Interprocedural Heap Analysis using Access Graphs and Value Contexts

with applications to liveness-based garbage collection

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under the guidance of

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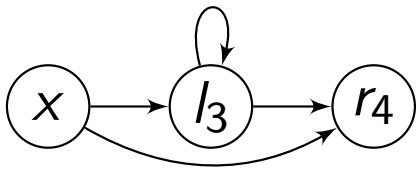
M.Tech Project

Outline

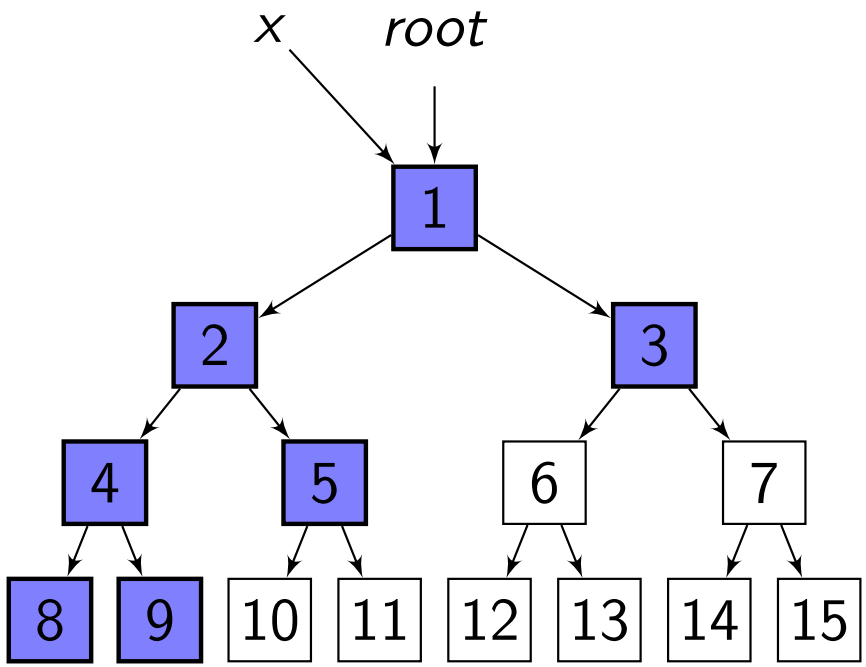
Background

Heap Reference Analysis [Khedker, Sanyal & Karkare, 2007]

```
S1: x = root
S2: while (x.val > M):
S3:     x = x.l
S4: x = x.r
S5: print x.val
S6: EXIT
```



Access graph for x at S_2.



The binary tree in the heap at S_2.
Filled nodes are live objects.

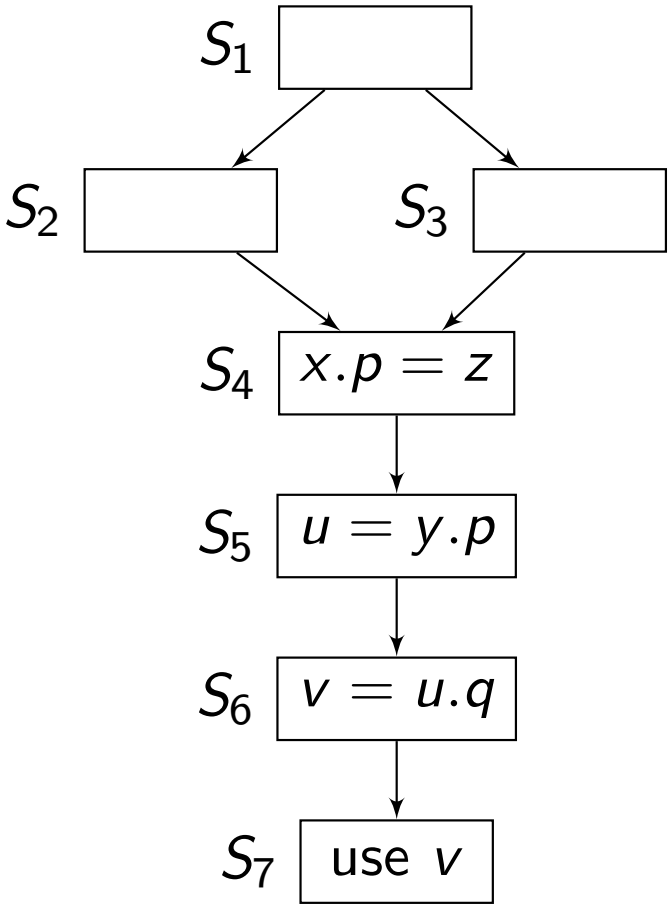
Key Issues

Three main issues in performing Heap Reference Analysis:

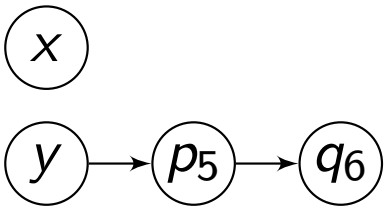
1. How to perform a precise **alias analysis** for arbitrary access paths in the heap?
2. How to implement whole-program heap reference analysis in an **inter-procedural** manner?
3. How to use the resulting access graphs to improve **garbage collection**?

Outline

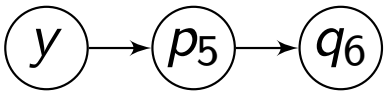
Need for Alias Analysis



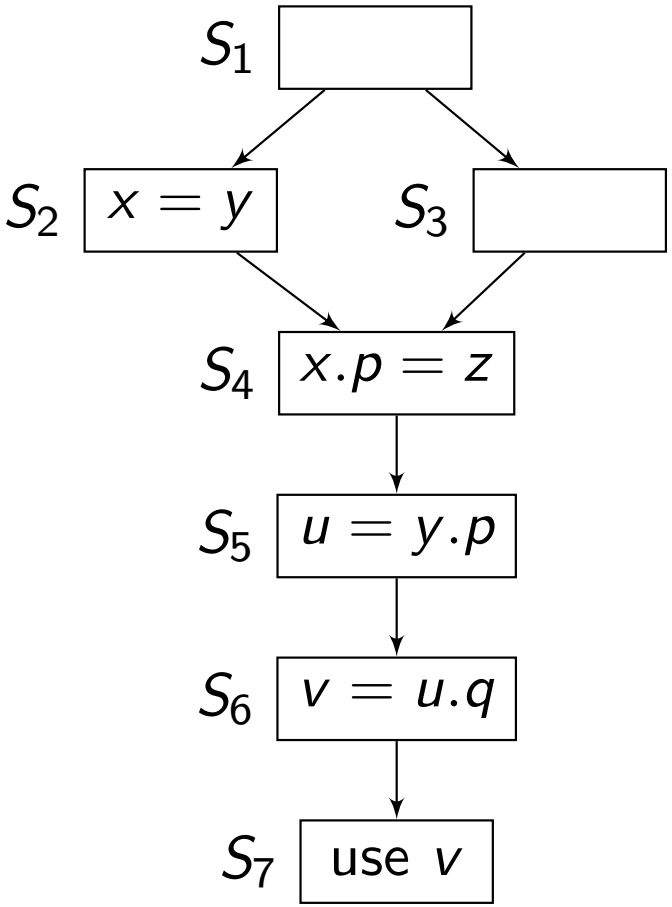
- x and y do not alias at S_4.
- $LVIN_4$



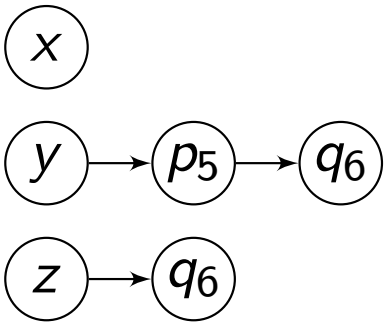
- $LVOUT_4$



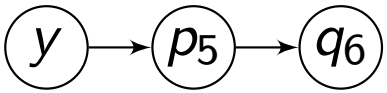
Need for Alias Analysis



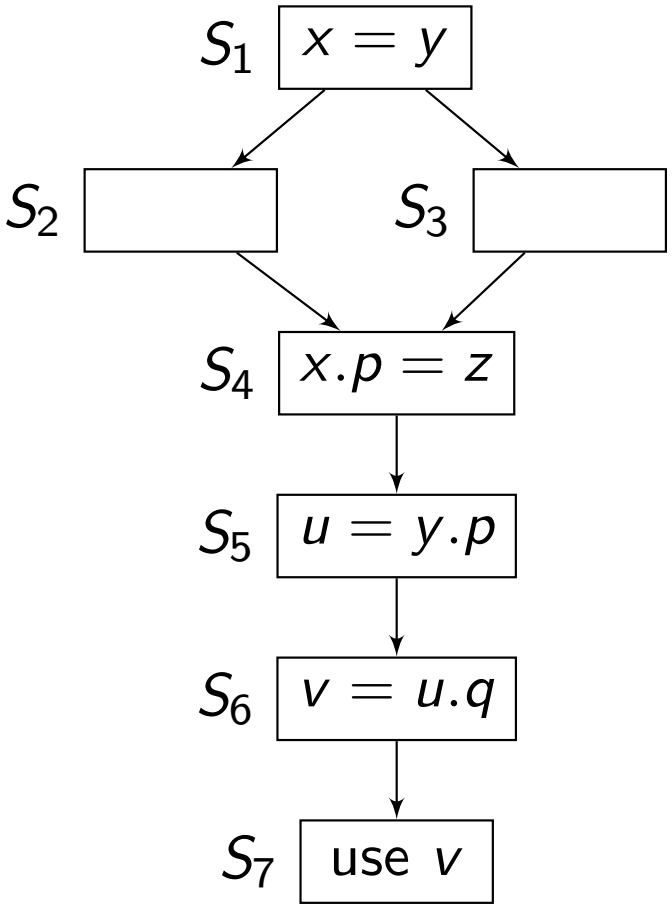
- x *may* alias y at S_4
- $LVIN_4$



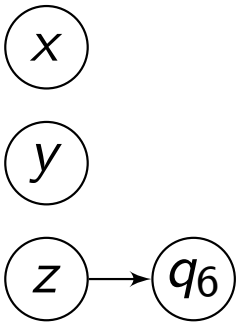
- $LVOUT_4$



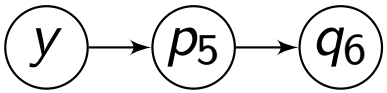
Need for Alias Analysis



- x *must* alias y at S_4
- $LVIN_4$

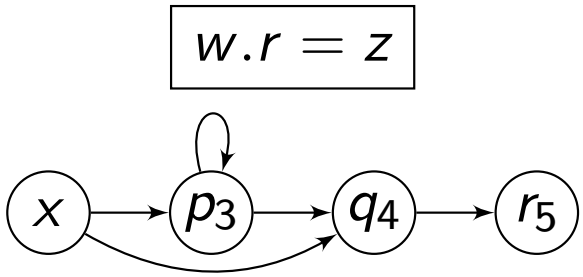


- $LVOUT_4$



Need for Alias Analysis

- May-alias analysis is required for sound heap liveness analysis.
- Must-alias analysis is desirable for performing strong updates.
- In general, alias queries may not be as straightforward as the preceeding examples:



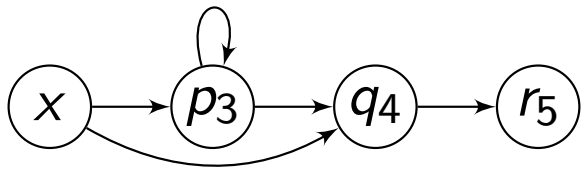
  In the above program, z is live if w may be aliased to any object accessible by the pattern $x(.p)*.q$.
- The key obervation is here is that we need to determine aliases between **live access patterns**.

Access Graphs and Access Patterns

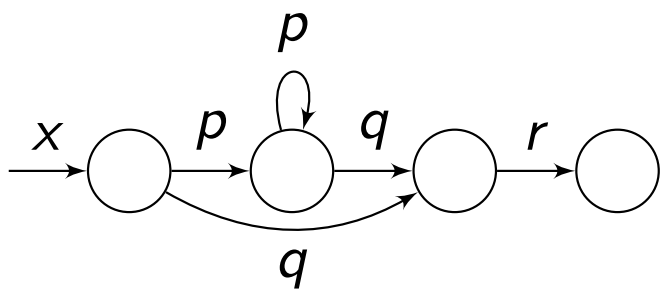
```
S1: w.r = z
S2: while (...):
S3:     x = x.p
S4: x = x.q
S5: x = x.r
S6: use x
S7: EXIT
```

Consider liveness at S_2.

- Access Graph



- Equivalent Automaton



- Access Patterns
  - $x/p_3 : x.p(.p)*$
  - $x/q_4 : x(.p)*.q$
  - $x/r_5 : x(.p)*.q.r$

Approaches to Heap Alias Analysis

Modelling an unbounded number of objects using a finite abstraction:

- Muchnick & Jones, 1981: k-limited graph
- Chase, Wegman & Zadeck, 1990: Merge on allocation sites
- Sagiv, Reps & Wilhelm, 1996: "Materialization"
- Sagiv, Reps & Wilhelm, 1999: 3-valued logic

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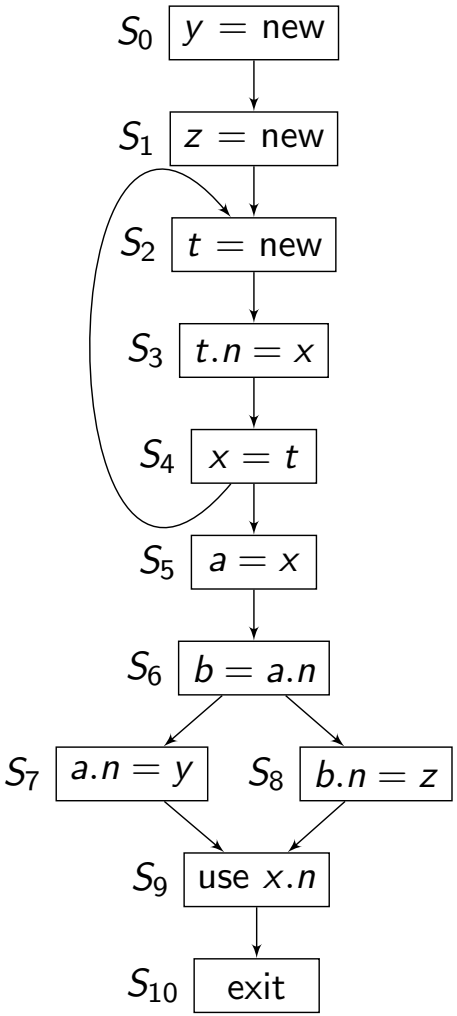
- Our approach: Use **access patterns** from liveness graphs to *improve expressibility* of points-to graph

Proposed Approach



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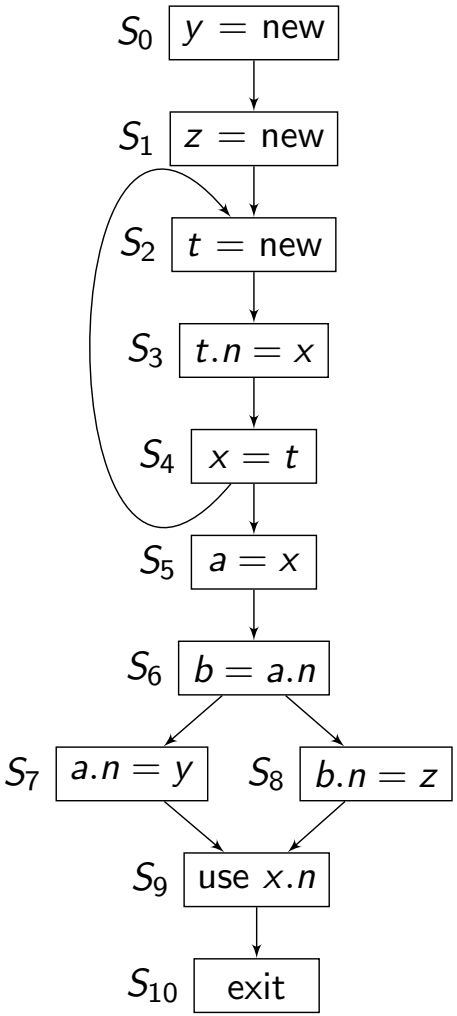
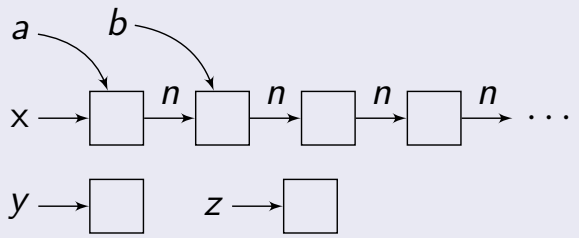


Actual heap layout after S_6



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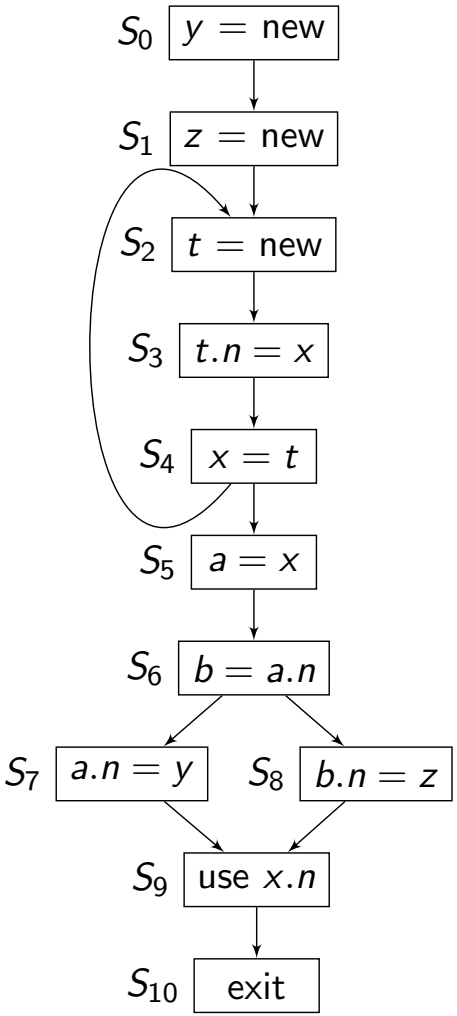

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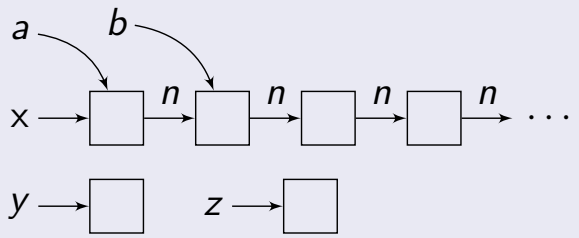
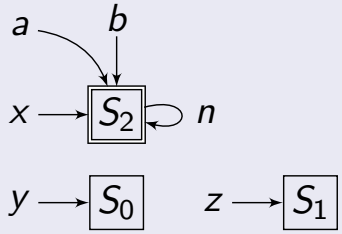


P_0: Initial Points-to Analysis

$PTOUT_6 = PTIN_7 = PTIN_8$:



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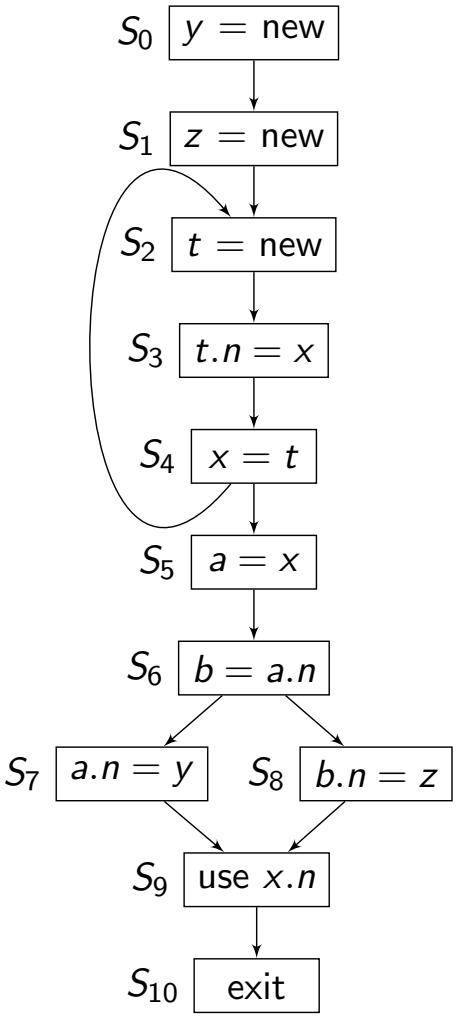

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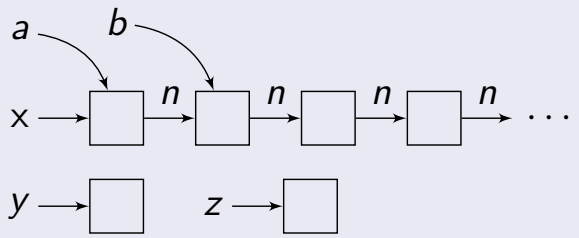

