Geometric Encoding

Forging the High Performance Context Sensitive Points-to Analysis for Java

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The prism research group, HKUST

Definition

- Points-to analysis:
  - A process to determine the set of variables that are possibly pointed-to by every pointer.

Points-to Analysis

- Does *list* point to object *o* ?

```
static void work() {
    Node list = init();
    Node list2 = createNewList();
}
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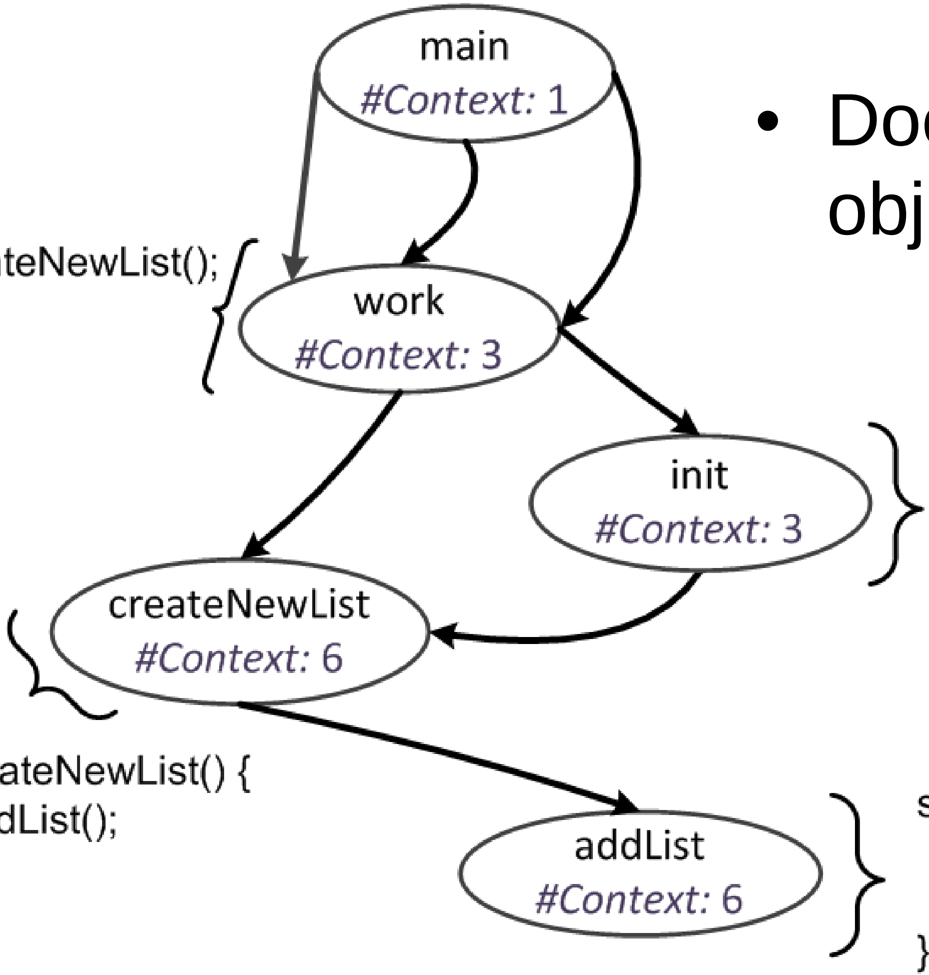

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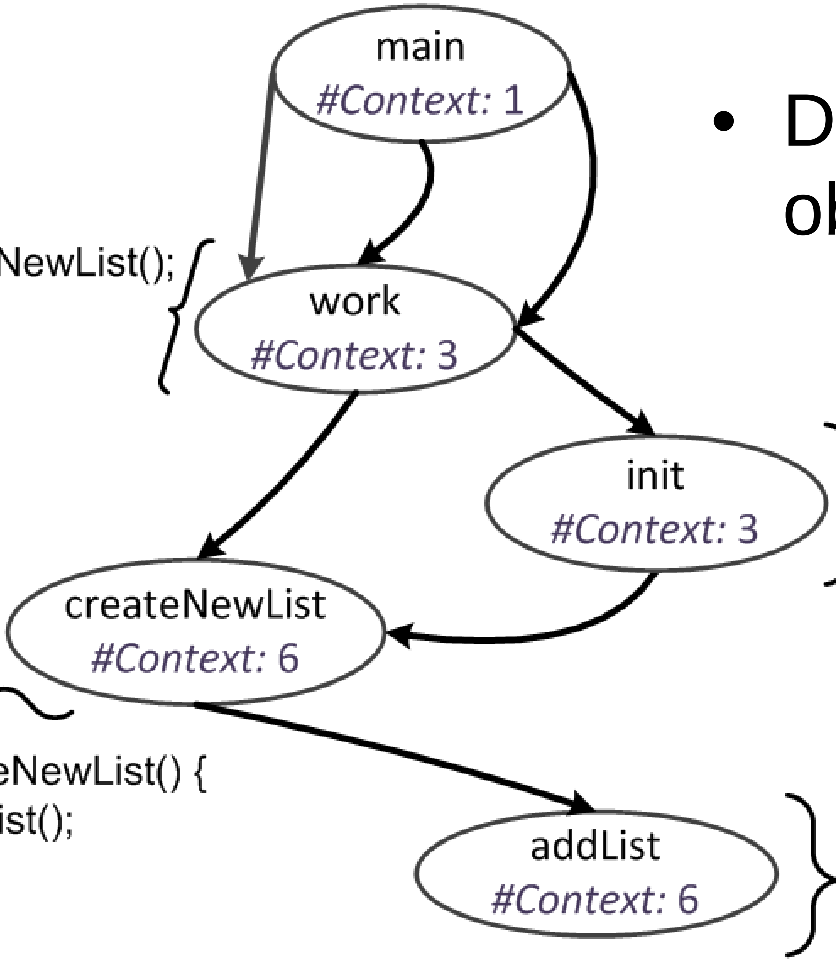

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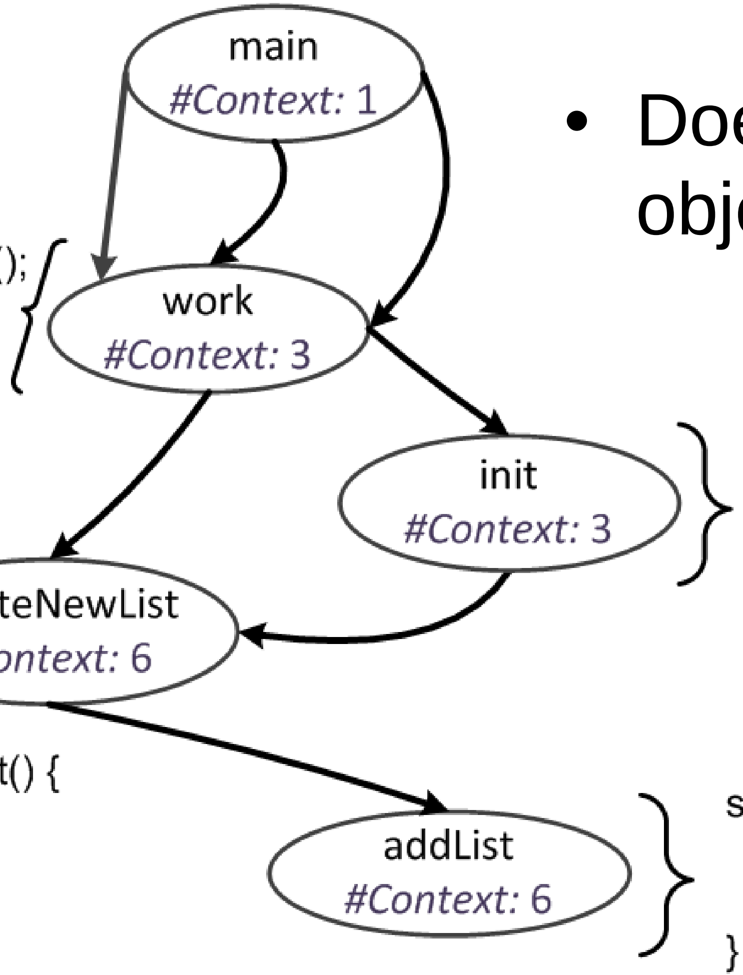

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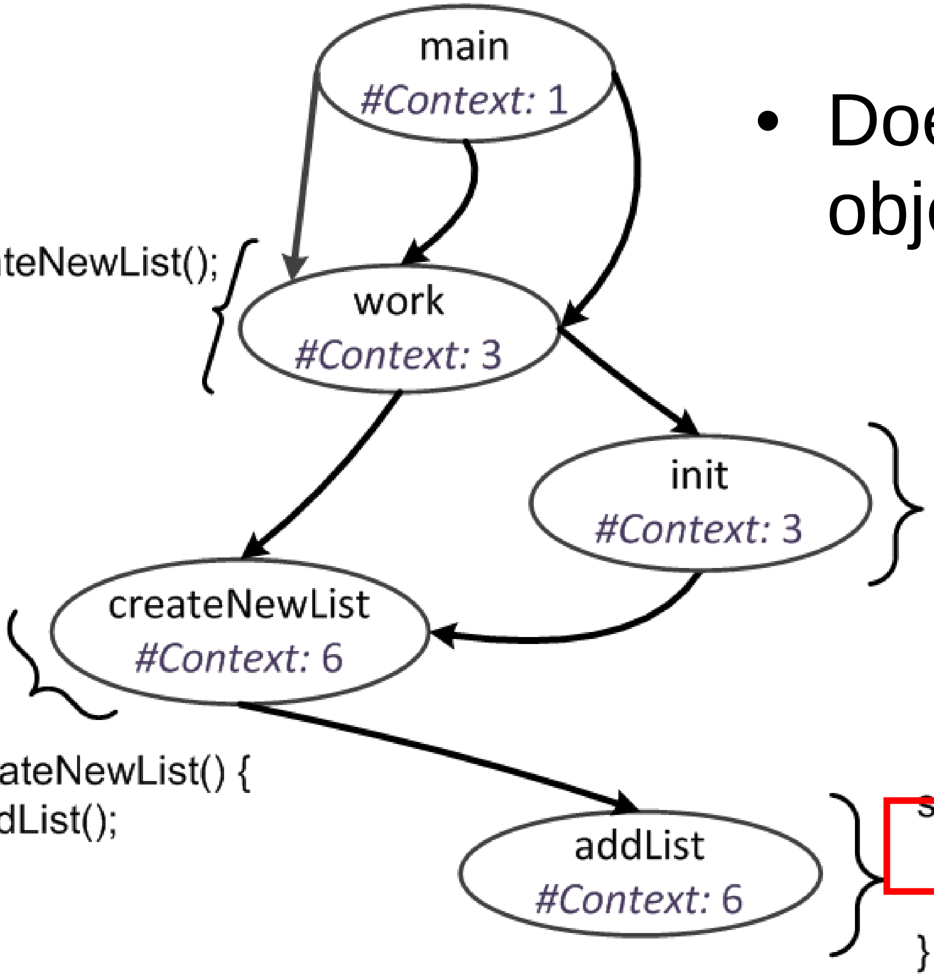

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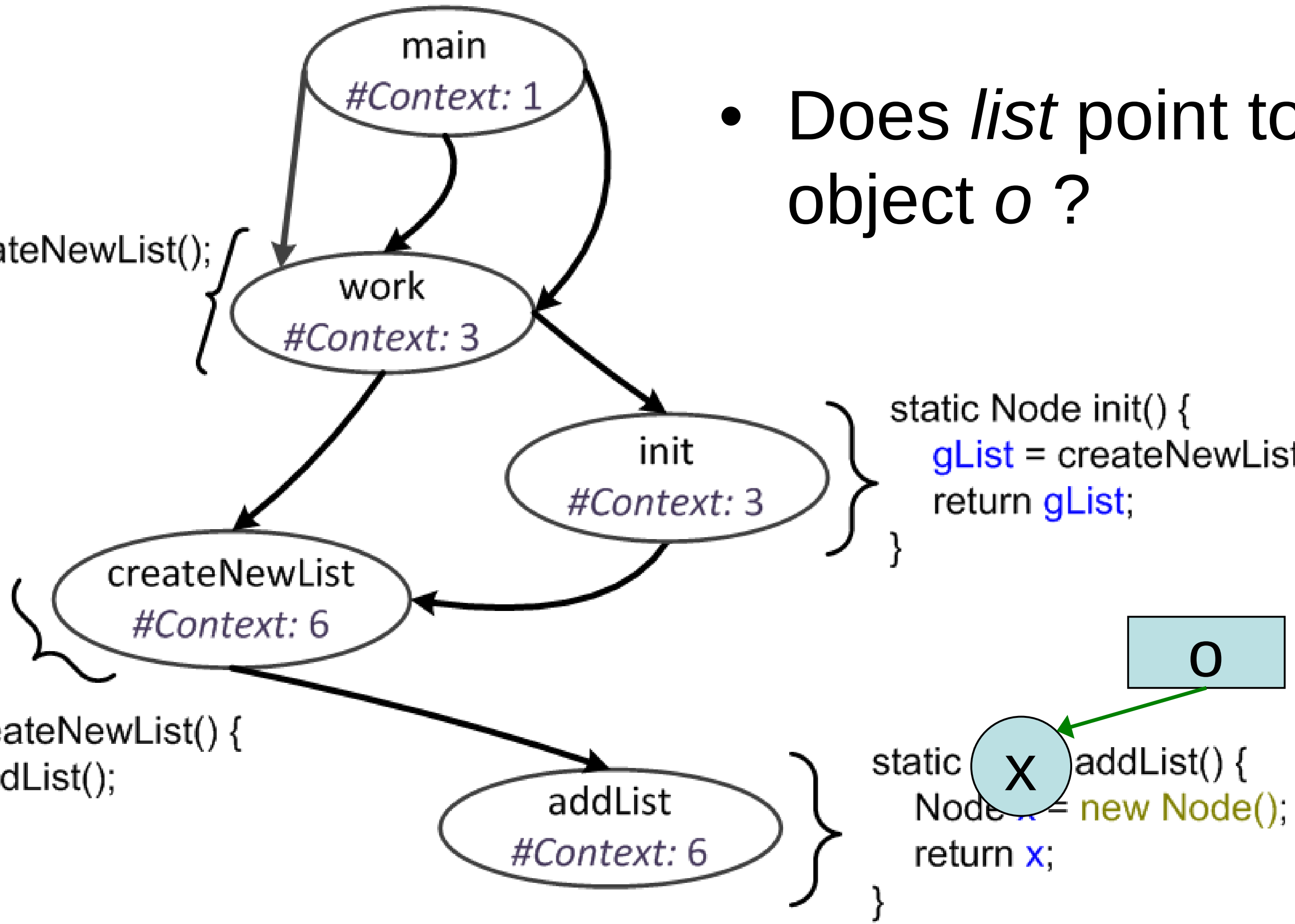

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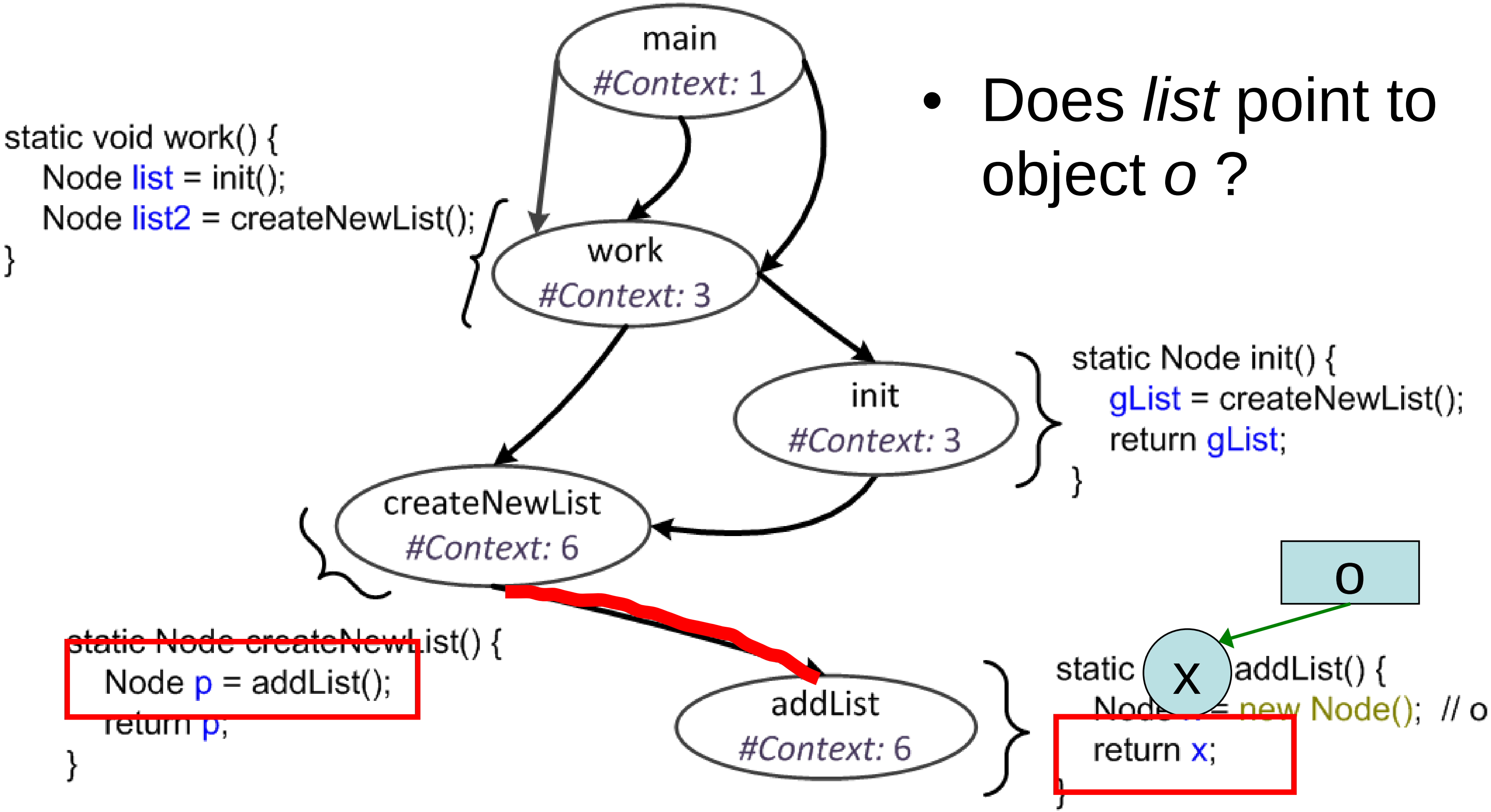

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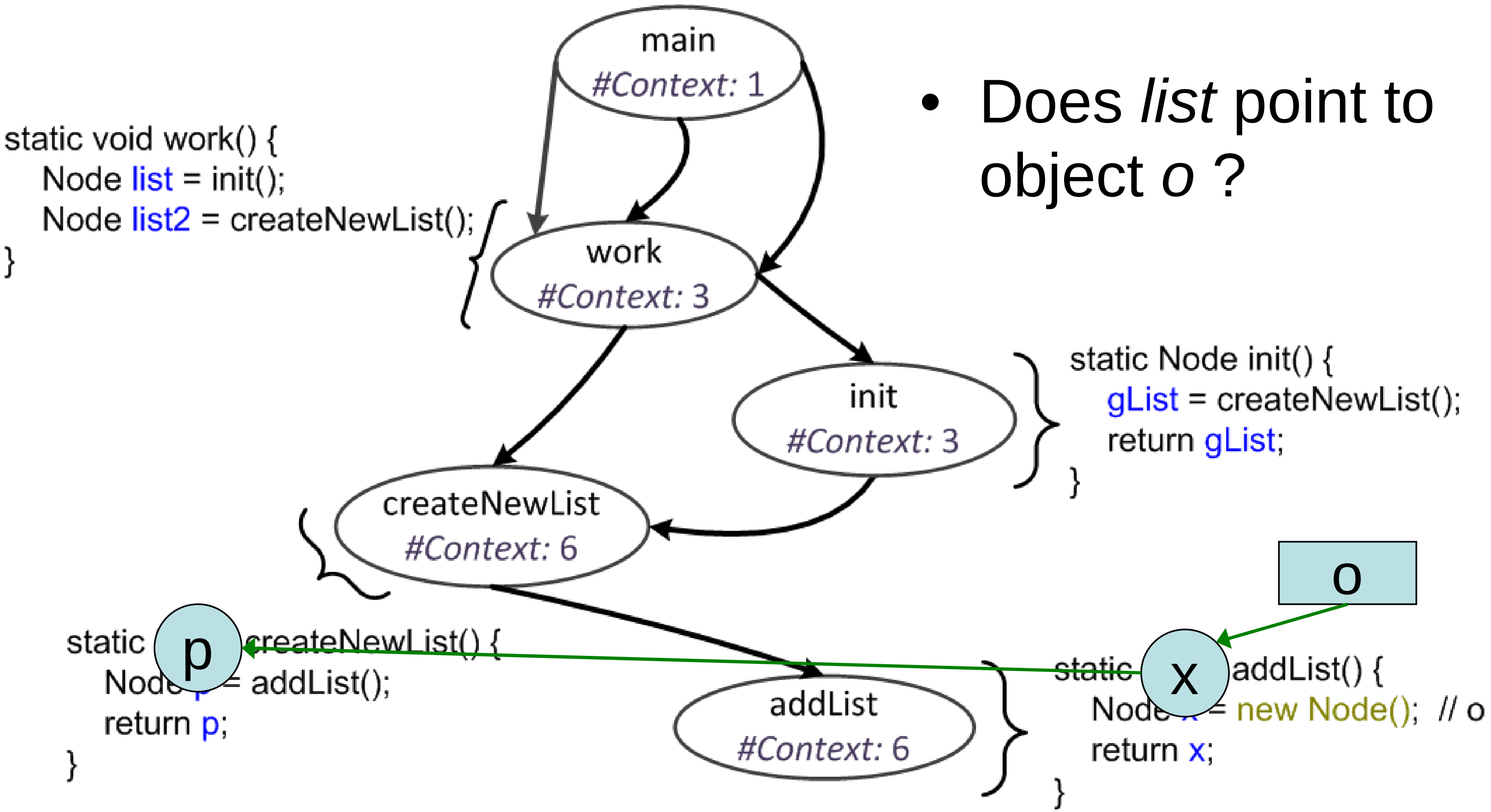

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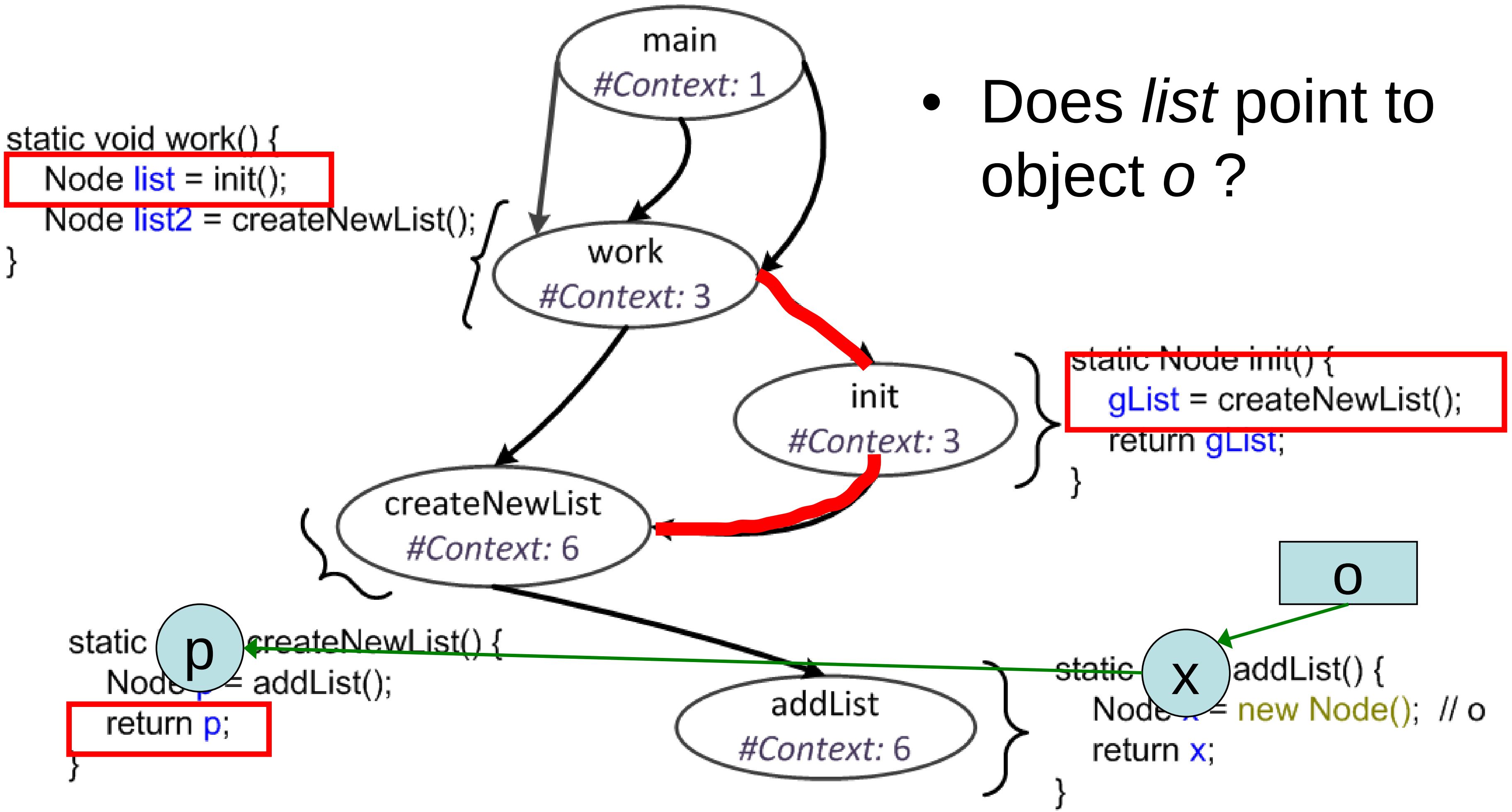

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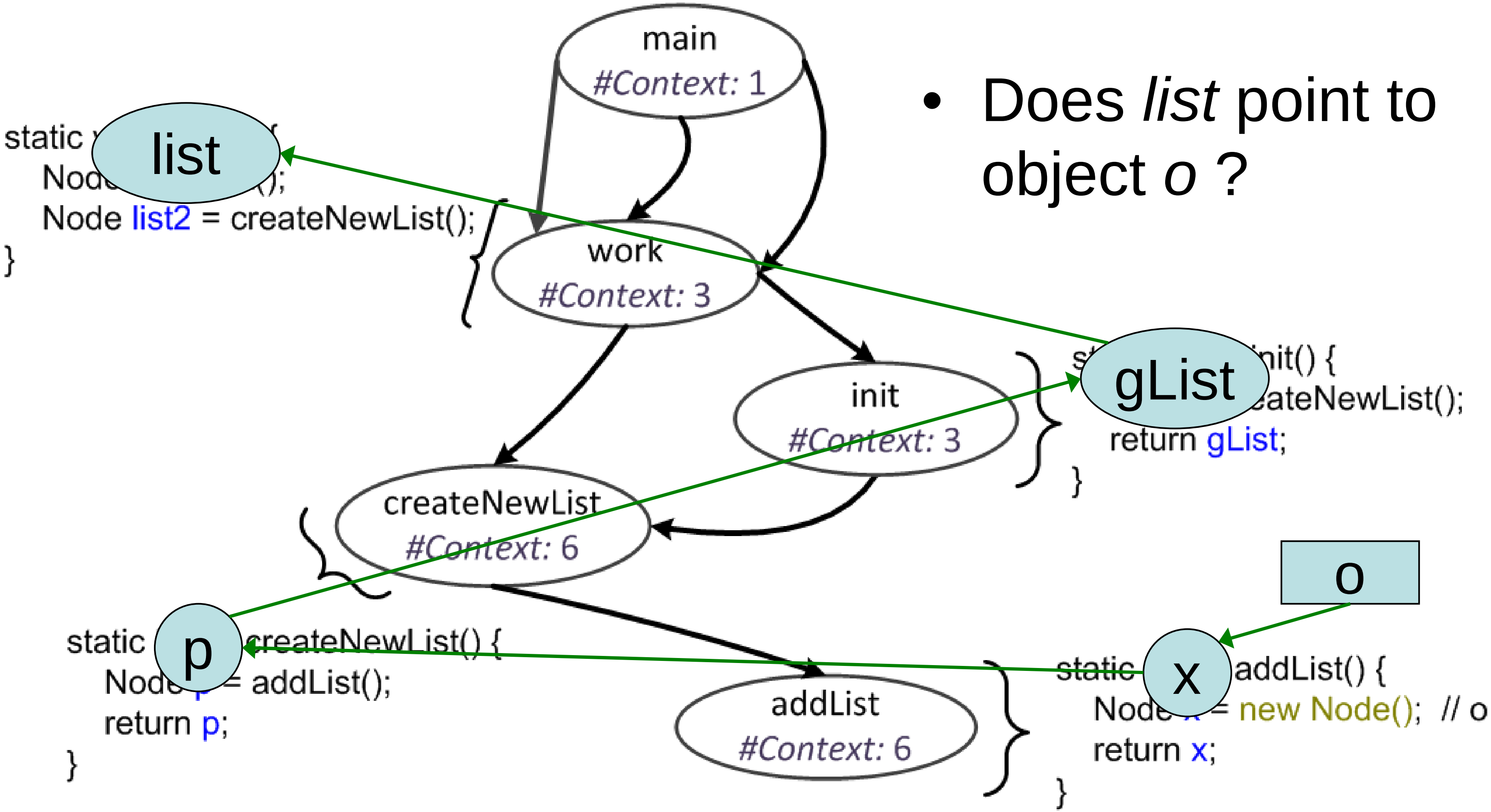

