Part 5

IPDFA Using Value Contexts

Value Contexts: Key Ideas

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  - the data flow values reaching E_p for the two contexts will also be identical

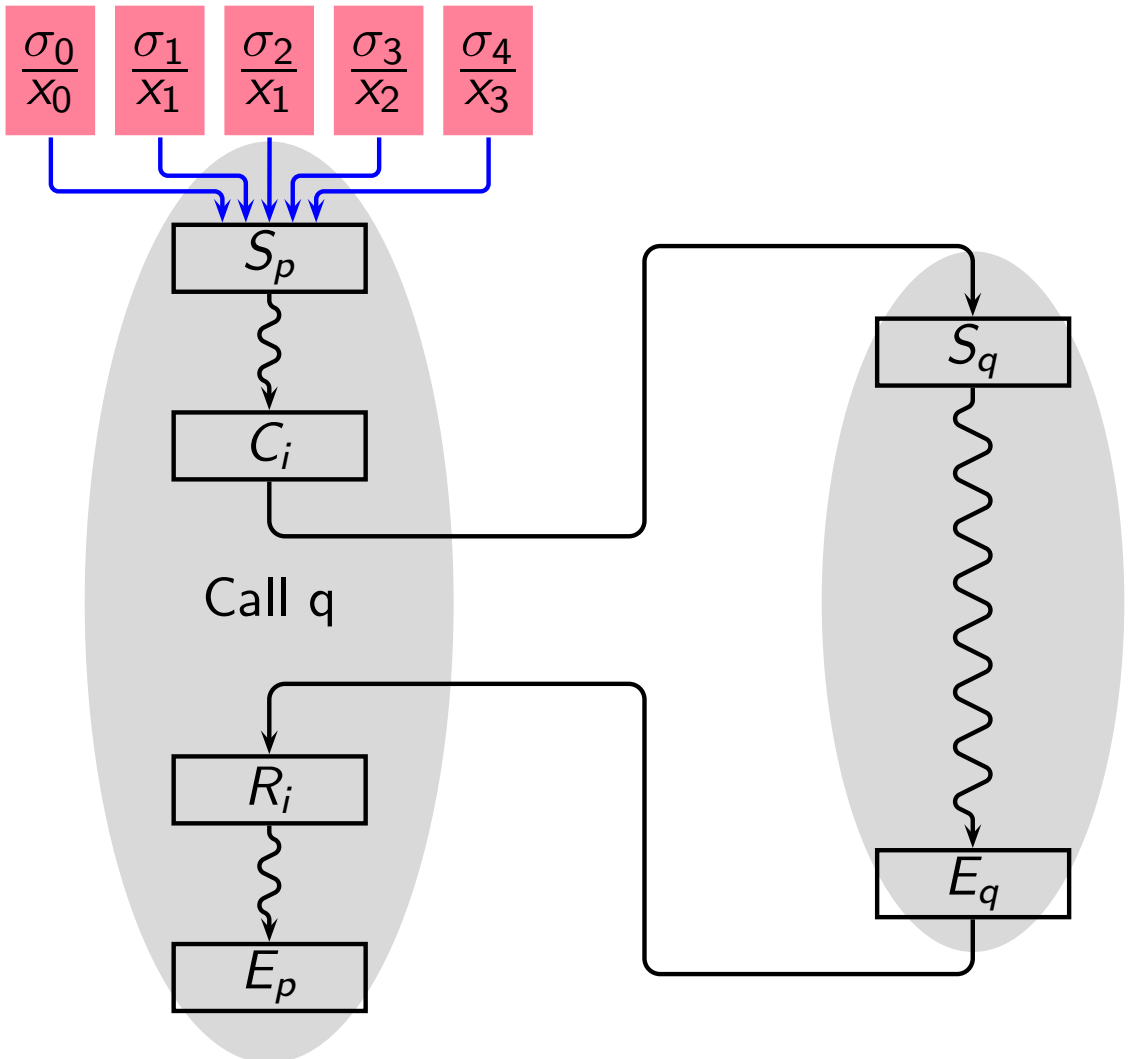
- We can reduce the amount of effort by using

  - Data flow values at S_p as value contexts
  - Maintaining distinct data flow values in p for each value context

Interprocedural Data Flow Analysis Using Value Contexts

- A value context is defined by a particular input data flow value reaching a procedure
- It is used to enumerate the summary flow functions in terms of (input $\mapsto$ output) pairs
- In order to compute these pairs, data flow analysis within a procedure is performed separately for each context (i.e. input data flow value)
- When a new call to a procedure is encounterd, the pairs are consulted do decide if the procedure needs to be analysed again
  - If it was already analysed once for the input value, output can be directly processed
  - Otherwise, a new context is created and the procedure is analysed for this new context

Understanding Value Contexts



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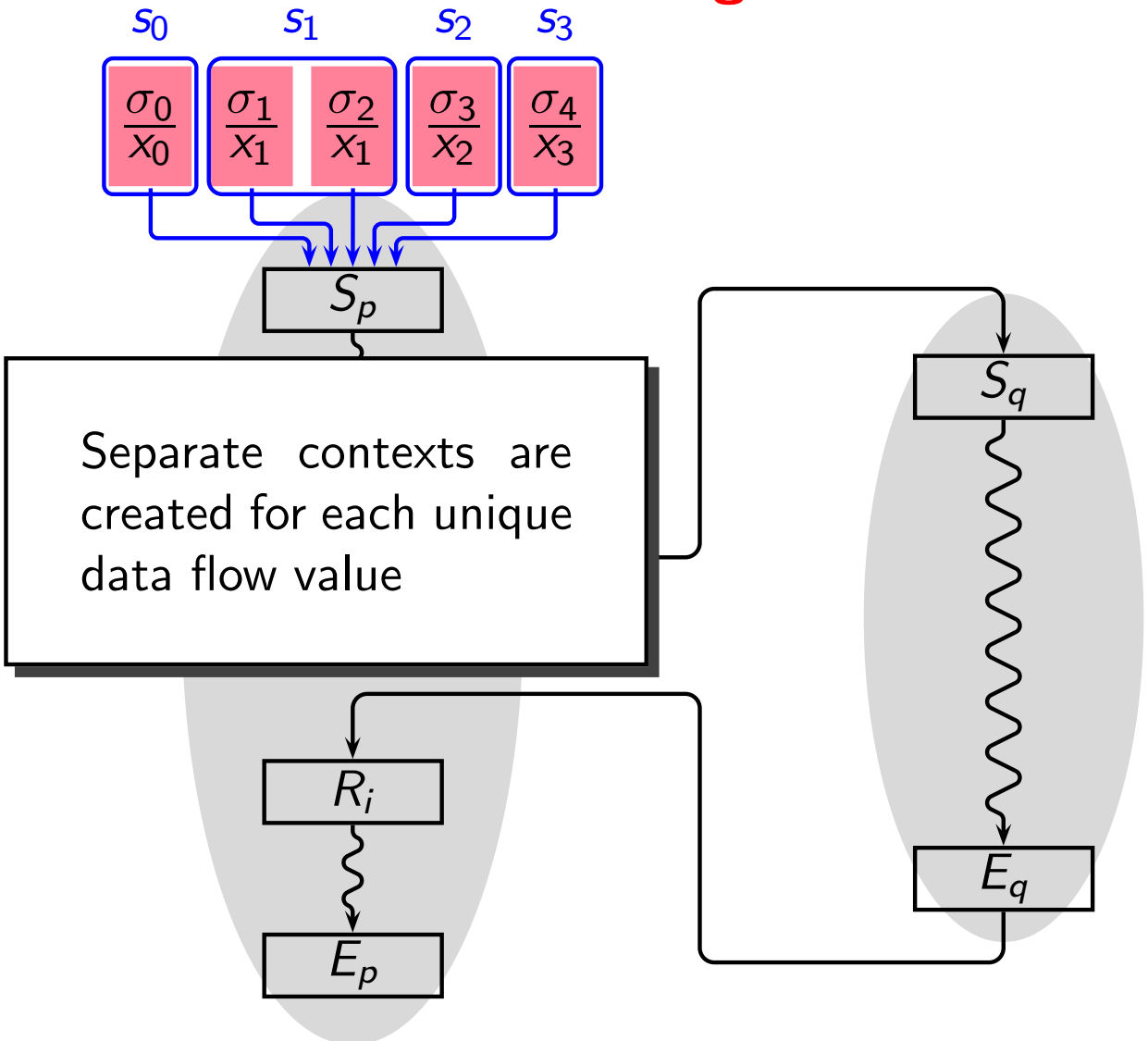

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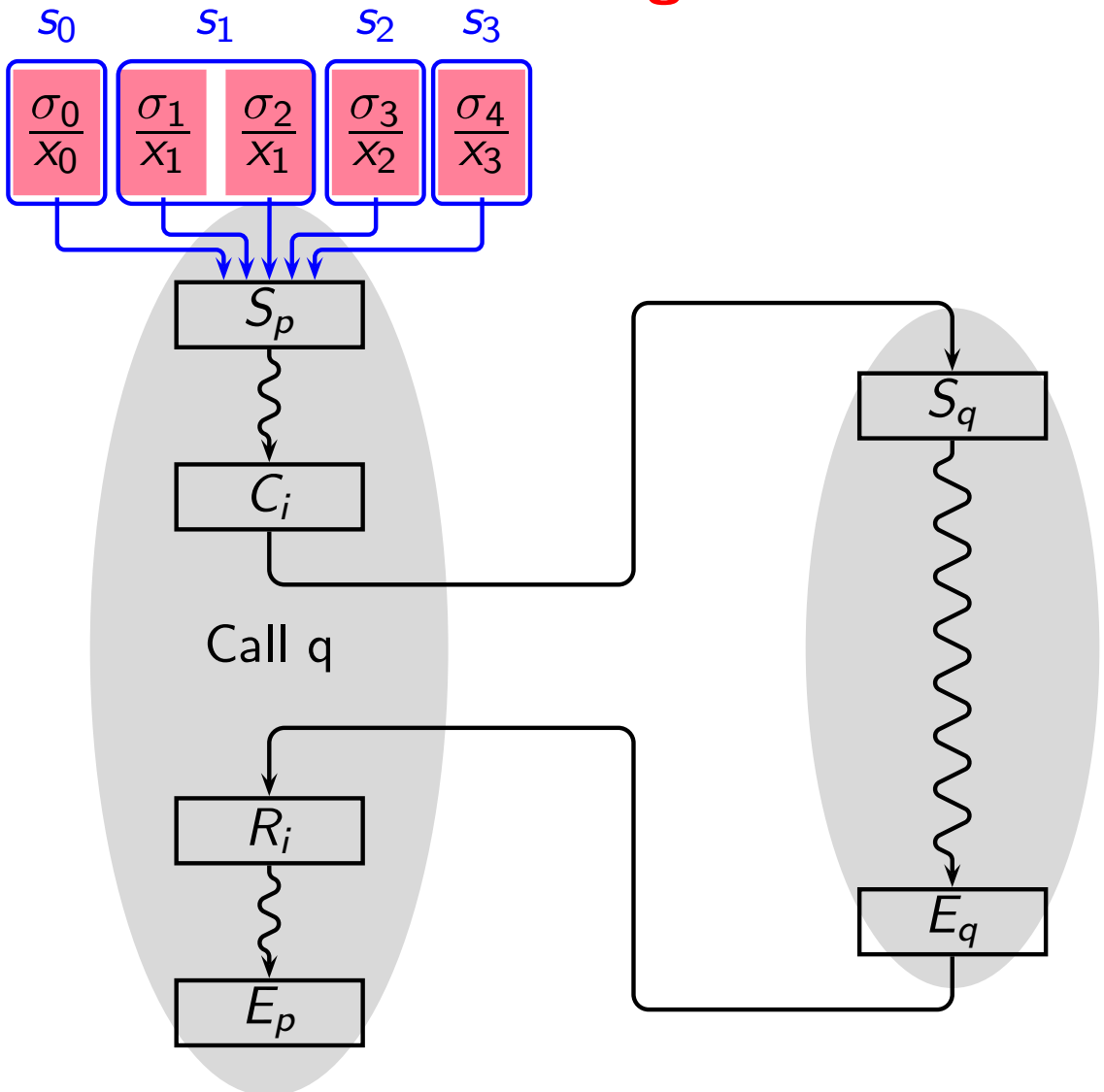

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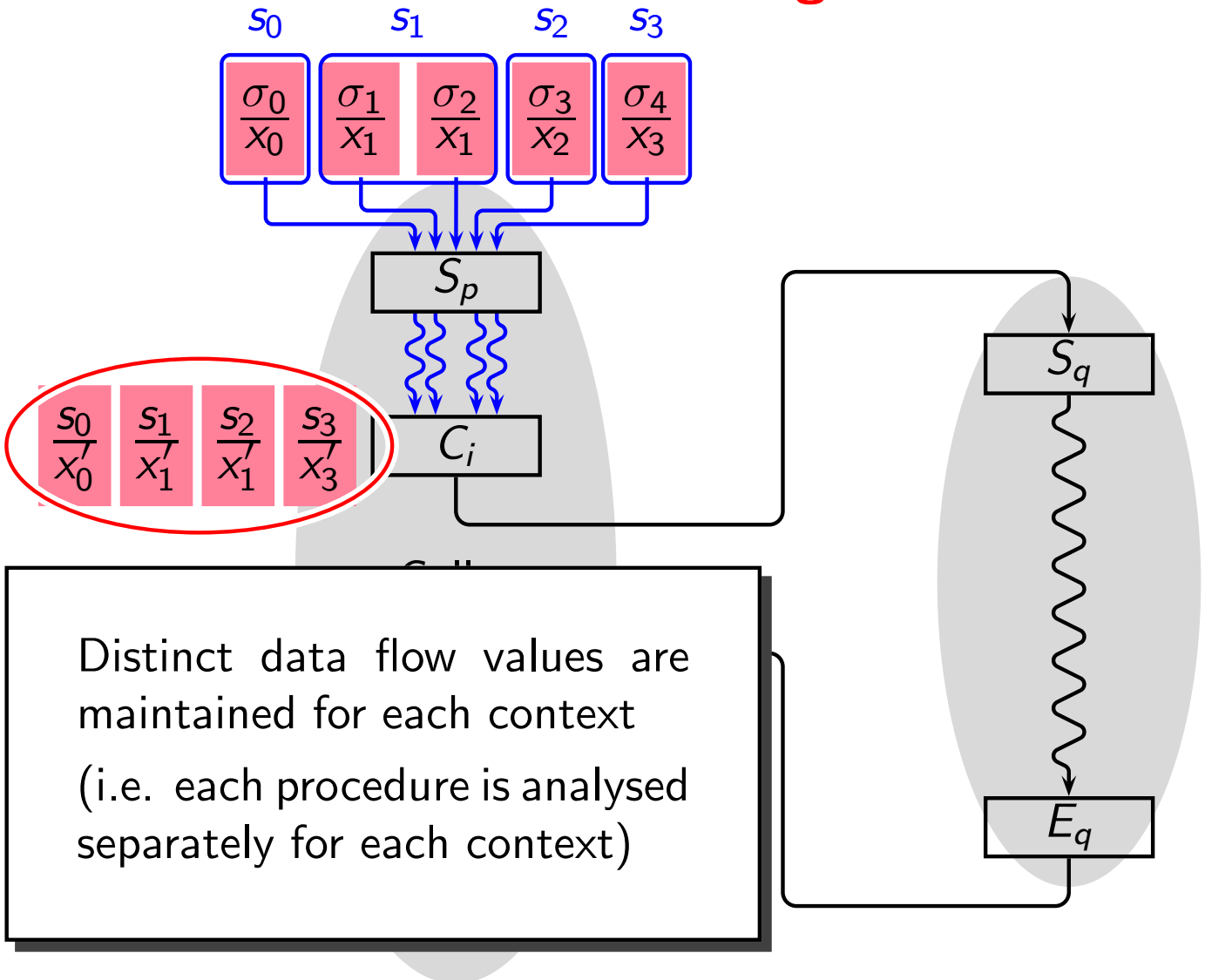
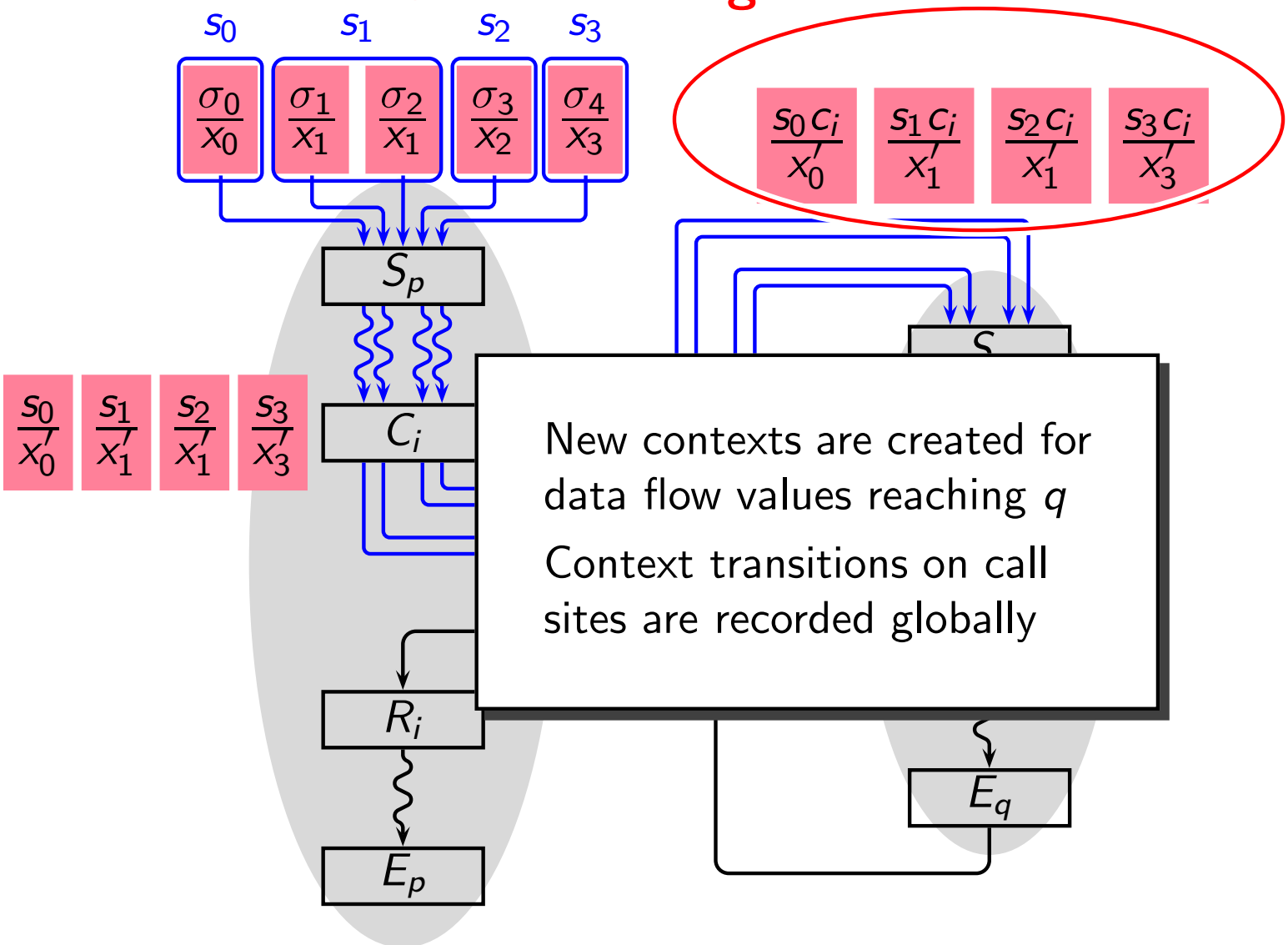


Distinct data flow values are maintained for each context

(i.e. each procedure is analysed separately for each context)

Understanding Value Contexts



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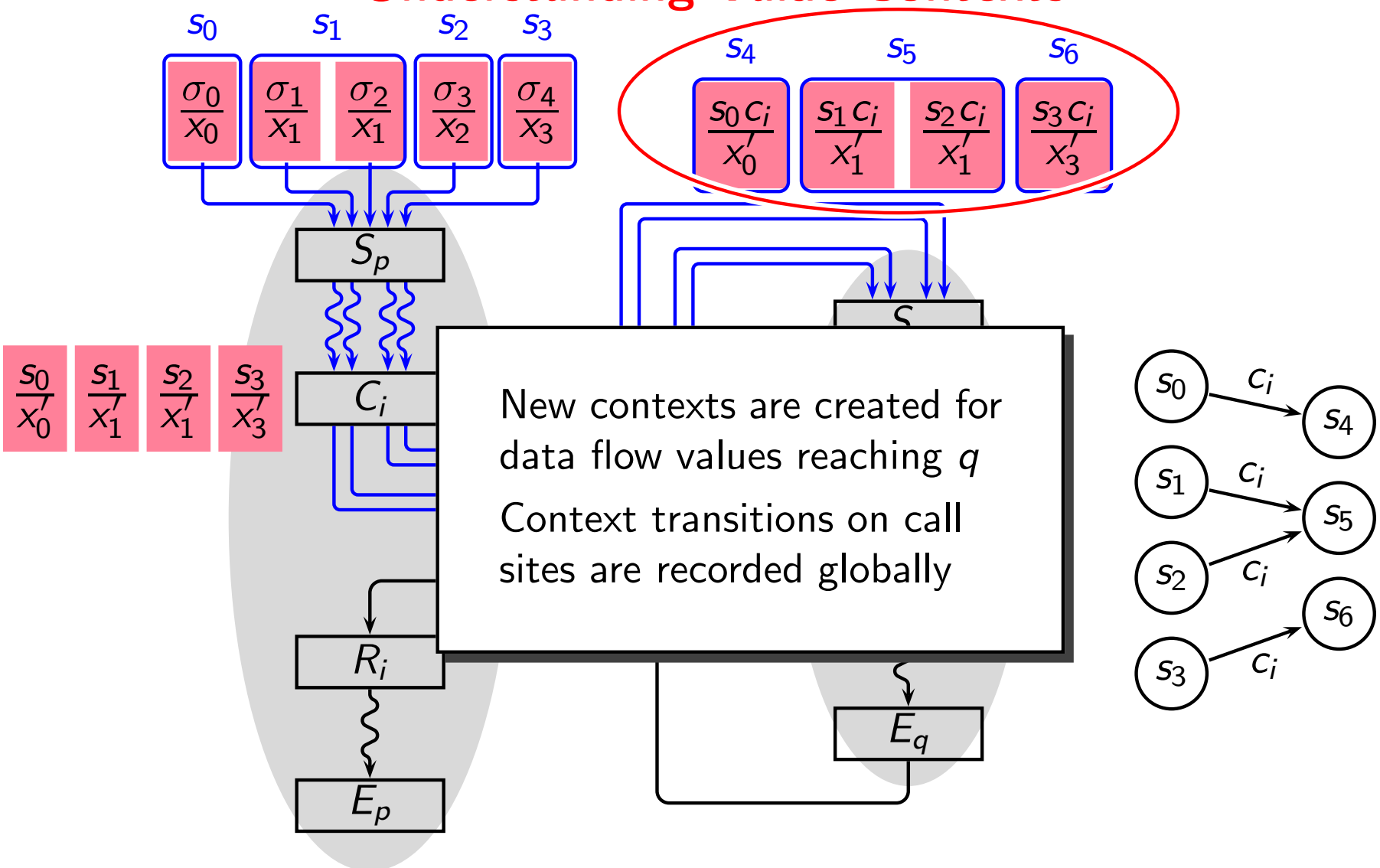

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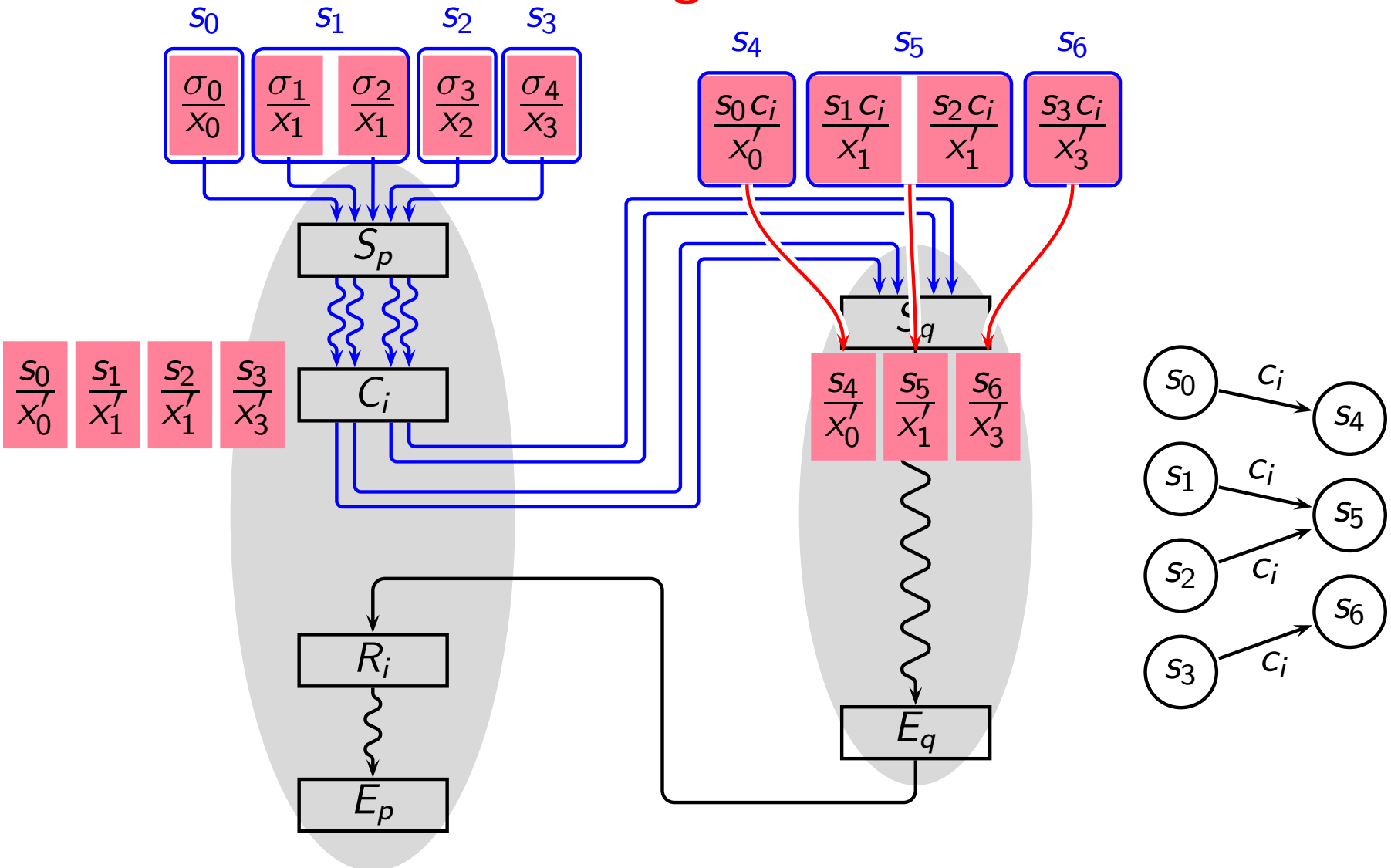

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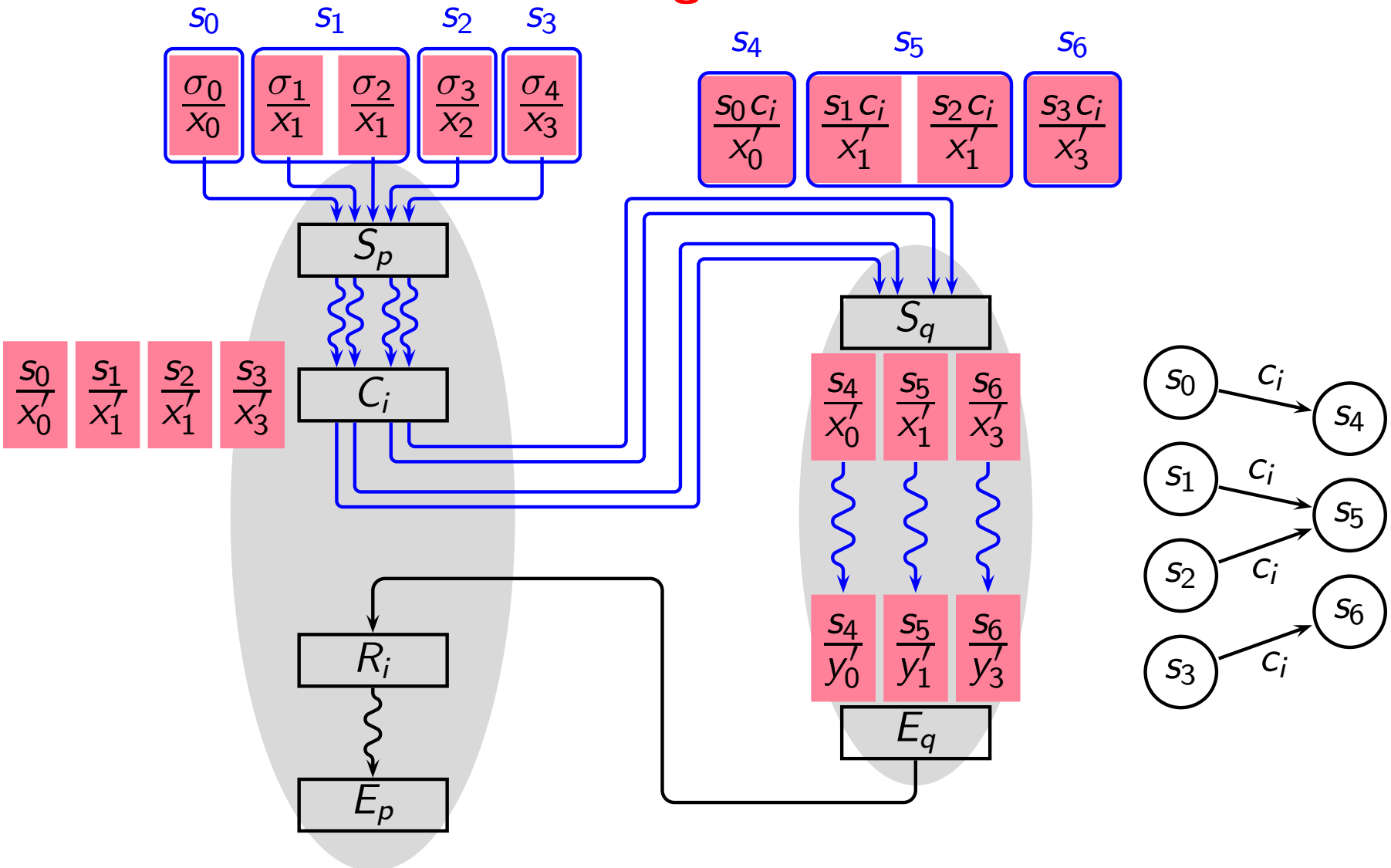

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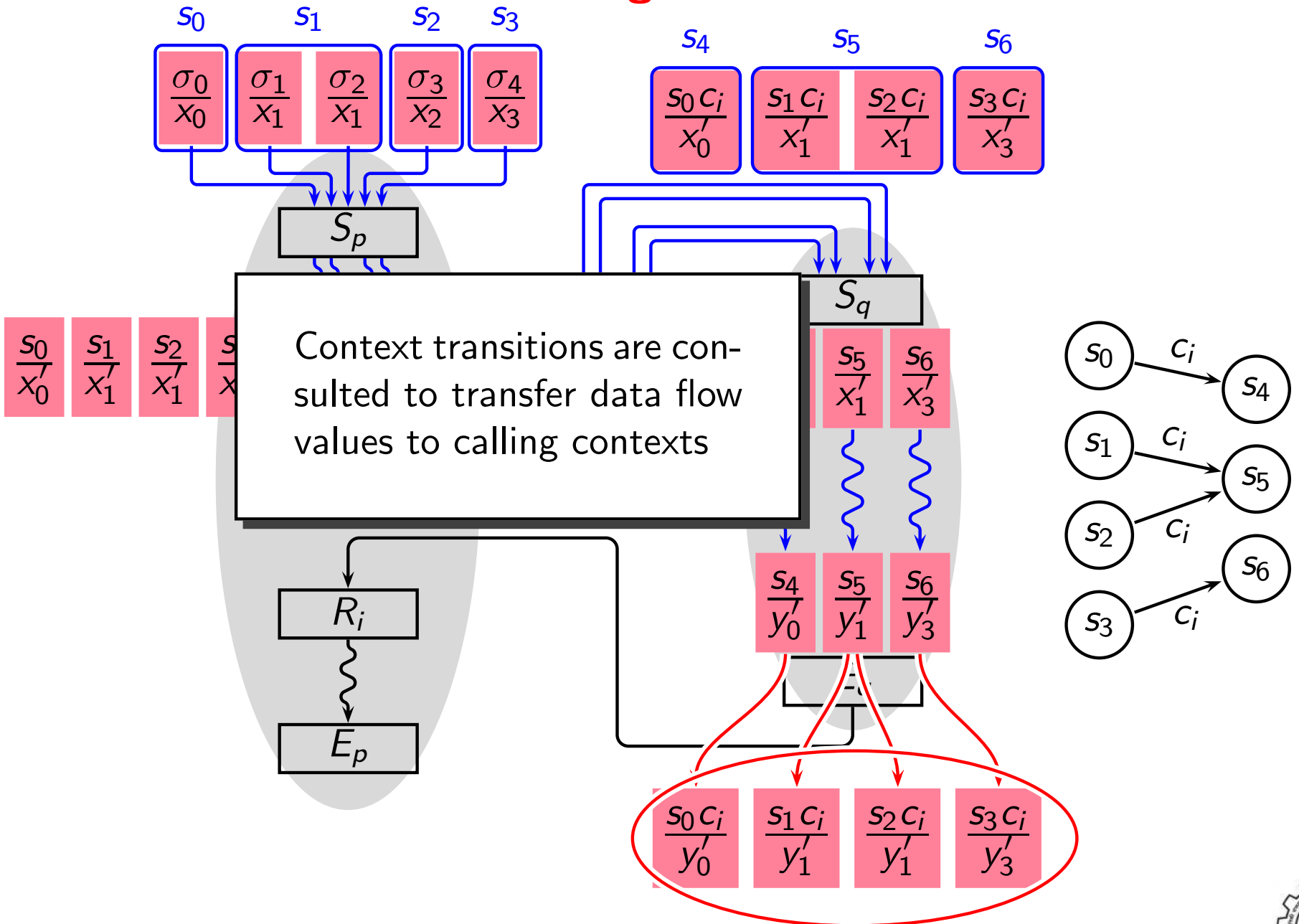

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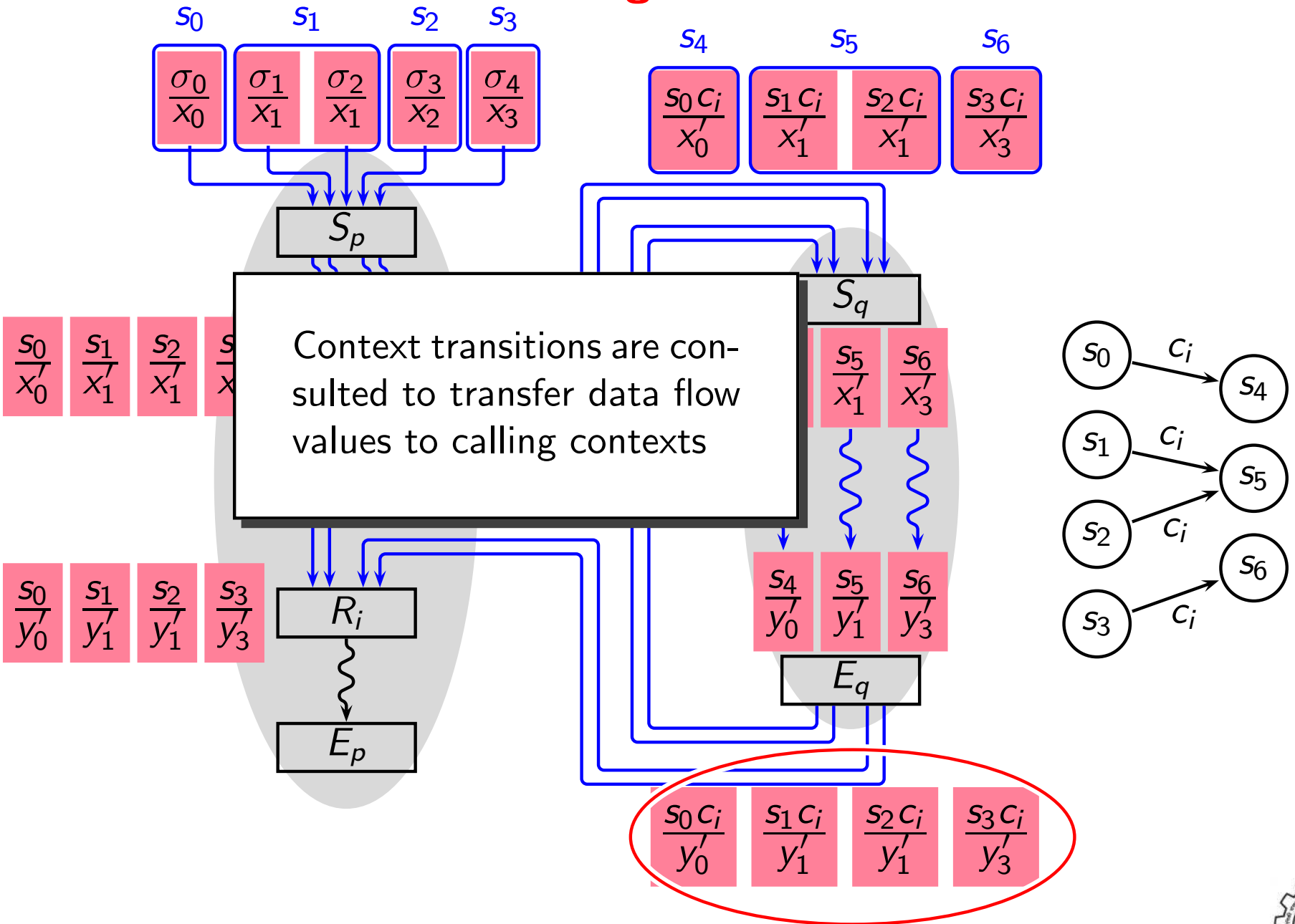

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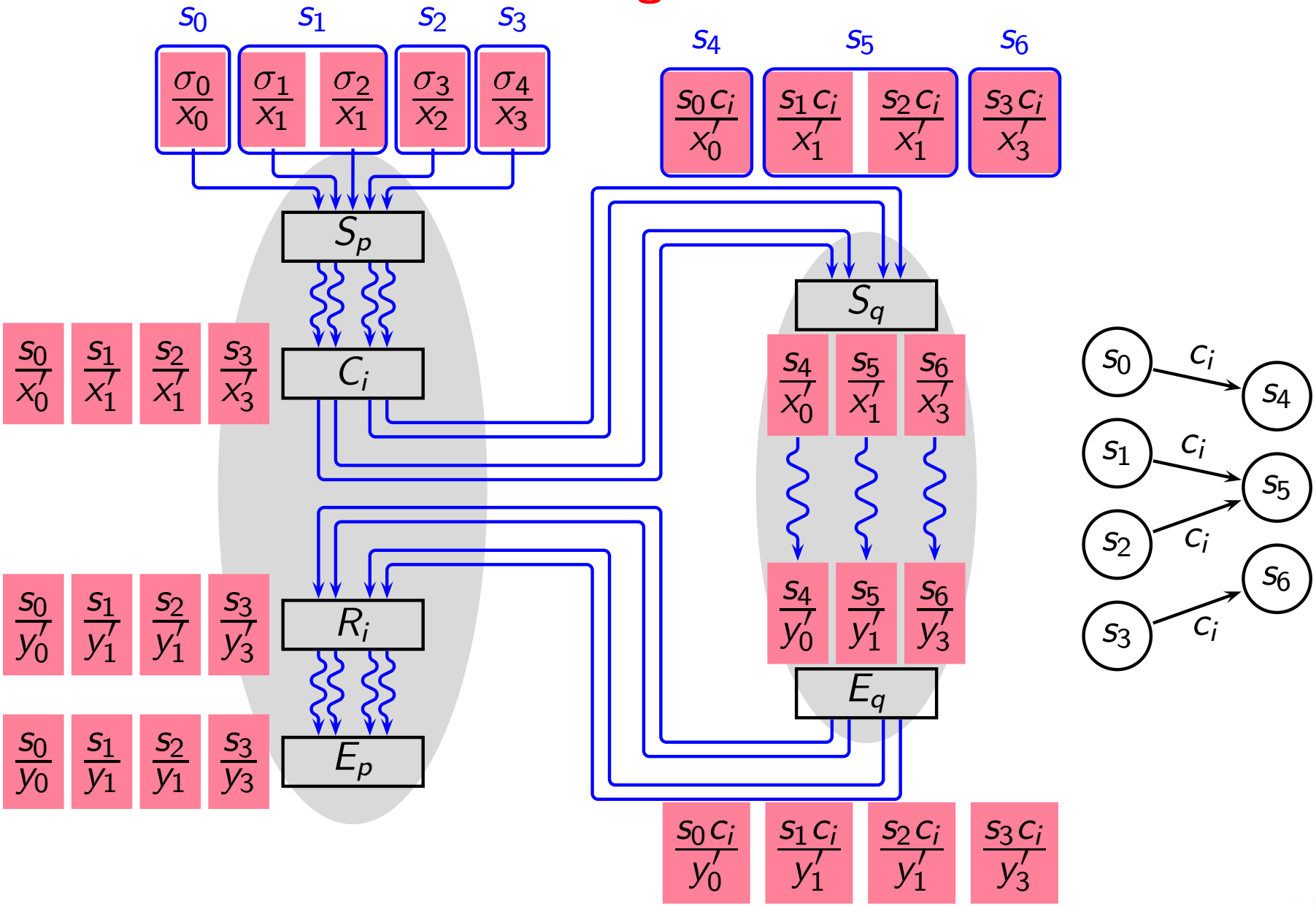

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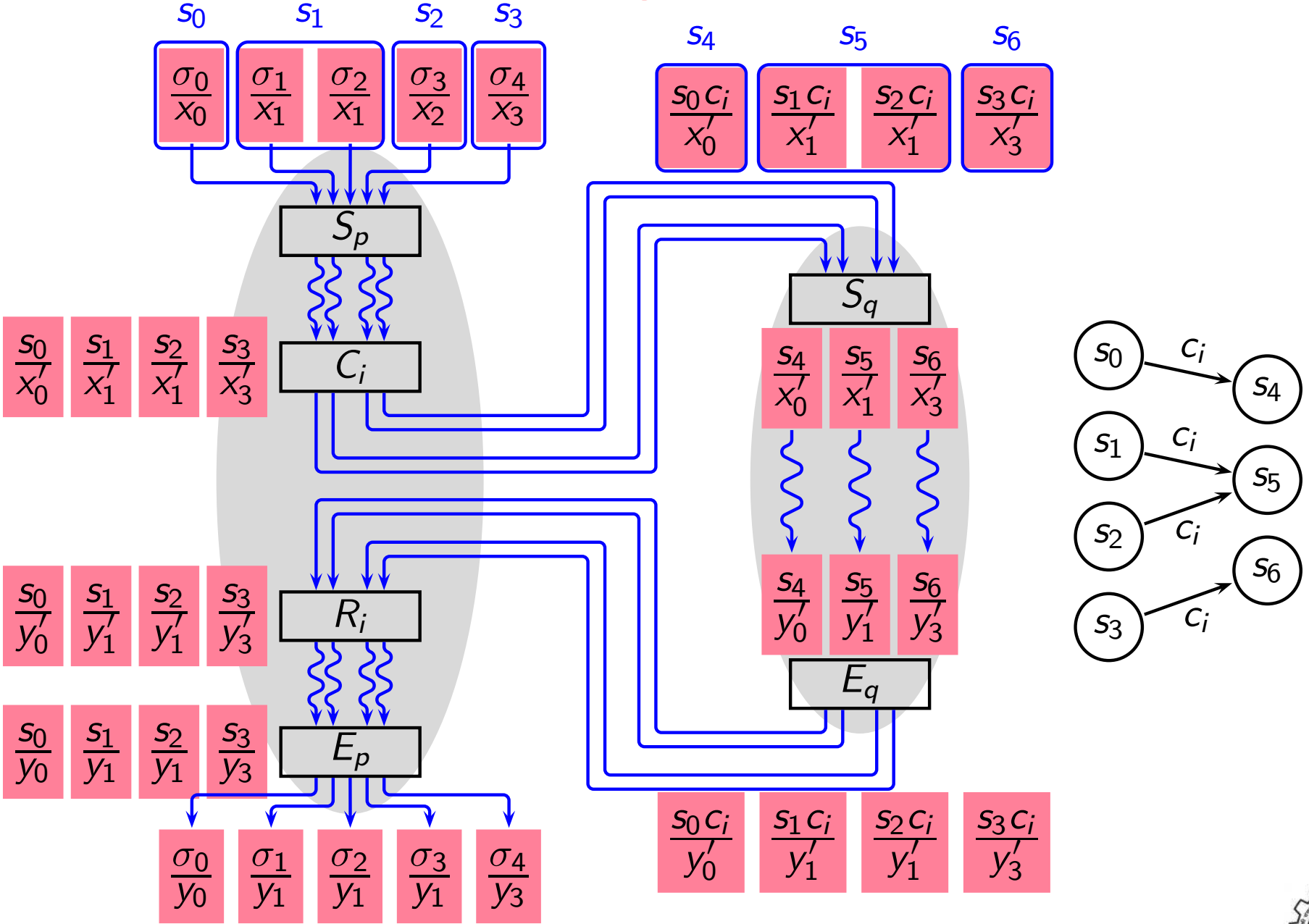

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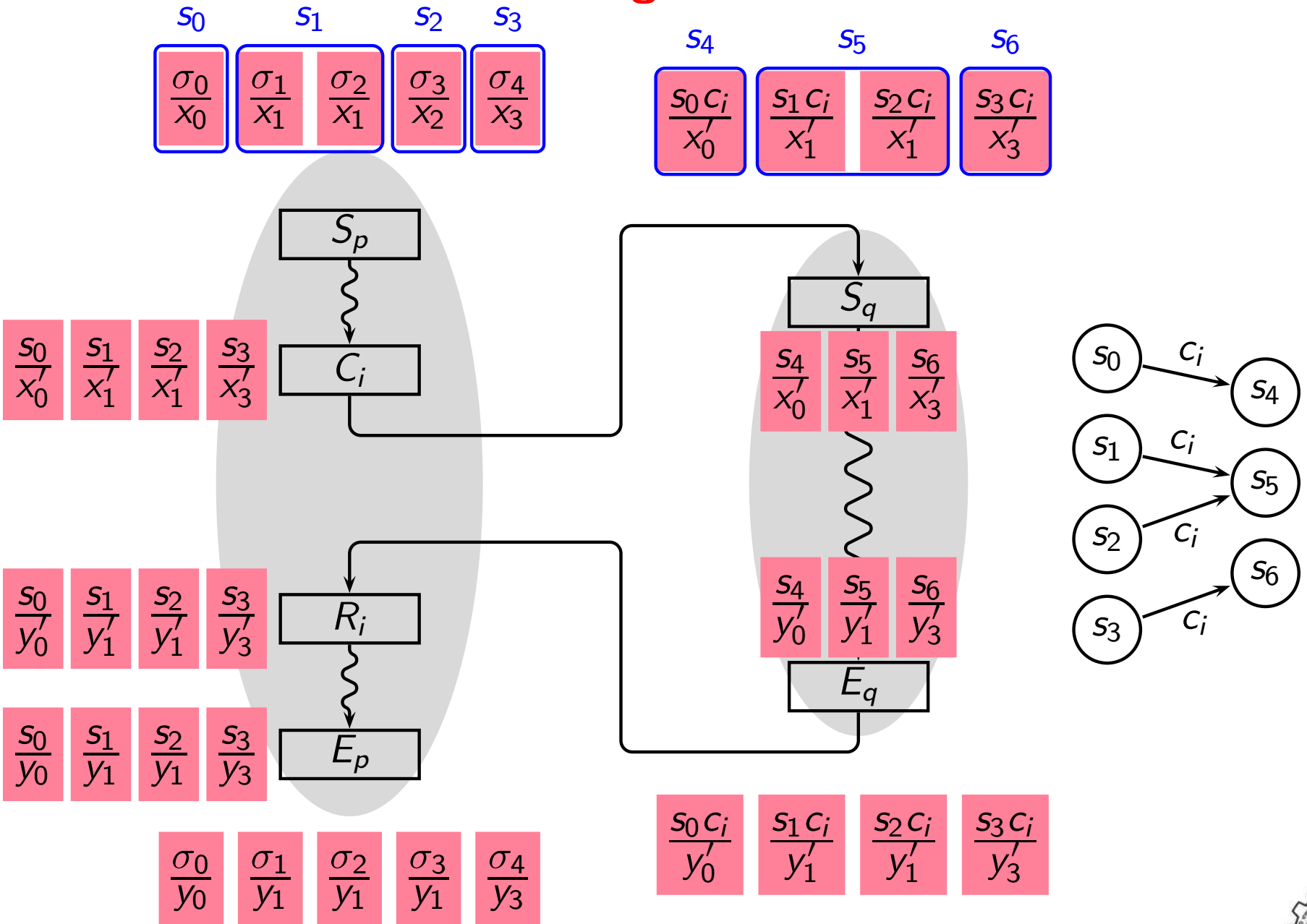

Defining Value Contexts

- The set of value contexts is $VC = Procs \times L$

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  where $proc \in Procs$ and $entryValue \in L$

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  - $exitValue : VC \mapsto L$ eg. $exitValue(X) = v$
  - $transitions : (VC \times CS) \mapsto VC$ eg. $X \xrightarrow{c_i} Y$

Interprocedural Data Flow Analysis Using Value Contexts

- The method works with a collection of control flow graphs

  No need of supergraph

  - No need to distinguish between C_i and R_i
  - No need of call $(C_i \rightarrow S_p)$ and return $(E_p \rightarrow E_i)$ edges