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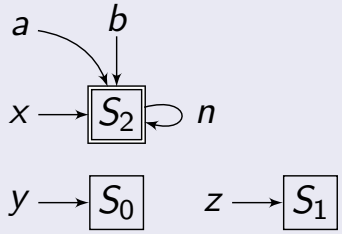
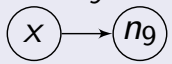
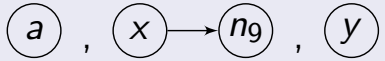


L_1: Liveness after P_0

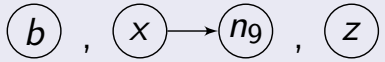
$LVIN_9 = LVOUT_7 = LVOUT_8$:



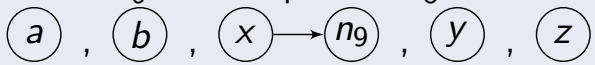
$LVIN_7$ (considering $a \overset{may}{=} x$):



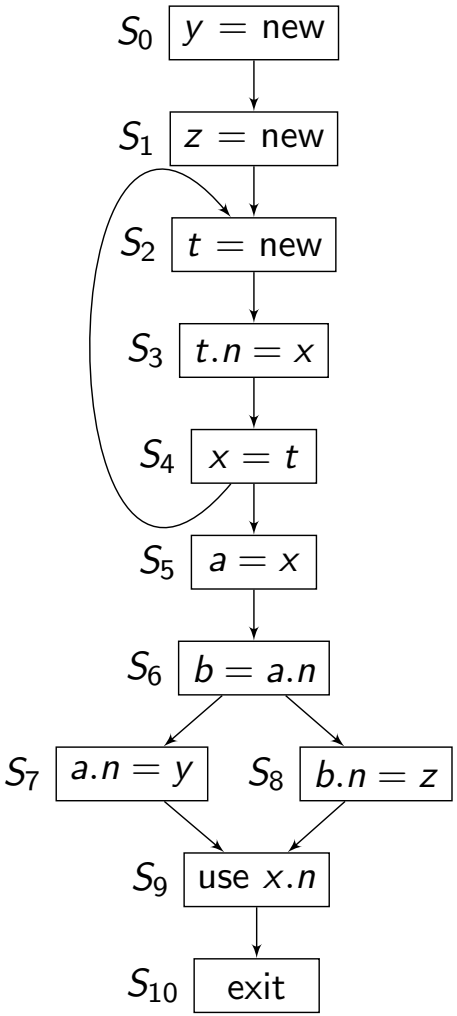
$LVIN_8$ (considering $b \overset{may}{=} x$):



$LVOUT_6 = LVIN_7 \cup LVIN_8$:



Proposed Approach



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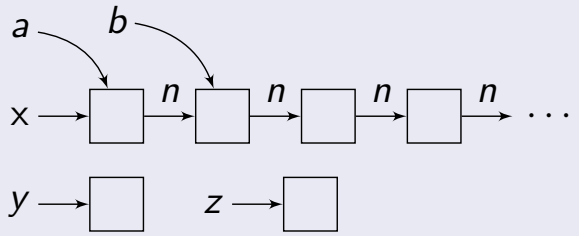

P_0: Initial Points-to Analysis

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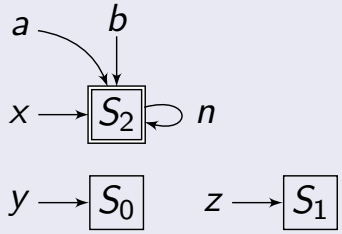
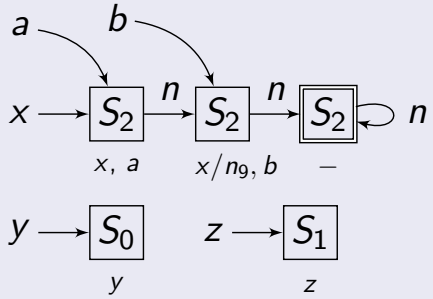


P_1: Points-to Analysis using L_1

$PTOUT_6 = PTIN_7 = PTIN_8$:



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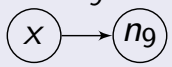

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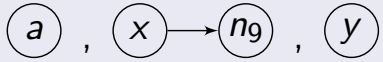

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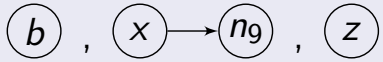

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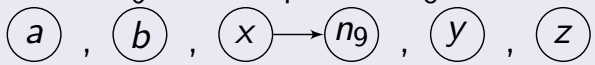
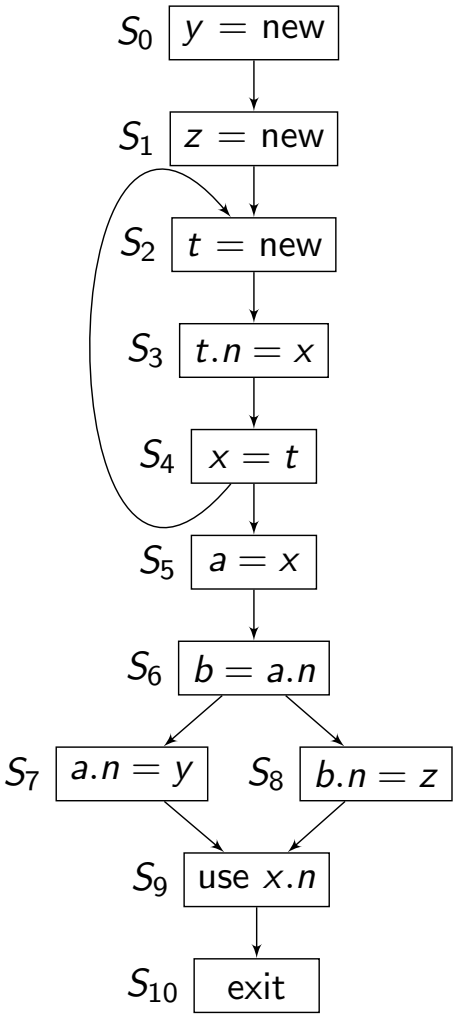


Proposed Approach



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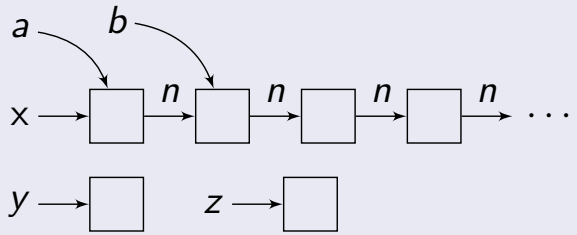

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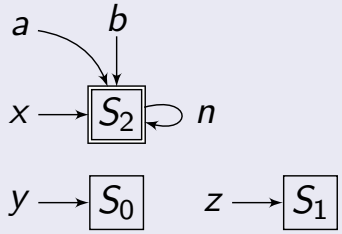

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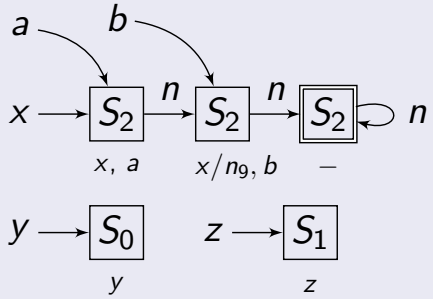


L_1: Liveness after P_0

$LVIN_9 = LVOUT_7 = LVOUT_8$:

$x \rightarrow n_9$

$LVIN_7$ (considering $a \overset{may}{=} x$):

a , $x \rightarrow n_9$, y

$LVIN_8$ (considering $b \overset{may}{=} x$):

b , $x \rightarrow n_9$, z

$LVOUT_6 = LVIN_7 \cup LVIN_8$:

a , b , $x \rightarrow n_9$, y , z

L_2: Liveness after P_1

$LVIN_9 = LVOUT_7 = LVOUT_8$:

$x \rightarrow n_9$

$LVIN_7$ (considering $a \overset{must}{=} x$):

x , y

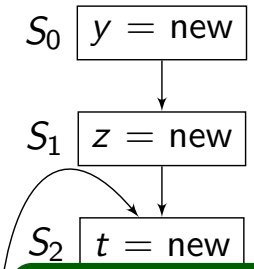
$LVIN_8$ (considering $b \neq x$):

$x \rightarrow n_9$

$LVOUT_6 = LVIN_7 \cup LVIN_8$:

$x \rightarrow n_9$, y

Proposed Approach



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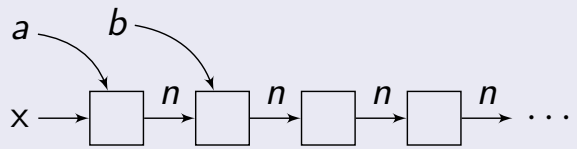

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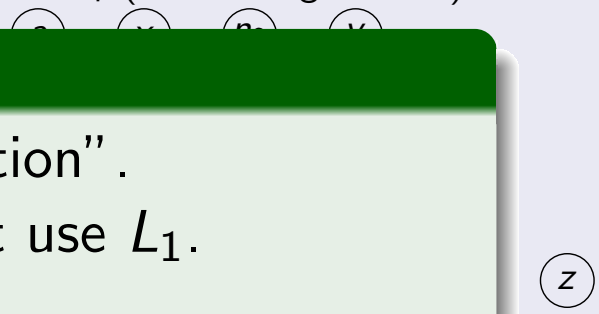
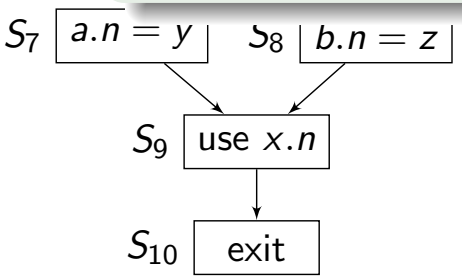


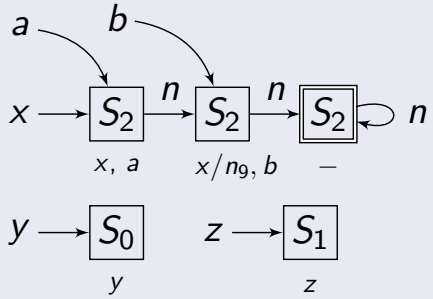
Note

- We are not performing "materialization".
- P_1 does not use P_0 and L_2 does not use L_1.
- These are new passes from scratch!
- L_i uses P_{i-1} for implicit updates.
- P_i uses L_i for expressibility.



P_1: Points-to Analysis using L_1

$PTOUT_6 = PTIN_7 = PTIN_8$:



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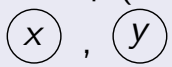
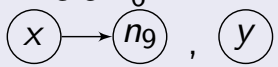


$LVIN_8$ (considering $b \neq x$):

$LVOUT_6 = LVIN_7 \cup LVIN_8$:



Proposed Approach

- Key idea: distinguish between objects accessible by distinct sets of access patterns.
- Thus, our approach is more precise than naive summarization in that:
  1. Unnecessary may-aliases are avoided.
  2. Useful must-aliases are discovered.
- Inter-dependence of liveness and points-to analysis:
  1. Perform naive points-to (summarize on alloc sites).
  2. Backward analysis to get huge liveness info (sound but imprecise).
  3. Again do points-to, distinguishing on access patterns found above.
  4. Another round of backward analysis to get precise liveness info.
  5. Fixed point...?

Accessor Relationship Graph

Symbol	Definition	Cardinality
V	Variables	Proportional to program size
M	Memory allocation sites	Proportional to program size
R	Field dereference points	Proportional to program size
A	Access graph nodes	$\|V\| + \|V\| \times \|R\|$
H	Heap graph nodes	$\|M\| \times 2^{\|A\|}$

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H	Heap graph nodes	$\|M\| \times 2^{\|A\|}$

Definition

Accessor Relationship Graph is a 3-tuple $\langle E_v, E_f, summary \rangle$, where:

- $E_v \subseteq V \times H$
- $E_f \subseteq H \times F \times H$
- $summary : H \rightarrow \{true, false\}$

Lattice Representation

Definition

$\langle E_v, E_f, summary \rangle \sqsupseteq \langle E'_v, E'_f, summary' \rangle$ if:

- $E_v \subseteq E'_v$
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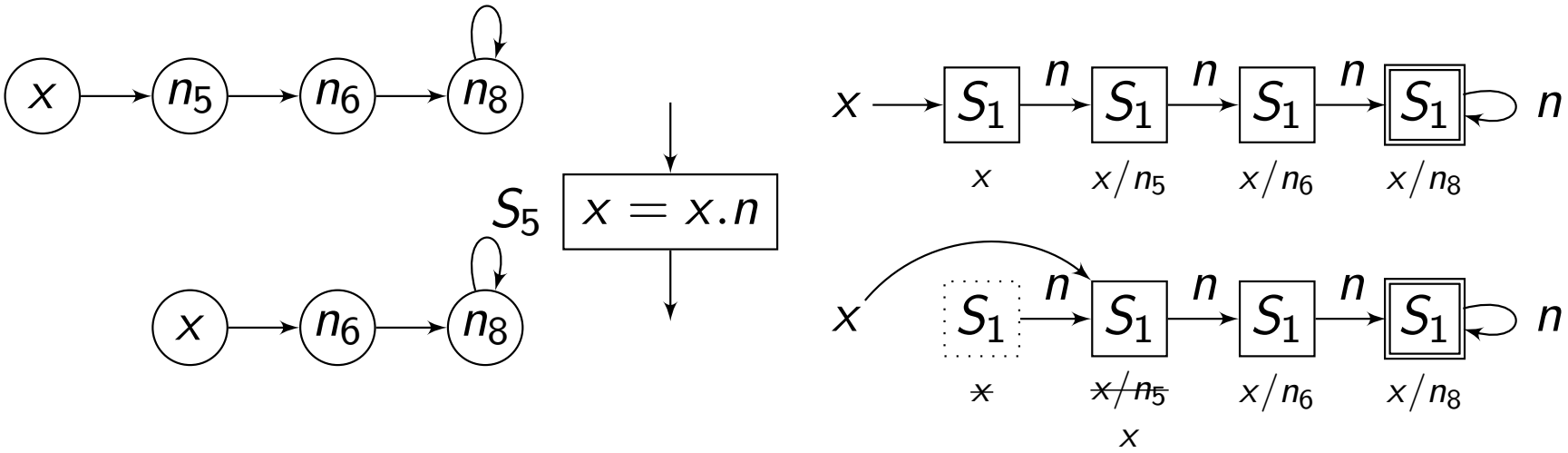
Definition

$\langle E_v, E_f, summary \rangle \sqcap \langle E'_v, E'_f, summary' \rangle = \langle E''_v, E''_f, summary'' \rangle$ such that:

- $E''_v = E_v \cup E'_v$
- $E''_f = E_f \cup E'_f$
- $\forall k \in H : summary''(k) = summary(k) \vee summary'(k)$

Data Flow Analysis

- Normalization: $\Theta(X, L)$ = Consistency + Reachability



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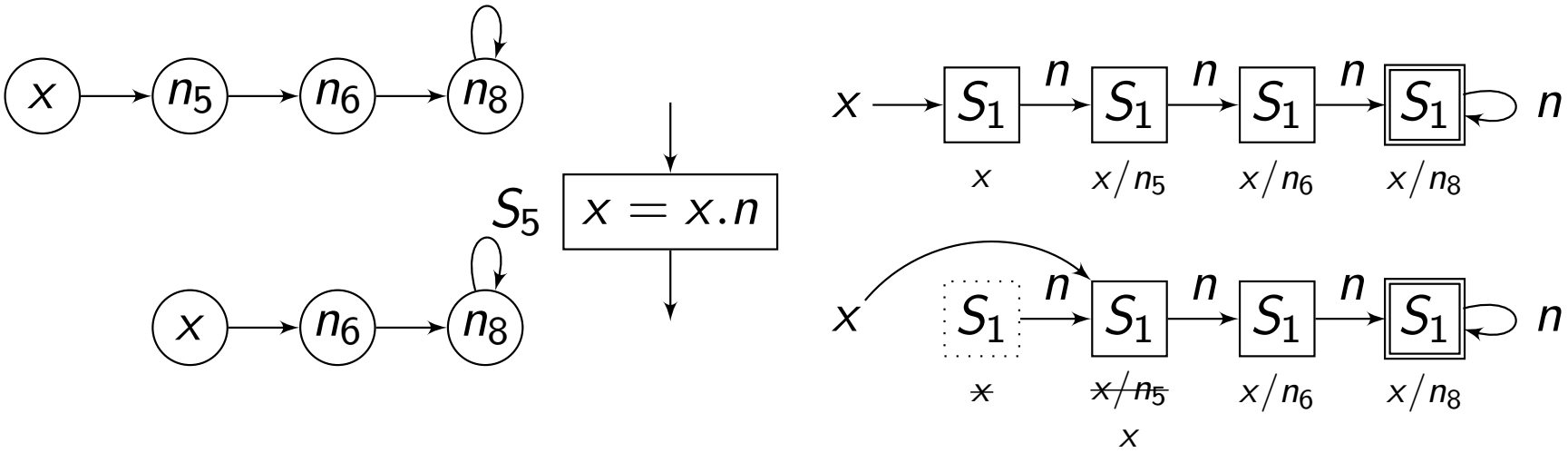

- Data Flow Equations:

$$PTIN_b = \bigsqcap_{p \in pred(b)} \Theta(PTOUT_p, LVIN_b)$$

$$PTOUT_b = \Theta(f_b(PTIN_b), LVOUT_b)$$

System Model

- $\hat{L} : S \times AP \rightarrow \{true, false\}$ (Results of liveness analysis)
- $\hat{P} : S \times AP \times AP \rightarrow \{true, false\}$ (Results of points-to analysis)
- $HLA : \hat{P} \rightarrow \hat{L}$ (Heap Liveness Analysis)
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$$\hat{L}_0 = \lambda s \lambda a.false$$

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Lemma (1)

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Proof.

1. $\forall k \geq 0 : \hat{L}_0 \subseteq \hat{L}_k$ (By Definition)
2. $\forall k \geq 0 : \hat{P}_0 \supseteq \hat{P}_k$ (Lemma 1)
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6. $\forall k > 0 : \hat{L}_2 \subseteq \hat{L}_k$ (Step 3 and 5)

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Outline

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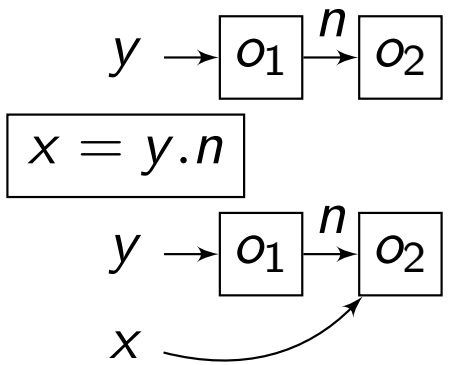

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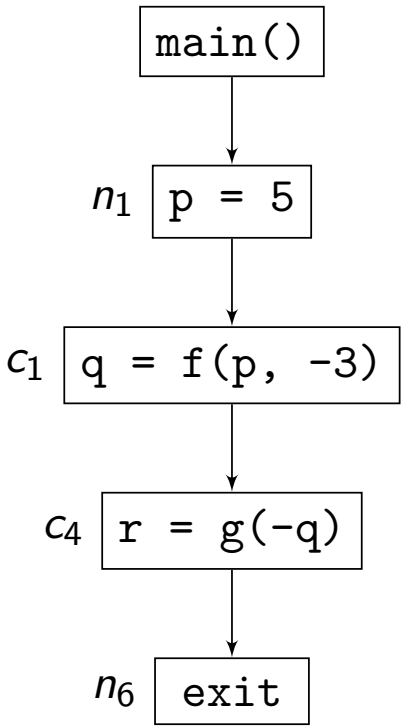
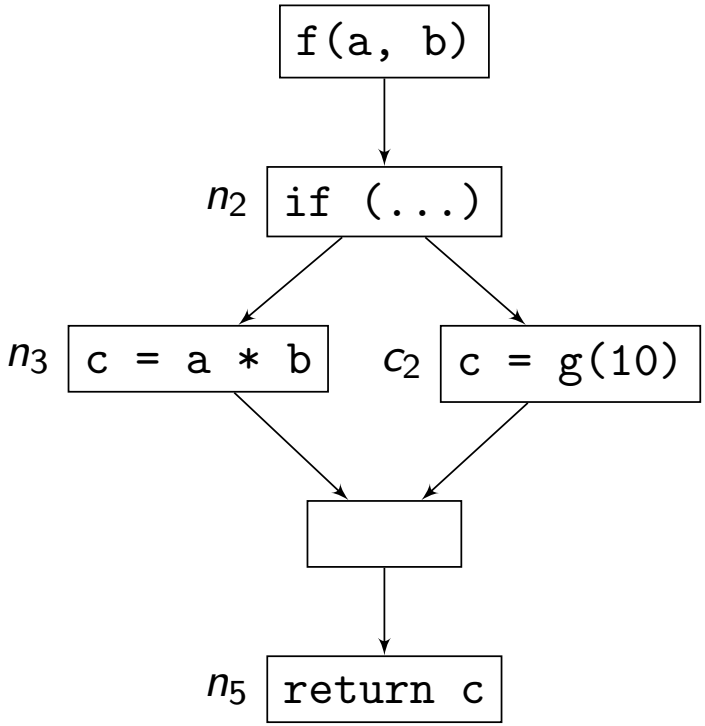
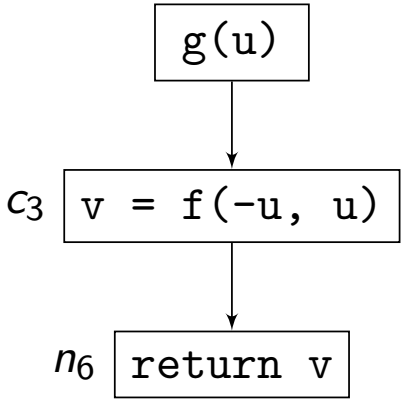
  - Record transition from this call-site to X
- Exit-sites: Set $exitValue(X)$ and add callers to work-list