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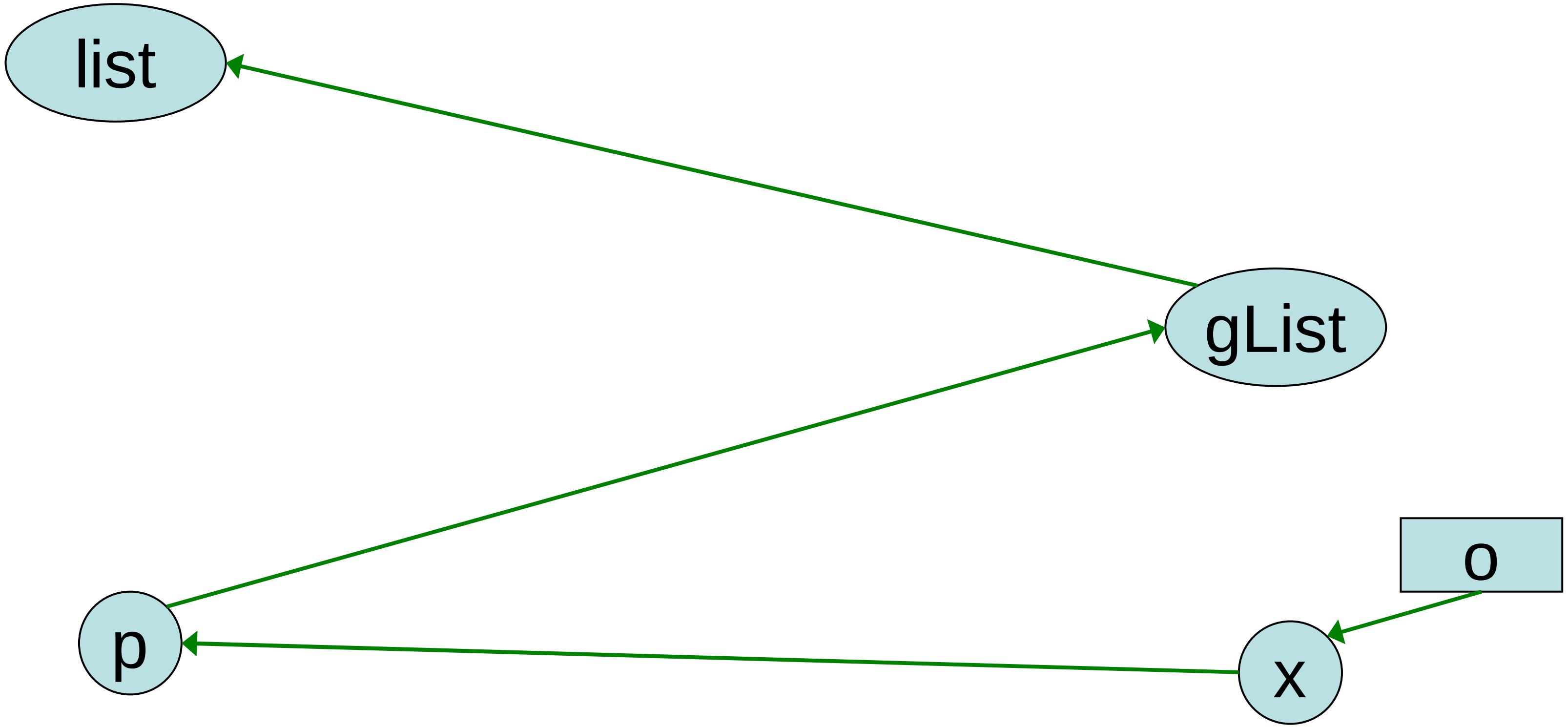

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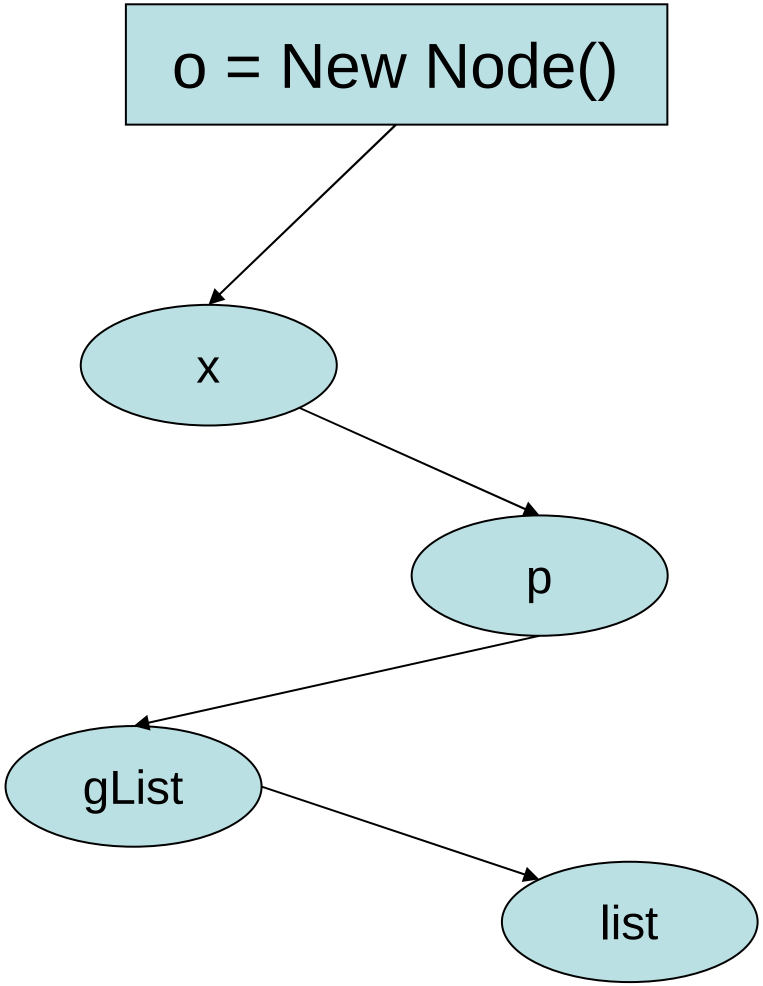
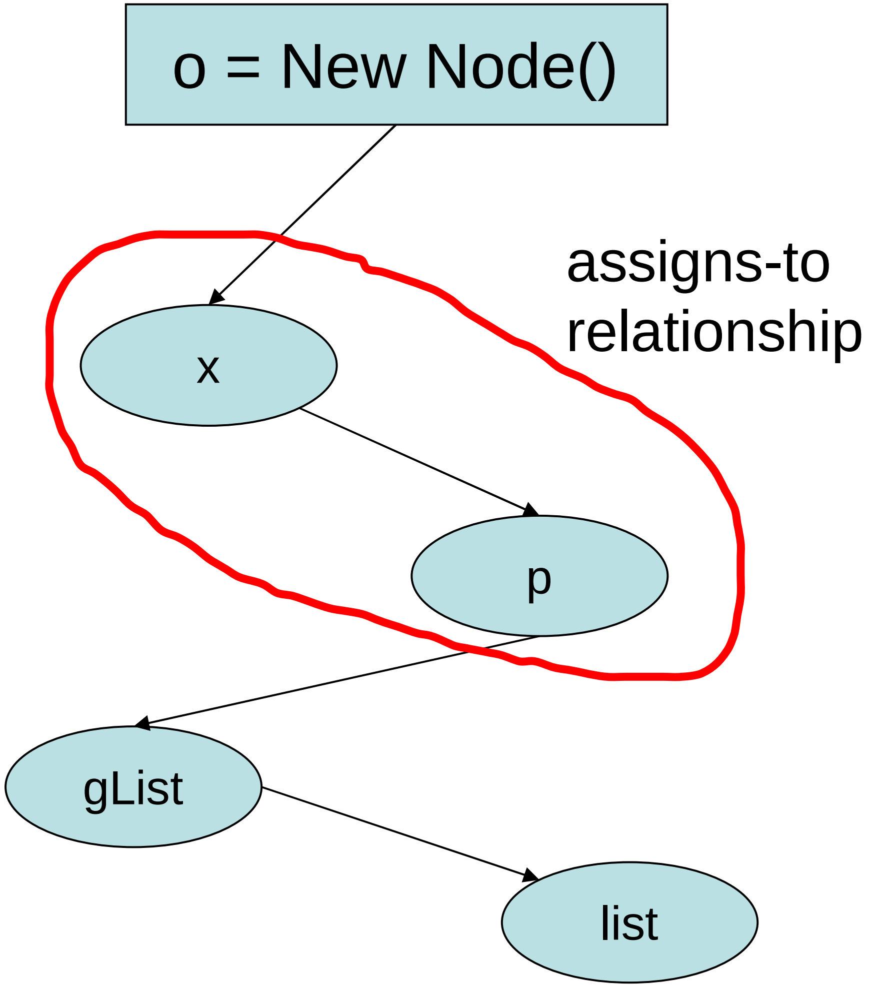


- Flow graph;

Points-to Analysis



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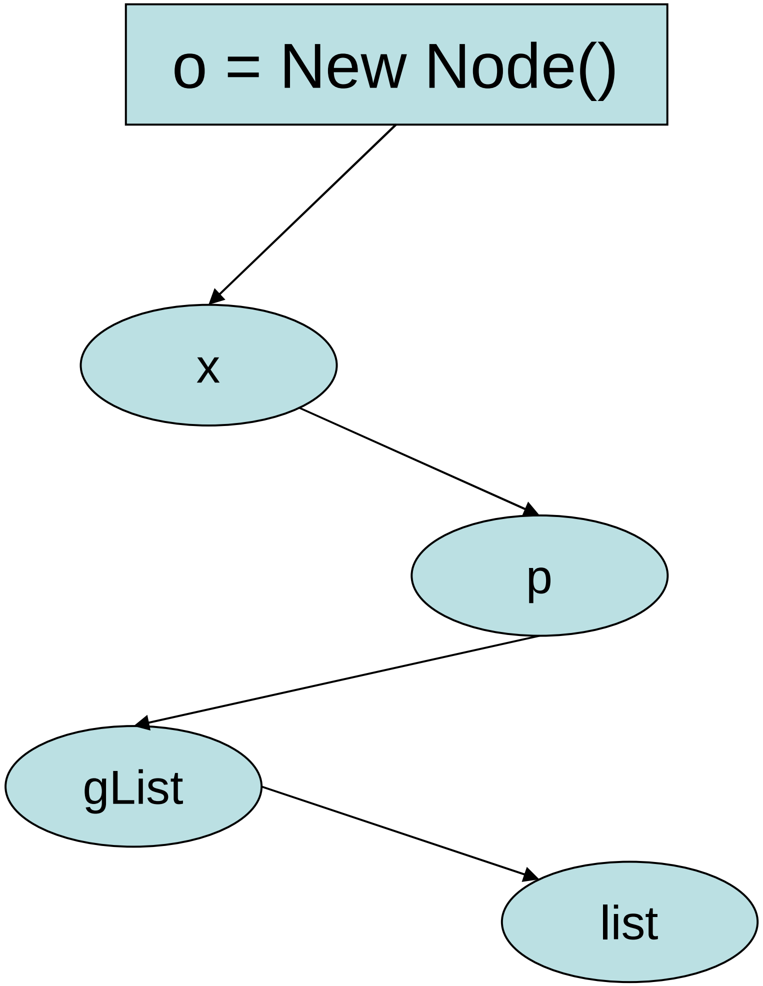
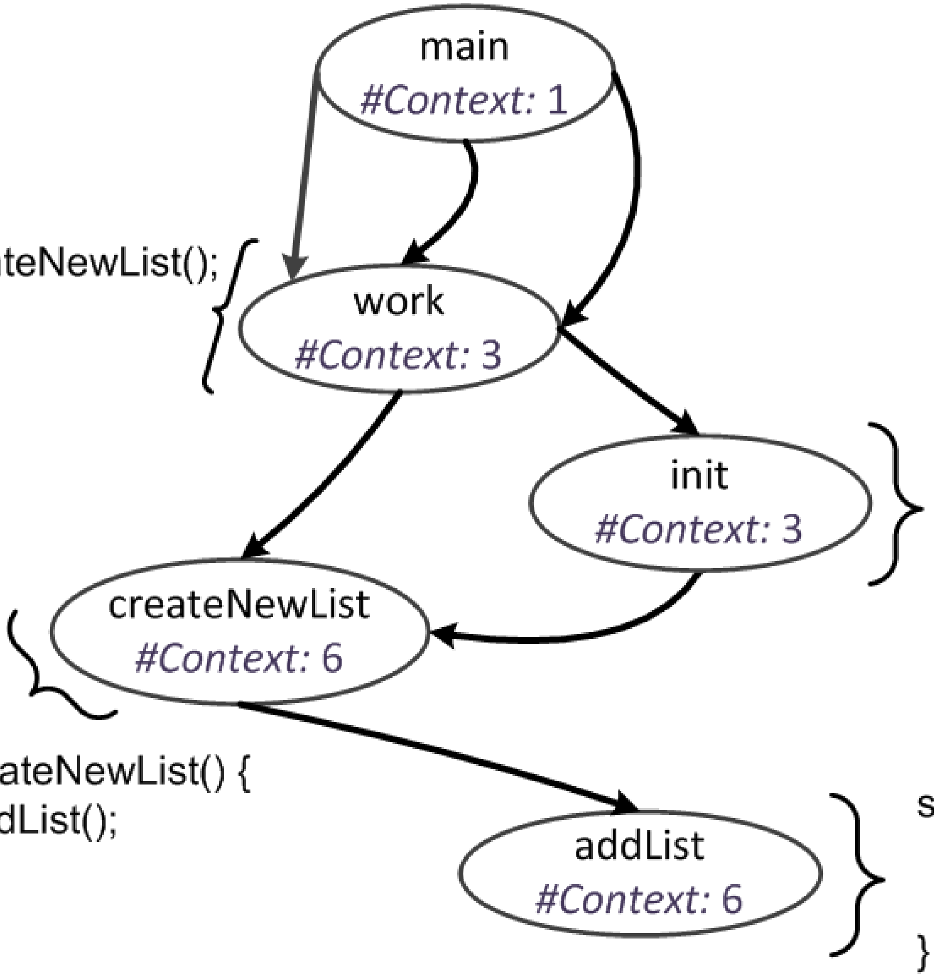


- Flow graph;
- Points-to relations can be obtained via the ***graph reachability analysis***;

Definition

- The previous demo is Anderson's analysis, which is *context insensitive*.
- It does not distinguish the runtime instances for the same syntactic variable.
- Cause any problem?

Context Sensitivity



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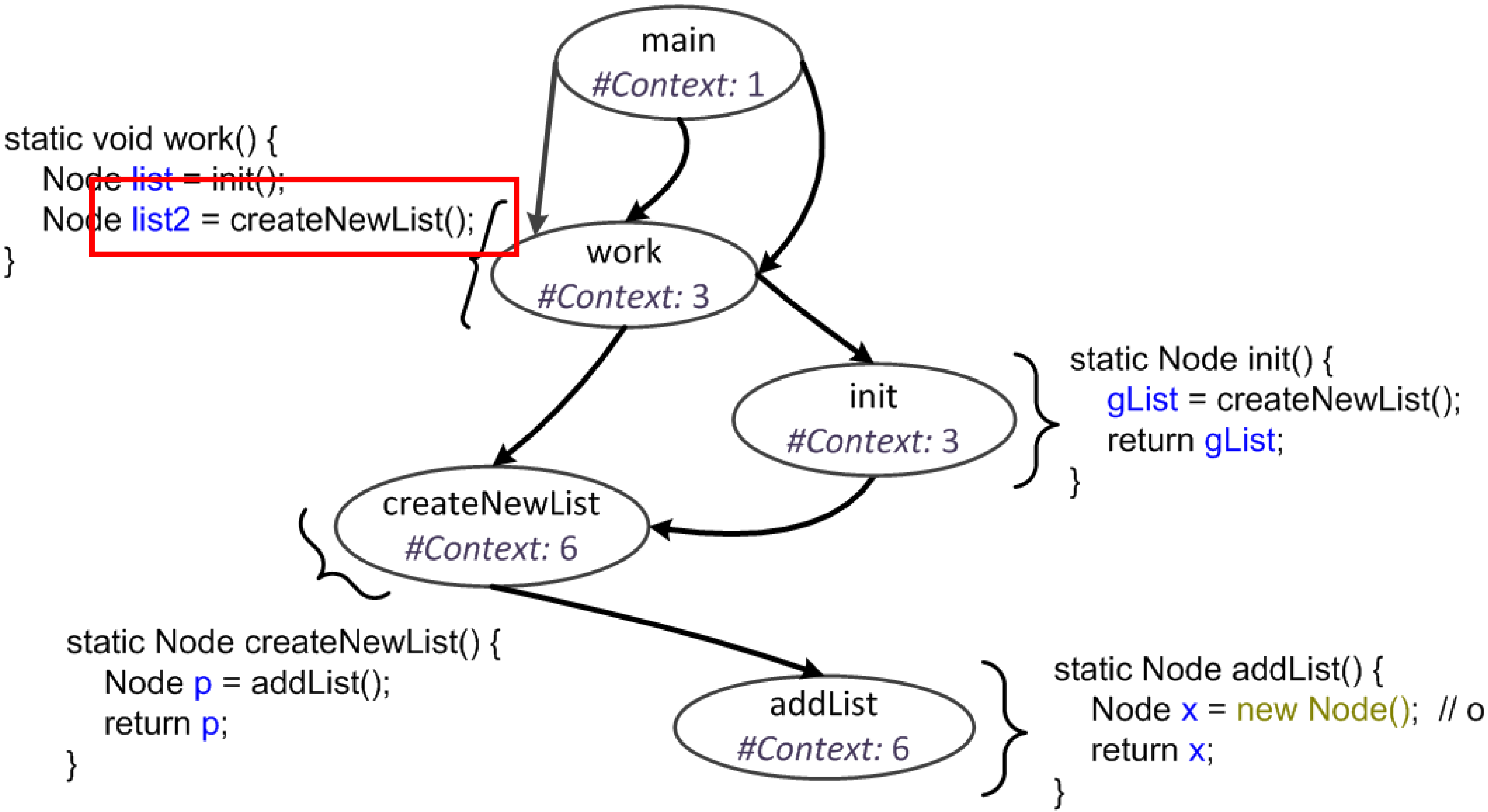

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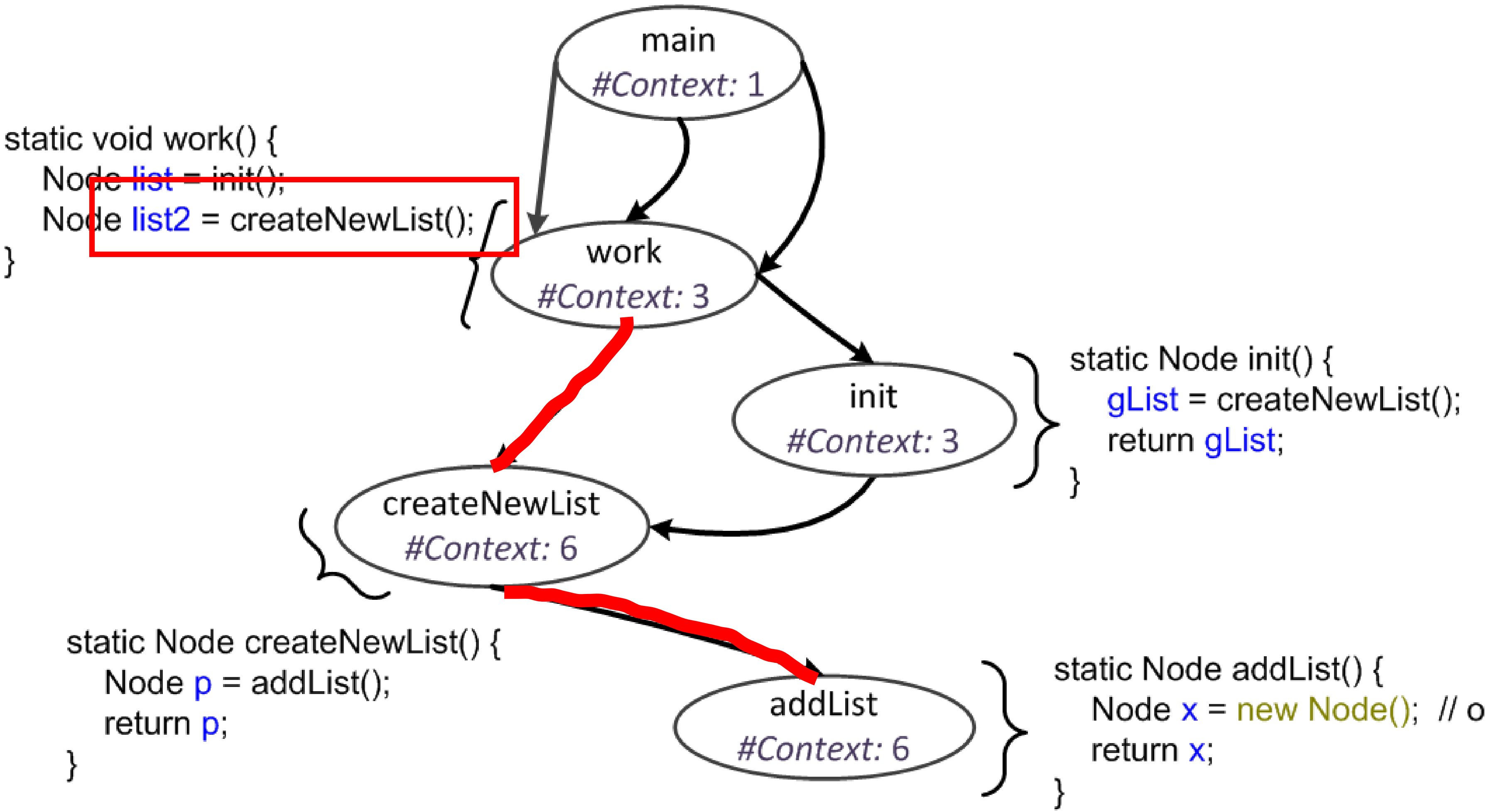

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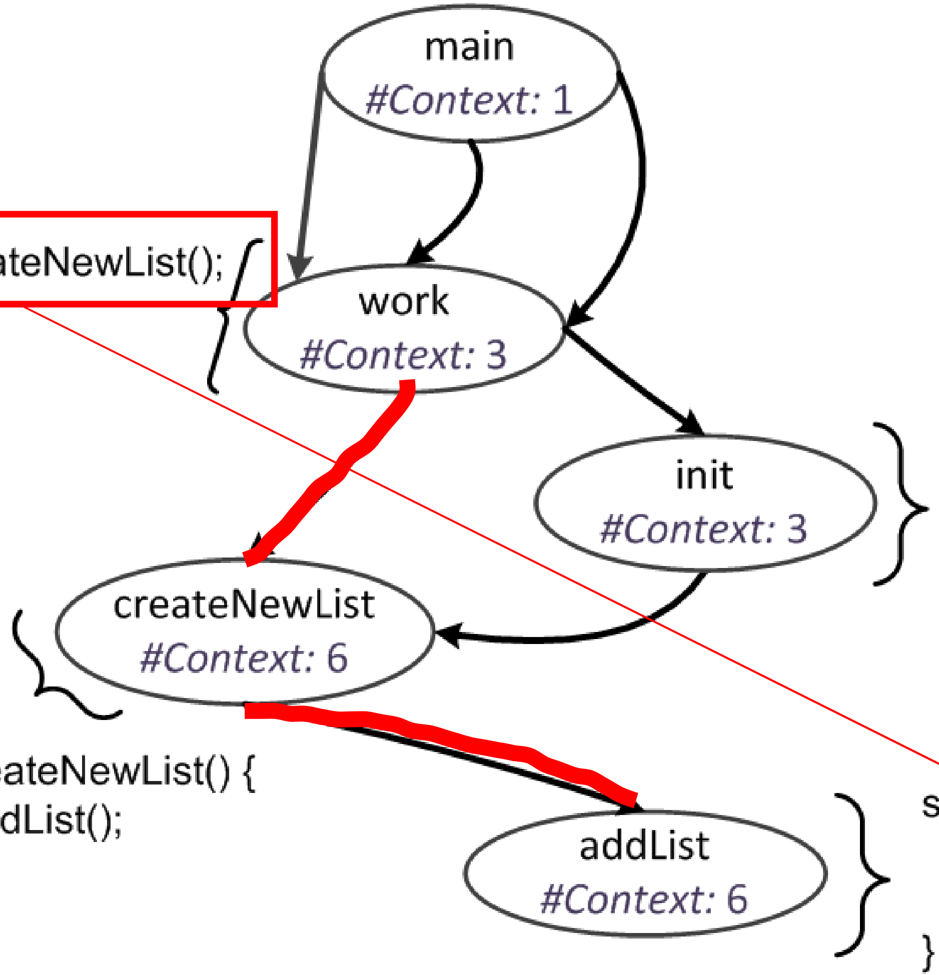

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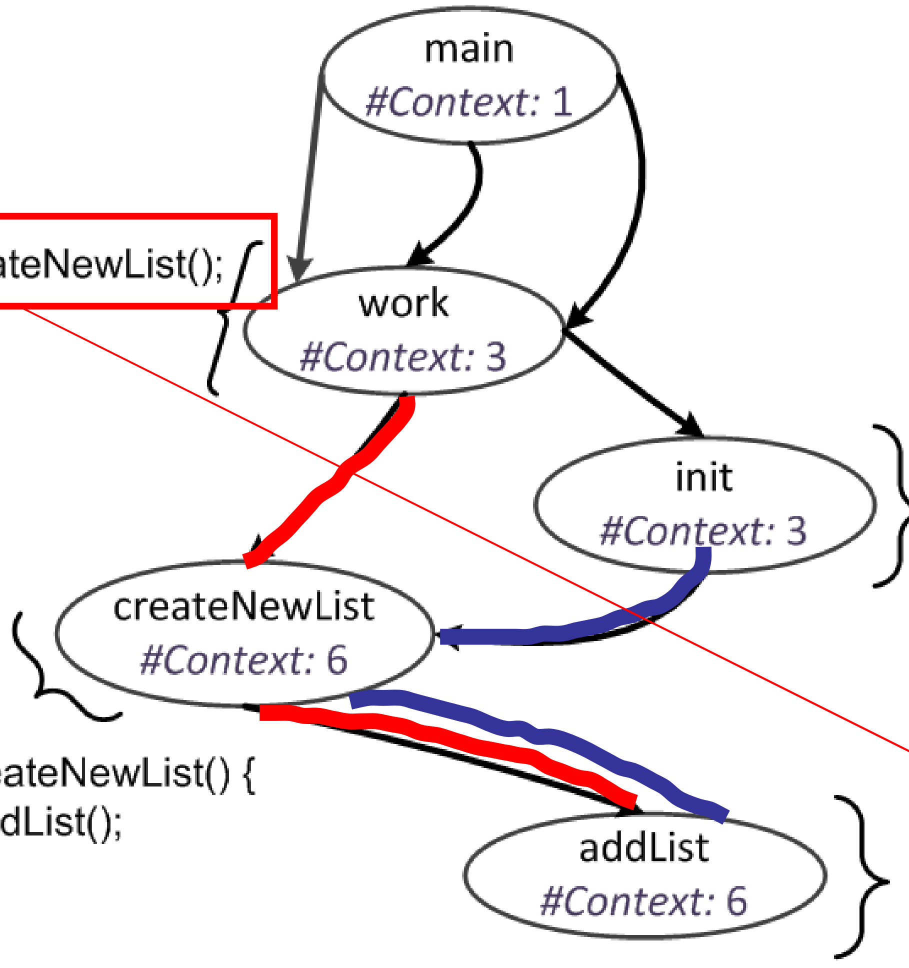

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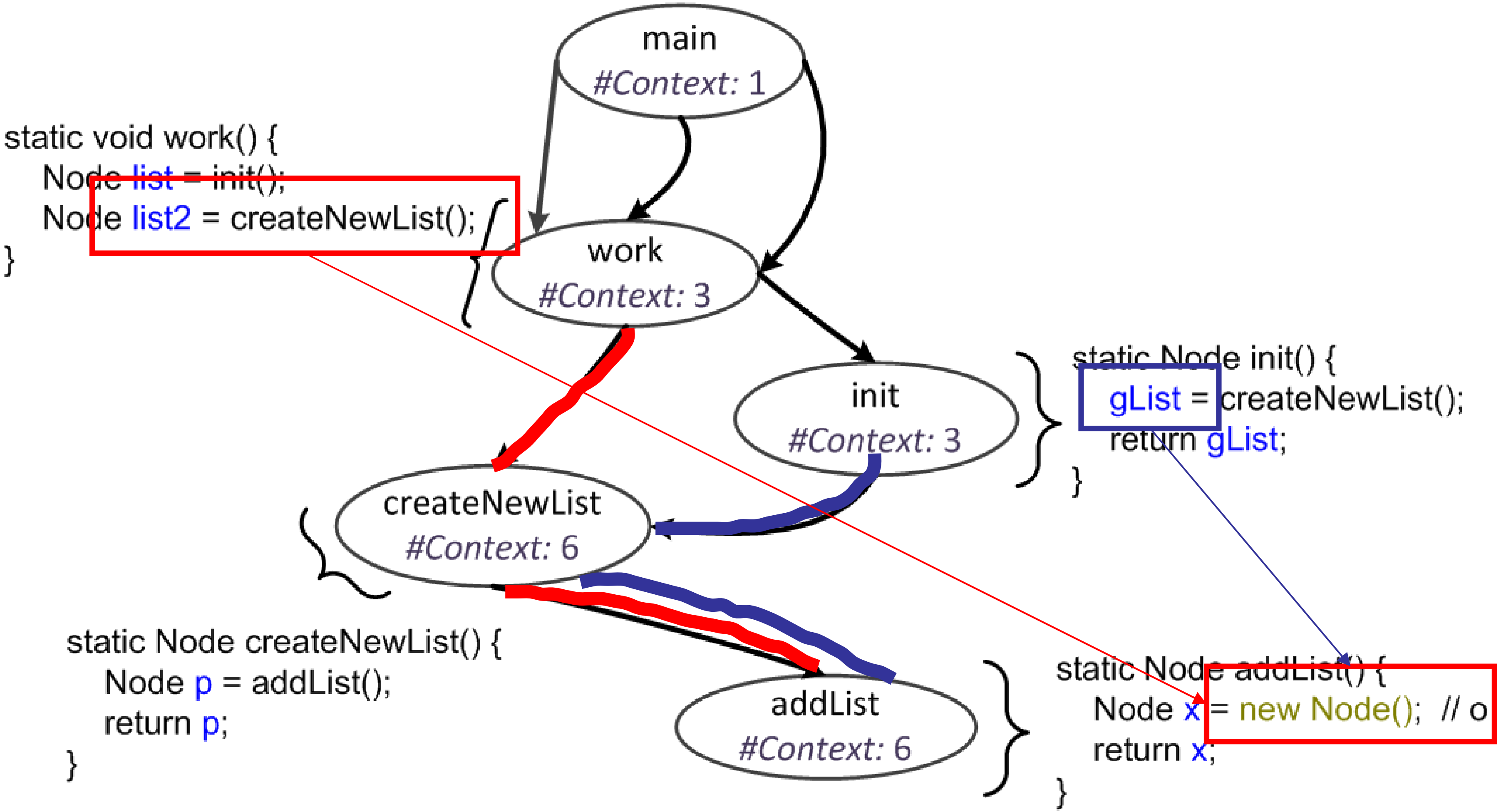

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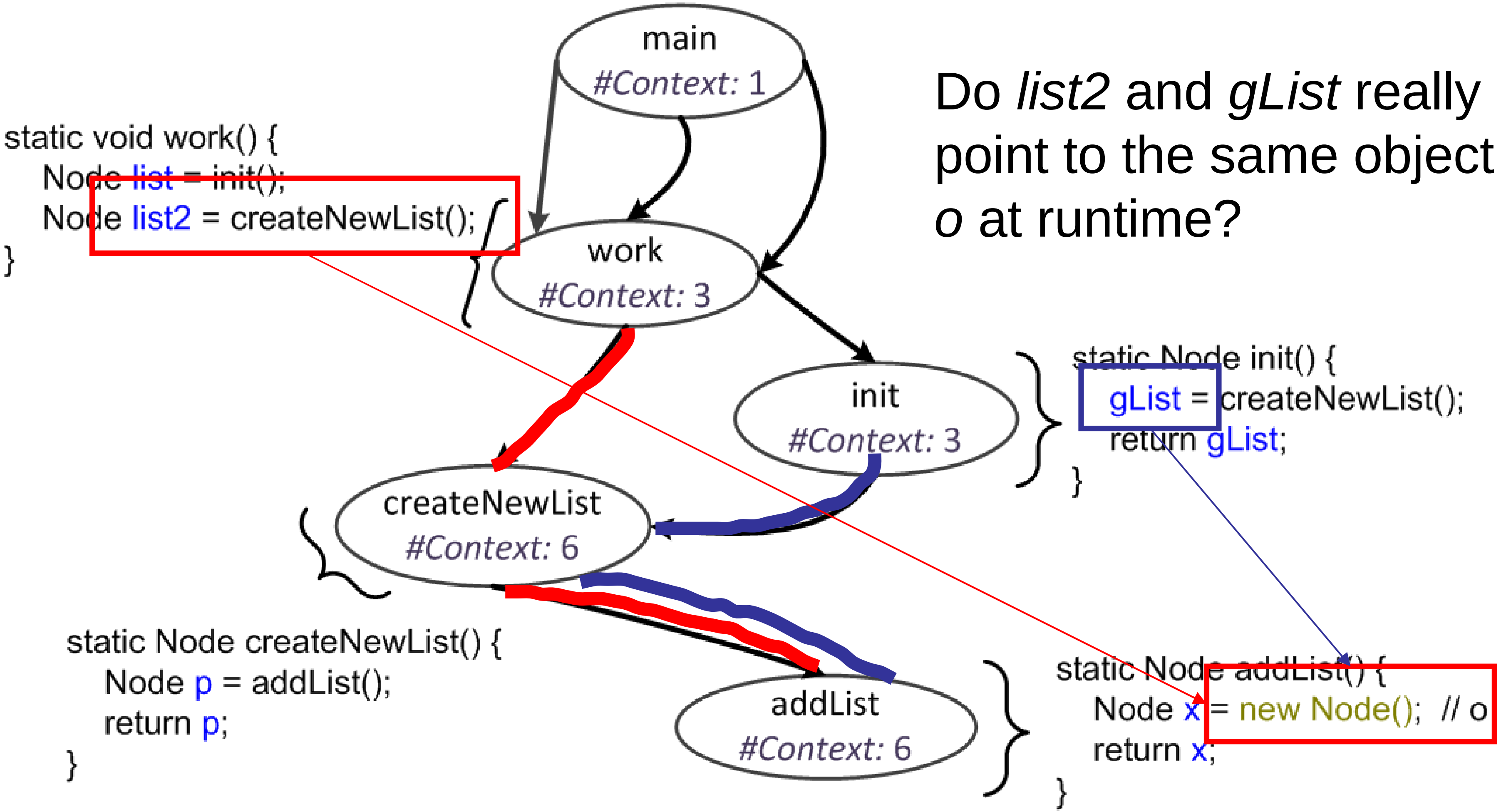
Context Sensitivity

Do *list2* and *gList* really point to the same object *o* at runtime?



