Efficiency, Precision, Simplicity, and Generality in Interprocedural Data Flow Analysis: Resurrecting the Classical Call Strings Method

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Outline

- Issues in interprocedural analysis
- The classical call strings approach to interprocedural data flow analysis
- The proposed variant of call strings approach
- Empirical Results
- Conclusions

A clarification:

Data flow analysis has nothing to do with data flow architectures!

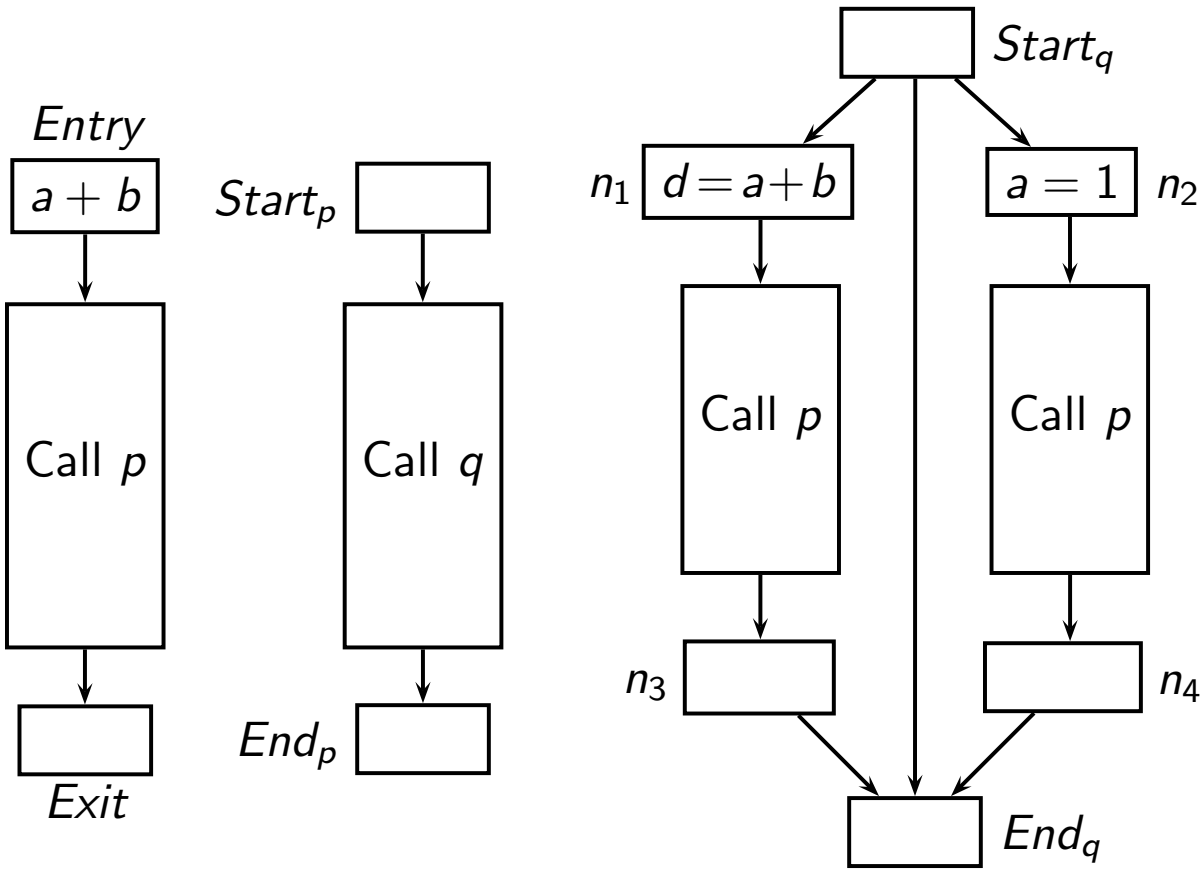
Part 2

Issues in Interprocedural Analysis

Interprocedural Analysis: Overview

- Extends the scope of data flow analysis across procedure boundaries
  Incorporates the effects of
  - procedure calls in the caller procedures, and
  - calling contexts in the callee procedures.
- Approaches :
  - Generic : Call strings approach, functional approach.
  - Problem specific : Alias analysis, Points-to analysis, Partial redundancy elimination, Constant propagation