Example - Sign Analysis







Context	Proc.	Entry	Exit

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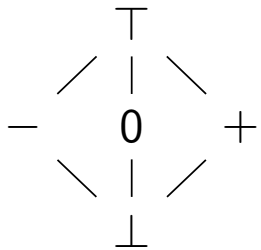

Component Lattice

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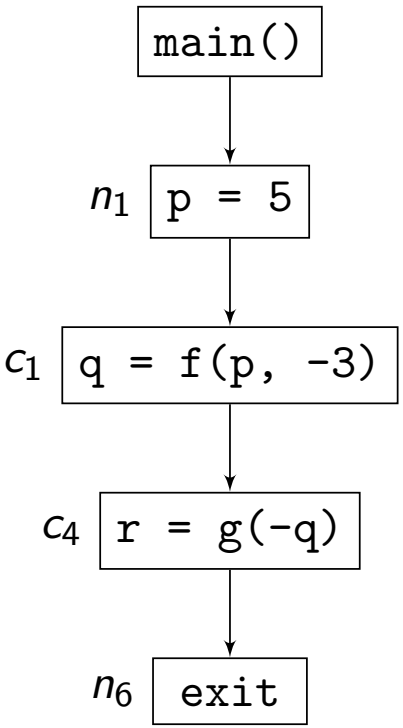

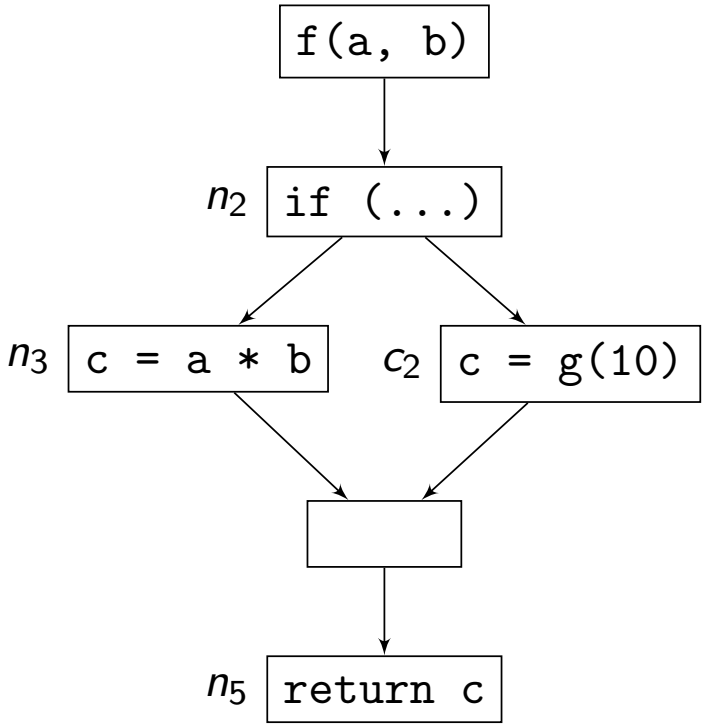

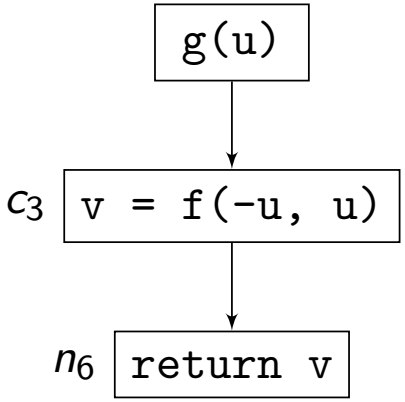

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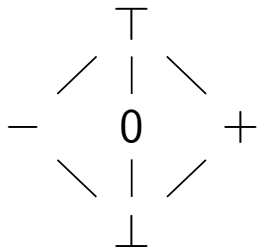

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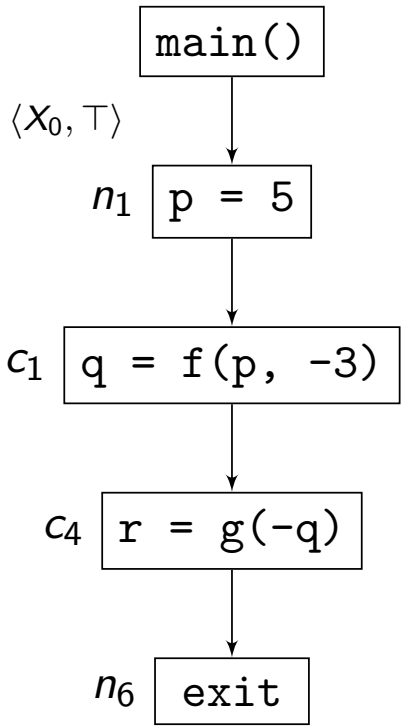

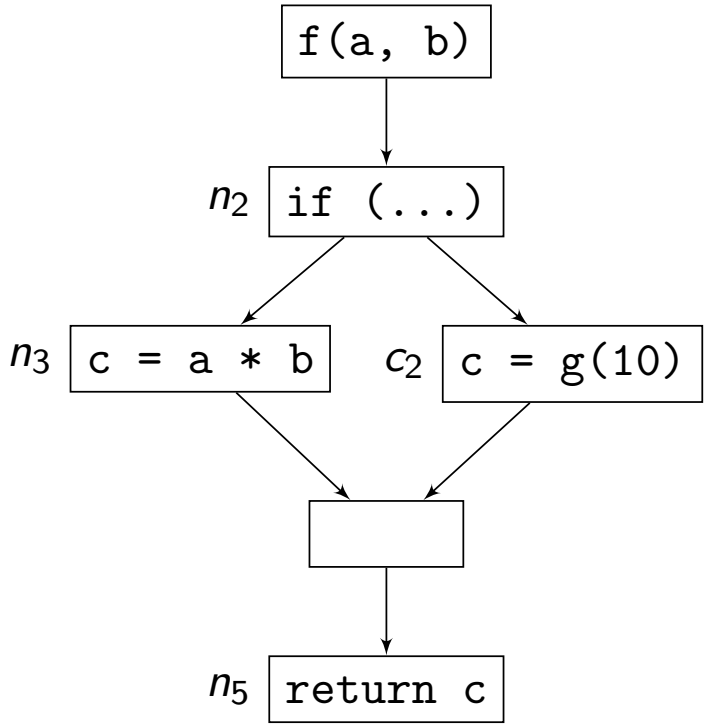

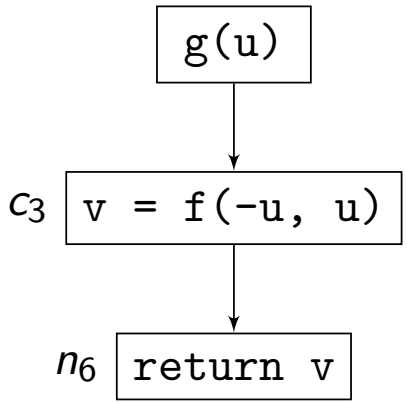

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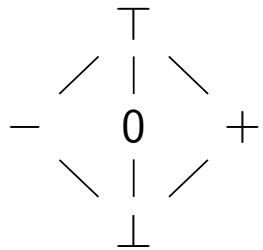

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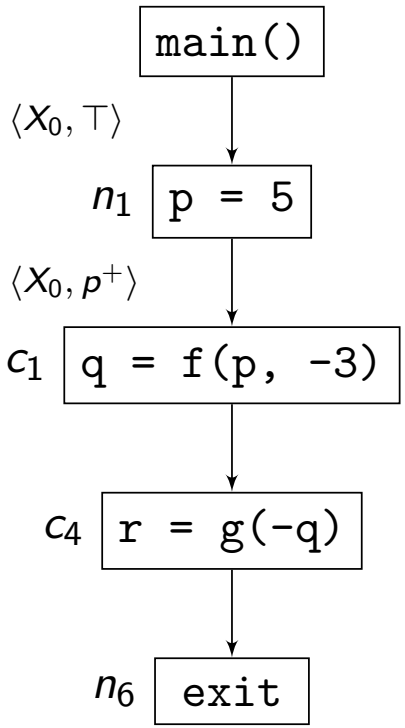

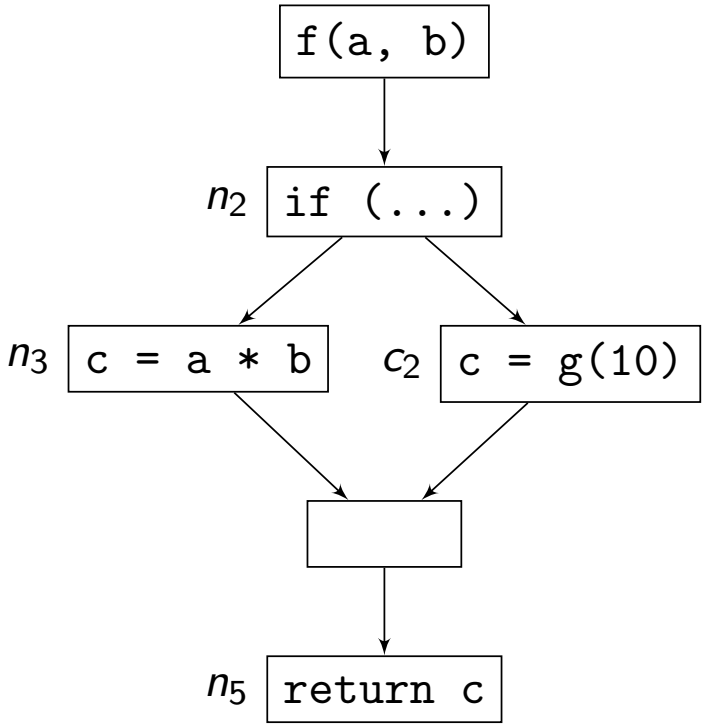

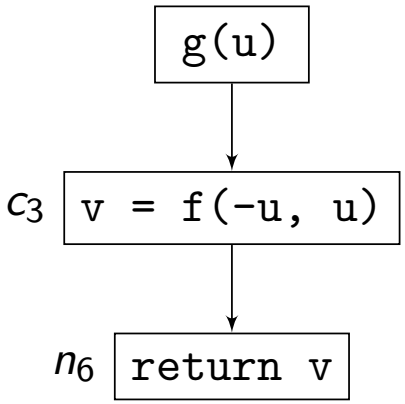

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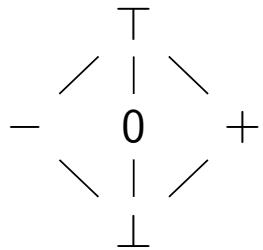

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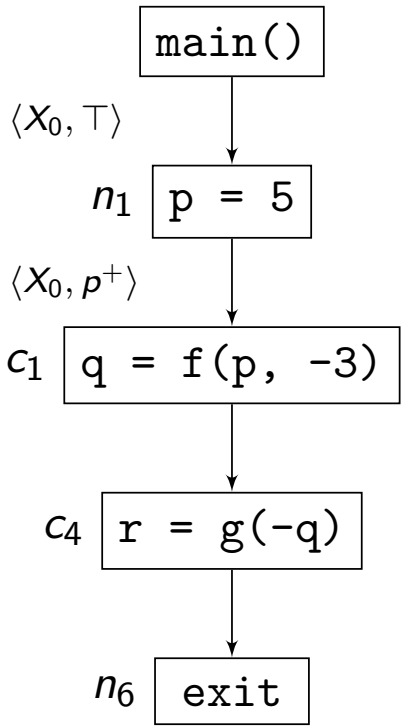

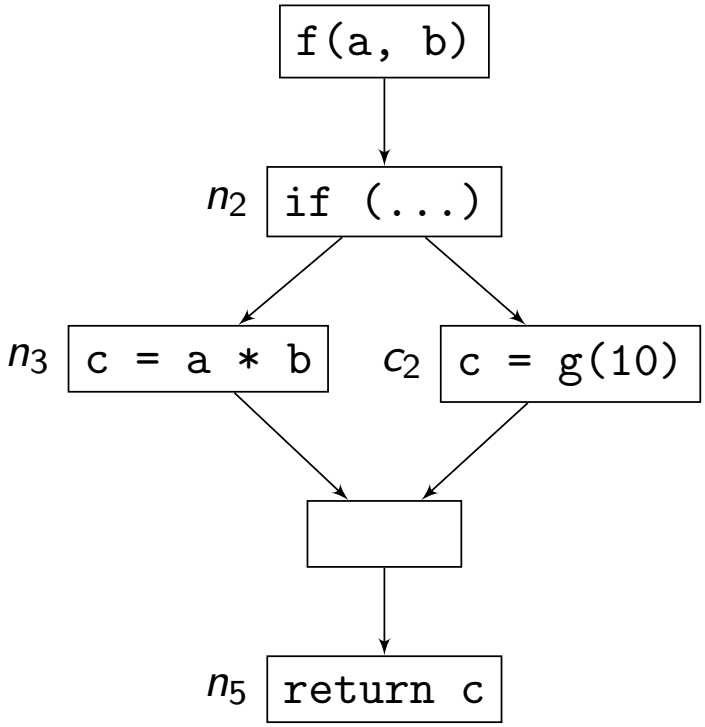

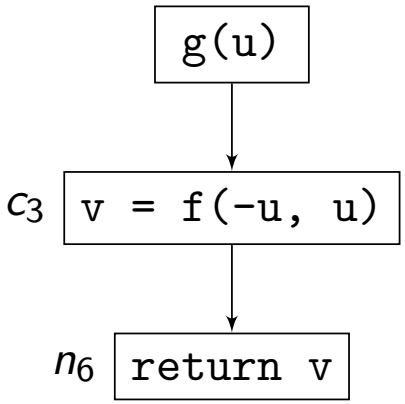

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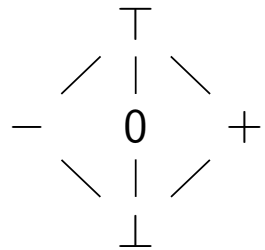

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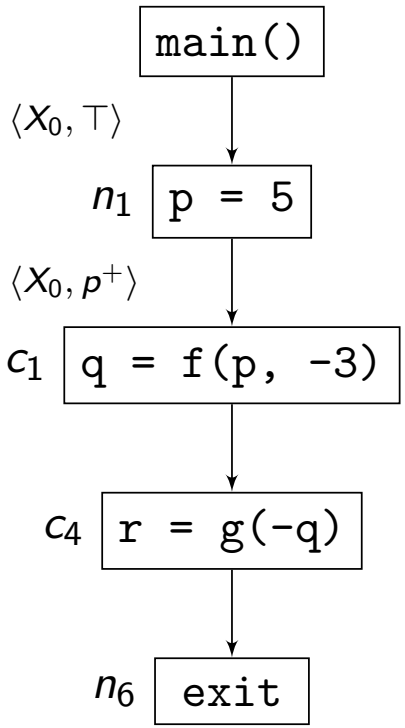
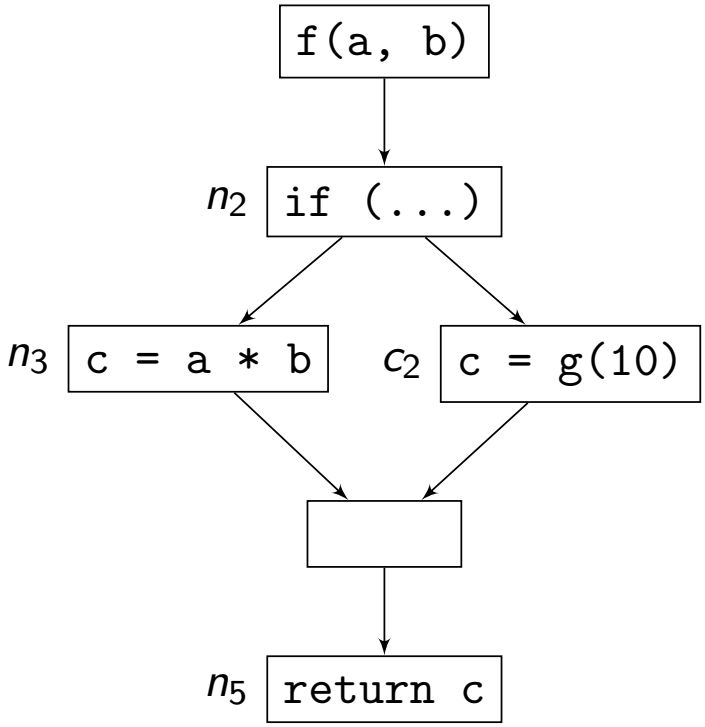
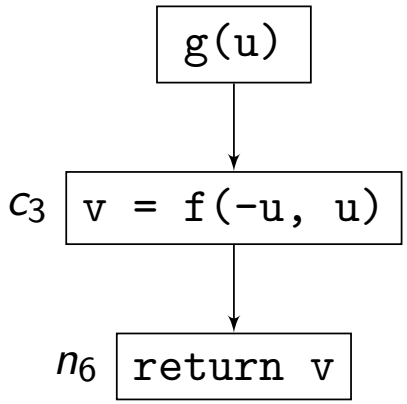
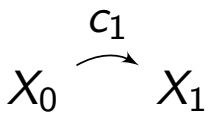