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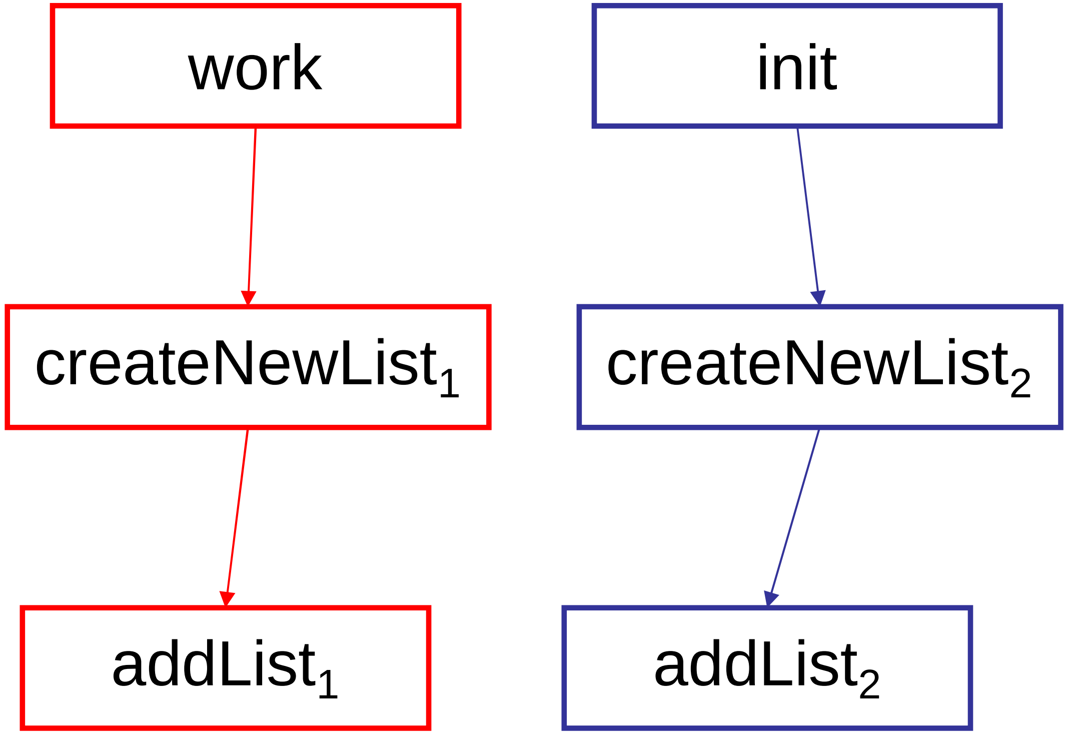

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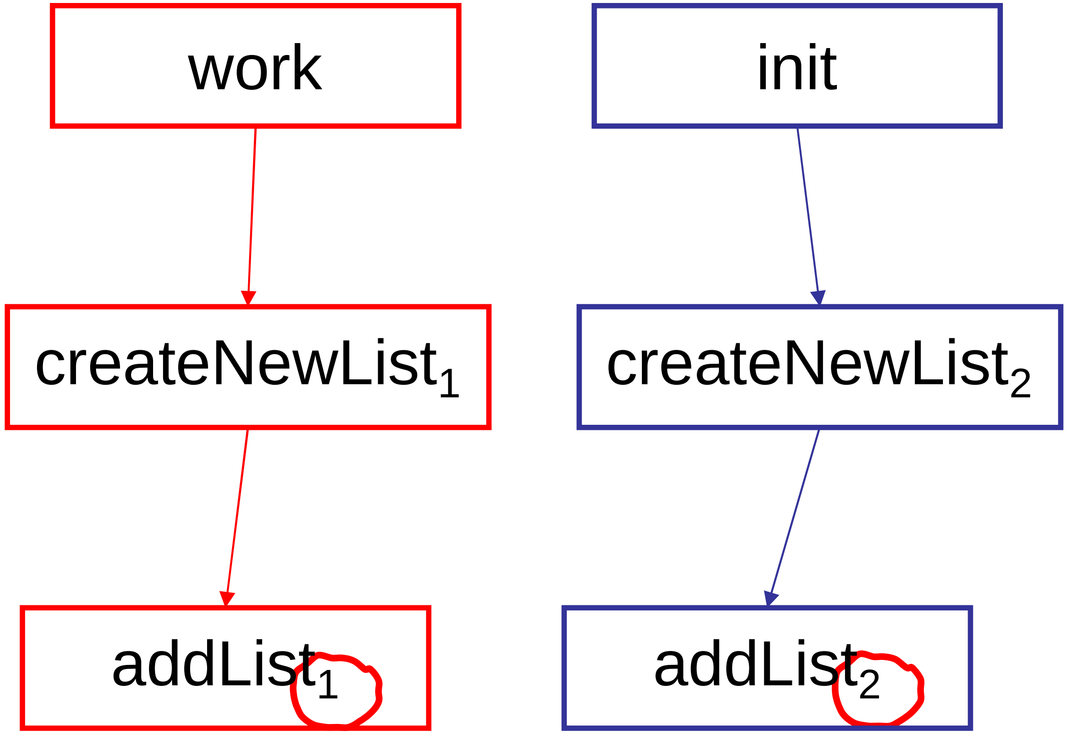
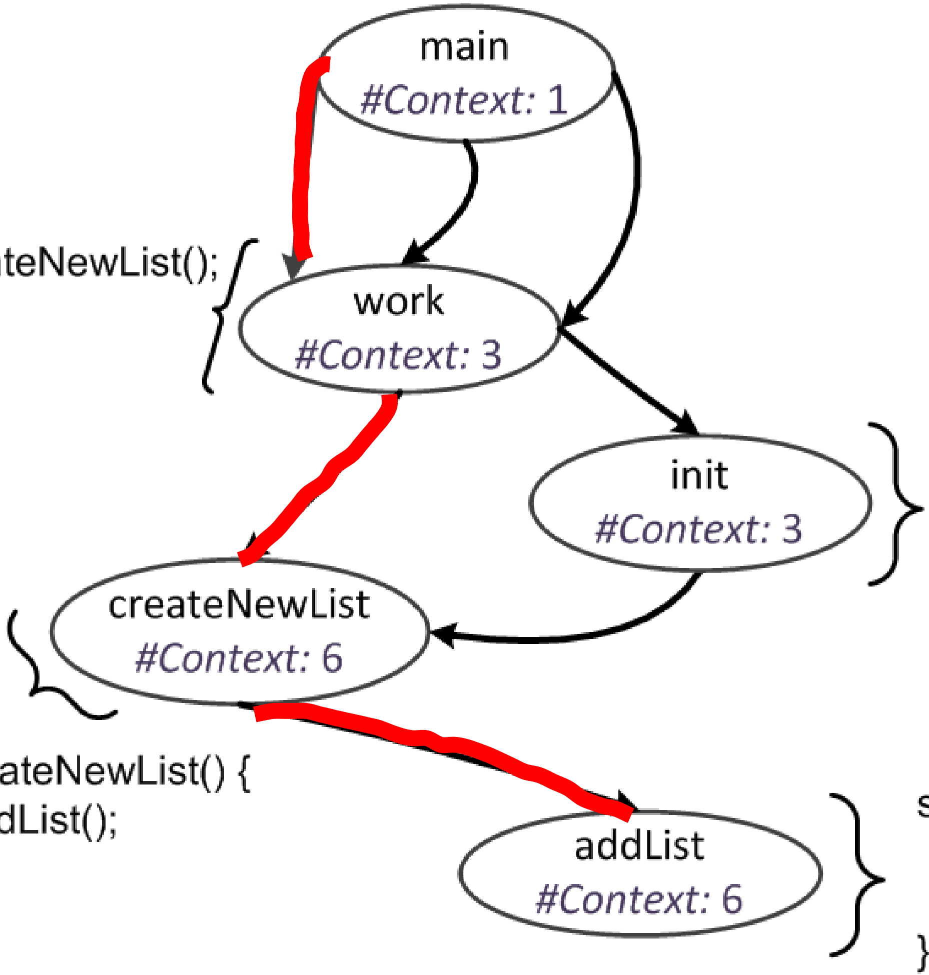


Context Sensitivity

- 6 paths to **addList()** from **main()**;

Context Sensitivity



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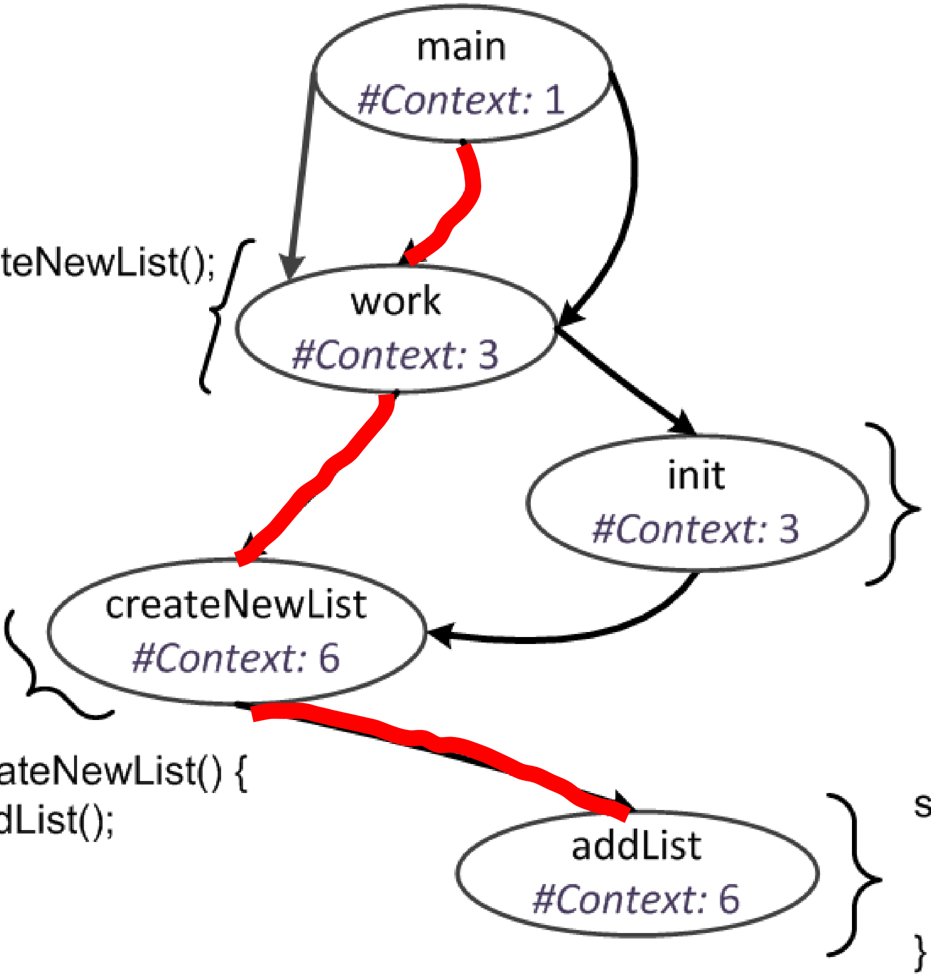

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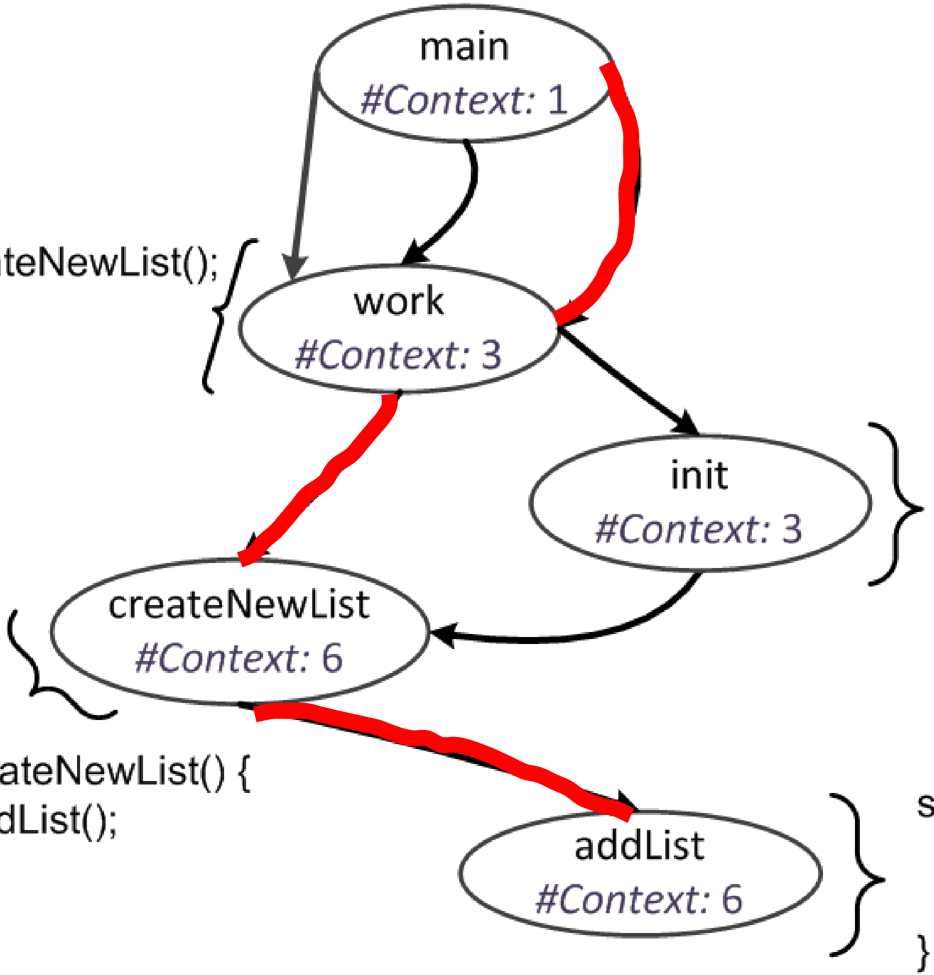

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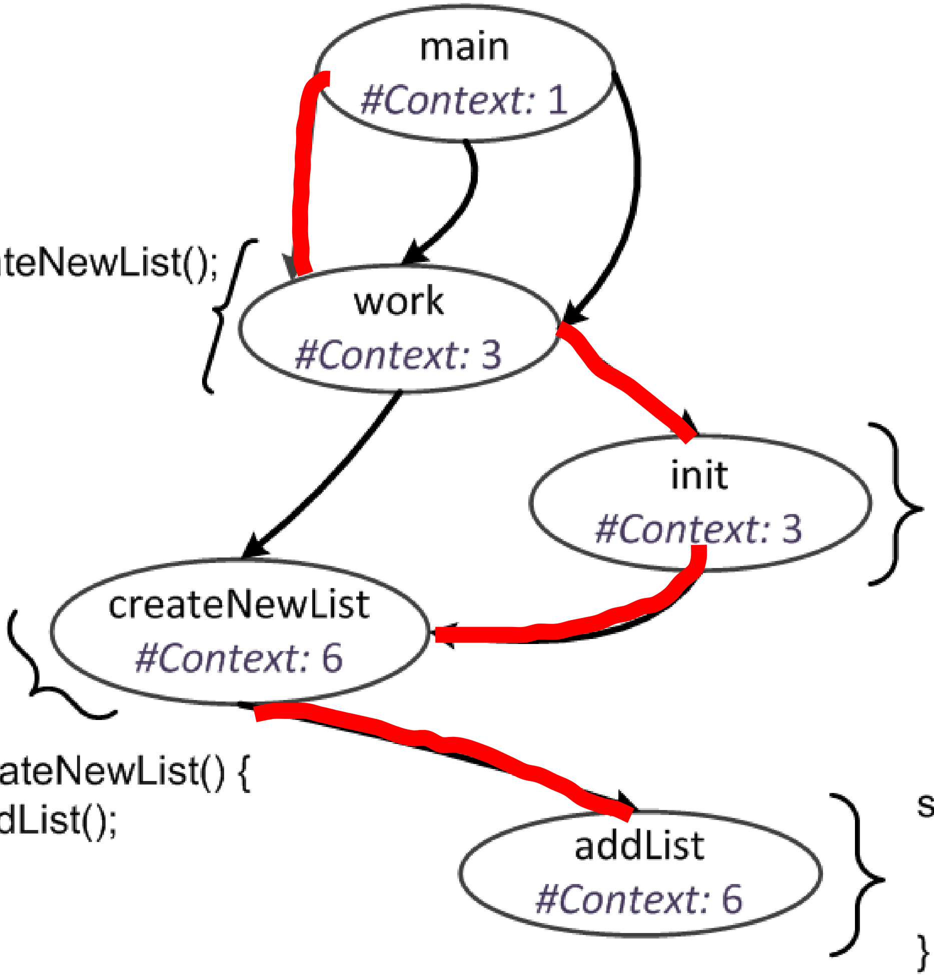

main

#Context: 1

work

#Context: 3

init

#Context: 3

createNewList

#Context: 6

addList

#Context: 6

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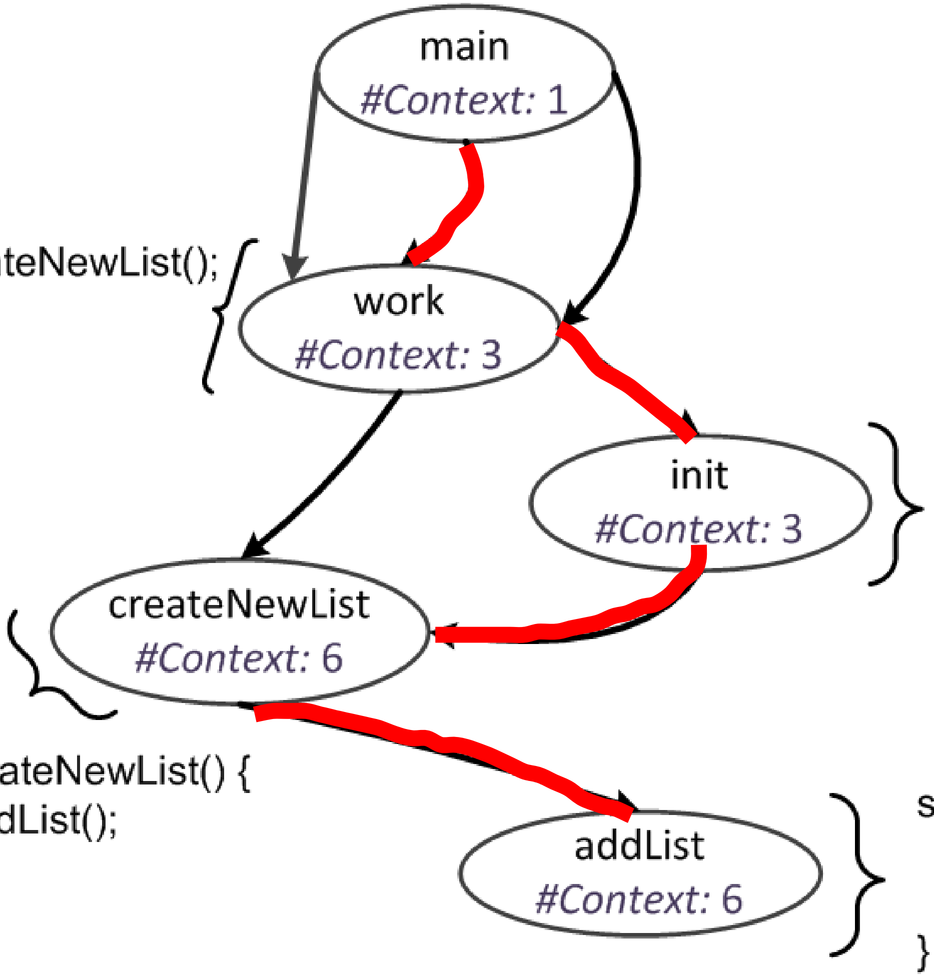

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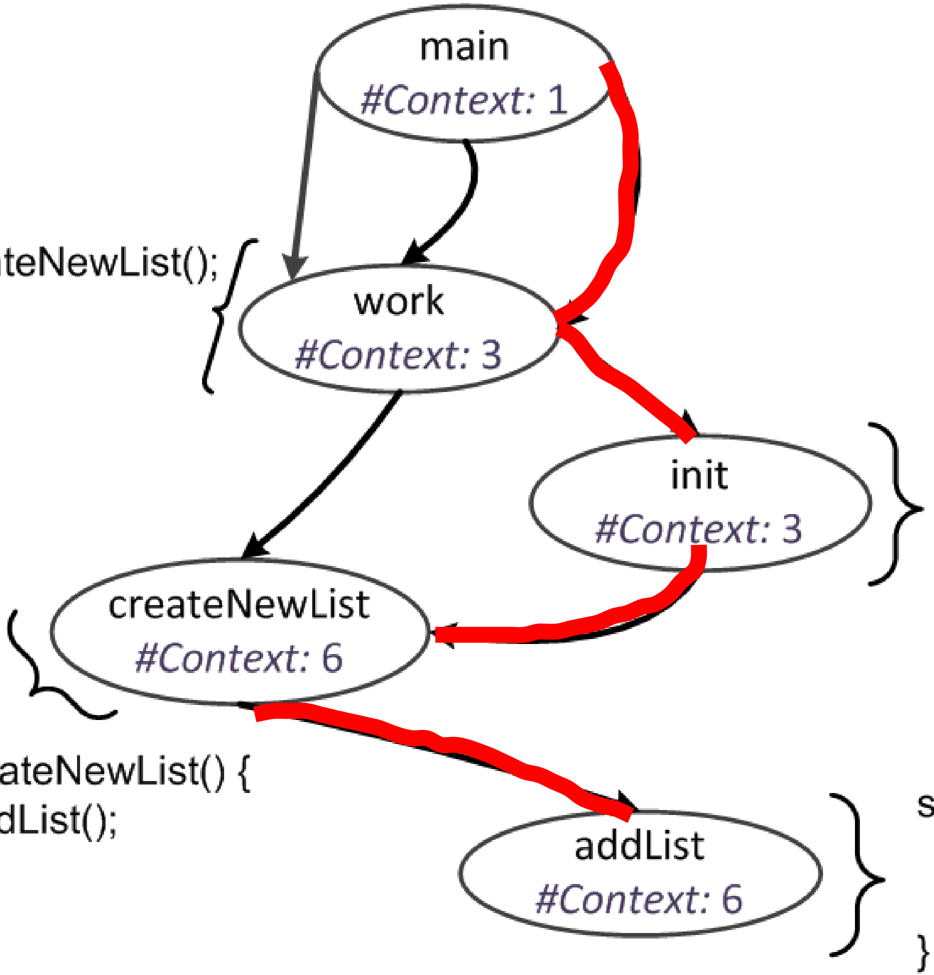

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New Algorithm

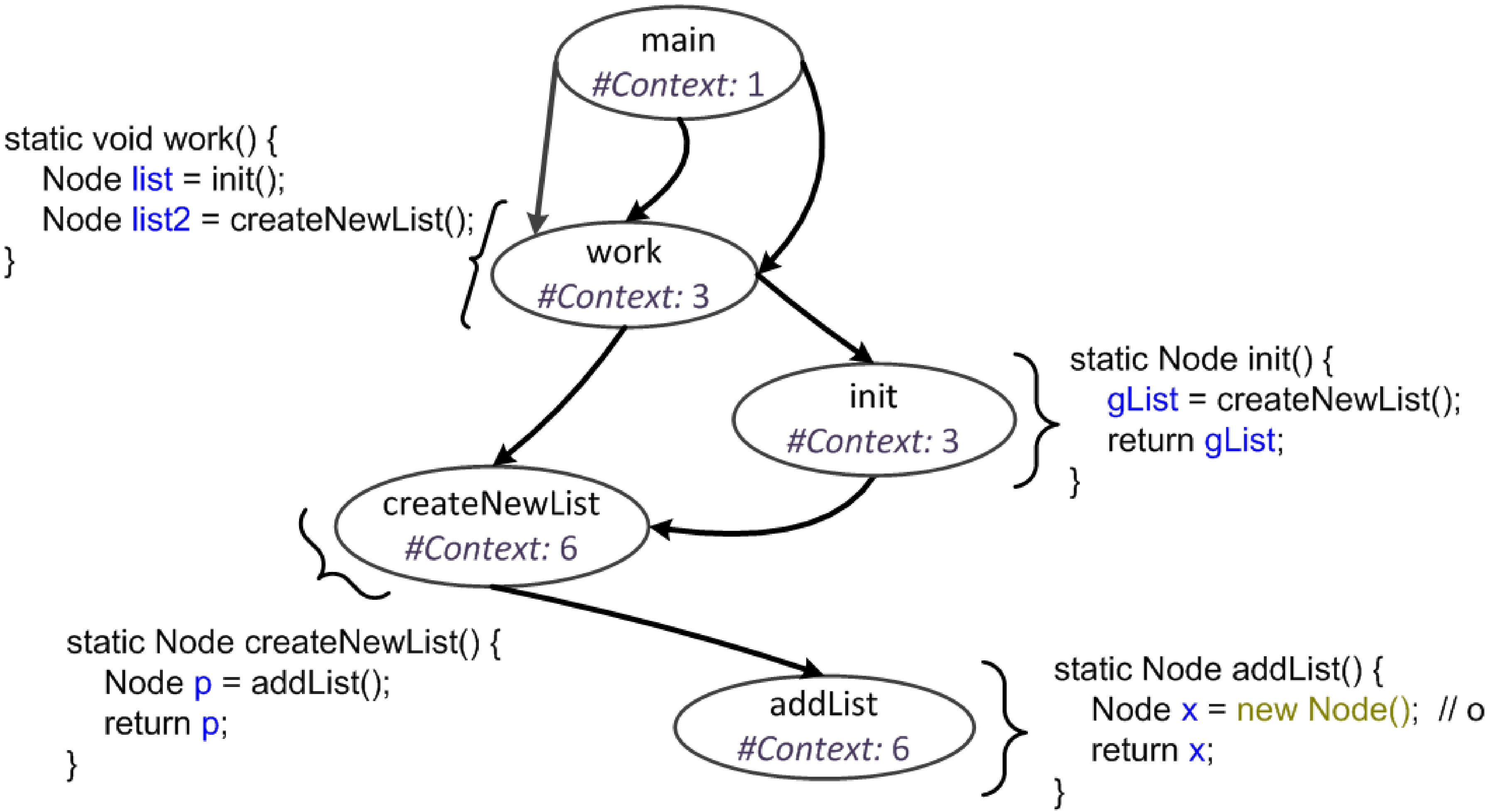
- How do we design an algorithm that can take advantage of the *context* ?

Context Sensitive Points-to Analysis

Step 1

- Build a context sensitive call graph by duplicating every function *N* times if it has *N* contexts.

Context Sensitive Call Graph



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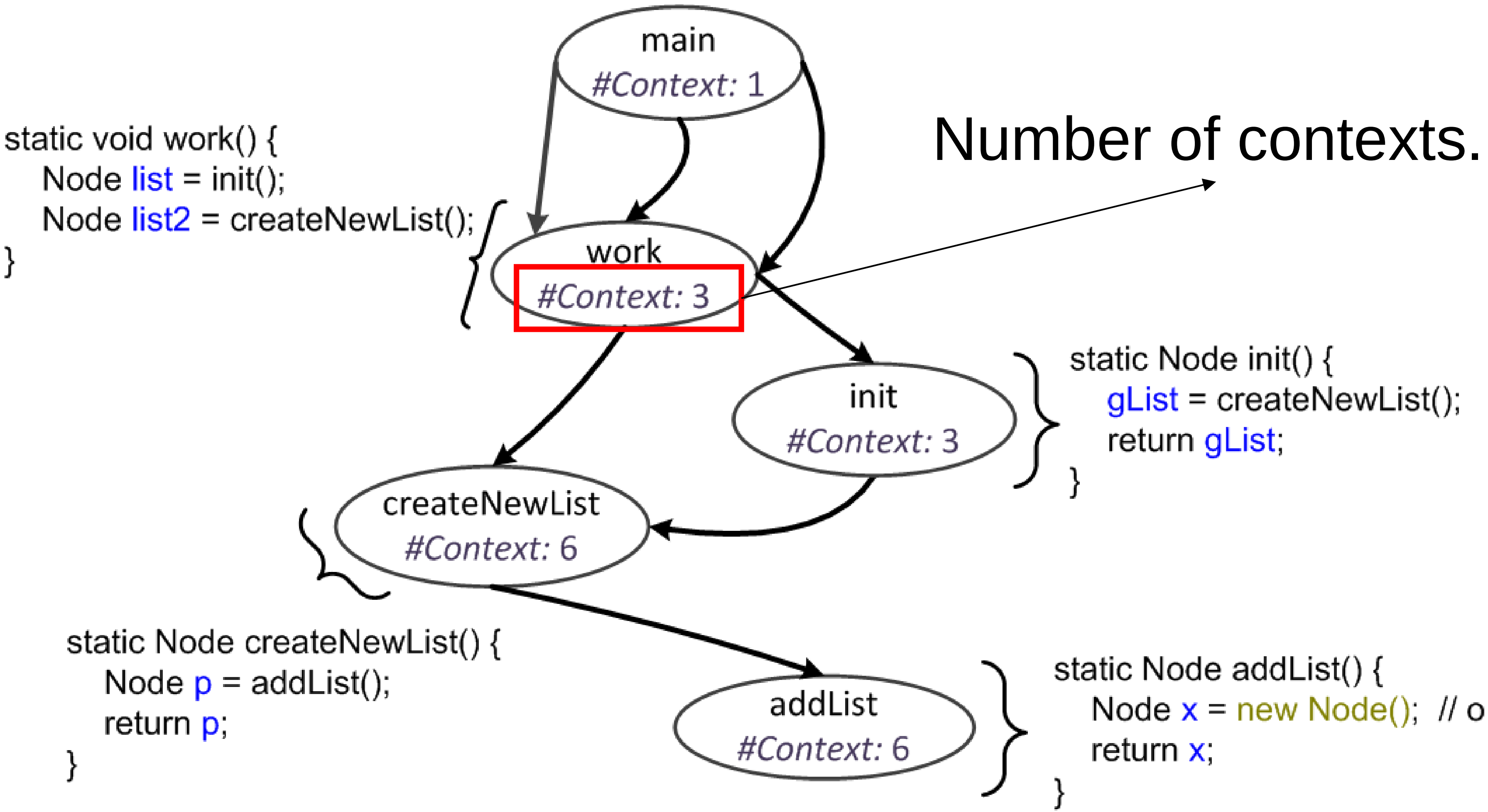

Number of contexts.

