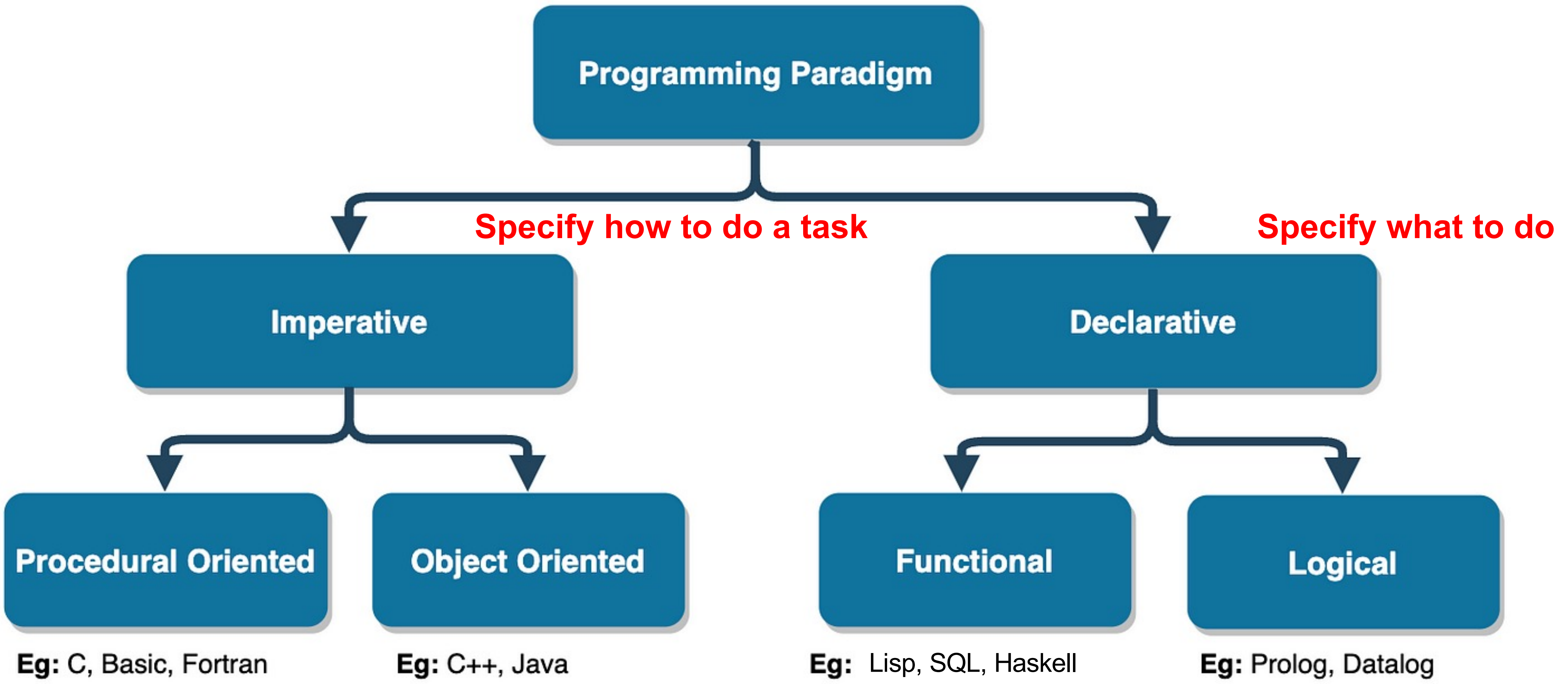

Logic Programming

- Logic programming
  - In a broad sense: the use of mathematical logic for programming

Logic Programming

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  - In a broad sense: the use of mathematical logic for programming

- Prolog (1972)
  - Use logical rules to specify how mathematical relations are computed
  - A prolog program is a database of logical rules

Logic Programming

- Example:
  - Nanjing is rainy
  - Beijing is rainy
  - Beijing is cold
  - If a city is both rainy and cold, then it is snowy

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  - **Query:** which city is snowy

Logic Programming

- Example:
  - Nanjing is rainy
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Facts

Rules

  - **Query:** which city is snowy
  - Search for solutions based on facts and rules

Logic Programming

- Expert systems
- Natural language processing
- Theorem provers
- Reasoning about safety a security
- **Program analysis/Compiler optimization**

What is Datalog?