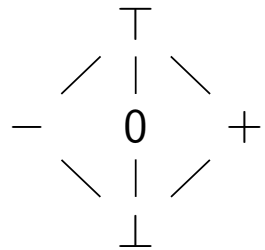


Context	Proc.	Entry	Exit
X_0	main	$\top$	$\top$
X_1	f	$a^+ b^-$	$\top$

Value Contexts

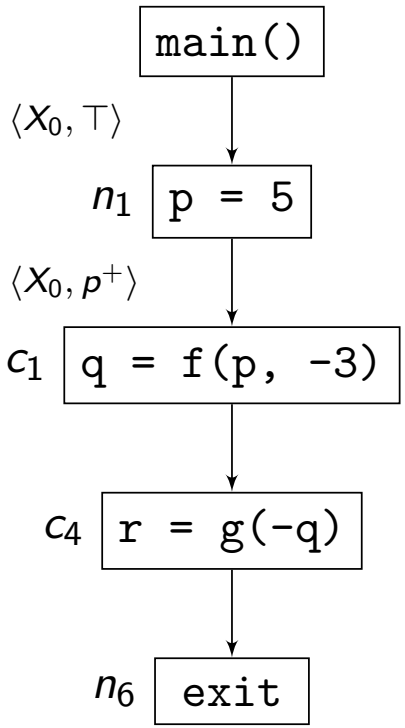


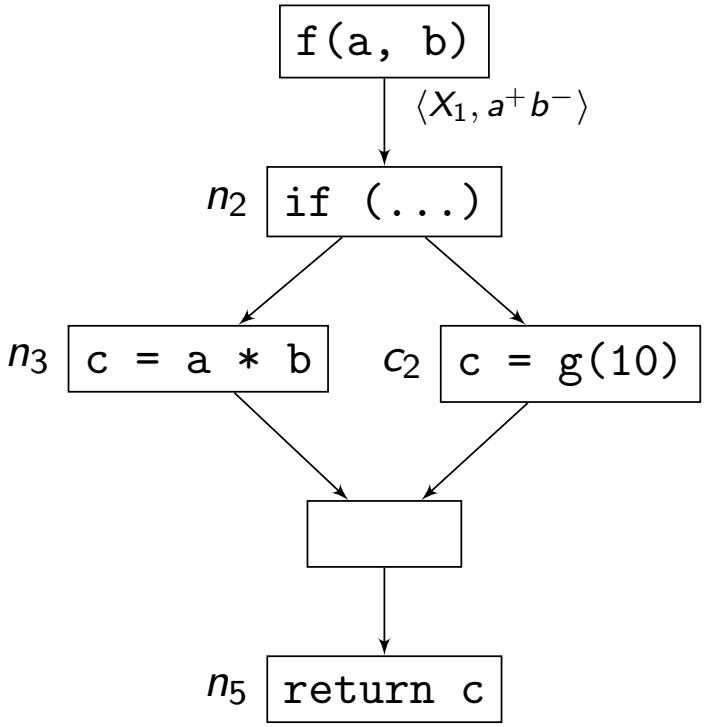
Context Transitions

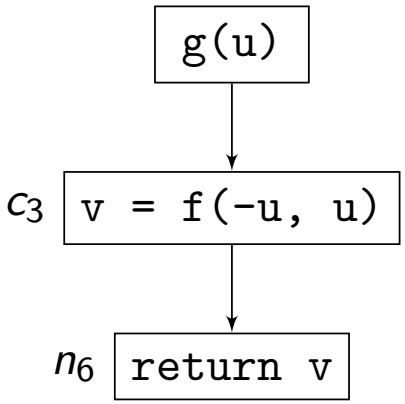


Component Lattice

Example - Sign Analysis

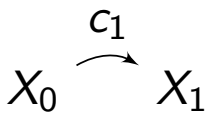




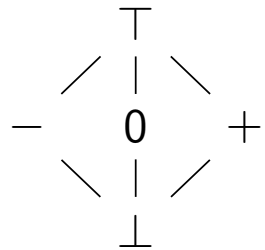


Context	Proc.	Entry	Exit
X_0	main	$\top$	$\top$
X_1	f	a^+b^-	$\top$

Value Contexts

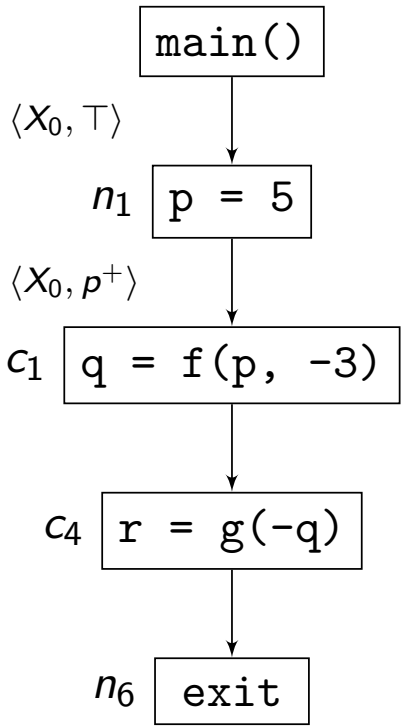


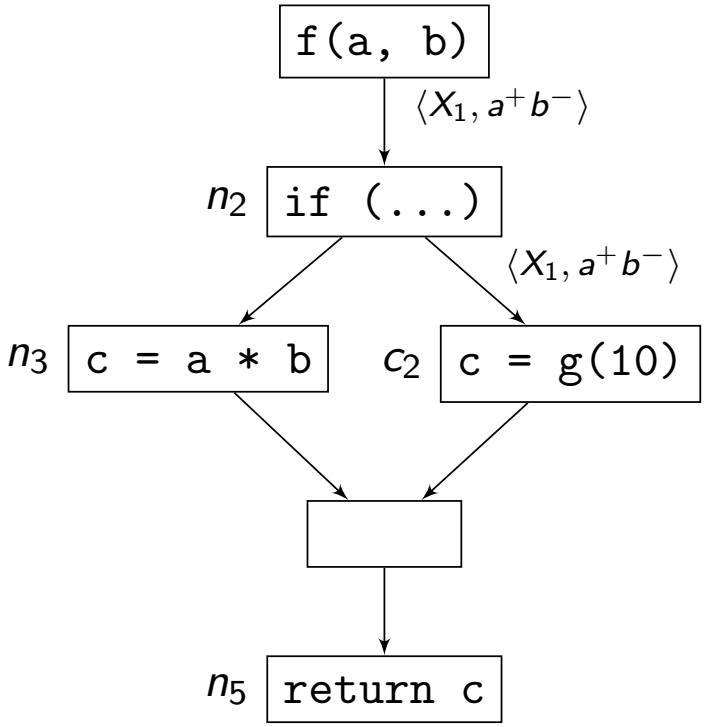
Context Transitions

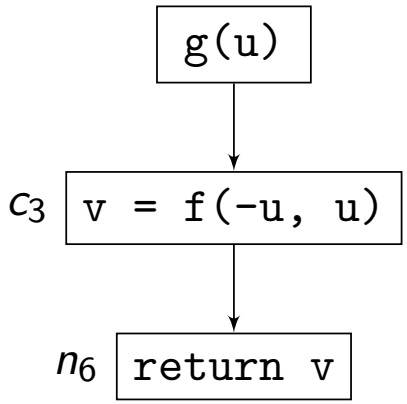


Component Lattice

Example - Sign Analysis

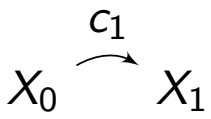




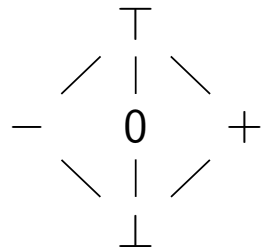


Context	Proc.	Entry	Exit
X_0	main	$\top$	$\top$
X_1	f	a^+b^-	$\top$

Value Contexts

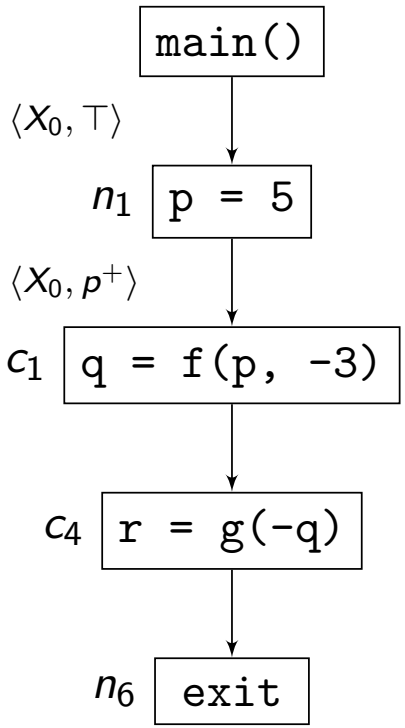


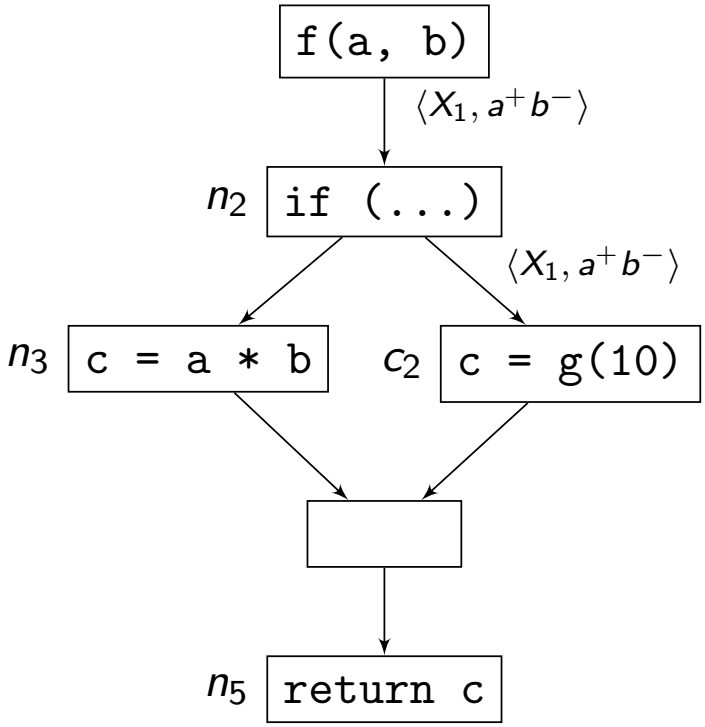
Context Transitions

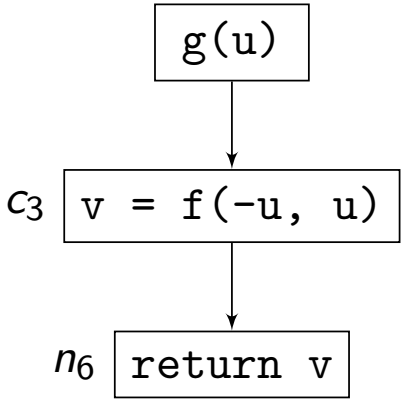


Component Lattice

Example - Sign Analysis

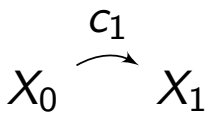




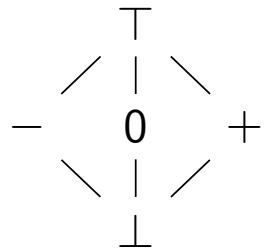


Context	Proc.	Entry	Exit
X_0	main	$\top$	$\top$
X_1	f	a^+b^-	$\top$
X_2	g	u^+	$\top$

Value Contexts

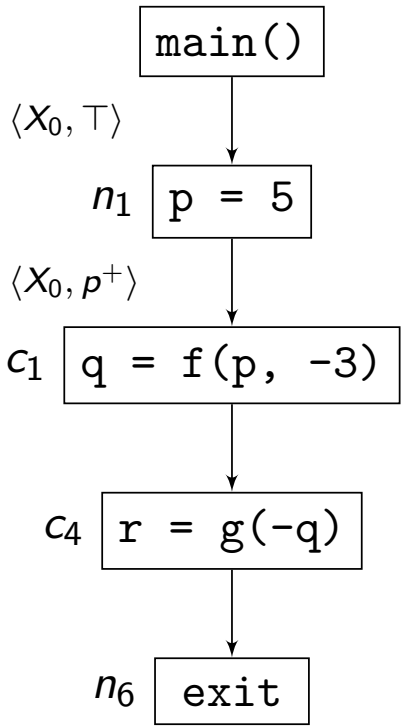


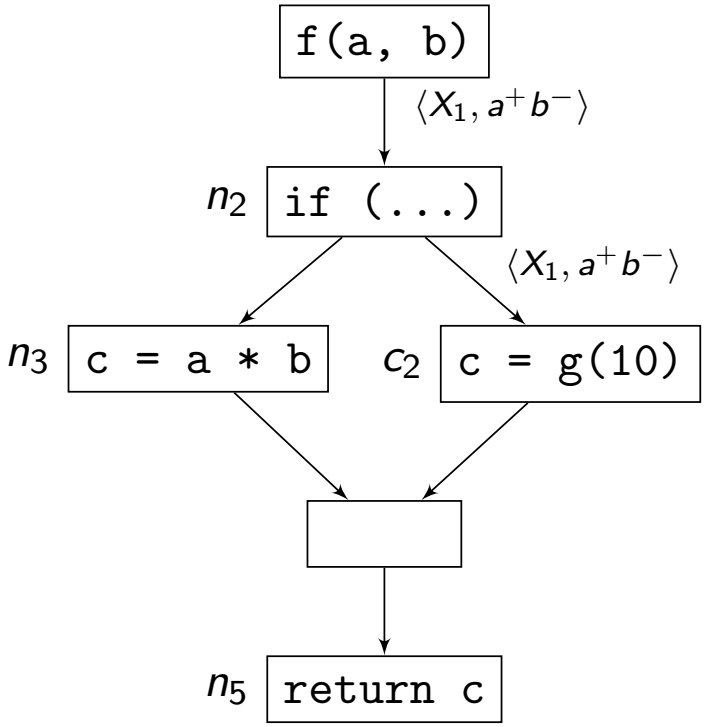
Context Transitions

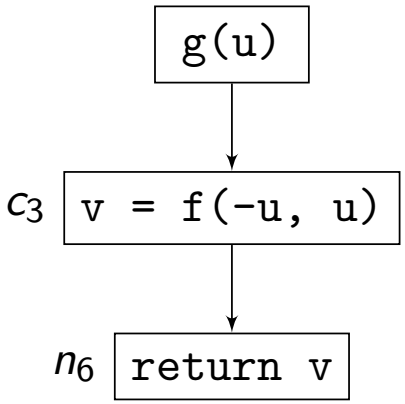


Component Lattice

Example - Sign Analysis

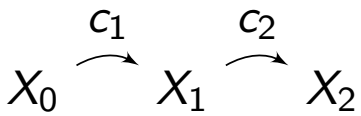




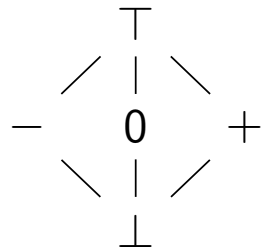


Context	Proc.	Entry	Exit
X_0	main	$\top$	$\top$
X_1	f	a^+b^-	$\top$
X_2	g	u^+	$\top$

Value Contexts

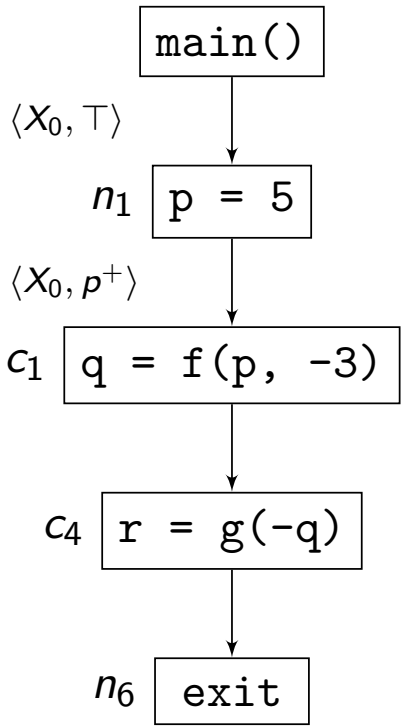


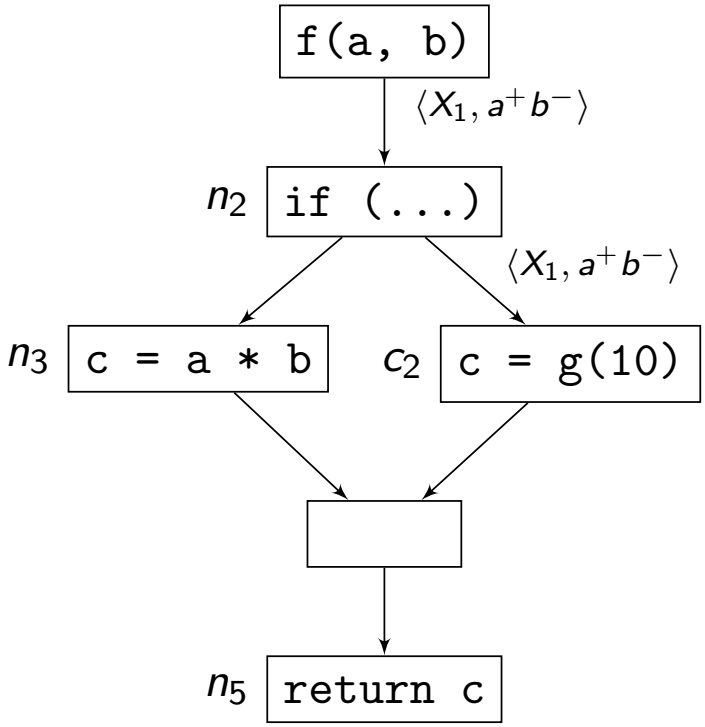
Context Transitions

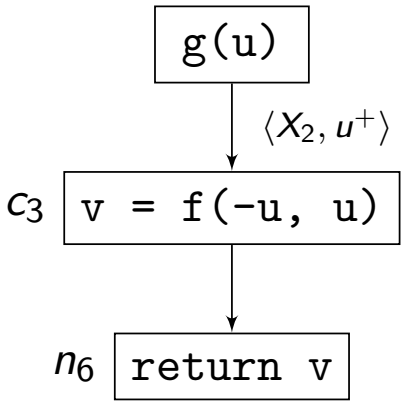


Component Lattice

Example - Sign Analysis

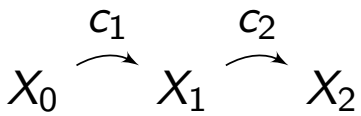




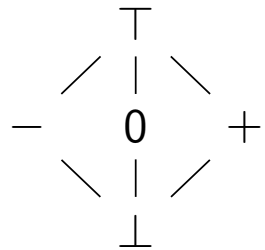


Context	Proc.	Entry	Exit
X_0	main	$\top$	$\top$
X_1	f	a^+b^-	$\top$
X_2	g	u^+	$\top$

Value Contexts

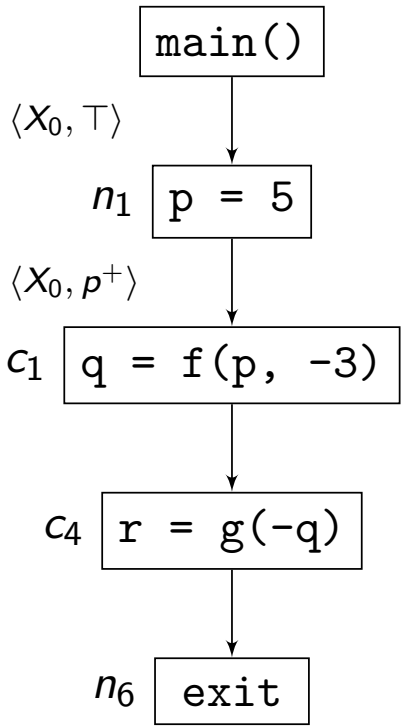


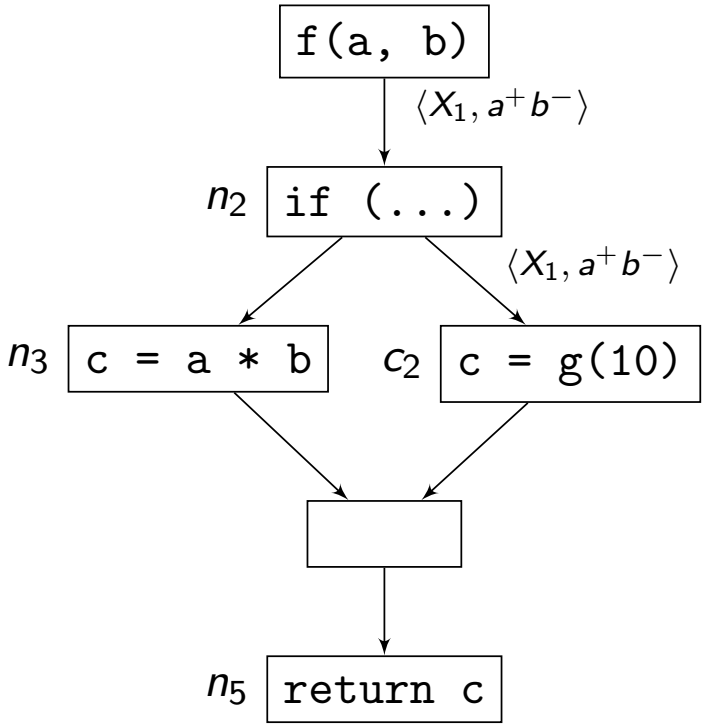
Context Transitions

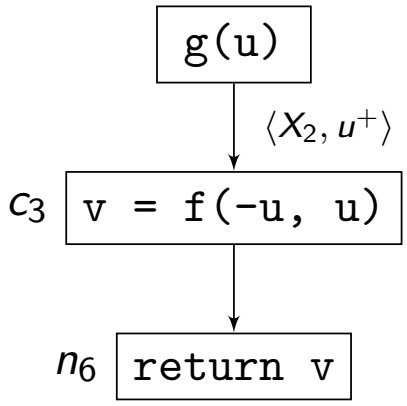


Component Lattice

Example - Sign Analysis

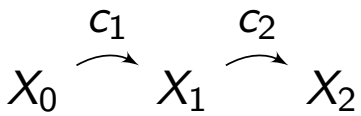




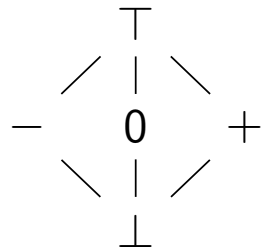


Context	Proc.	Entry	Exit
X_0	main	$\top$	$\top$
X_1	f	a^+b^-	$\top$
X_2	g	u^+	$\top$
X_3	f	a^-b^+	$\top$

Value Contexts

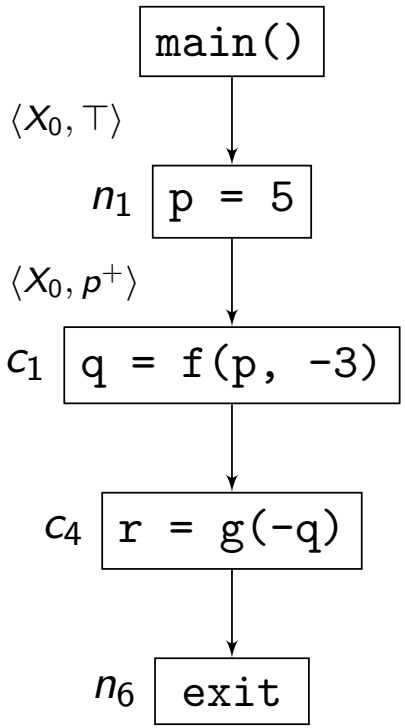


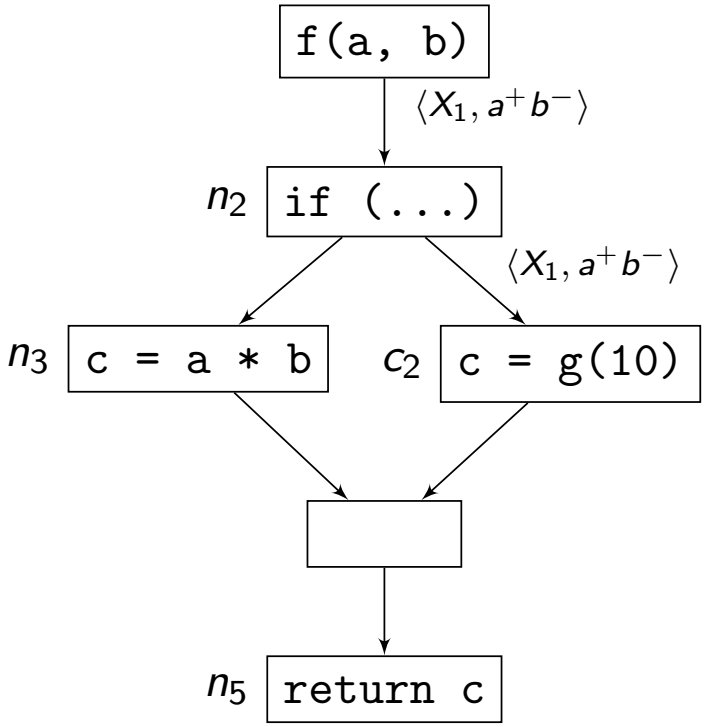
Context Transitions

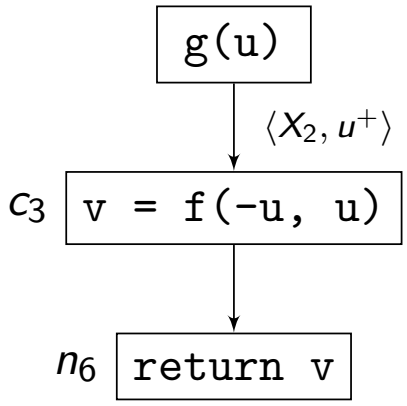


Component Lattice

Example - Sign Analysis

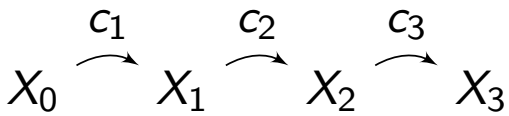




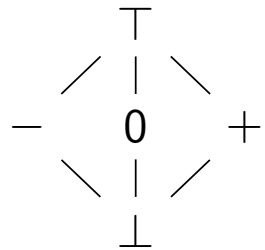


Context	Proc.	Entry	Exit
X_0	main	$\top$	$\top$
X_1	f	a^+b^-	$\top$
X_2	g	u^+	$\top$
X_3	f	a^-b^+	$\top$