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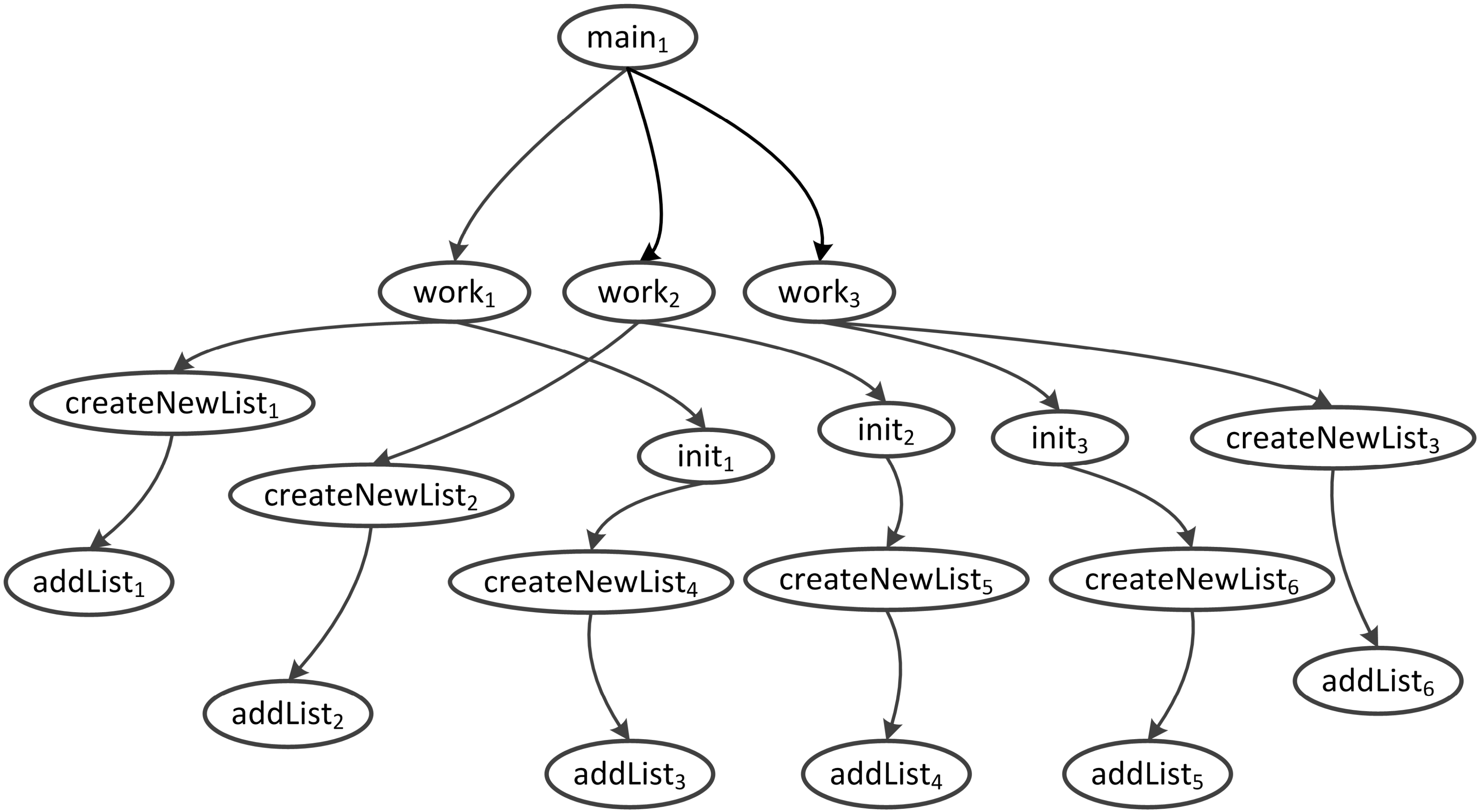
main$_1$
work$_1$
work$_2$
work$_3$
createNewList$_1$
createNewList$_2$
init$_1$
init$_2$
init$_3$
createNewList$_3$
addList$_1$
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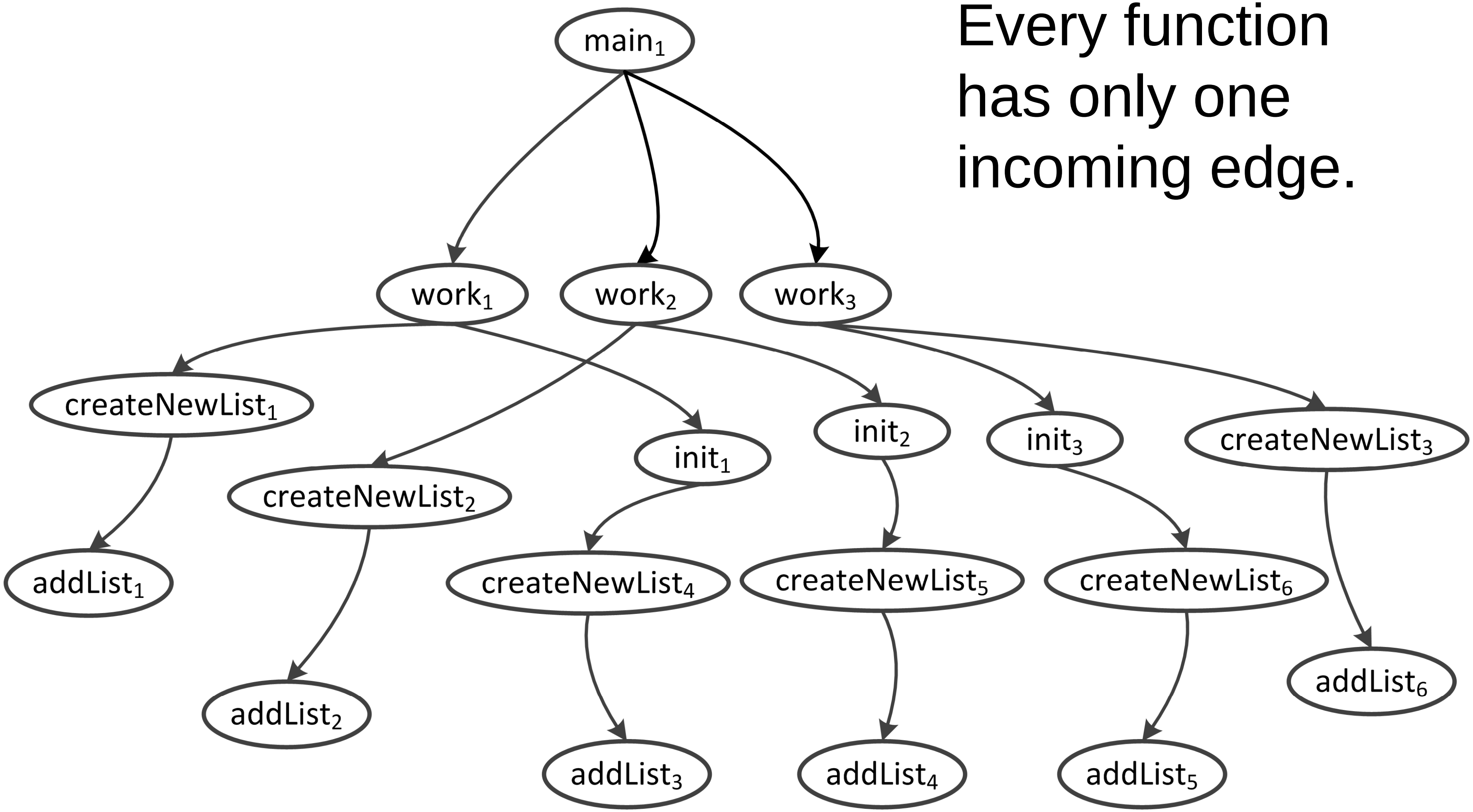
addList$_5$



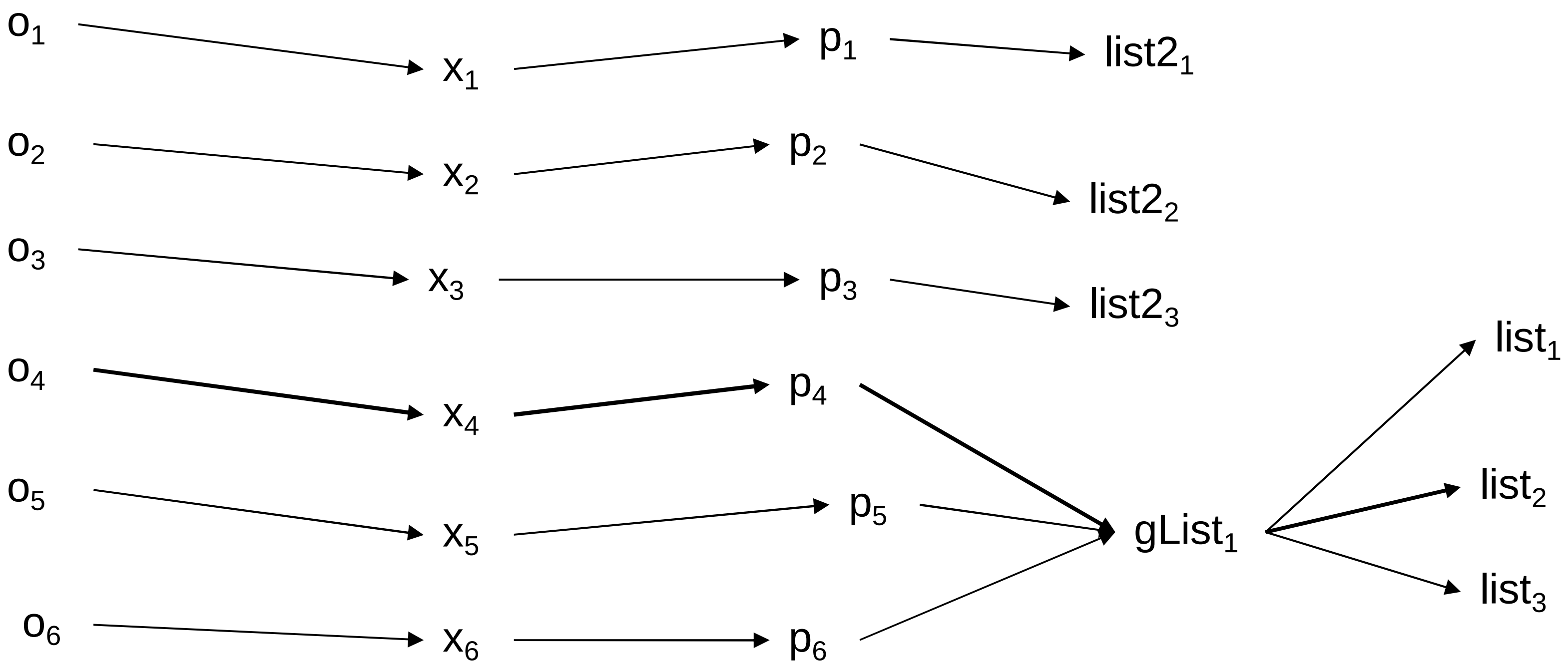
Every function has only one incoming edge.

Context Sensitive Points-to Analysis

Step 2

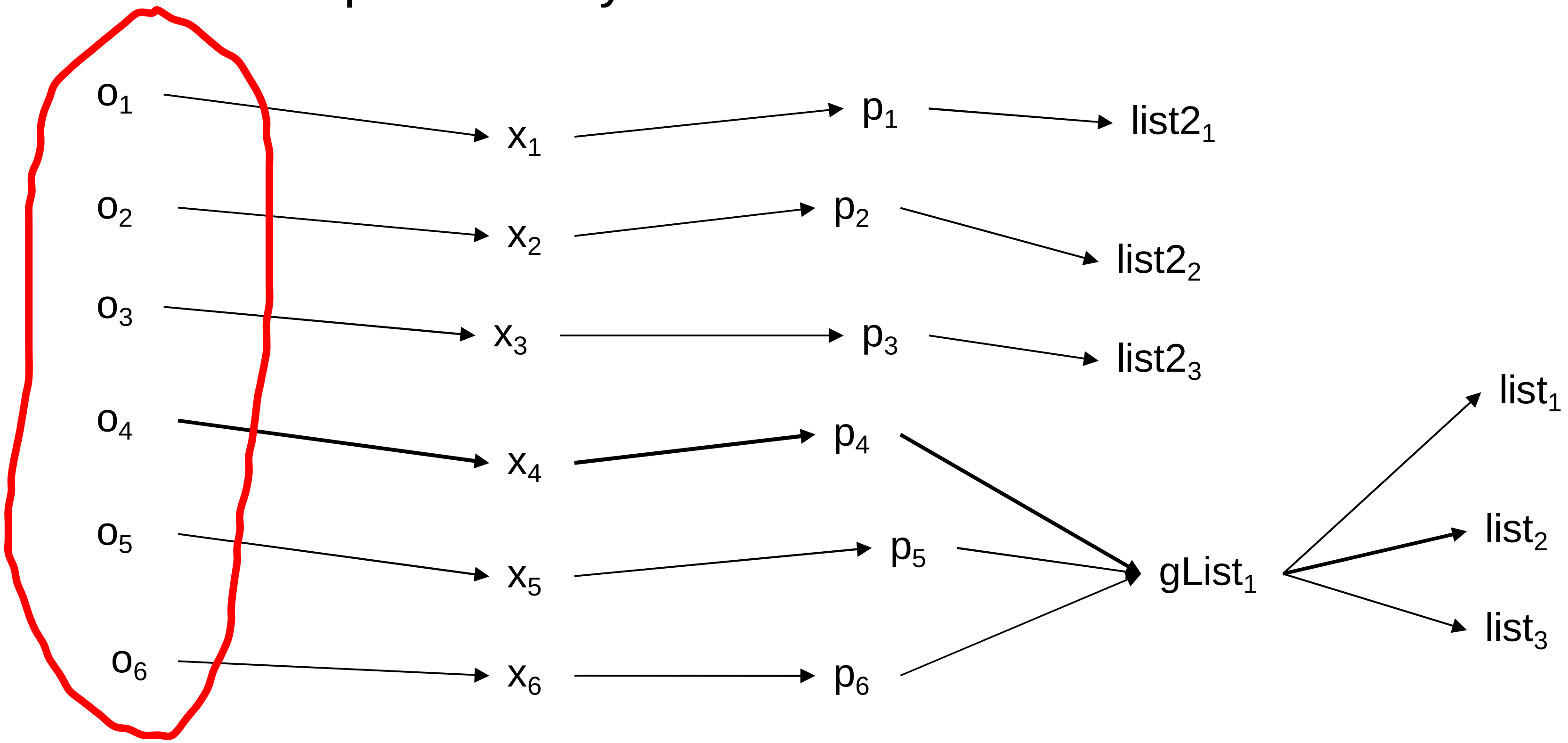
- Apply the Anderson's analysis to the context sensitive call graph.

Context Sensitive Flow Graph



Context Sensitive Flow Graph

heap sensitivity



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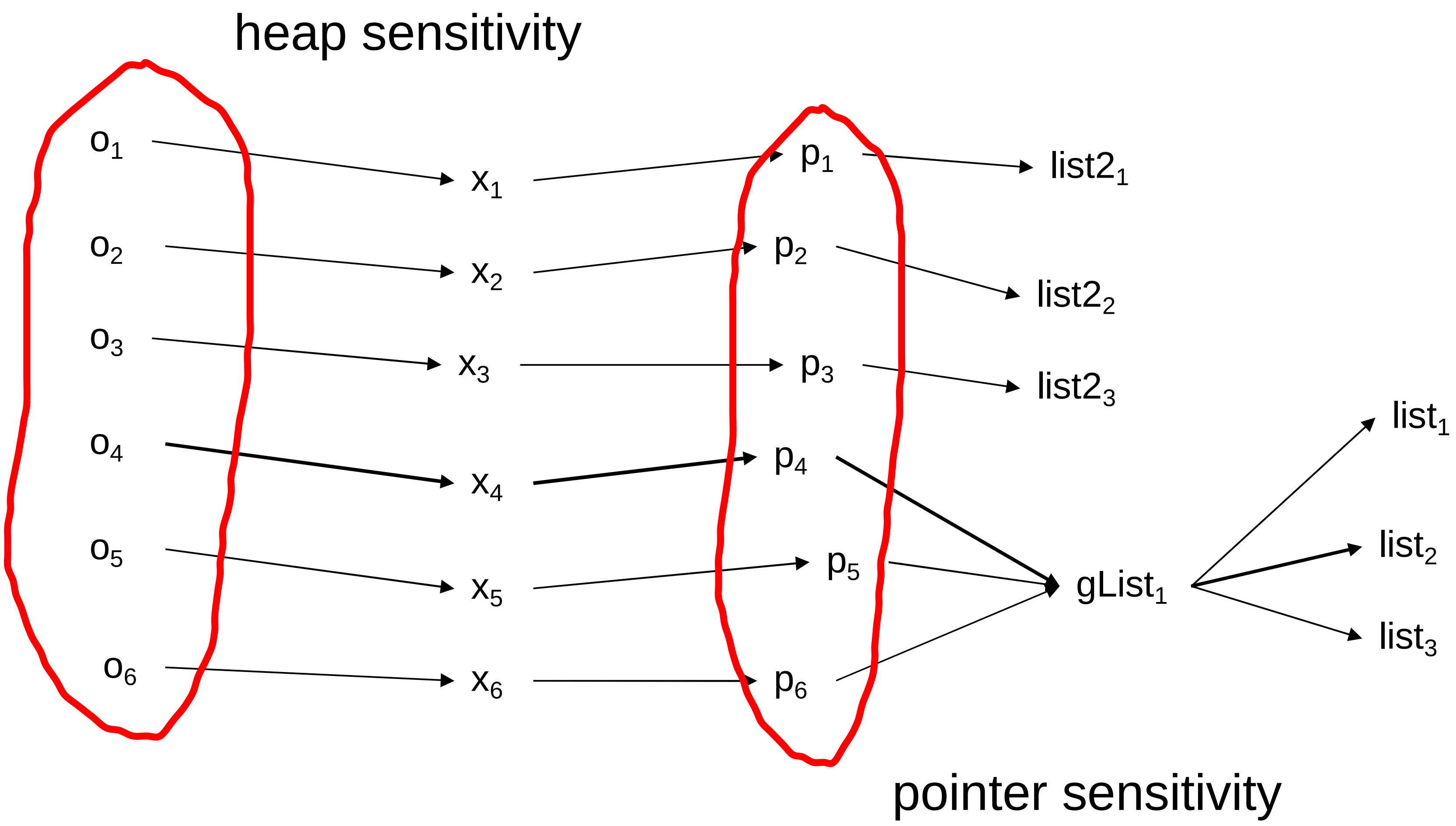

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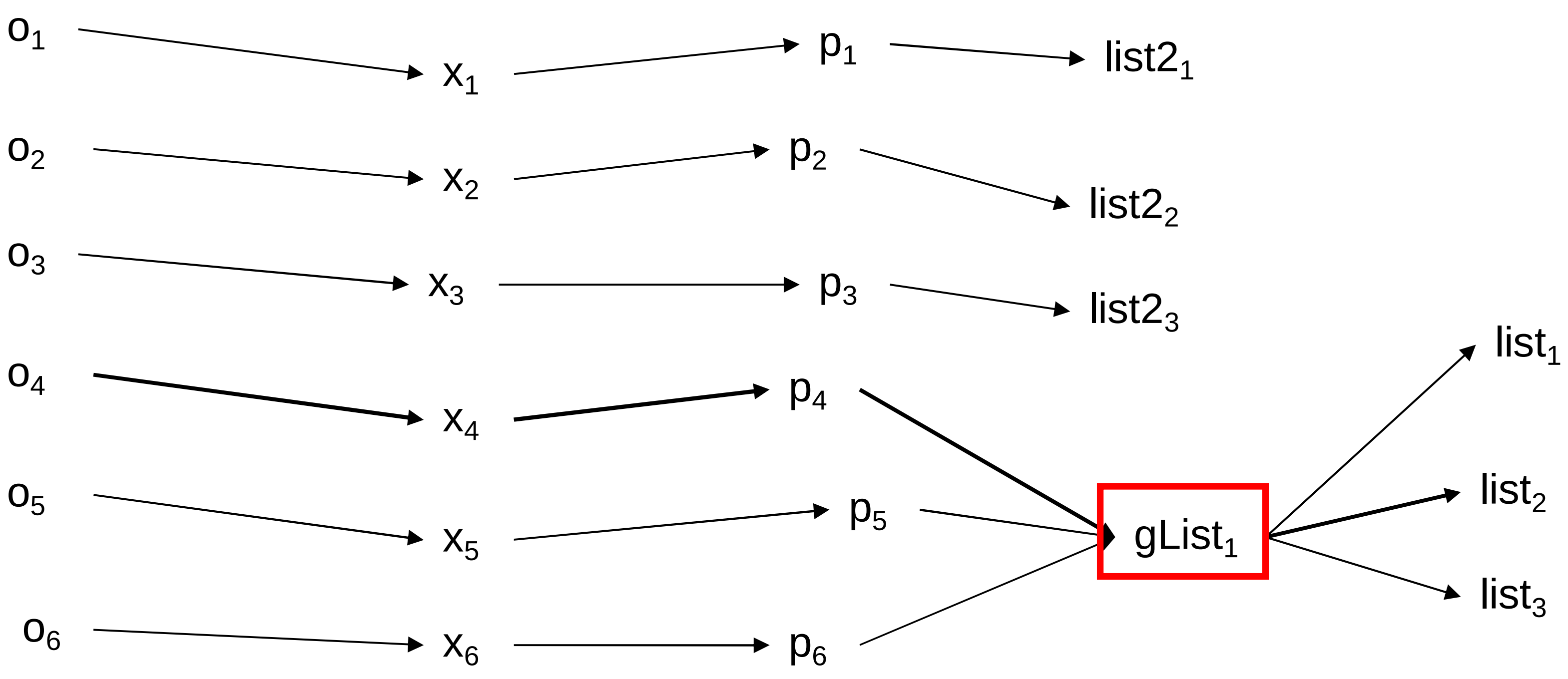

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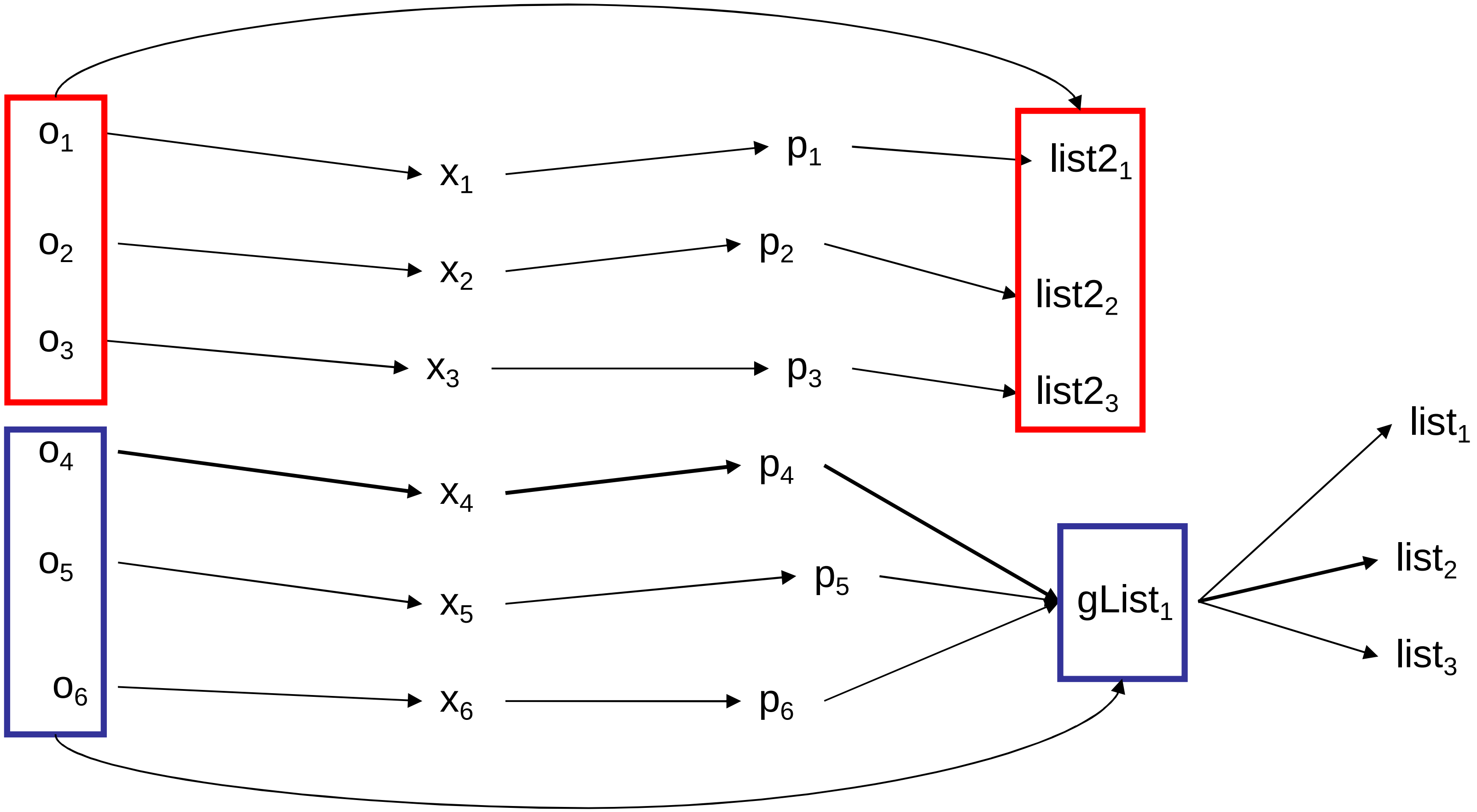


Context Sensitive Points-to Analysis

- How can we do reachability analysis with the context sensitive flow graph efficiently?

Challenge

- The flow graph is extremely large!
- Handling a graph with billions of nodes is not an easy job.

bddbddb [PLDI04]

- Store the initial assigns-to relations into the BDD;
- Store the initial points-to relations into another BDD;
- Iteratively apply the BDD join operator until the points-to relations fixed;

bddbddb [PLDI04]

- Advantages:
  - A very large flow-to graph can be handled within 1GB memory;
  - Programming with BDD is not so difficult.

bddbddb [PLDI04]

- Problems:
  - – Multi-dimensional sensitivity (both pointer and heap) support are inefficient;
  - – Although consider the pointer sensitivity only, the time efficiency is still not satisfiable;

EPA [ISSTA08]

- High level idea:
  - Do not number the contexts to 1, 2, 3... but use callsite string to represent contexts;
  - Extract the shared prefix of the context string to achieve compression.

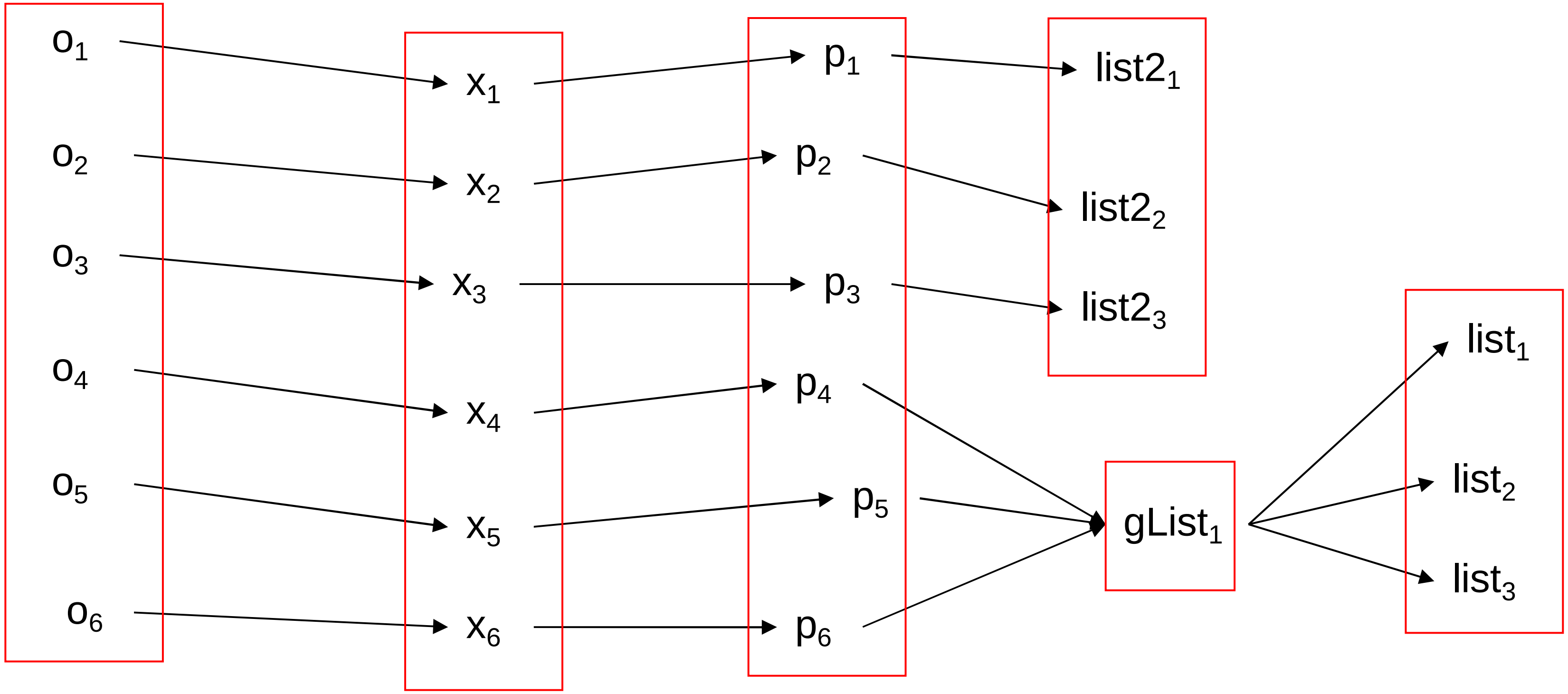
EPA [ISSTA08]

- Problems:
  - Procedure summary based design: less efficient compared to whole program analysis because of more actions (e.g. method escape analysis, symbolic placeholder instantiation, etc.).

Context Sensitive Flow Graph

- Let's see the flow graph again.....

Context Sensitive Flow Graph



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THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

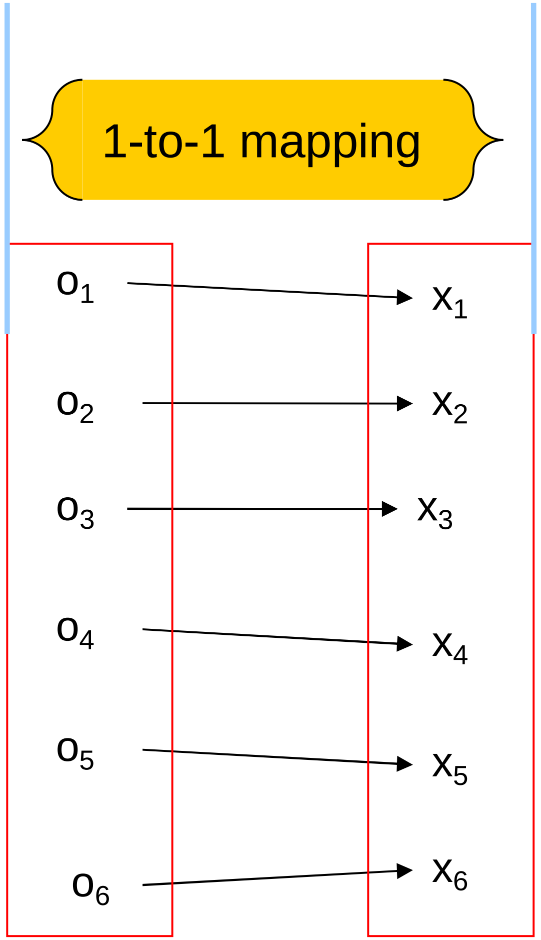
Context Sensitive Flow Graph

- Can you find anything interesting from the *group view* of the flow graph?