- Maintain a work list WL of entries $\langle context, node \rangle$

  (in reverse post order of nodes within a procedure for forward flows)

- Notation:

$\langle p,v \rangle$	Context for procedure p with data flow value v
$X \vert m$	Work list entry for context X for node m
$X.v$	Data flow value in context X is v
$Out_m[X]$	Data flow value of context X in Out_m
$X \xrightarrow{C_i} Y$	Transition from context X to context Y at call site C_i

Interprocedural Data Flow Analysis Using Value Contexts: An Overview

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  Update WL
- Repeat until WL is empty

Interprocedural Data Flow Analysis Using Value Contexts (2)

Select $X|n$ from WL. Compute In_n. Let $X.v$ be in In_n

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- If $n = C_i$ calling procedure p
  - If some context $\langle p,v \rangle$ exists (say Y) /* p is the callee */
    - record the transition $X \xrightarrow{C_i} Y$
    - $Out_{C_i}[X] = Out_{C_i}[X] \sqcap exitValue(Y)$
    - if there is a change, add $X|m$, $\forall m \in succ(C_i)$ to WL
  - If it does not exist

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Select $X|n$ from WL. Compute In_n. Let $X.v$ be in In_n

- If $n = C_i$ calling procedure p
  - If some context $\langle p,v \rangle$ exists (say Y) /* p is the callee */
  - If it does not exist
    - create a new context $Y = \langle p,v \rangle$ /* p is the callee */
    - initialize $exitValue(Y) = \top$
    - record the transition $X \xrightarrow{C_i} Y$
    - initialize $Out_m[Y] = \top$ for all nodes m of procedure p
    - add entries $Y|m$ for all nodes m of procedure p to WL

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  - Set $exitValue(X) = v$ /* E_p is an empty block */
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- If $n = E_p$
  - Set $exitValue(X) = v$ /* E_p is an empty block */
  - Find out all transitions $Z \xrightarrow{C_j} X$
    - Set $Out_{C_j}[Z] = Out_{C_j}[Z] \sqcap v$
    - If there is a change, add $Z|m$, $\forall m \in succ(C_j)$ to WL
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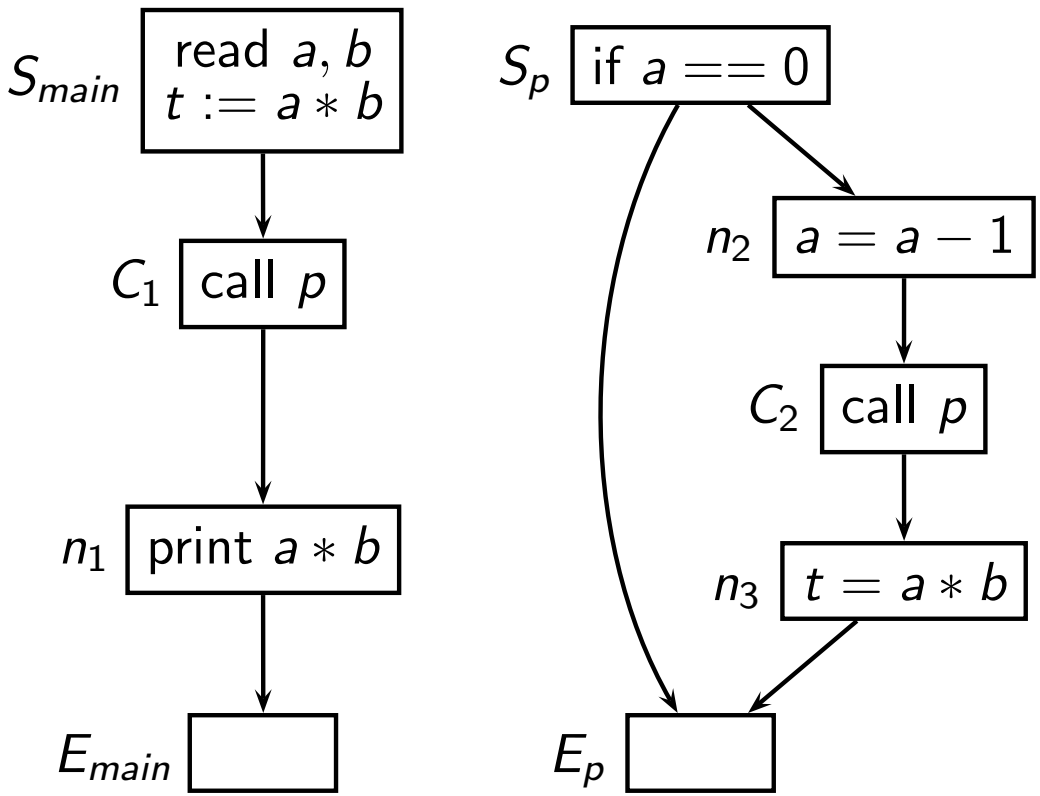
Available Expressions Analysis Using Value Contexts



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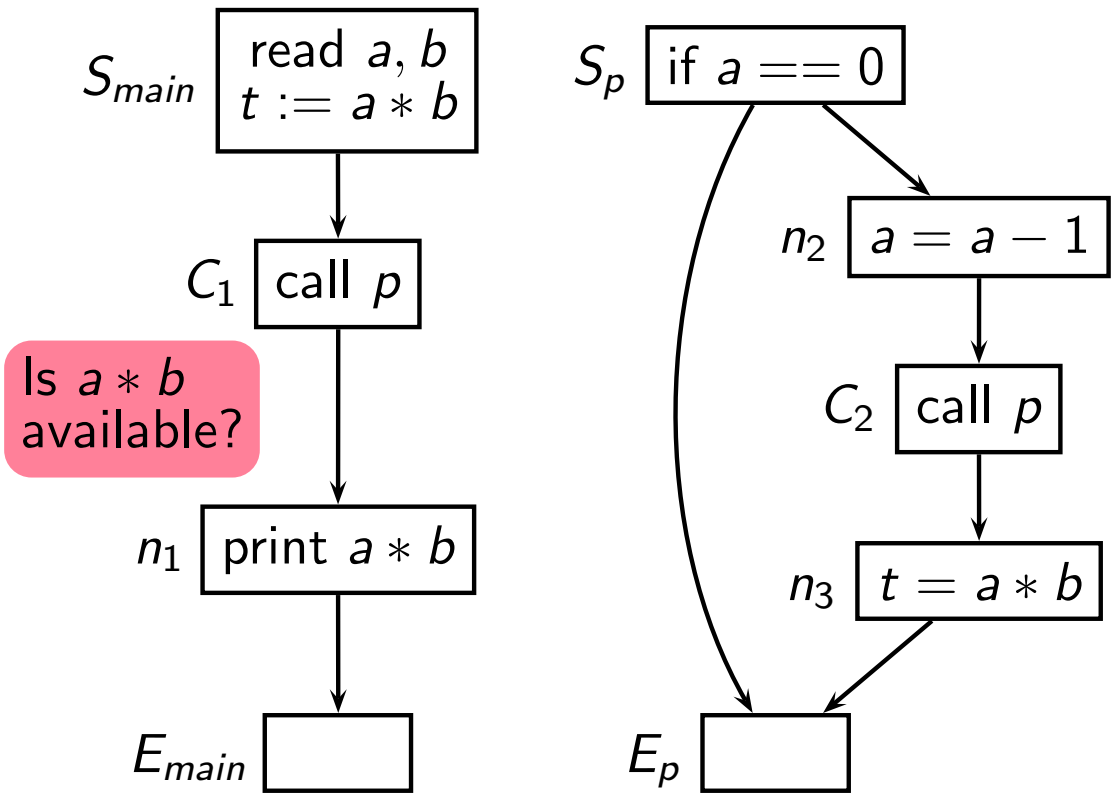