- Datalog is a subset of Prolog
  - All Datalog programs terminate
  - Ordering of rules does not matter
  - Not Turing complete

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- Souffle Datalog engine --- https://souffle-lang.github.io/
  - .decl rainy (c:symbol)
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  - .decl snowy(c:symbol)
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  - .decl rainy (c:symbol)
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  - rainy(“Nanjing”)
  - rainy(“Beijing”)
  - cold(“Beijing”)
  - snowy(c) :- rainy(c), cold(c)

Predicate/Atom

- Predicates are N-ary relations
  - predicate(x, y, z)

- Examples
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  - rainy(“Nanjing”)
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  - brother(x, y) -- x is y’s brother
  - speaks(x, a) -- x speaks language a

Datalog Programming Model

- A Datalog program is a database of Horn clauses
  - h is true **if** the assumptions l_1 l_2 … l_n are simultaneously true
  - **if** --- a sufficient but not necessary condition

$$h \ :\text{-}\ l_1\ l_2\ \ldots\ l_n$$

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```
h :- l1 l2 … ln
```

- **Example:**
  - rainy("Nanjing")
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Datalog Programming Model

- All rules hold for any instantiation of its variables
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- Ordering of rules does not matter for results (Prolog vs. Datalog)
- Rules may be recursive
  - reachable(a, b) :- edge(a, b);
  - reachable(a, c) :- edge(a, b), reachable(b, c)

Datalog Programming Model

- Negation is allowed in assumptions
  - more_than_one_hop(a, b) :- reachable(a, b), ¬edge(a, b)

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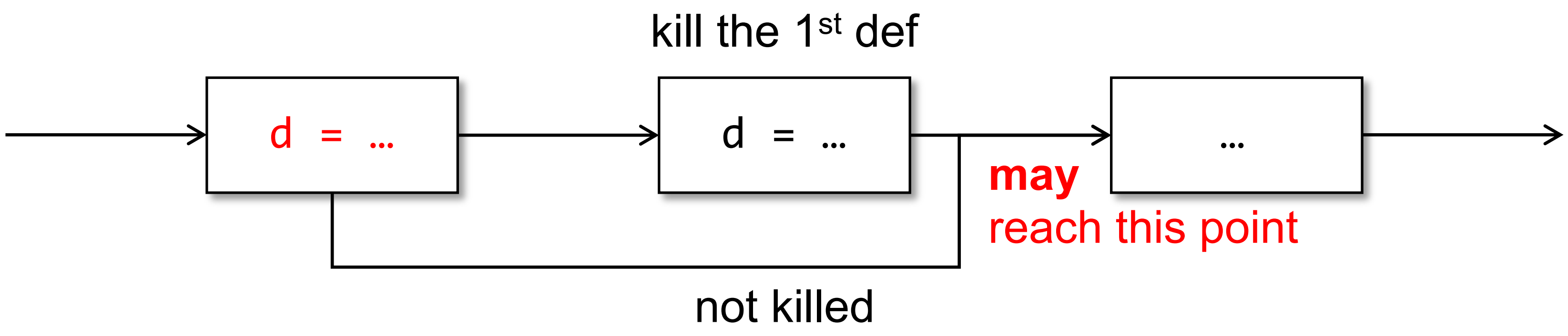
- All rules must be well-formed. Example of bad rules:
  - more_than_one_hop(a, b) :- ¬edge(a, b)
  - **Bad:** a, b on the left do not appear in the positive predicate on the right
  - **Goal:** to ensure termination

Reaching Definitions by Datalog

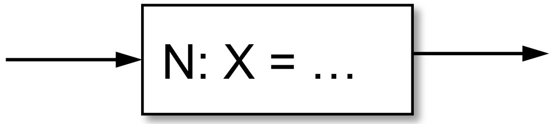
Recap: Reaching Definition

- A definition *d* may reach a program point, if there is a path from *d* to the program point such that *d* is not killed along the path.



Reaching Definitions by Datalog

- def(B, N, X)
  - the Nth statement in Block B may define the variable X.



Block B

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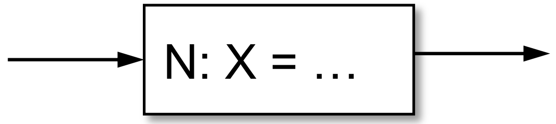

Block B

- succ(B, N, C)