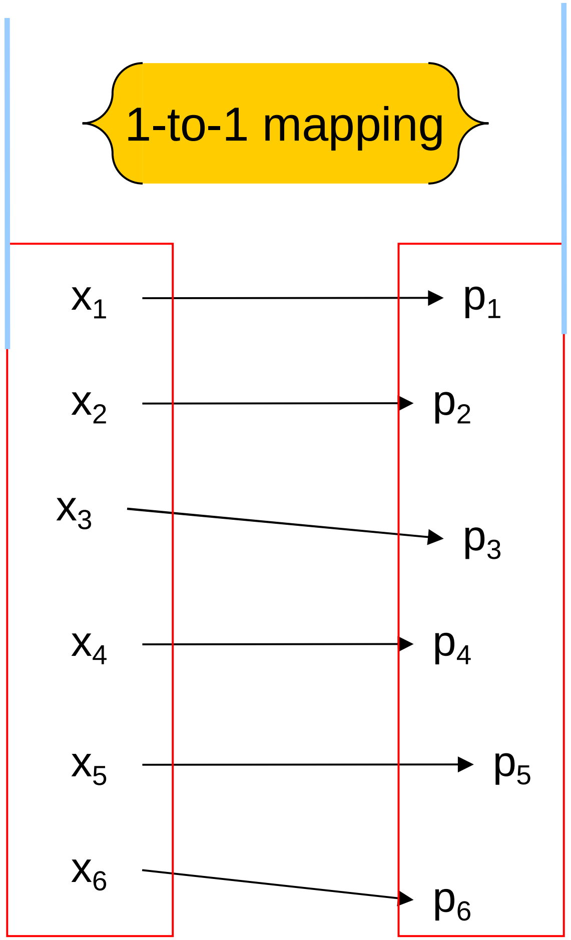
Context Sensitive Flow Graph

- Yes, the flow graph is constructed by many mapping structures.

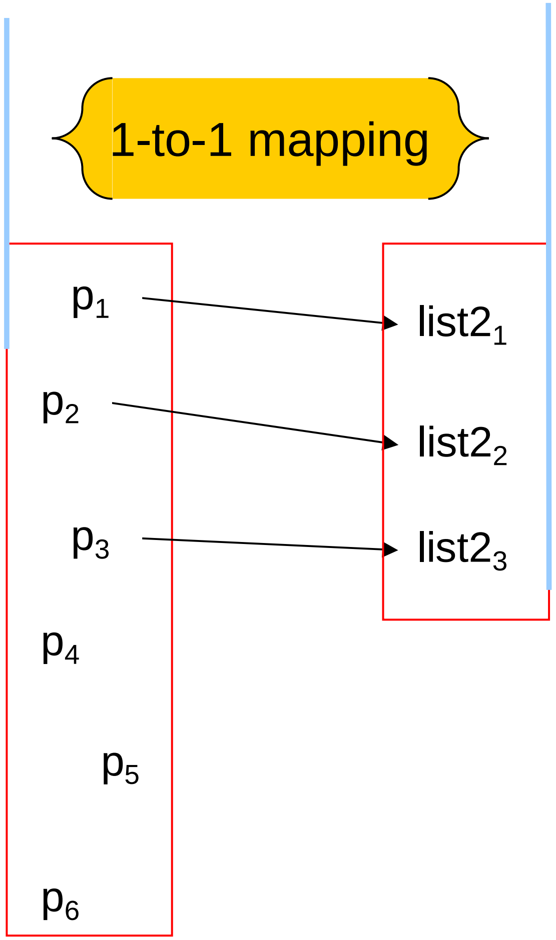
Context Sensitive Flow Graph



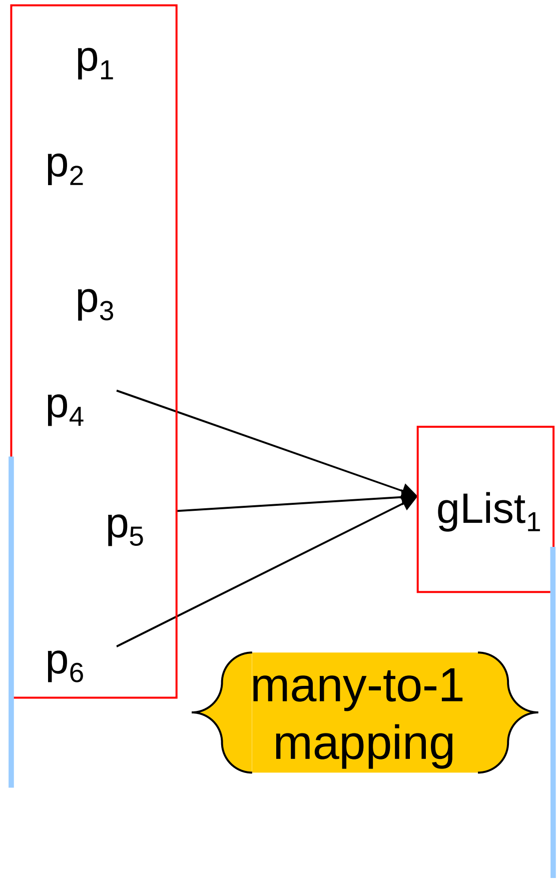
Context Sensitive Flow Graph



Context Sensitive Flow Graph

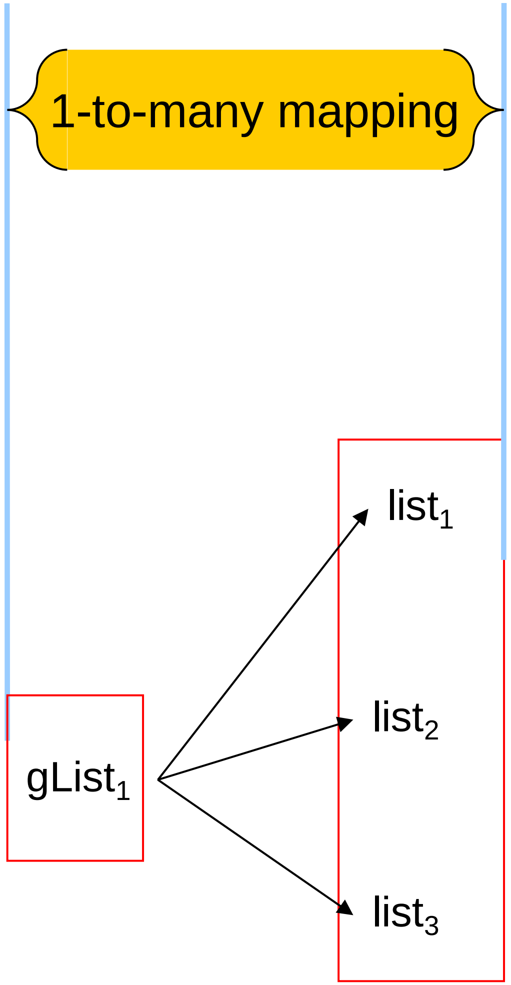


Context Sensitive Flow Graph



many-to-1 mapping

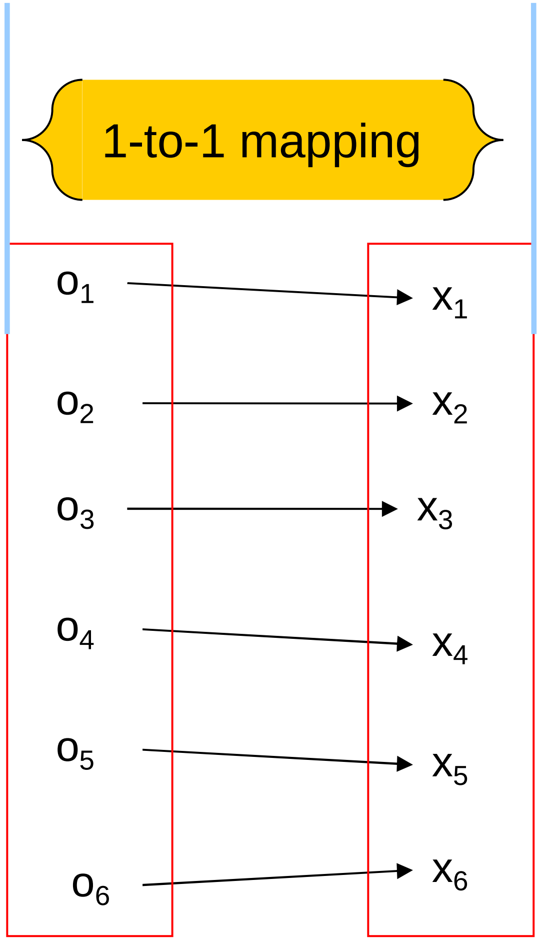
Context Sensitive Flow Graph



Context Sensitive Flow Graph

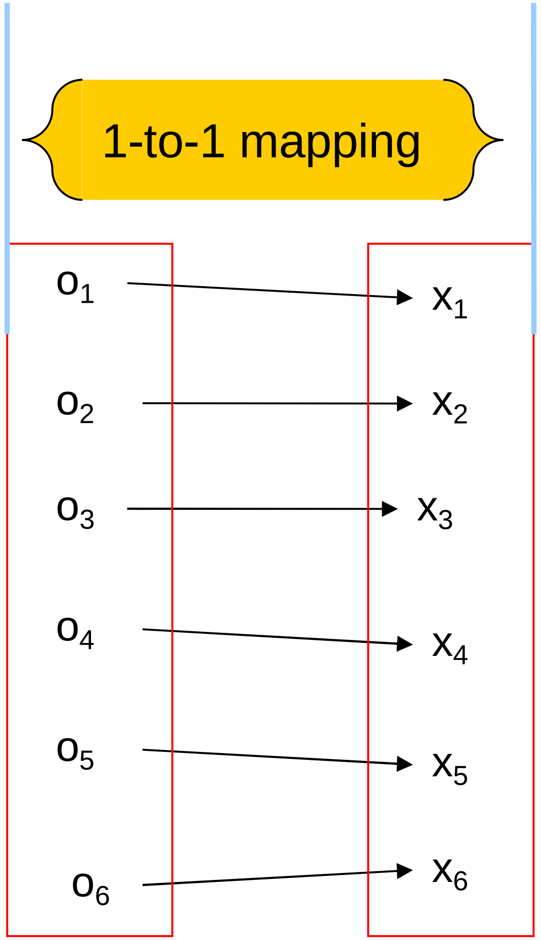
- Any other observations?

Context Sensitive Flow Graph



Please look at the subscripts....

Context Sensitive Flow Graph

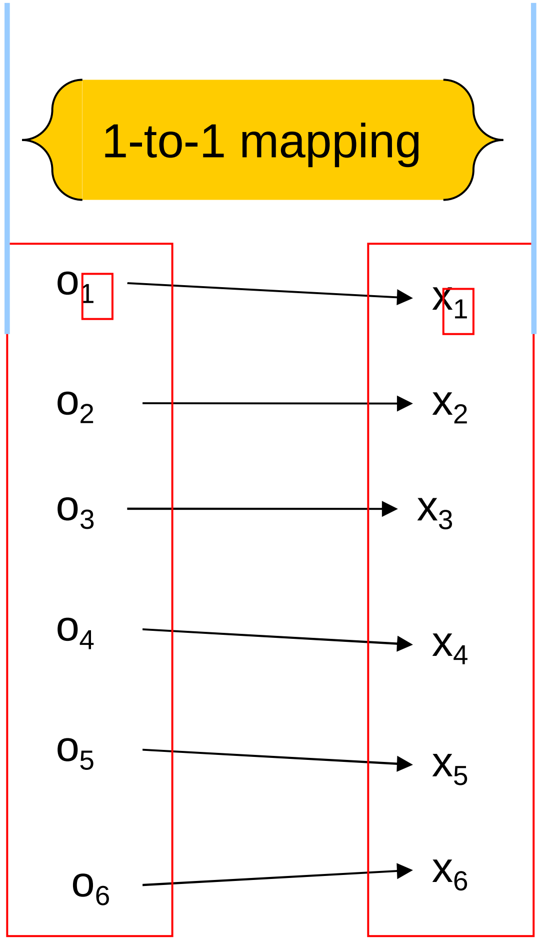


Please look at the subscripts....

o : [1, 6]
x : [1, 6]

Consecutive numbers

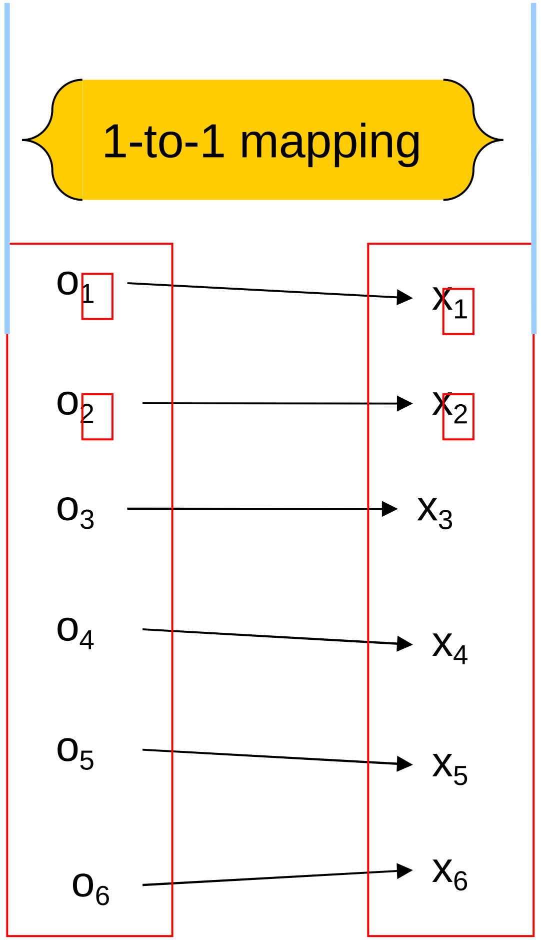
Context Sensitive Flow Graph



Please look at the subscripts....

1 -> 1

Context Sensitive Flow Graph

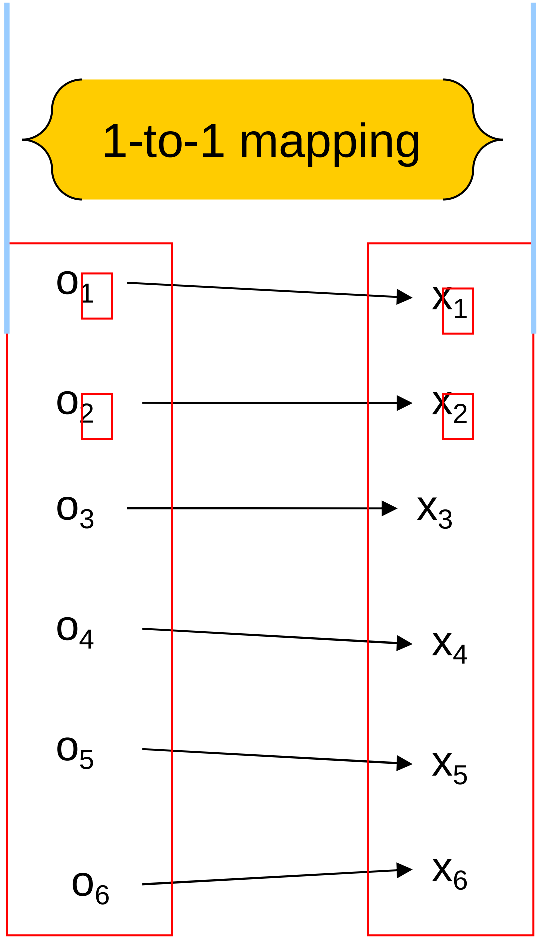


Please look at the subscripts....

1 -> 1

2 -> 2

Context Sensitive Flow Graph



Please look at the subscripts....

1 -> 1

2 -> 2

……………..

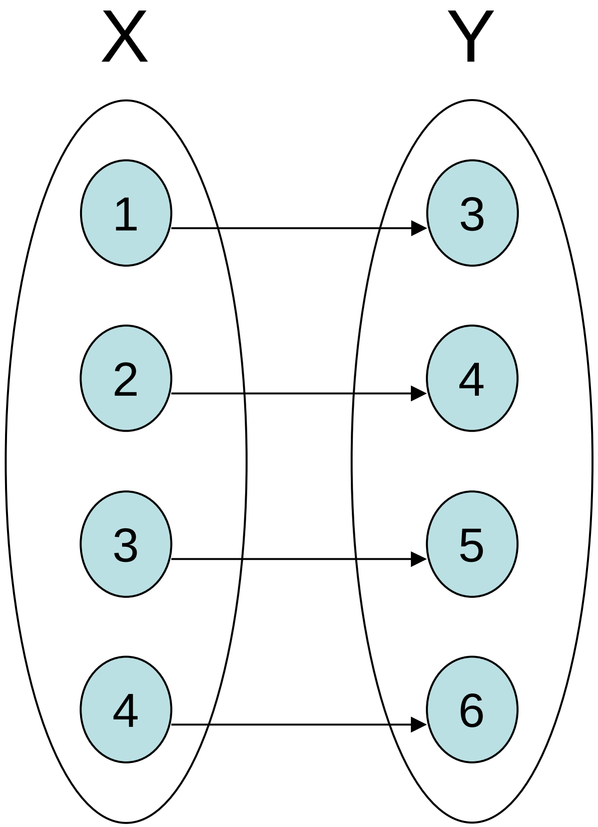
Context Sensitive Flow Graph

- We call this *ordering law*:
  - – Y = map(X);
  - – Elements in X are numbered consecutively;
  - – Elements in Y are numbered consecutively;
  - – a < b in X   => map(a) < map(b).

Context Sensitive Flow Graph

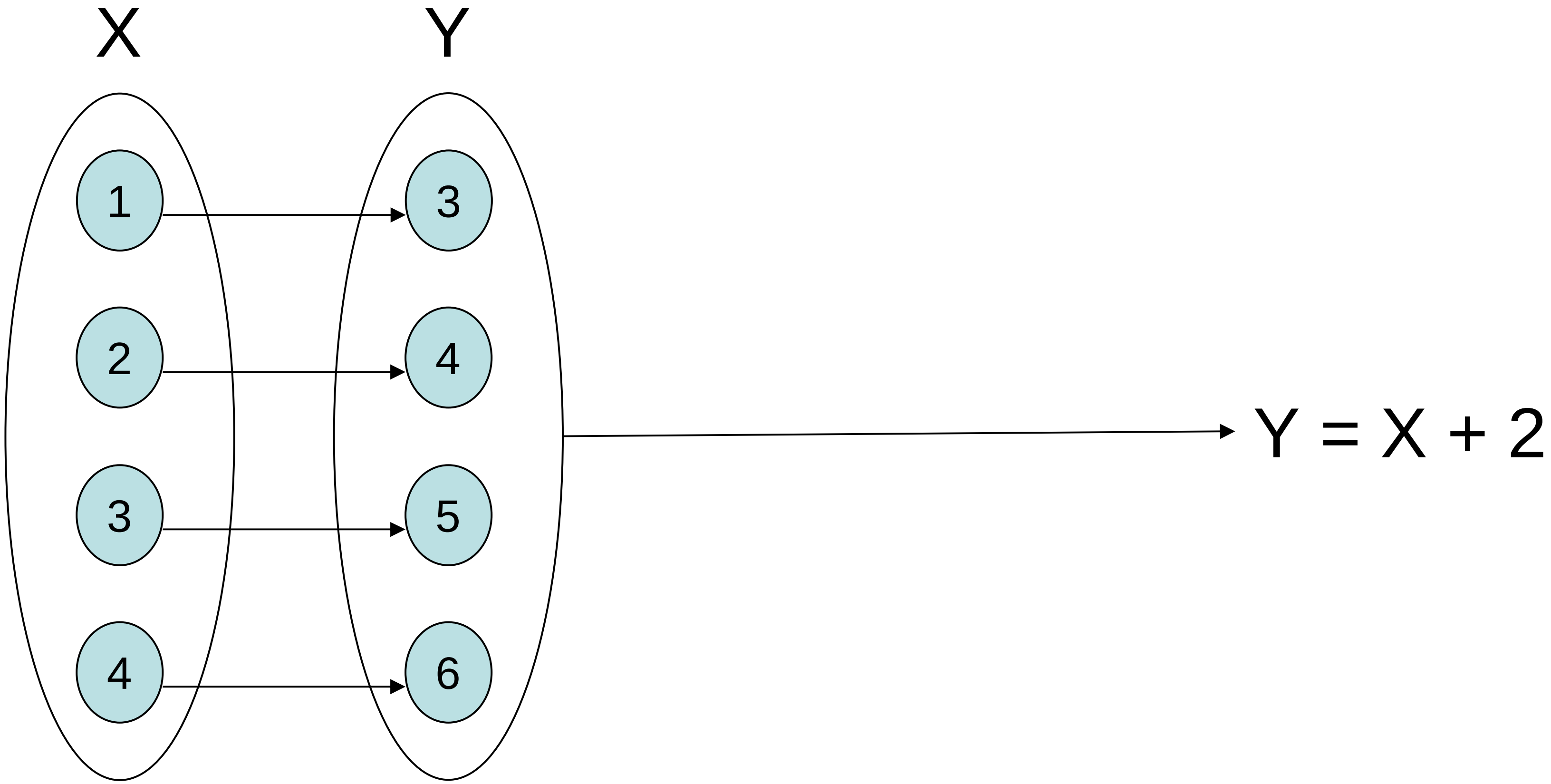
- Is it useful for our points-to analysis?

Geometric Encoding

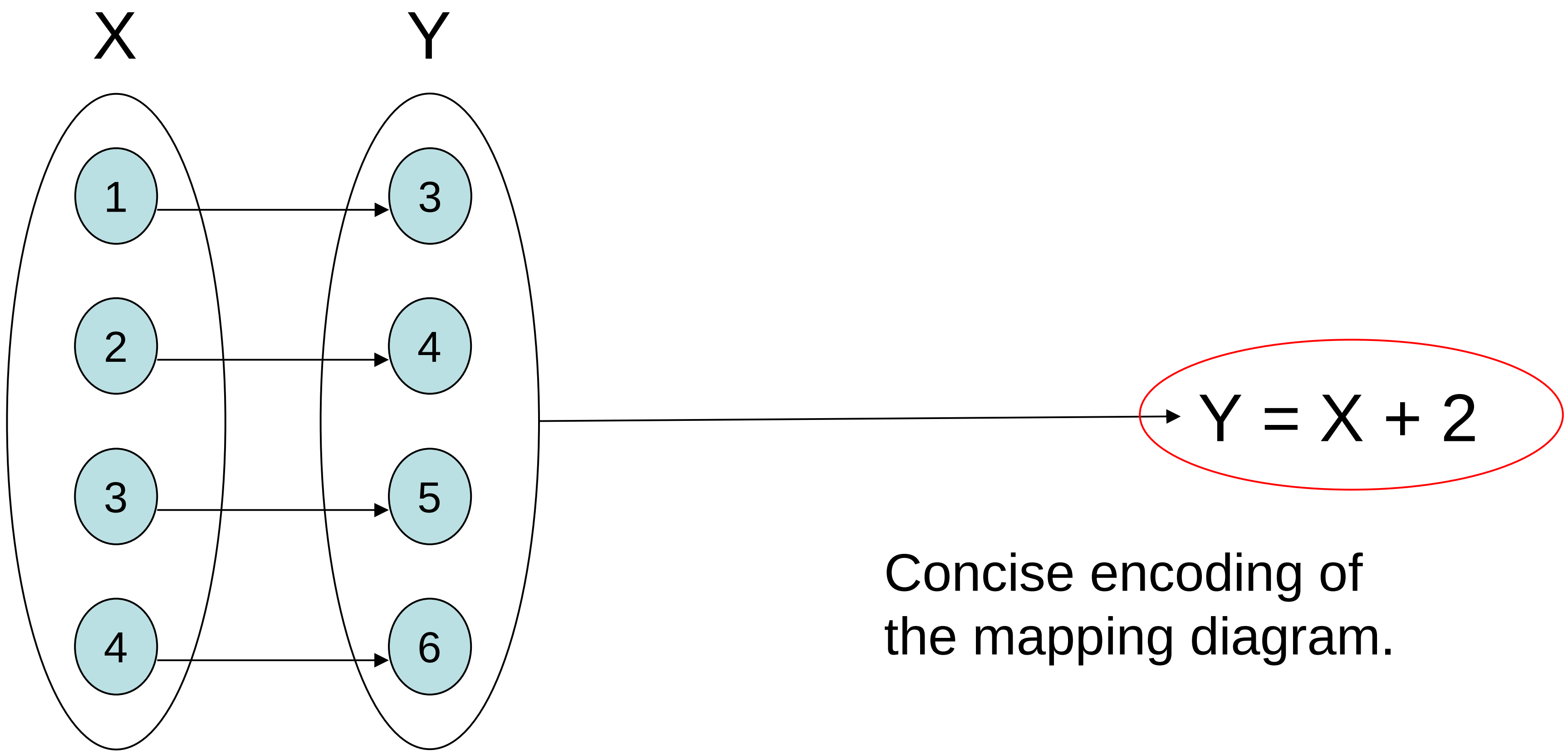


1-to-1 mapping with ordering law.......

Geometric Encoding



Geometric Encoding



Concise encoding of the mapping diagram.

Geometric Encoding

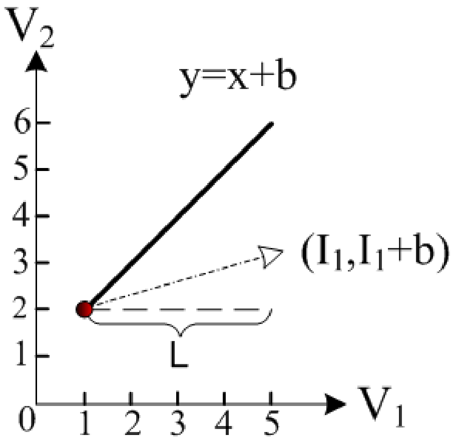
- Next, we visualize all the mapping relations that conform to the ordering law.