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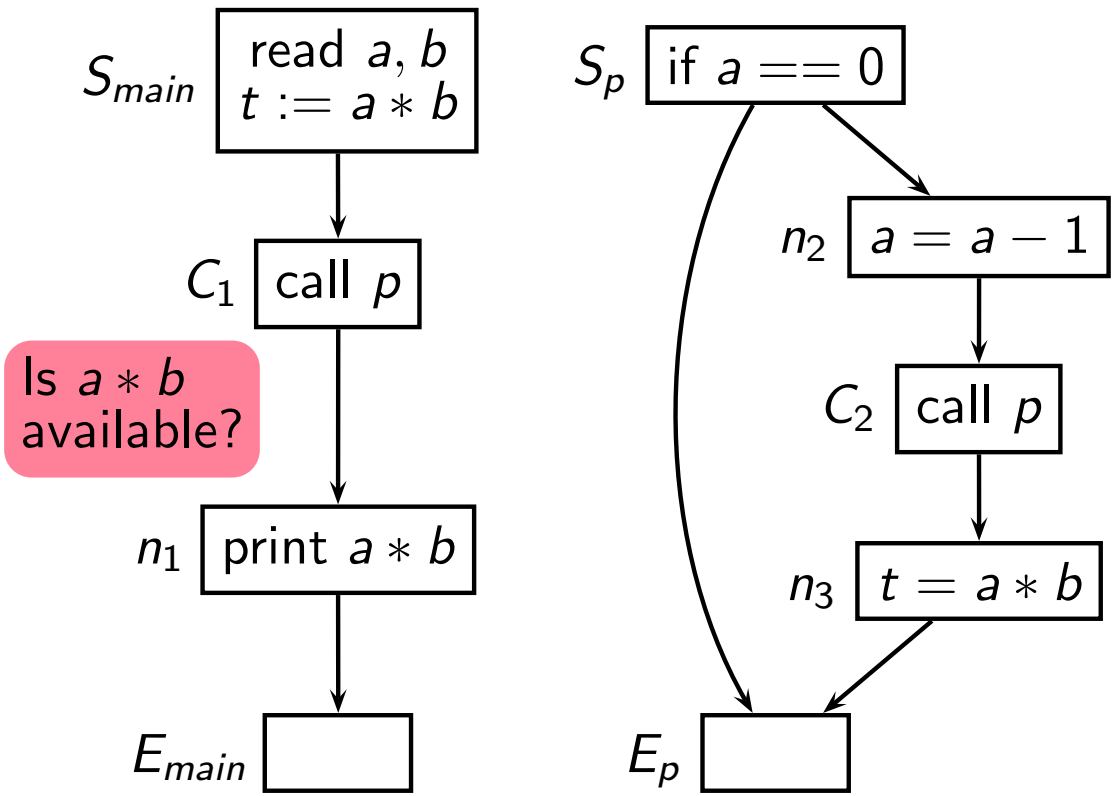


```
int a, b, t;
void p()
{  if (a == 0)
   {  a = a-1;
      p();
      t = a*b;
   }
}
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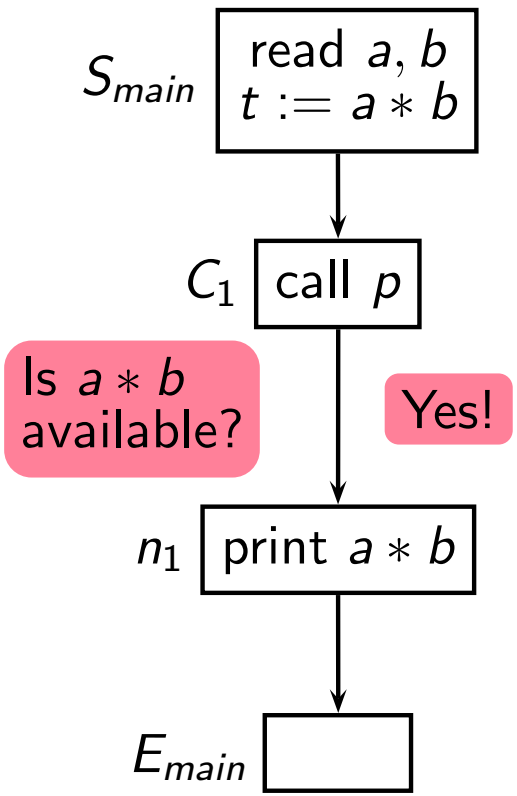
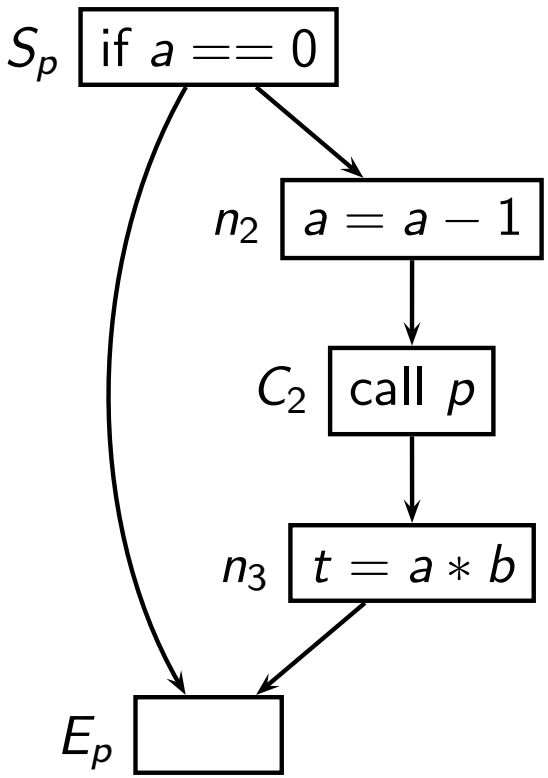
Available Expressions Analysis Using Value Contexts



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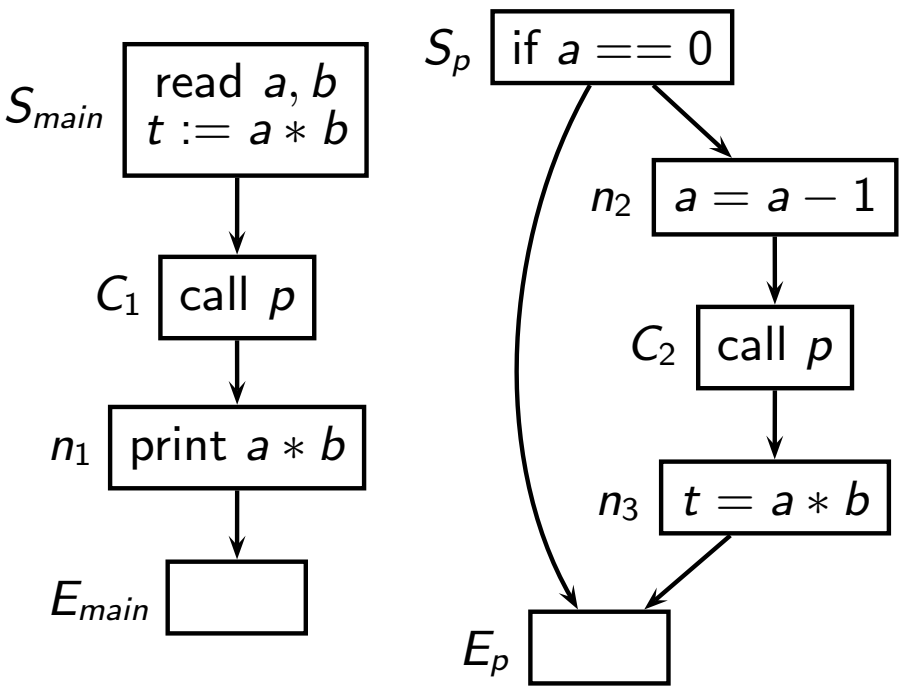

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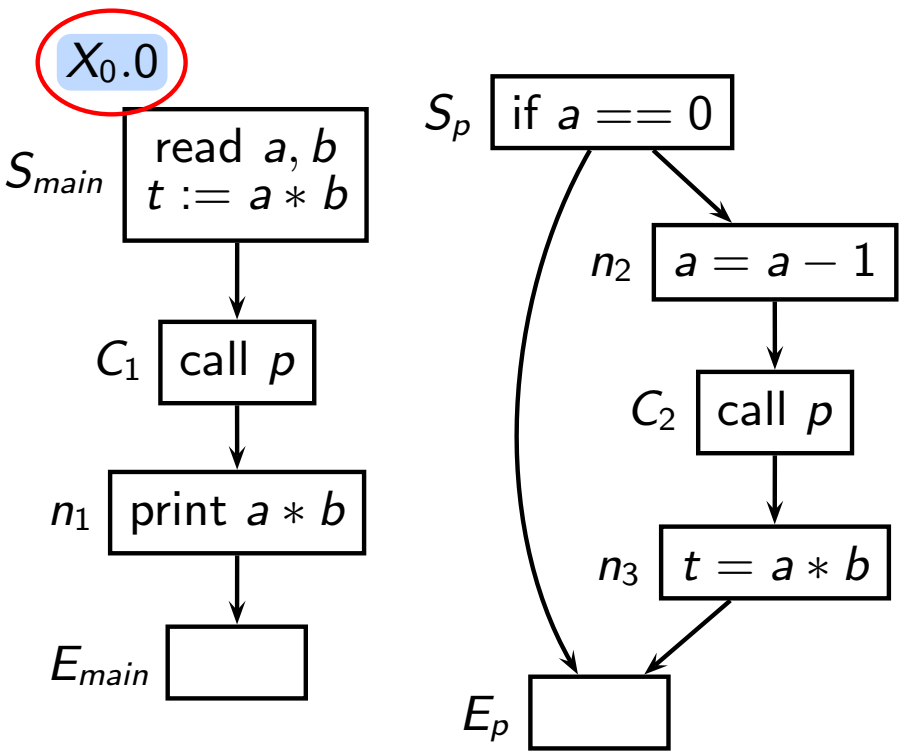
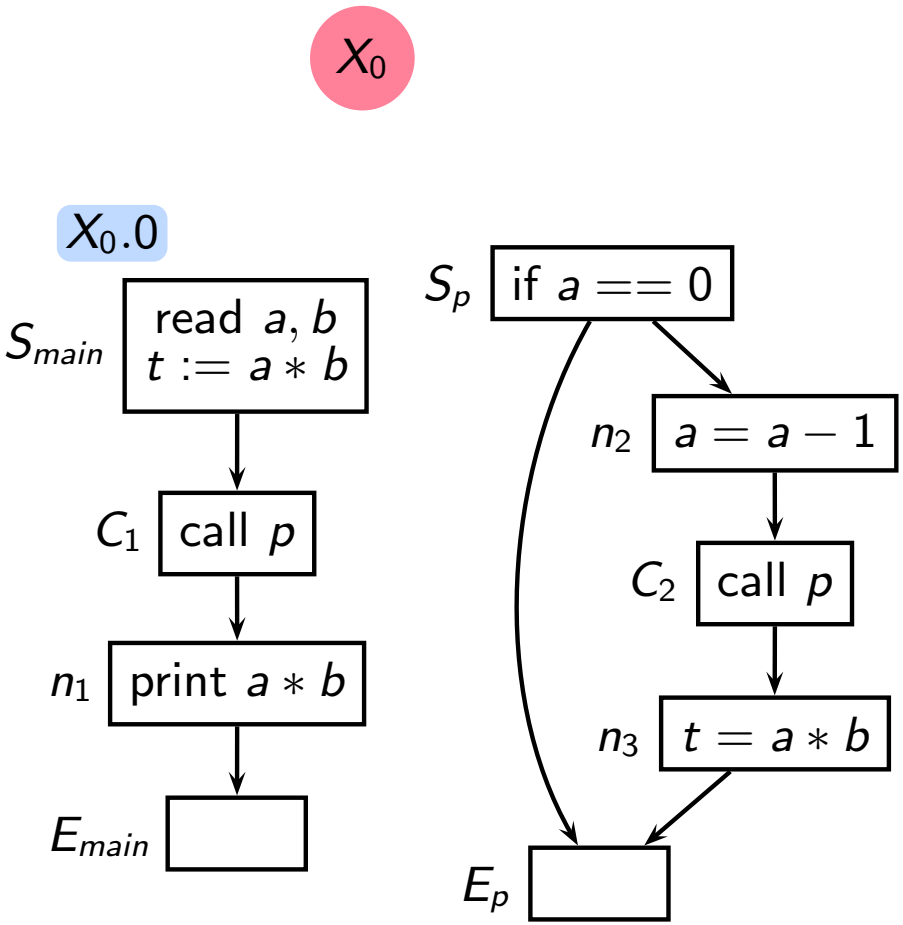


Create a new context X_0 with BI which is 0 for available expressions analysis

Available Expressions Analysis Using Value Contexts

$WL = [X_0|S_m, X_0|C_1, X_0|n_1, X_0|E_m]$



Context	*exitValue*
$X_0 = \langle$main,0$\rangle$	1

Create a new context X_0 with *BI* which is 0 for available expressions analysis

Initialize $exitValue(X_0)$ to $\top = 1$

Initialize the work list with all nodes in procedure main for X_0

Initialize $Out_n[X_0]$ for all n in main to $\top$

Available Expressions Analysis Using Value Contexts

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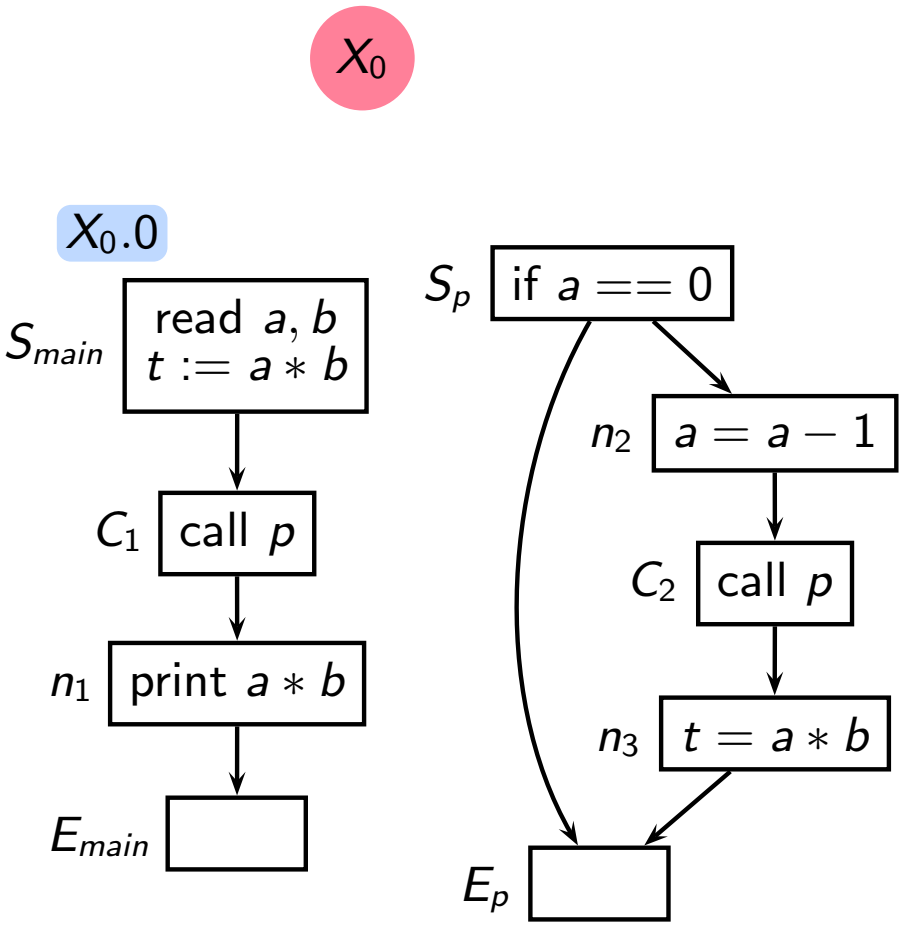

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Compute the data flow values for S_m for context X_0

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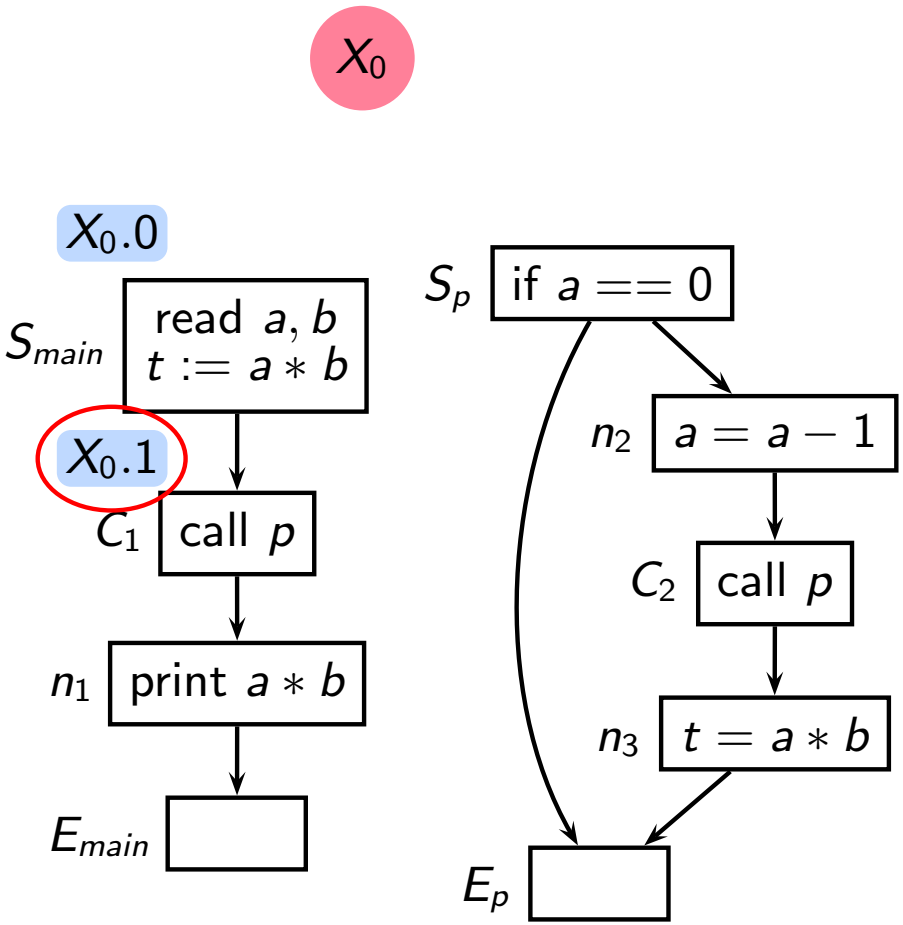

Context	*exitValue*
$X_0 = \langle$main,0$\rangle$	1

Compute the data flow values for S_m for context X_0

It does not change

Available Expressions Analysis Using Value Contexts

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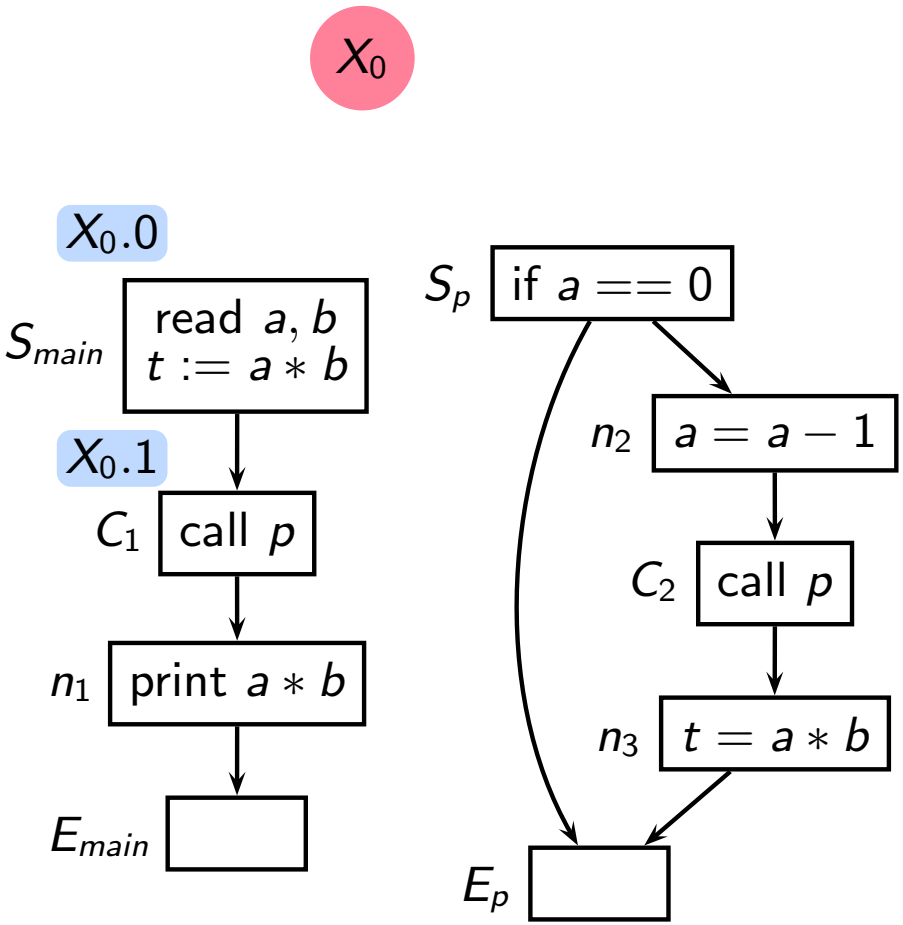
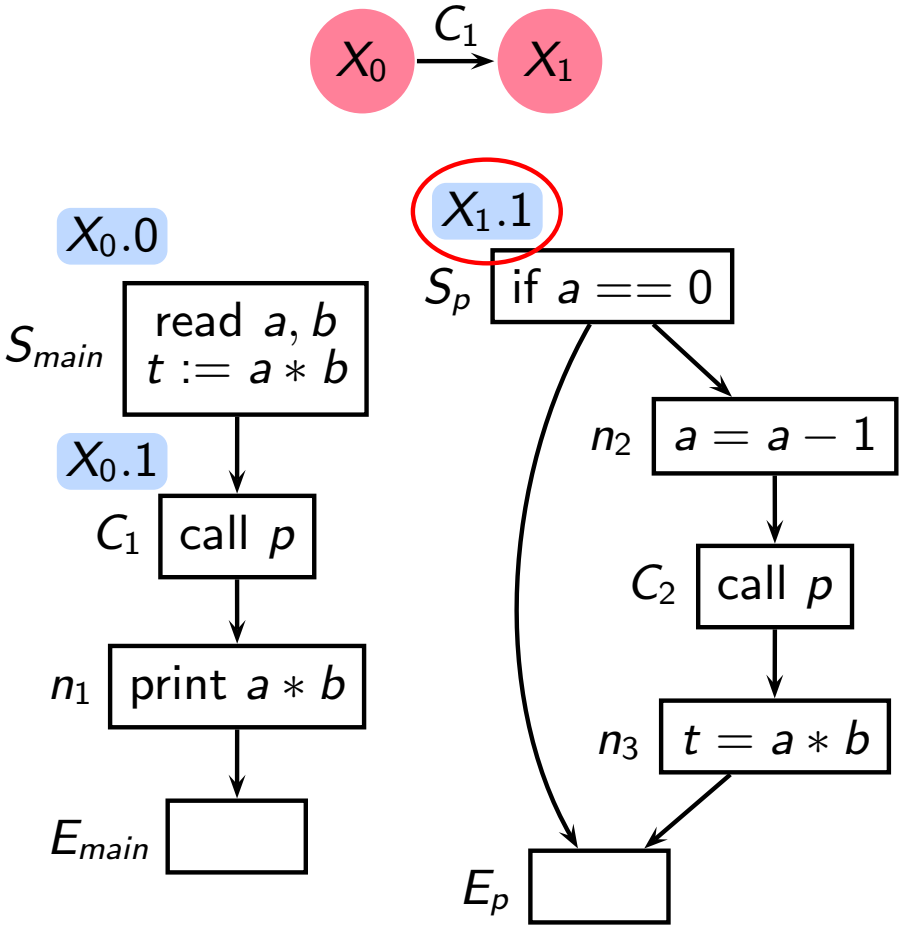


Context	*exitValue*
$X_0 = \langle$main,0$\rangle$	1

Available Expressions Analysis Using Value Contexts

$WL = [X_1|S_p, X_1|n_2, X_1|C_2, X_1|n_3, X_1|E_p, X_0|n_1, X_0|E_m]$



Context	*exitValue*
$X_0 = \langle$main,0$\rangle$	1
$X_1 = \langle$p,1$\rangle$	1

Create a new context X_1 with entry value 1

Record the transition to X_1

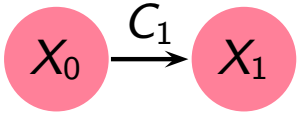
Initialize $exitValue(X_1)$ to $\top = 1$

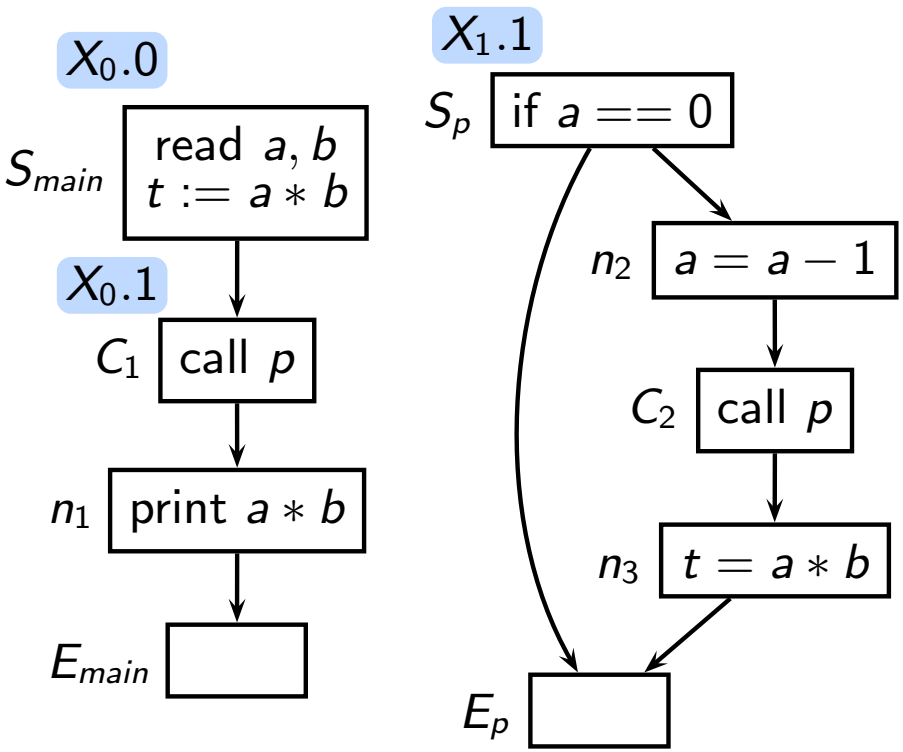
Add all nodes of procedure p to the work list for X_1

Initialize $Out_n[X_1]$ for all n in p to $\top$

Available Expressions Analysis Using Value Contexts

$WL = [X_1|S_p, X_1|n_2, X_1|C_2, X_1|n_3, X_1|E_p, X_0|n_1, X_0|E_m]$

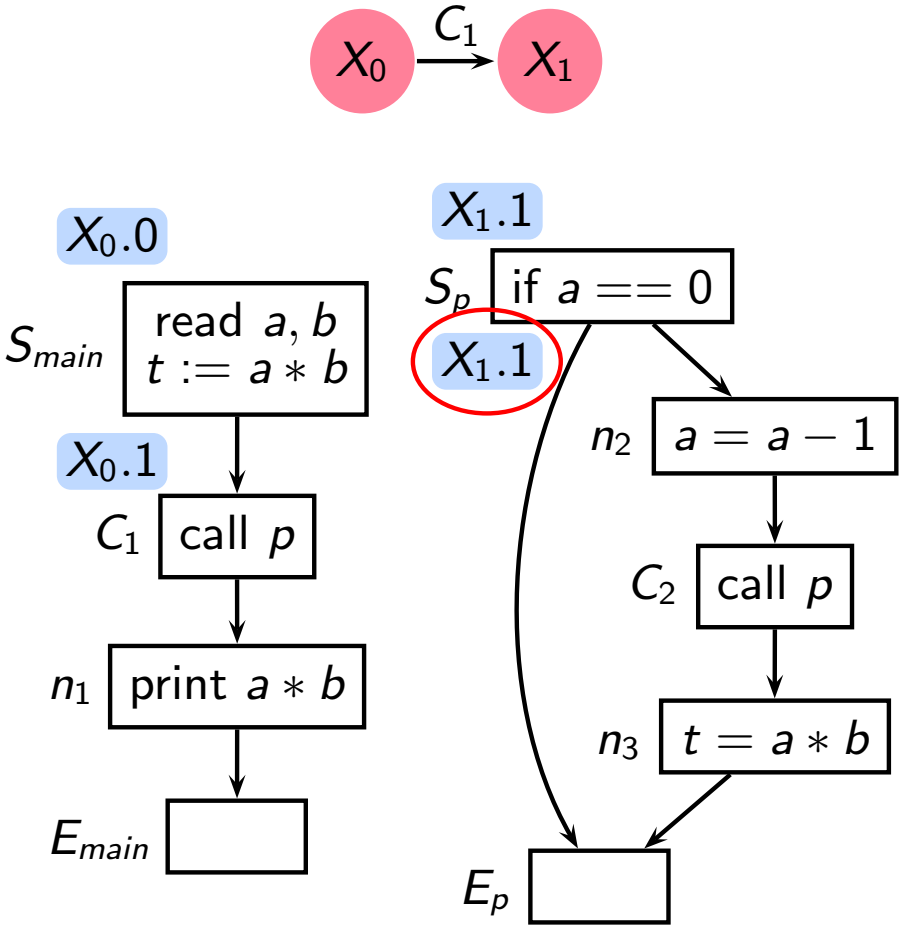




Context	*exitValue*
$X_0 = \langle$main,0$\rangle$	1
$X_1 = \langle$p,1$\rangle$	1

Available Expressions Analysis Using Value Contexts

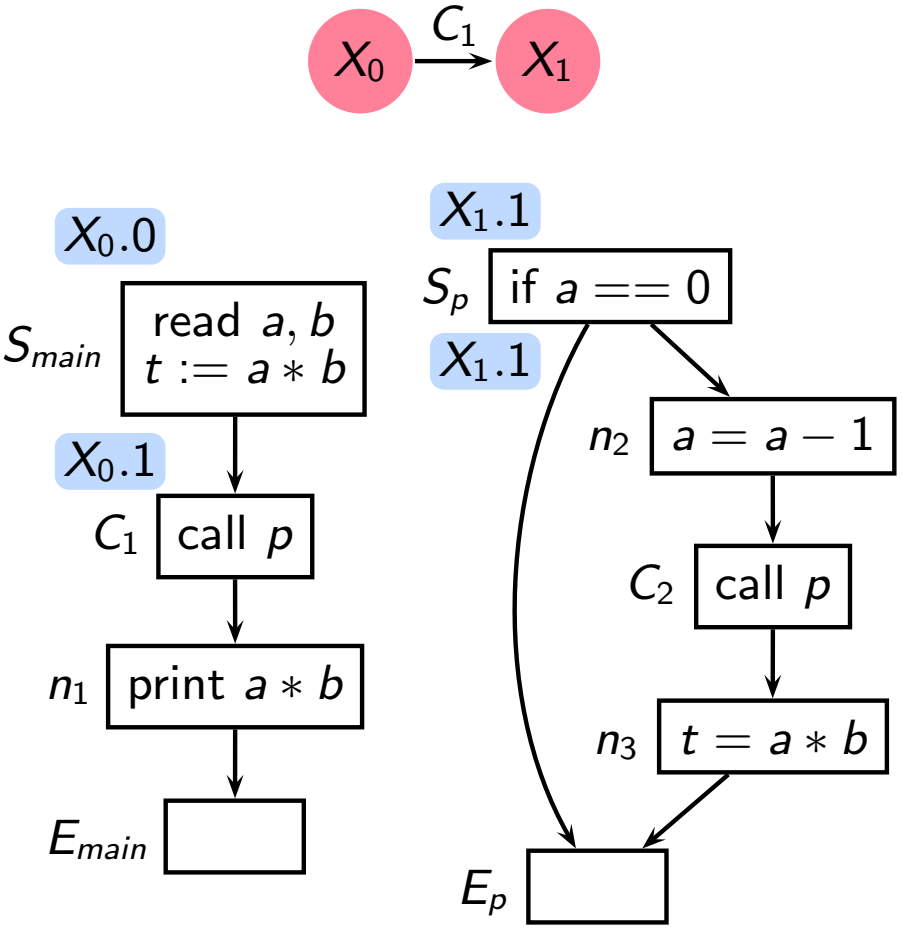
$$WL = [X_1|n_2, X_1|C_2, X_1|n_3, X_1|E_p, X_0|n_1, X_0|E_m]$$



Context	*exitValue*
$X_0 = \langle$main,0$\rangle$	1
$X_1 = \langle$p,1$\rangle$	1

Available Expressions Analysis Using Value Contexts

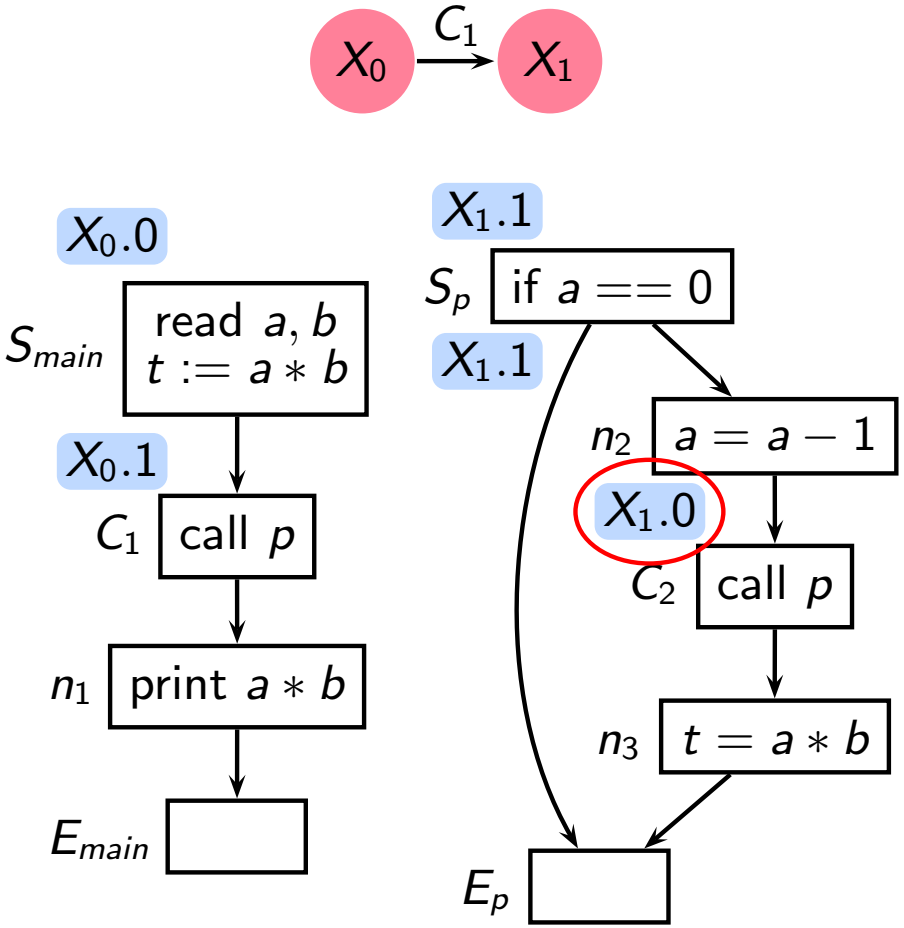
$WL = [X_1|n_2, X_1|C_2, X_1|n_3, X_1|E_p, X_0|n_1, X_0|E_m]$



Context	*exitValue*
$X_0 = \langle$main,0$\rangle$	1
$X_1 = \langle$p,1$\rangle$	1

Available Expressions Analysis Using Value Contexts

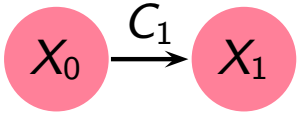
$$WL = [X_1|n_2, X_1|C_2, X_1|n_3, X_1|E_p, X_0|n_1, X_0|E_m]$$

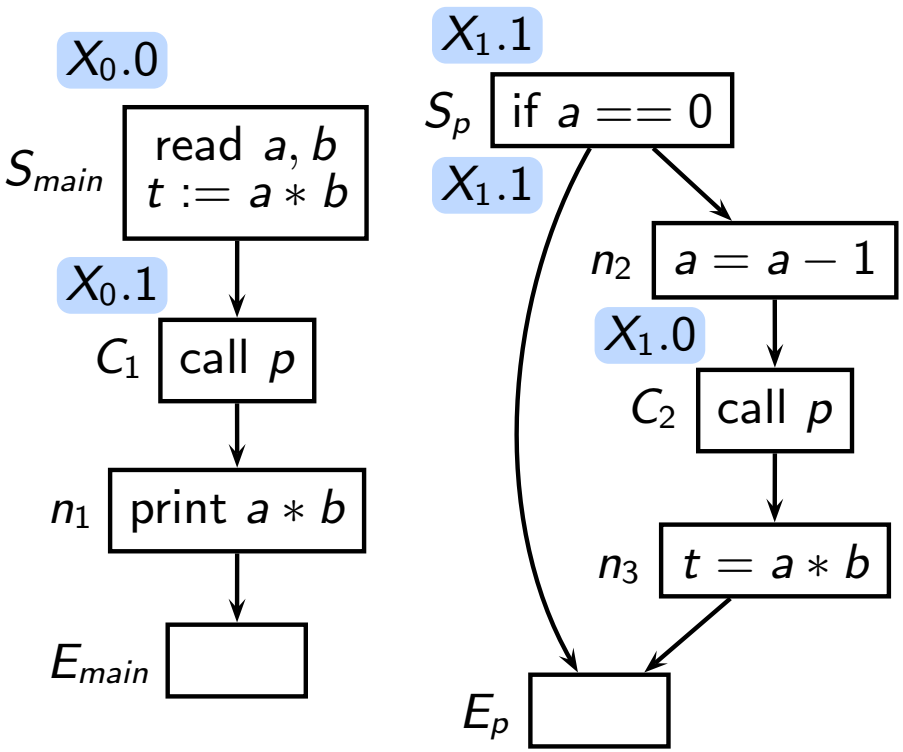


Context	*exitValue*
$X_0 = \langle$main,0$\rangle$	1
$X_1 = \langle$p,1$\rangle$	1

Available Expressions Analysis Using Value Contexts

$WL = [X_1|C_2, X_1|n_3, X_1|E_p, X_0|n_1, X_0|E_m]$

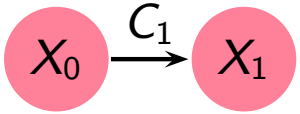


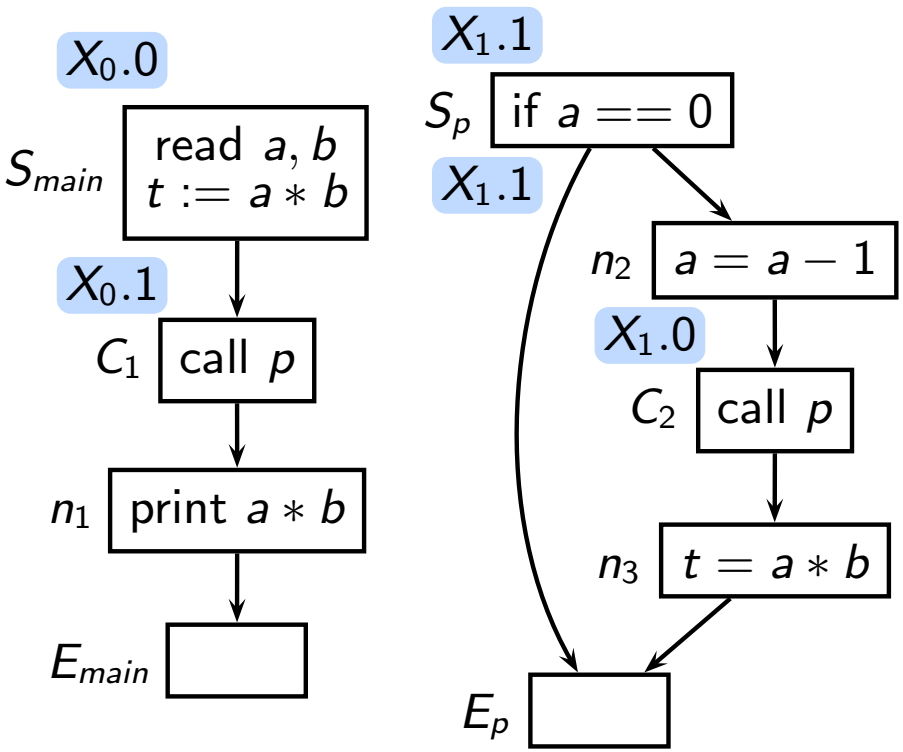


Context	*exitValue*
$X_0 = \langle$main,0$\rangle$	1
$X_1 = \langle$p,1$\rangle$	1

Available Expressions Analysis Using Value Contexts

$WL = [X_1|C_2, X_1|n_3, X_1|E_p, X_0|n_1, X_0|E_m]$

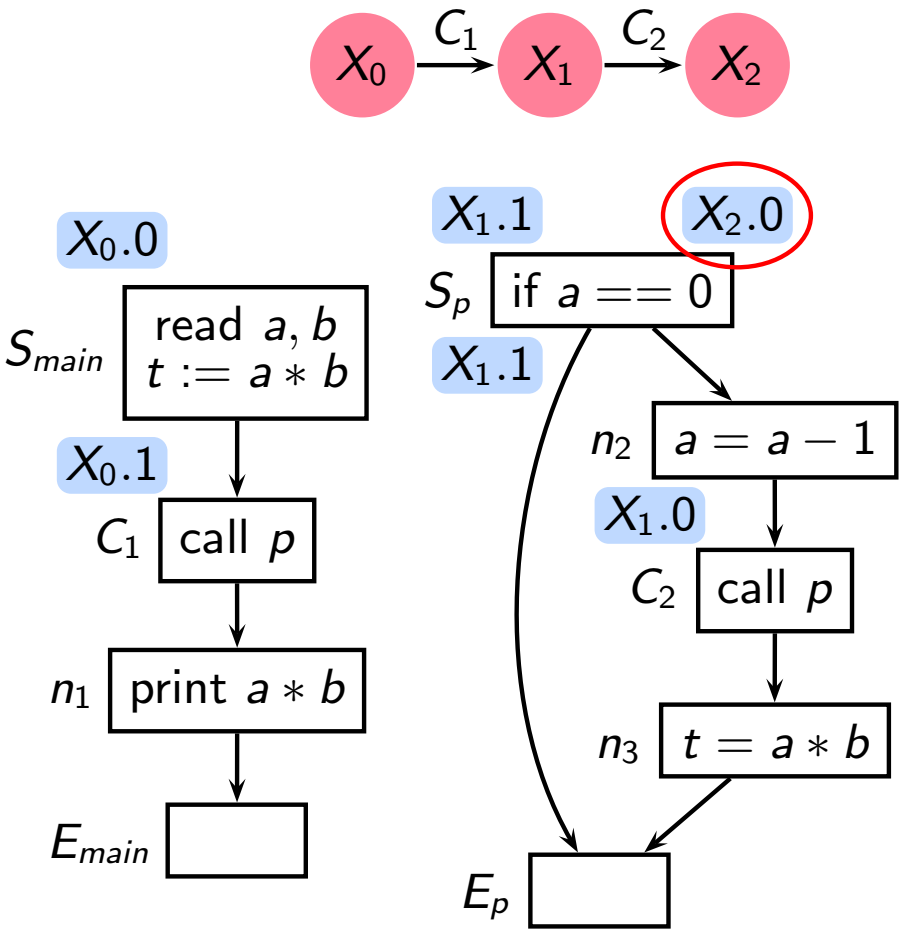




Context	*exitValue*
$X_0 = \langle$main,0$\rangle$	1
$X_1 = \langle$p,1$\rangle$	1

Available Expressions Analysis Using Value Contexts

$WL = [X_1|C_2, X_1|n_3, X_1|E_p, X_0|n_1, X_0|E_m]$



Context	*exitValue*
$X_0 = \langle$main,0$\rangle$	1
$X_1 = \langle$p,1$\rangle$	1
$X_2 = \langle$p,0$\rangle$	1

Since there is no context for p with value 0, create context X_2

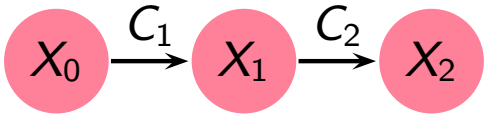
Record the transition to X_2

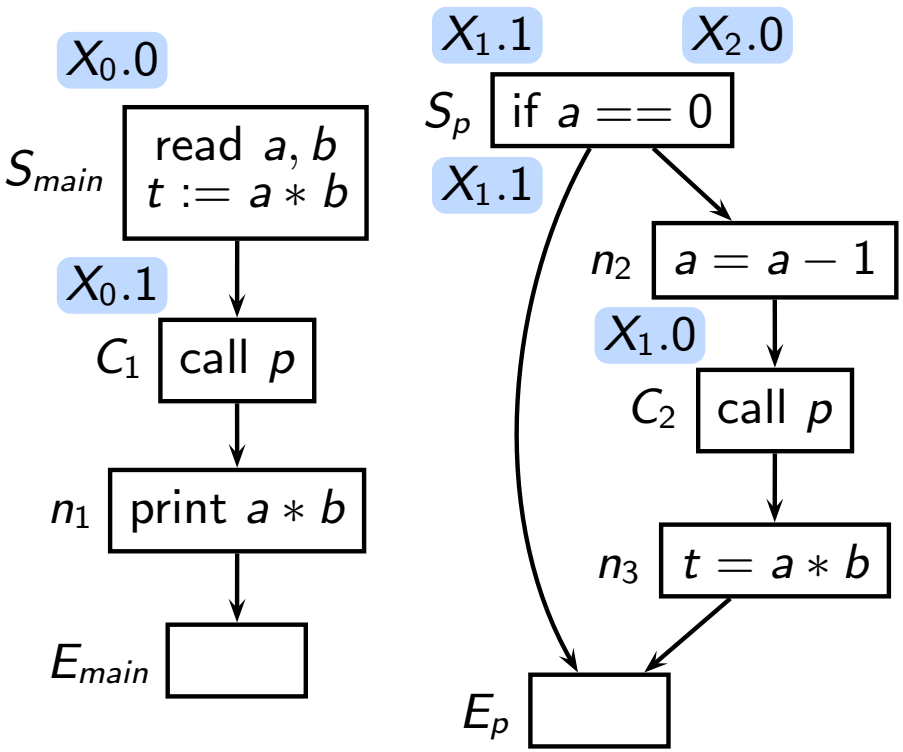
Initialize $exitValue(X_2)$ to $\top = 1$

Add all nodes of procedure p to the work list for X_2 Initialize $Out_n[X_2]$ for all n in p to $\top$

Available Expressions Analysis Using Value Contexts

$$WL = [X_2|S_p, X_2|n_2, X_2|C_2, X_2|n_3, X_2|E_p, X_1|n_3, X_1|E_p, X_0|n_1, X_0|E_m]$$

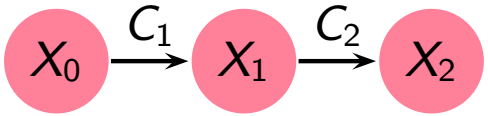


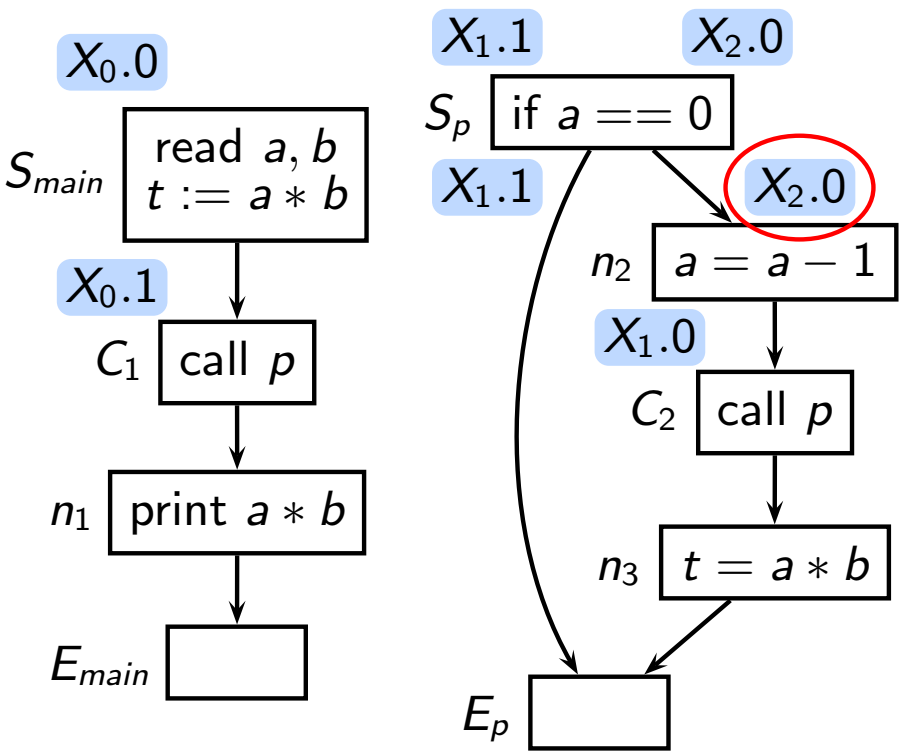


Context	*exitValue*
$X_0 = \langle$main,0$\rangle$	1
$X_1 = \langle$p,1$\rangle$	1
$X_2 = \langle$p,0$\rangle$	1

Available Expressions Analysis Using Value Contexts

$$WL = [X_2|S_p, X_2|n_2, X_2|C_2, X_2|n_3, X_2|E_p, X_1|n_3, X_1|E_p, X_0|n_1, X_0|E_m]$$

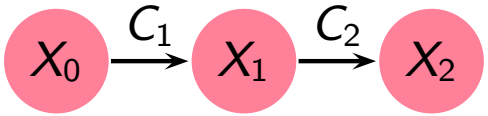


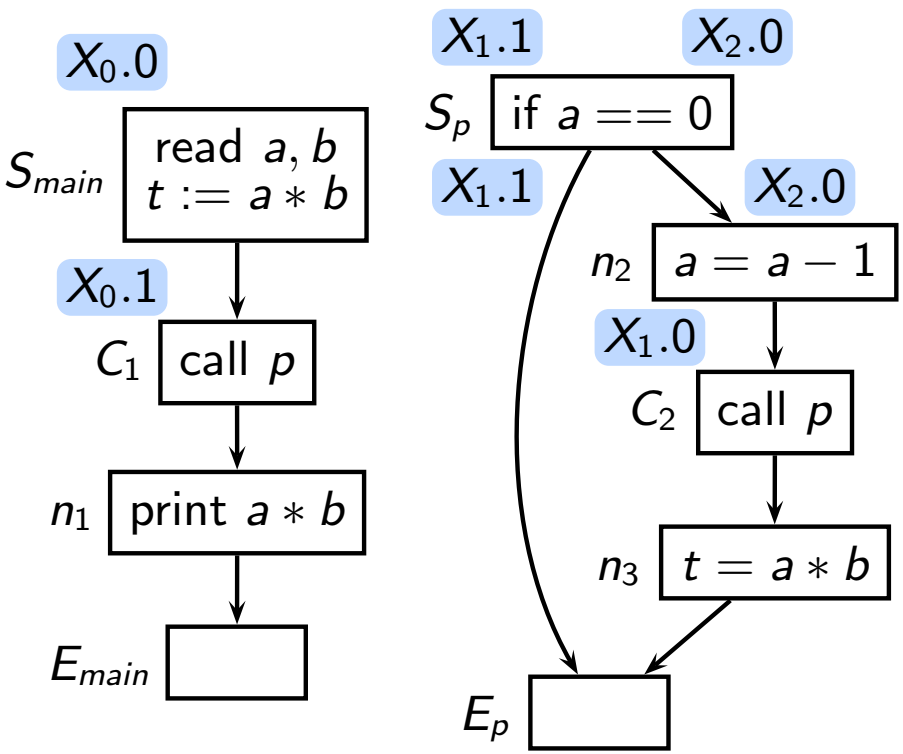


Context	*exitValue*
$X_0 = \langle$main,0$\rangle$	1
$X_1 = \langle$p,1$\rangle$	1
$X_2 = \langle$p,0$\rangle$	1

Available Expressions Analysis Using Value Contexts

$$WL = [X_2|n_2, X_2|C_2, X_2|n_3, X_2|E_p, X_1|n_3, X_1|E_p, X_0|n_1, X_0|E_m]$$

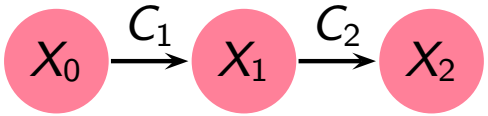


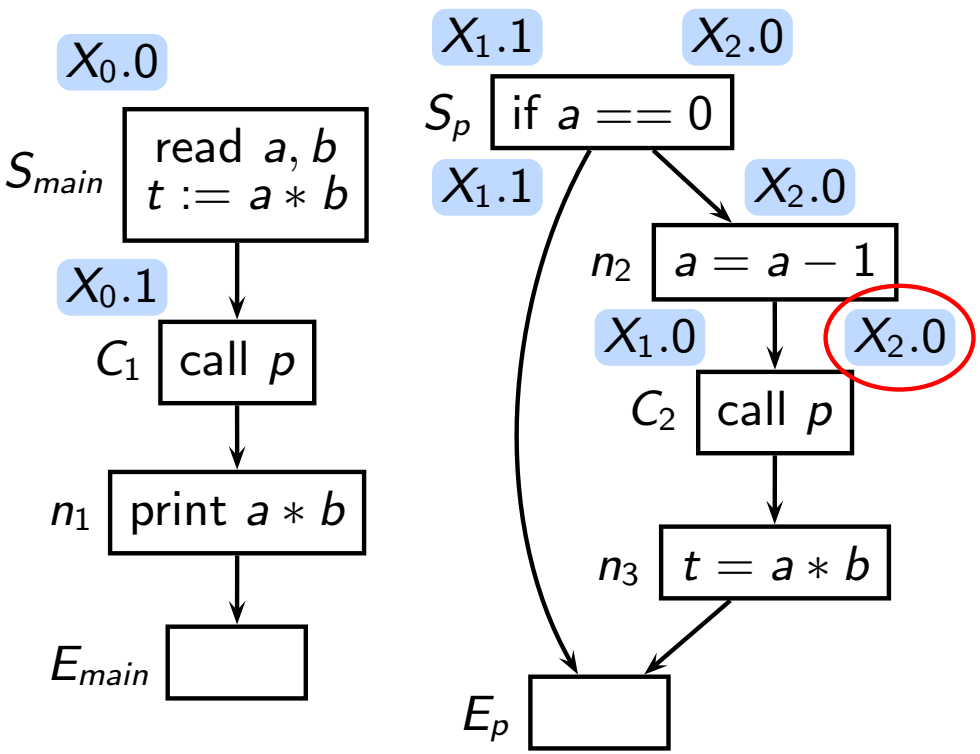


Context	*exitValue*
$X_0 = \langle$main,0$\rangle$	1
$X_1 = \langle$p,1$\rangle$	1
$X_2 = \langle$p,0$\rangle$	1

Available Expressions Analysis Using Value Contexts

$$WL = [X_2|n_2, X_2|C_2, X_2|n_3, X_2|E_p, X_1|n_3, X_1|E_p, X_0|n_1, X_0|E_m]$$

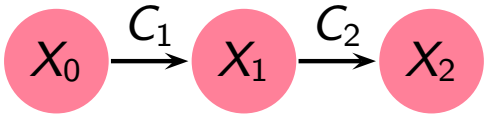


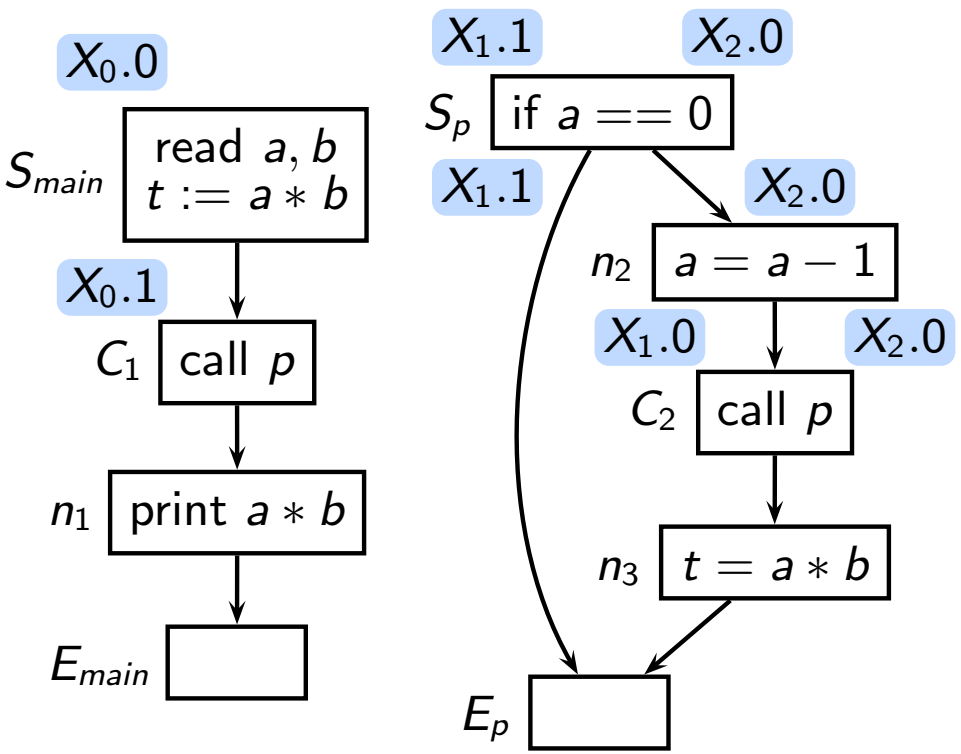


Context	*exitValue*
$X_0 = \langle$main,0$\rangle$	1
$X_1 = \langle$p,1$\rangle$	1
$X_2 = \langle$p,0$\rangle$	1

Available Expressions Analysis Using Value Contexts

$WL = [X_2|C_2, X_2|n_3, X_2|E_p, X_1|n_3, X_1|E_p, X_0|n_1, X_0|E_m]$

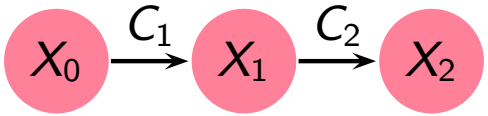


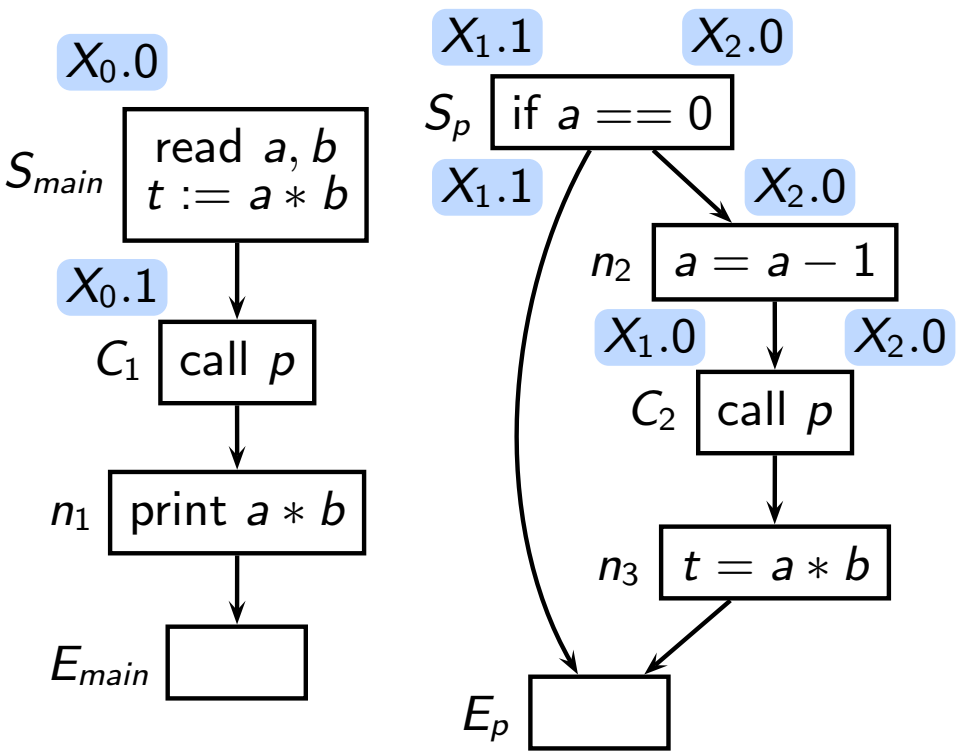


Context	*exitValue*
$X_0 = \langle$main,0$\rangle$	1
$X_1 = \langle$p,1$\rangle$	1
$X_2 = \langle$p,0$\rangle$	1

Available Expressions Analysis Using Value Contexts

$WL = [X_2|C_2, X_2|n_3, X_2|E_p, X_1|n_3, X_1|E_p, X_0|n_1, X_0|E_m]$



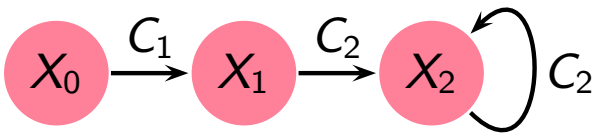


Context	*exitValue*
$X_0 = \langle$main,0$\rangle$	1
$X_1 = \langle$p,1$\rangle$	1
$X_2 = \langle$p,0$\rangle$	1

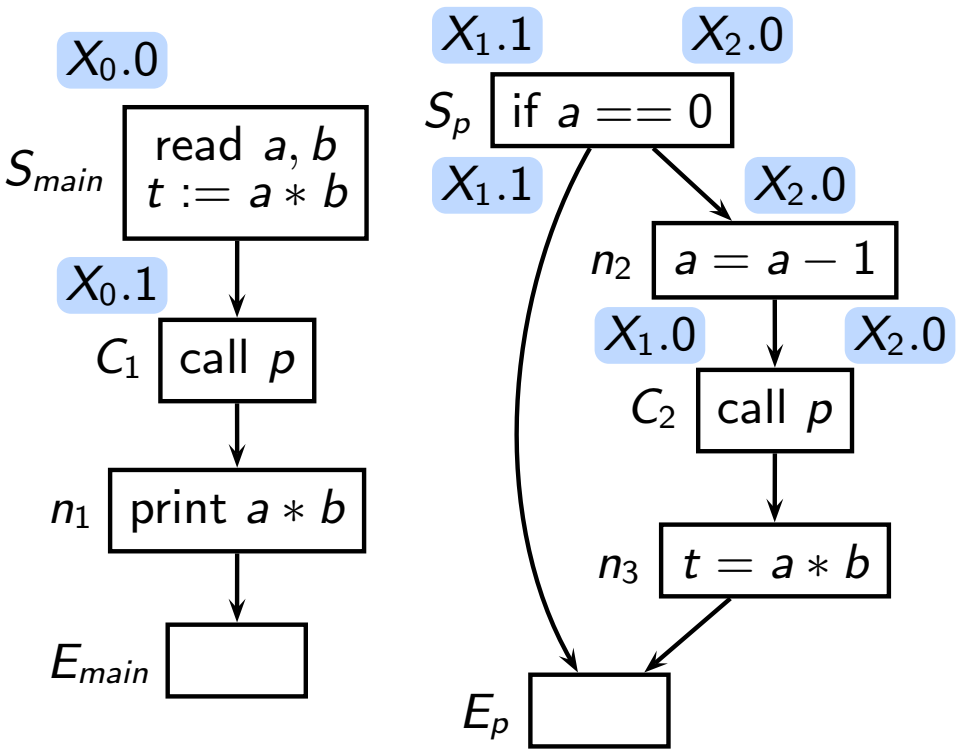
p has context X_2 with value 0 so no need to create a new context

Available Expressions Analysis Using Value Contexts

$WL = [X_2|C_2, X_2|n_3, X_2|E_p, X_1|n_3, X_1|E_p, X_0|n_1, X_0|E_m]$



Context	*exitValue*
$X_0 = \langle \text{main},0 \rangle$	1
$X_1 = \langle \text{p},1 \rangle$	1
$X_2 = \langle \text{p},0 \rangle$	1

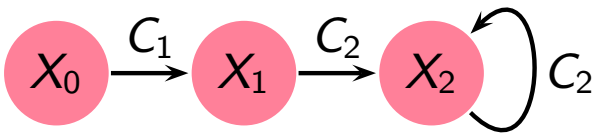


p has context X_2 with value 0 so no need to create a new context

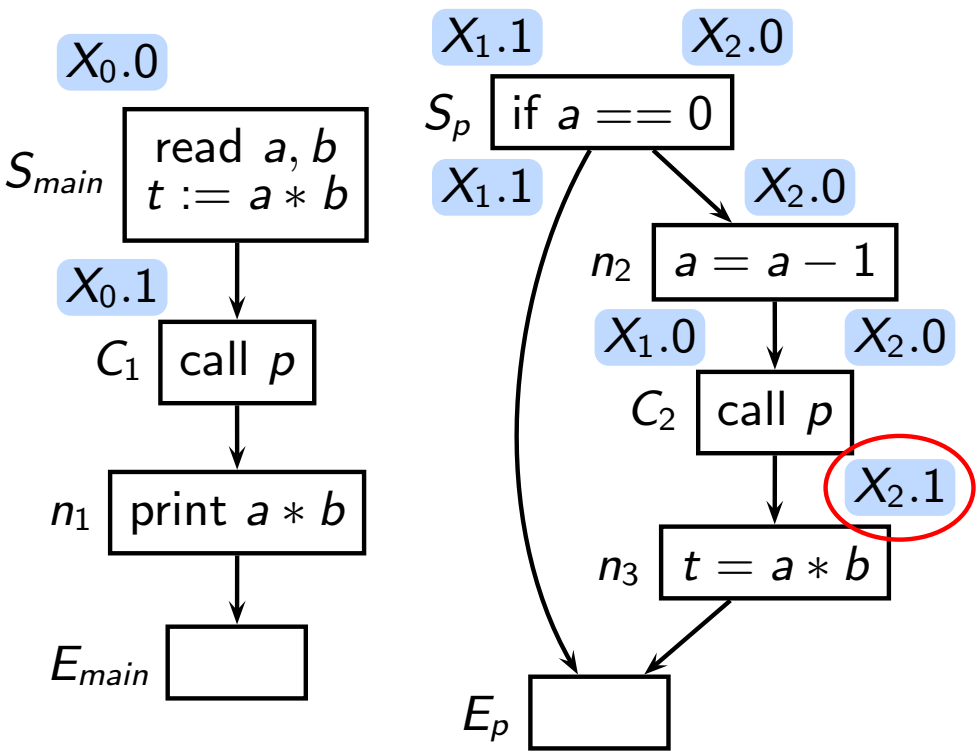
Record the transition from context X_2 to itself

Available Expressions Analysis Using Value Contexts

$$WL = [X_2|C_2, X_2|n_3, X_2|E_p, X_1|n_3, X_1|E_p, X_0|n_1, X_0|E_m]$$



Context	*exitValue*