Value Contexts

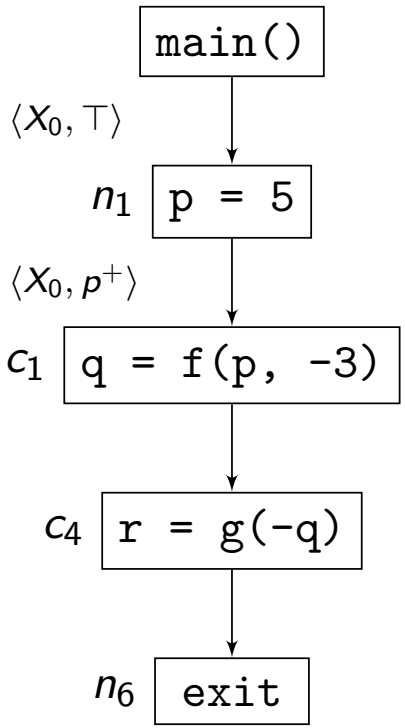


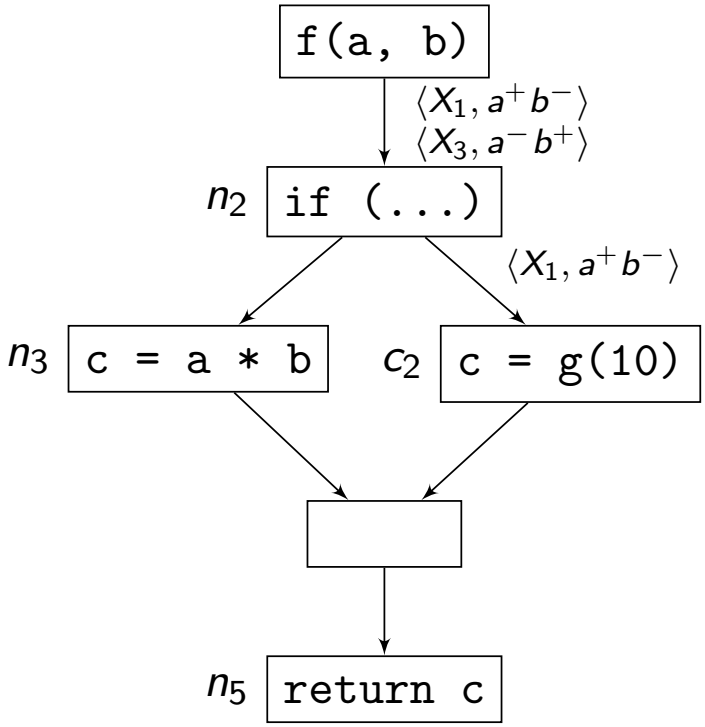
Context Transitions

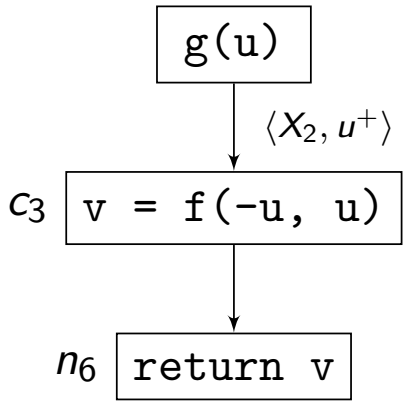


Component Lattice

Example - Sign Analysis

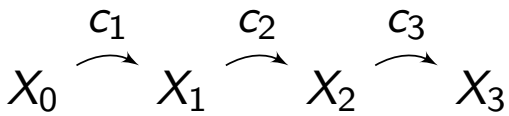




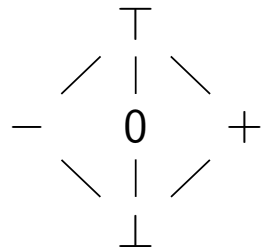


Context	Proc.	Entry	Exit
X_0	main	$\top$	$\top$
X_1	f	a^+b^-	$\top$
X_2	g	u^+	$\top$
X_3	f	a^-b^+	$\top$

Value Contexts

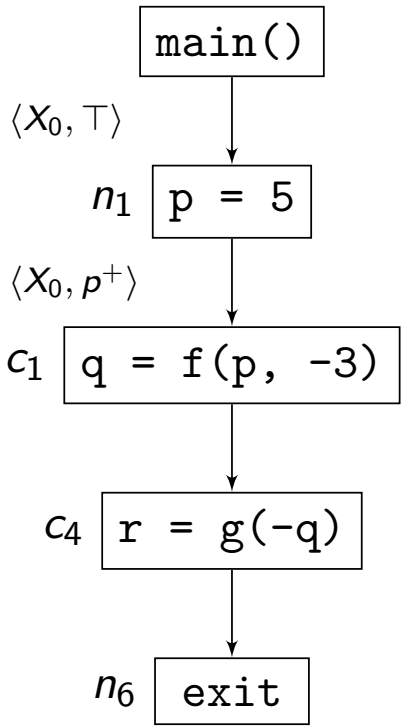


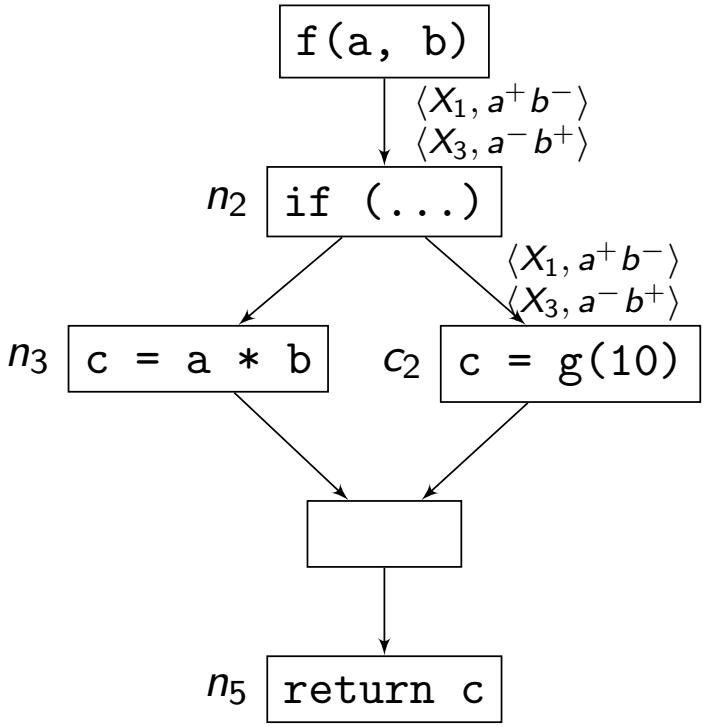
Context Transitions

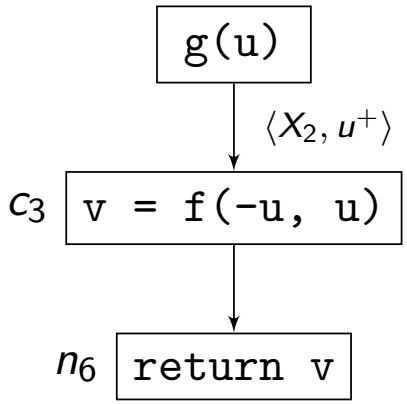


Component Lattice

Example - Sign Analysis

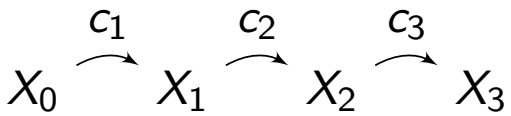




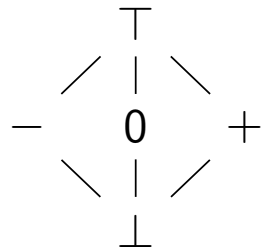


Context	Proc.	Entry	Exit
X_0	main	$\top$	$\top$
X_1	f	a^+b^-	$\top$
X_2	g	u^+	$\top$
X_3	f	a^-b^+	$\top$

Value Contexts

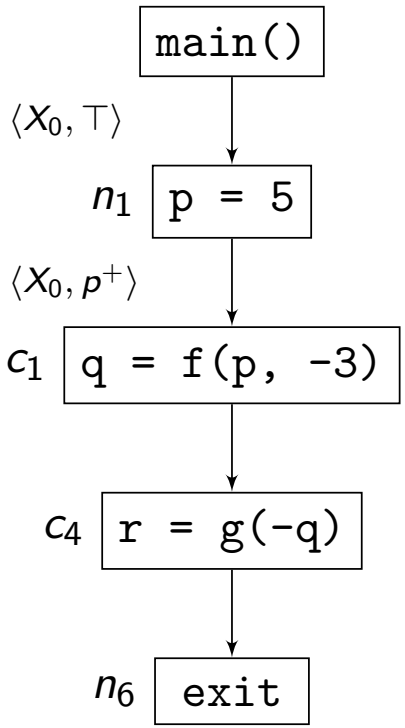


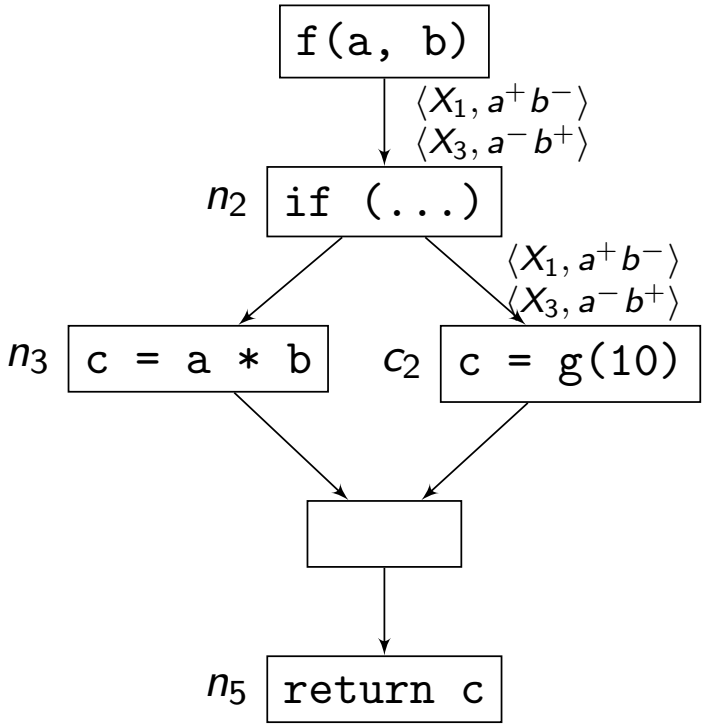
Context Transitions

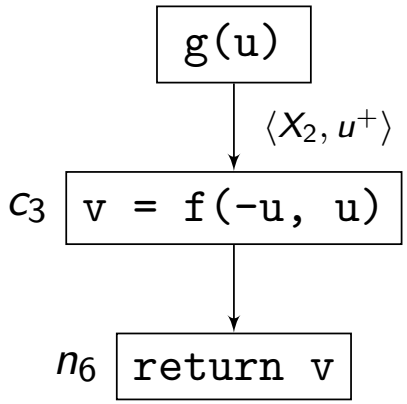


Component Lattice

Example - Sign Analysis

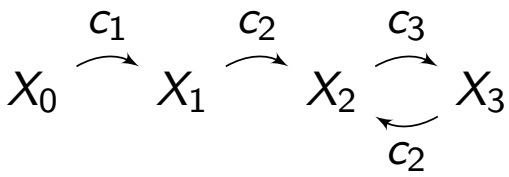




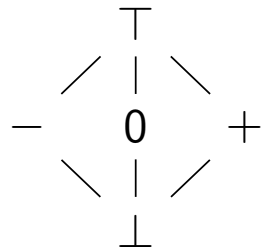


Context	Proc.	Entry	Exit
X_0	main	$\top$	$\top$
X_1	f	a^+b^-	$\top$
X_2	g	u^+	$\top$
X_3	f	a^-b^+	$\top$

Value Contexts

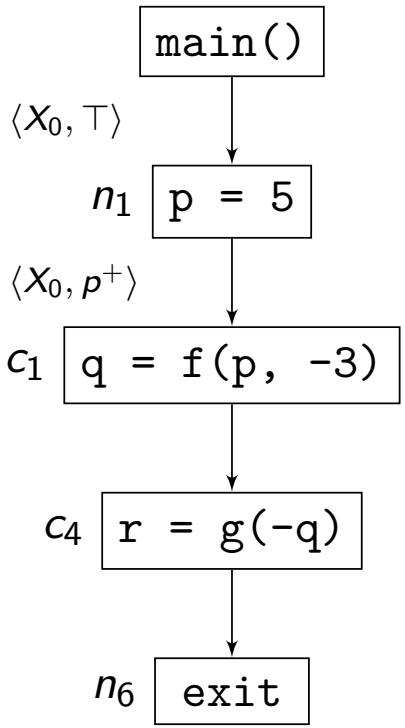


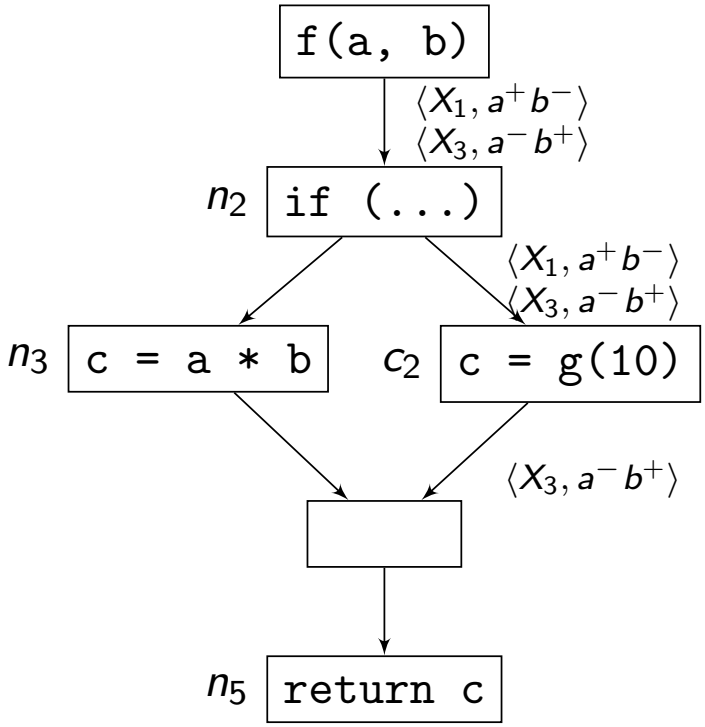
Context Transitions

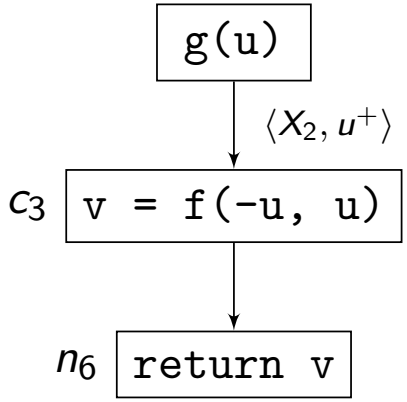


Component Lattice

Example - Sign Analysis

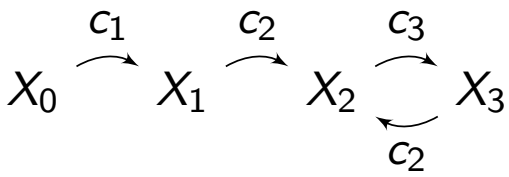




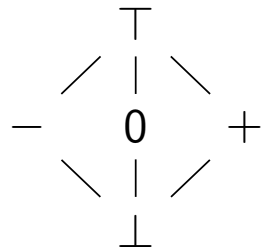


Context	Proc.	Entry	Exit
X_0	main	$\top$	$\top$
X_1	f	a^+b^-	$\top$
X_2	g	u^+	$\top$
X_3	f	a^-b^+	$\top$

Value Contexts

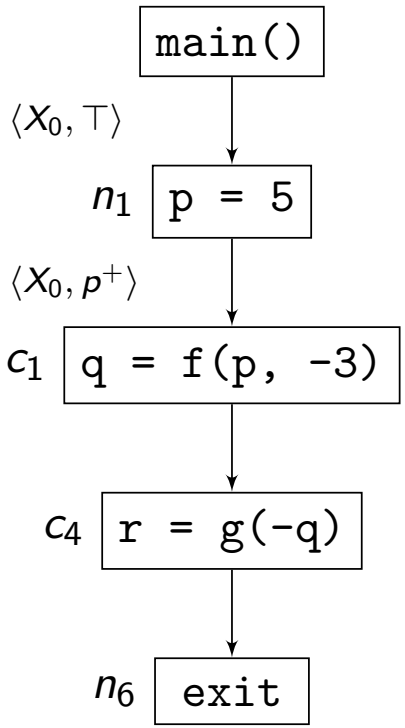


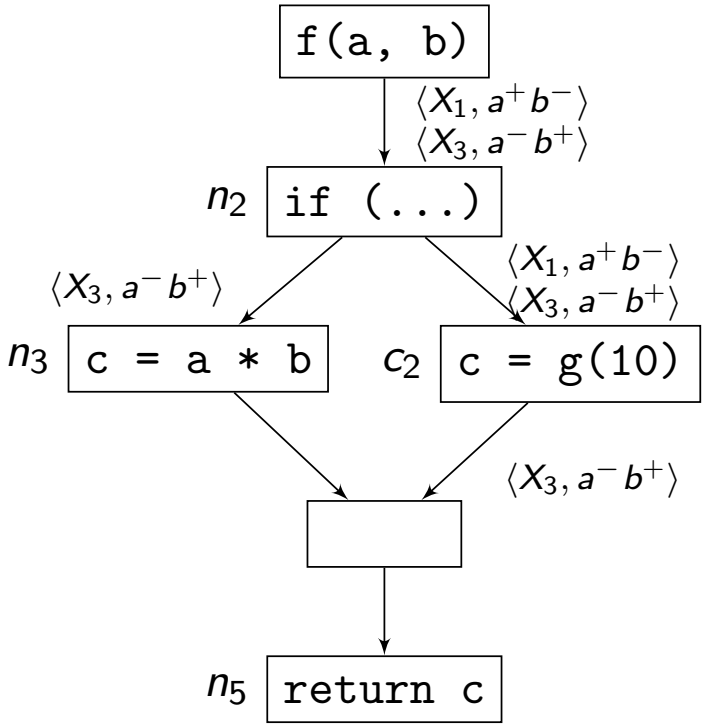
Context Transitions

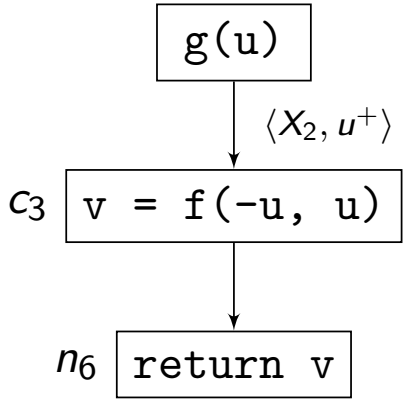


Component Lattice

Example - Sign Analysis

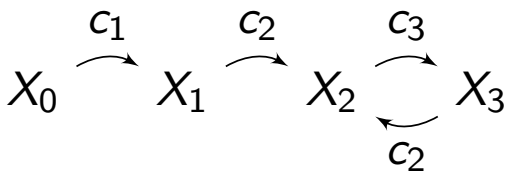




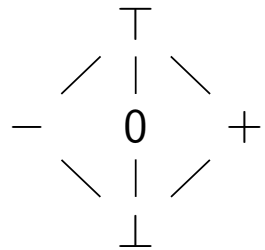


Context	Proc.	Entry	Exit
X_0	main	$\top$	$\top$
X_1	f	a^+b^-	$\top$
X_2	g	u^+	$\top$
X_3	f	a^-b^+	$\top$