Defining Interprocedural Context for Static Analysis



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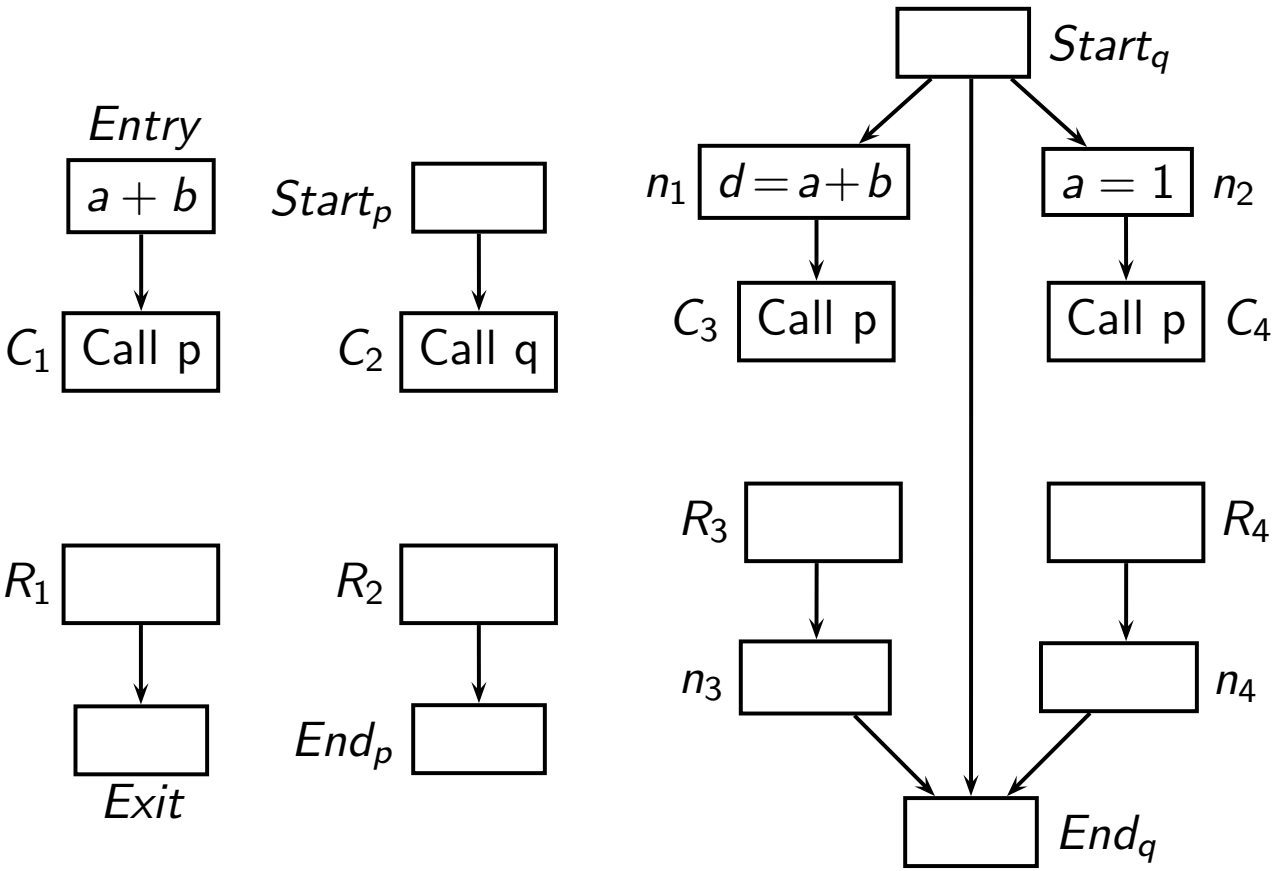

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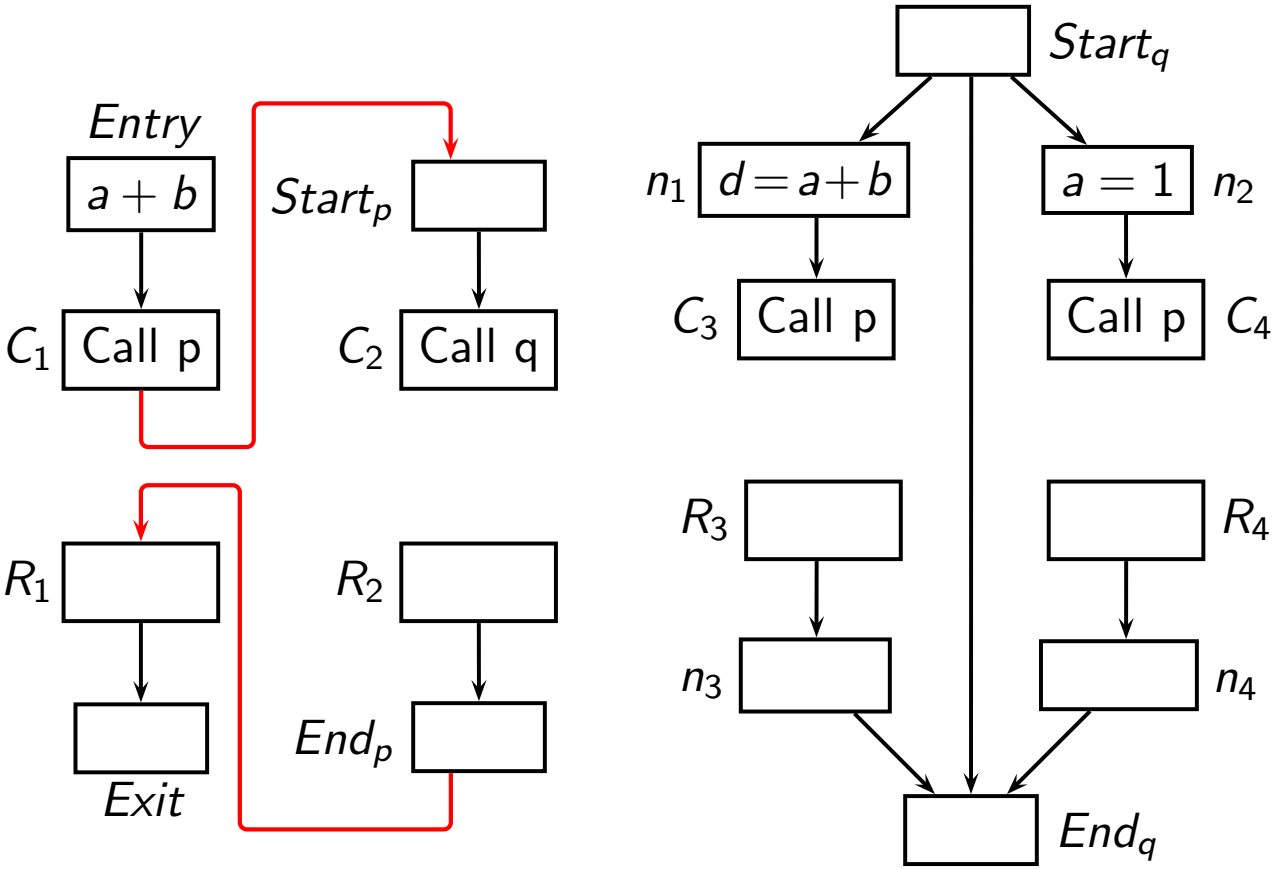