$X_0 = \langle \text{main},0 \rangle$	1
$X_1 = \langle \text{p},1 \rangle$	1
$X_2 = \langle \text{p},0 \rangle$	1



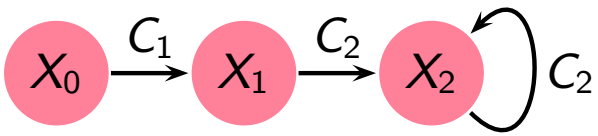
p has context X_2 with value 0 so no need to create a new context

Record the transition from context X_2 to itself

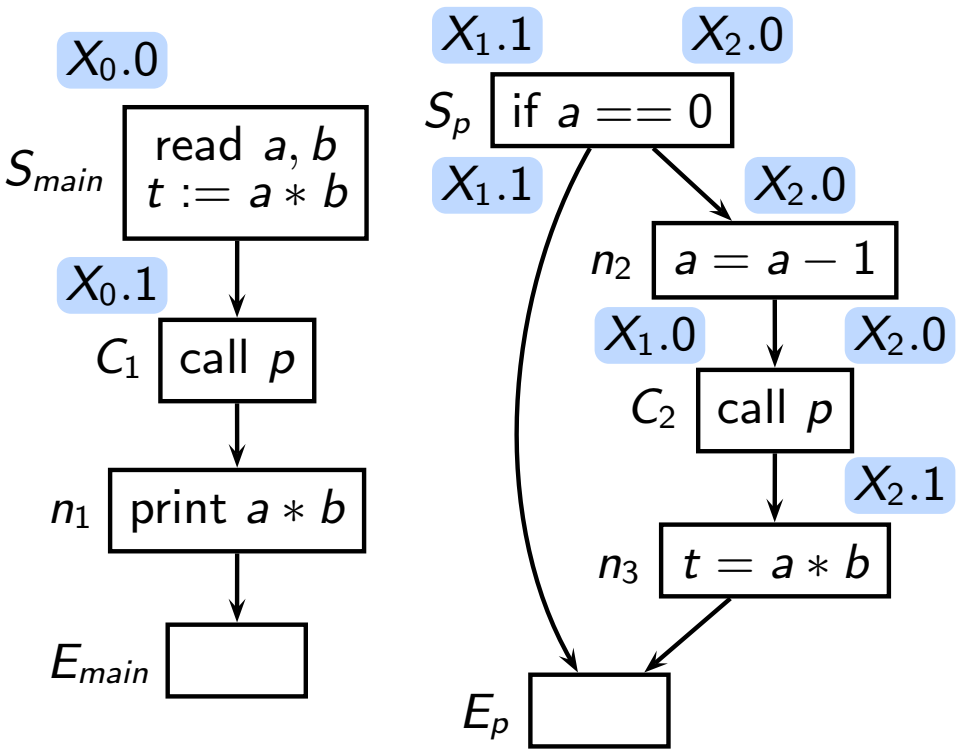
Use the $exitValue(X_2)$ to compute $Out_{C_2}[X_2]$

Available Expressions Analysis Using Value Contexts

$WL = [X_2|n_3, X_2|E_p, X_1|n_3, X_1|E_p, X_0|n_1, X_0|E_m]$

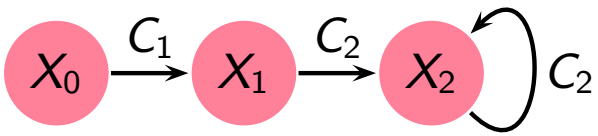


Context	*exitValue*
$X_0 = \langle$main,0$\rangle$	1
$X_1 = \langle$p,1$\rangle$	1
$X_2 = \langle$p,0$\rangle$	1

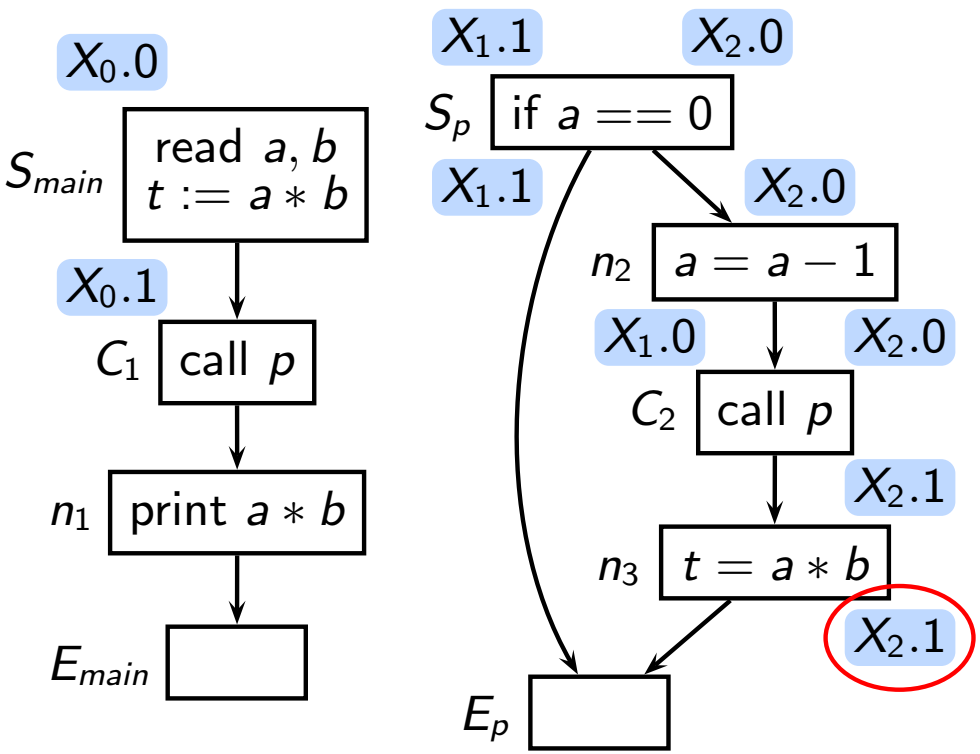


Available Expressions Analysis Using Value Contexts

$WL = [X_2|n_3, X_2|E_p, X_1|n_3, X_1|E_p, X_0|n_1, X_0|E_m]$

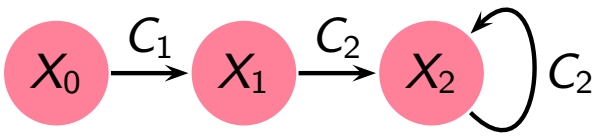


Context	*exitValue*
$X_0 = \langle \text{main},0 \rangle$	1
$X_1 = \langle \text{p},1 \rangle$	1
$X_2 = \langle \text{p},0 \rangle$	1

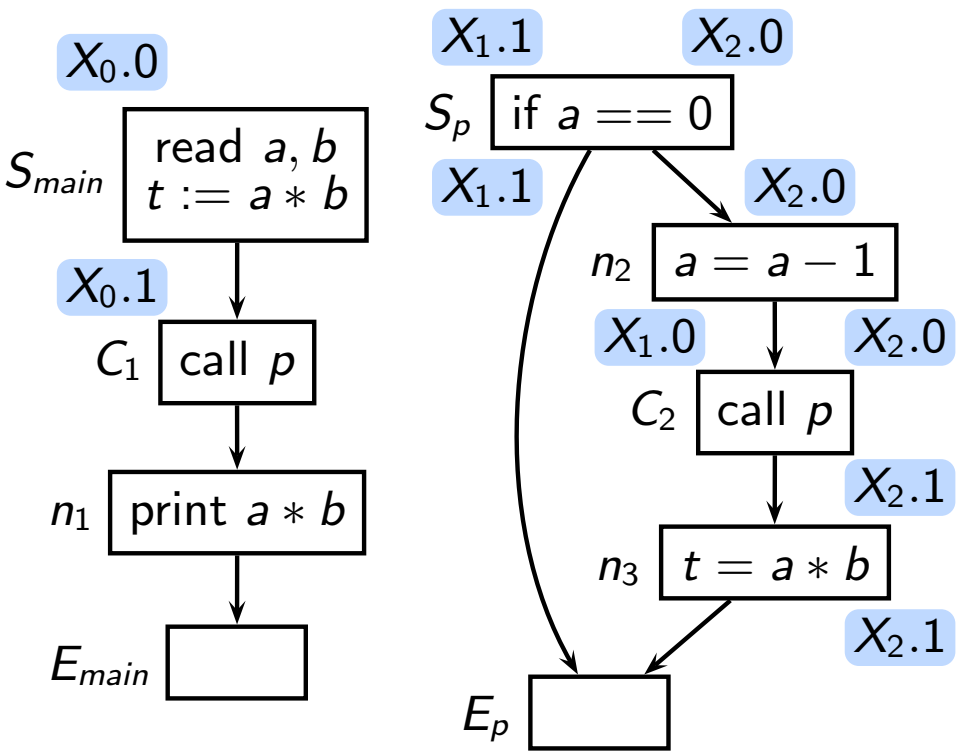


Available Expressions Analysis Using Value Contexts

$WL = [X_2|E_p, X_1|n_3, X_1|E_p, X_0|n_1, X_0|E_m]$

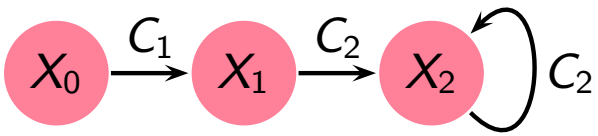


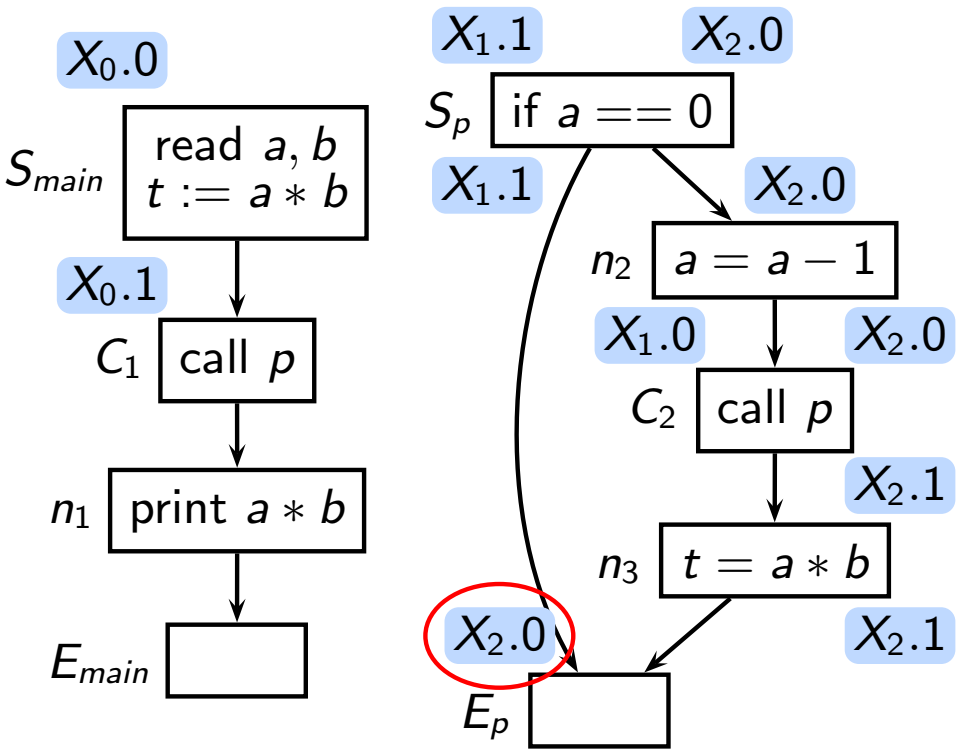
Context	*exitValue*
$X_0 = \langle$main,0$\rangle$	1
$X_1 = \langle$p,1$\rangle$	1
$X_2 = \langle$p,0$\rangle$	1



Available Expressions Analysis Using Value Contexts

$WL = [X_2|E_p, X_1|n_3, X_1|E_p, X_0|n_1, X_0|E_m]$



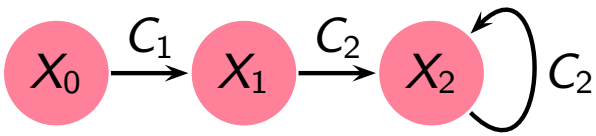


Context	*exitValue*
$X_0 = \langle$main,0$\rangle$	1
$X_1 = \langle$p,1$\rangle$	1
$X_2 = \langle$p,0$\rangle$	1

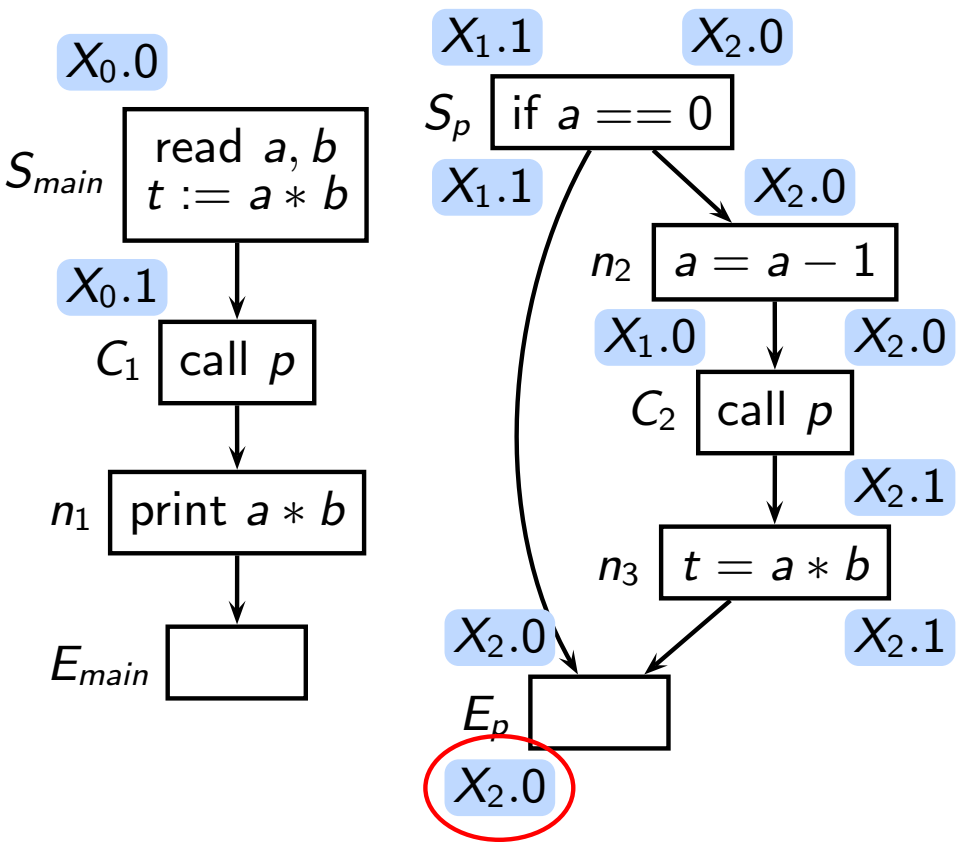
At E_p the values from S_p and n_3 are merged for context X_2

Available Expressions Analysis Using Value Contexts

$WL = [X_2|E_p, X_1|n_3, X_1|E_p, X_0|n_1, X_0|E_m]$



Context	*exitValue*
$X_0 = \langle \text{main},0 \rangle$	1
$X_1 = \langle \text{p},1 \rangle$	1
$X_2 = \langle \text{p},0 \rangle$	0

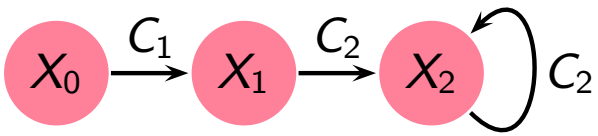


At E_p the values from S_p and n_3 are merged for context X_2

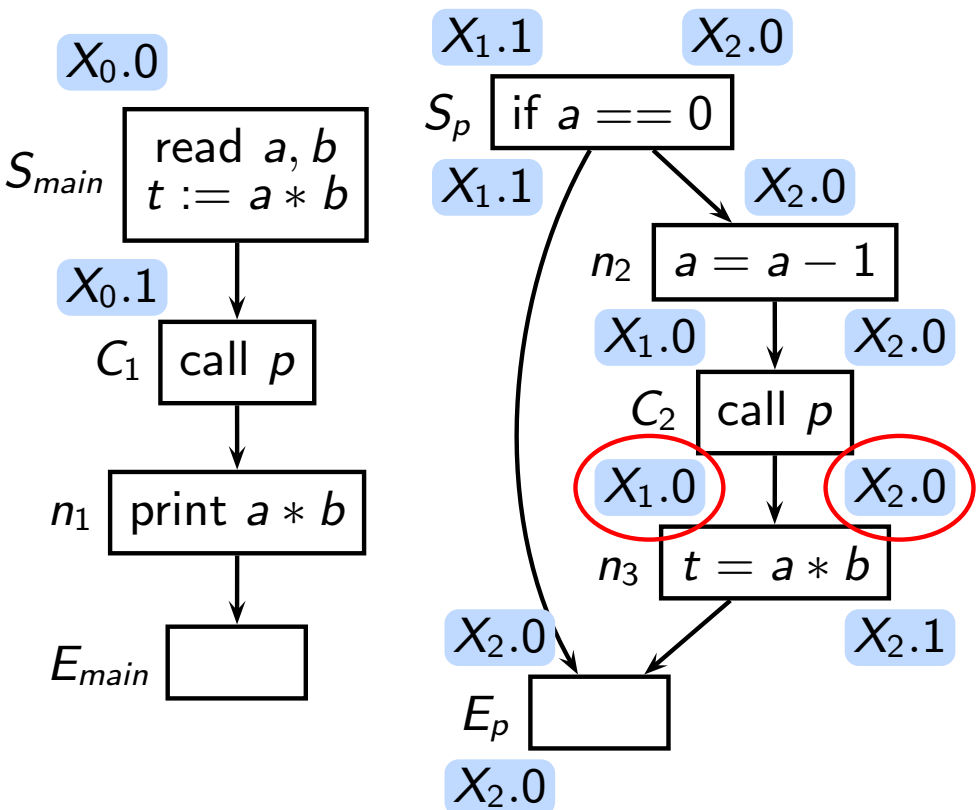
exitValue(X_2) is set to 0

Available Expressions Analysis Using Value Contexts

$WL = [X_2|E_p, X_1|n_3, X_1|E_p, X_0|n_1, X_0|E_m]$



Context	*exitValue*
$X_0 = \langle \text{main},0 \rangle$	1
$X_1 = \langle \text{p},1 \rangle$	1
$X_2 = \langle \text{p},0 \rangle$	0



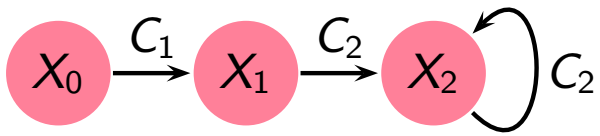
At E_p the values from S_p and n_3 are merged for context X_2

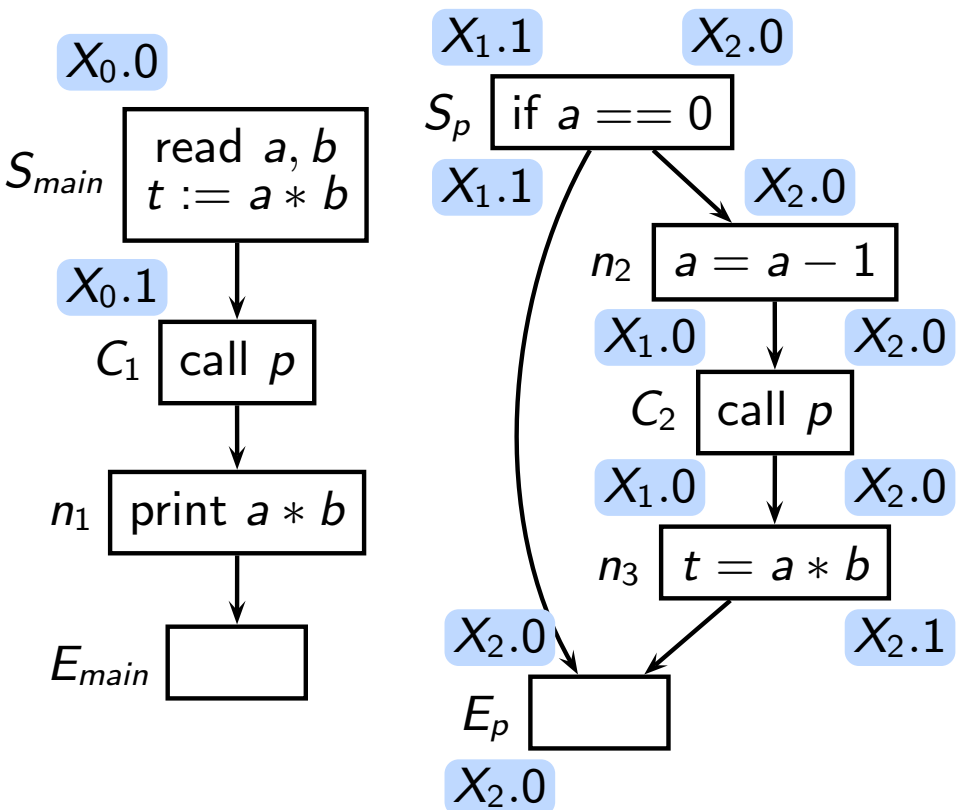
exitValue(X_2) is set to 0

Since X_2 has transitions $X_1 \xrightarrow{C_2} X_2$ and $X_2 \xrightarrow{C_2} X_2$, $Out_{C_2}[X_1]$ and $Out_{C_2}[X_2]$ become 0

Available Expressions Analysis Using Value Contexts

$WL = [X_2|n_3, X_1|n_3, X_1|E_p, X_0|n_1, X_0|E_m]$





Context	*exitValue*
$X_0 = \langle$main,0$\rangle$	1
$X_1 = \langle$p,1$\rangle$	1
$X_2 = \langle$p,0$\rangle$	0

At E_p the values from S_p and n_3 are merged for context X_2

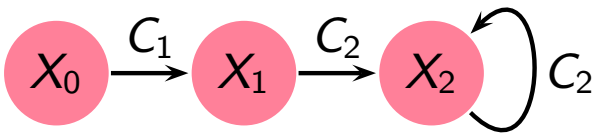
exitValue(X_2) is set to 0

Since X_2 has transitions $X_1 \xrightarrow{C_2} X_2$ and $X_2 \xrightarrow{C_2} X_2$, $Out_{C_2}[X_1]$ and $Out_{C_2}[X_2]$ become 0

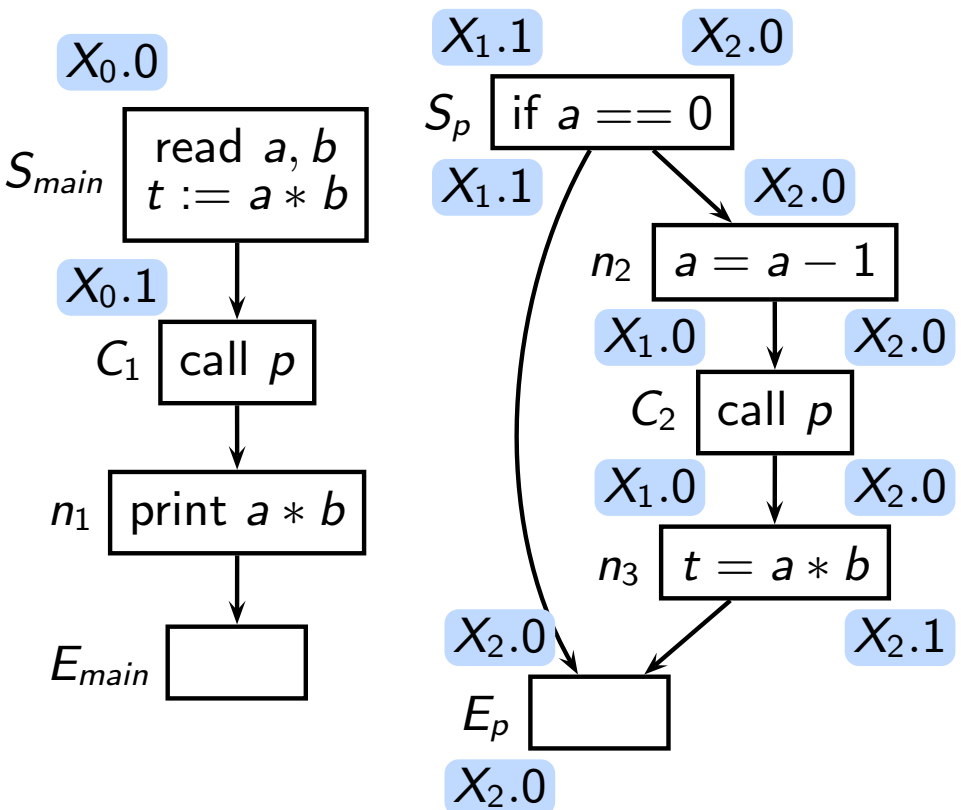
Since $Out_{C_2}[X_2]$ changes, $X_2|n_3$ is added to the work list

Available Expressions Analysis Using Value Contexts

$WL = [X_2|n_3, X_1|n_3, X_1|E_p, X_0|n_1, X_0|E_m]$



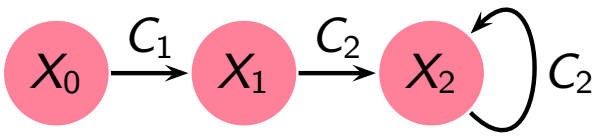
Context	*exitValue*
$X_0 = \langle \text{main},0 \rangle$	1
$X_1 = \langle \text{p},1 \rangle$	1
$X_2 = \langle \text{p},0 \rangle$	0



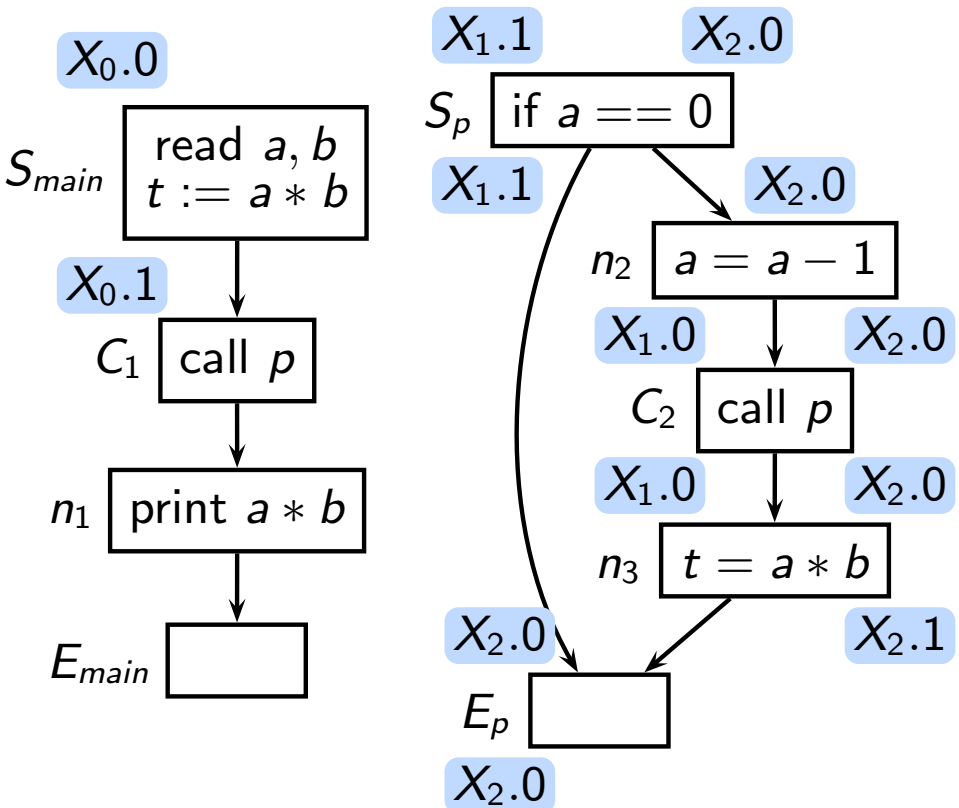
There is no change in $Out_{n_3}[X_2]$ (because it was initialized to $\top$)

Available Expressions Analysis Using Value Contexts

$WL = [X_1|n_3, X_1|E_p, X_0|n_1, X_0|E_m]$



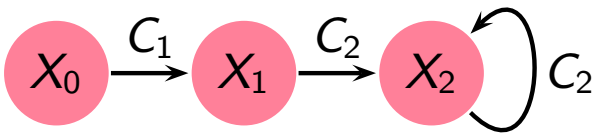
Context	*exitValue*
$X_0 = \langle \text{main},0 \rangle$	1
$X_1 = \langle \text{p},1 \rangle$	1
$X_2 = \langle \text{p},0 \rangle$	0



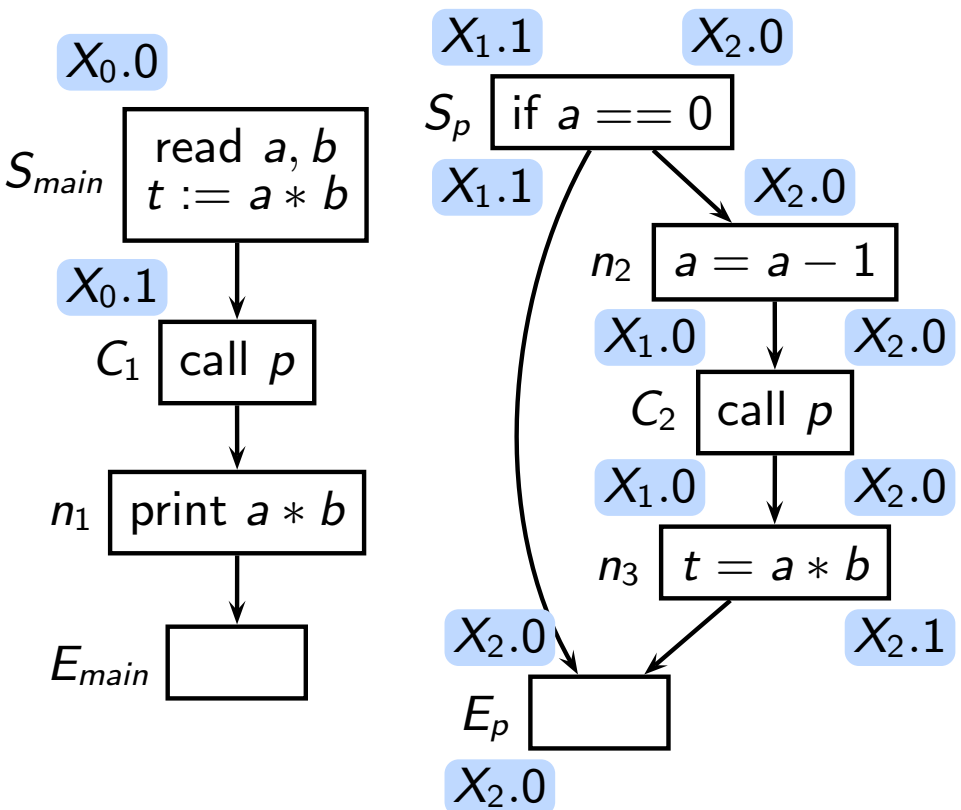
There is no change in $Out_{n_3}[X_2]$ (because it was initialized to $\top$)

Available Expressions Analysis Using Value Contexts

$WL = [X_1|n_3, X_1|E_p, X_0|n_1, X_0|E_m]$



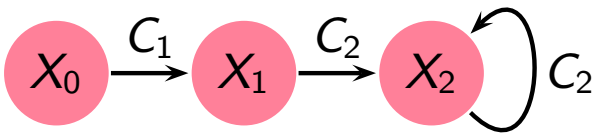
Context	*exitValue*
$X_0 = \langle \text{main},0 \rangle$	1
$X_1 = \langle \text{p},1 \rangle$	1
$X_2 = \langle \text{p},0 \rangle$	0



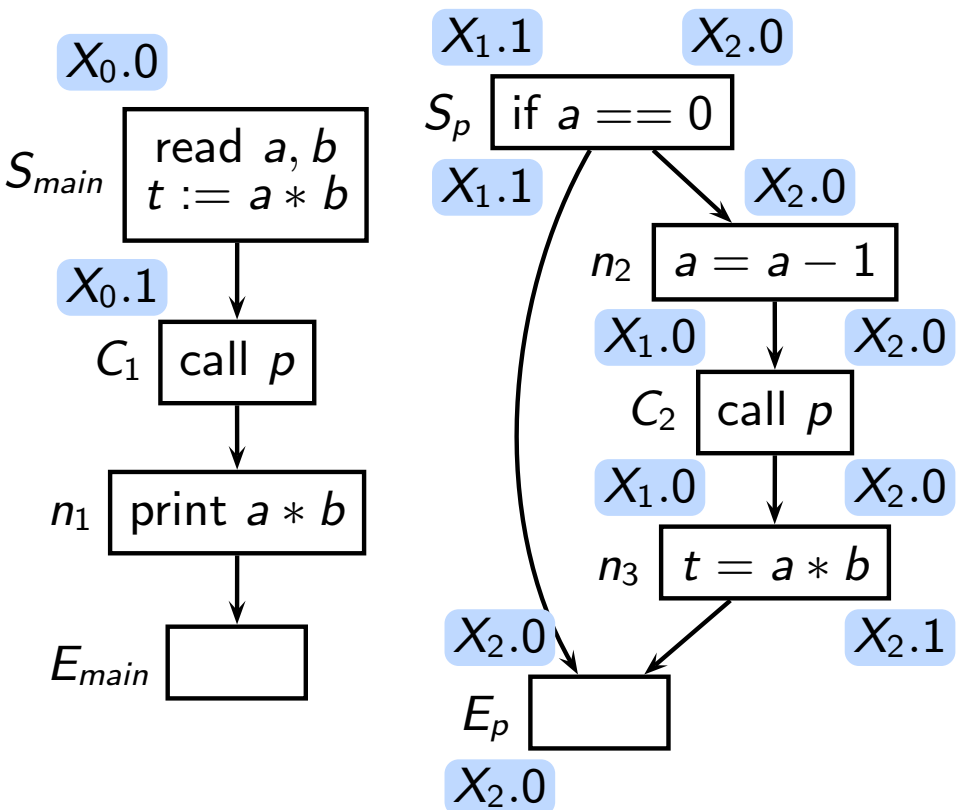
There is no change in $Out_{n_3}[X_1]$ either

Available Expressions Analysis Using Value Contexts

$WL = [X_1|E_p, X_0|n_1, X_0|E_m]$



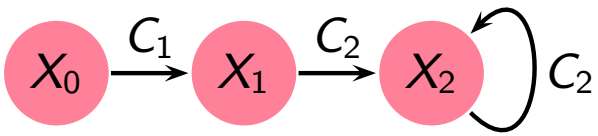
Context	*exitValue*
$X_0 = \langle$main,0$\rangle$	1
$X_1 = \langle$p,1$\rangle$	1
$X_2 = \langle$p,0$\rangle$	0

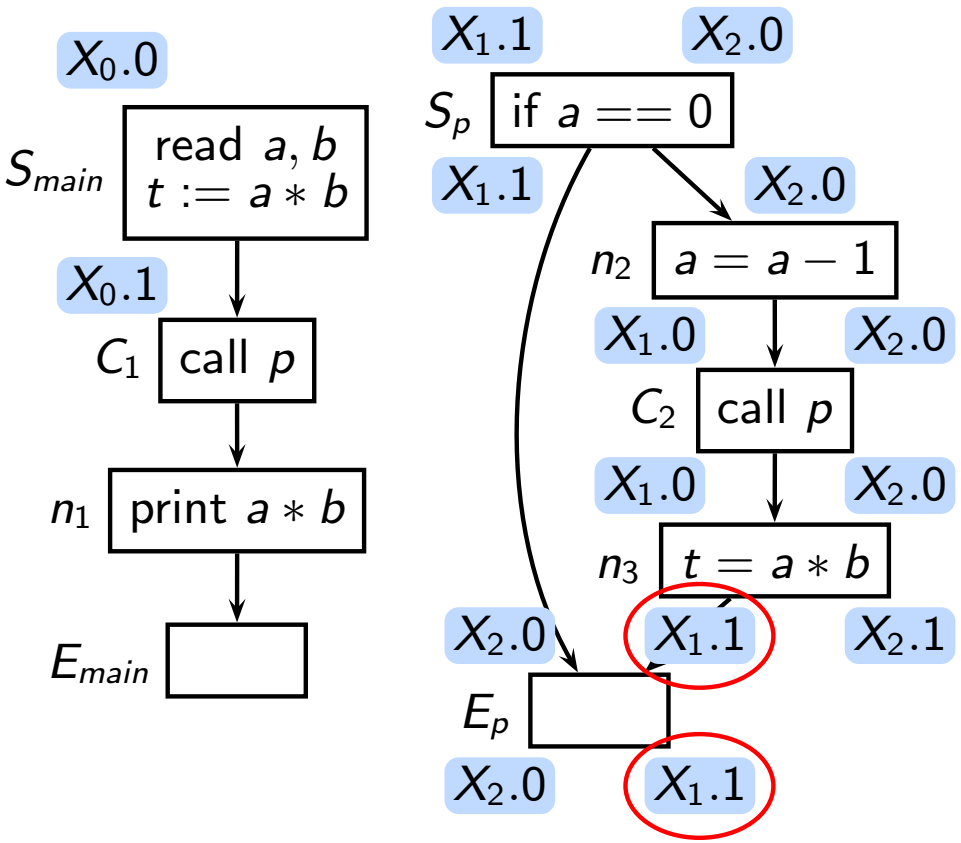


There is no change in $Out_{n_3}[X_1]$ either

Available Expressions Analysis Using Value Contexts

$WL = [X_1|E_p, X_0|n_1, X_0|E_m]$



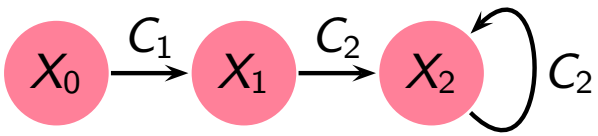


Context	*exitValue*
$X_0 = \langle$main,0$\rangle$	1
$X_1 = \langle$p,1$\rangle$	1
$X_2 = \langle$p,0$\rangle$	0

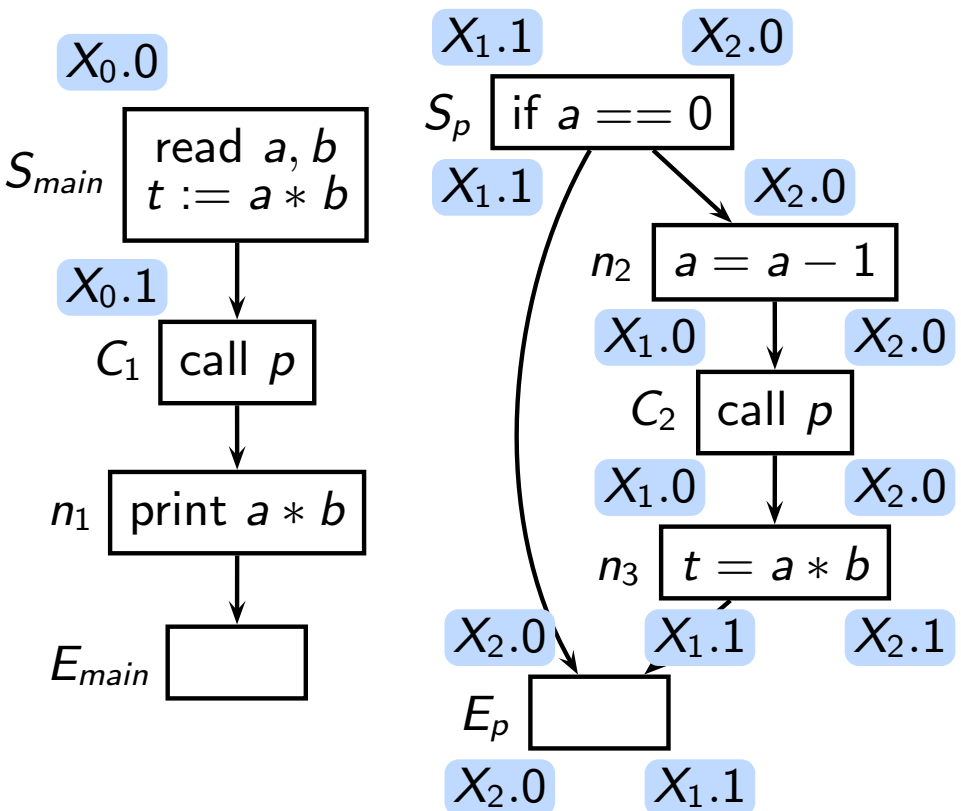
At E_p the values from S_p and n_3 are merged for context X_1

Available Expressions Analysis Using Value Contexts

$WL = [X_1|E_p, X_0|n_1, X_0|E_m]$



Context	*exitValue*
$X_0 = \langle \text{main},0 \rangle$	1
$X_1 = \langle \text{p},1 \rangle$	1
$X_2 = \langle \text{p},0 \rangle$	0

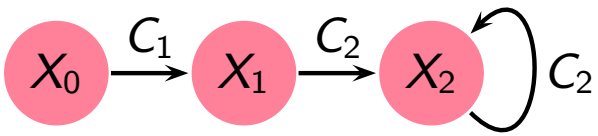


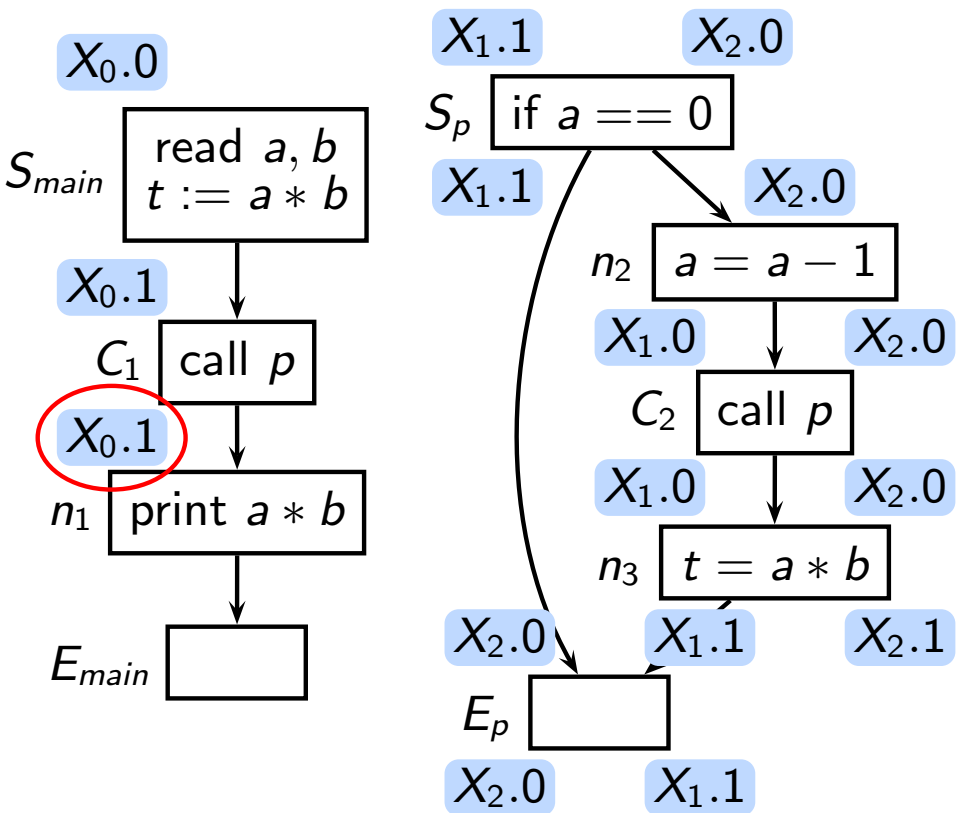
At E_p the values from S_p and n_3 are merged for context X_1

exitValue(X_1) remains 1

Available Expressions Analysis Using Value Contexts

$WL = [X_1|E_p, X_0|n_1, X_0|E_m]$





Context	*exitValue*
$X_0 = \langle$main,0$\rangle$	1
$X_1 = \langle$p,1$\rangle$	1
$X_2 = \langle$p,0$\rangle$	0

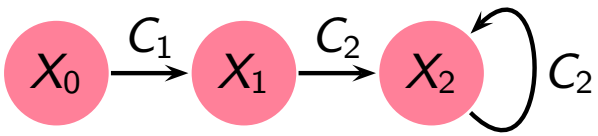
At E_p the values from S_p and n_3 are merged for context X_1

$exitValue(X_1)$ remains 1

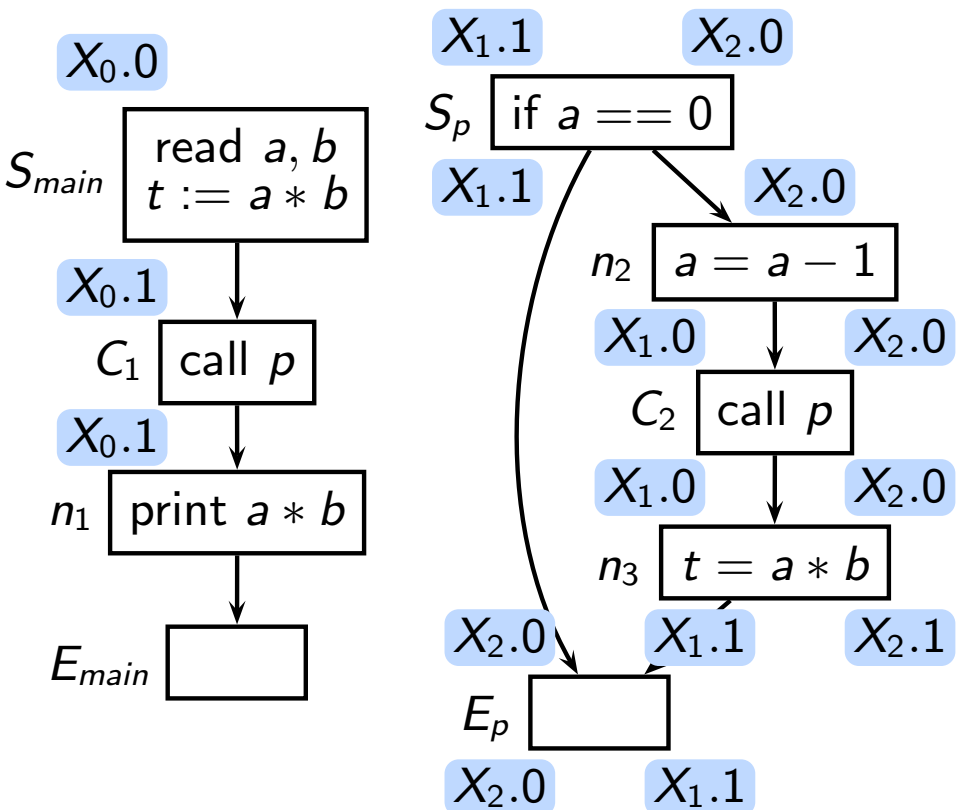
Since X_1 has transition $X_0 \xrightarrow{C_1} X_1$, $Out_{C_1}[X_0]$ becomes 1

Available Expressions Analysis Using Value Contexts

$WL = [X_0|n_1, X_0|E_m]$

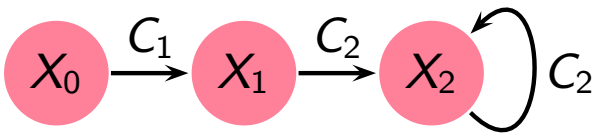


Context	*exitValue*
$X_0 = \langle \text{main},0 \rangle$	1
$X_1 = \langle \text{p},1 \rangle$	1
$X_2 = \langle \text{p},0 \rangle$	0

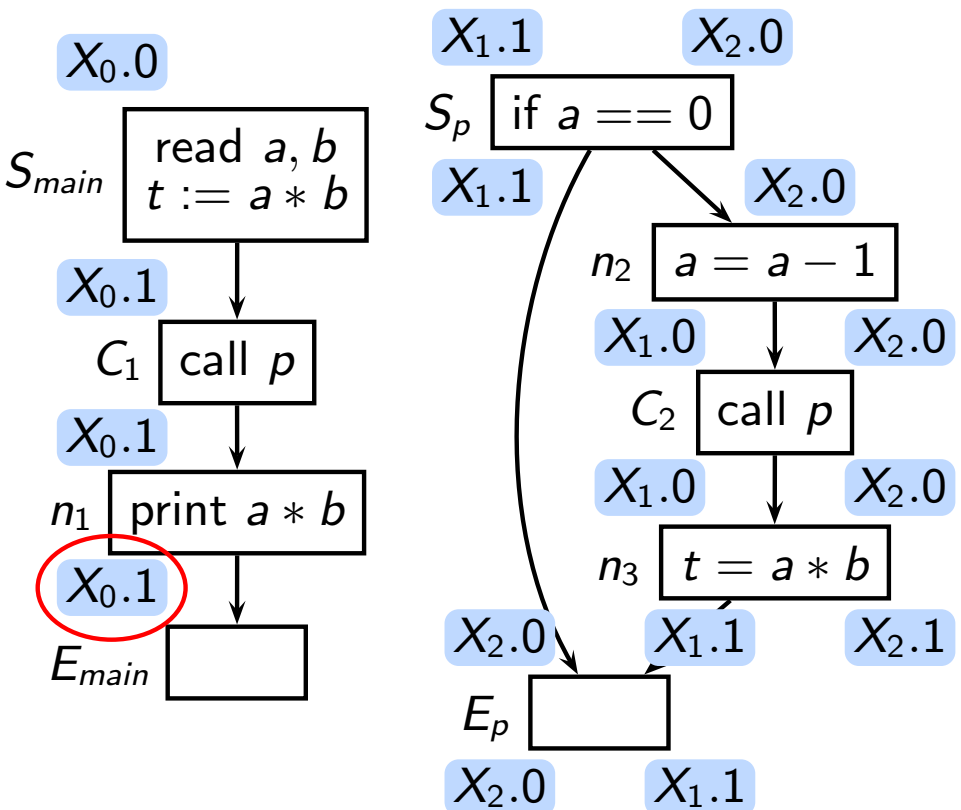


Available Expressions Analysis Using Value Contexts

$WL = [X_0|n_1, X_0|E_m]$

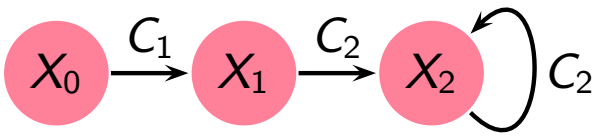


Context	*exitValue*
$X_0 = \langle \text{main},0 \rangle$	1
$X_1 = \langle \text{p},1 \rangle$	1
$X_2 = \langle \text{p},0 \rangle$	0

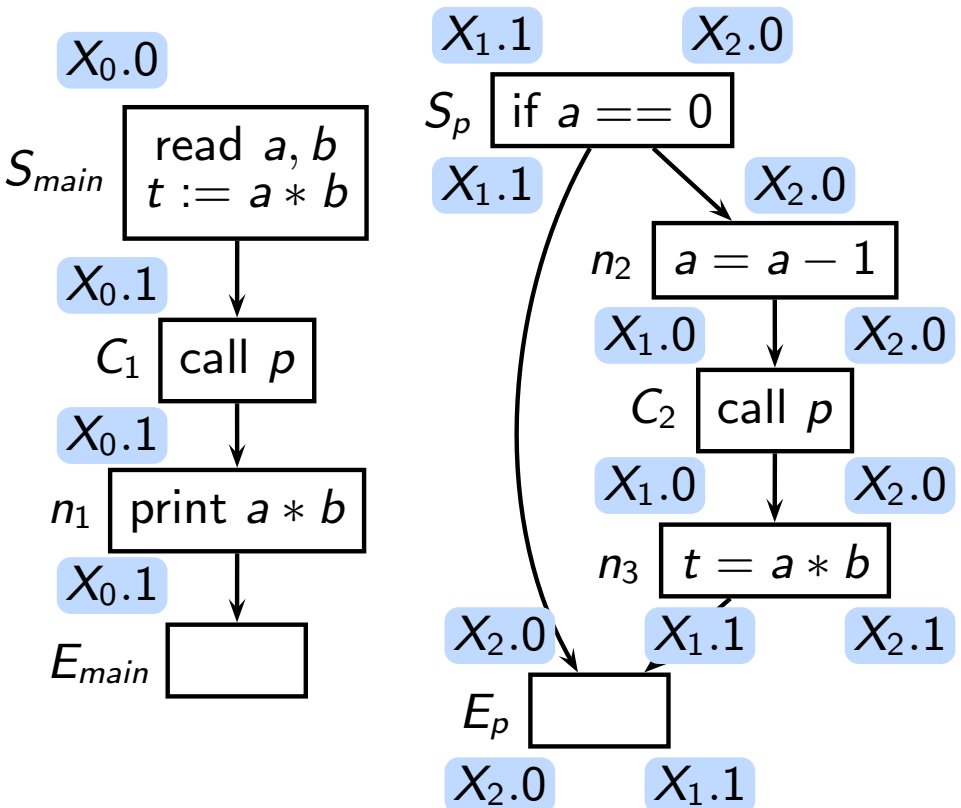


Available Expressions Analysis Using Value Contexts

$WL = [X_0|E_m]$

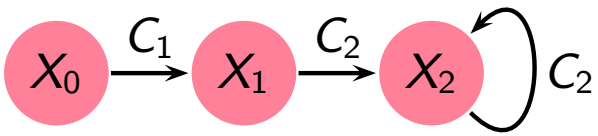


Context	*exitValue*
$X_0 = \langle \text{main},0 \rangle$	1
$X_1 = \langle \text{p},1 \rangle$	1
$X_2 = \langle \text{p},0 \rangle$	0

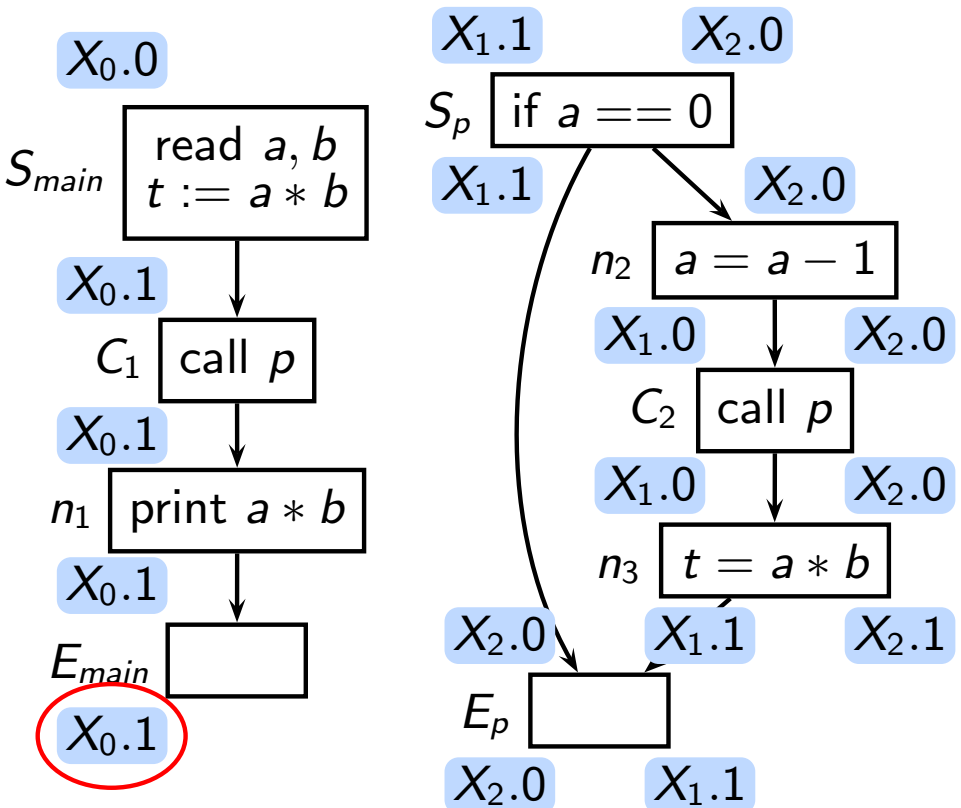


Available Expressions Analysis Using Value Contexts

$WL = [X_0 | E_m]$

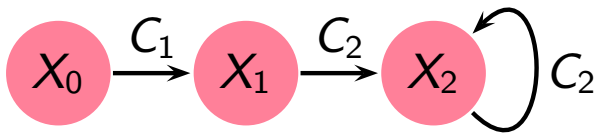


Context	*exitValue*
$X_0 = \langle \text{main},0 \rangle$	1
$X_1 = \langle \text{p},1 \rangle$	1