Geometric Encoding

1-to-1 mapping

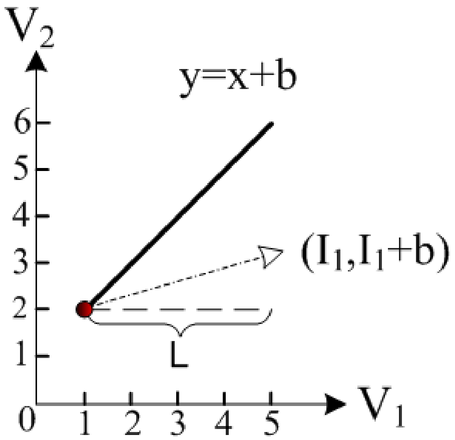
Geometric Encoding

1-to-1 mapping



Geometric Encoding

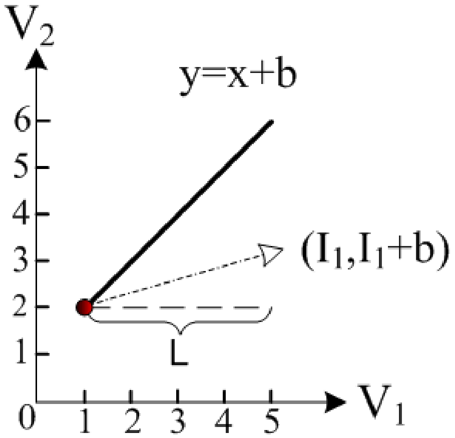
1-to-1 mapping



$(I_1, I_1 + b, L)$

Geometric Encoding

1-to-1 mapping

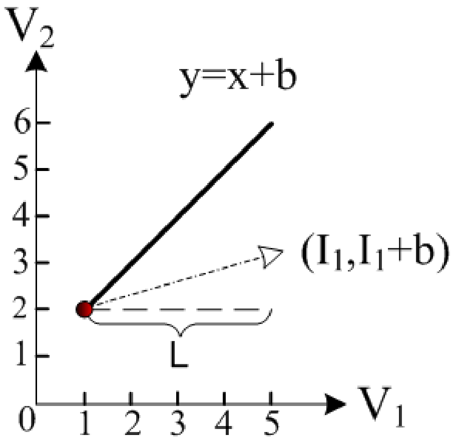


$(I_1, I_1 + b, L)$

many-to-many
(1-to-many,
many-to-1)

Geometric Encoding

1-to-1 mapping



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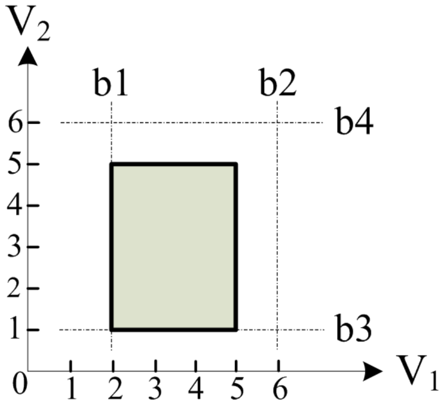
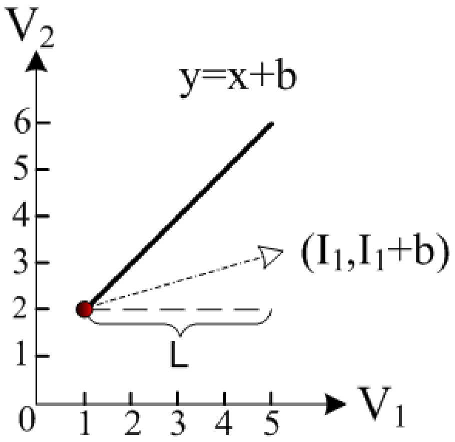
many-to-many (1-to-many, many-to-1)



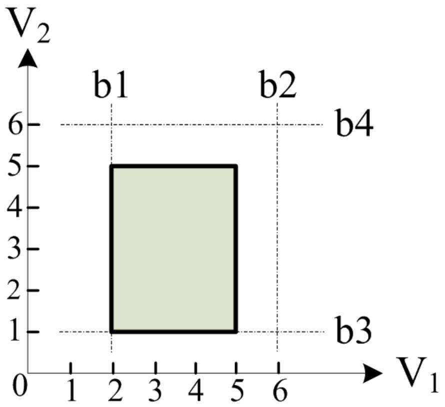
Geometric Encoding

1-to-1 mapping



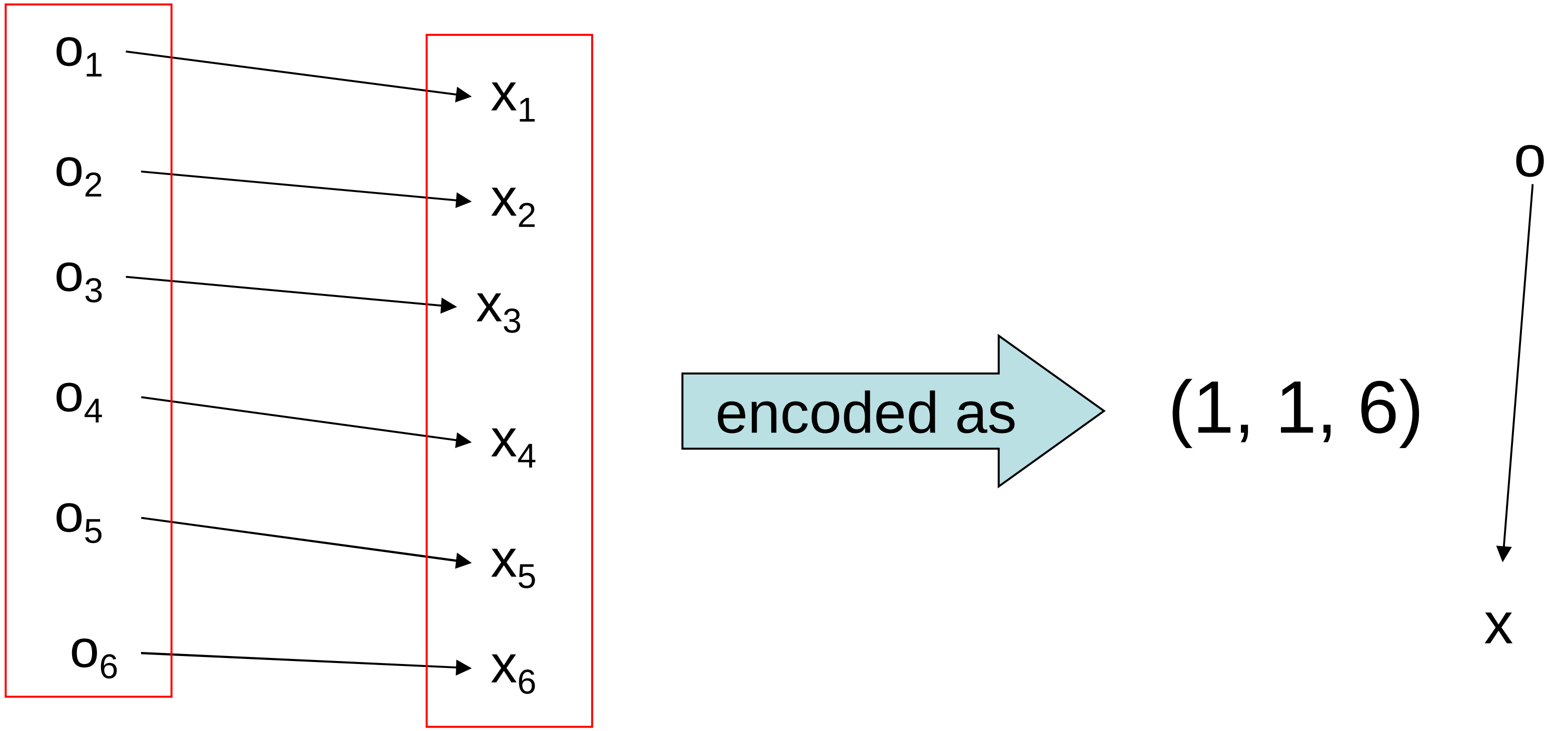
$(I_1, I_1 + b, L)$

many-to-many (1-to-many, many-to-1)

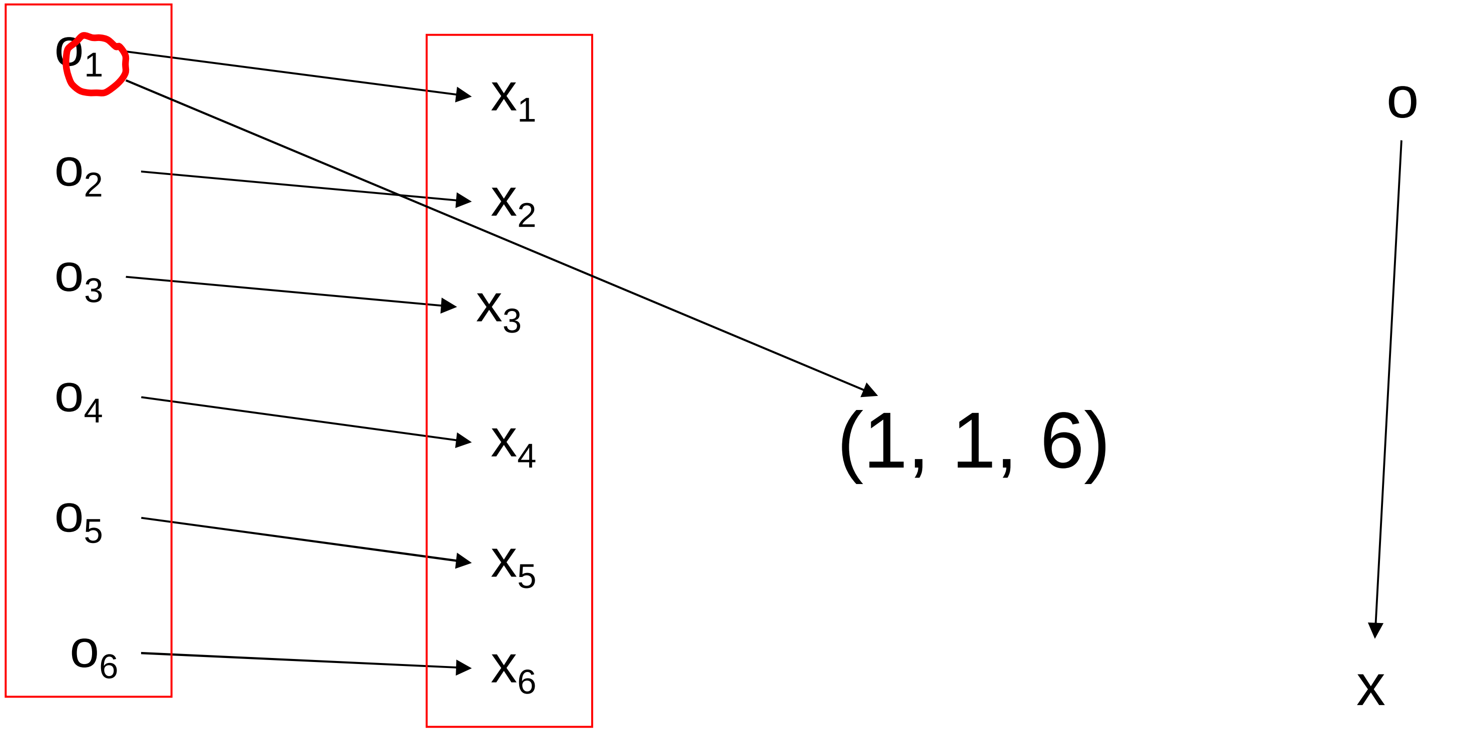


$(b_1, b_3, b_2 - b_1, b_4 - b_3)$

Geometric Encoding



Geometric Encoding



o_1 o_2 o_3 o_4 o_5 o_6

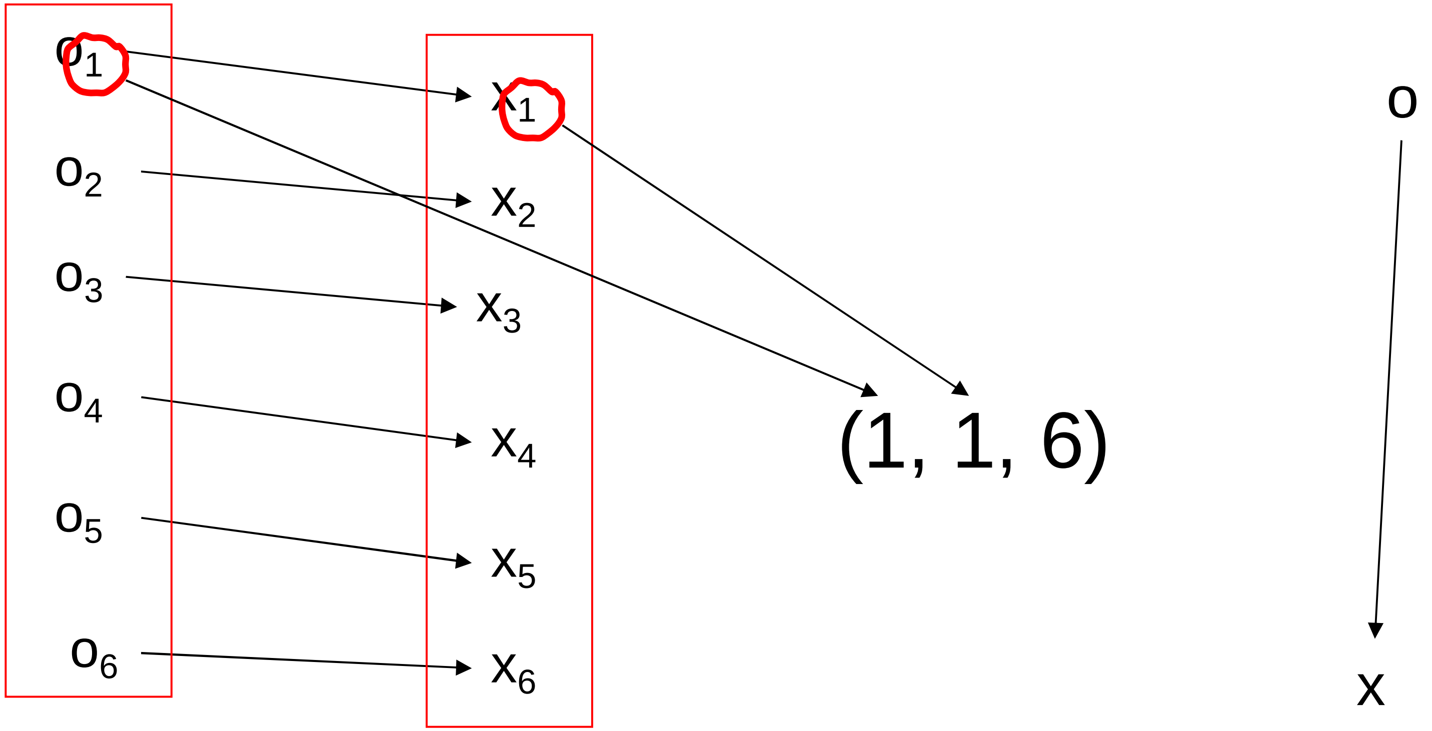
x_1 x_2 x_3 x_4 x_5 x_6

(1, 1, 6)

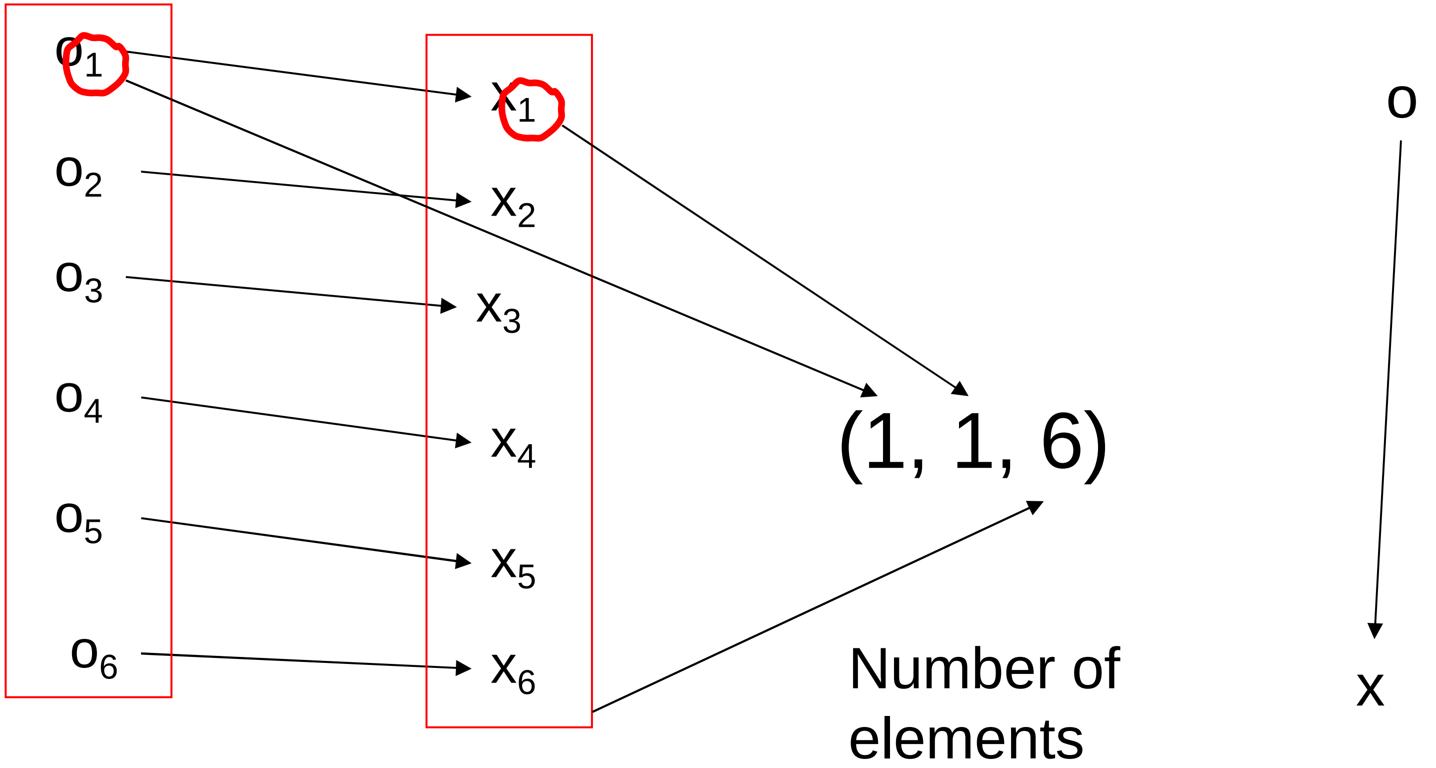
o

x

Geometric Encoding



Geometric Encoding



Geometric Encoding

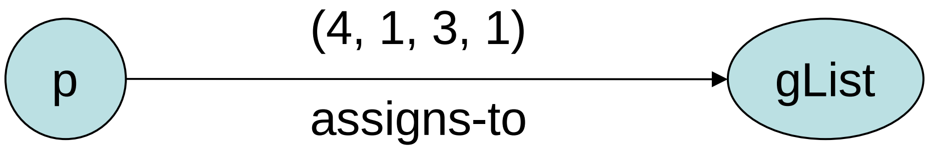
How can we do reachability analysis with the flow graph compressed by geometric encoding?

Inference Rules

- Pointer assignment:

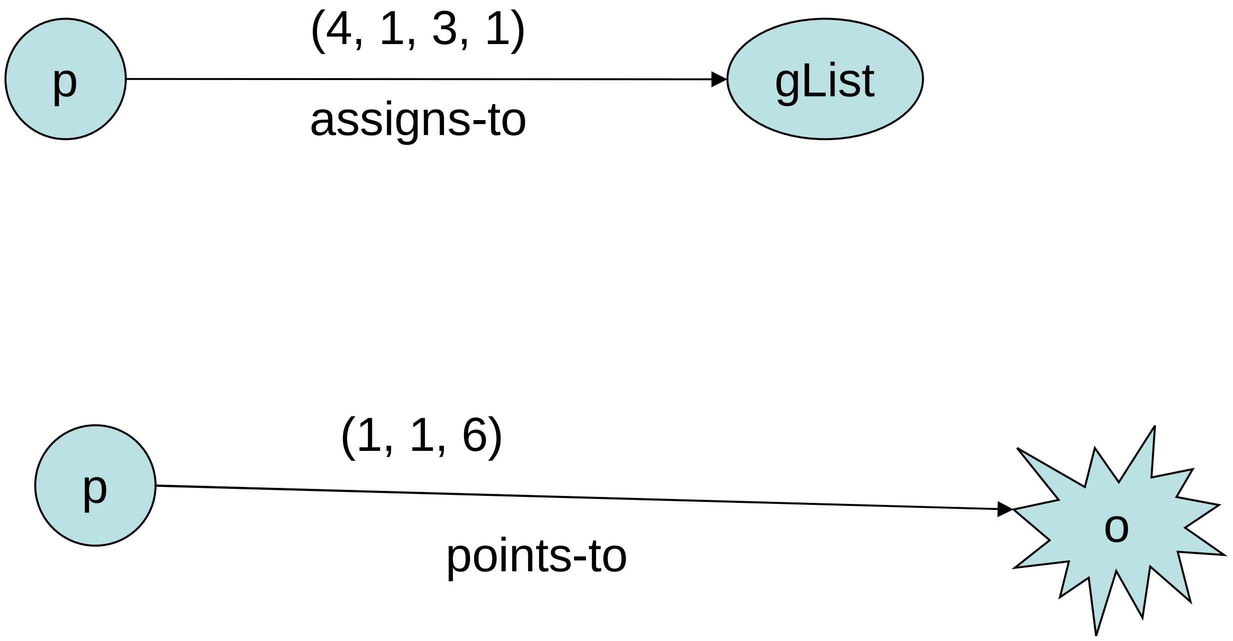
Inference Rules

- Pointer assignment:



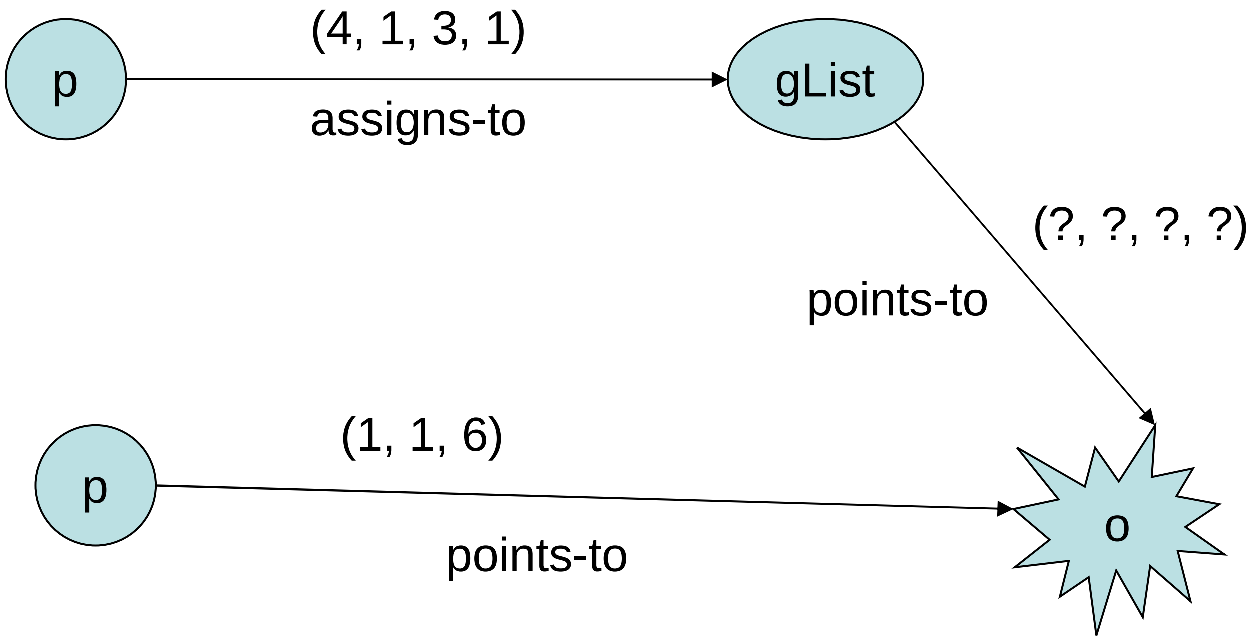
Inference Rules

- Pointer assignment:

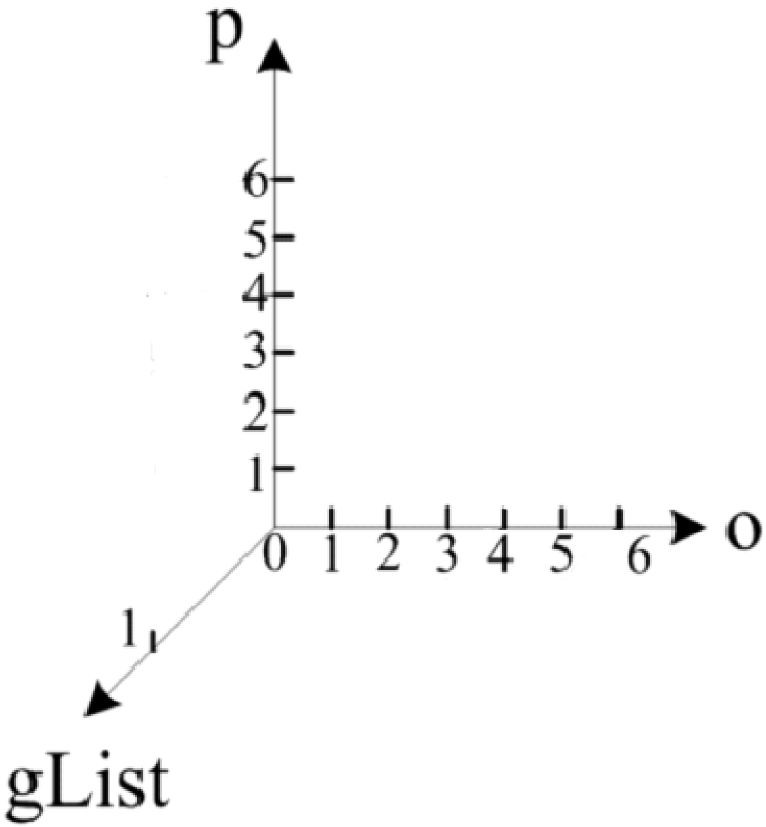


Inference Rules

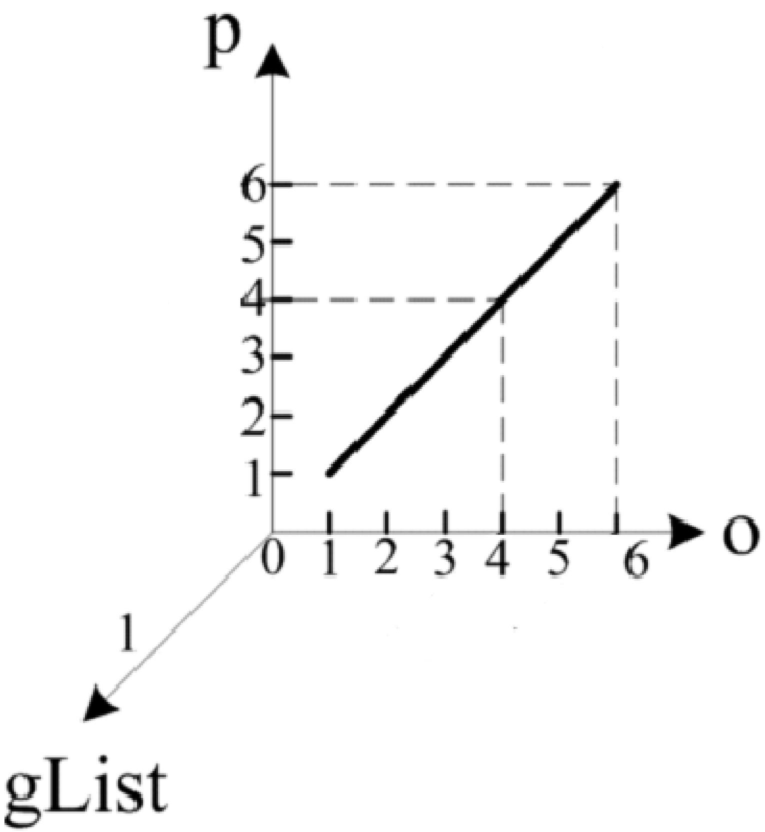
- Pointer assignment:

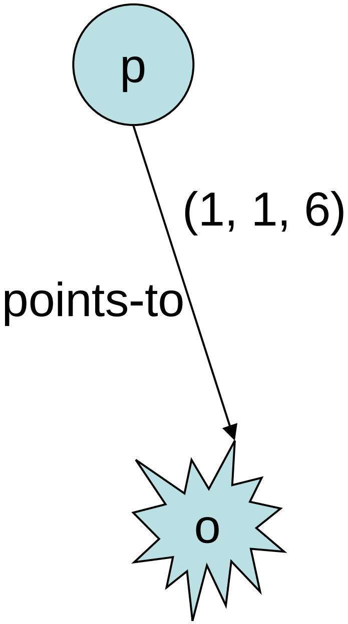


Inference Rules

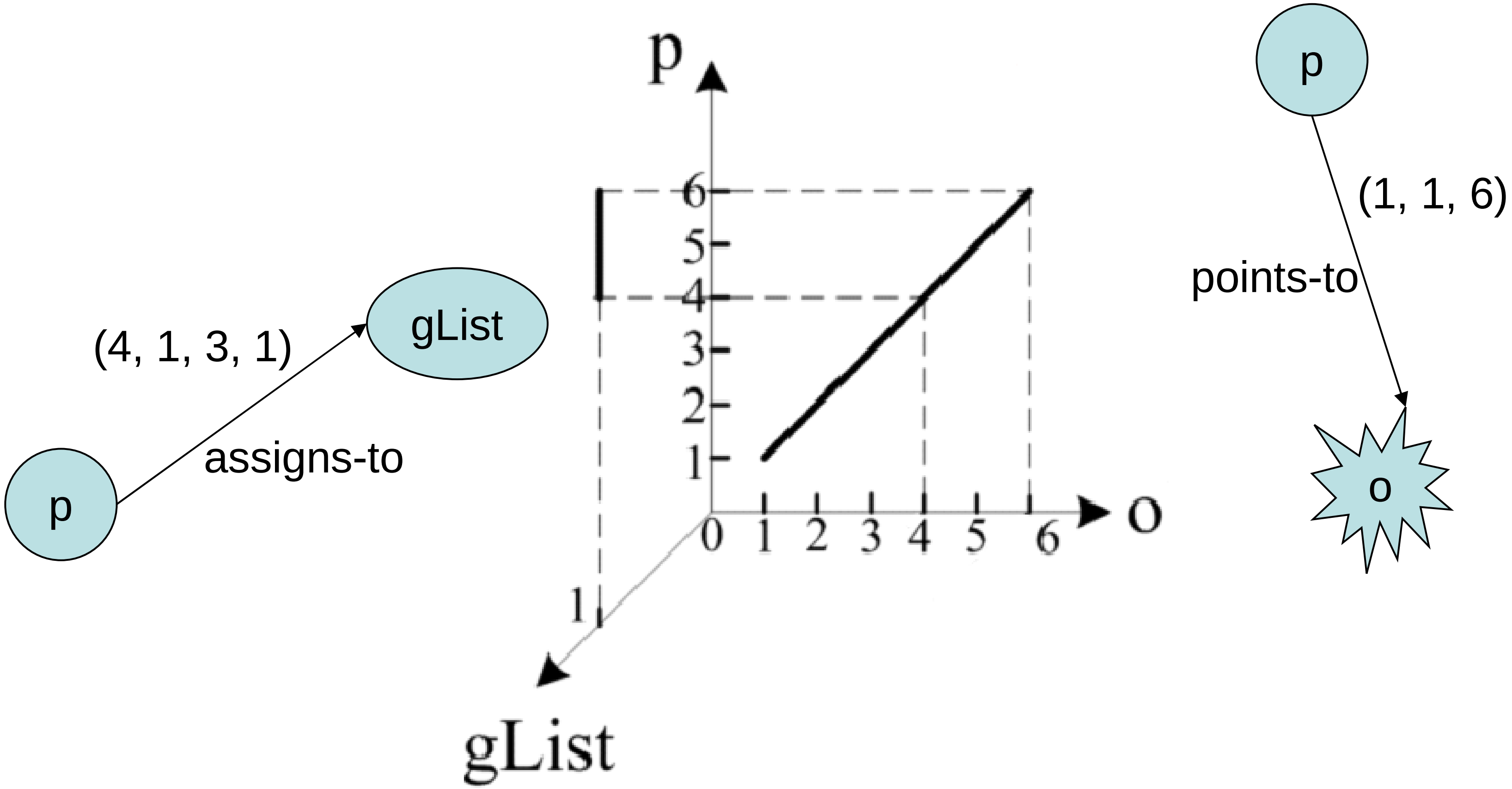


Inference Rules

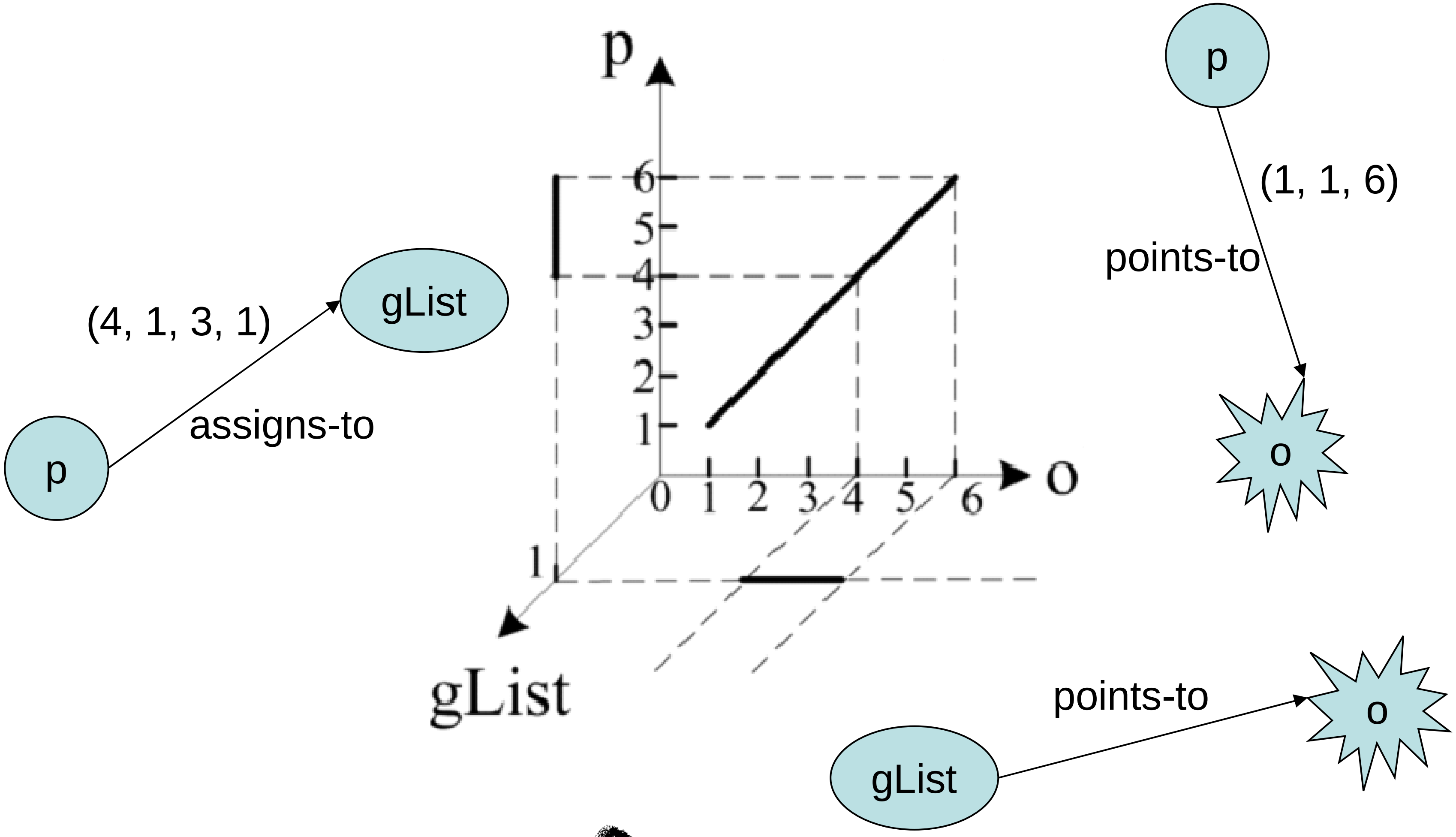




Inference Rules



Inference Rules



p

(4, 1, 3, 1)

assigns-to

gList

p

(1, 1, 6)

points-to

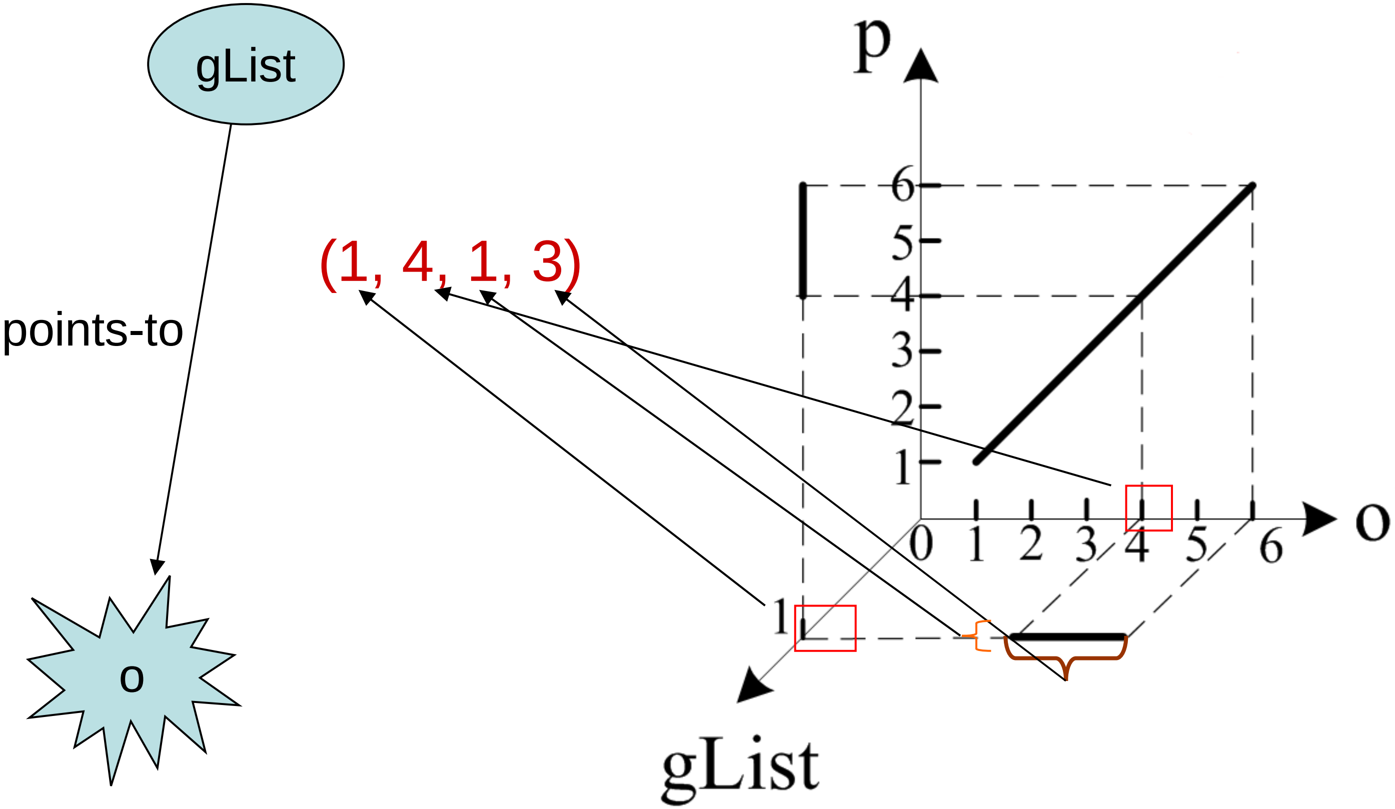
o

gList

points-to

o

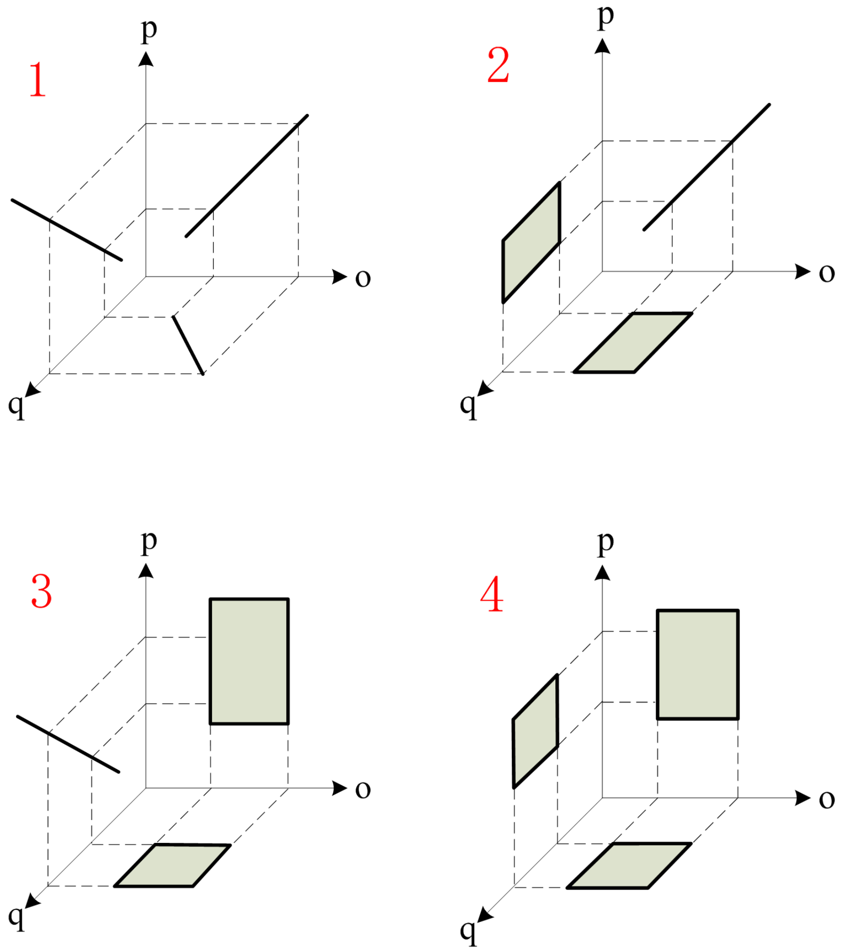
Inference Rules



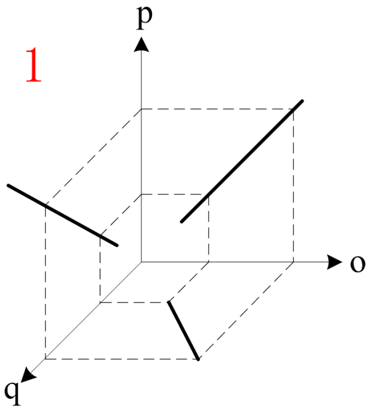
Inference Rules

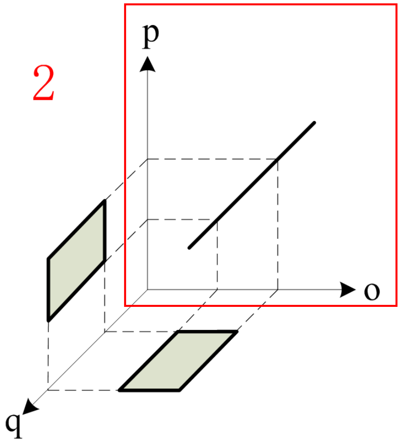