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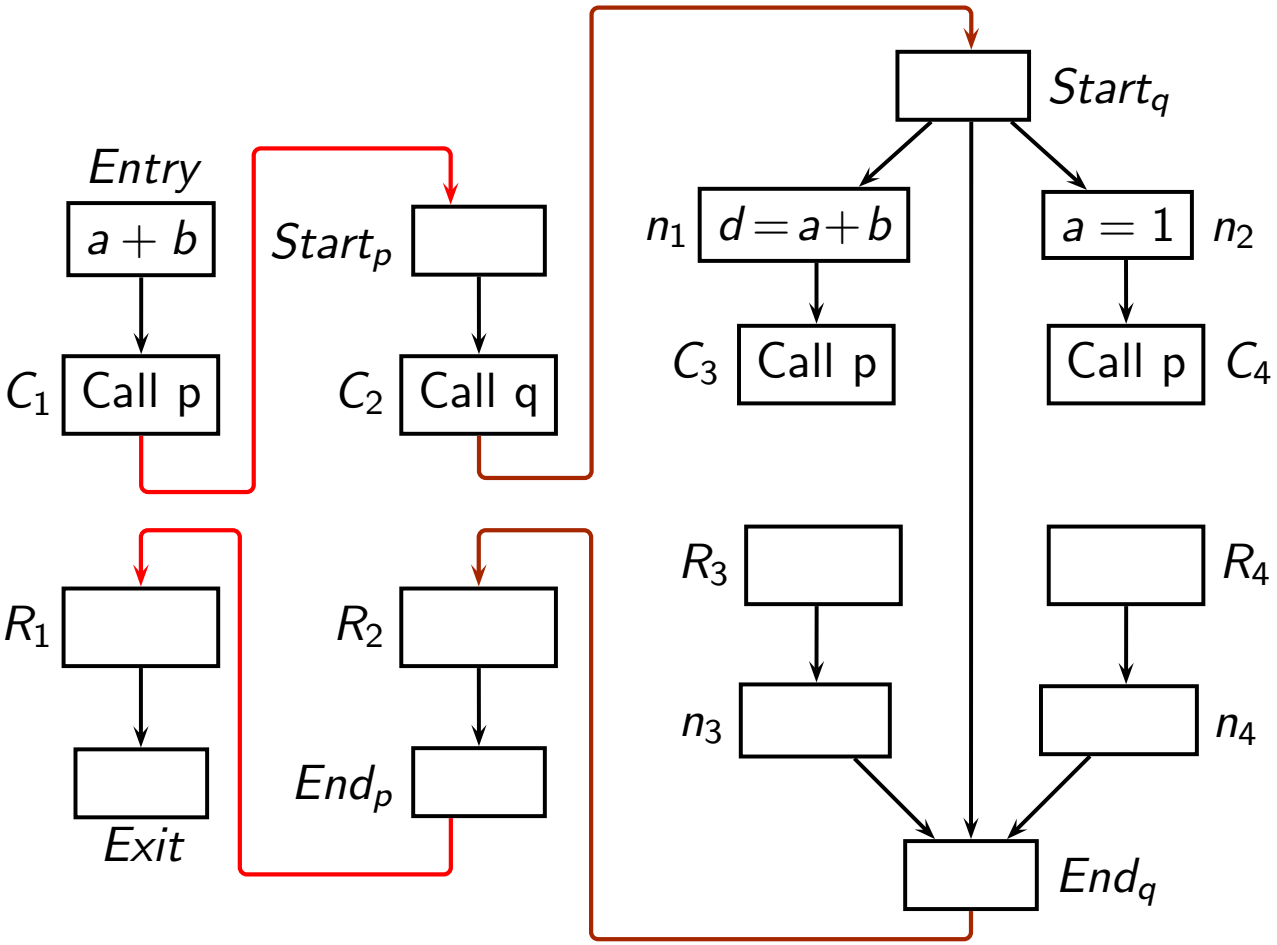