Value Contexts

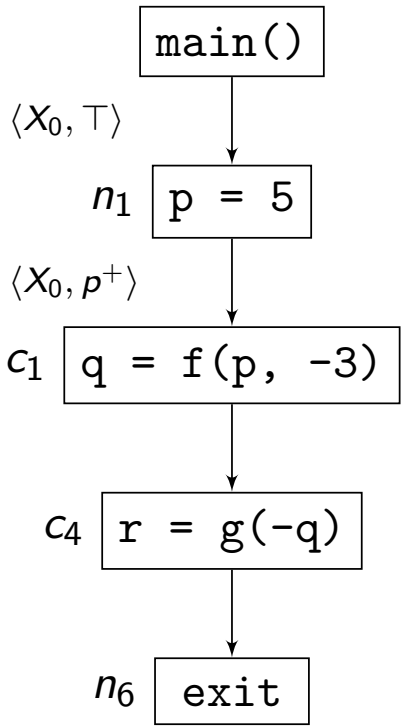


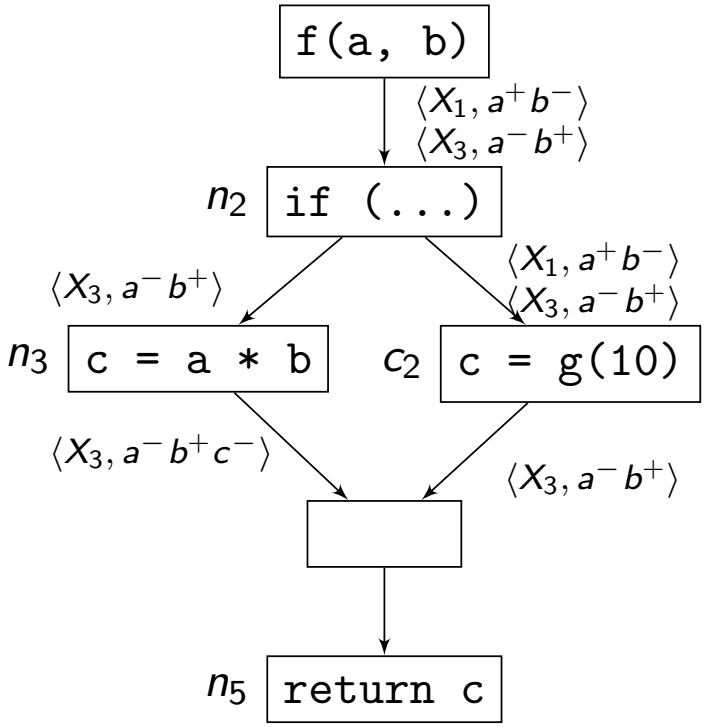
Context Transitions

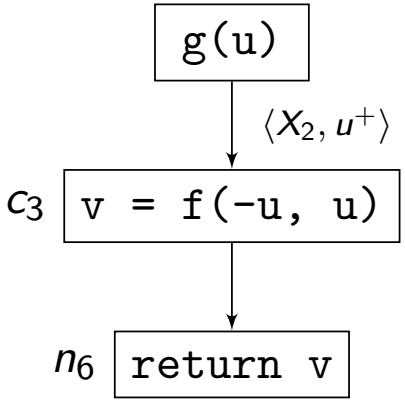


Component Lattice

Example - Sign Analysis

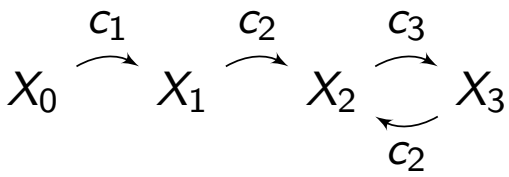




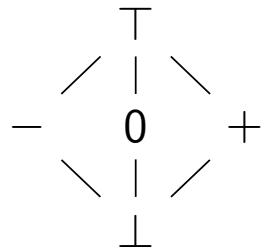


Context	Proc.	Entry	Exit
X_0	main	$\top$	$\top$
X_1	f	a^+b^-	$\top$
X_2	g	u^+	$\top$
X_3	f	a^-b^+	$\top$

Value Contexts

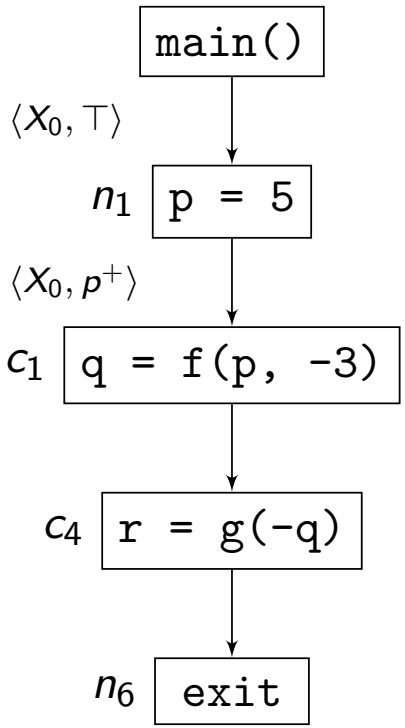


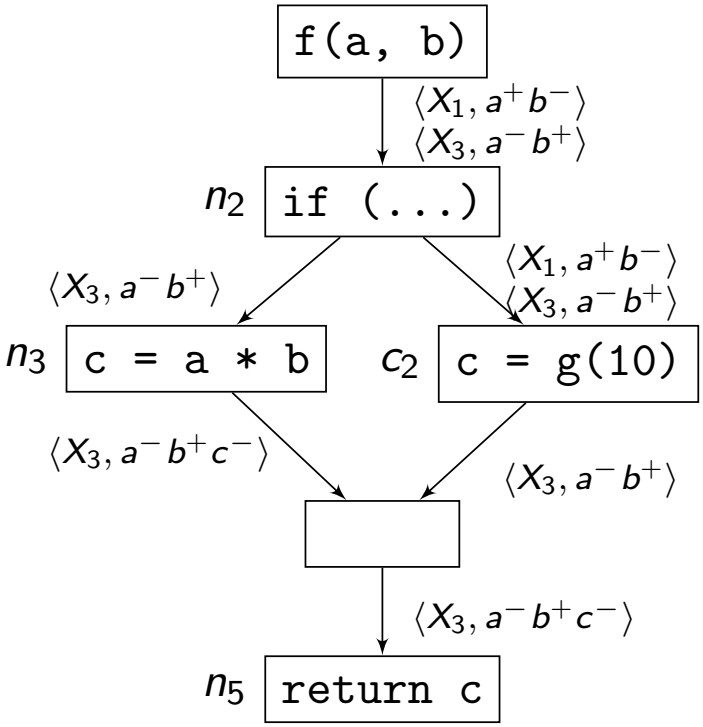
Context Transitions

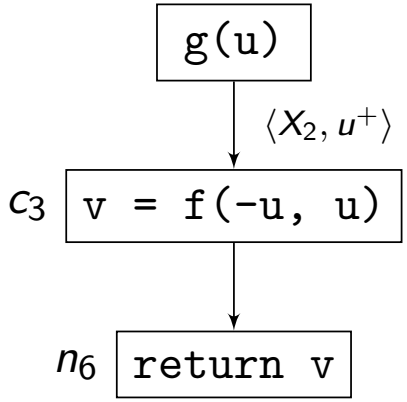


Component Lattice

Example - Sign Analysis

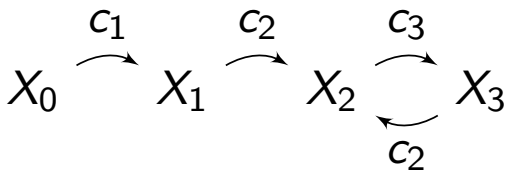




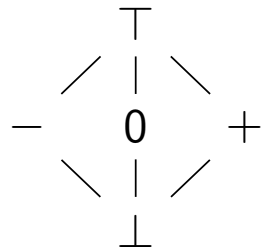


Context	Proc.	Entry	Exit
X_0	main	$\top$	$\top$
X_1	f	a^+b^-	$\top$
X_2	g	u^+	$\top$
X_3	f	a^-b^+	$\top$

Value Contexts

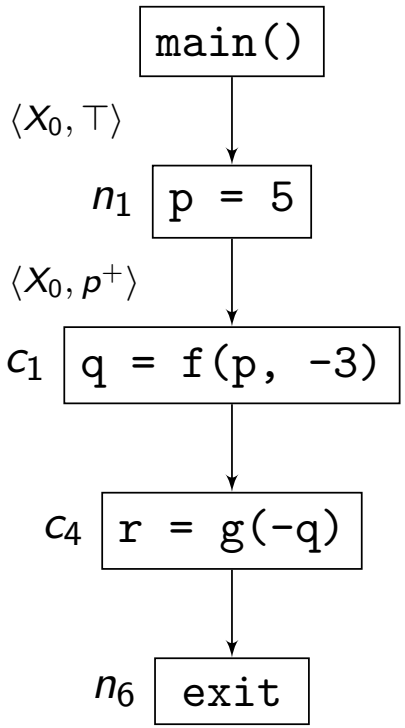


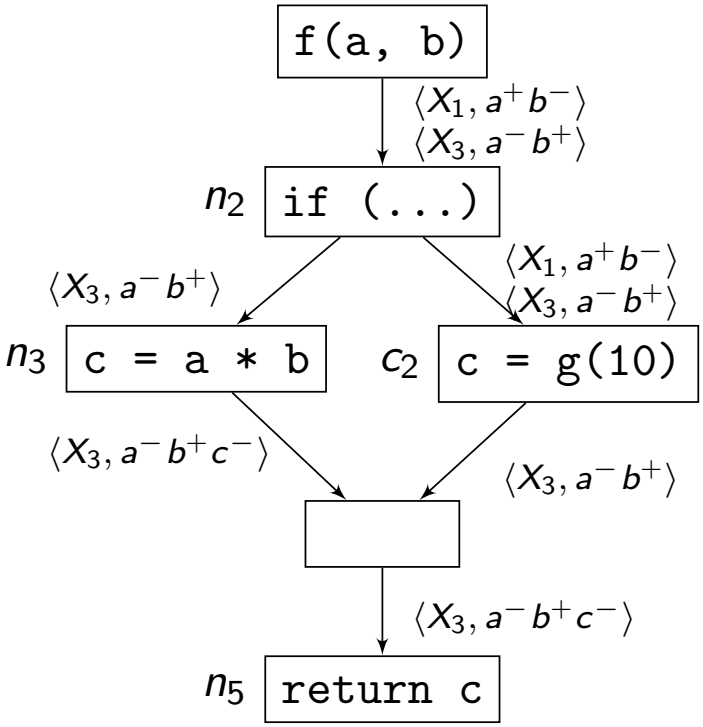
Context Transitions

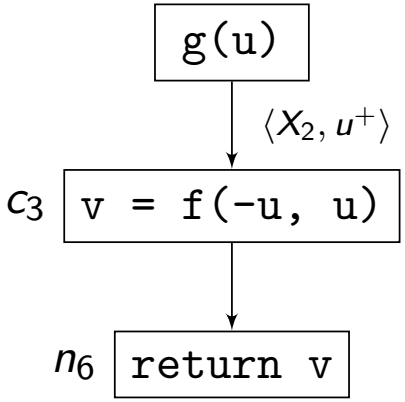


Component Lattice

Example - Sign Analysis

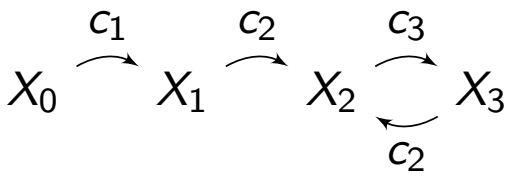




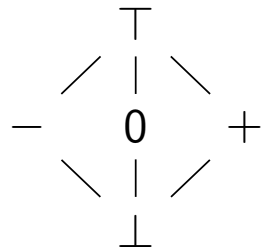


Context	Proc.	Entry	Exit
X_0	main	$\top$	$\top$
X_1	f	a^+b^-	$\top$
X_2	g	u^+	$\top$
X_3	f	a^-b^+	$a^-b^+c^-$

Value Contexts

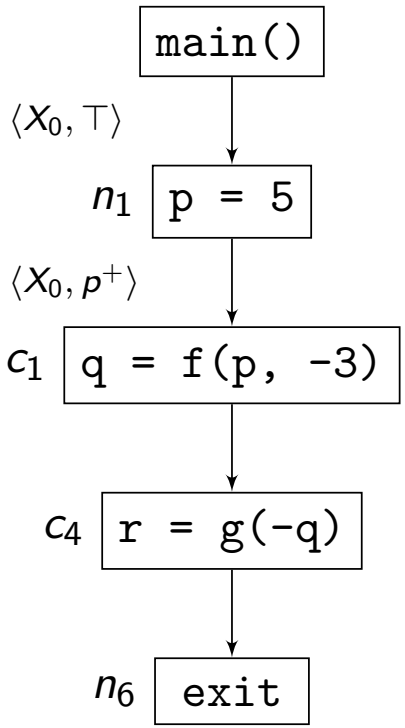


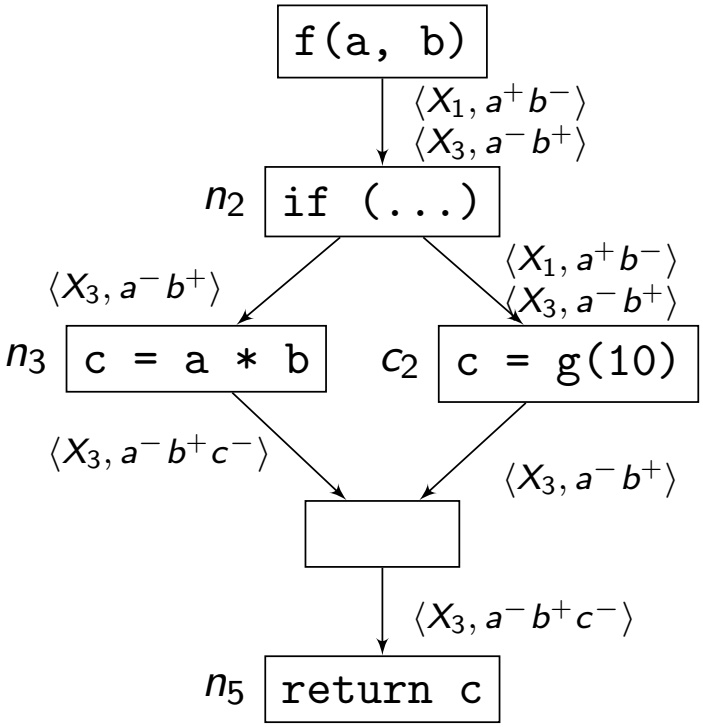
Context Transitions

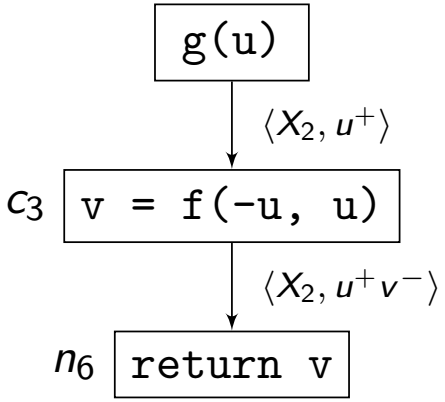


Component Lattice

Example - Sign Analysis

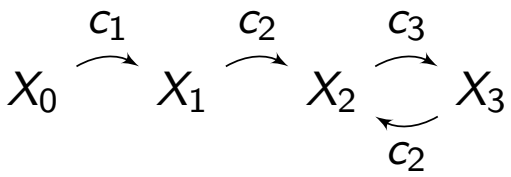




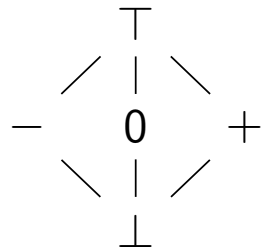


Context	Proc.	Entry	Exit
X_0	main	$\top$	$\top$
X_1	f	a^+b^-	$\top$
X_2	g	u^+	$\top$
X_3	f	a^-b^+	$a^-b^+c^-$

Value Contexts

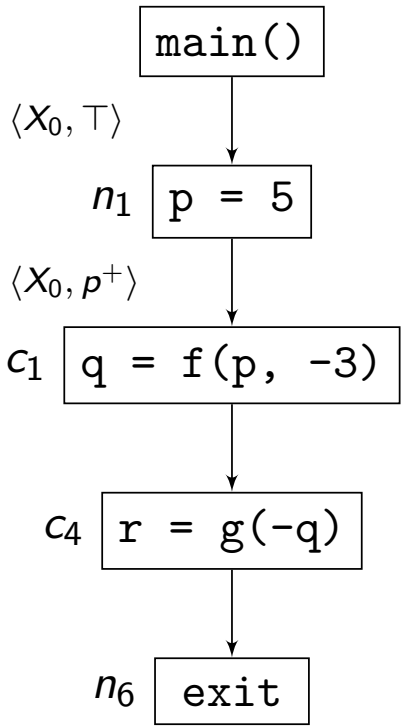


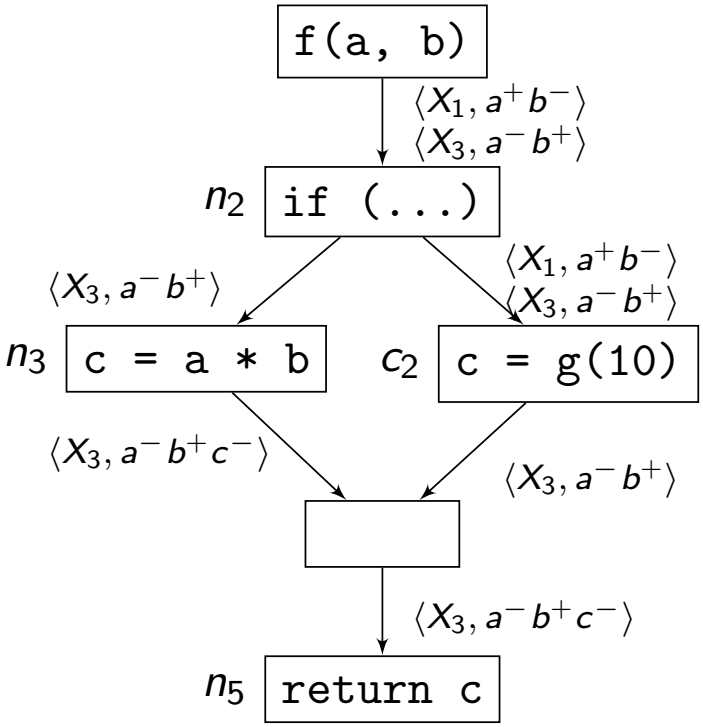
Context Transitions

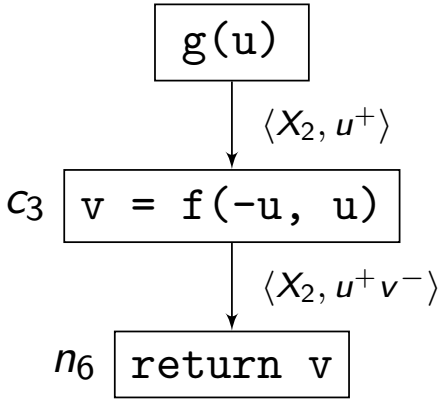


Component Lattice

Example - Sign Analysis

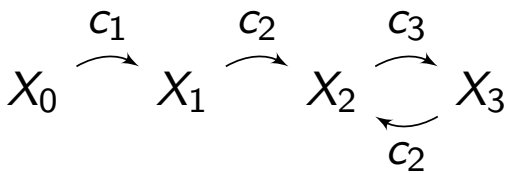




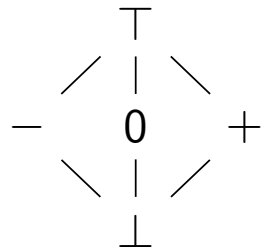


Context	Proc.	Entry	Exit
X_0	main	$\top$	$\top$
X_1	f	a^+b^-	$\top$
X_2	g	u^+	u^+v^-
X_3	f	a^-b^+	$a^-b^+c^-$