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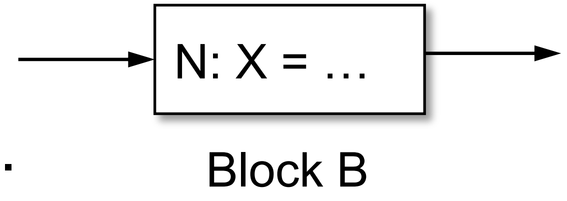
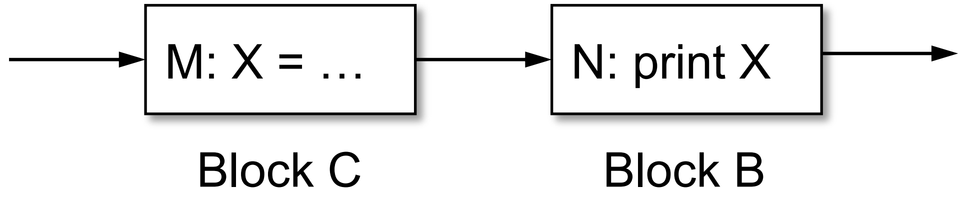


- succ(B, N, C)
  - block C is a successor of block B, and B has N statements.

- rd(B, N, C, M, X)
  - the definition of variable X at the Mth statement of block C reaches the Nth statement in B.



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- rd(B, 0, C, M, X) :- rd(D, N, C, M, X), succ(D, N, B)

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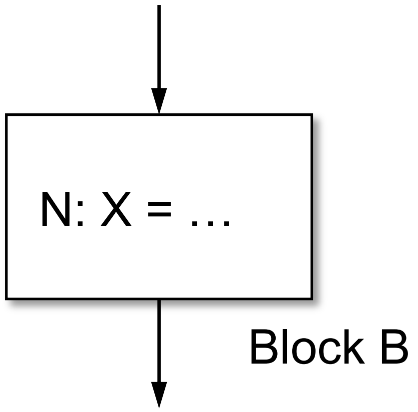

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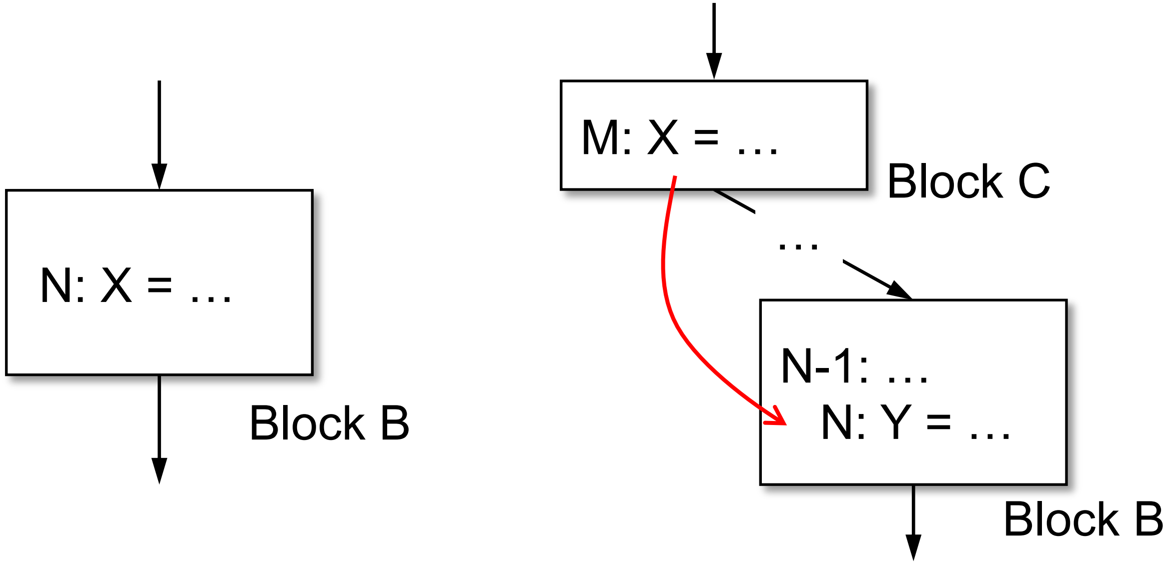

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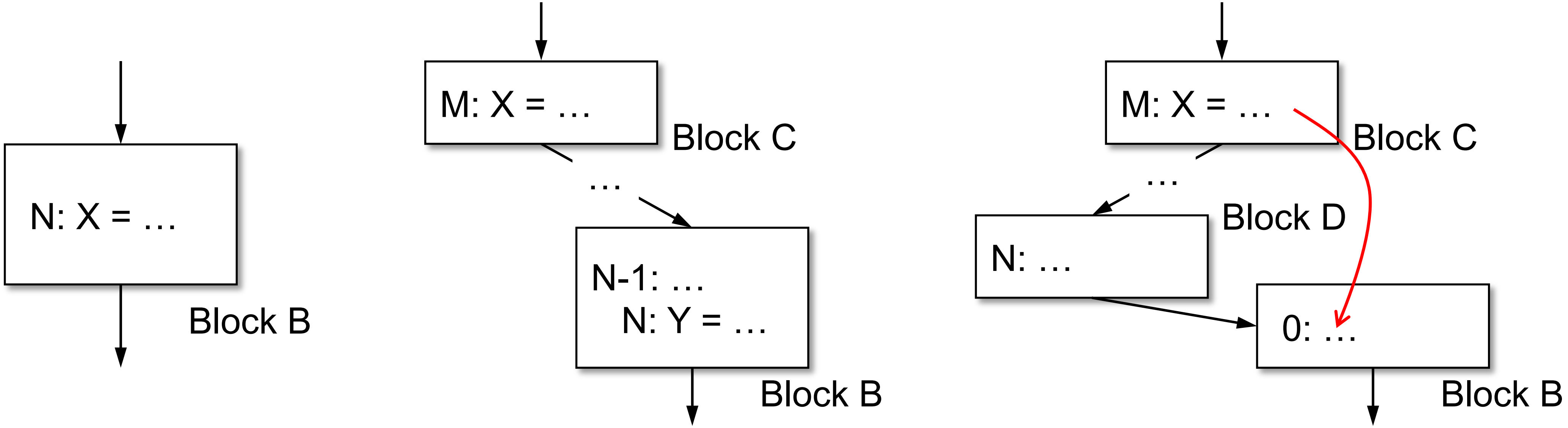

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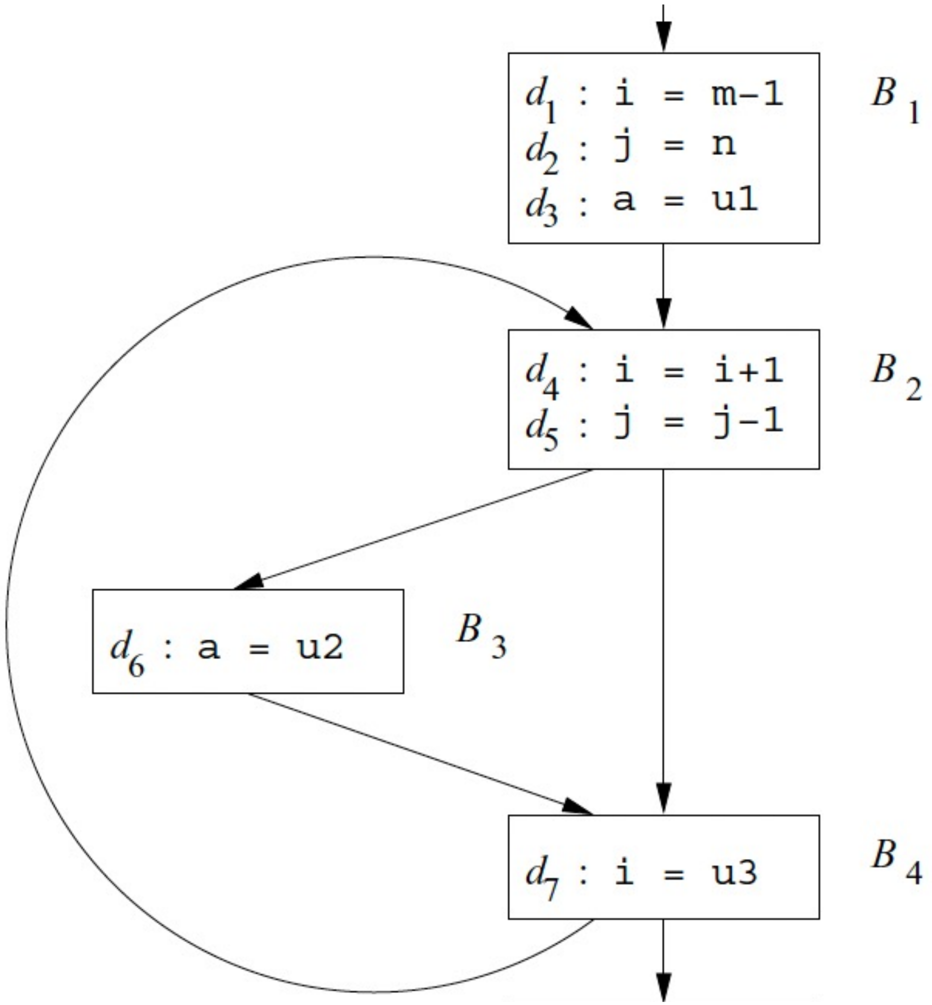

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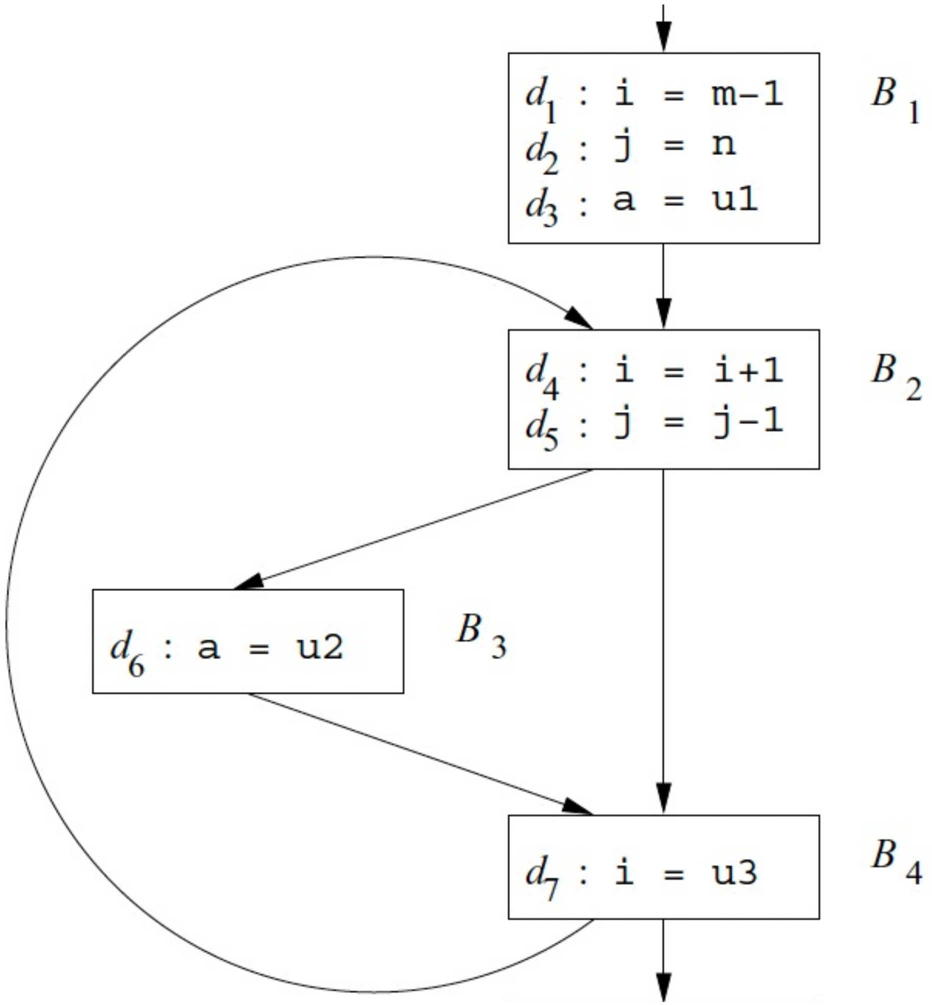
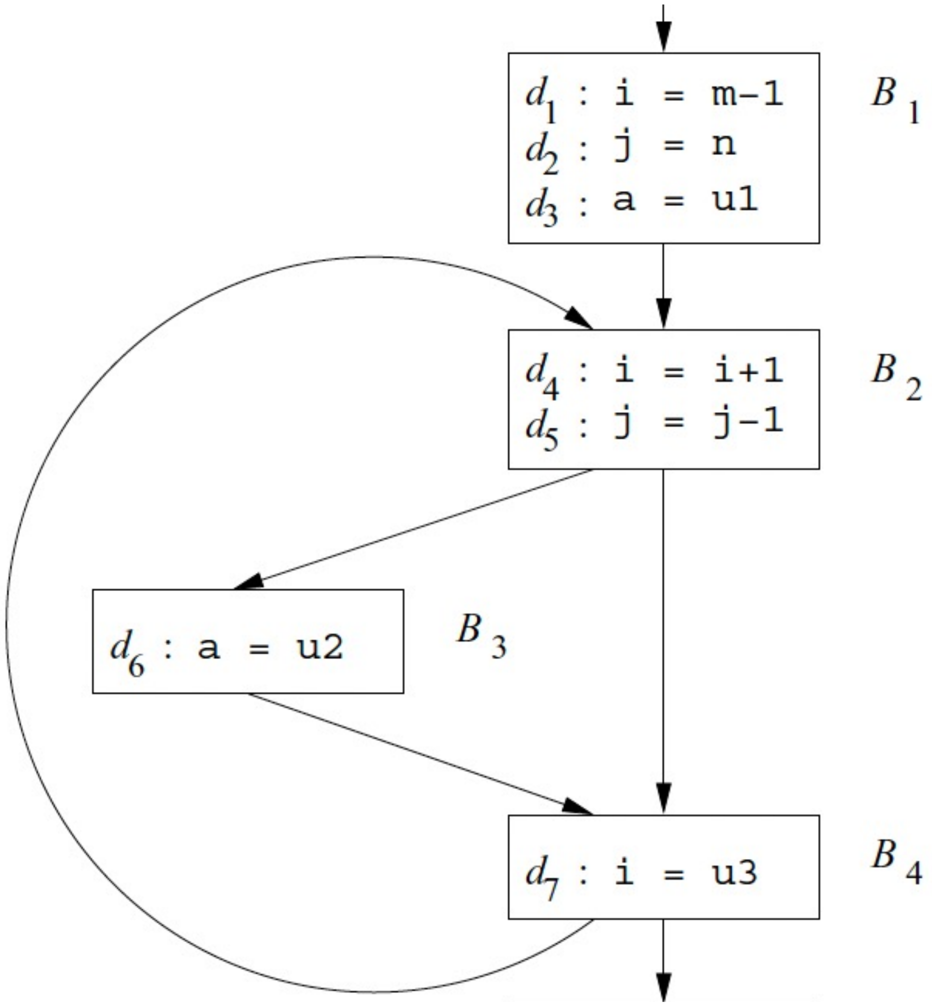


- def(B_1, 1, i)
- def(B_1, 2, j)
- def(B_1, 3, a)
- def(B_2, 1, i)
- def(B_2, 2, j)
- def(B_3, 1, a)
- def(B_4, 1, i)

Reaching Definitions by Datalog



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- def(B_4, 1, i)

- succ(B_1, 3, B_2)
- succ(B_2, 2, B_3)
- succ(B_2, 2, B_4)
- succ(B_3, 1, B_4)