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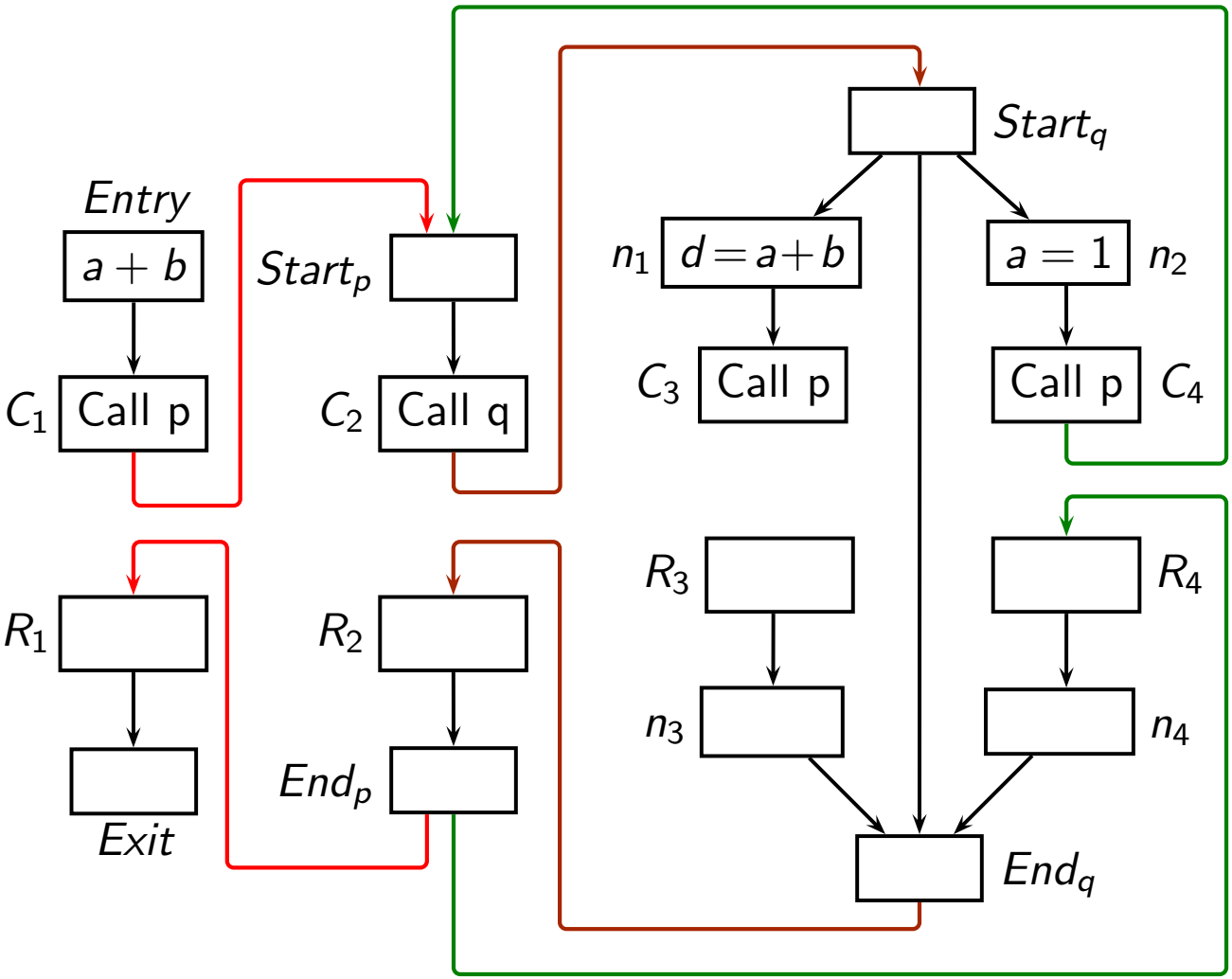