$X_2 = \langle \text{p},0 \rangle$	0

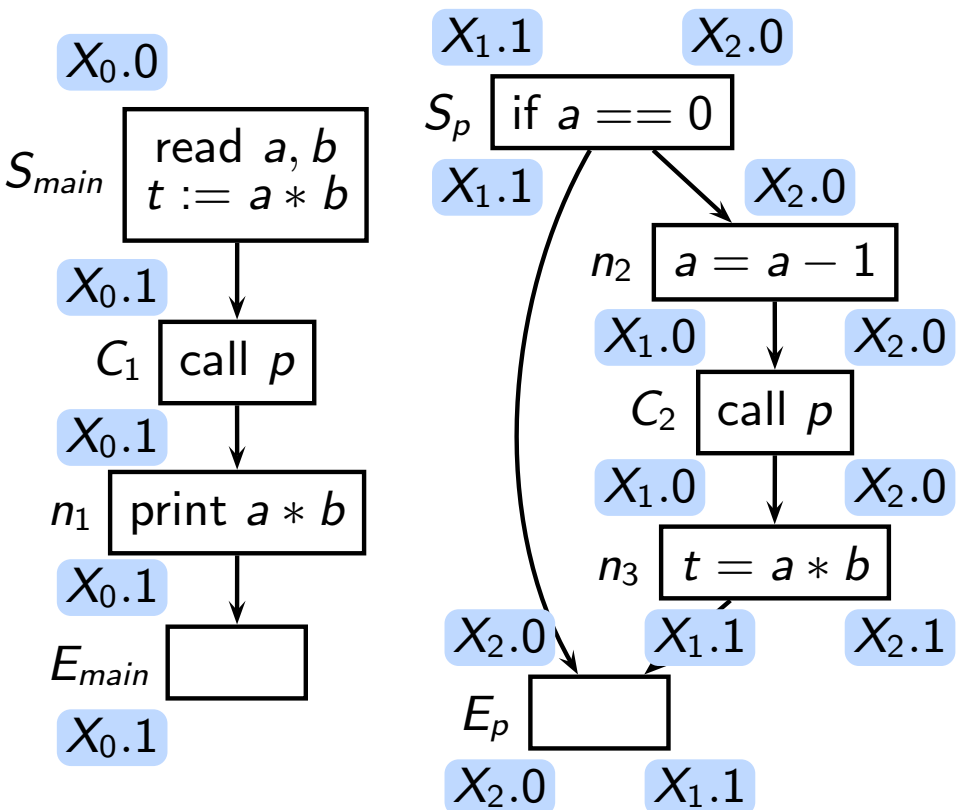


Available Expressions Analysis Using Value Contexts

$WL = [X_0|E_m]$

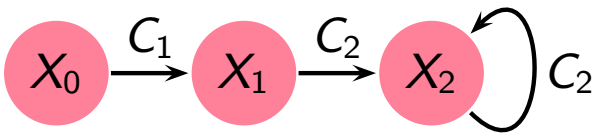


Context	*exitValue*
$X_0 = \langle \text{main},0 \rangle$	1
$X_1 = \langle \text{p},1 \rangle$	1
$X_2 = \langle \text{p},0 \rangle$	0

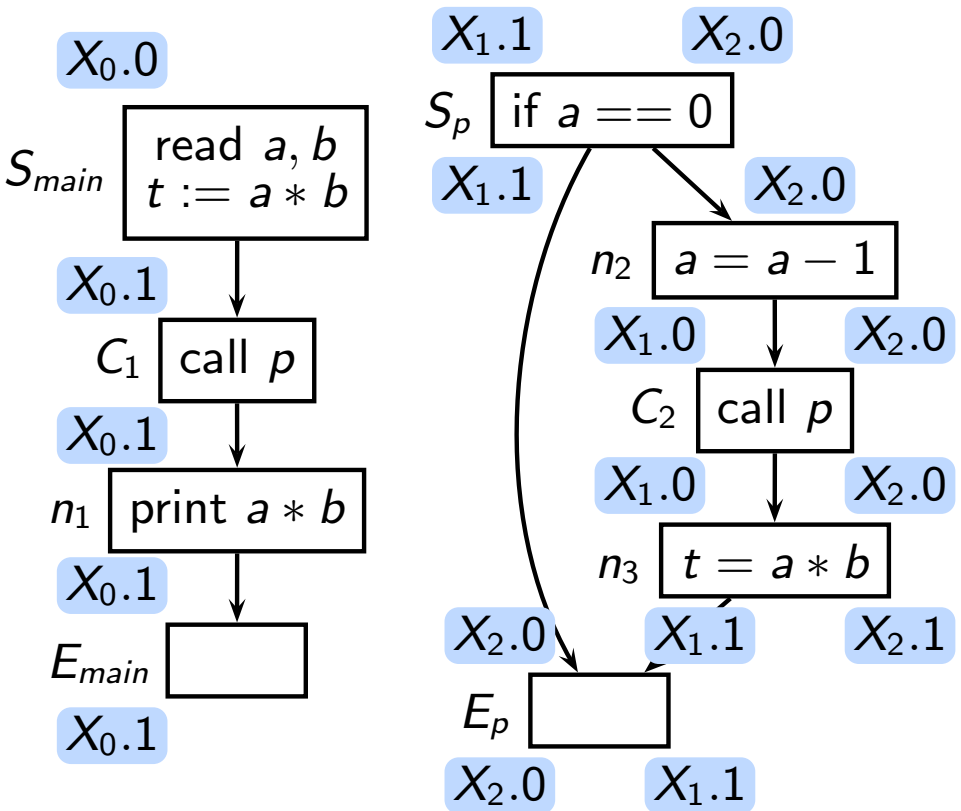


Available Expressions Analysis Using Value Contexts

$WL = [\ ]$



Context	*exitValue*
$X_0 = \langle \text{main},0 \rangle$	1
$X_1 = \langle \text{p},1 \rangle$	1
$X_2 = \langle \text{p},0 \rangle$	0



Work list is empty and the analysis is over

A Trace of Value Context Based Analysis (1)

S. No.	Work List	Sel. node	Data flow value	New context	New trans.	exit value	Addition to the work list
1				$X_0 = \langle m,0 \rangle$		$X_0.1$	$X_0 \vert S_m, X_0 \vert C_1, X_0 \vert n_1, X_0 \vert E_m$
2	$X_0 \vert S_m, X_0 \vert C_1, X_0 \vert n_1, X_0 \vert E_m$	S_m	$Out_{S_m}[X_0] = 1$				
3	$X_0 \vert C_1, X_0 \vert n_1, X_0 \vert E_m$	C_1		$X_1 = \langle p,1 \rangle$	$X_0 \xrightarrow{C_1} X_1$	$X_1.1$	$X_1 \vert S_p, X_1 \vert n_2, X_1 \vert C_2, X_1 \vert n_3, X_1 \vert E_p$
4	$X_1 \vert S_p, X_1 \vert n_2, X_1 \vert C_2, X_1 \vert n_3, X_1 \vert E_p, X_0 \vert n_1, X_0 \vert E_m$	S_p	$Out_{S_p}[X_1] = 1$				
5	$X_1 \vert n_2, X_1 \vert C_2, X_1 \vert n_3, X_1 \vert E_p, X_0 \vert n_1, X_0 \vert E_m$	n_2	$Out_{n_2}[X_1] = 0$				
6	$X_1 \vert C_2, X_1 \vert n_3, X_1 \vert E_p, X_0 \vert n_1, X_0 \vert E_m$	C_2		$X_2 = \langle p,0 \rangle$	$X_1 \xrightarrow{C_2} X_2$	$X_2.1$	$X_2 \vert S_p, X_2 \vert n_2, X_2 \vert C_2, X_2 \vert n_3, X_2 \vert E_p$
7	$X_2 \vert S_p, X_2 \vert n_2, X_2 \vert C_2, X_2 \vert n_3, X_2 \vert E_p, X_1 \vert n_3, X_1 \vert E_p, X_0 \vert n_1, X_0 \vert E_m$	S_p	$Out_{S_p}[X_2] = 0$				

A Trace of Value Context Based Analysis (2)

S. No.	Work List	Sel. node	Data flow value	New context	New trans.	exit value	Addition to the work list
8	$X_2\|n_2, X_2\|C_2, X_2\|n_3, X_2\|E_p,$ $X_1\|n_3, X_1\|E_p, X_0\|n_1, X_0\|E_m$	n_2	$Out_{n_2}[X_2]=0$				
9	$X_2\|C_2, X_2\|n_3, X_2\|E_p, X_1\|n_3,$ $X_1\|E_p, X_0\|n_1, X_0\|E_m$	C_2	$Out_{C_2}[X_2]=1$		$X_2 \xrightarrow{C_2} X_2$		
10	$X_2\|n_3, X_2\|E_p, X_1\|n_3, X_1\|E_p,$ $X_0\|n_1, X_0\|E_m$	n_3	$Out_{n_3}[X_2]=1$				
11	$X_2\|E_p, X_1\|n_3, X_1\|E_p, X_0\|n_1,$ $X_0\|E_m$	E_p	$Out_{E_p}[X_2]=0$ $Out_{C_2}[X_2]=0$ $Out_{C_2}[X_1]=0$			$X_2.0$	$X_2\|n_3$
12	$X_2\|n_3, X_1\|n_3, X_1\|E_p, X_0\|n_1,$ $X_0\|E_m$	n_3	No change				
13	$X_1\|n_3, X_1\|E_p, X_0\|n_1, X_0\|E_m$	n_3	$Out_{n_3}[X_1]=1$				
14	$X_1\|E_p, X_0\|n_1, X_0\|E_m$	E_p	$Out_{E_p}[X_1]=1$ $Out_{C_1}[X_0]=1$			$X_1.1$	
15	$X_0\|n_1, X_0\|E_m$	n_1	$Out_{n_1}[X_0]=1$				
16	$X_0\|E_m$	E_m	$Out_{E_m}[X_0]=1$				

Merging ExitValue with Previous Out Value at the Call Site

Select $X|n$ from WL. Compute In_n. Let $X.v$ be in In_n

- If $n = C_i$ calling procedure p
  - If some context $\langle p,v \rangle$ exists (say Y) /* p is the callee */
    - record the transition $X \xrightarrow{C_i} Y$
    - $Out_{C_i}[X] = Out_{C_i}[X] \sqcap exitValue(Y)$
    - if there is a change, add $X|m$, $\forall m \in succ(C_i)$ to WL

Merging ExitValue with Previous Out Value at the Call Site

Select $X|n$ from WL. Compute In_n. Let $X.v$ be in In_n

- If $n = C_i$ calling procedure p
  - If some context $\langle p,v \rangle$ exists (say Y) /* p is the callee */
    - record the transition $X \xrightarrow{C_i} Y$
    - $Out_{C_i}[X] = \boxed{Out_{C_i}[X] \sqcap} exitValue(Y)$
    - if there is a change, add $X|m$, $\forall m \in succ(C_i)$ to WL

Merging ExitValue with Previous Out Value at the Call Site

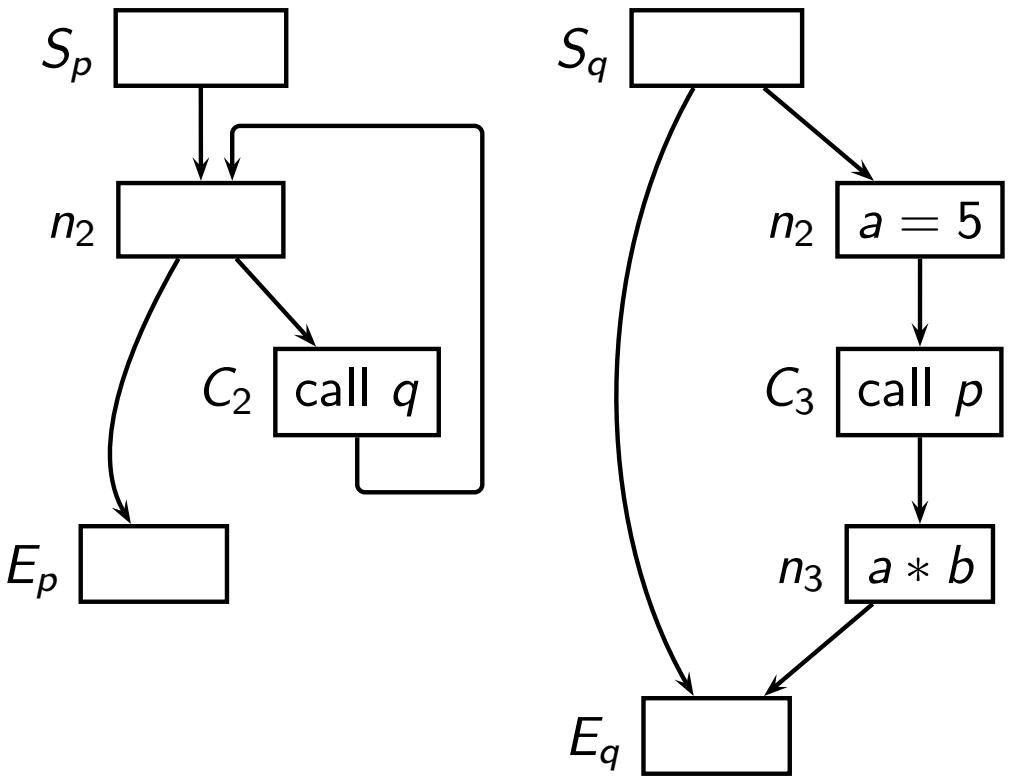
Select $X|n$ from WL. Compute In_n. Let $X.v$ be in In_n

- If $n = C_i$ calling procedure p
  - If some context $\langle p,v \rangle$ exists (say Y) /* p is the callee */
    - record the transition $X \xrightarrow{C_i} Y$
    - $Out_{C_i}[X] = \boxed{Out_{C_i}[X] \sqcap} exitValue(Y)$
    - if there is a change, add $X|m$, $\forall m \in succ(C_i)$ to WL

  Analogy:
  - At the intraprocedural level, we merge the values at the entry of a loop to compute the glb across all iterations of the loop
  - At the interprocedural level, we want to compute the glb across repeated calls at the same call site (perhaps in a loop)

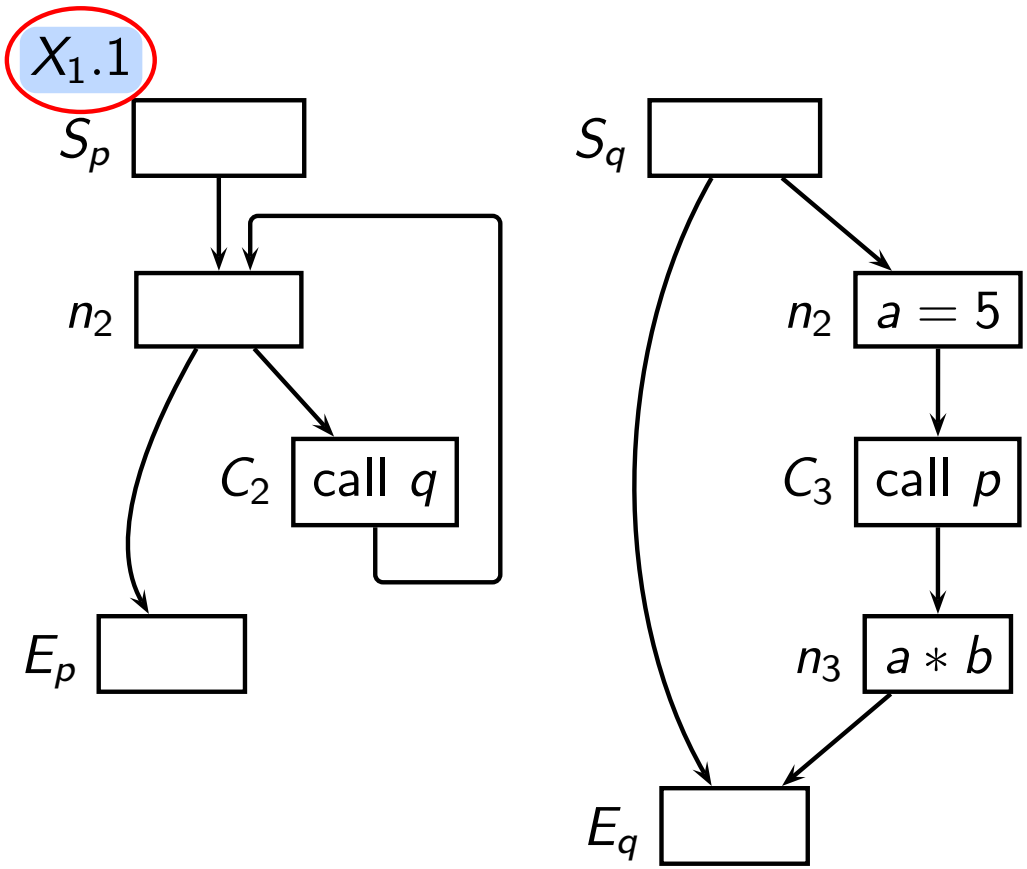
Partially Available Expressions Analysis Using Value Contexts

This example illustrates non-termination of analysis if the *exitValue* is not merged with the previous *Out* value



We assume that procedure main calls procedure p (and not q) and the expression $a * b$ is partially available on entry to p

Partially Available Expressions Analysis Using Value Contexts

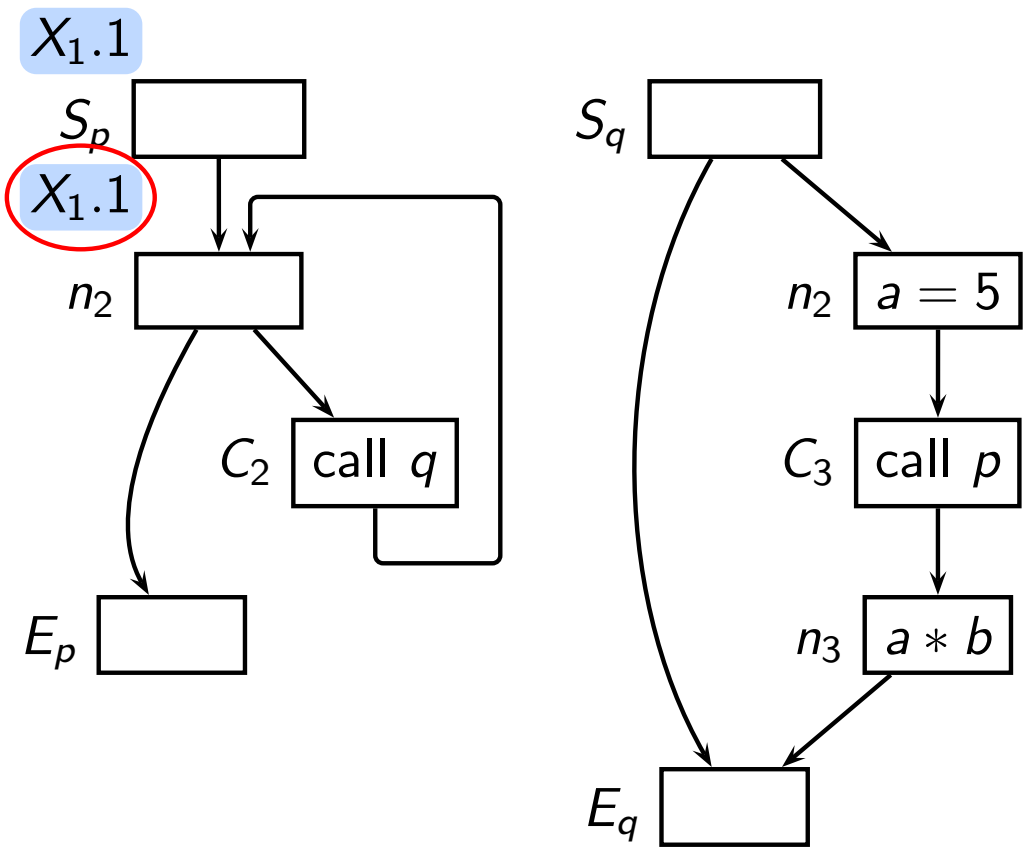


Context	*exitValue*
$X_1 = \langle p,1 \rangle$	0

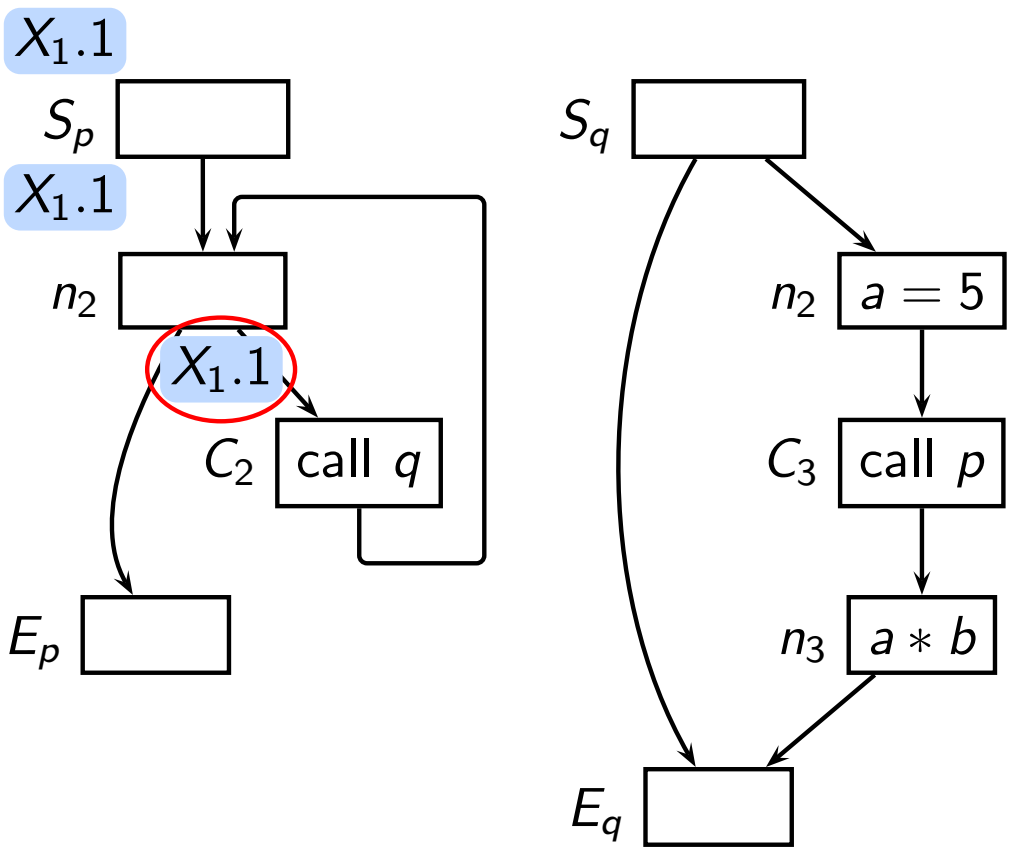
We create context X_1 for entry value 1 with *exitValue* as 0 ($\top$ for partially available expressions analysis)

Partially Available Expressions Analysis Using Value Contexts

Context	*exitValue*
$X_1 = \langle p,1 \rangle$	0



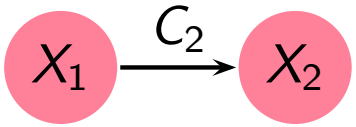
Partially Available Expressions Analysis Using Value Contexts

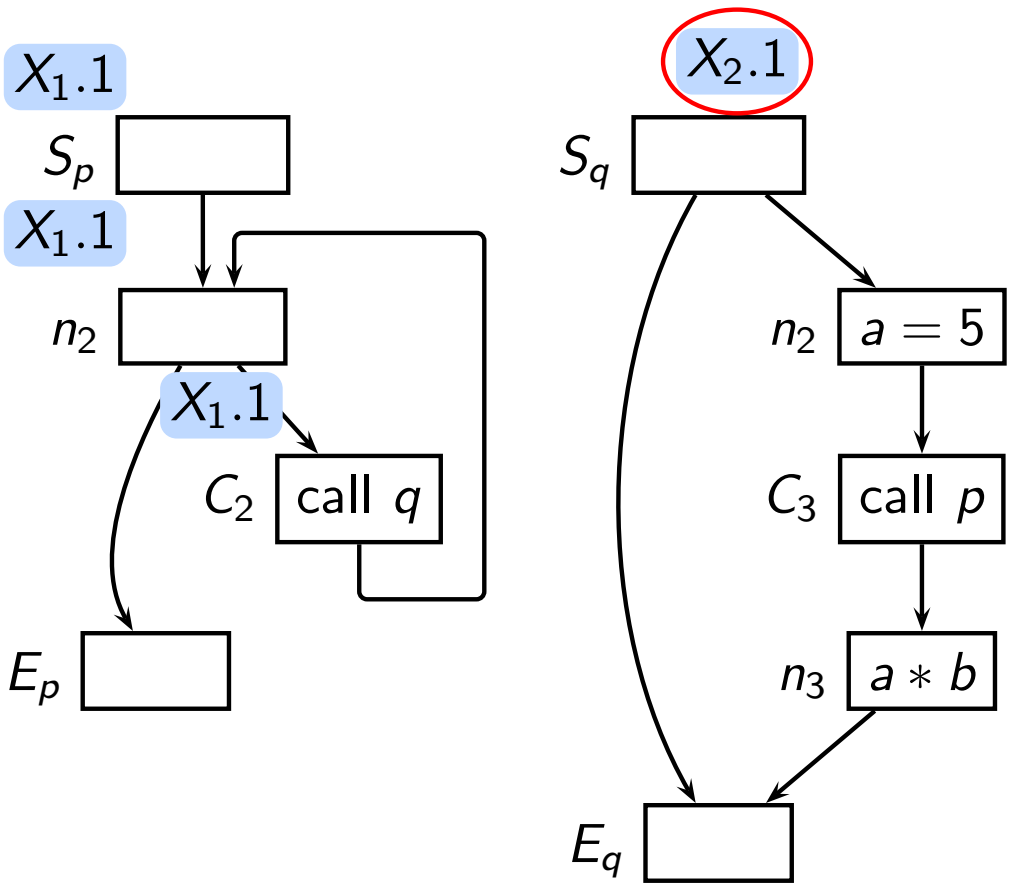


Context	*exitValue*
$X_1 = \langle p,1 \rangle$	0

Value 1 reaches q and a new context must be created for it

Partially Available Expressions Analysis Using Value Contexts

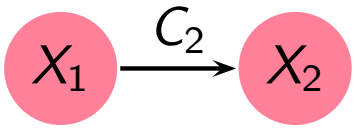


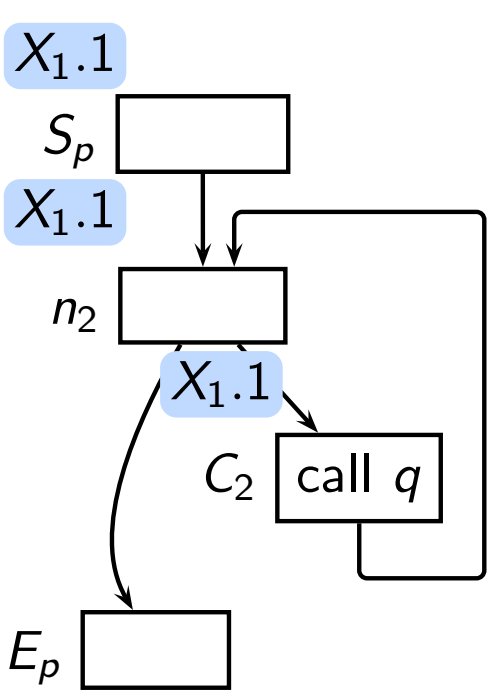


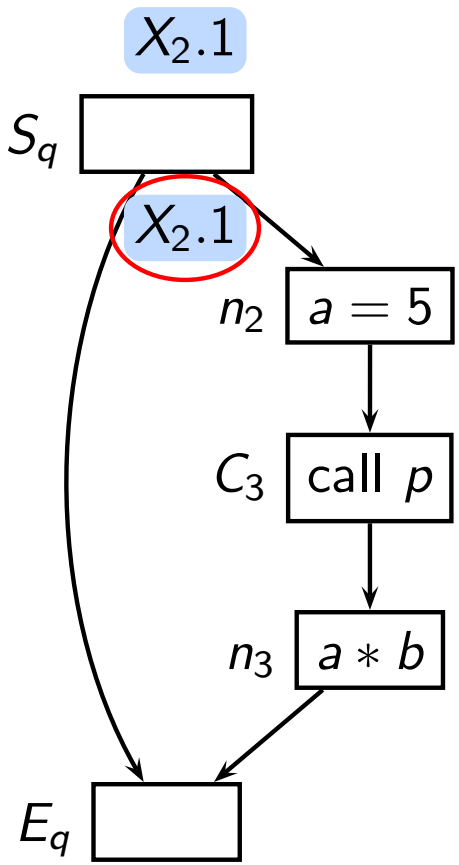
Context	*exitValue*
$X_1 = \langle p,1 \rangle$	0
$X_2 = \langle q,1 \rangle$	0

We create context X_2 for value 1 reaching q and record a transition from X_1 to X_2 on C_2

Partially Available Expressions Analysis Using Value Contexts

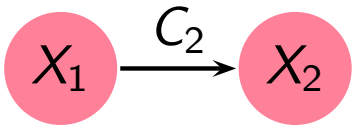


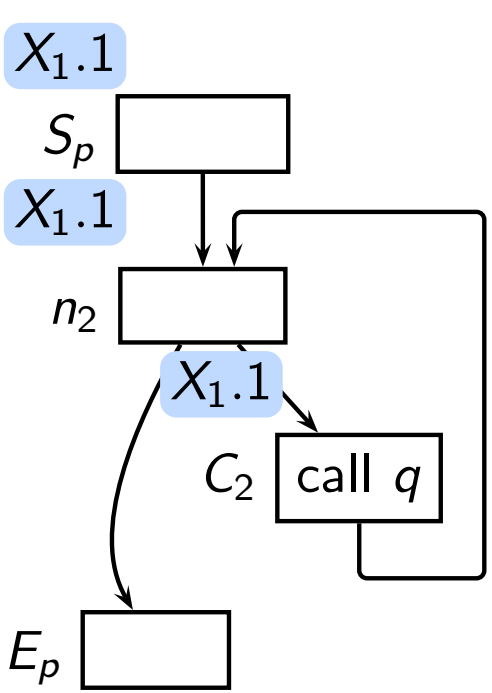


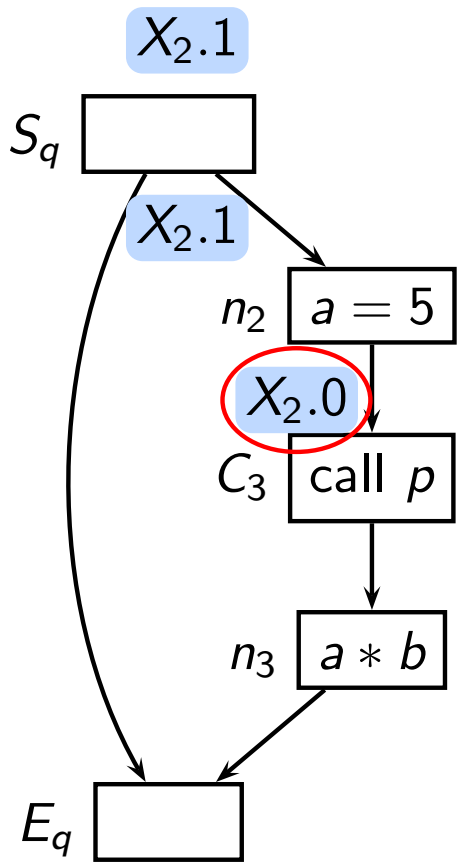


Context	*exitValue*
$X_1 = \langle p,1 \rangle$	0
$X_2 = \langle q,1 \rangle$	0

Partially Available Expressions Analysis Using Value Contexts



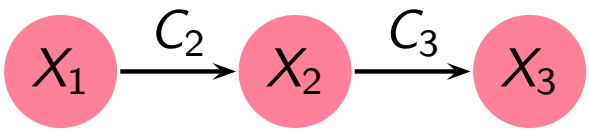


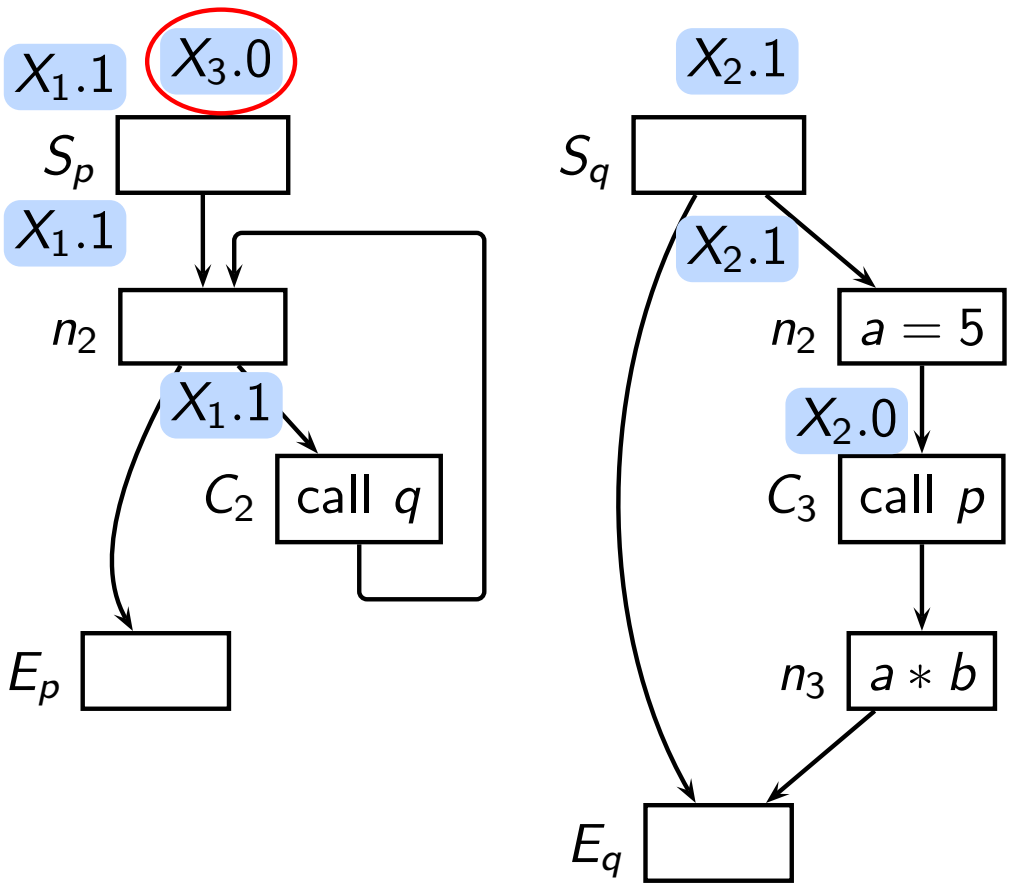


Context	*exitValue*
$X_1 = \langle p,1 \rangle$	0
$X_2 = \langle q,1 \rangle$	0

The expression is killed in node n_2 and data flow value 0 reaches the call site C_3 that calls p

Partially Available Expressions Analysis Using Value Contexts

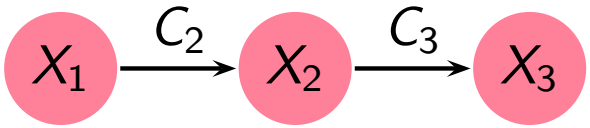


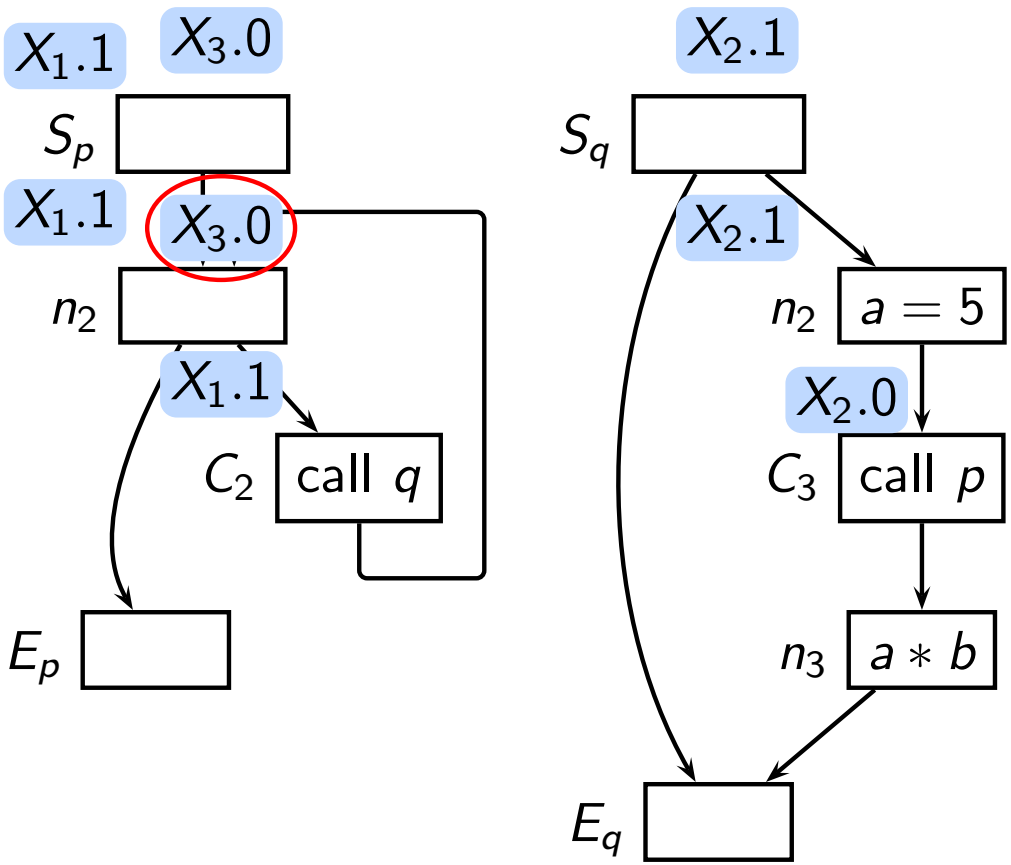


Context	*exitValue*
$X_1 = \langle p,1 \rangle$	0
$X_2 = \langle q,1 \rangle$	0
$X_3 = \langle p,0 \rangle$	0

We create context X_3 for the new value (0) reaching p and record transition from X_2 to X_3 on C_3

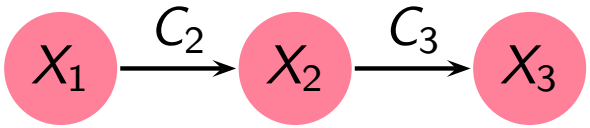
Partially Available Expressions Analysis Using Value Contexts

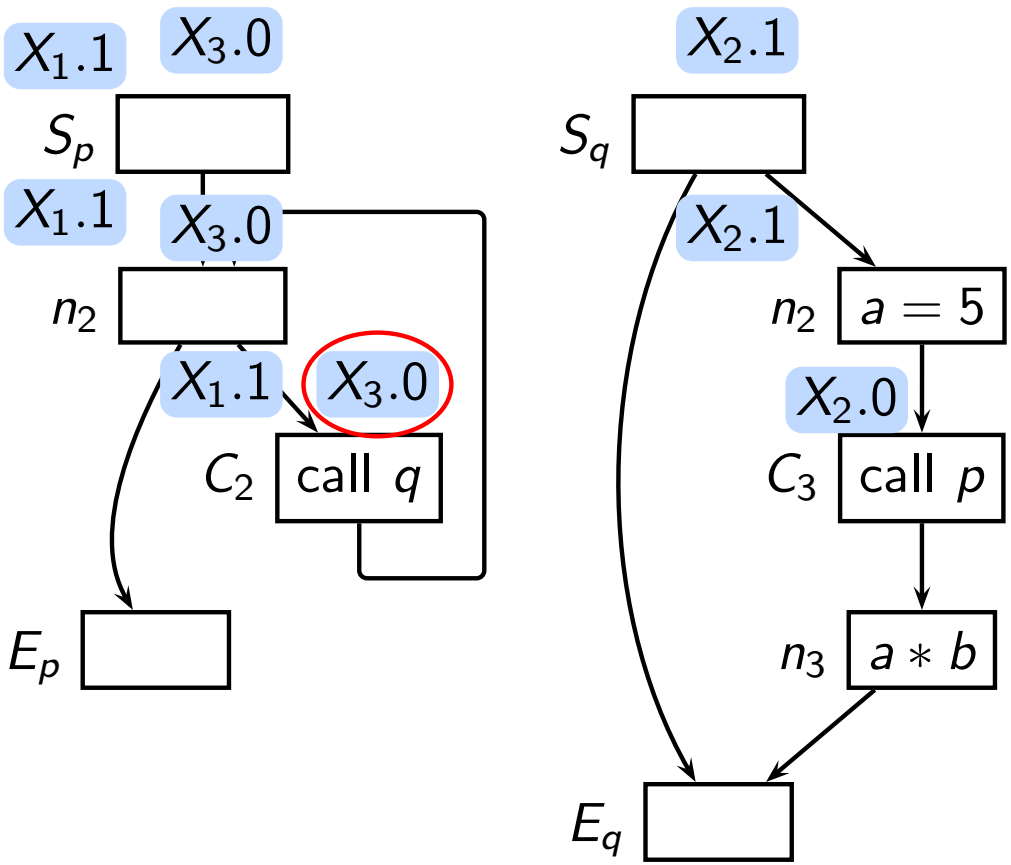




Context	*exitValue*
$X_1 = \langle p,1 \rangle$	0
$X_2 = \langle q,1 \rangle$	0
$X_3 = \langle p,0 \rangle$	0

Partially Available Expressions Analysis Using Value Contexts

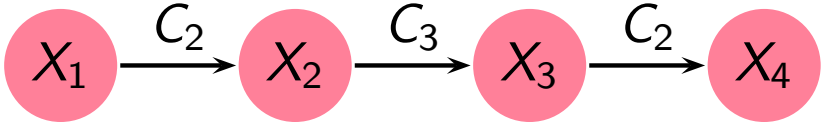


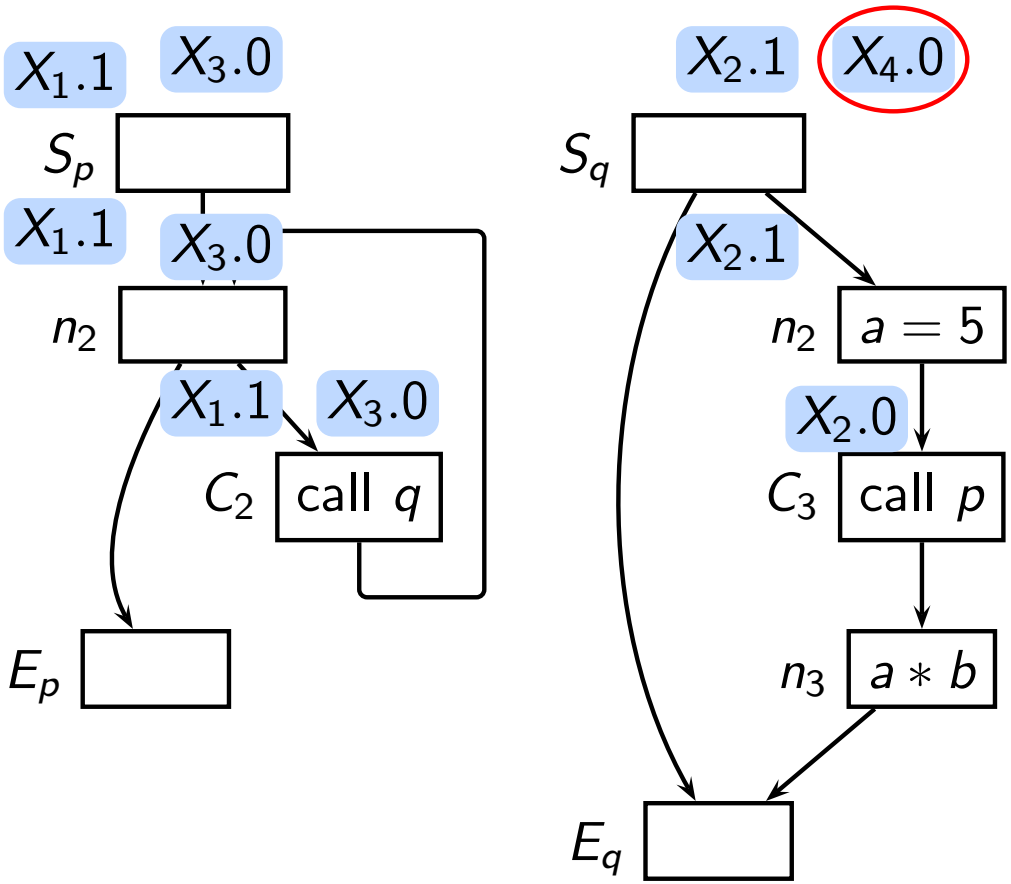


Context	*exitValue*