- Pointer assignment inference problem:
  - Input: p = q, p -> o
  - Infer: q -> o

Inference Rules

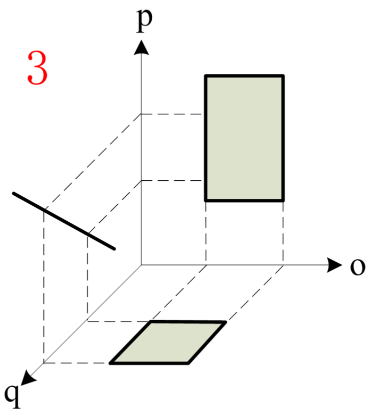


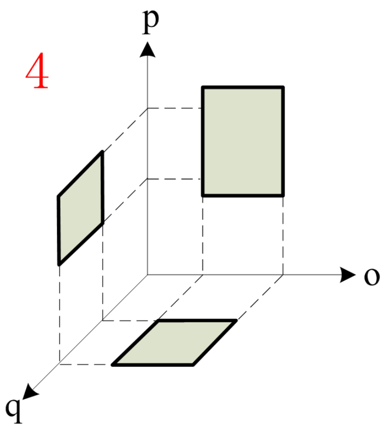
Inference Rules





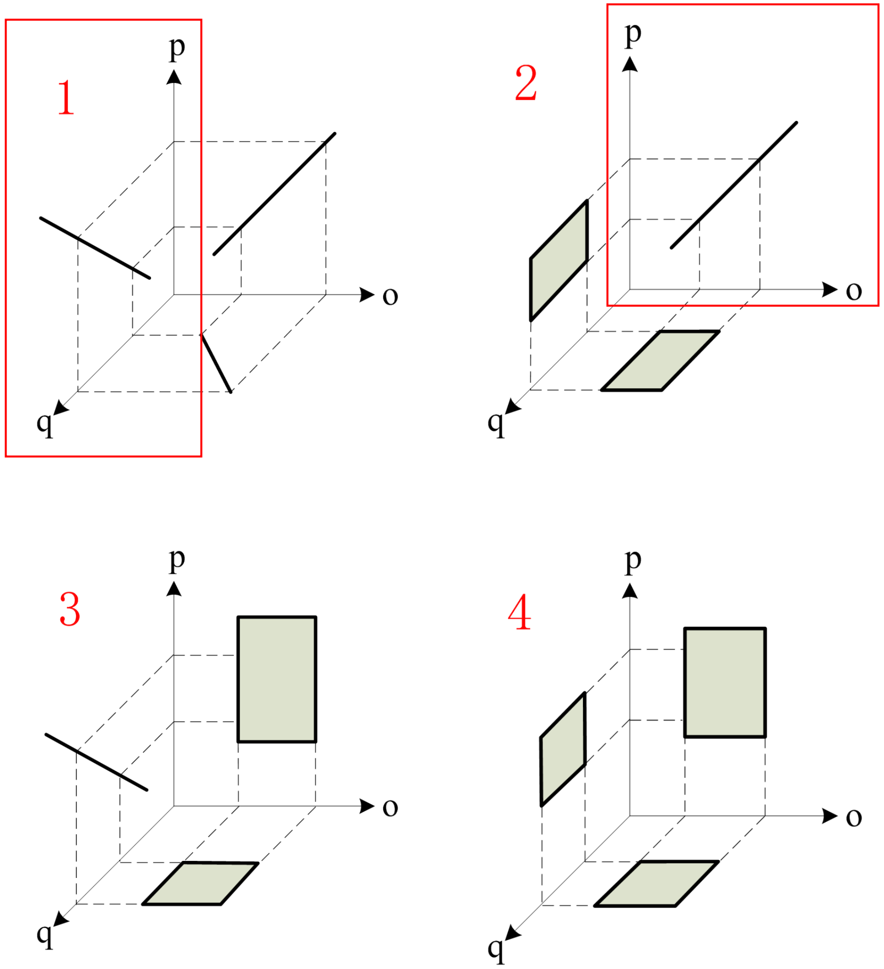
p points-to o





Inference Rules

p assigns-to q

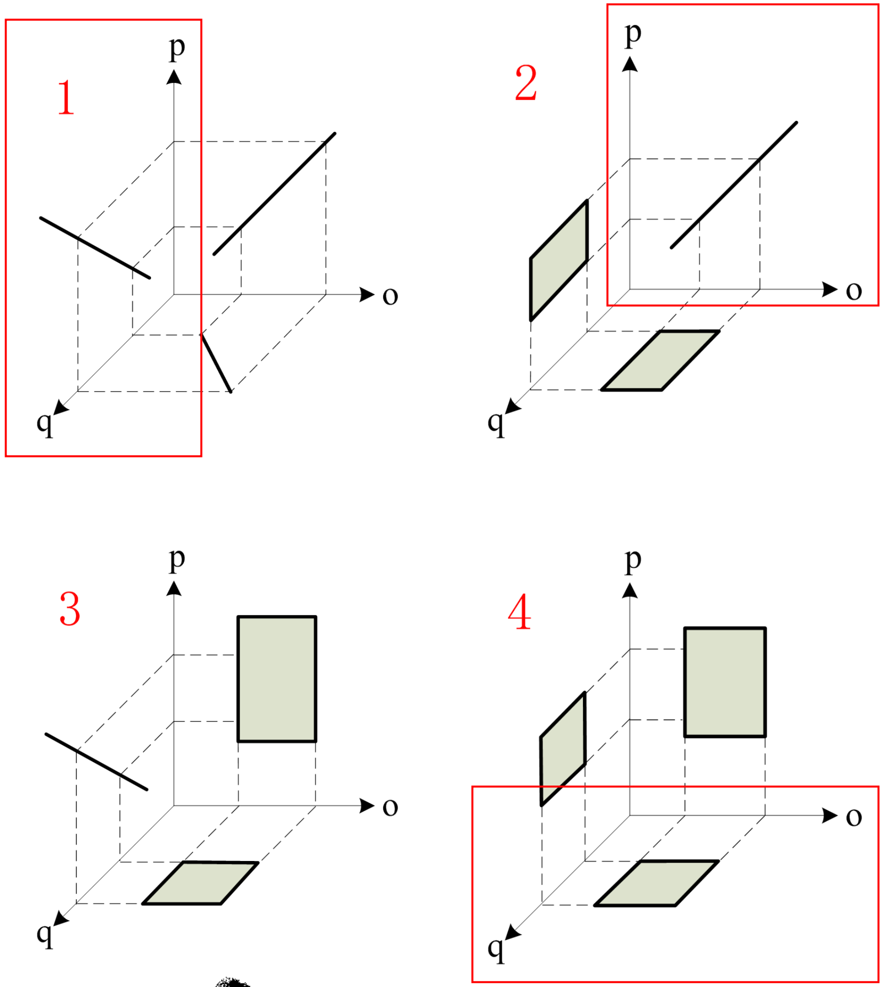


p points-to o

Inference Rules

p assigns-to q

p points-to o



q points-to o

Inference Rules

- Pointer Dereference:
  - a.k.a complex constraints instantiation
  - e.g.   p = q.f

- Please read our paper for details...

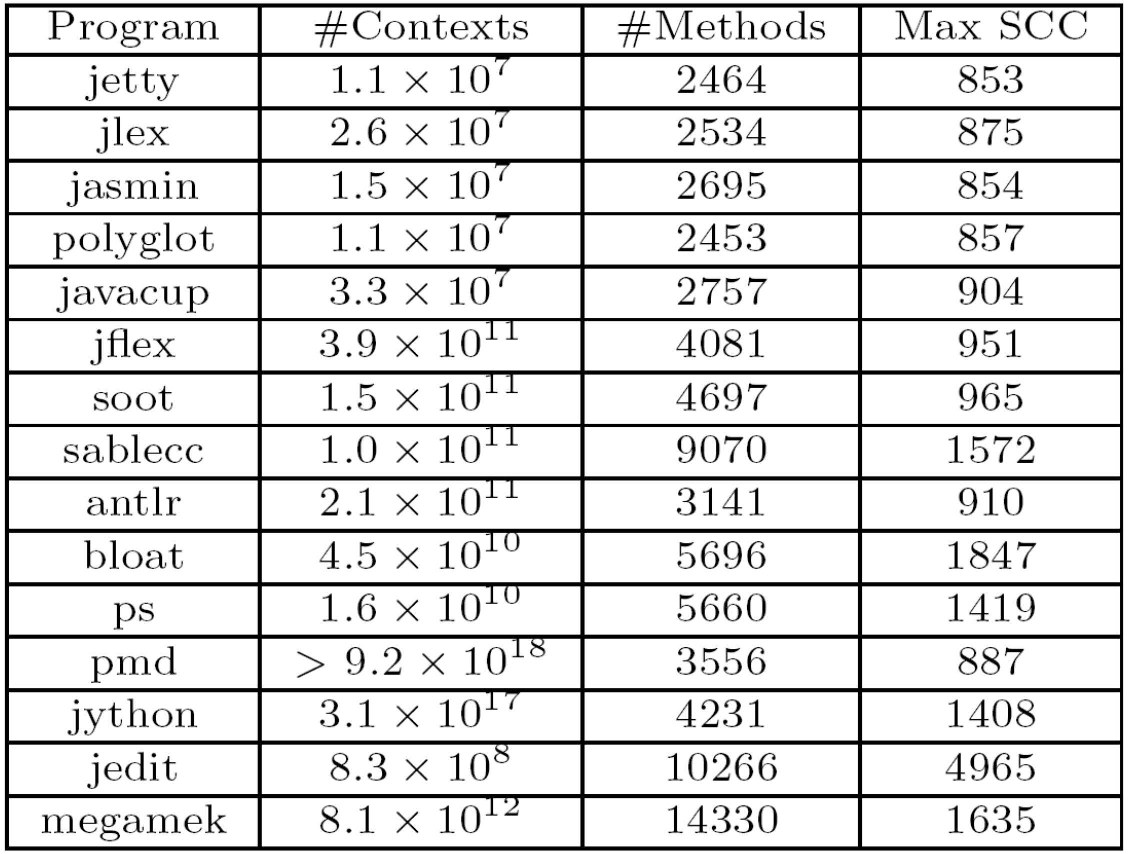
Experiment

- Questions:
  - Performance?
  - Precision?

Experimental Configuration

- Evaluated algorithm:
  - Two encoding instances: *Geom* and *HeapIns*
- State of the art:
  - Paddle 1-Object Sensitivity
  - Both BDD and worklist based
- Execution environment:
  - Soot 2.4.0
  - JDK 1.3.1_20 (analysis library)
  - JRockit 28.1 (backbone our algorithms and Paddle)
  - Intel Xeon 3.0 G
  - 15G RAM

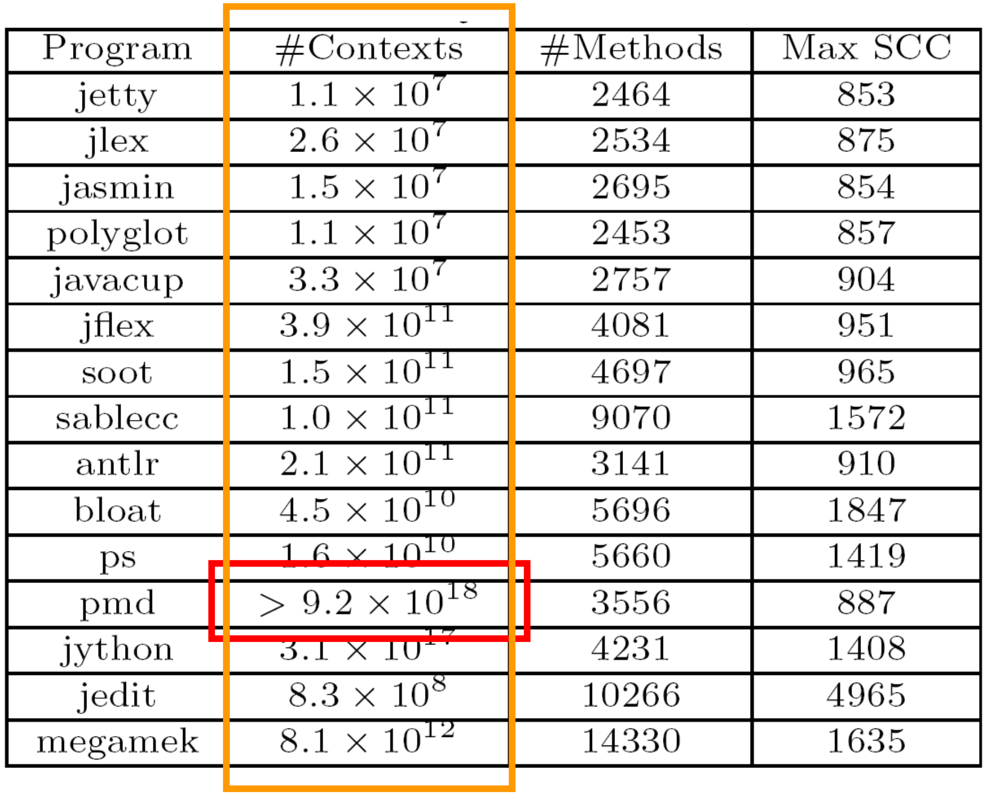
Benchmark



Program	#Contexts	#Methods	Max SCC
jetty	1.1×10^{7}	2464	853
jlex	2.6×10^{7}	2534	875
jasmin	1.5×10^{7}	2695	854
polyglot	1.1×10^{7}	2453	857
javacup	3.3×10^{7}	2757	904
jflex	3.9×10^{11}	4081	951
soot	1.5×10^{11}	4697	965
sablecc	1.0×10^{11}	9070	1572
antlr	2.1×10^{11}	3141	910
bloat	4.5×10^{10}	5696	1847
ps	1.6×10^{10}	5660	1419
pmd	$> 9.2 \times 10^{18}$	3556	887
jython	3.1×10^{17}	4231	1408
jedit	8.3×10^{8}	10266	4965
megamek	8.1×10^{12}	14330	1635

Benchmark

- The number of contexts is very large!
- 9.2 * 10^{18} = 2^63



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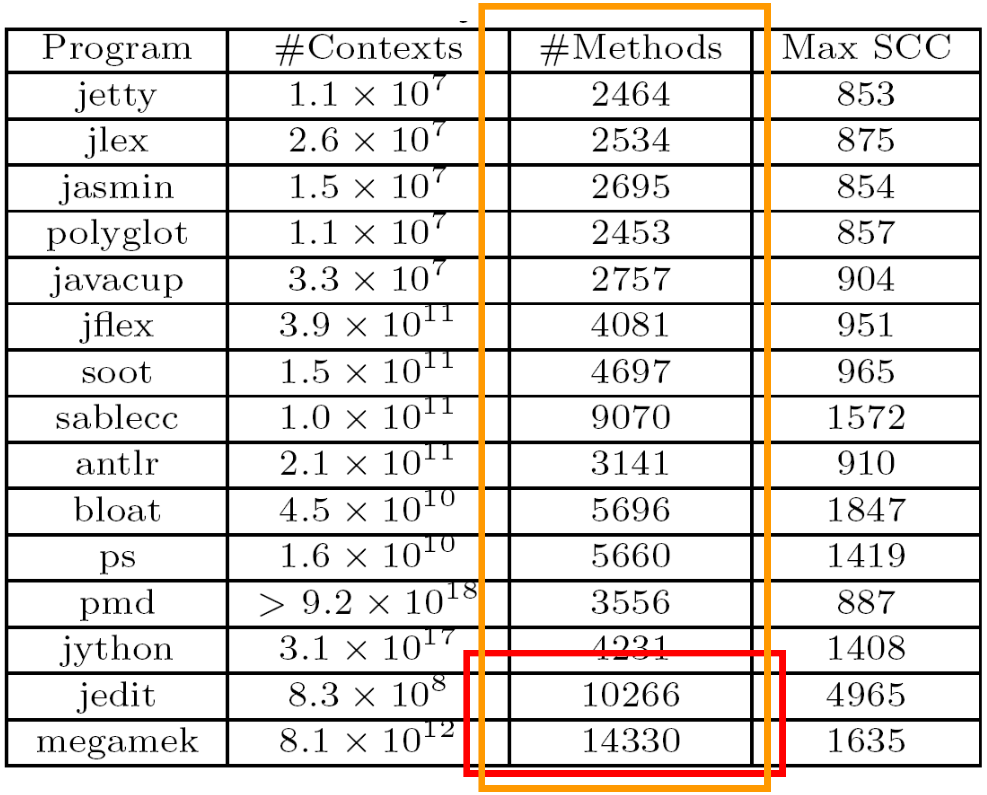
Benchmark

- The number of contexts is very large!
- 9.2 * 10^18 = 2^63
- The benchmark size is also very large!



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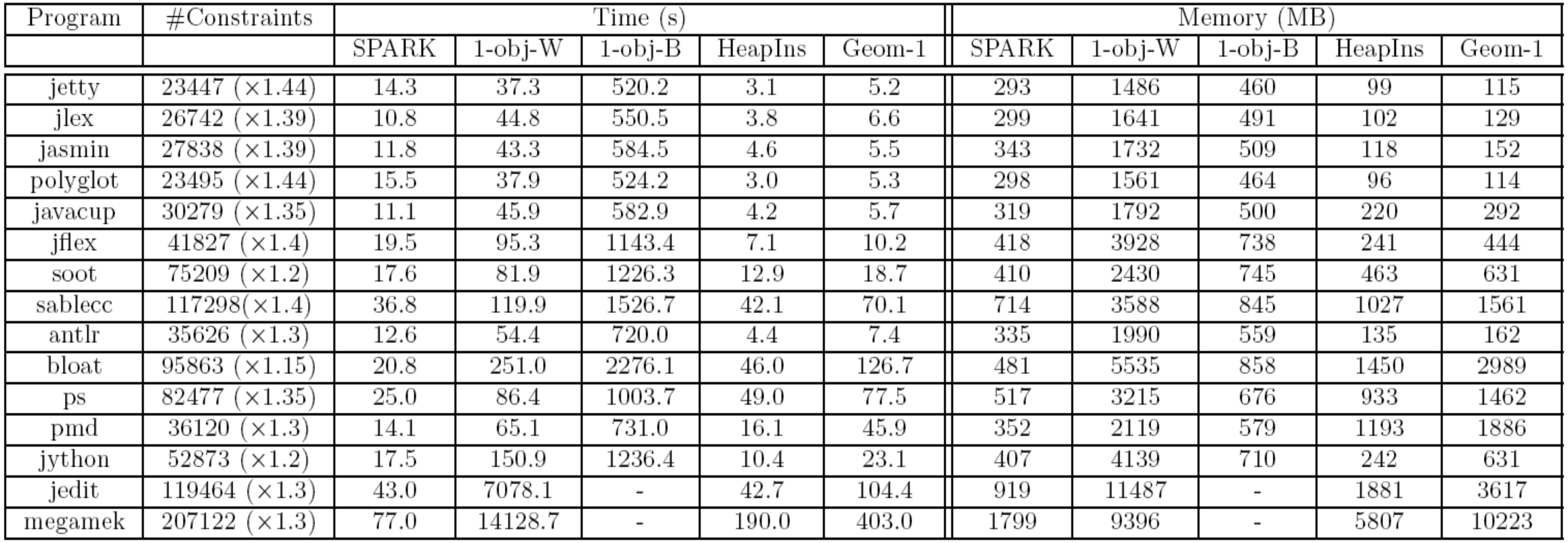
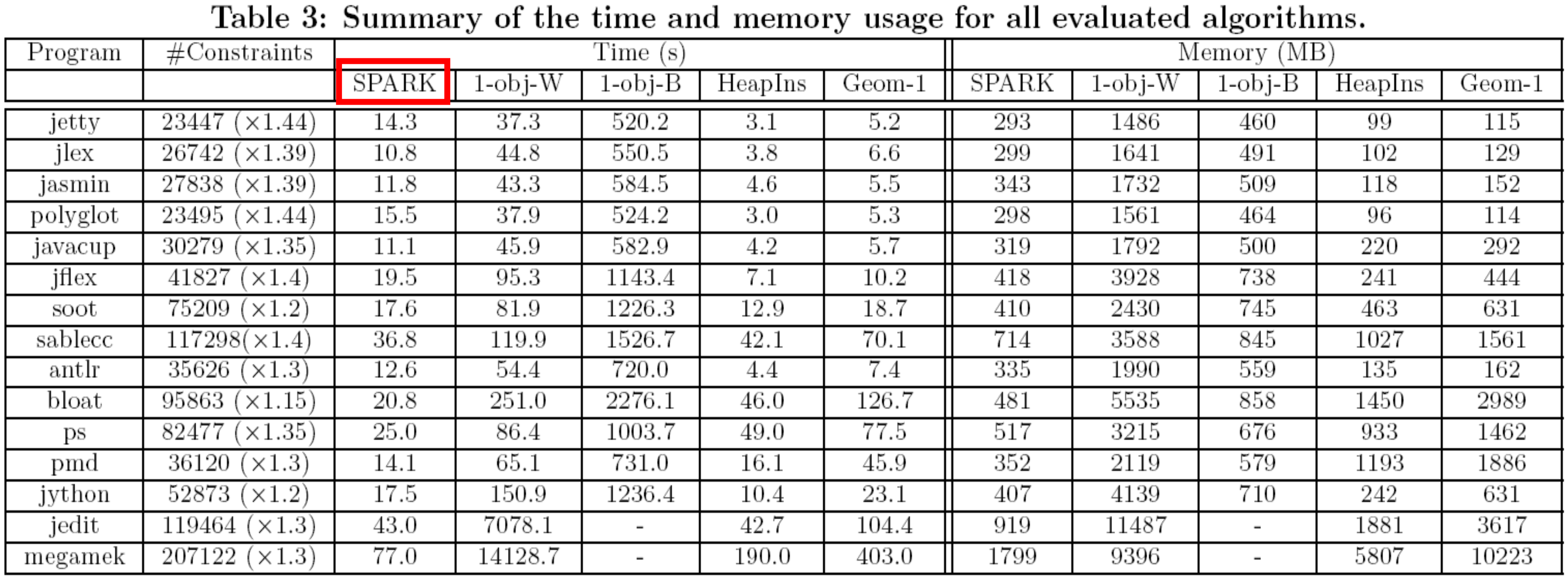
Performance Evaluation

Table 3: Summary of the time and memory usage for all evaluated algorithms.