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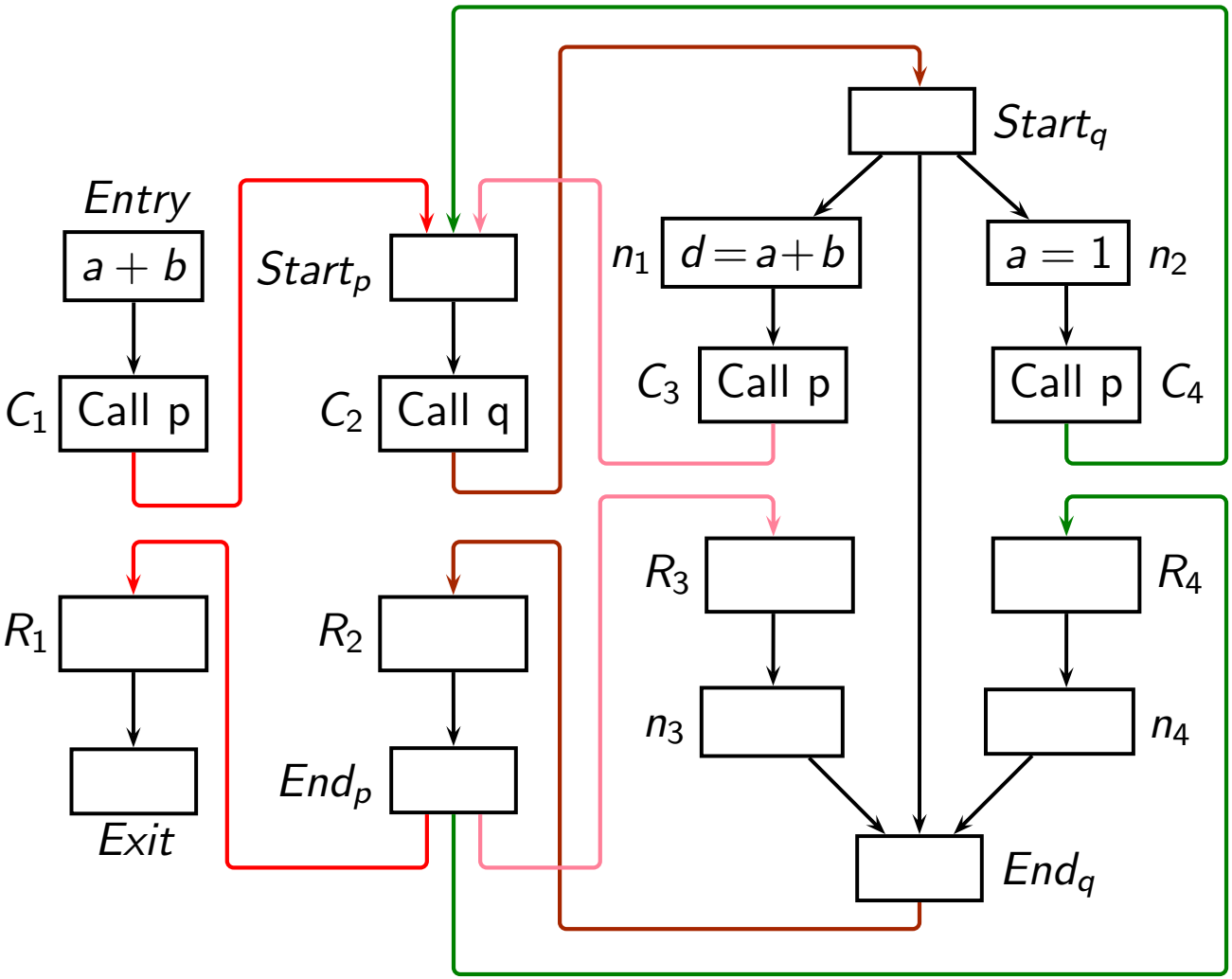

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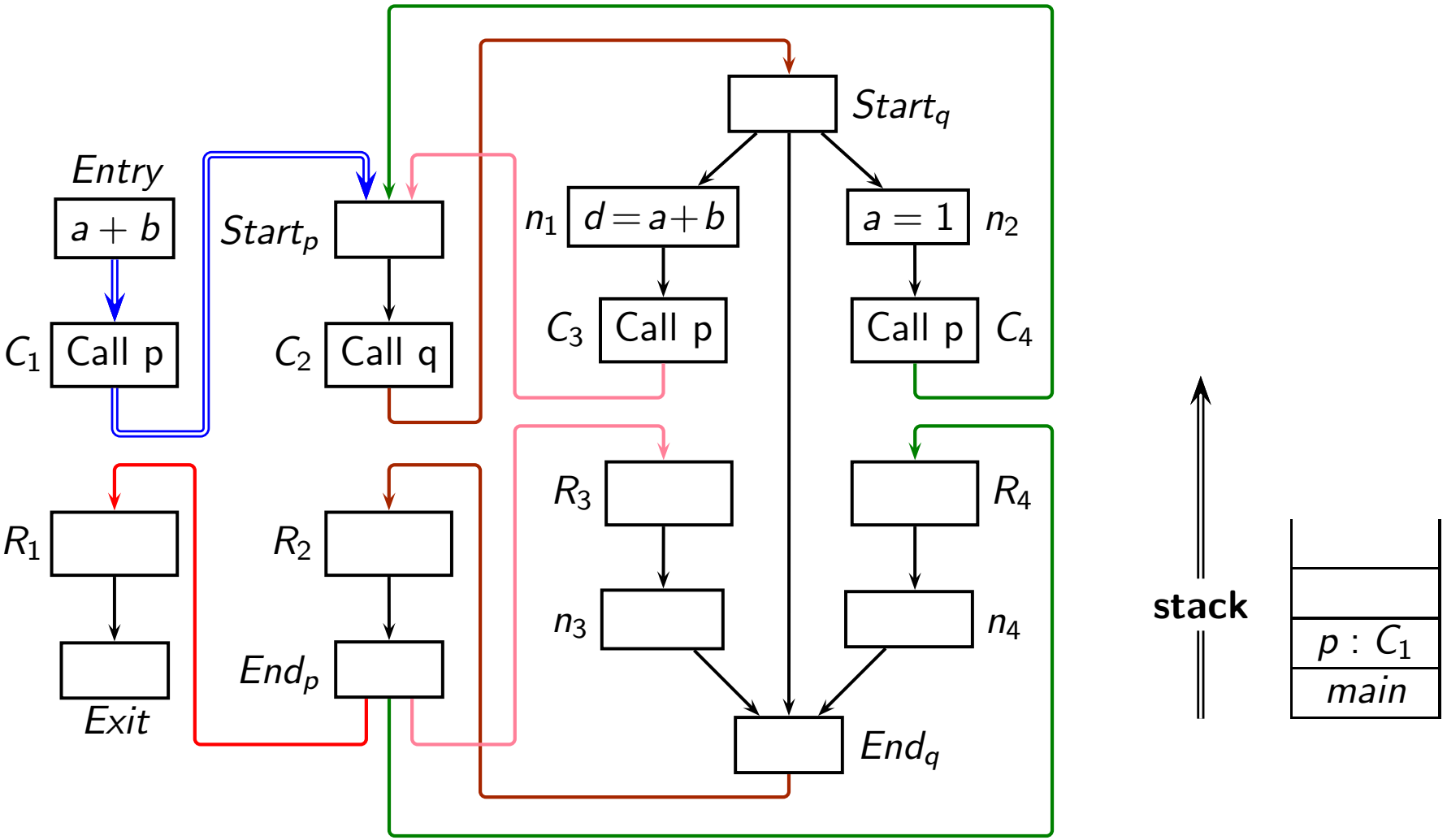