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Reaching Definitions by Datalog

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Reaching Definitions by Datalog

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- rd(B
- rd(B

We just define facts and rules.
Analysis is automatically done by Datalog engines!

- def(B_1, 1, i)
- def(B_1, 2, j)
- def(B_1, 3, a)
- def(B_2, 1, i)
- def(B_2, 2, j)
- def(B_3, 1, a)
- def(B_4, 1, i)
- succ(B_1, 3, B_2)
- succ(B_2, 2, B_3)
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Reaching Definitions by Datalog

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Query Example: rd(B_4, 1, B_1, 1, i)

- def(B_1, 1, i)
- def(B_1, 2, j)
- def(B_1, 3, a)
- def(B_2, 1, i)
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Pointer Analysis by Datalog

Pointer Analysis by Datalog

- Four kinds of Java statements and ignore procedural call
- **Object creation.** h: T v = **new** T();
- **Copy.** v = w;
- **Field store.** v.f = w;
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- pts(V, H) variable V can point to a heap object H
- hpts(H, F, G) field F of heap object H can point to heap obj G

Pointer Analysis by Datalog

$$
\begin{array}{lrll}
1) & pts(V,H) & \texttt{:-} & \text{“}H:\ T\ V\ = \texttt{new}\ T\text{”} \\
2) & pts(V,H) & \texttt{:-} & \text{“}V = W\text{”}\ \& \\