Program	#Constraints	Time (s)					Memory (MB)				
		SPARK	1-obj-W	1-obj-B	HeapIns	Geom-1	SPARK	1-obj-W	1-obj-B	HeapIns	Geom-1
jetty	23447 (×1.44)	14.3	37.3	520.2	3.1	5.2	293	1486	460	99	115
jlex	26742 (×1.39)	10.8	44.8	550.5	3.8	6.6	299	1641	491	102	129
jasmin	27838 (×1.39)	11.8	43.3	584.5	4.6	5.5	343	1732	509	118	152
polyglot	23495 (×1.44)	15.5	37.9	524.2	3.0	5.3	298	1561	464	96	114
javacup	30279 (×1.35)	11.1	45.9	582.9	4.2	5.7	319	1792	500	220	292
jflex	41827 (×1.4)	19.5	95.3	1143.4	7.1	10.2	418	3928	738	241	444
soot	75209 (×1.2)	17.6	81.9	1226.3	12.9	18.7	410	2430	745	463	631
sablecc	117298(×1.4)	36.8	119.9	1526.7	42.1	70.1	714	3588	845	1027	1561
antlr	35626 (×1.3)	12.6	54.4	720.0	4.4	7.4	335	1990	559	135	162
bloat	95863 (×1.15)	20.8	251.0	2276.1	46.0	126.7	481	5535	858	1450	2989
ps	82477 (×1.35)	25.0	86.4	1003.7	49.0	77.5	517	3215	676	933	1462
pmd	36120 (×1.3)	14.1	65.1	731.0	16.1	45.9	352	2119	579	1193	1886
jython	52873 (×1.2)	17.5	150.9	1236.4	10.4	23.1	407	4139	710	242	631
jedit	119464 (×1.3)	43.0	7078.1	-	42.7	104.4	919	11487	-	1881	3617
megamek	207122 (×1.3)	77.0	14128.7	-	190.0	403.0	1799	9396	-	5807	10223

Performance Evaluation



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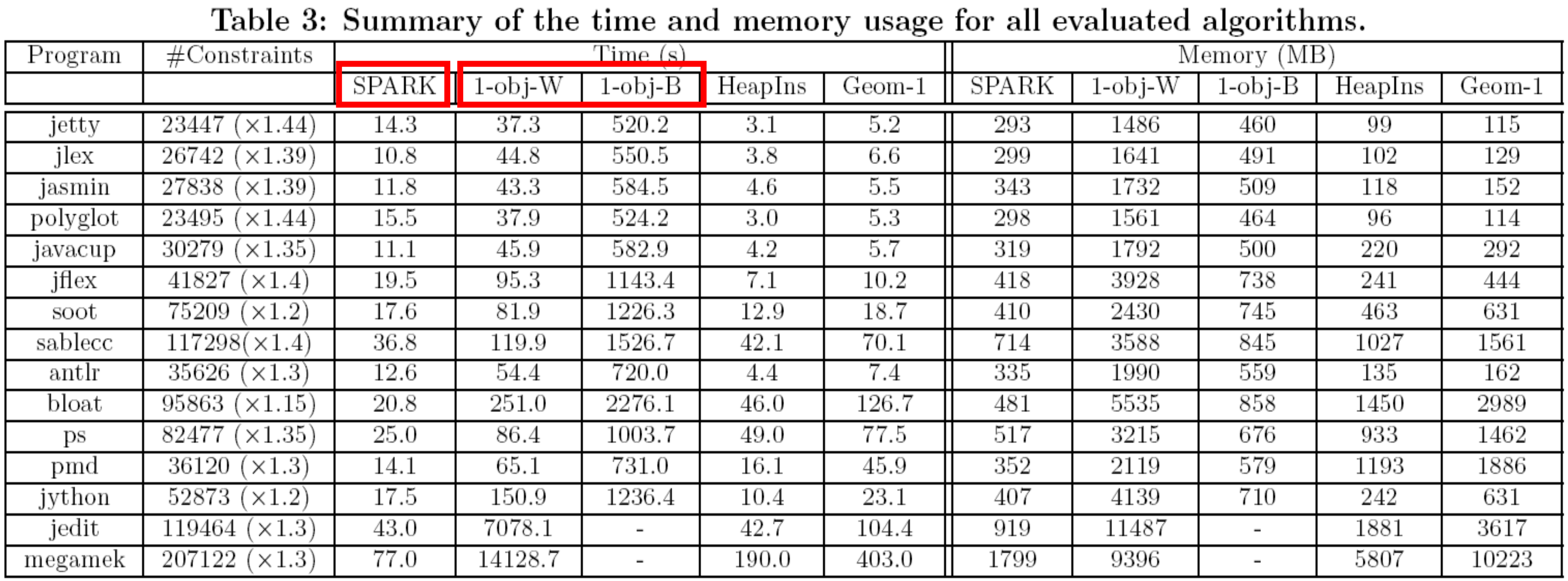
megamek	207122 (×1.3)	77.0	14128.7	-	190.0	403.0	1799	9396	-	5807	10223

Performance Evaluation



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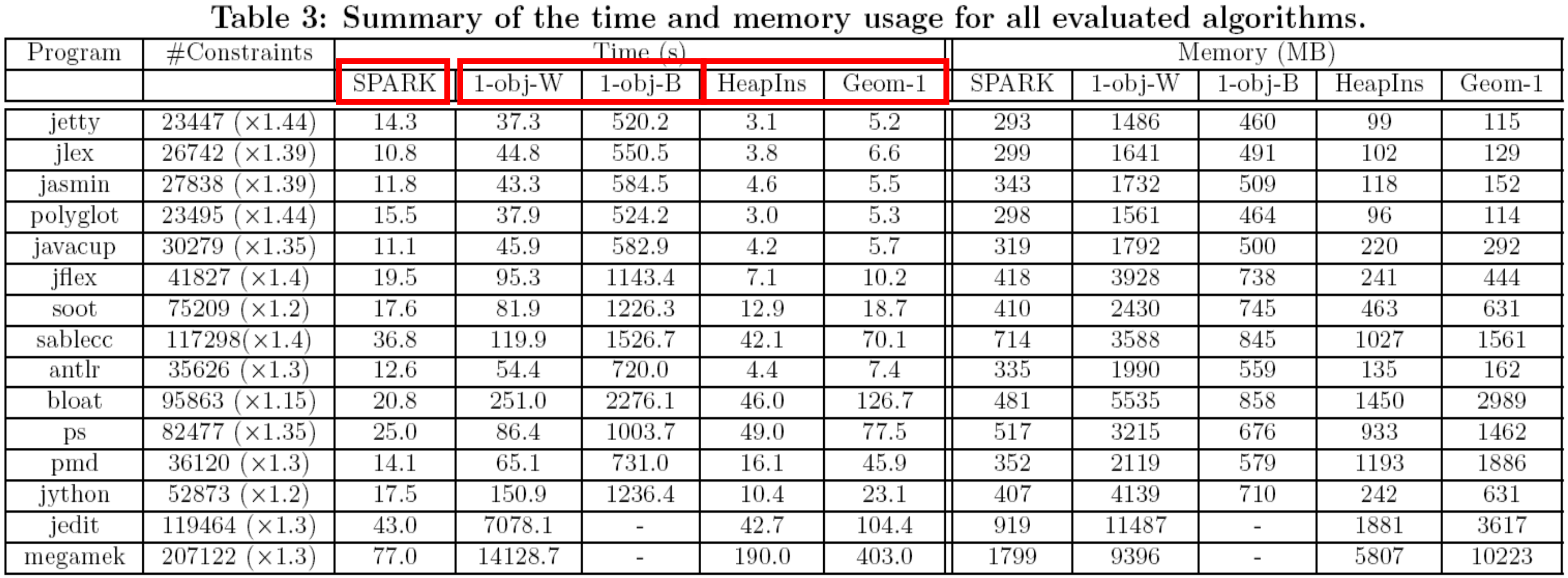
Performance Evaluation



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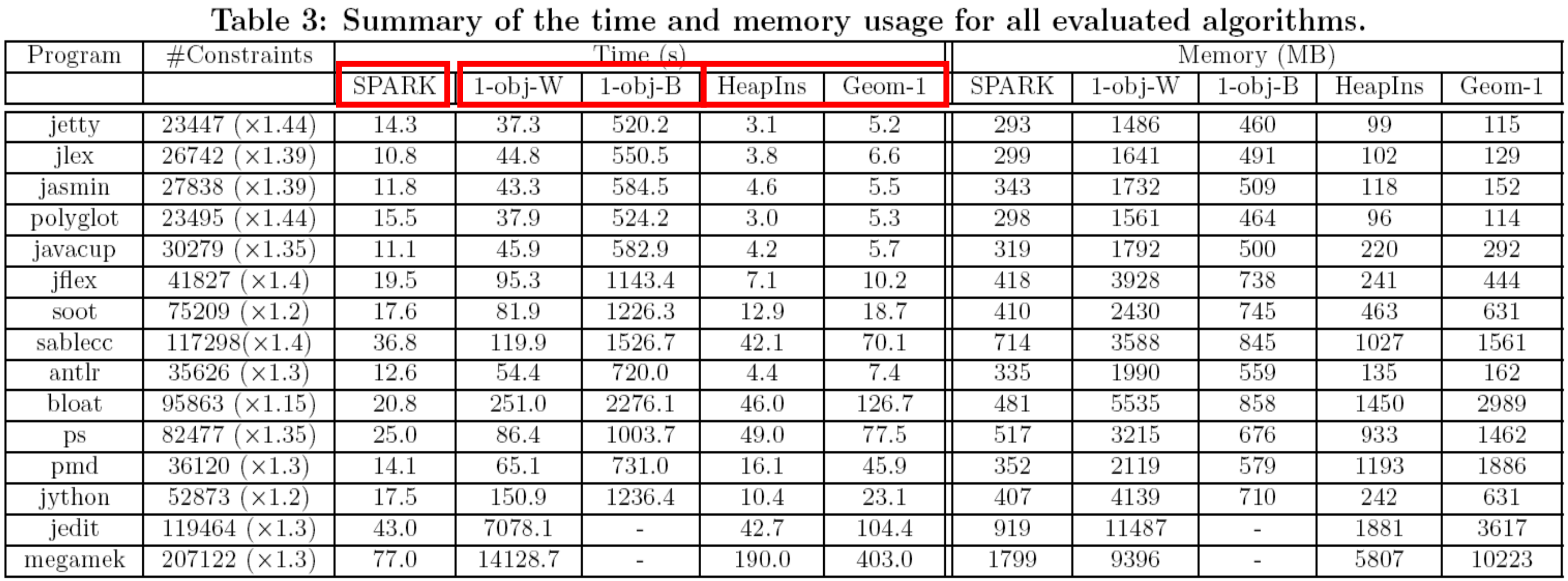
HeapIns: points-to analysis with simplified geometric encoding;

Geom-1: points-to analysis with geometric encoding and context sensitive modeling for the recursive calls

Performance Evaluation



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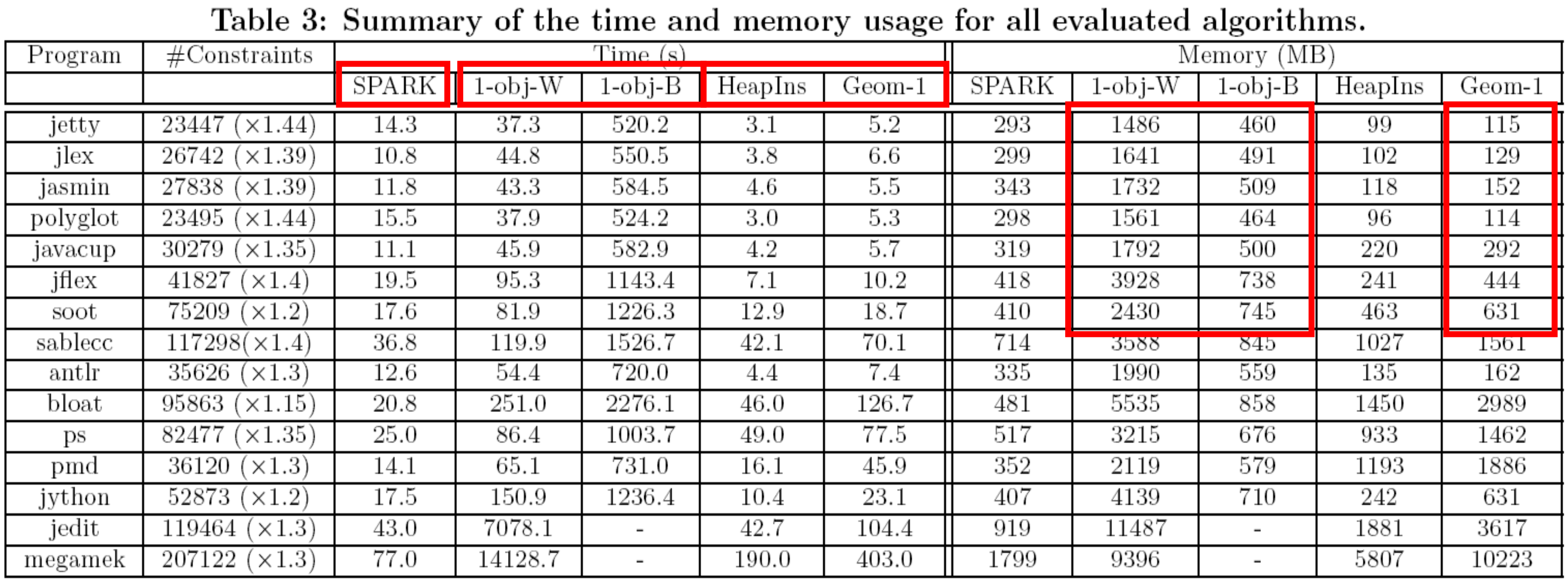
HeapIns and Geom-1 are:

- 23.9x and 11.6x faster than 1-obj-W;
- 111x and 68.3x faster than 1-obj-B;

Performance Evaluation



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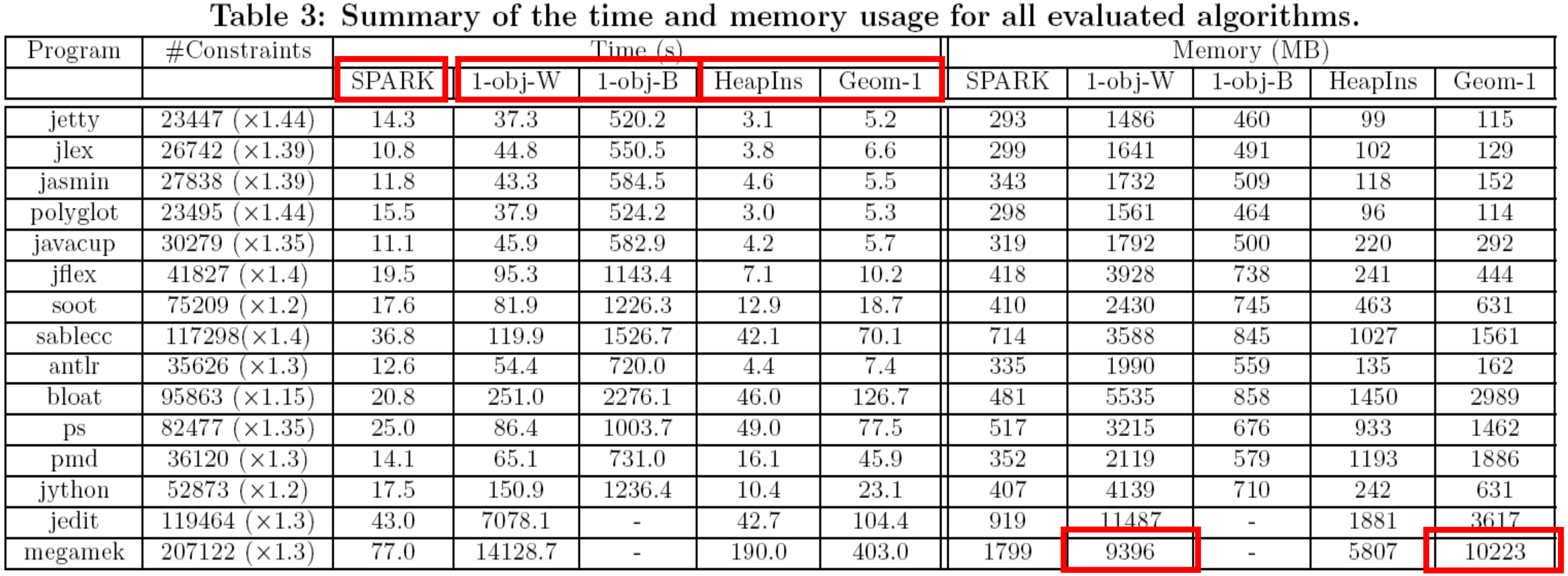
Performance Evaluation



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HeapIns and Geom-1 are:

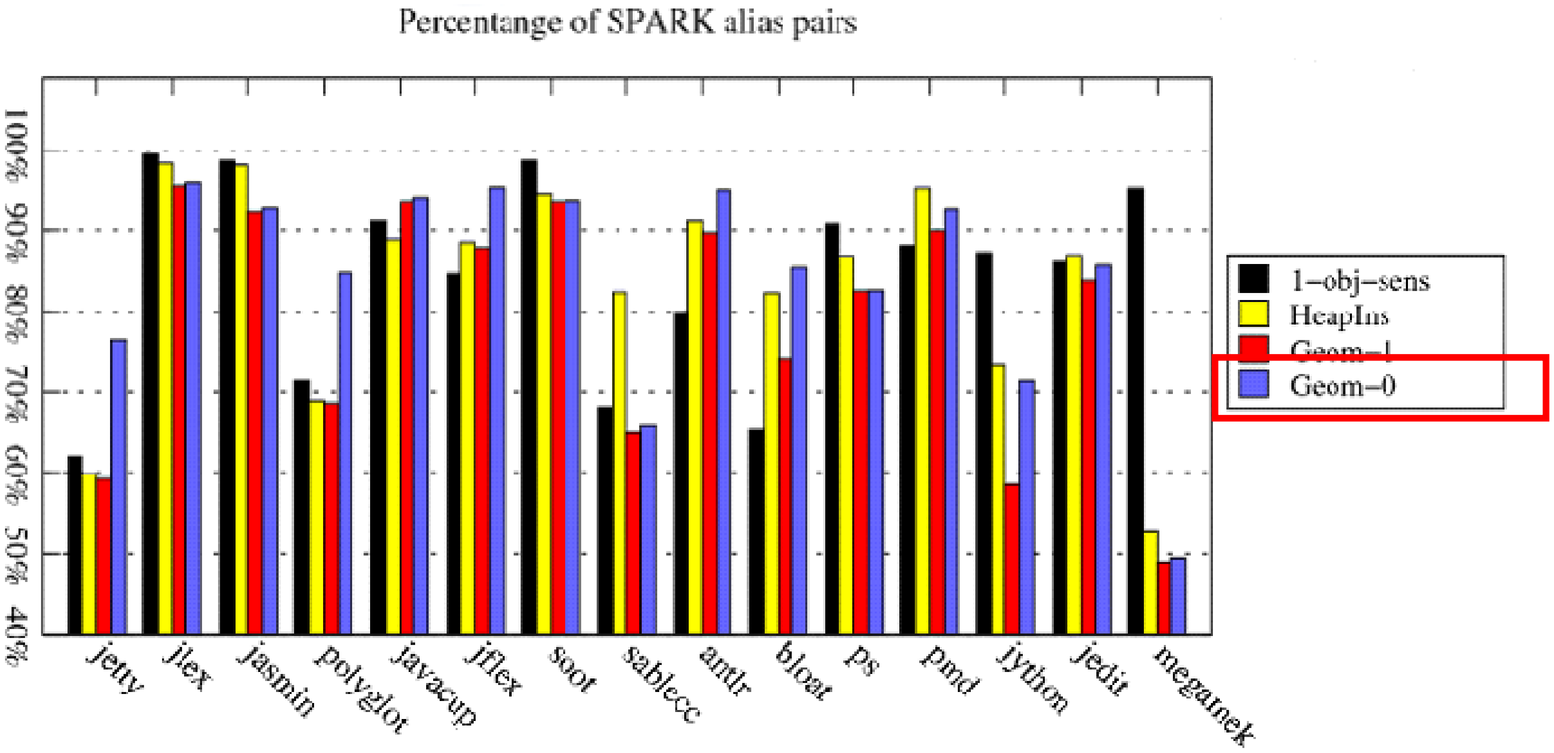
- requires 9.6x and 6.7x memory than 1-obj-W.

Alias Analysis

- Determine two pointers p and q may point to the same object or not;

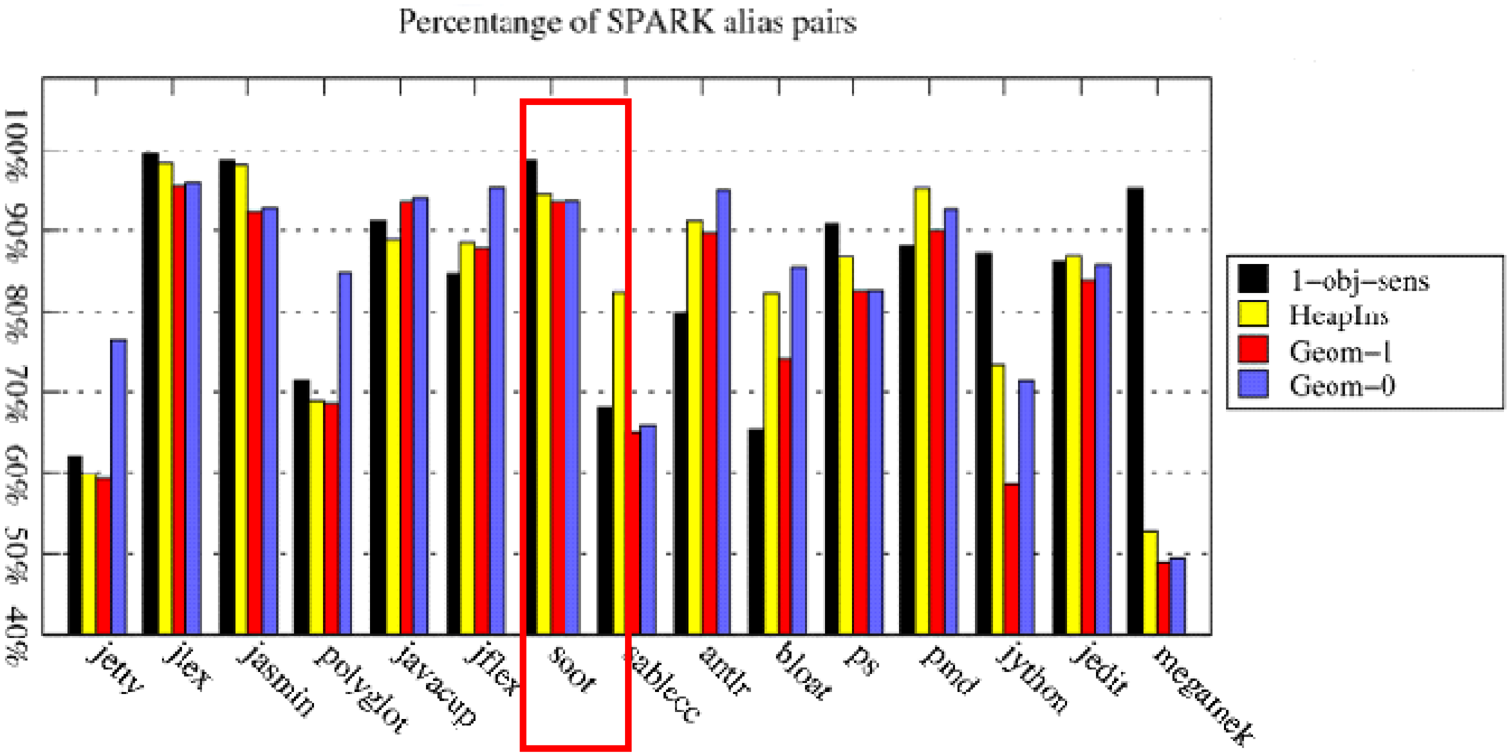
- Improving the precision of the alias analysis is not easy.

Alias Analysis



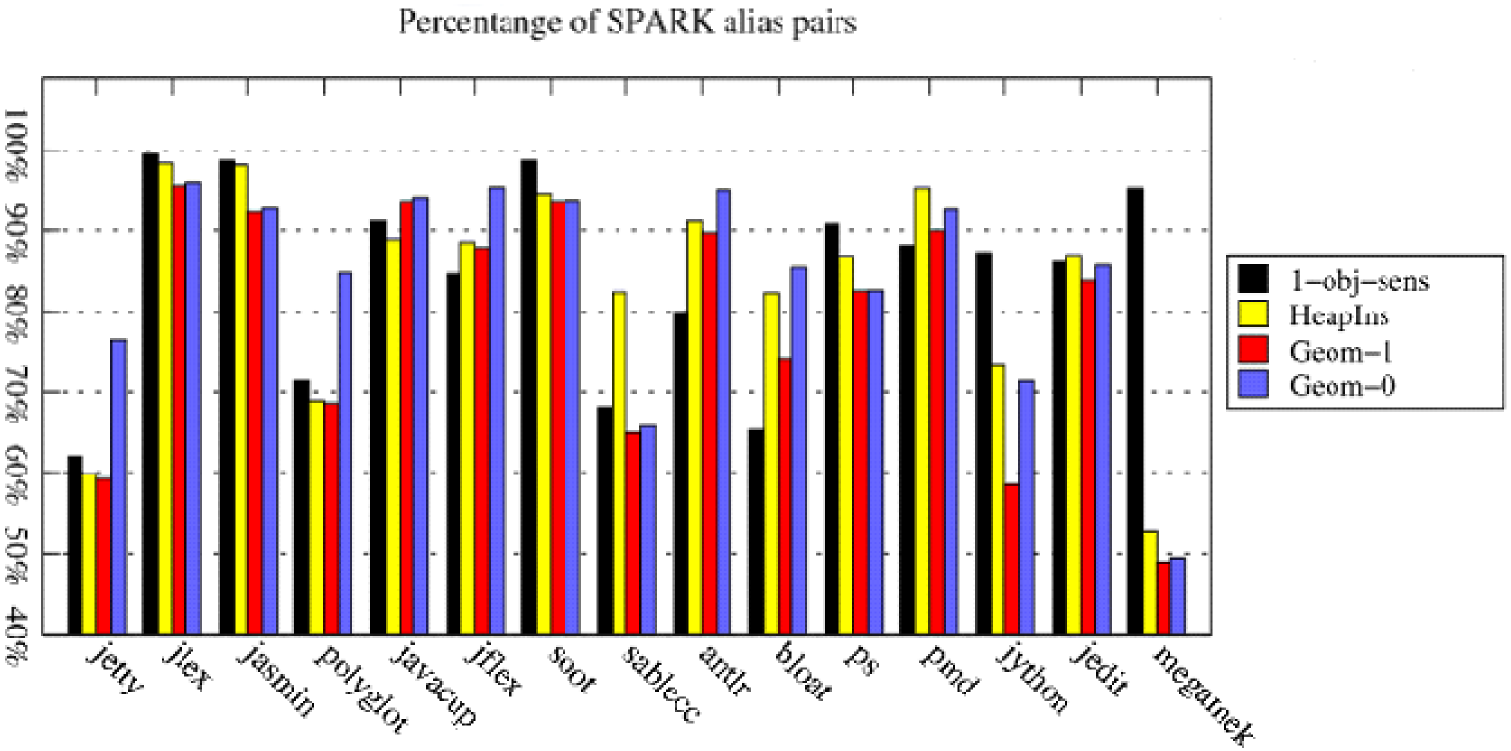
Geom-0 means the context insensitive modeling for the recursive calls.

Alias Analysis



Percentage of the alias pairs computed by SPARK.
The lower is better.

Alias Analysis



- 1-obj reduces 15.5%;
- HeapIns reduces 16.8%;
- Geom-1 reduces 21.2%.

Summary

- New data representation:
  - – We develop the geometric encoding, it has good compression rate for the working data of the points-to analysis.

Summary

- Soundness:
  - Geometric encoding has a sound calculating system for context sensitive points-to analysis.

Summary

- Easy to work with:
  - The complexity of writing a points-to analysis with geometric encoding is not too high.

Summary

- Good performance:
  - Geometric encoding based points-to analysis is 11.6x and 68.3x faster than 1-obj-W and 1-obj-B.

Summary

- Good precision:
  - – Geometric encoding based points-to analysis performs better than 1-obj-sens in alias analysis.

Other Results

- More experimental results and analyses can be found in our paper;

- We are still improving our methodology. Please visit us at

  www.cse.ust.hk/prism

  for up-to-date information.

Thanks for your attention!

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Points-to Algorithm

Anderson's analysis

=

Worklist Selection

+

Points-to Propagation

+

Complex Constraints Instantiation

Points-to Algorithm

Anderson's analysis

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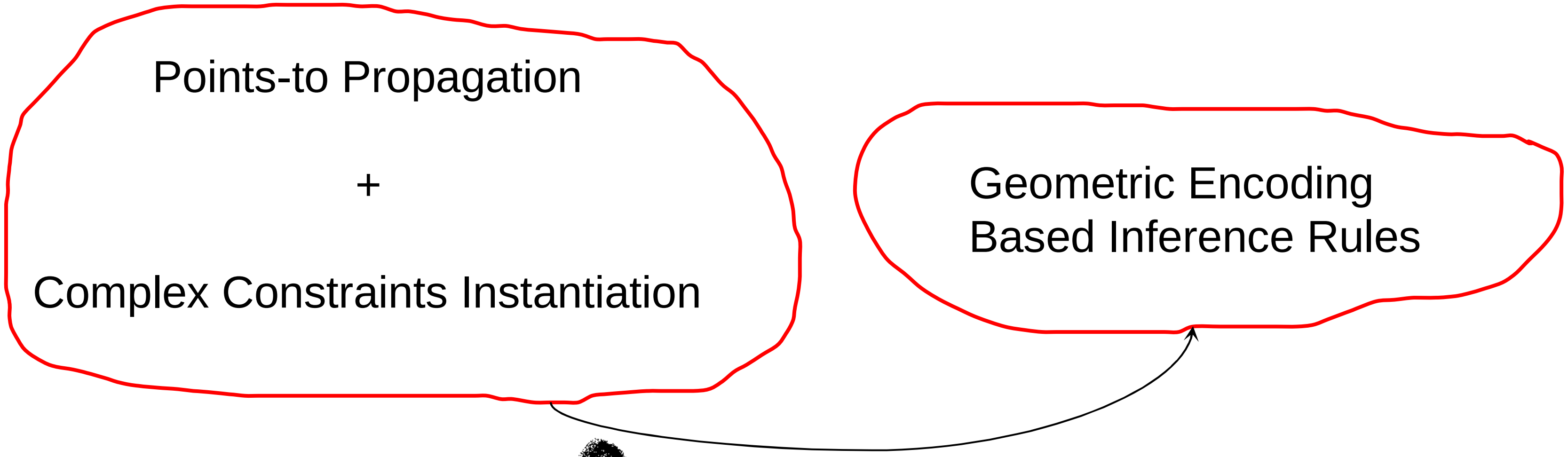


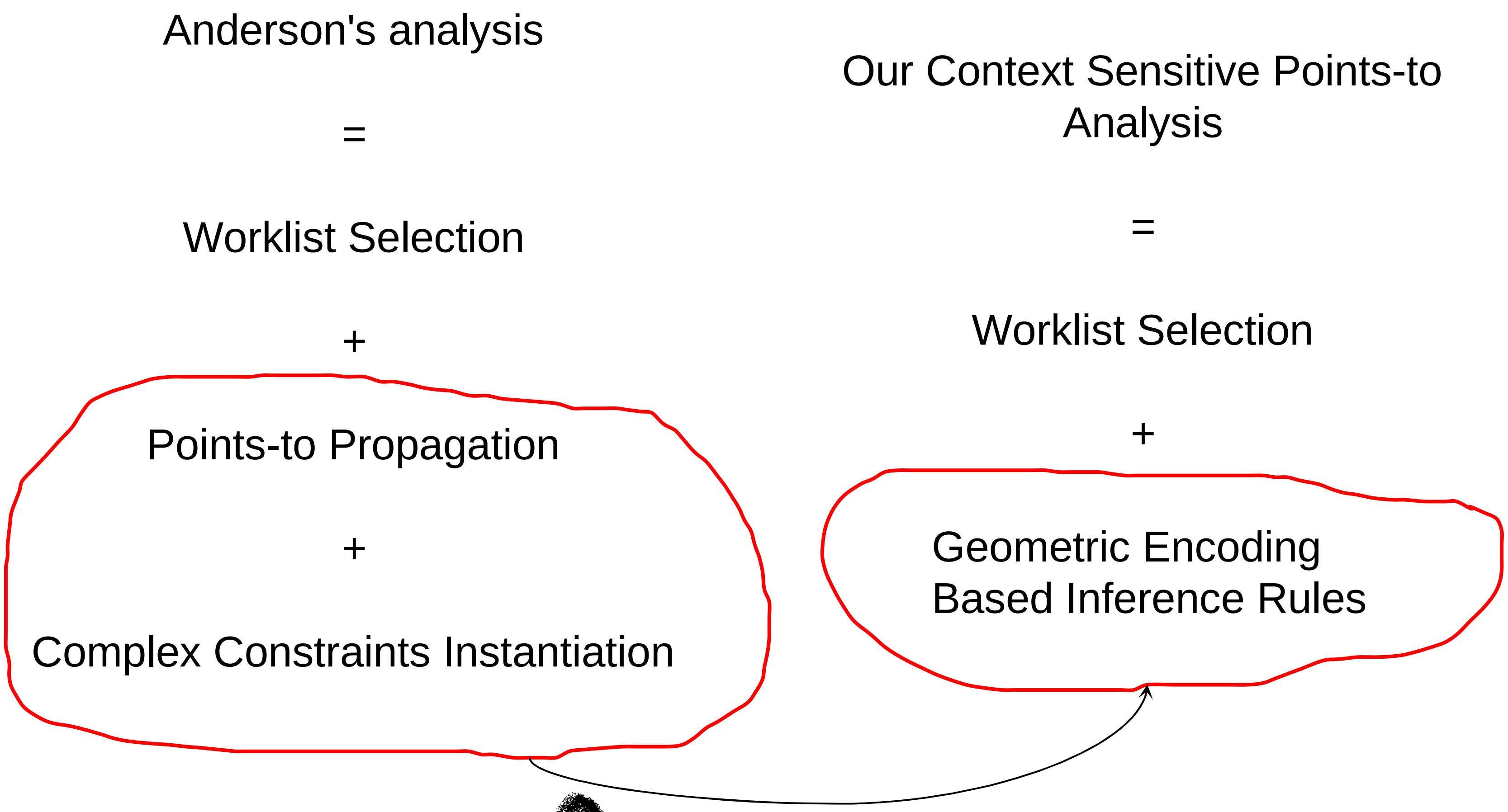
Points-to Propagation

+

Complex Constraints Instantiation

Geometric Encoding
Based Inference Rules

Points-to Algorithm



Anderson's analysis

=

Worklist Selection

+

Points-to Propagation

+

Complex Constraints Instantiation

Our Context Sensitive Points-to Analysis

=

Worklist Selection

+

Geometric Encoding Based Inference Rules

Other Characteristics

- With geometric encoding:
  - – Context sensitive model for the recursive calls;
  - – Simplified geometric encoding (HeapIns);
  - – Parameters to control the analysis time.

Other Characteristics

- Compared to EPA [ISSTA 08]:
  - We have the same compression capability with EPA;
  - We can handle global pointer correctly without trading-off precision.