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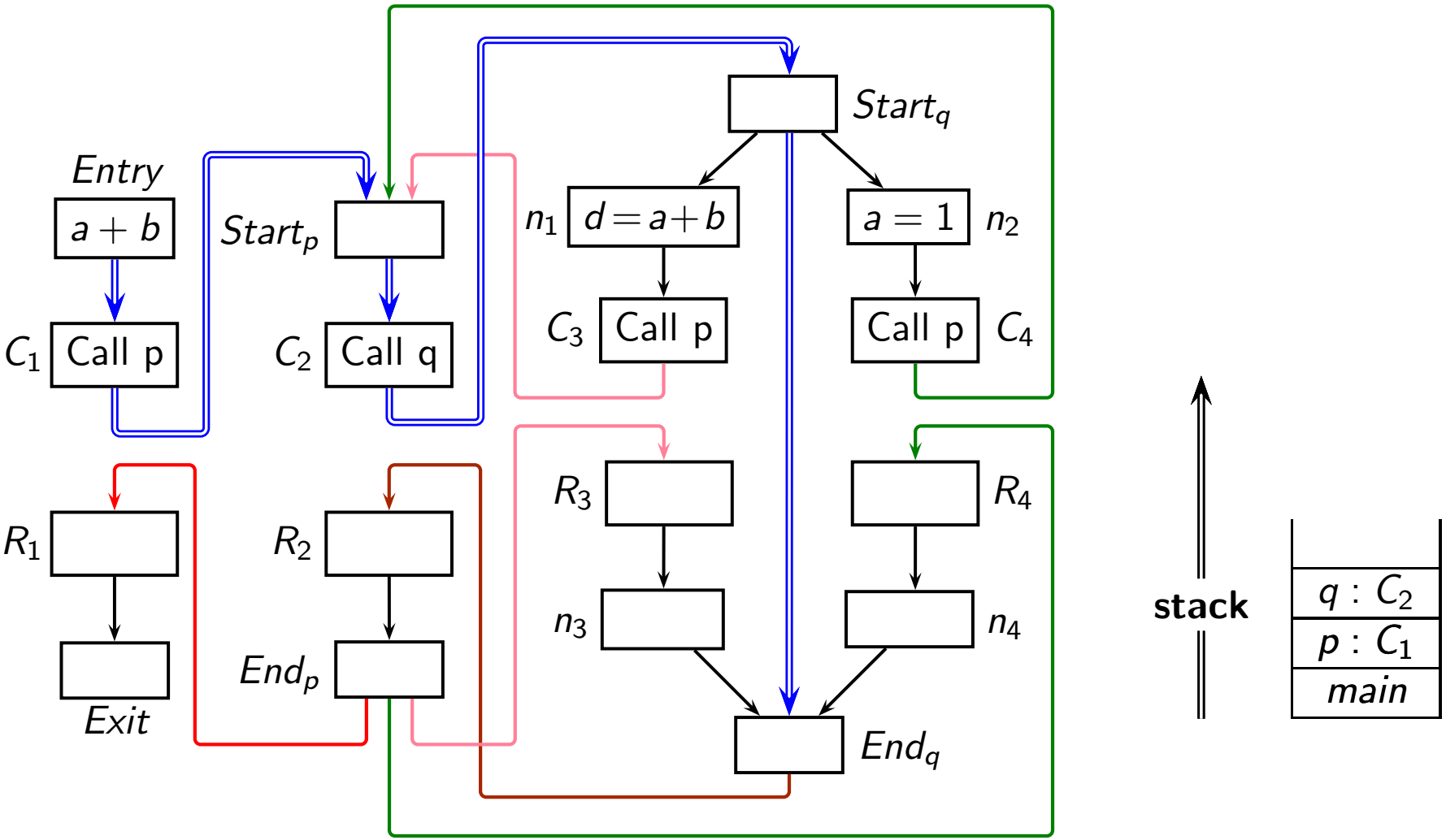