 & & & pts(W,H) \\
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Pointer Analysis by Datalog

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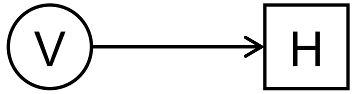

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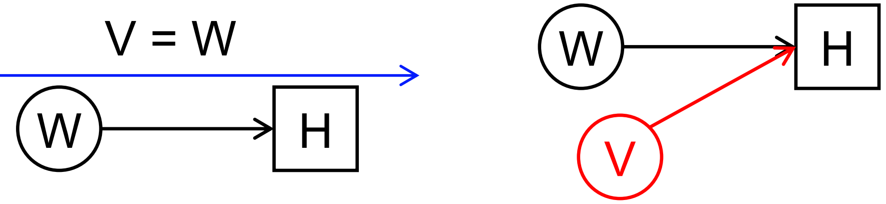

Pointer Analysis by Datalog

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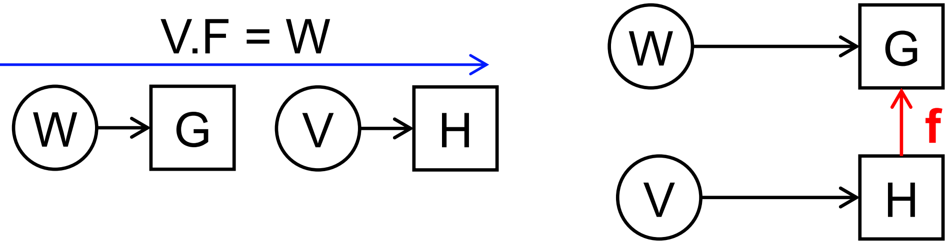

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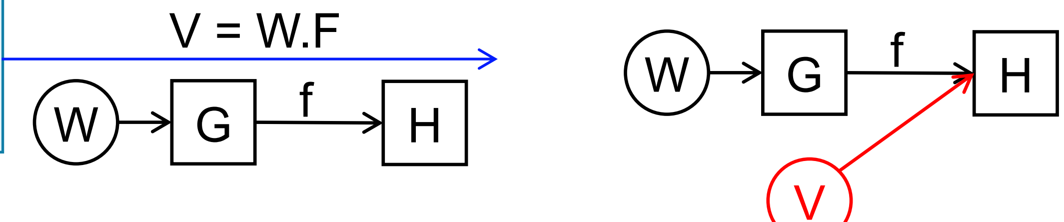

Interprocedural Pointer Analysis

- Dealing with method invocation in Java programs
- x = y.n(z)

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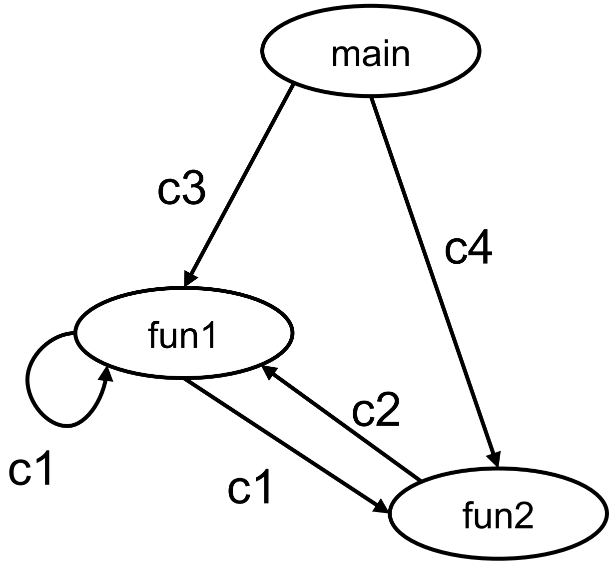
It is **context-insensitive** as we always do the same thing when calling a function, i.e., do not distinguish different call sites of the same function

Context-Sensitive Pointer Analysis



Call chains:
- c_3-c_1-…
- c_4-c_2-c_1-…
- …

- Assume we already have the call graph.
- Calling context:
  - call chains, paths in the graph

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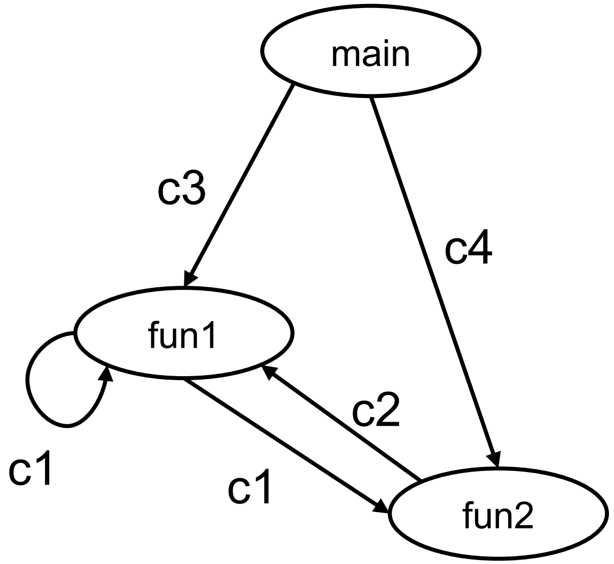

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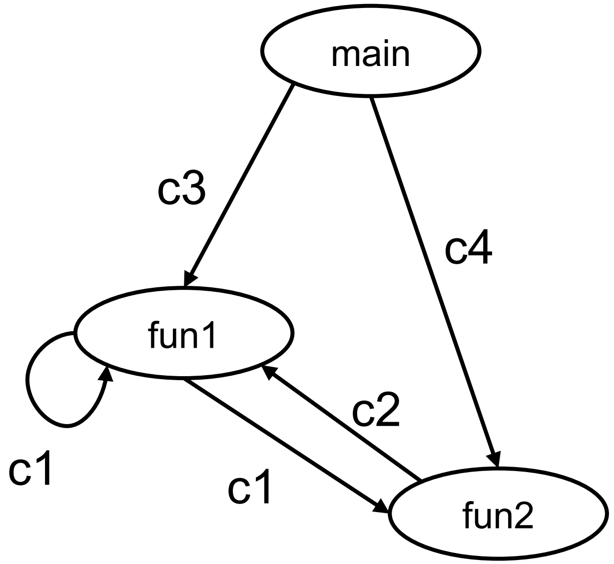