$X_1 = \langle p,1 \rangle$	0
$X_2 = \langle q,1 \rangle$	0
$X_3 = \langle p,0 \rangle$	0

And now the value 0 reaches q at call site C_2

Partially Available Expressions Analysis Using Value Contexts

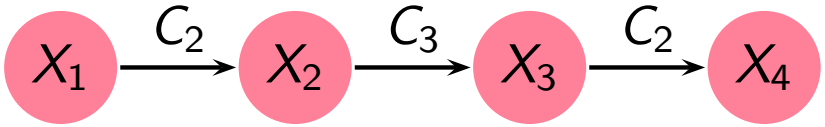


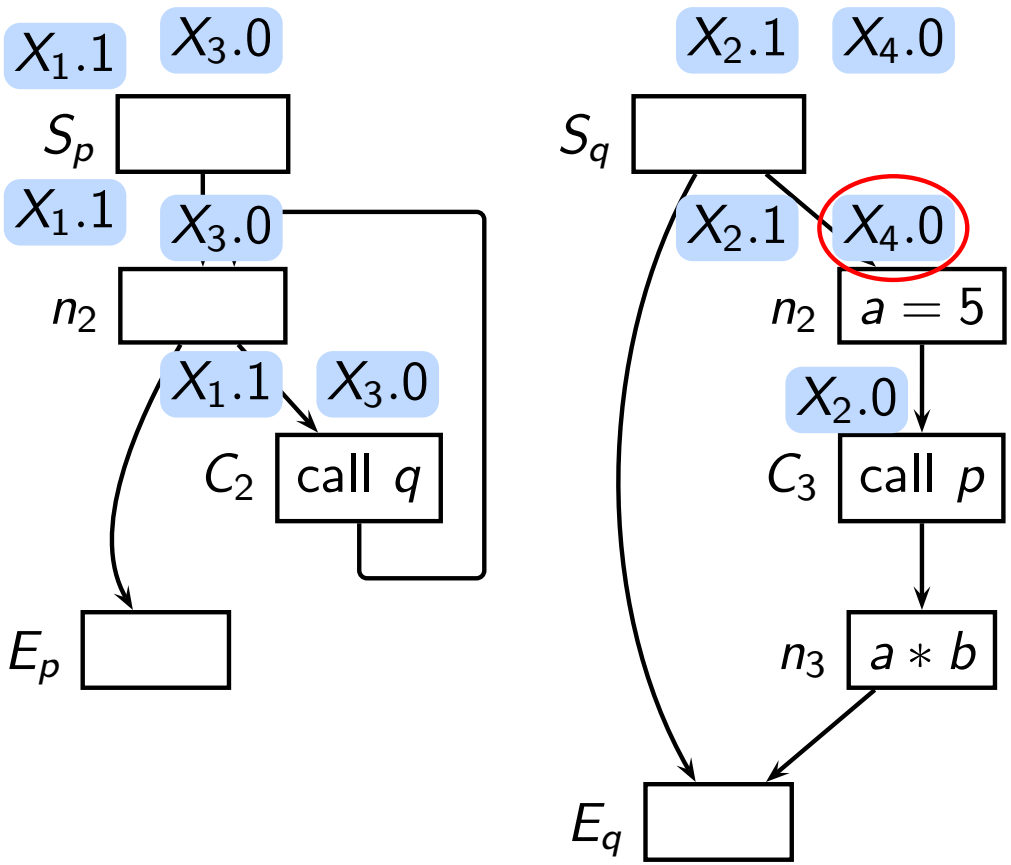


Context	*exitValue*
$X_1 = \langle p,1 \rangle$	0
$X_2 = \langle q,1 \rangle$	0
$X_3 = \langle p,0 \rangle$	0
$X_4 = \langle q,0 \rangle$	0

We create context X_4 for the new value (0) reaching p and record transition from X_3 to X_4 on C_2

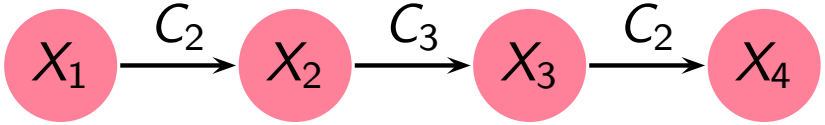
Partially Available Expressions Analysis Using Value Contexts



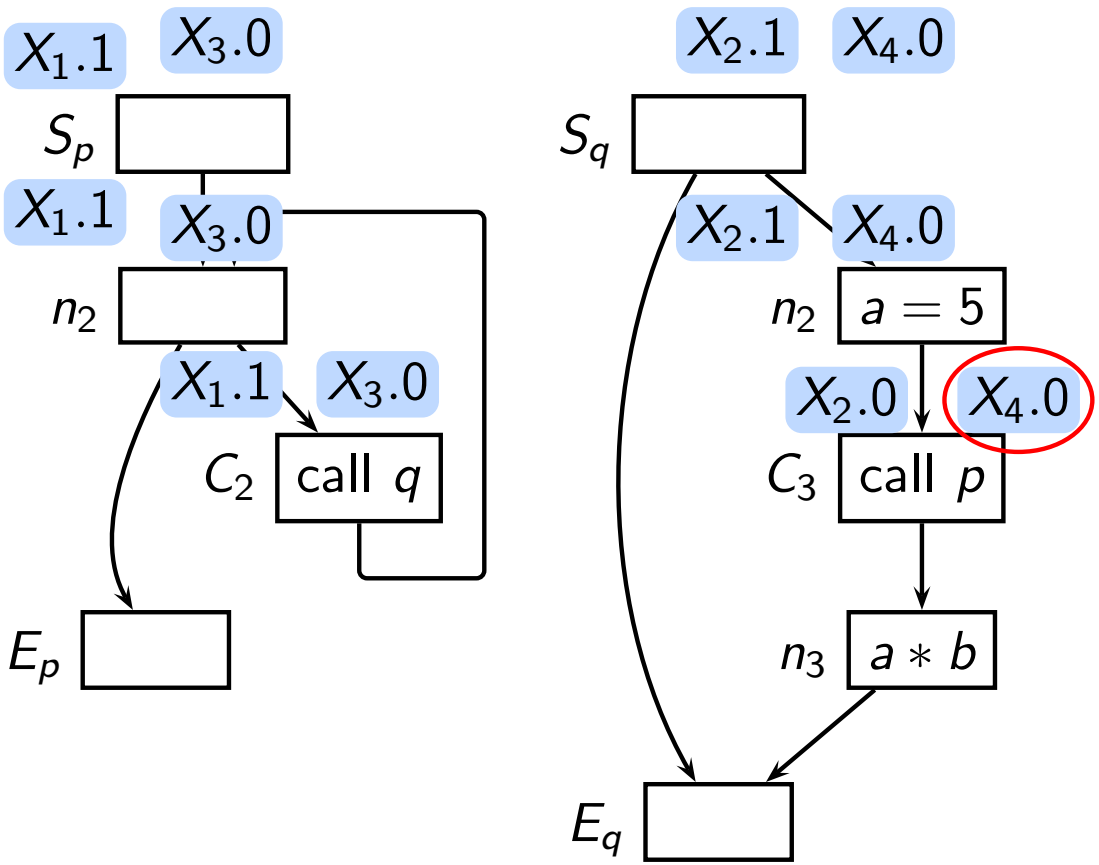


Context	*exitValue*
$X_1 = \langle p,1 \rangle$	0
$X_2 = \langle q,1 \rangle$	0
$X_3 = \langle p,0 \rangle$	0
$X_4 = \langle q,0 \rangle$	0

Partially Available Expressions Analysis Using Value Contexts

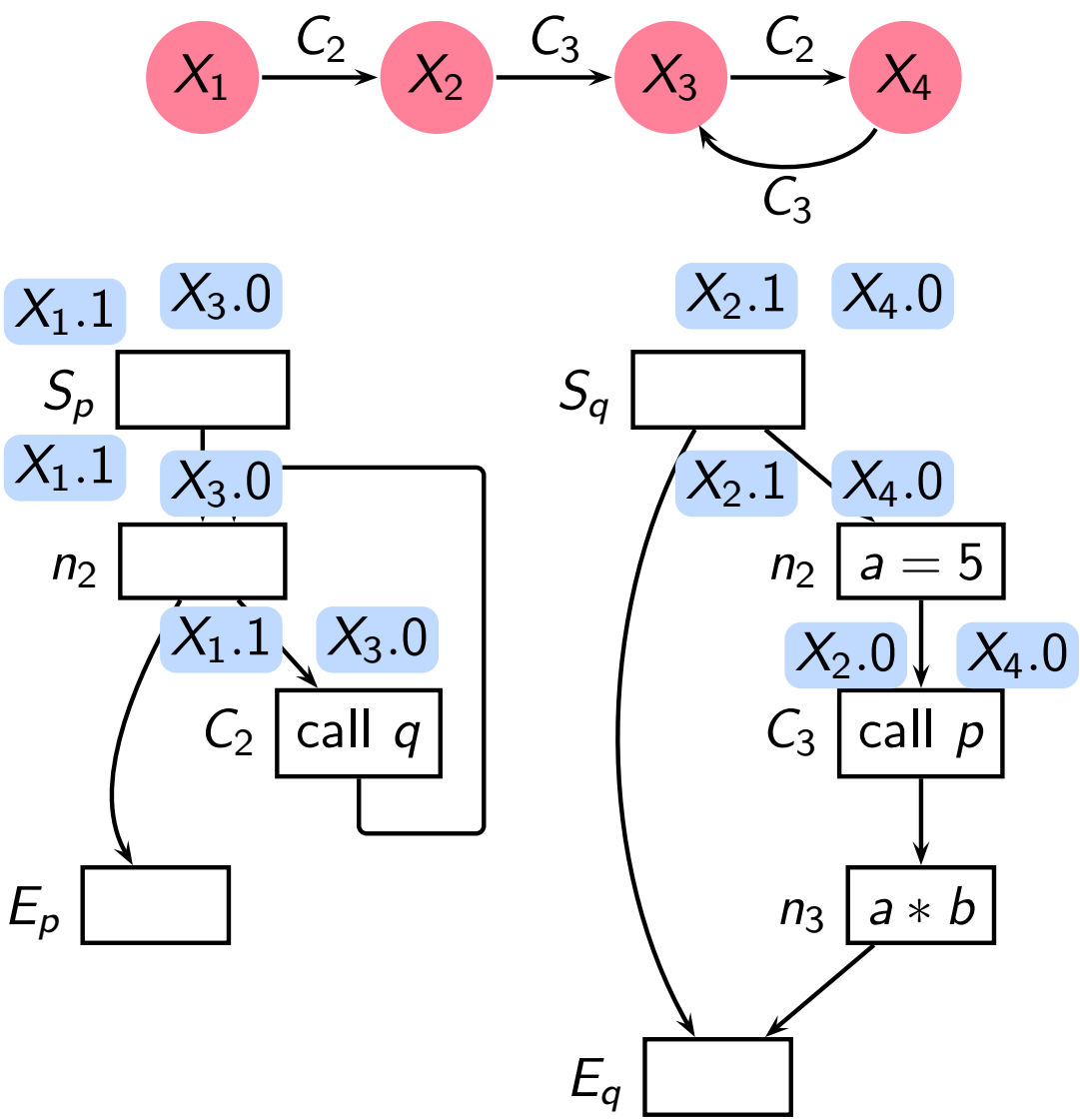


Context	*exitValue*
$X_1 = \langle p,1 \rangle$	0
$X_2 = \langle q,1 \rangle$	0
$X_3 = \langle p,0 \rangle$	0
$X_4 = \langle q,0 \rangle$	0



And now the value 0 reaches p at call site C_3

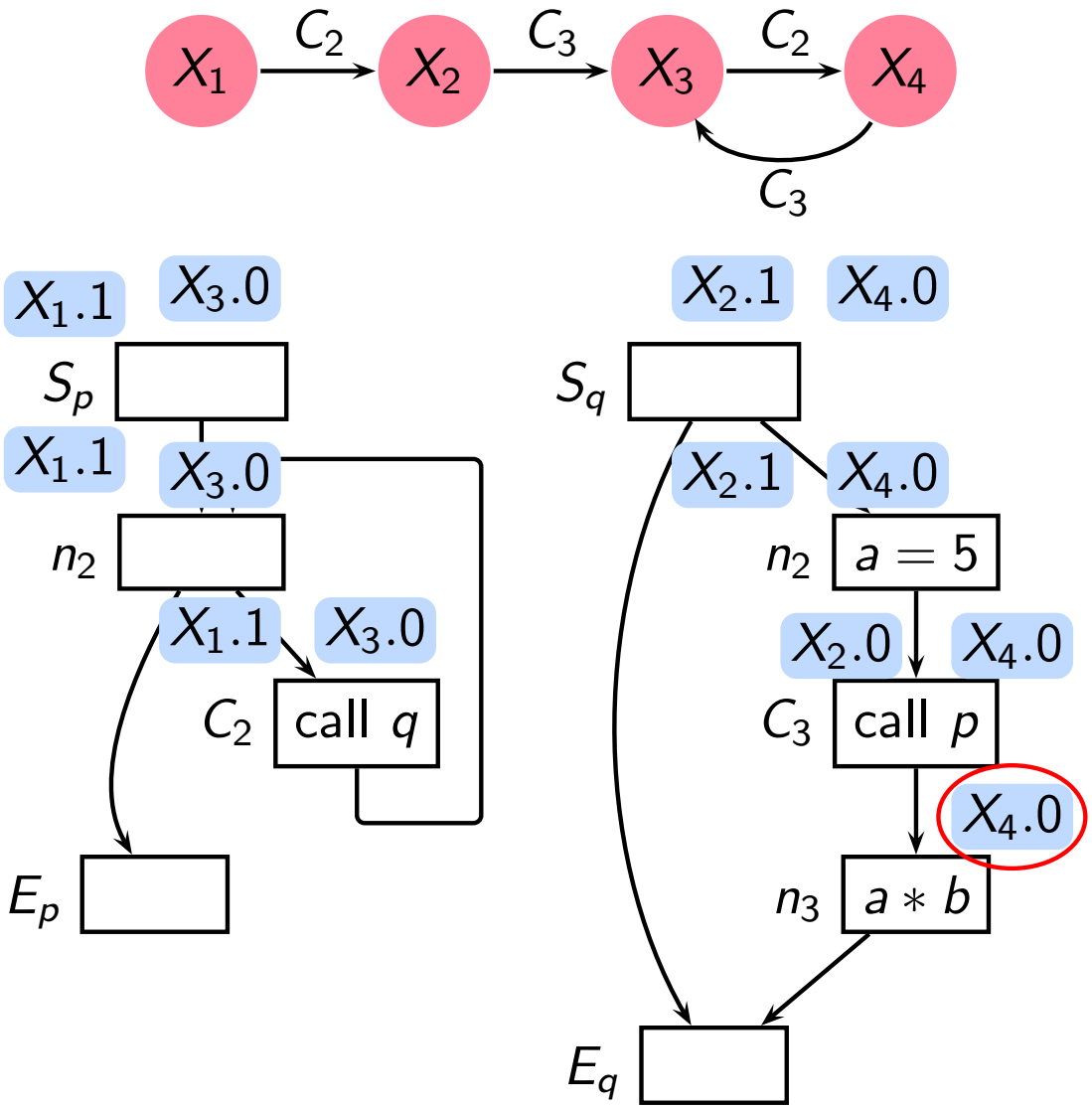
Partially Available Expressions Analysis Using Value Contexts



Context	*exitValue*
$X_1 = \langle p,1 \rangle$	0
$X_2 = \langle q,1 \rangle$	0
$X_3 = \langle p,0 \rangle$	0
$X_4 = \langle q,0 \rangle$	0

We already have context X_3 with entry value 0 for p so no need to analyse p again

Partially Available Expressions Analysis Using Value Contexts

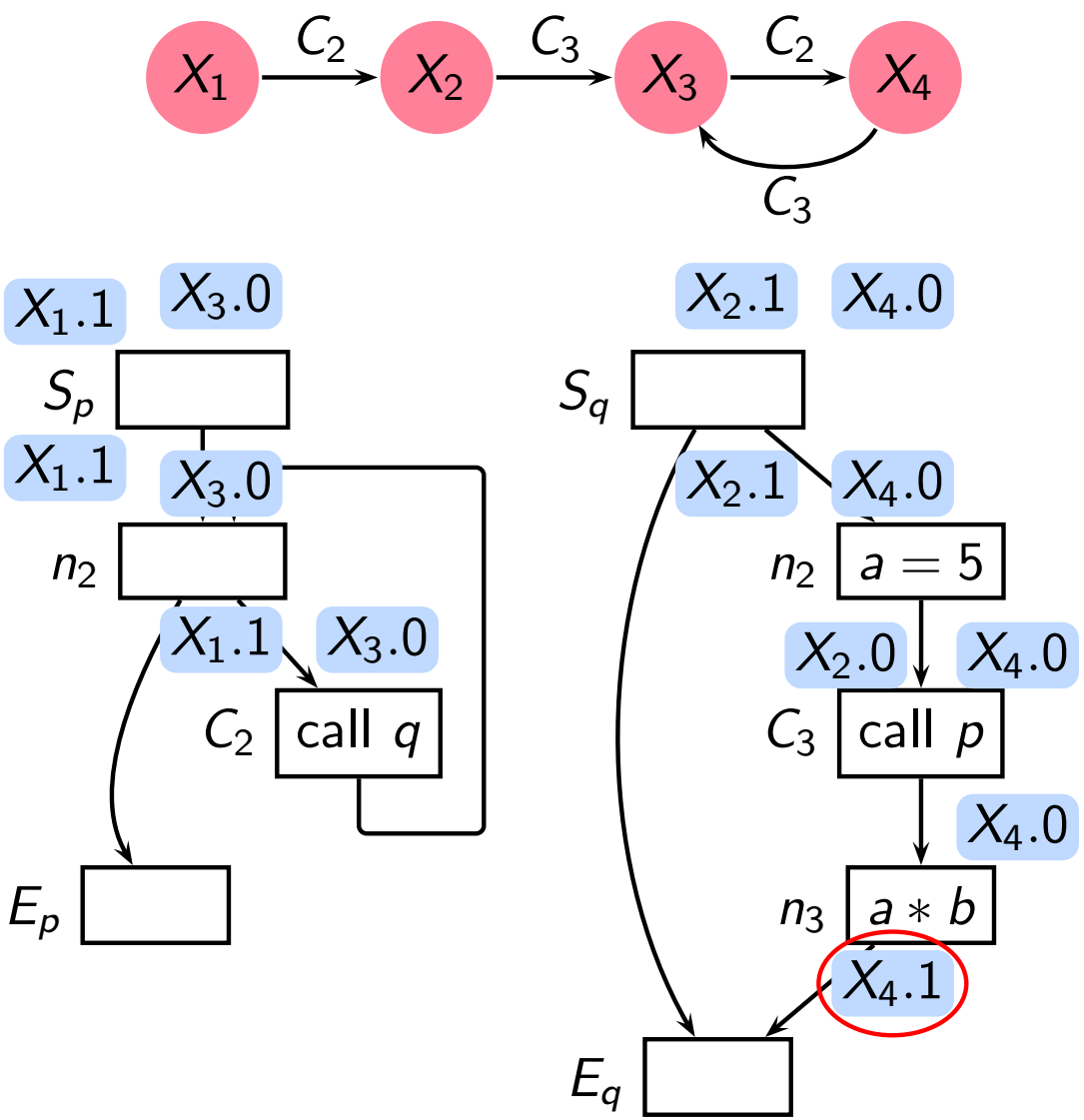


Context	*exitValue*
$X_1 = \langle p,1 \rangle$	0
$X_2 = \langle q,1 \rangle$	0
$X_3 = \langle p,0 \rangle$	0
$X_4 = \langle q,0 \rangle$	0

We use the *exitValue* for X_3 to compute Out_{C_3} for the context X_4 (because of the transition $X_4 \xrightarrow{C_3} X_3$)

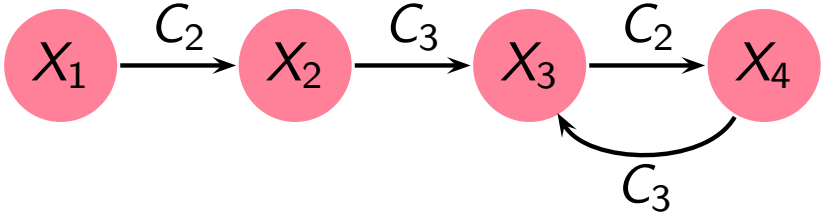
The analysis of p is not yet over for any context, and so we get the $\top$ value

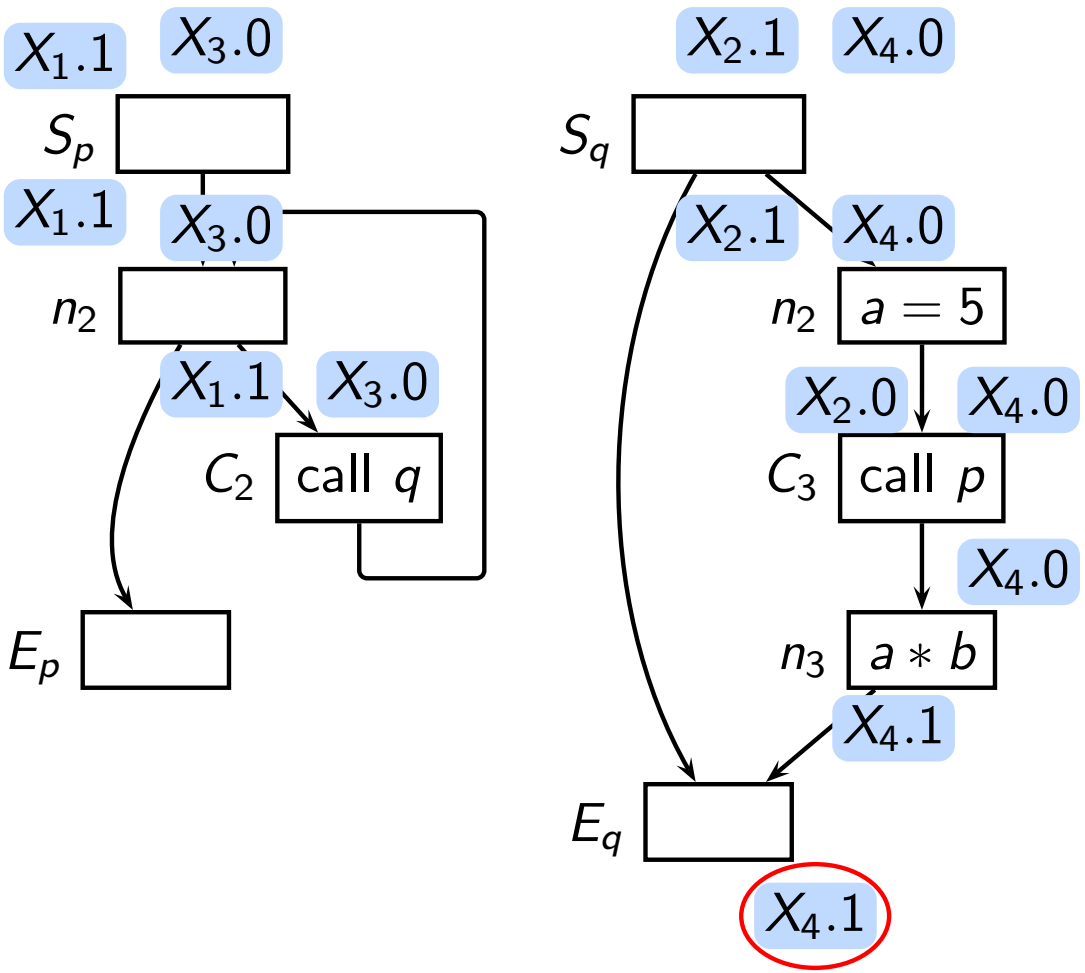
Partially Available Expressions Analysis Using Value Contexts



Context	*exitValue*
$X_1 = \langle p,1 \rangle$	0
$X_2 = \langle q,1 \rangle$	0
$X_3 = \langle p,0 \rangle$	0
$X_4 = \langle q,0 \rangle$	0

Partially Available Expressions Analysis Using Value Contexts



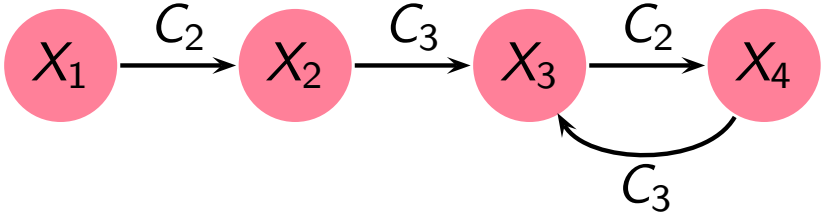


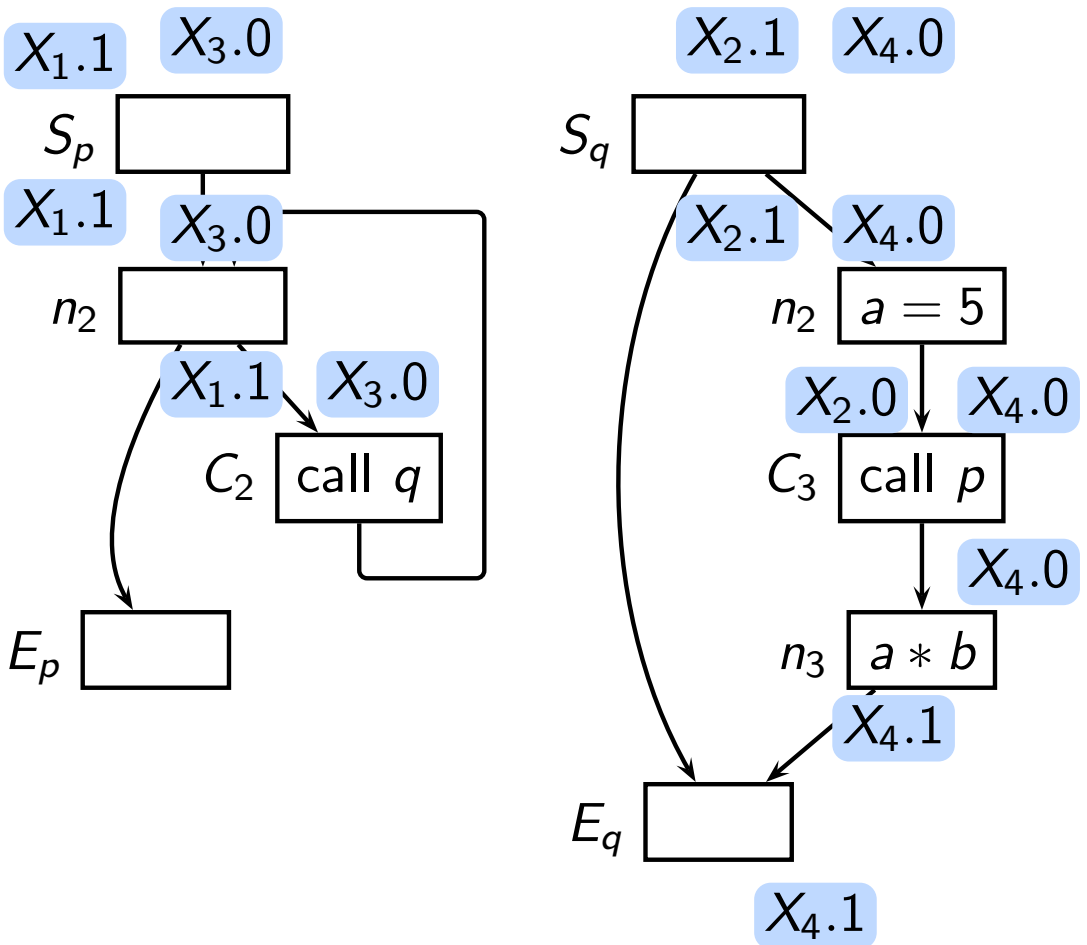
Context	*exitValue*
$X_1 = \langle p,1 \rangle$	0
$X_2 = \langle q,1 \rangle$	0
$X_3 = \langle p,0 \rangle$	0
$X_4 = \langle q,0 \rangle$	0

The analysis of q for X_4 is now and the *exitValue* of X_4 becomes 1

This change in X_4 must be propagated to X_3 in the caller p (identified from the transition $X_3 \xrightarrow{C_2} X_4$)

Partially Available Expressions Analysis Using Value Contexts



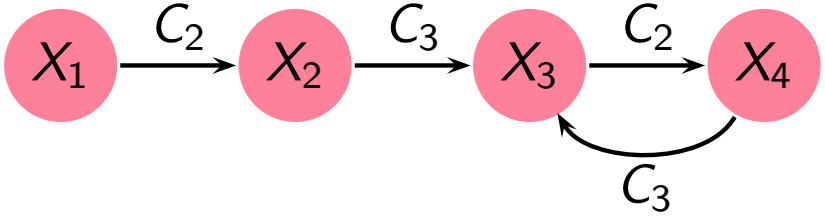


Context	*exitValue*
$X_1 = \langle p,1 \rangle$	0
$X_2 = \langle q,1 \rangle$	0
$X_3 = \langle p,0 \rangle$	0
$X_4 = \langle q,0 \rangle$	1

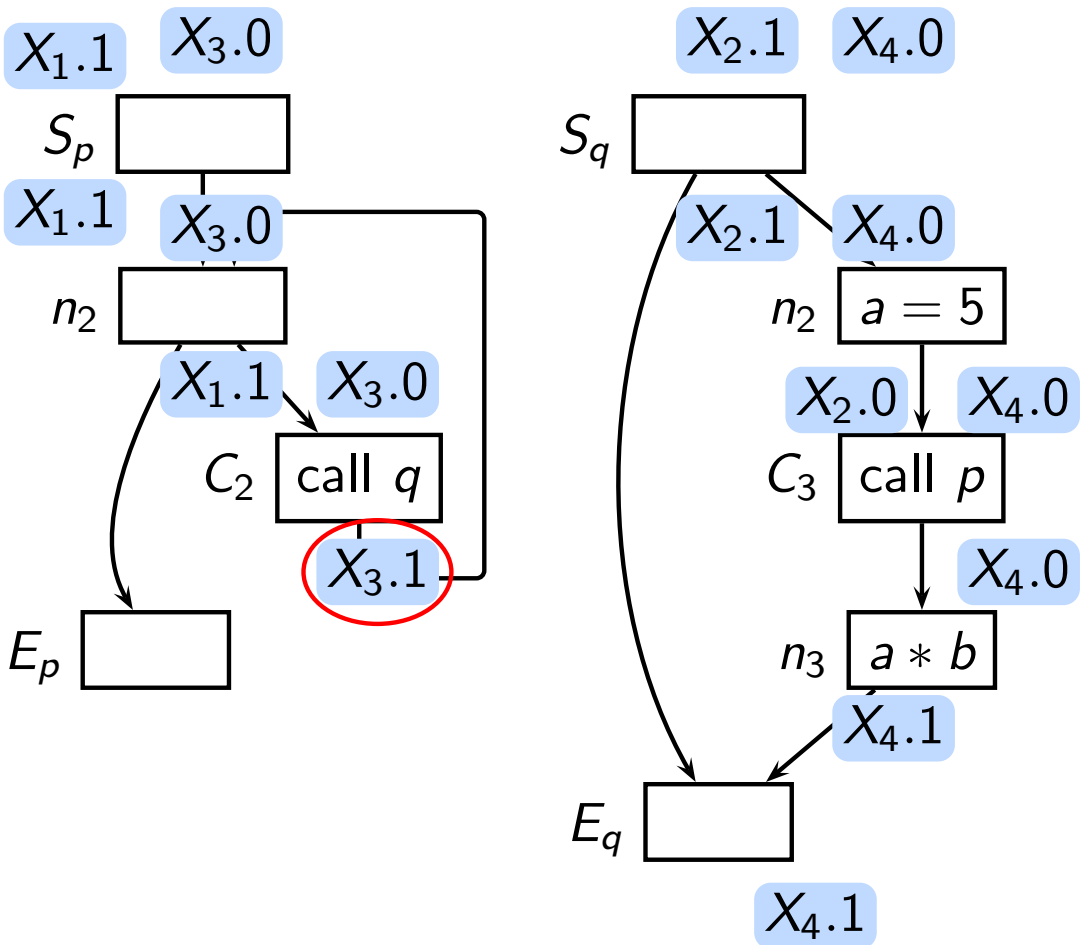
The analysis of q for X_4 is now and the *exitValue* of X_4 becomes 1

This change in X_4 must be propagated to X_3 in the caller p (identified from the transition $X_3 \xrightarrow{C_2} X_4$)

Partially Available Expressions Analysis Using Value Contexts

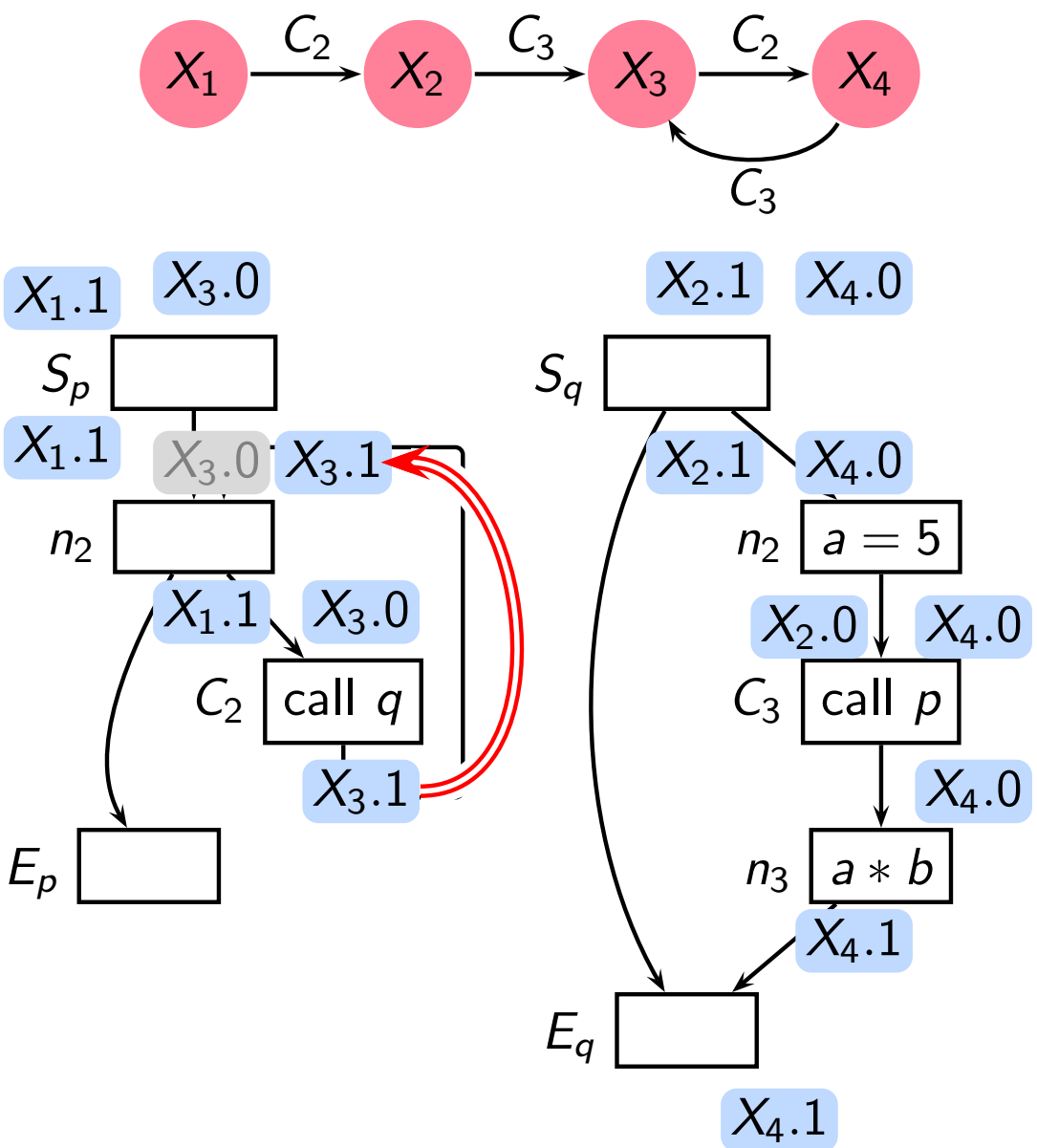


Context	*exitValue*
$X_1 = \langle p,1 \rangle$	0
$X_2 = \langle q,1 \rangle$	0
$X_3 = \langle p,0 \rangle$	0
$X_4 = \langle q,0 \rangle$	1



Out_{C_2} becomes 1 for X_3 which changes the value at In_{n_2} for X_3 to 1

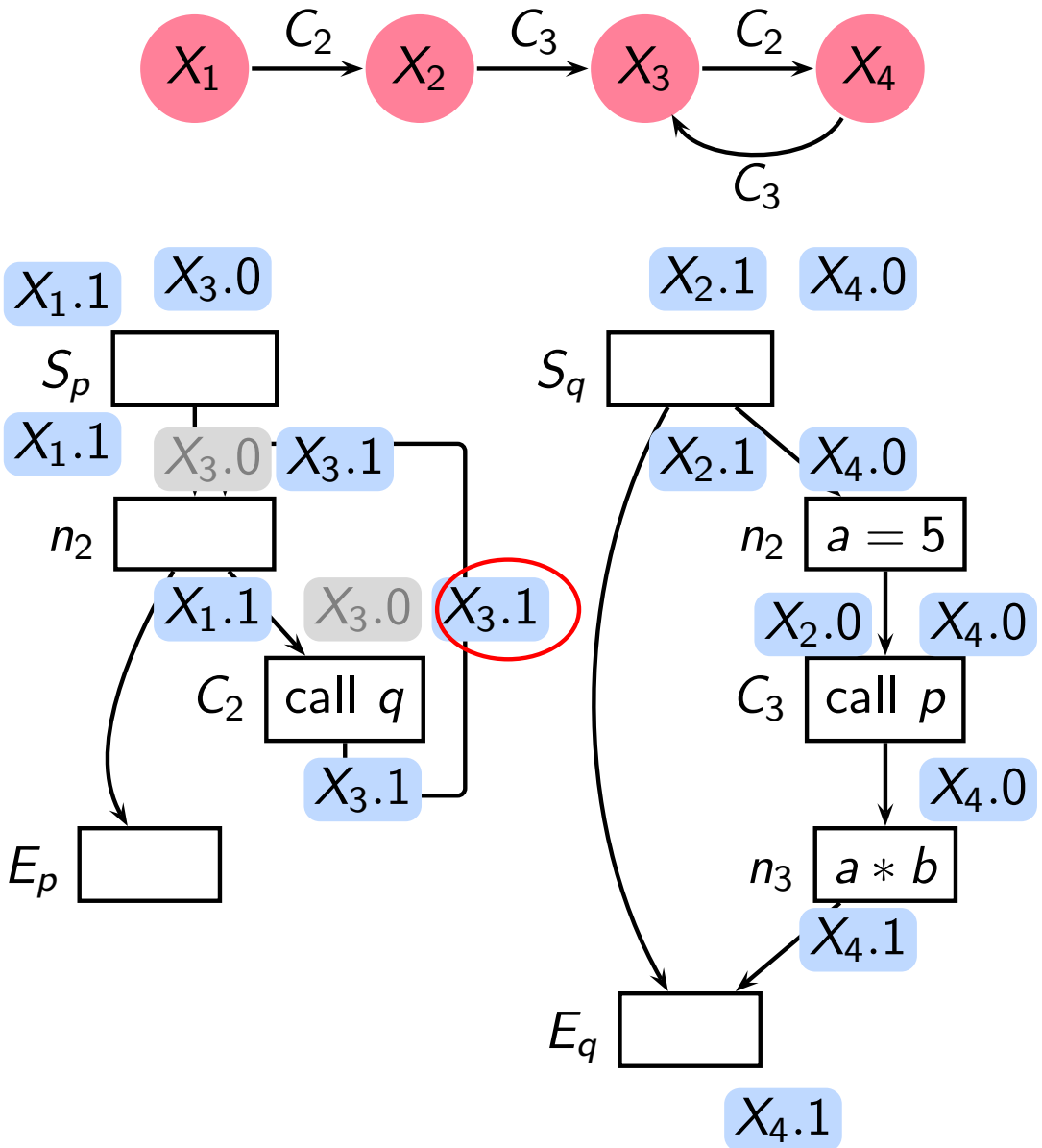
Partially Available Expressions Analysis Using Value Contexts



Context	*exitValue*
$X_1 = \langle p,1 \rangle$	0
$X_2 = \langle q,1 \rangle$	0
$X_3 = \langle p,0 \rangle$	0
$X_4 = \langle q,0 \rangle$	1

Out_{C_2} becomes 1 for X_3 which changes the value at In_{n_2} for X_3 to 1

Partially Available Expressions Analysis Using Value Contexts

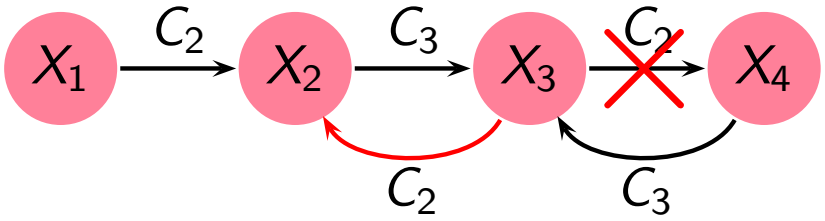


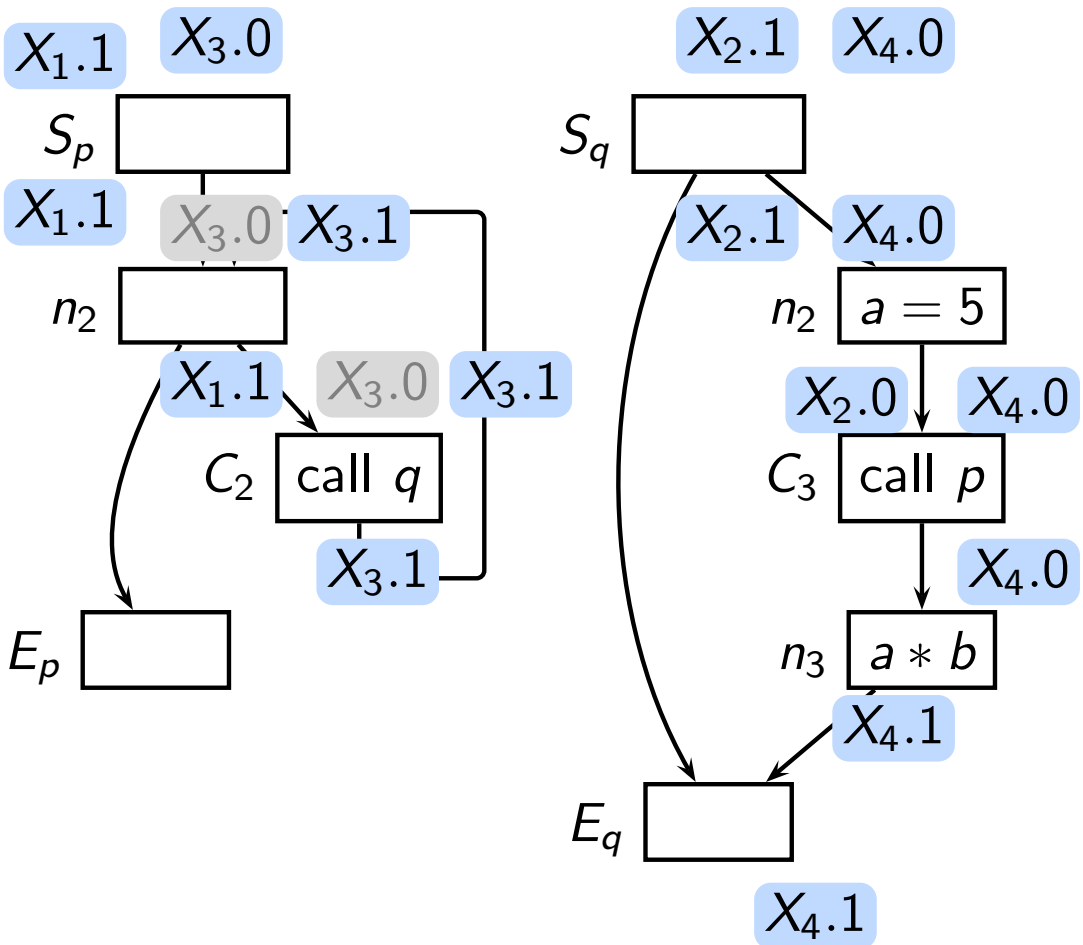
Context	*exitValue*
$X_1 = \langle p,1 \rangle$	0
$X_2 = \langle q,1 \rangle$	0
$X_3 = \langle p,0 \rangle$	0
$X_4 = \langle q,0 \rangle$	1

In_{C_2} becomes 1 for X_3

Since we have a context for q with entry value 1 (X_2), we remove the transition $X_3 \xrightarrow{C_2} X_4$ and add the transition $X_3 \xrightarrow{C_2} X_2$

Partially Available Expressions Analysis Using Value Contexts





Context	*exitValue*
$X_1 = \langle p,1 \rangle$	0
$X_2 = \langle q,1 \rangle$	0
$X_3 = \langle p,0 \rangle$	0
$X_4 = \langle q,0 \rangle$	1

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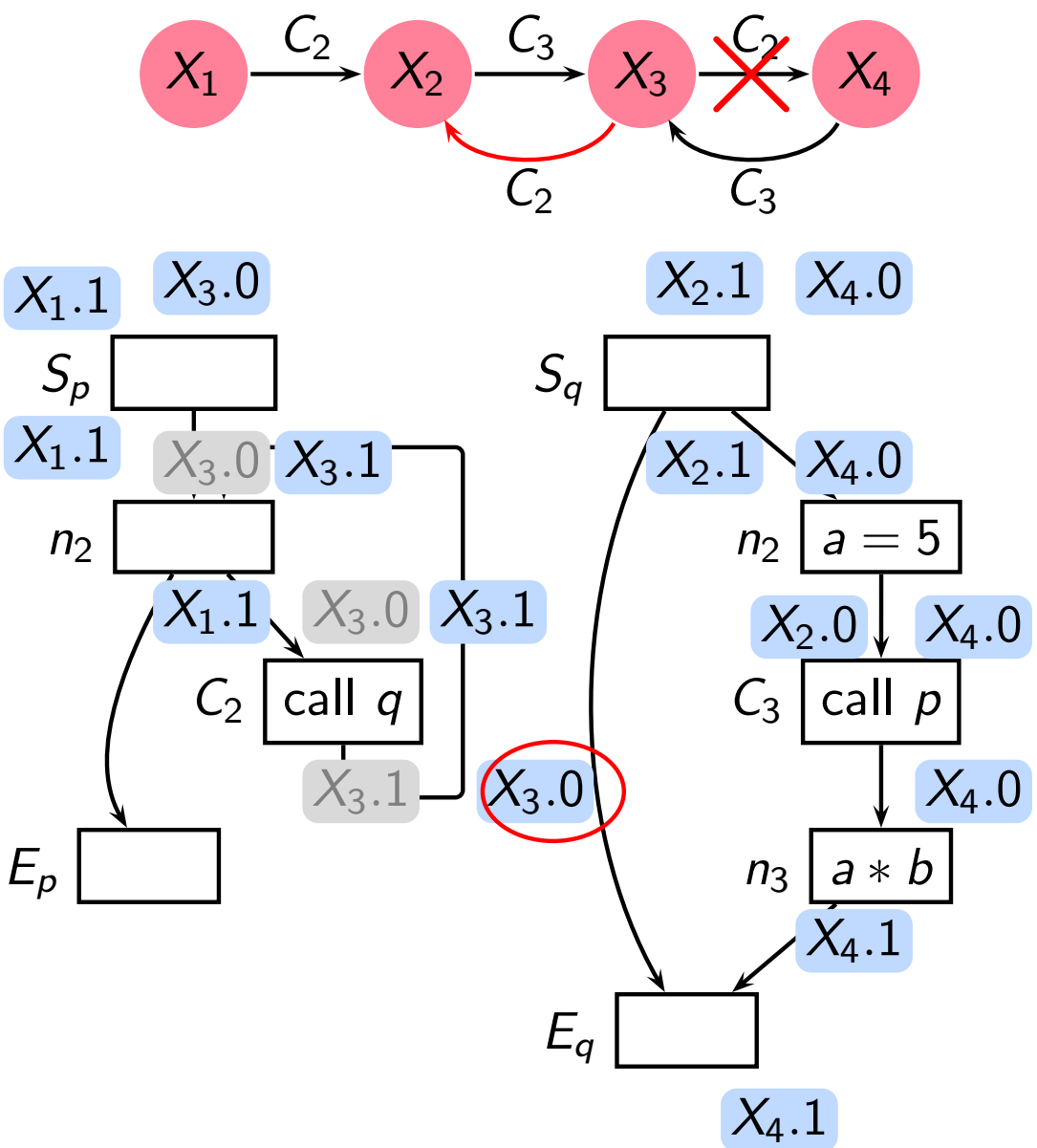
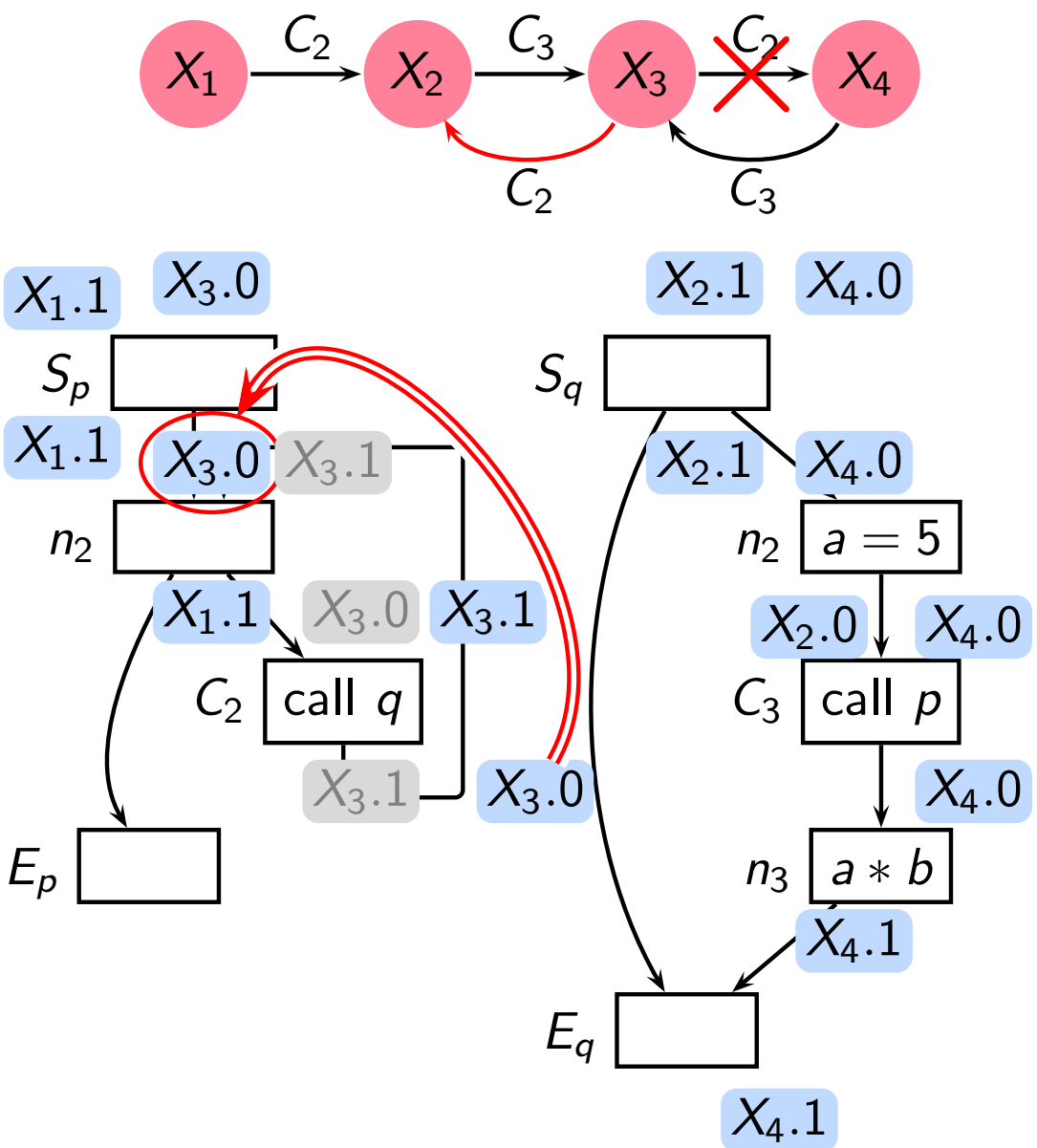
Partially Available Expressions Analysis Using Value Contexts



Context	*exitValue*
$X_1 = \langle p,1 \rangle$	0
$X_2 = \langle q,1 \rangle$	0
$X_3 = \langle p,0 \rangle$	0
$X_4 = \langle q,0 \rangle$	1

We use the *exitValue* of X_2 to compute the value of X_3 in Out_{C_2}

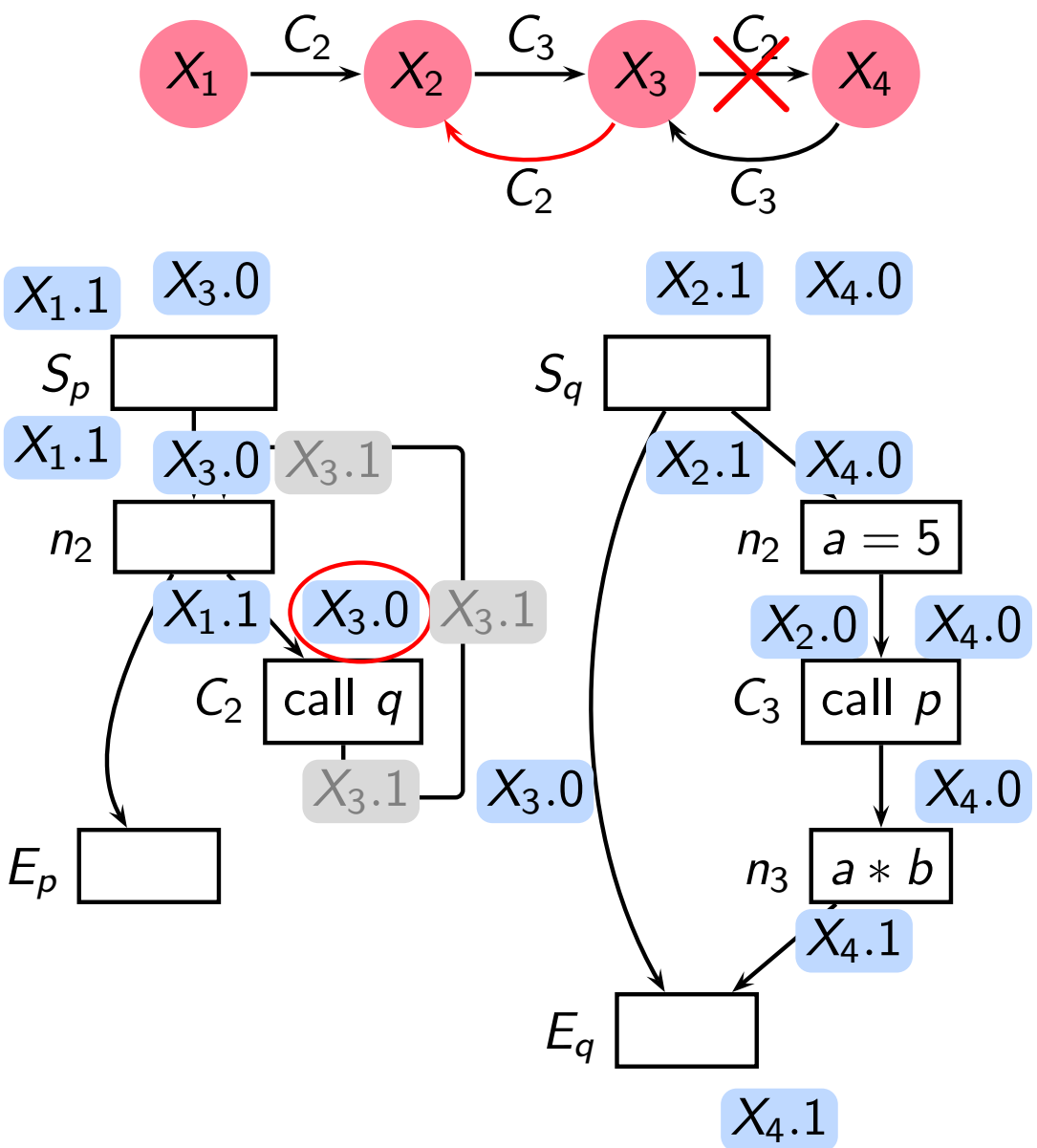
Partially Available Expressions Analysis Using Value Contexts



Context	*exitValue*
$X_1 = \langle p,1 \rangle$	0
$X_2 = \langle q,1 \rangle$	0
$X_3 = \langle p,0 \rangle$	0
$X_4 = \langle q,0 \rangle$	1

The value of X_3 in In_{n_2} once again becomes 0

Partially Available Expressions Analysis Using Value Contexts

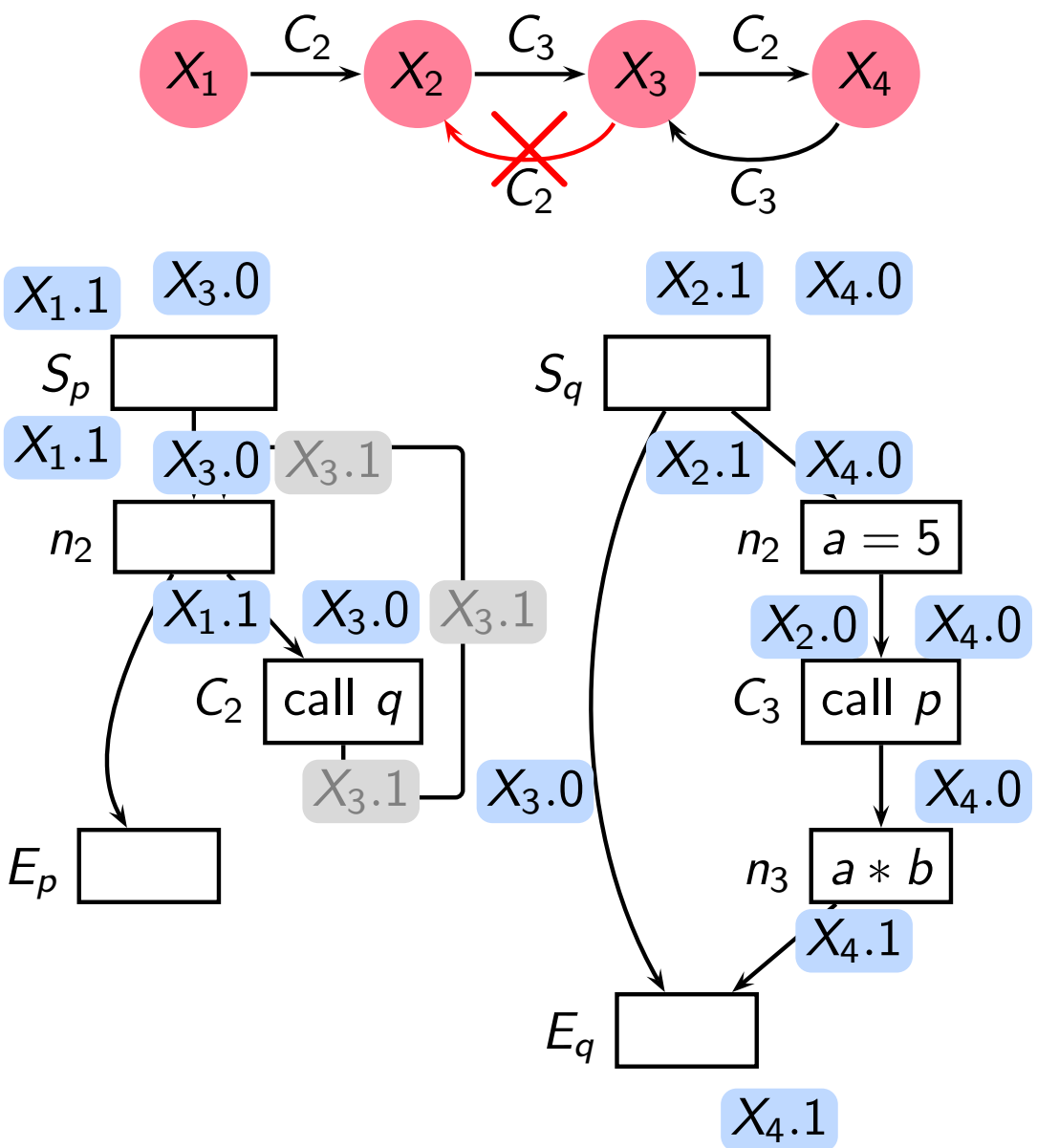


Context	*exitValue*
$X_1 = \langle p,1 \rangle$	0
$X_2 = \langle q,1 \rangle$	0
$X_3 = \langle p,0 \rangle$	0
$X_4 = \langle q,0 \rangle$	1

The value of X_3 in In_{C_2} once again becomes 0

The transition from X_3 needs to be restored to $X_3 \xrightarrow{C_2} X_4$ removing the transition $X_3 \xrightarrow{C_2} X_2$

Partially Available Expressions Analysis Using Value Contexts

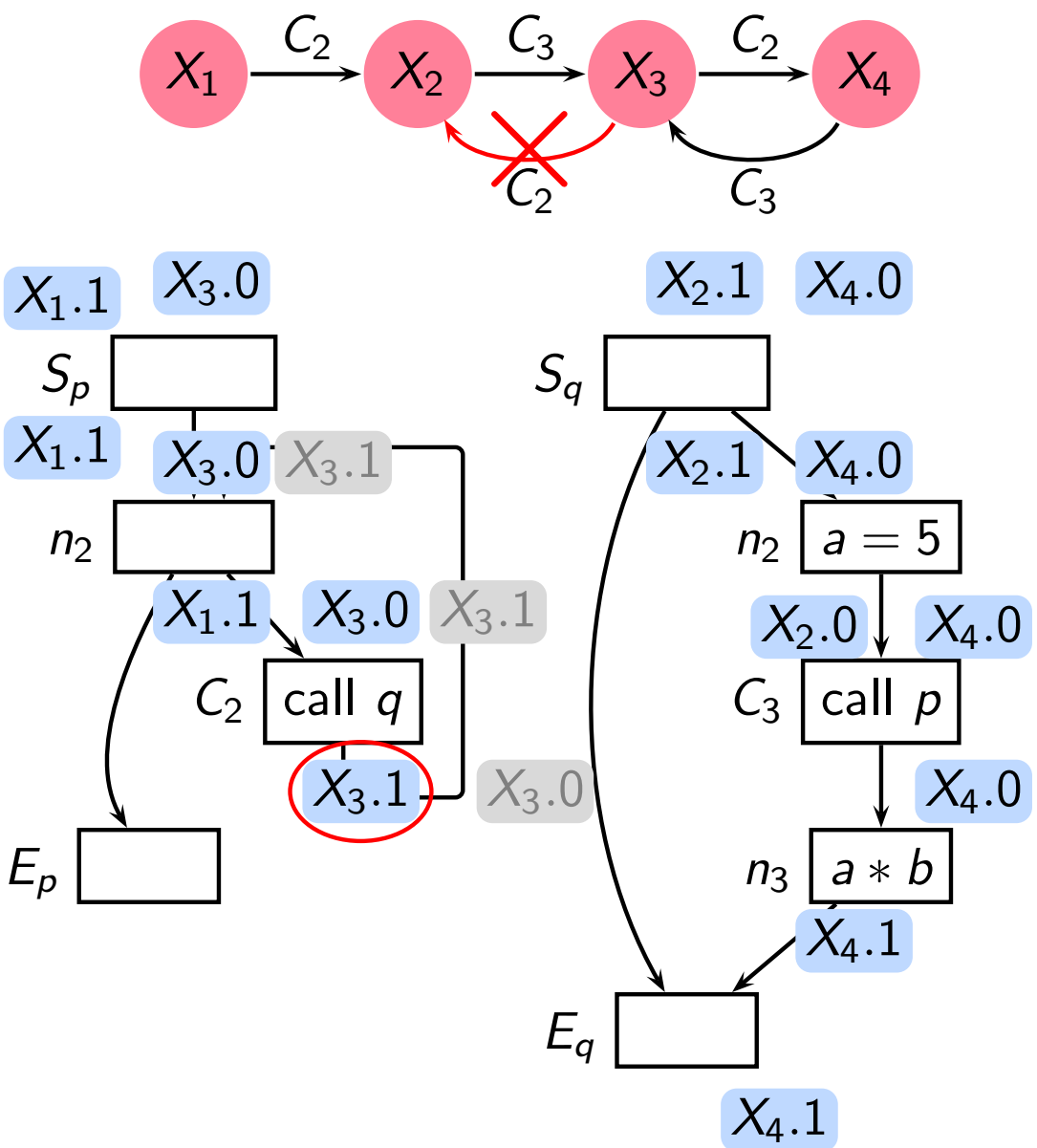


Context	*exitValue*
$X_1 = \langle p,1 \rangle$	0
$X_2 = \langle q,1 \rangle$	0
$X_3 = \langle p,0 \rangle$	0
$X_4 = \langle q,0 \rangle$	1

The value of X_3 in In_{C_2} once again becomes 0

The transition from X_3 needs to be restored to $X_3 \xrightarrow{C_2} X_4$ removing the transition $X_3 \xrightarrow{C_2} X_2$

Partially Available Expressions Analysis Using Value Contexts

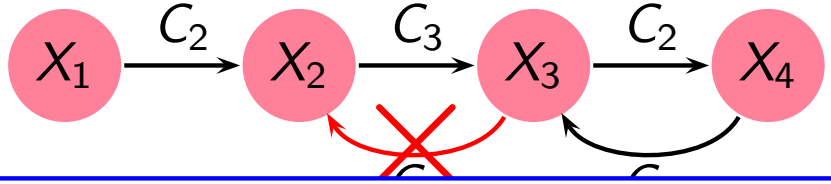


Context	*exitValue*
$X_1 = \langle p,1 \rangle$	0
$X_2 = \langle q,1 \rangle$	0
$X_3 = \langle p,0 \rangle$	0
$X_4 = \langle q,0 \rangle$	1

We use the *exitValue* of X_4 to compute Out_{C_2} for X_3 which once again becomes 0

Thus we are back to the same situation

Partially Available Expressions Analysis Using Value Contexts



Context	*exitValue*
$X_1 = \langle p,1 \rangle$	0

- The process would not terminate so long as the processing of the nodes in the loop continues
- If the work list organization allows processing of E_p, then the *exitValue* of X_3 will also change to 1 which will lead to termination
- Our underlying flow functions are monotonic and a fixed point exists; non-termination is caused by the algorithm because its progress depends on the order of the nodes in the work list
- We avoid this problem by taking a meet at the exit of call nodes when the exit values of existing contexts are used at the call sites in the callers