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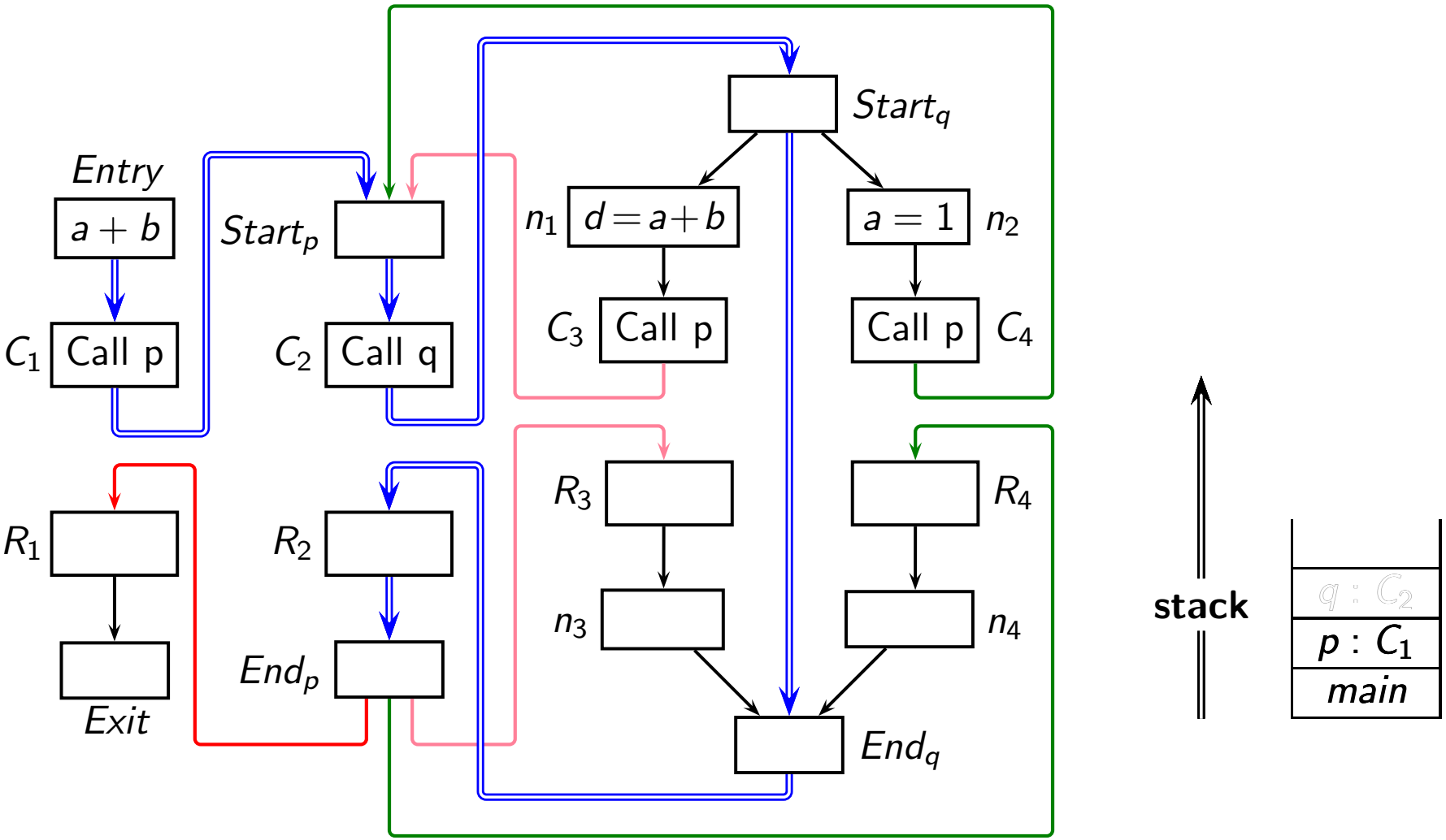

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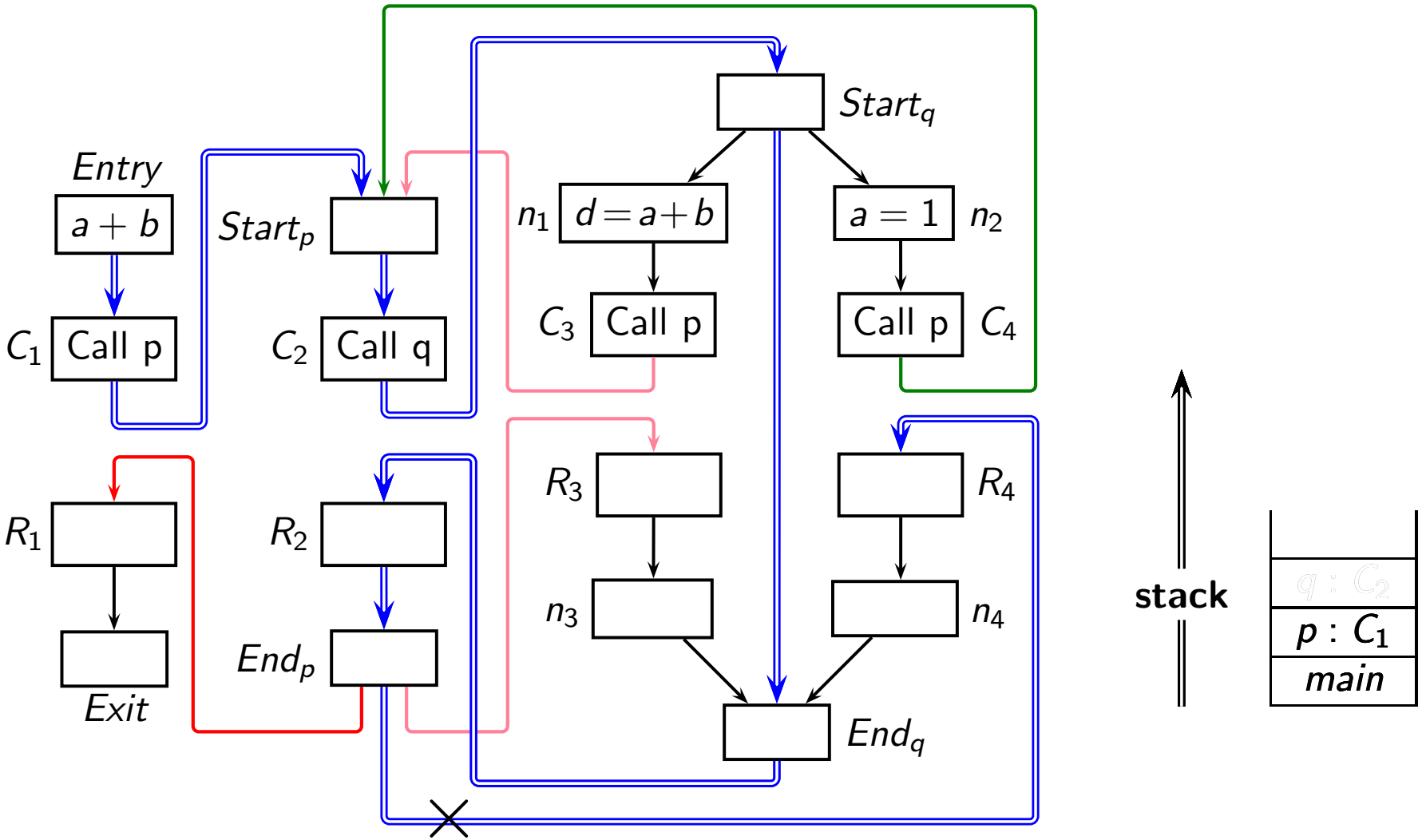