Value Contexts

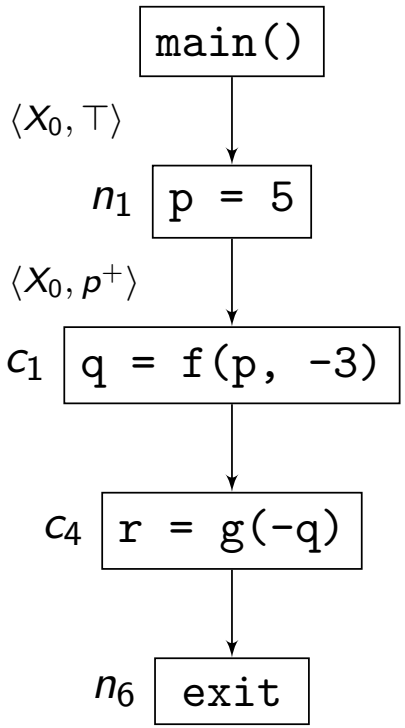


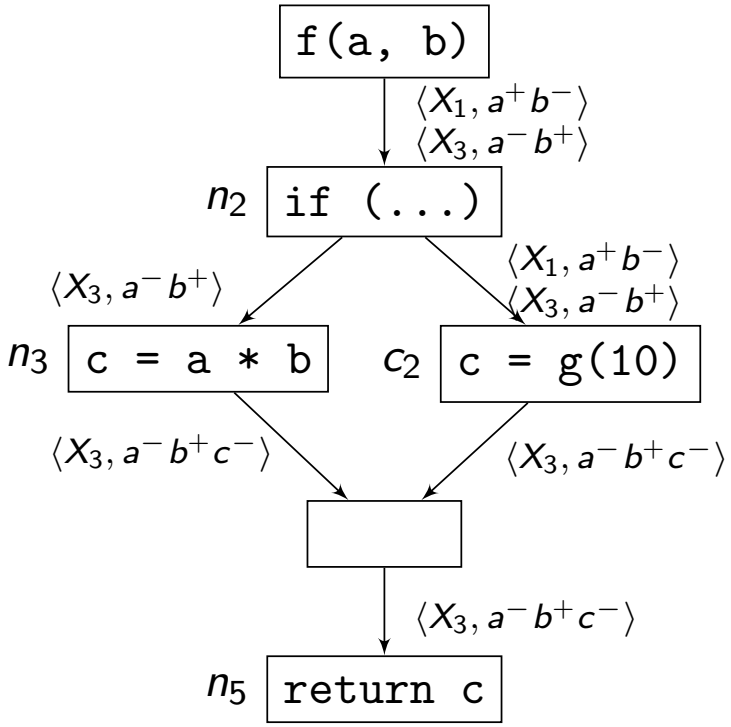
Context Transitions

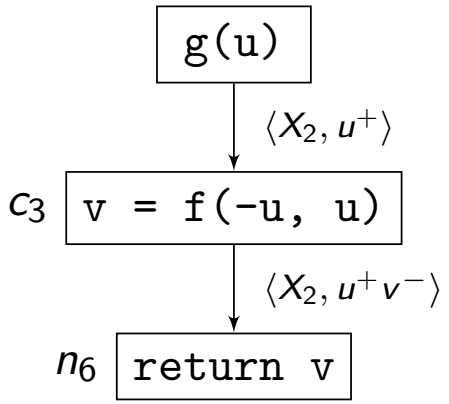


Component Lattice

Example - Sign Analysis

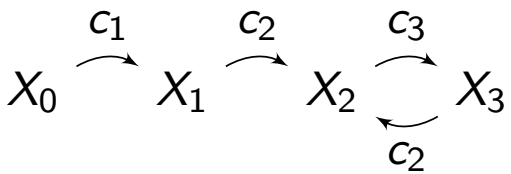




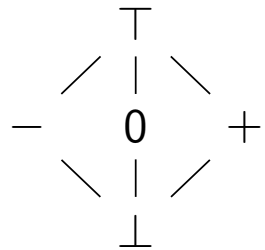


Context	Proc.	Entry	Exit
X_0	main	$\top$	$\top$
X_1	f	a^+b^-	$\top$
X_2	g	u^+	u^+v^-
X_3	f	a^-b^+	$a^-b^+c^-$

Value Contexts

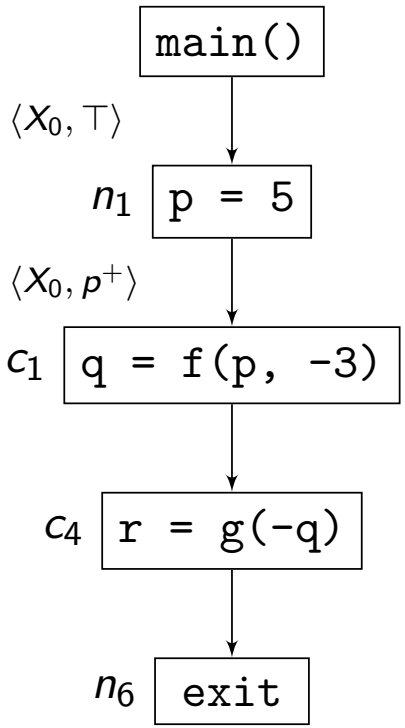


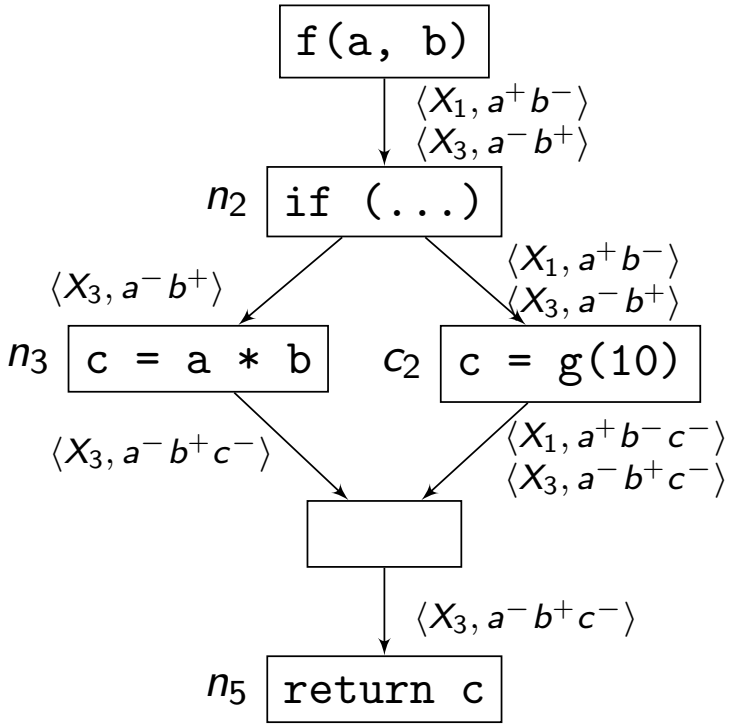
Context Transitions

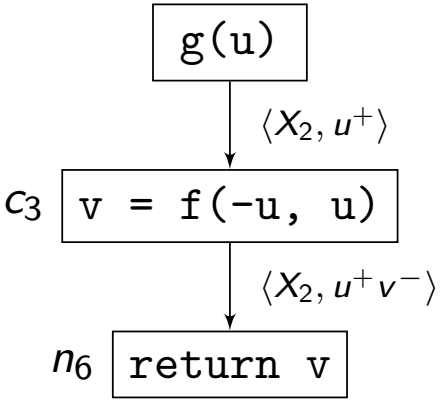


Component Lattice

Example - Sign Analysis

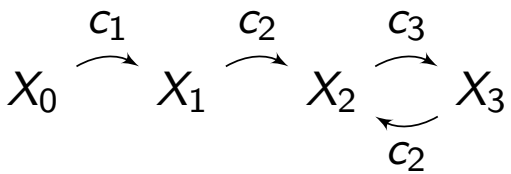




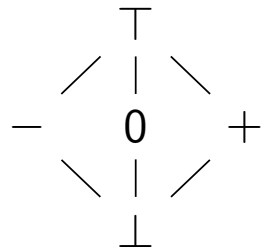


Context	Proc.	Entry	Exit
X_0	main	$\top$	$\top$
X_1	f	a^+b^-	$\top$
X_2	g	u^+	u^+v^-
X_3	f	a^-b^+	$a^-b^+c^-$

Value Contexts

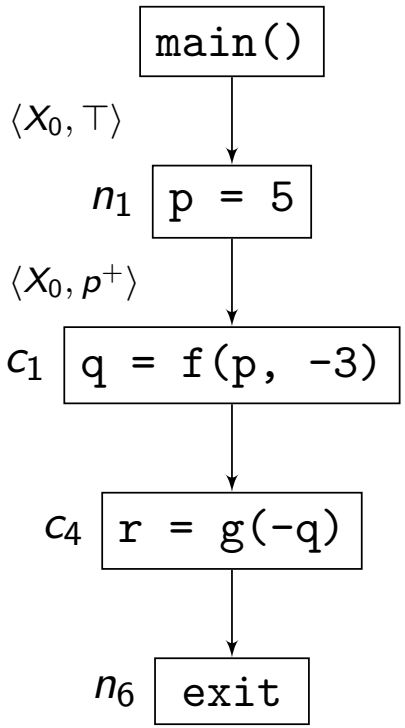


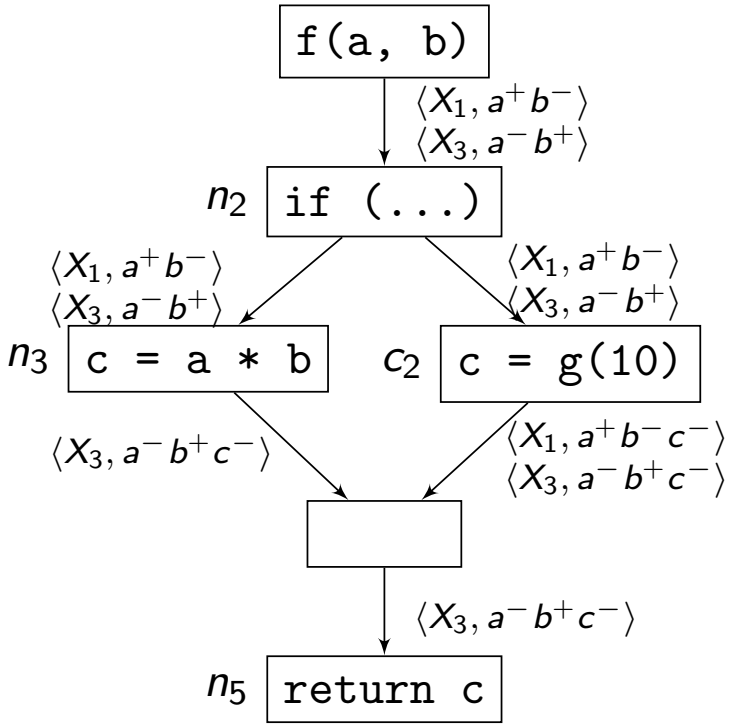
Context Transitions

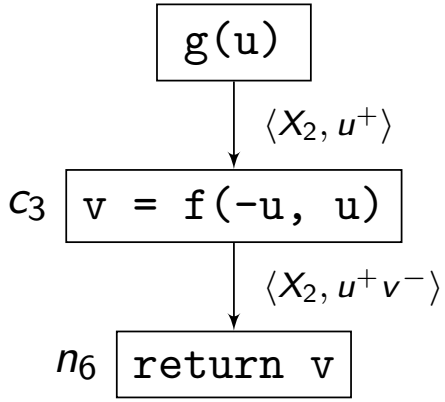


Component Lattice

Example - Sign Analysis

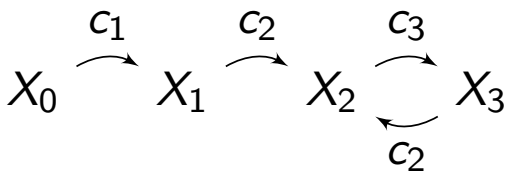




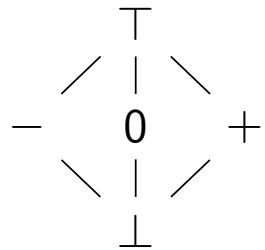


Context	Proc.	Entry	Exit
X_0	main	$\top$	$\top$
X_1	f	a^+b^-	$\top$
X_2	g	u^+	u^+v^-
X_3	f	a^-b^+	$a^-b^+c^-$

Value Contexts

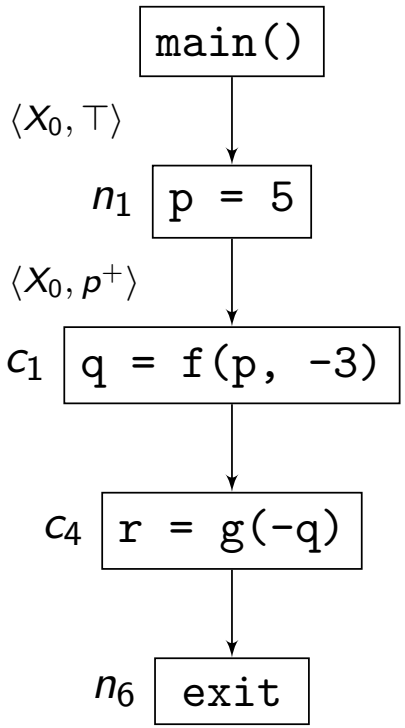


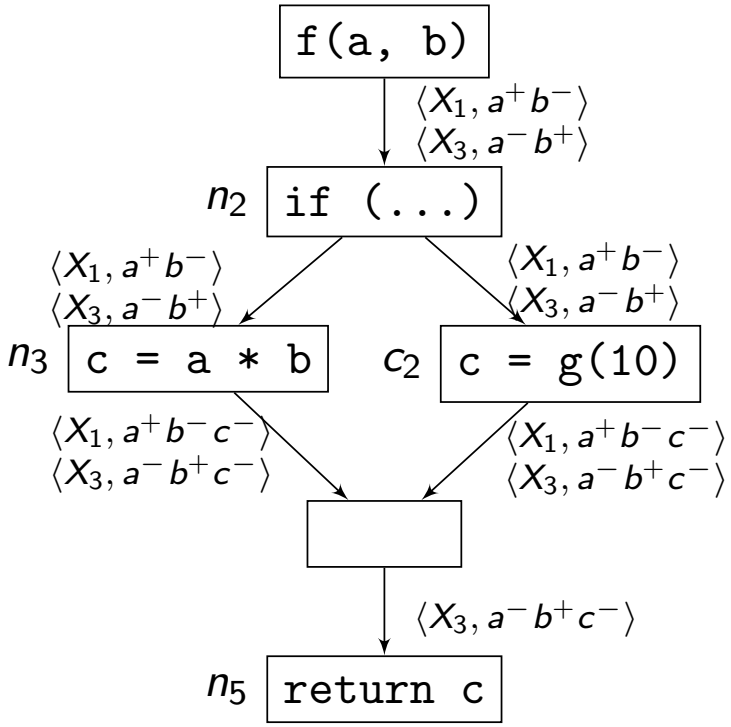
Context Transitions

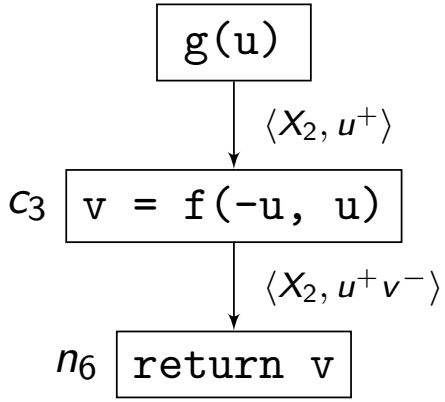


Component Lattice

Example - Sign Analysis

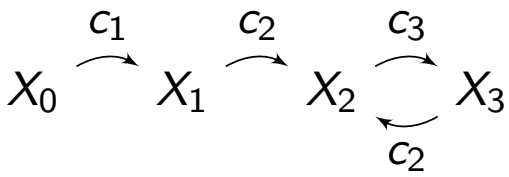




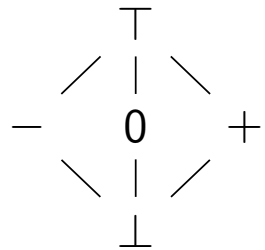


Context	Proc.	Entry	Exit
X_0	main	$\top$	$\top$
X_1	f	a^+b^-	$\top$
X_2	g	u^+	u^+v^-
X_3	f	a^-b^+	$a^-b^+c^-$

Value Contexts

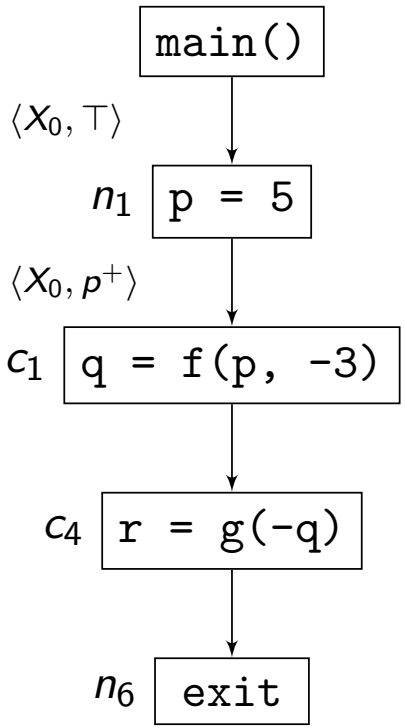


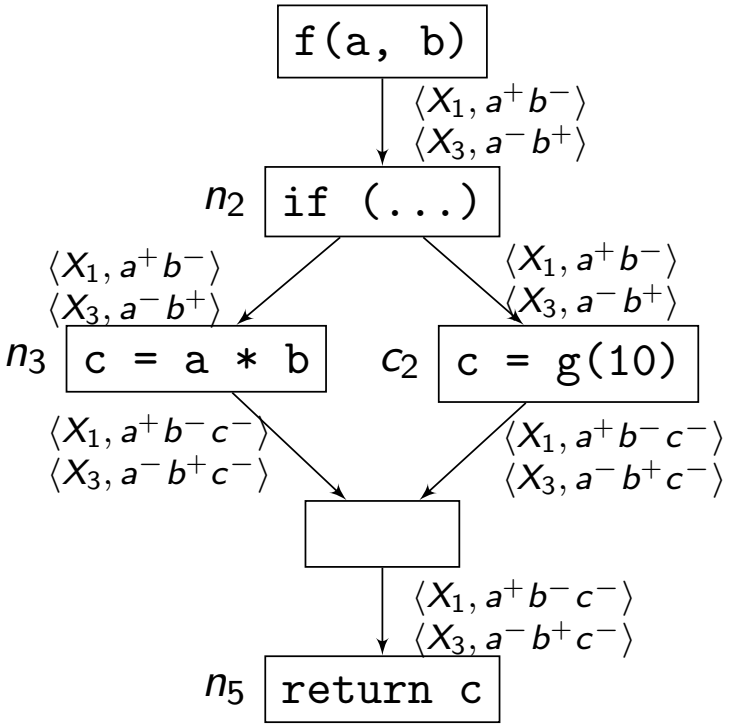
Context Transitions

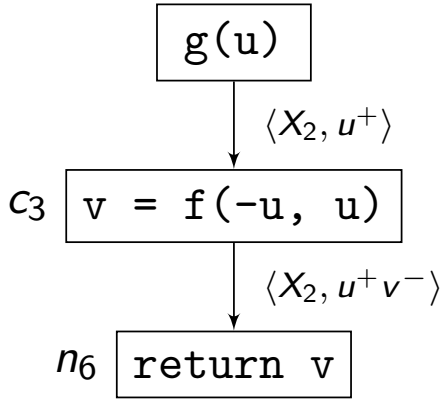


Component Lattice

Example - Sign Analysis







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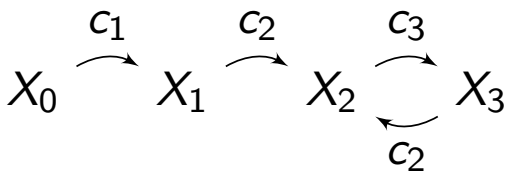

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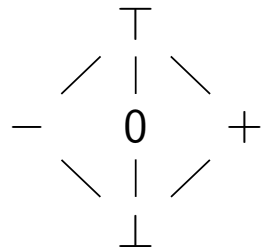

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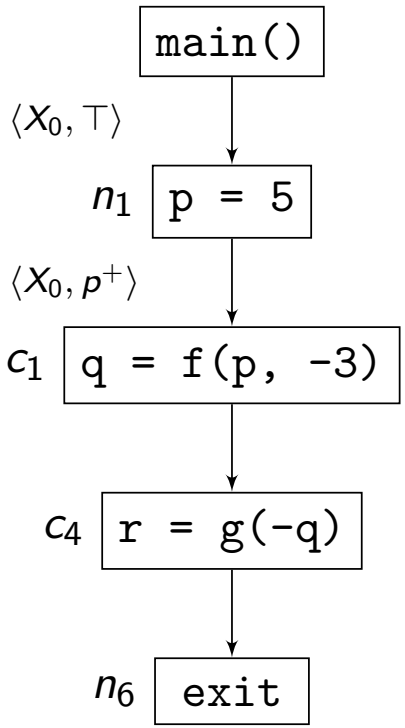