$X_4.1$

Defining Value Context Method Using Data Flow Equations

- The overall data flow values Γ are sets of $X.v$ where X is a context and $v \in L$ is the underlying data flow value.
- We merge underlying data flow values only if the contexts are same

$$\Gamma_1 \uplus \Gamma_2 = \{X.w \mid \begin{array}{lcll} X.u \in \Gamma_1 \wedge X.v \in \Gamma_2 & \Rightarrow & w = u \sqcap v, \\ X.u \in \Gamma_1 \wedge X.v \notin \Gamma_2 & \Rightarrow & w = u, \\ X.u \notin \Gamma_1 \wedge X.v \in \Gamma_2 & \Rightarrow & w = v \end{array} \}$$

  Effectively, if a context does not exist in Γ, its value is $\top$ in Γ
- Data flow variables for node n in procedure p are $In(p, n)$ and $Out(p, n)$
- The flow function for node n in procedure p is $f(p, n)$

Defining Value Context Method Using Data Flow Equations

We assume the following auxiliary functions

- Function *context* maintains the context information

  $context(p, v)$ returns the context of procedure p for entry value v

  If no such context exists, the function creates a new context and returns it
- Function $exitValue(X)$ returns the exit valus of context X

  If context X does not exist, the function returns $\top \in L$
- Function *gpred* extends the predcessor relation pred (which is local to a procedure) to a global level across procedures

$$gpred(p, n) = \begin{cases} \{(q, m) \mid \text{ call site } m \text{ in } q \text{ calls } p\} & n \text{ is } S_p \\ \{(p, m) \mid m \in pred(n)\} & \text{otherwise} \end{cases}$$

Defining Value Context Method Using Data Flow Equations

We define data flow equations for a forward data flow analysis

$$In(p,n) = \begin{cases} \{X.v \mid X = context(p,v), Y.v \in In(q,m), \\ \qquad (q,m) \in gpred(p,n)\} & n \text{ is } S_p \\ \biguplus_{(p,m) \in gpred(p,n)} Out(p,m) & \text{otherwise} \end{cases}$$

$$Out(p,n) = \begin{cases} Out(p,n) \uplus \{X.v \mid X.v' \in In(p,m), & n \text{ calls } q \\ \qquad Y = context(q,v'), \\ \qquad v = exitValue(Y)\ \} \\ \{X.v \mid X.v' \in In(p,m), v = f(p,n)(v')\} & \text{otherwise} \end{cases}$$

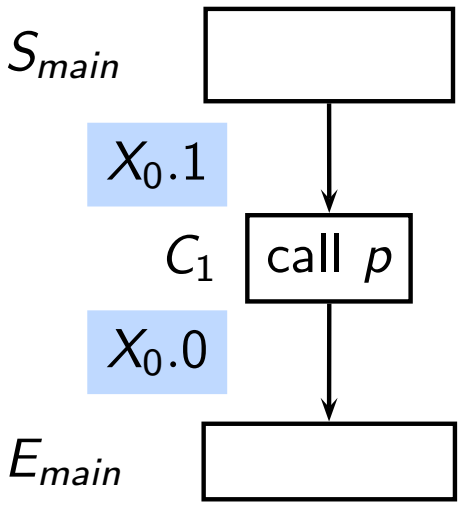
Value Contexts and Interprocedurally Valid Paths

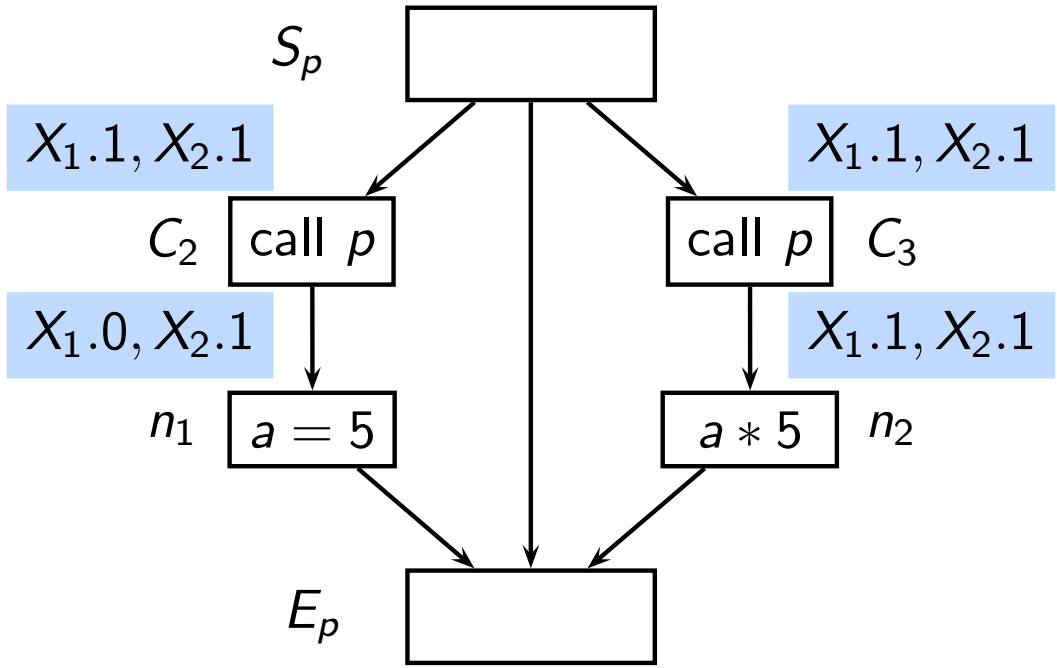
The role of value contexts in context sensitivity

- Value contexts preserve interprocedurally valid paths
- Value contexts consider only interprocedurally valid paths

We explain this with the help of an example by illustrating paths using a staircase diagram

Value Contexts and Interprocedurally Valid Paths: Example

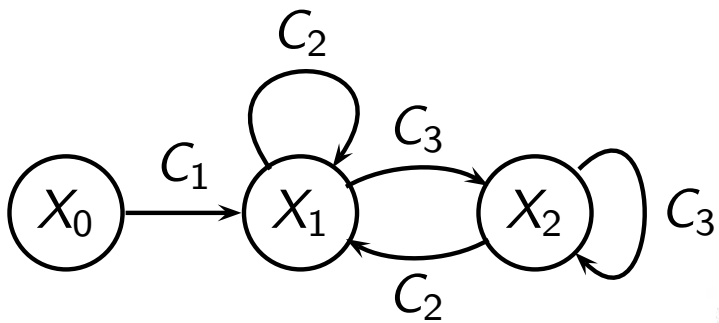




Context Transition Table

Context	*exitValue*
X_0 : $\langle \text{main}, 0 \rangle$	1
X_1 : $\langle p, 0 \rangle$	1
X_2 : $\langle p, 1 \rangle$	1

Context Transition Graph



Value Contexts and Interprocedurally Valid Paths: Example

We explain the data flow value at the entry of C_2 by dividing the paths into the following two categories:

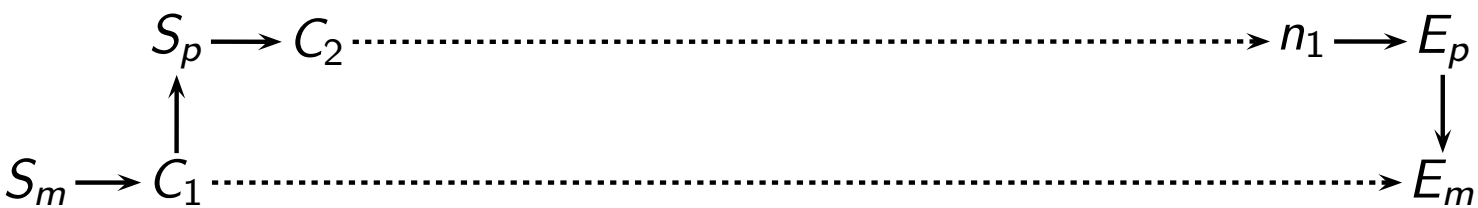
A. Paths in which the innermost recursion is along the call at C_2.

B. Paths in which the innermost recursion is along the call at C_3.

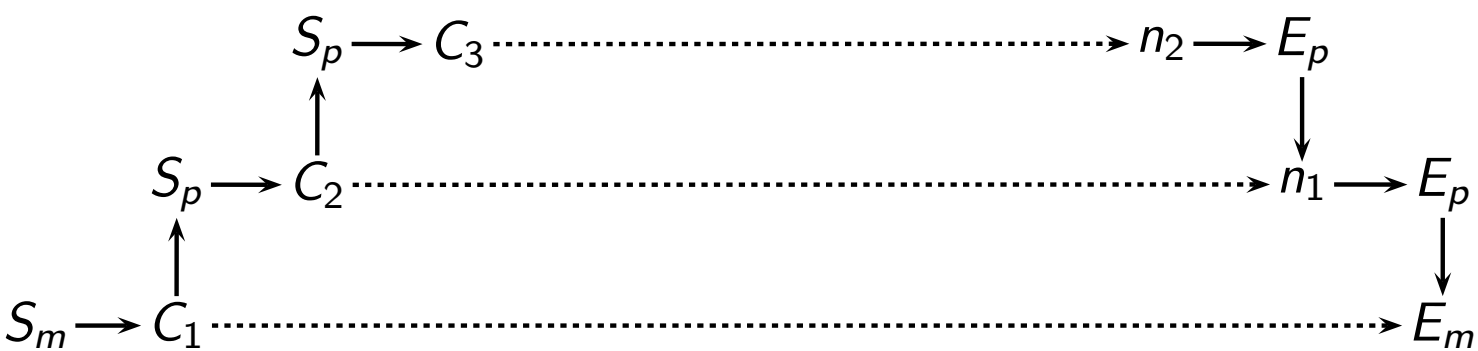
We draw the staircase diagrams of the example paths in the two categories

Innermost Recursion Along the Call at C_2

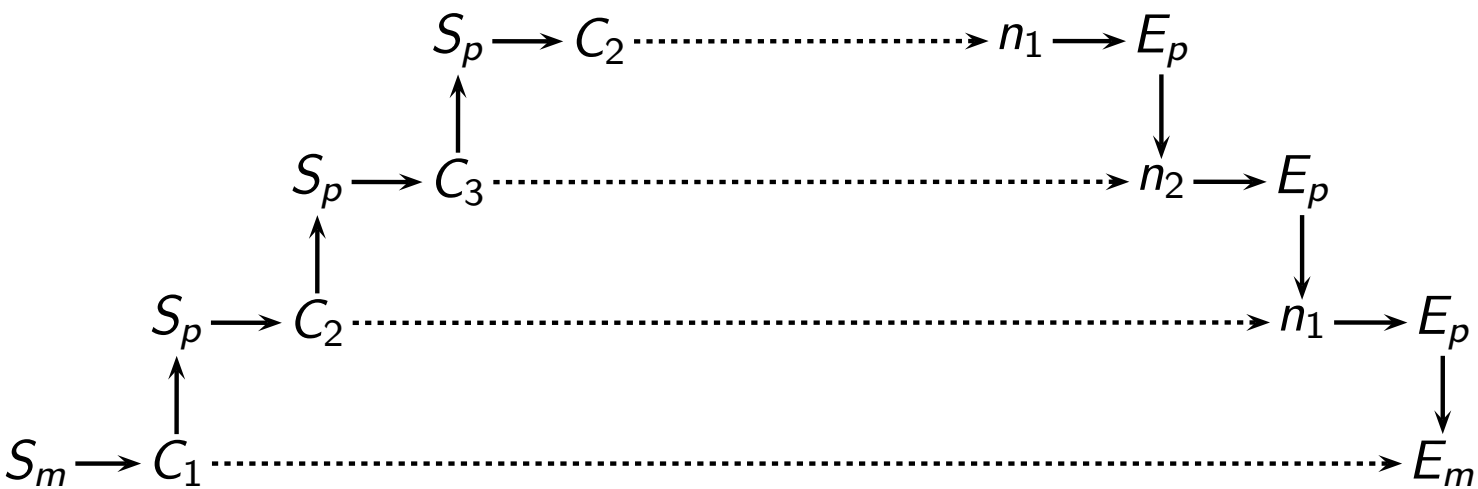
Innermost Recursion Along the Call at C_2



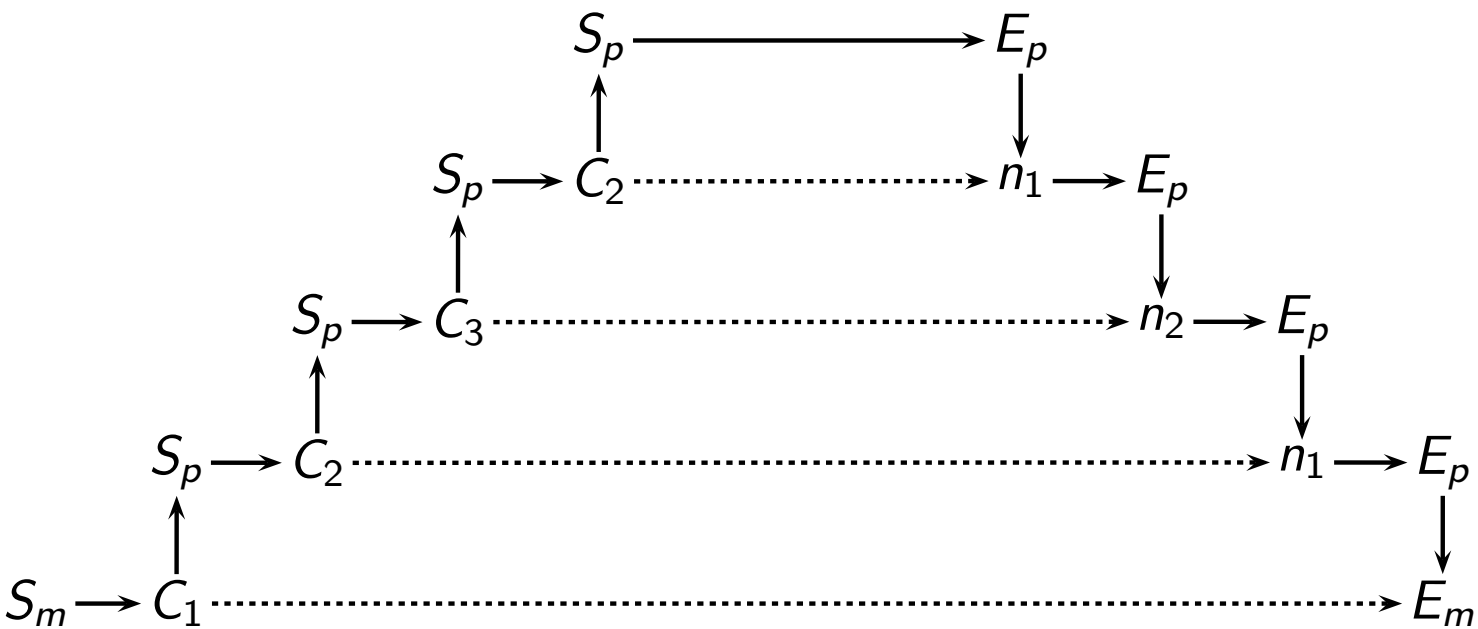
Innermost Recursion Along the Call at C_2



Innermost Recursion Along the Call at C_2

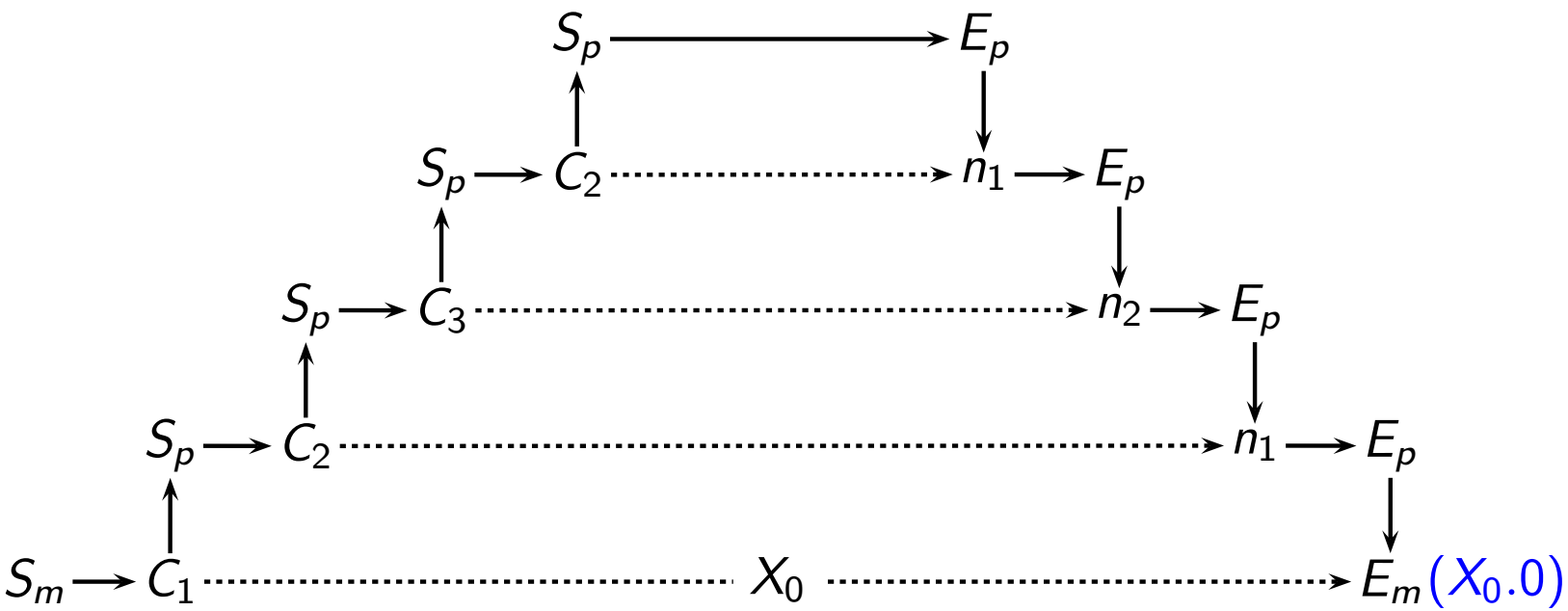


Innermost Recursion Along the Call at C_2



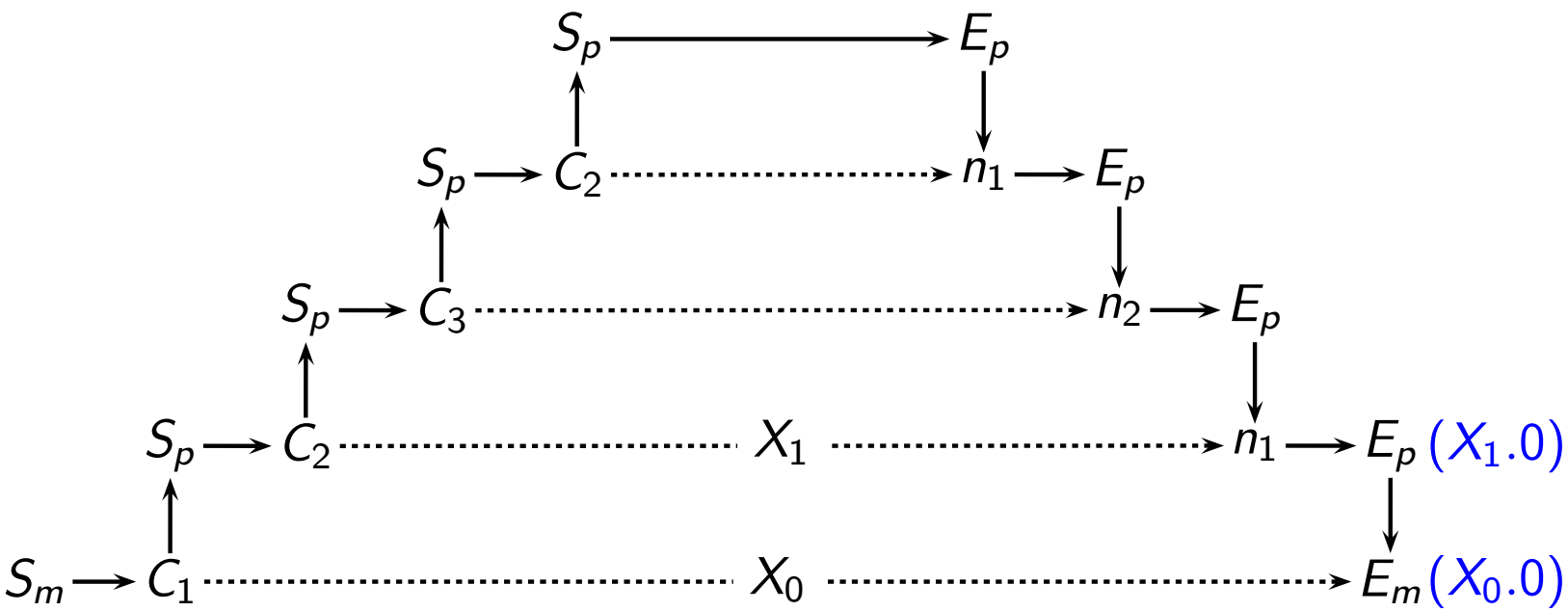
Innermost Recursion Along the Call at C_2

B_l is 0



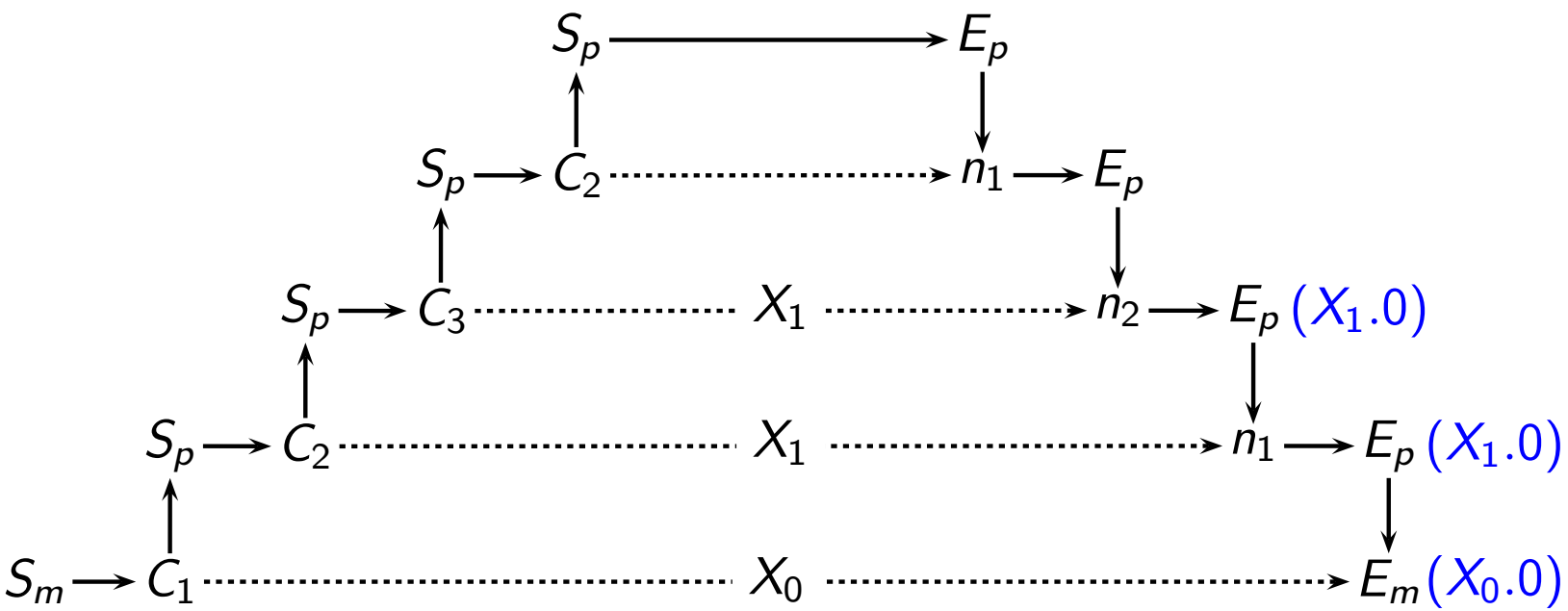
Innermost Recursion Along the Call at C_2

$Bl$is 0



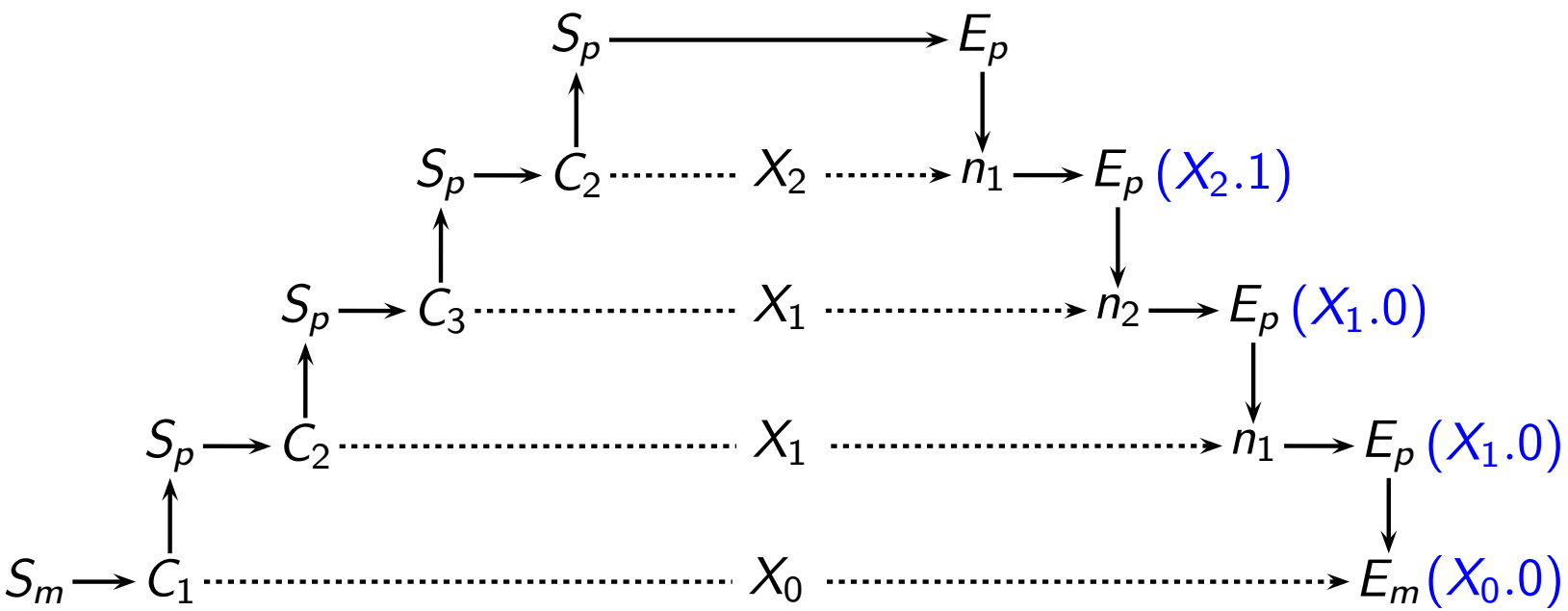
Innermost Recursion Along the Call at C_2

n_1 kills the liveness of a
New context is not required



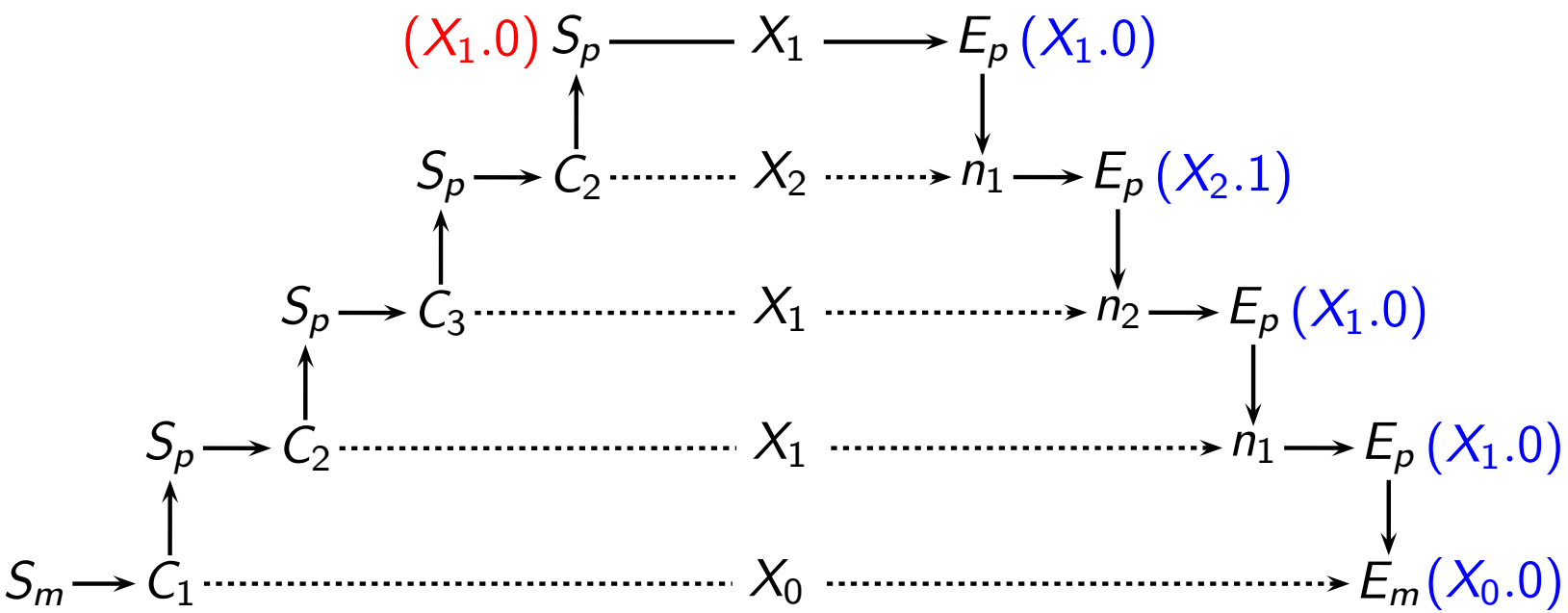
Innermost Recursion Along the Call at C_2

n_2 generates the liveness of a
New context is required



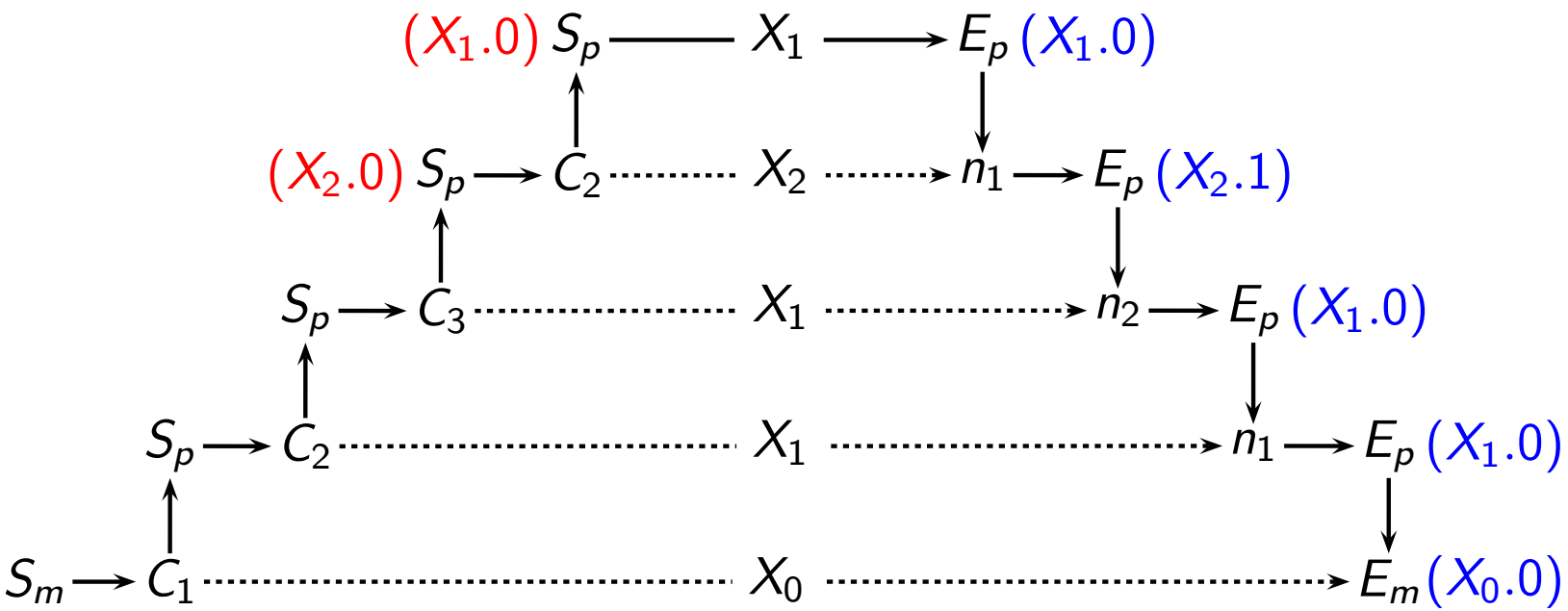
Innermost Recursion Along the Call at C_2

exitValue of X_1 is 0



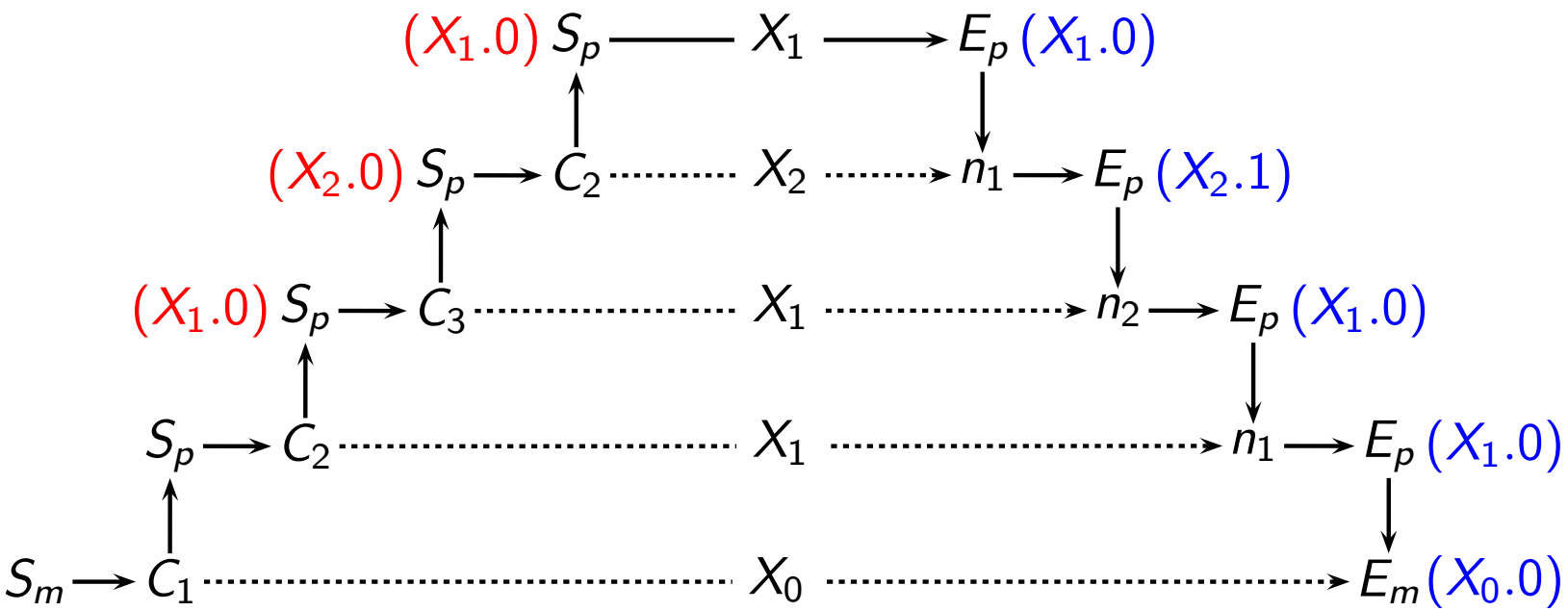
Innermost Recursion Along the Call at C_2

exitValue of X_2 is 0



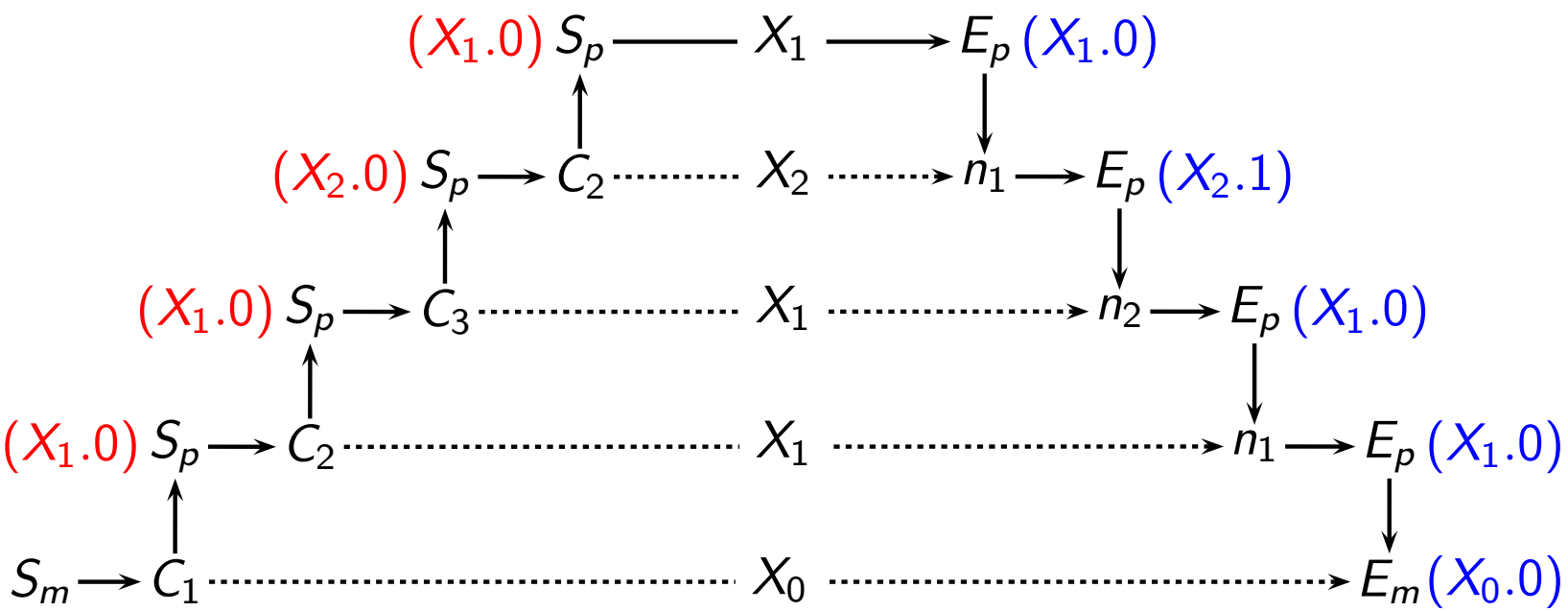
Innermost Recursion Along the Call at C_2

exitValue of X_1 remains 0



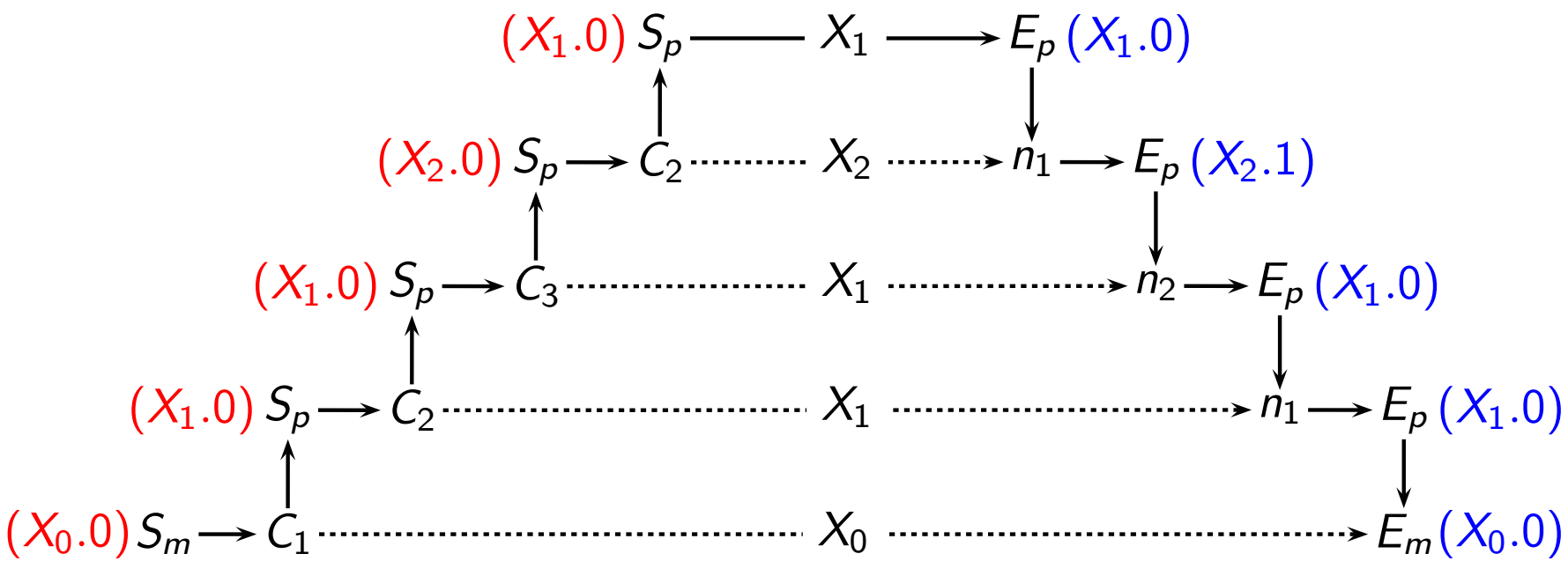
Innermost Recursion Along the Call at C_2

exitValue of X_1 remains 0



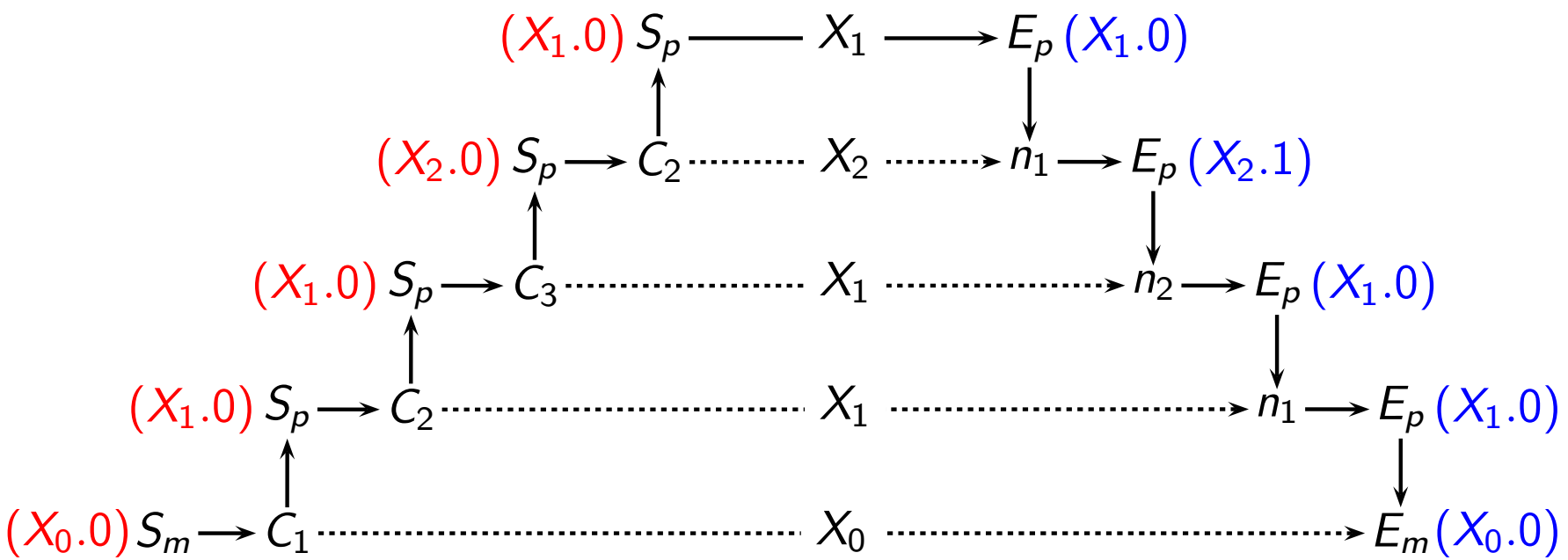
Innermost Recursion Along the Call at C_2

exitValue of X_0 is 0



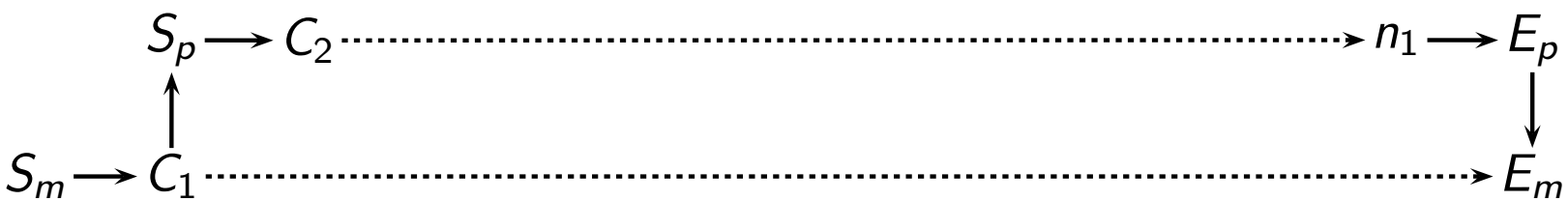
Innermost Recursion Along the Call at C_2

For this example, the innermost call determines the *exitValue* of contexts

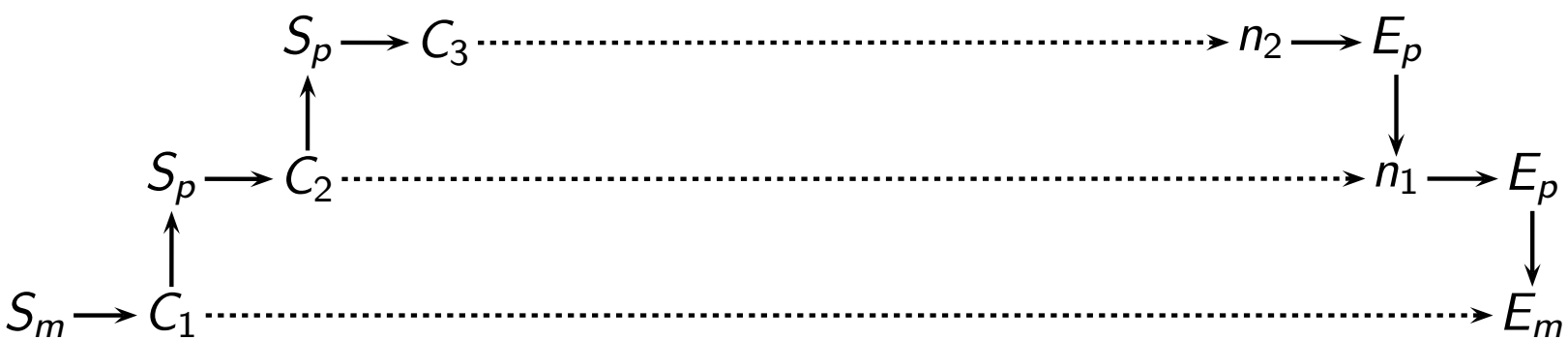


Innermost Recursion Along the Call at C_3

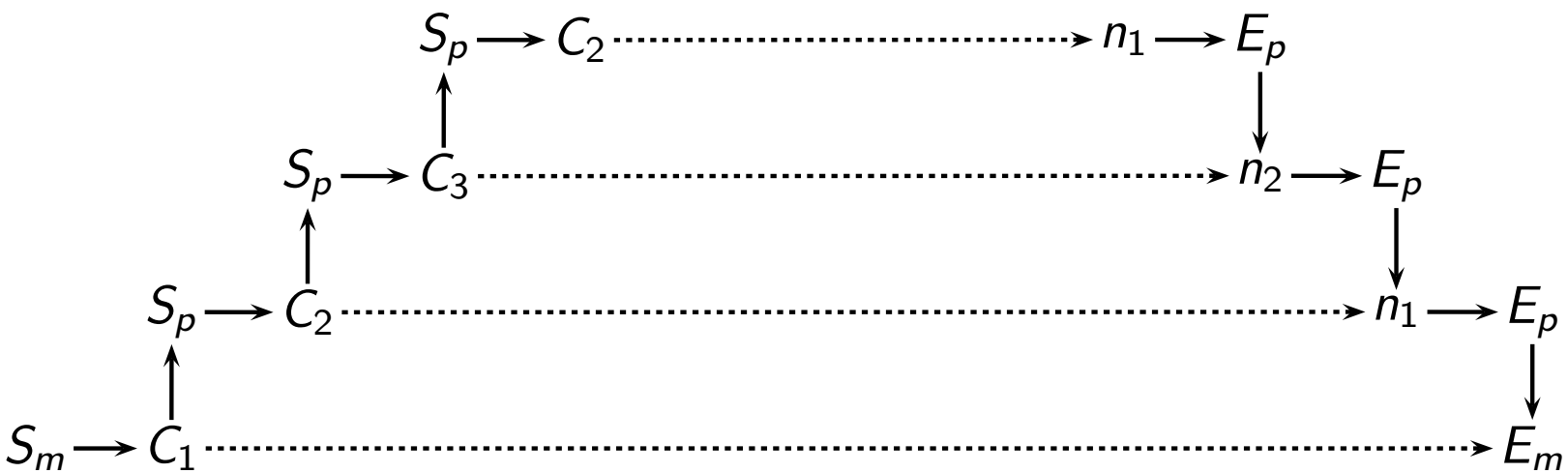
Innermost Recursion Along the Call at C_3



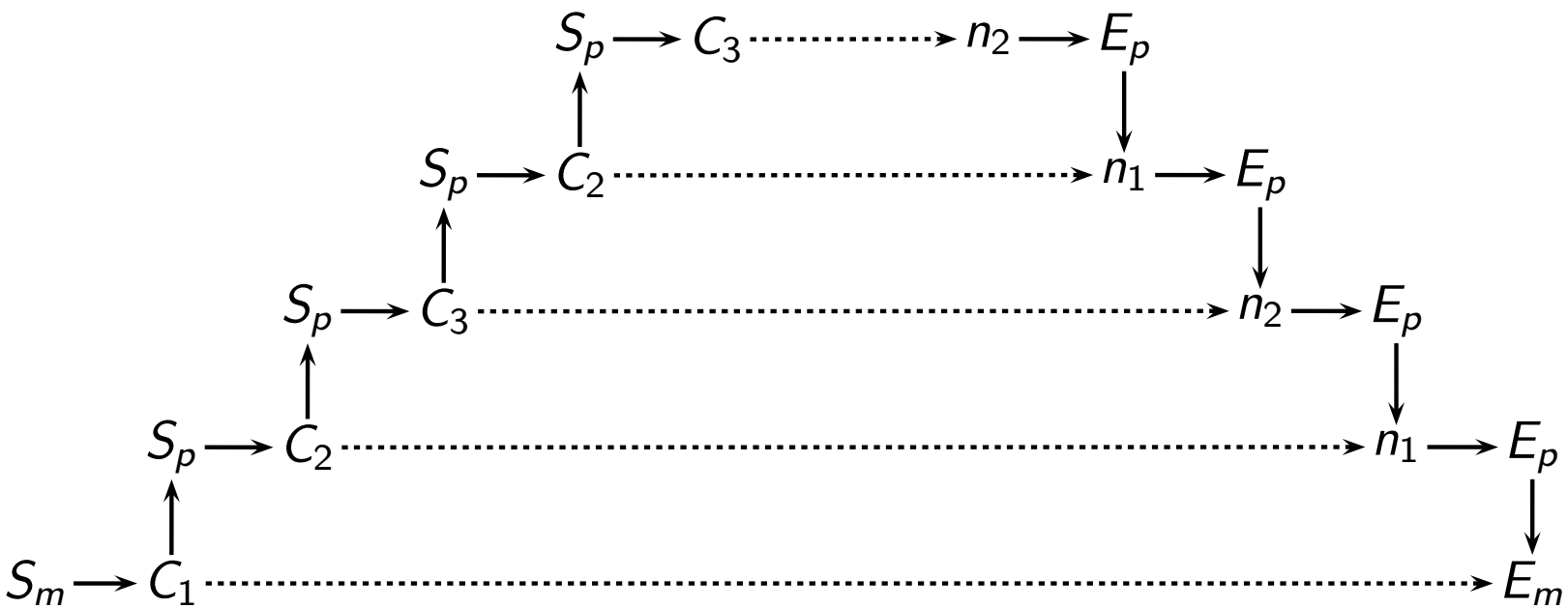
Innermost Recursion Along the Call at C_3



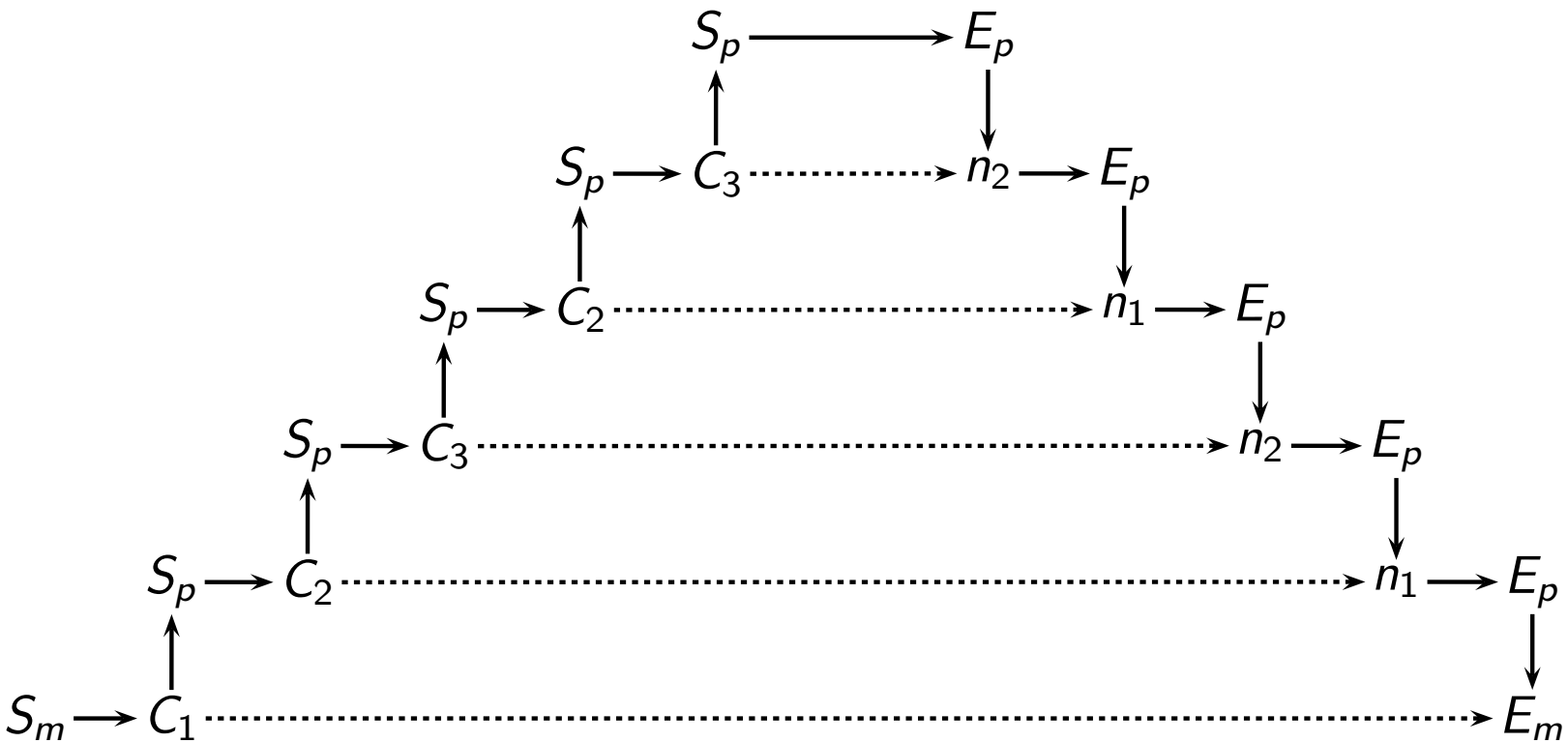
Innermost Recursion Along the Call at C_3



Innermost Recursion Along the Call at C_3

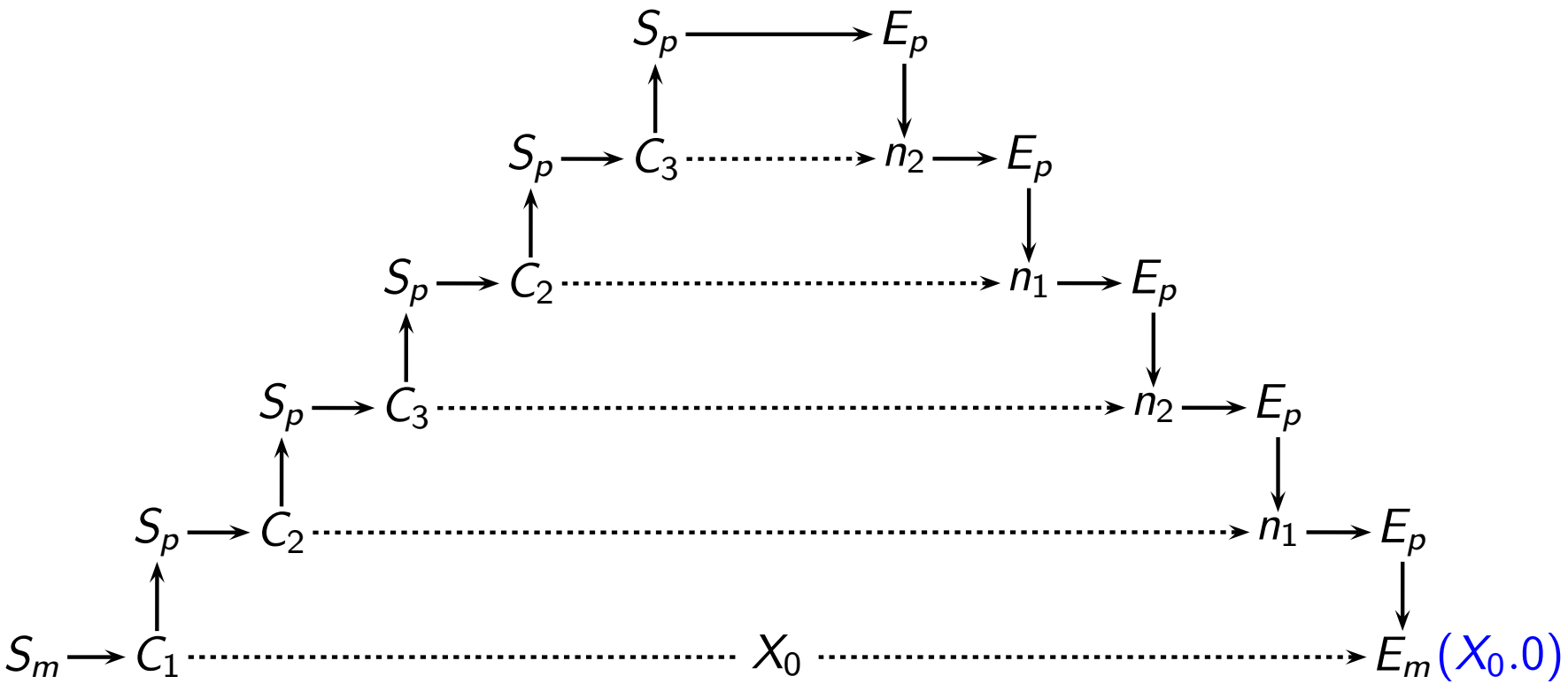


Innermost Recursion Along the Call at C_3



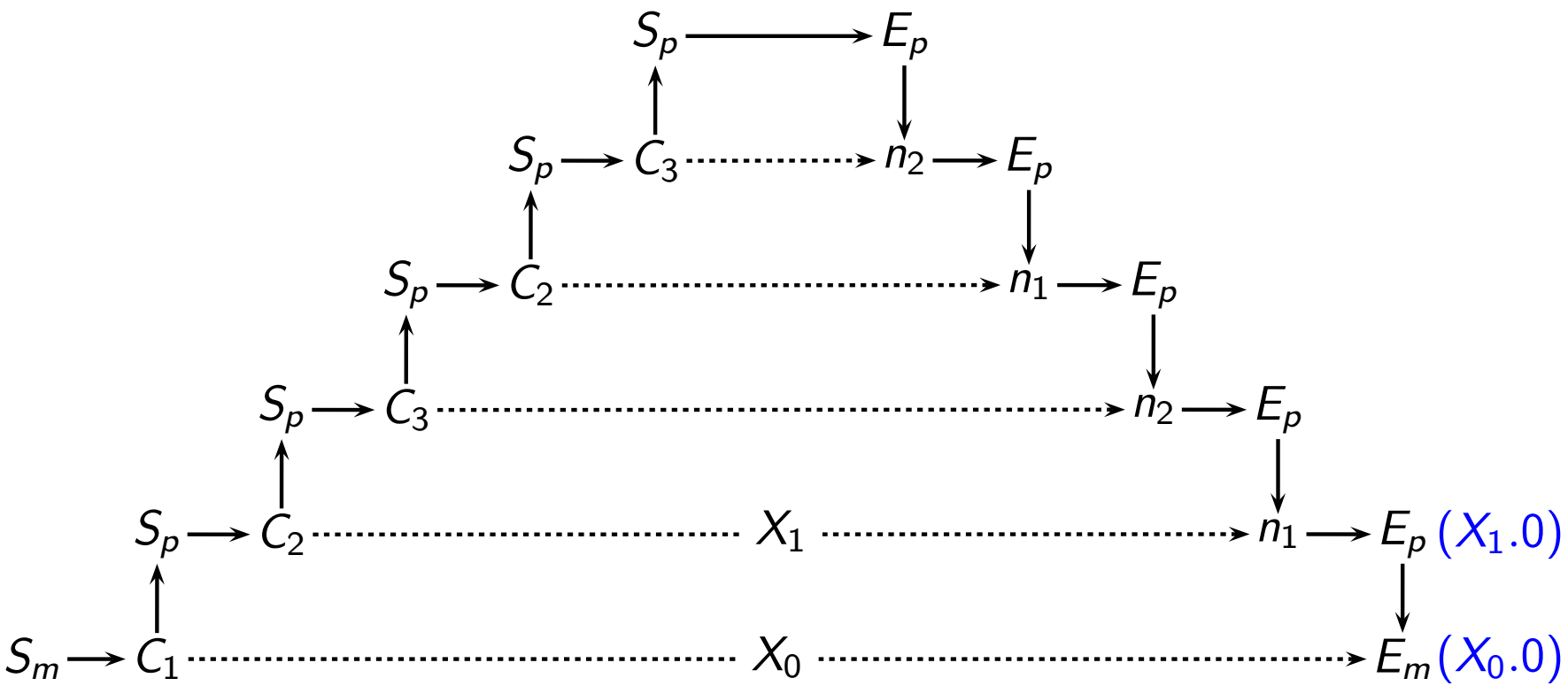
Innermost Recursion Along the Call at C_3

$Bl$is 0



Innermost Recursion Along the Call at C_3

n_1 kills the liveness of a
New context is not required



Innermost Recursion Along the Call at C_3

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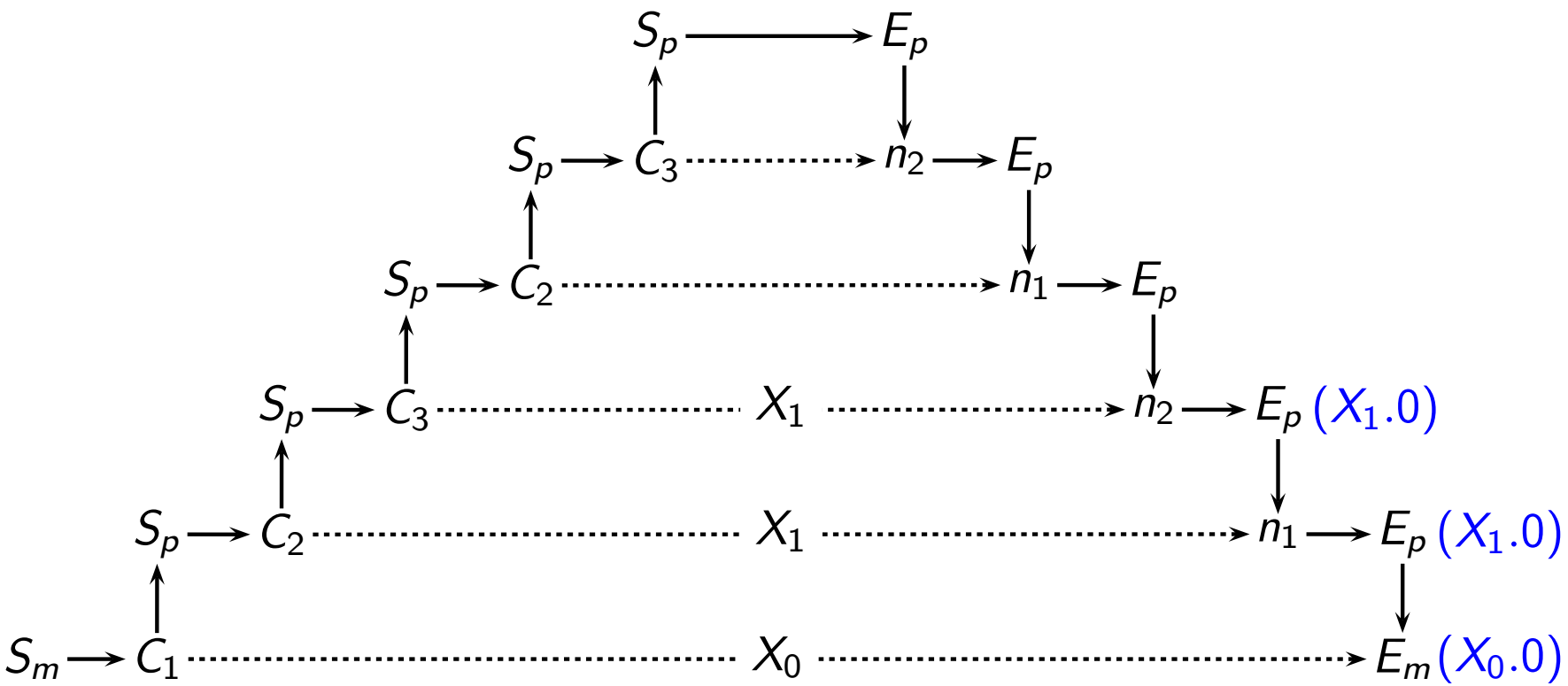
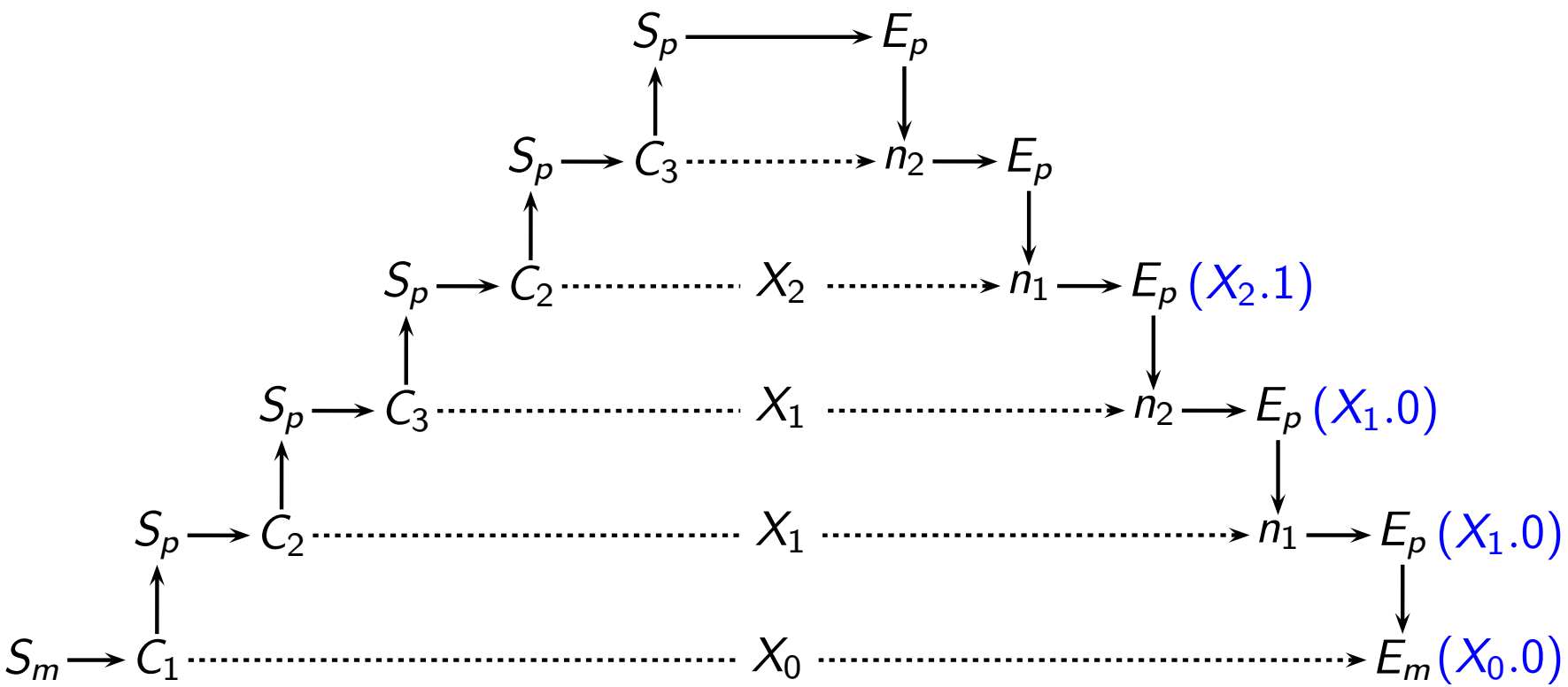


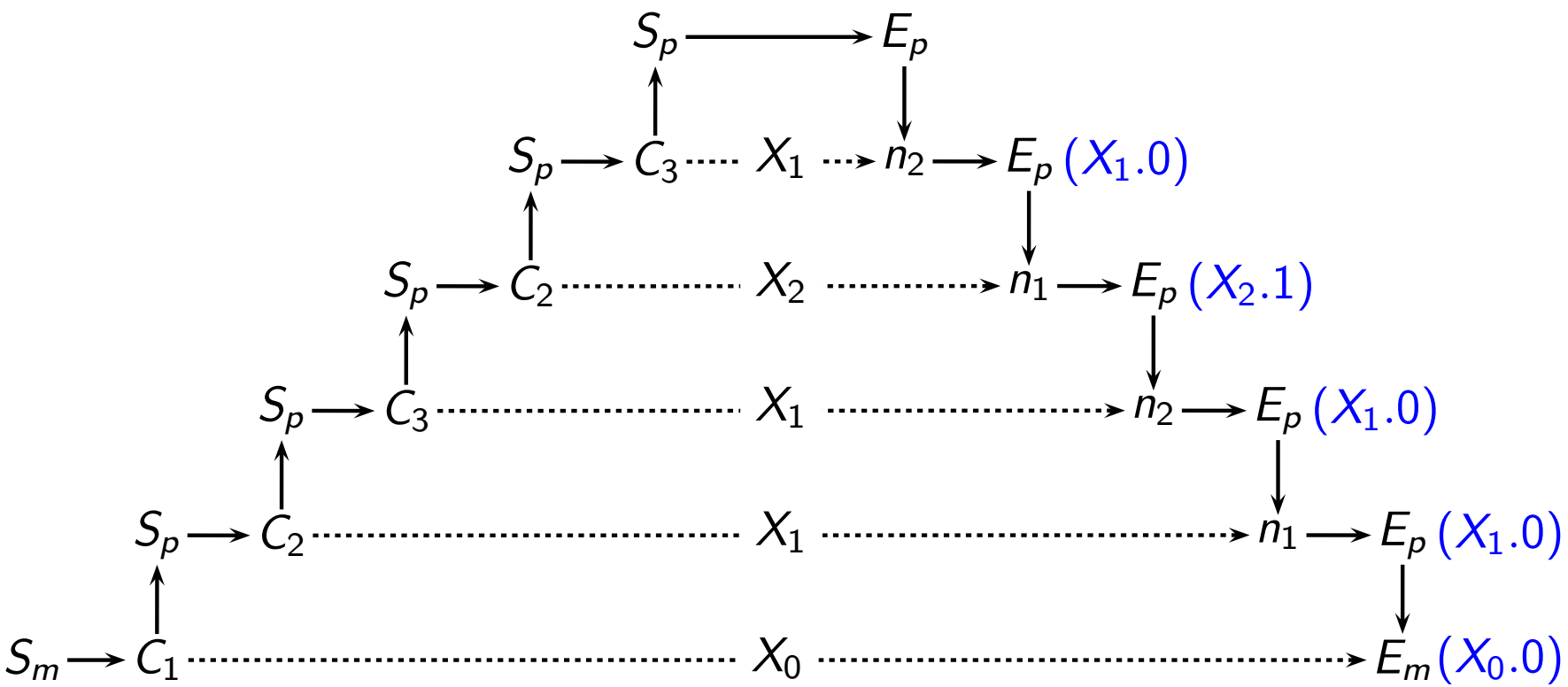
Innermost Recursion Along the Call at C_3

n_2 generates the liveness of a
New context is required



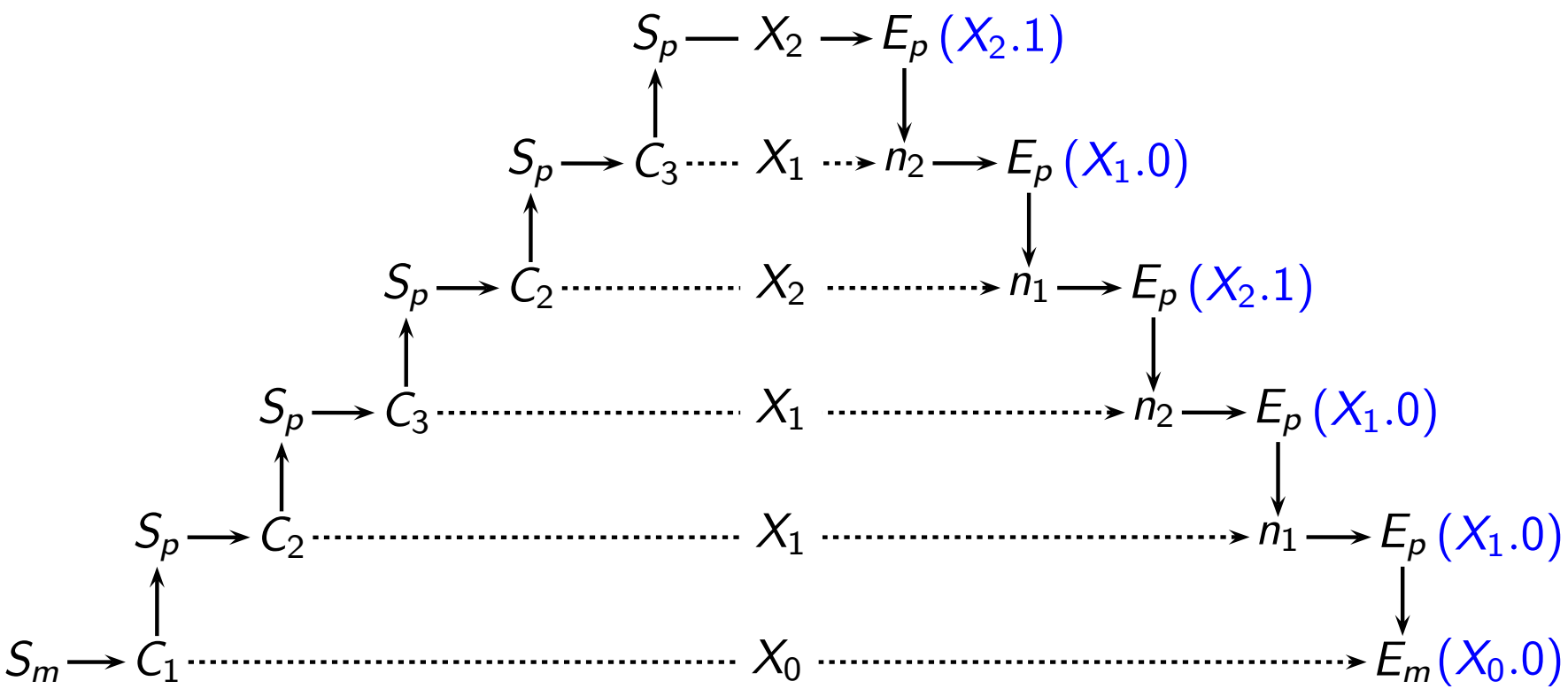
Innermost Recursion Along the Call at C_3

n_1 kills the liveness of a
New context is not required



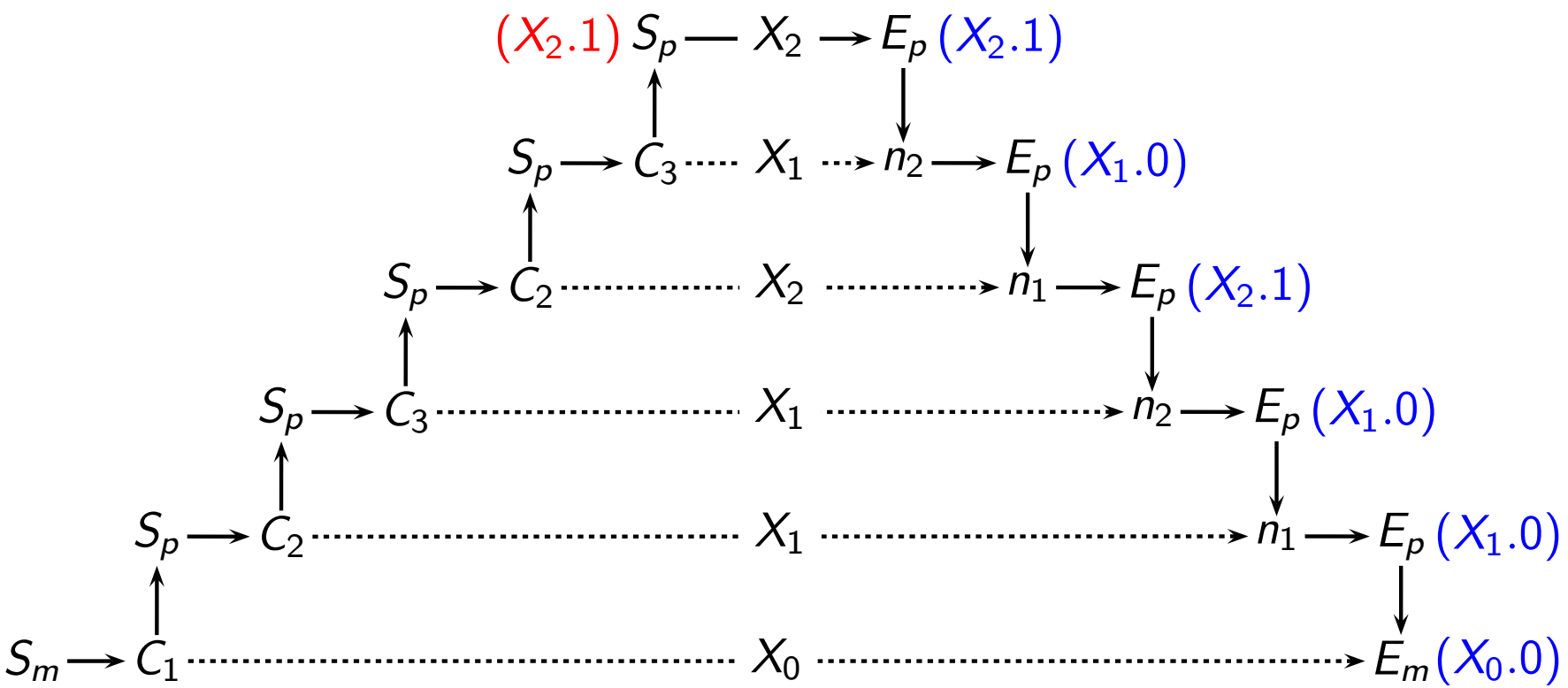
Innermost Recursion Along the Call at C_3

n_2 generates the liveness of a
New context is not required



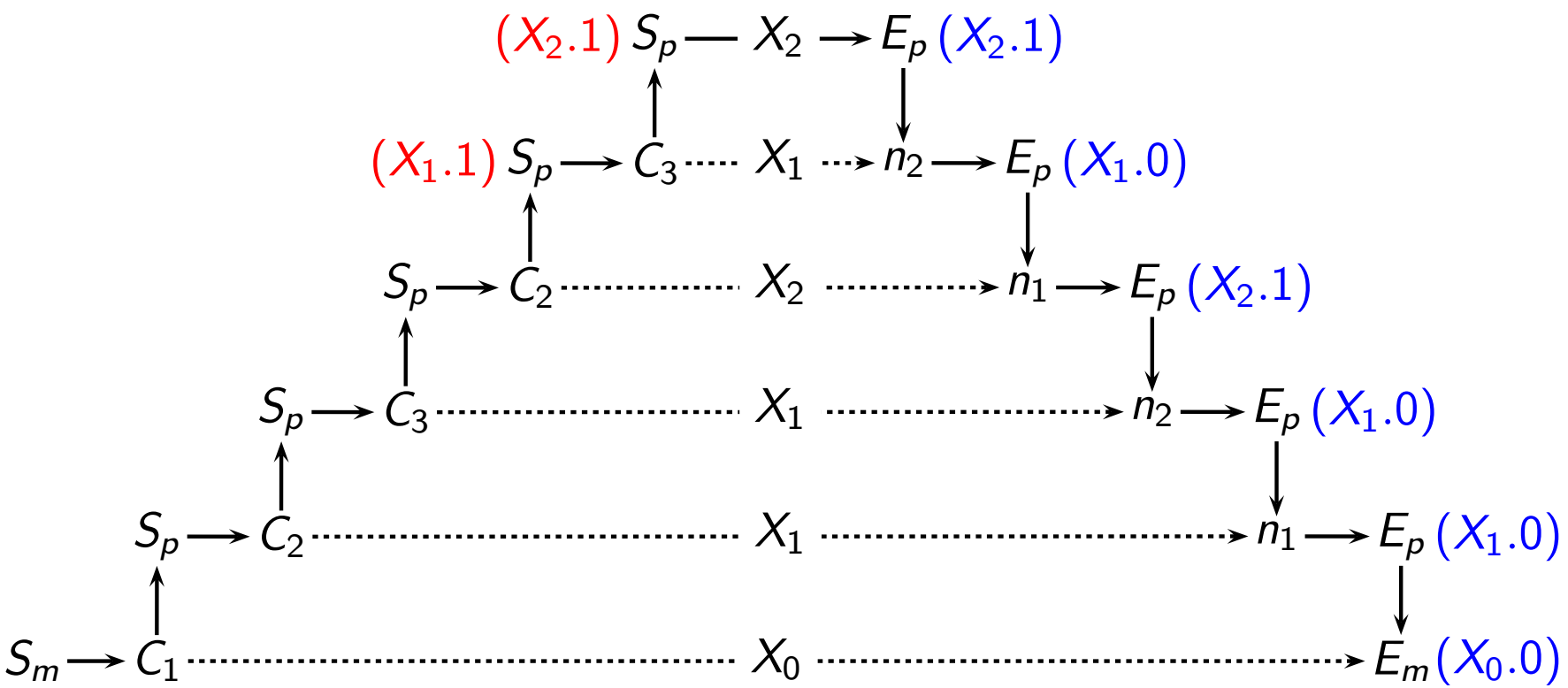
Innermost Recursion Along the Call at C_3

exitValue of X_2 is 1 (after merging with previous value 0)



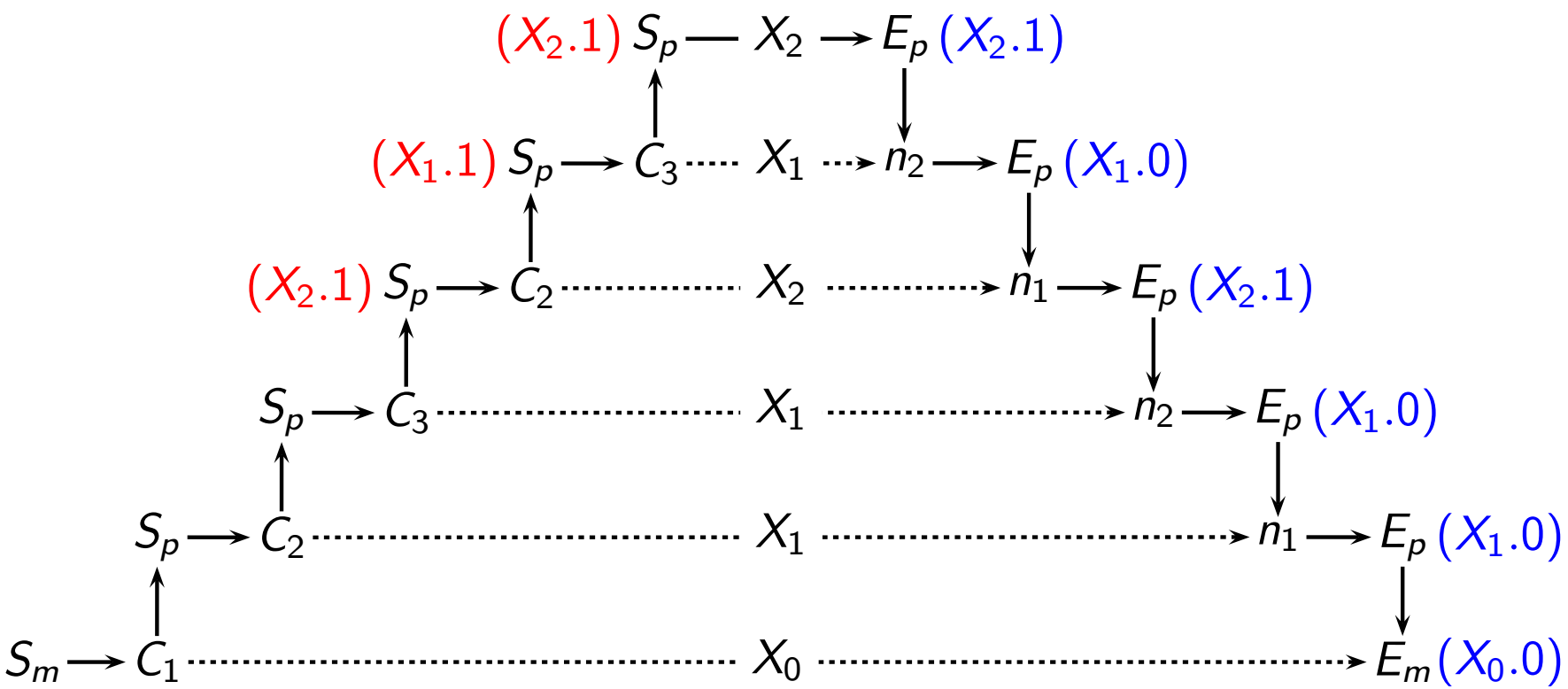
Innermost Recursion Along the Call at C_3

exitValue of X_1 is 1 (after merging with previous value 0)



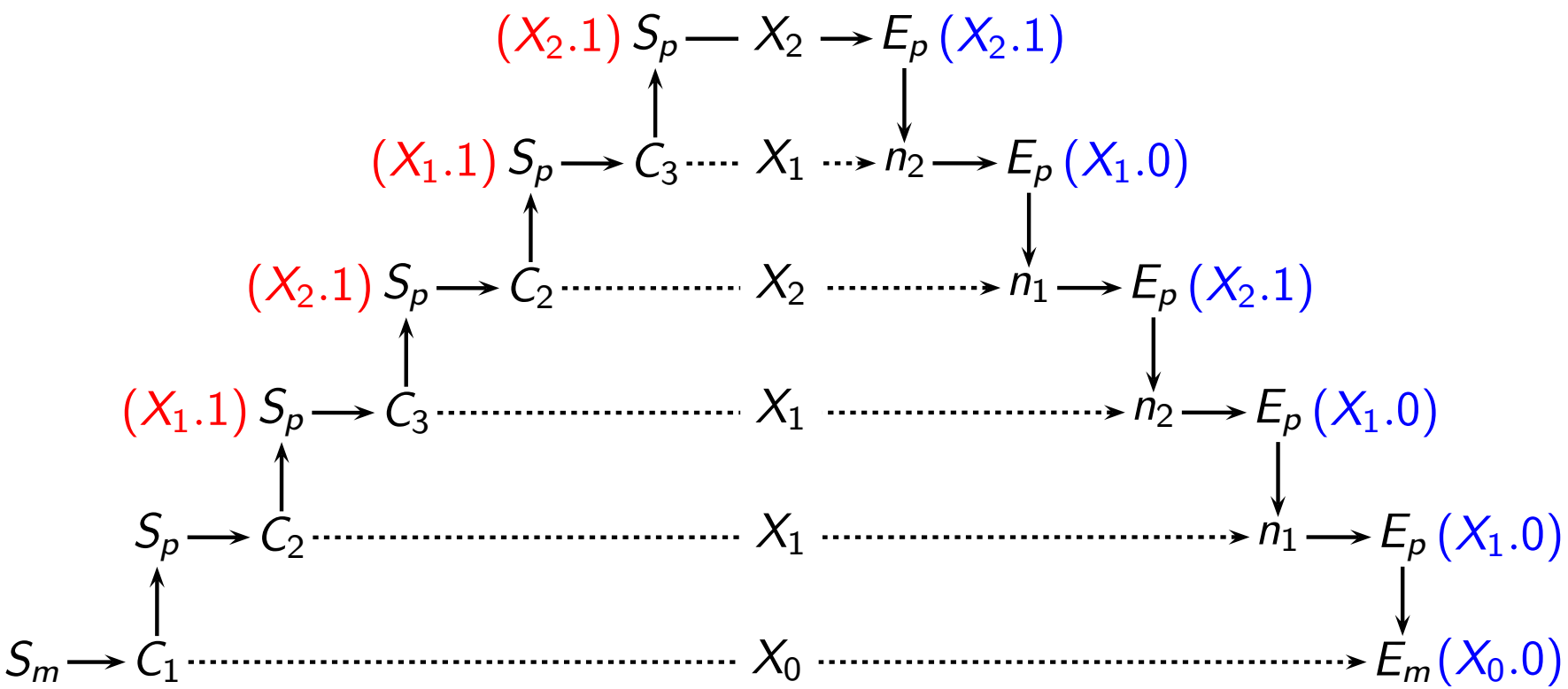
Innermost Recursion Along the Call at C_3

exitValue of X_2 remains 1



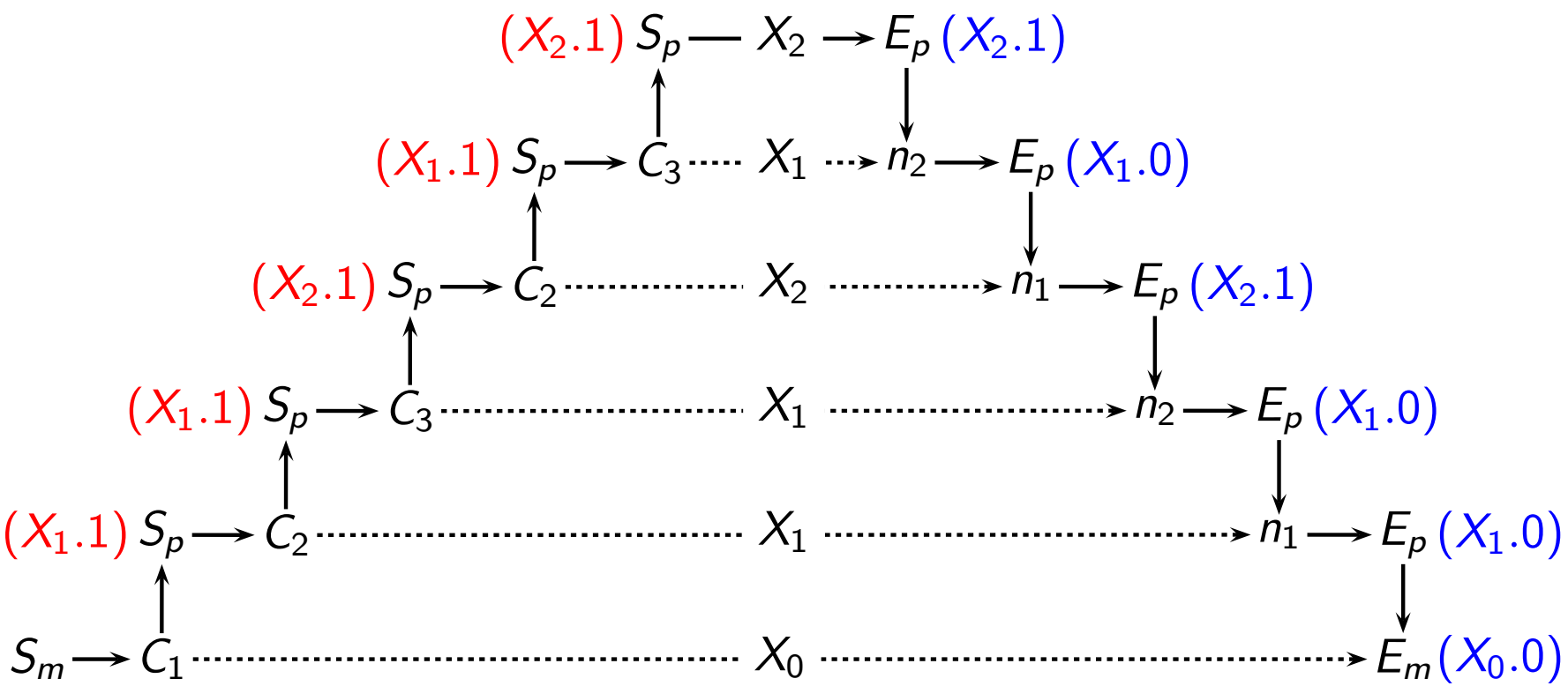
Innermost Recursion Along the Call at C_3

exitValue of X_1 remains 1



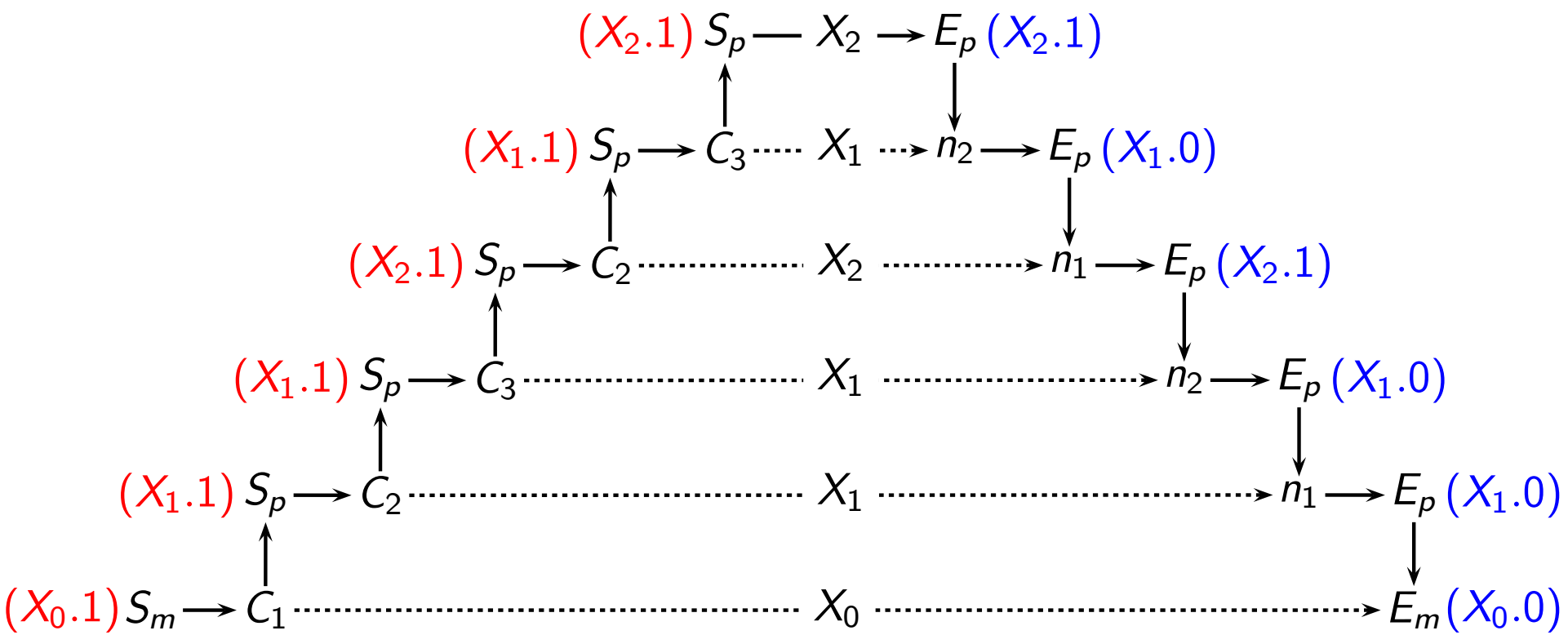
Innermost Recursion Along the Call at C_3

exitValue of X_1 remains 1



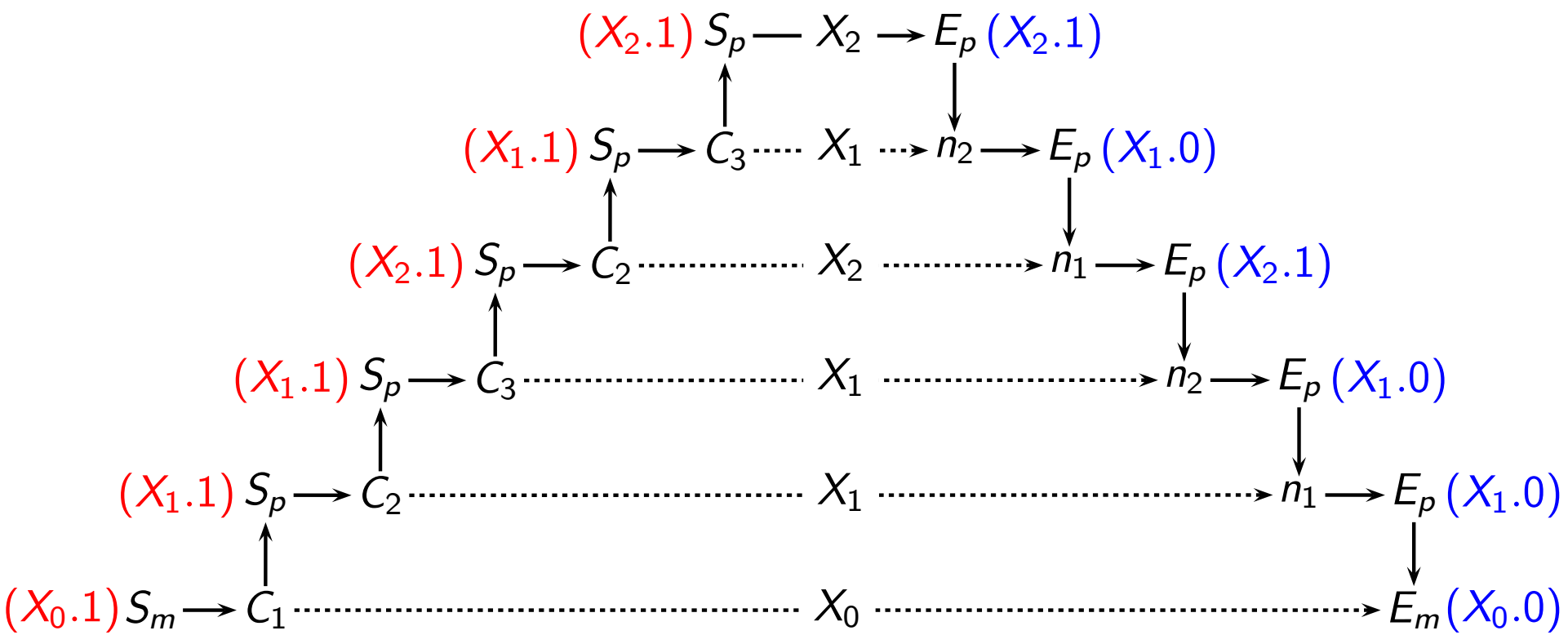
Innermost Recursion Along the Call at C_3

exitValue of X_0 is 1 (after merging with previous value 0)



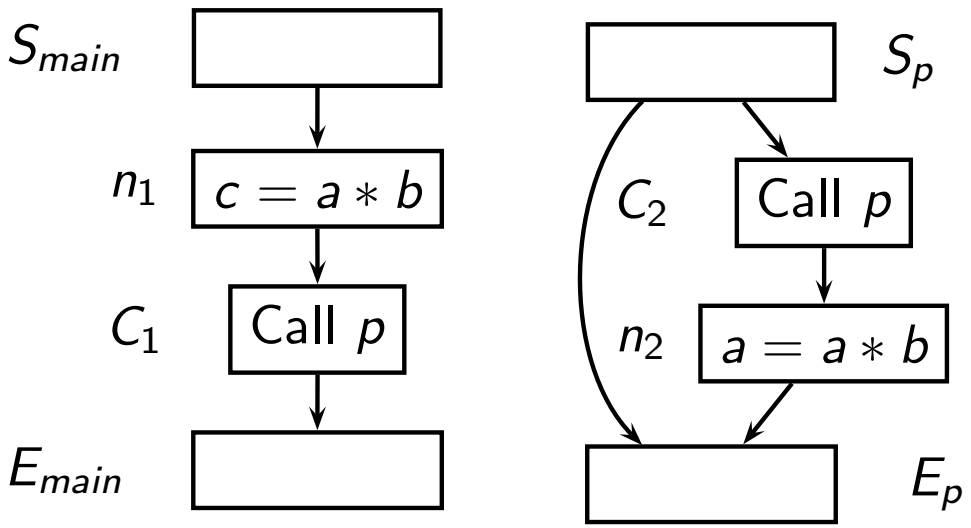
Innermost Recursion Along the Call at C_3

Again, the innermost call determines the *exitValue* of contexts
The final values at the entry of C_3 are 1 (union of 1 and 0)



Tutorial Problem #1 for Value Contexts