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- Assume we already have the call graph.
- Calling context:
  - call chains, paths in the graph
- Context-sensitive analysis:
  - analyze functions in different calling context
- **Difficulty**: Infinite # calling contexts
- **Solution**: restrict the length of call chains

Context-Sensitive Pointer Analysis

- invokes(S, **C**, M, **D**)
- call site S in context C, invokes the method M of context D

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- V points to H in context C

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- hpts(H, F, G)
- same as before, field F of H points to G

Context-Sensitive Pointer Analysis

	Context-Insensitive	Context-Sensitive
1	pts(V, H) :- "H : T V = new T()"	pts(V, **C,** H) :- "H : T V = new T()", **invoke(H, C, _, _)**

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5	pts(V, H) :- invokes(S, M), formal(M, I, V), actual(S, I, W), pts(W, H)	pts(V, D, H) :- invokes(S, C, M, D), formal(M, I, V), actual(S, I, W), pts(W, C, H)

PART V: Object Sensitivity

Recap: Context Sensitivity

```
    class List {
        int x;
        void foo() {
c1          print(x);
        }
    }


    class A {
       void bar(List a) {
c2         a.foo();
c3         a.foo();
       }
       …
    }
```

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```

A context-sensitive analysis analyzes the call chains $\mathbf{c_2c_1}$; $\mathbf{c_3c_1}$ separately to distinguish the calling context.

Object Sensitivity

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A new form of context-sensitivity, especially for **OO programs**. It does not distinguish contexts based on call sites.

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A new form of context-sensitivity, especially for **OO programs**. It does not distinguish contexts based on call sites.

An object-sensitive analysis will not separately analyze $\mathbf{c_2c_1}$ and $\mathbf{c_3c_1}$, because they use the same object a.

No Silver Bullet

- Object-sensitivity is a tradeoff between precision and efficiency.

Ana Milanova, Atanas Rountev, Barbara Ryder.
Parameterized object sensitivity for points-to analysis for Java.
ACM Transactions on Software Engineering and Methodology, 14(1), 2005.
https://doi.org/10.1145/1044834.1044835

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Rice Theorem: It is impossible to decide a property of programs, which depends only on the semantics and not on the syntax, unless the property is trivial (true of all programs, or false of all programs).

THANKS!