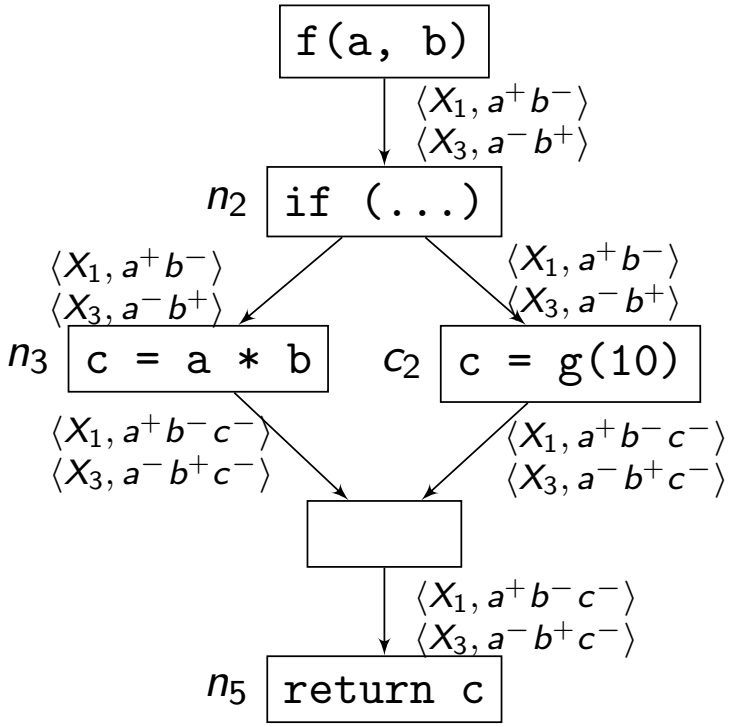

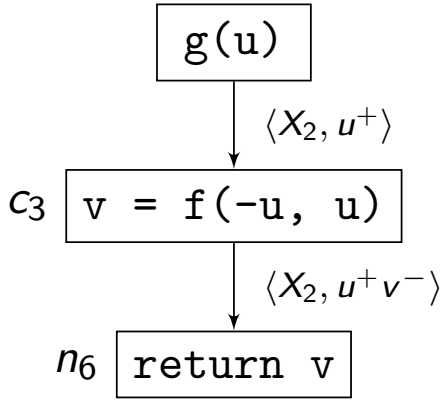

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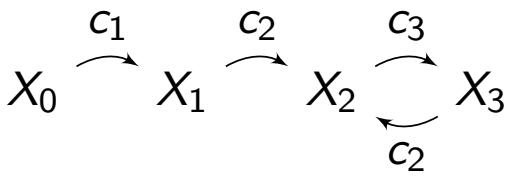

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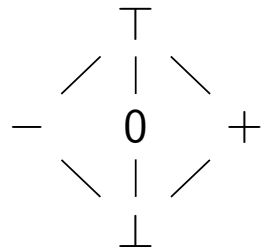

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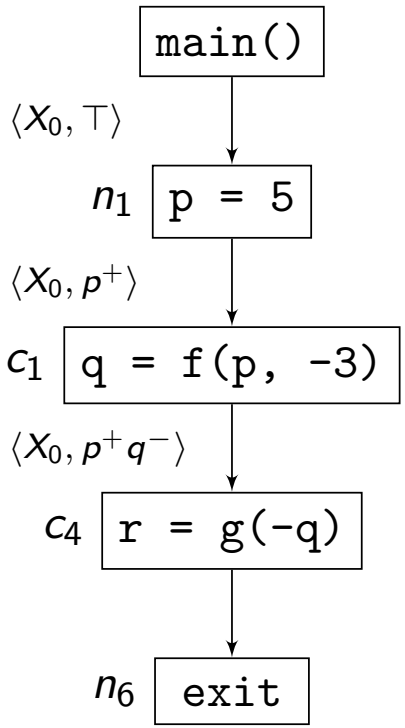

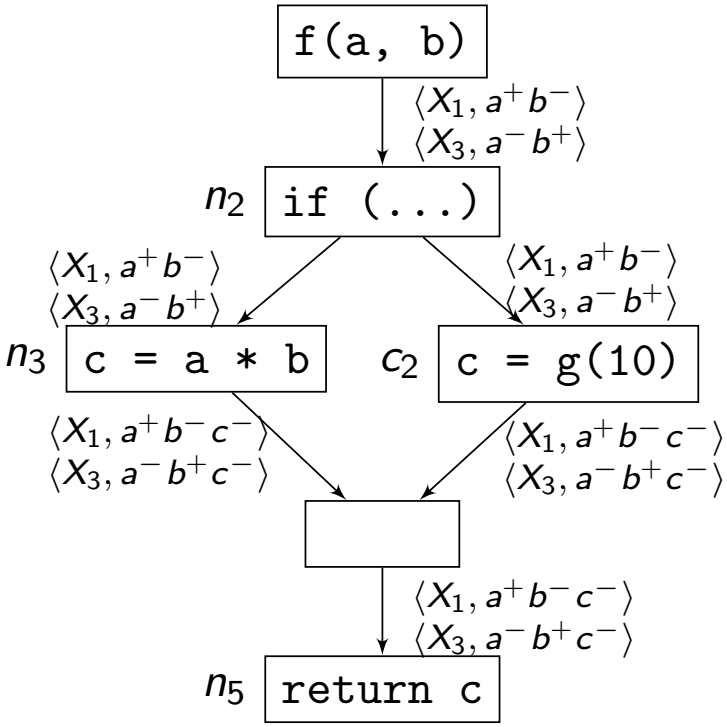

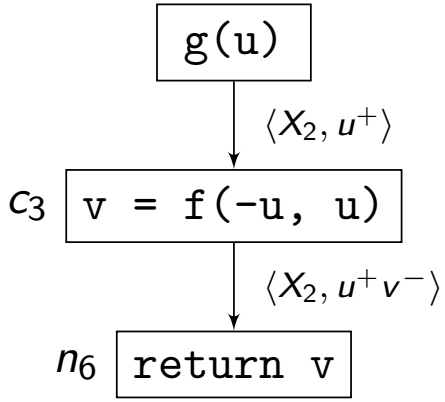

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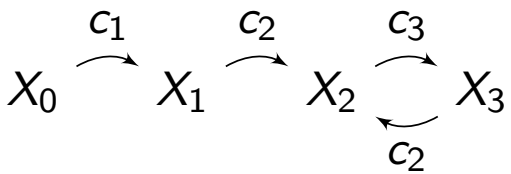

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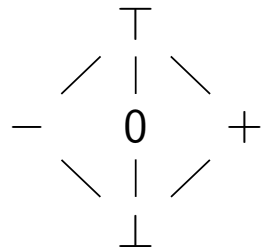

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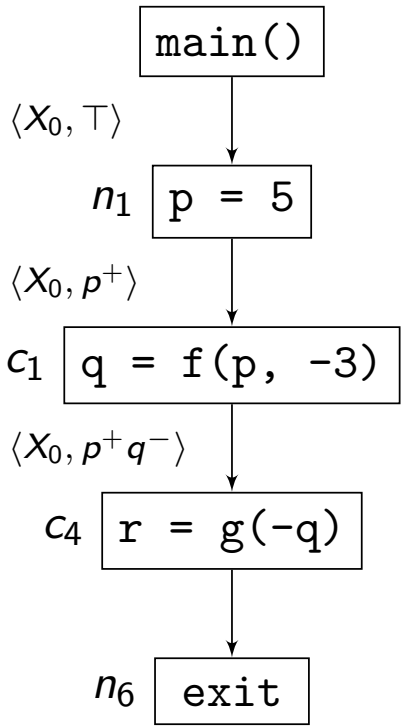

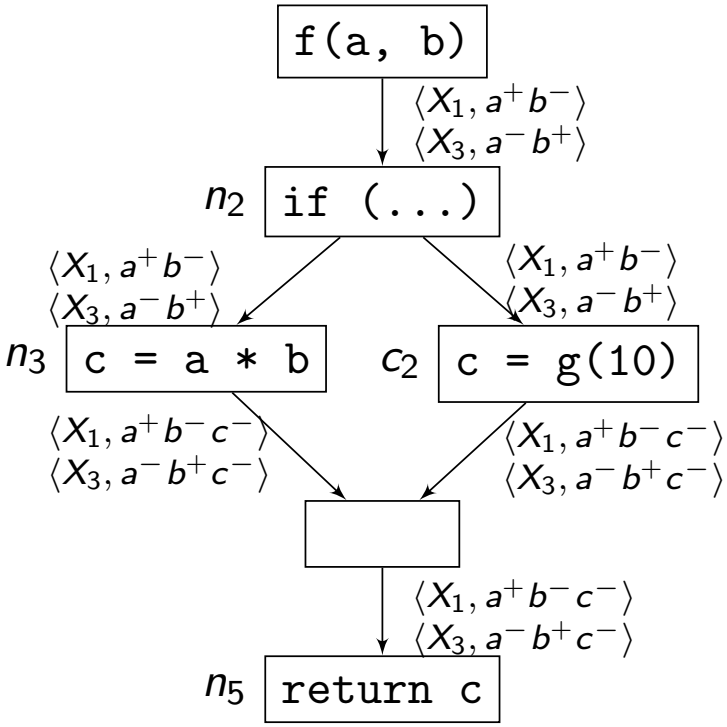

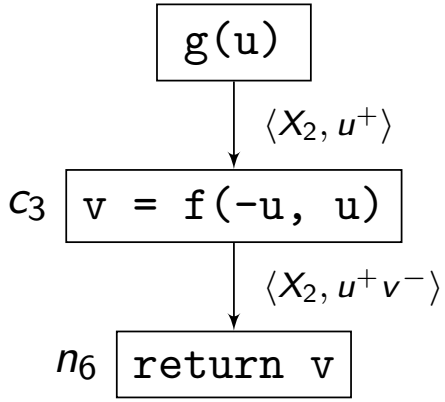

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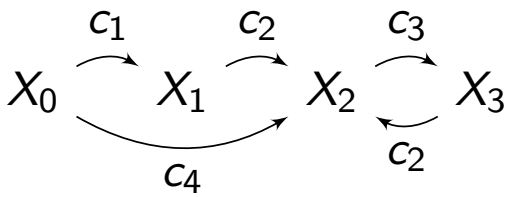

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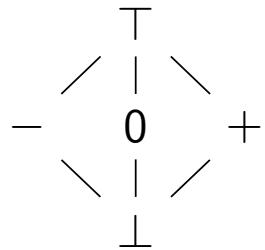

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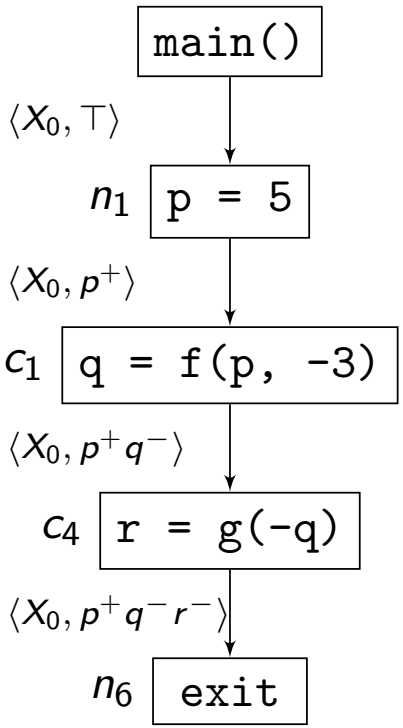

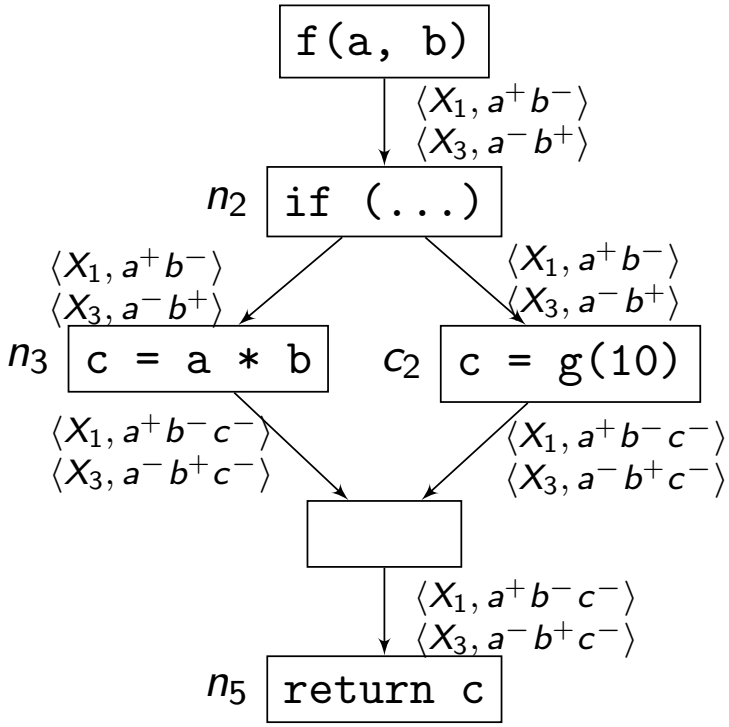

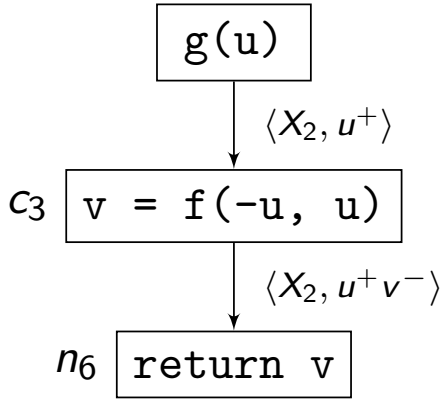

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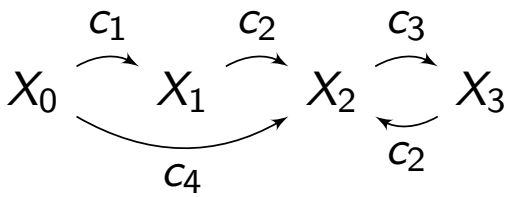

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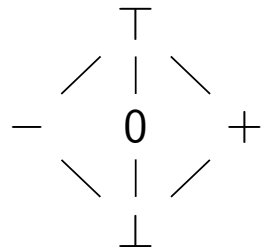

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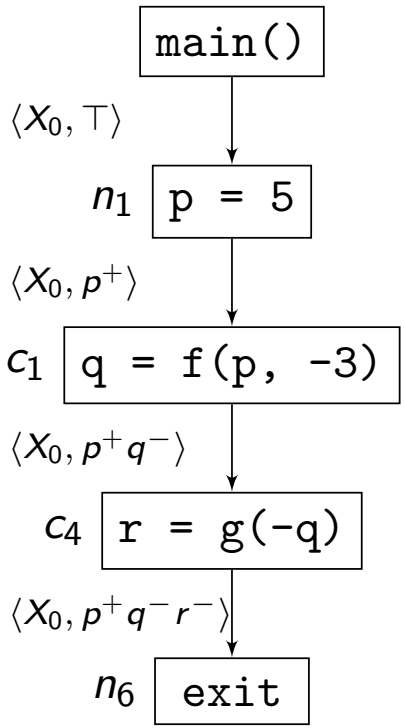

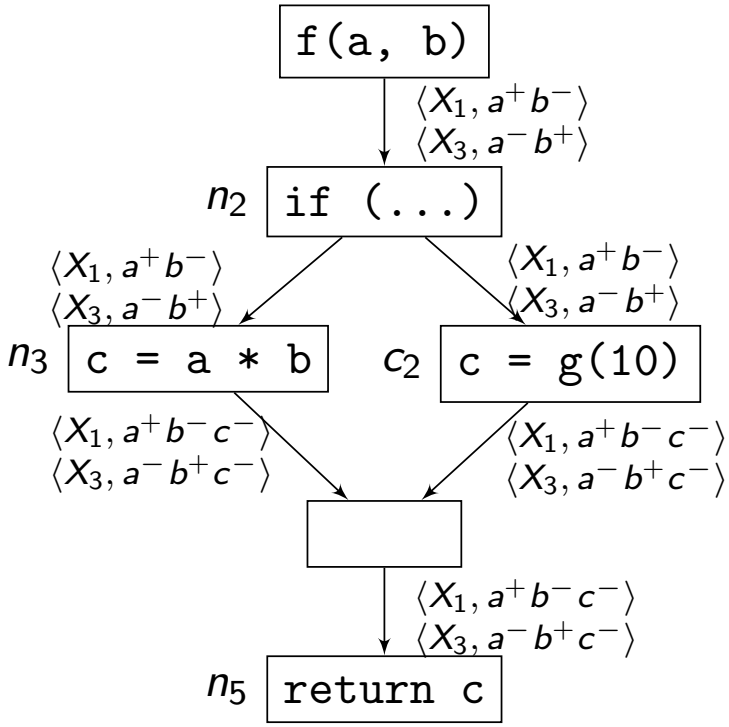

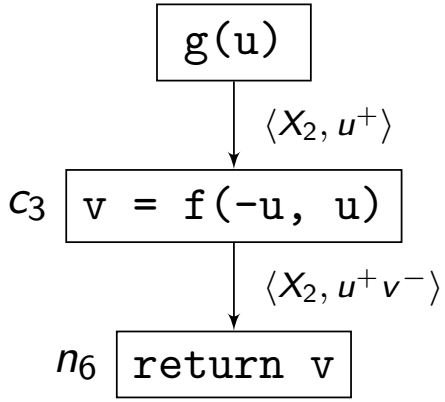

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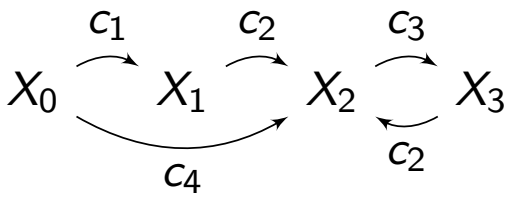

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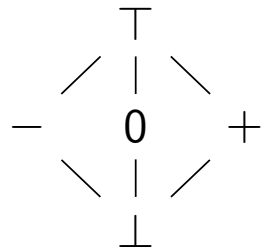

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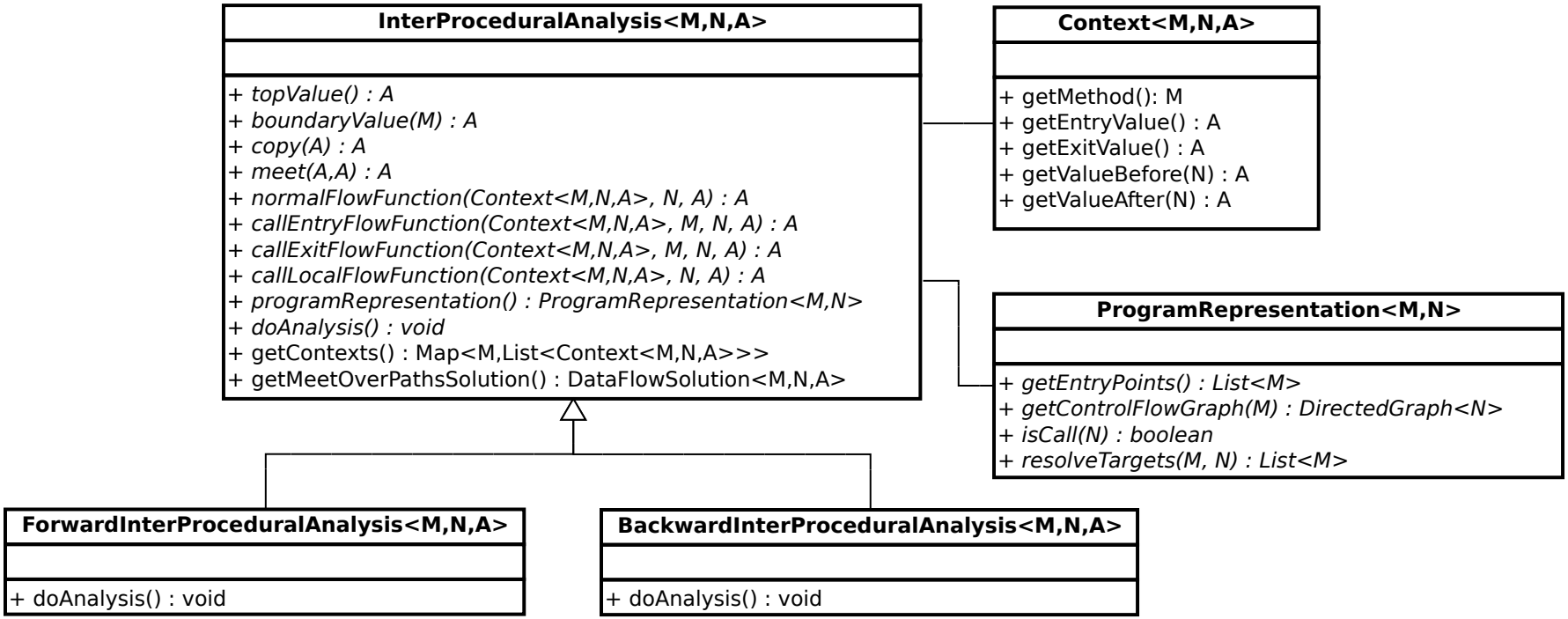
Implementation Framework



https://github.com/rohanpadhye/vasco

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4. Resume the program. Let garbage collection run as normal.

Outline

Summary

The following were the main contributions of this project:

1. A liveness-driven heap abstraction for precise alias analysis.
2. A generic access graph library implemented in Java.
3. A generic inter-procedural data flow analysis framework implemented in Java.
4. A flow- and context-sensitive points-to analysis implemented in Soot that constructs precise call graphs.
5. A technique for performing dynamic heap pruning implemented using the Java Debug Interface (JDI).

Future Work

1. Implementation of an inter-procedural liveness-driven heap points-to analysis.
2. Performance analysis of dynamic heap pruning on real benchmarks.
3. Shape analysis using accessor relationship graphs.