```
 1. int a,b,c;
 2. void main()
 3. {   c = a*b;
 4.     p();
 5. }
 6. void p()
 7. {  if (...)
 8.    {  p();
 9.       Is a*b available?
10.       a = a*b;
11.    }
12. }
```



Tutorial Problem #2 for Value Contexts

Perform interprocedural live variables analysis using value contexts

```
main()
{
   p();
}
```

```
p()
{  while (...)
   {  printf ("%d\n",a);
      p();
   }
}
```

Observe the change in edges in the transition diagram

Tutorial Problem #3 for Value Contexts

Perform interprocedural available expressions analysis using value contexts

```
main()
{
    c = a*b;
    p();
}
```

```
p()
{
    while (a > b)
    {
        p();
        a = a*b;
    }
}
```

Observe the change in edges in the transition diagram

Tutorial Problem #4 for Value Contexts

Perform interprocedural available expressions analysis using value contexts

```
1.  main()
2.  {
3.      c = a*b;
4.      p();
5.      a = a*b;
6.  }
```

```
 7.  p()
 8.  {   if (...)
 9.      {   a = a*b;
10.          p();
11.      }
12.      else if (...)
13.      {   c = a * b;
14.          p();
15.          c = a;
16.      }
17.      else
18.          ; /* ignore */
19.  }
```


Tutorial Problem #5 for Value Contexts

Perform interprocedural live variables analysis using value contexts

```
main()
{
  a = 5; b = 3;
  c = 7; d = 2;
  p();
  a = a + 2;
  e = c+d;
  d = a*b;
  q();
  print a+c+e;
}
```

```
p()
{
  b = 2;
  if (b<d)
     c = a+b;
  else
     q();
  print c+d;
}
```

```
q()
{
  a = 1;
  p();
  a = a*b;
}
```

Context sensitivity: e is live on entry to p but not before its call in main

Result of Tutorial #5

```
main()
{
  a = 5; b = 3;
  c = 7; d = 2;
  /*{a,d}*/
  p();
  /*{a,b,c,d}*/
  a = a + 2;
  e = c+d;
  /*{a,b,e}*/
  d = a*b;
  /*{d,e}*/
  q();
  /*{a,c,e}*/
  print a+c+e;
}
```

```
p()
{  /*{a,d,e}*/
  b = 2;
  if (b<d)
    /*{a,b,d,e}*/
     c = a+b;
  else
    /*{d,e}*/
     q();
  /*{a,b,c,d,e}*/
  print c+d;
}
```

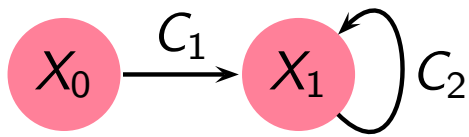
```
q()
{
  /*{d,e}*/
  a = 1;
  /*{a,d,e}*/
  p();
  /*{a,b,c,d,e}*/
  a = a*b;
}
```

Tutorial Problem #6: Interprocedural Points-to Analysis

```
main()
{   x = &y;
    z = &x;
    y = &z;
    p(); /* C1 */
}

p()
{   if (...)
    {   p(); /* C2 */
        x = *x;
    }
}
```

Value contexts method requires three contexts as shown below in the transition diagram



Reaching Definitions Analysis in GCC 4.0

Program	LoC	$\#F$	$\#C$	$3K$ length bound				Proposed Approach		
				K	#CS	Max	Time	#CS	Max	Time
hanoi	33	2	4	4	100000+	99922	3973 $\times 10^3$	8	7	2.37
bit_gray	53	5	11	7	100000+	31374	2705 $\times 10^3$	17	6	3.83
analyzer	288	14	20	2	21	4	20.33	21	4	1.39
distray	331	9	21	6	96	28	322.41	22	4	1.11
mason	350	9	13	8	100000+	22143	432 $\times 10^3$	14	4	0.43
fourinarow	676	17	45	5	510	158	397.76	46	7	1.86
sim	1146	13	45	8	100000+	33546	1427 $\times 10^3$	211	105	234.16
181_mcf	1299	17	24	6	32789	32767	484 $\times 10^3$	41	11	5.15
256_bzip2	3320	63	198	7	492	63	258.33	406	34	200.19

- LoC is the number of lines of code,
- $\#F$ is the number of procedures,
- $\#C$ is the number of call sites,
- $\#CS$ is the number of call strings
- Max denotes the maximum number of call strings reaching any node.
- Analysis time is in milliseconds.

(Implementation was carried out by Seema Ravandale.)

Some Observations

- Compromising on precision may not be necessary for efficiency.
- Separating the necessary information from redundant information is much more significant.
- Data flow propagation in real programs seems to involve only a small subset of all possible values.

  Much fewer changes than the theoretically possible worst case number of changes.
- A precise modelling of the process of analysis is often an eye opener.

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  # distinct tagged values =

  Min (# actual contexts, # actual data flow values)