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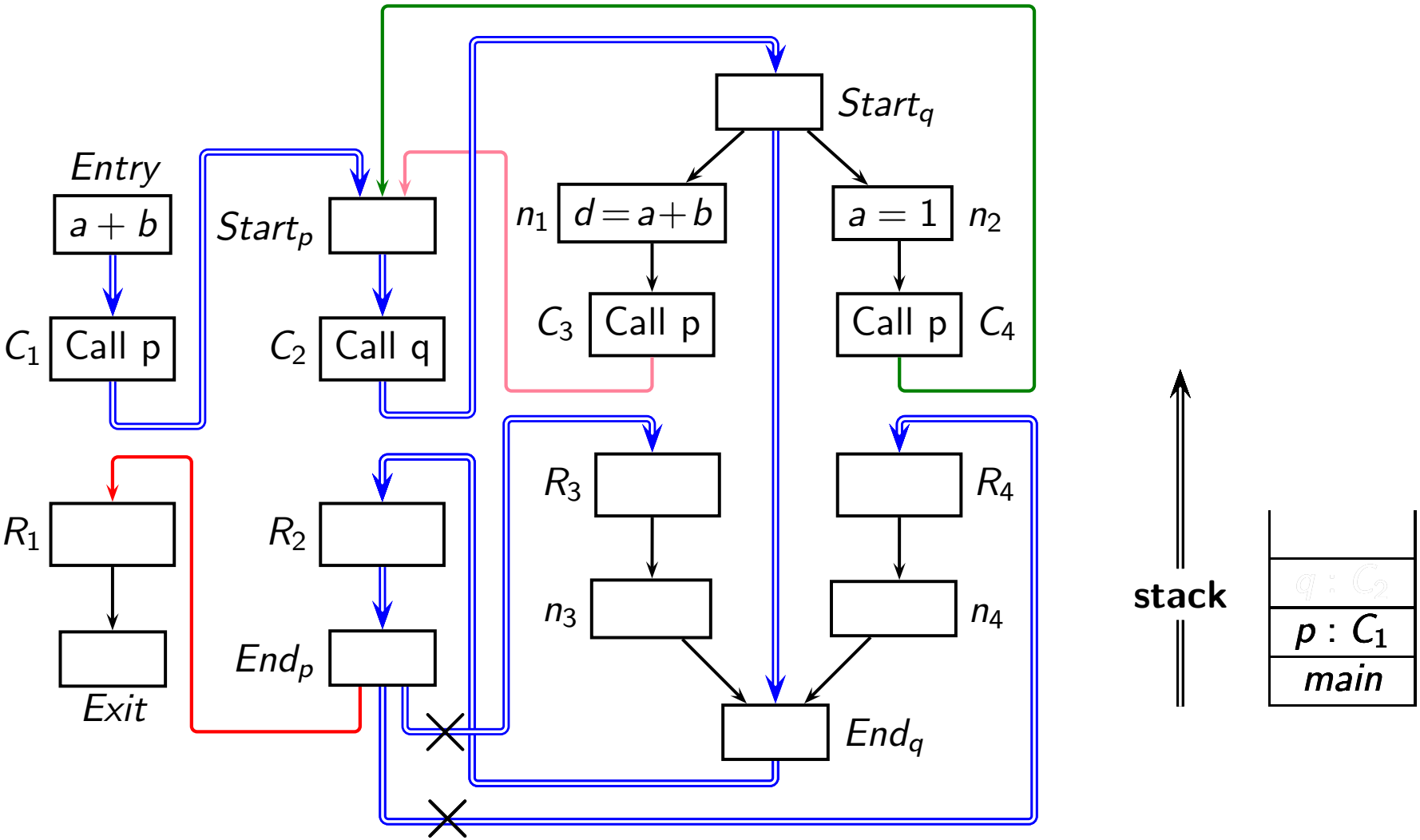

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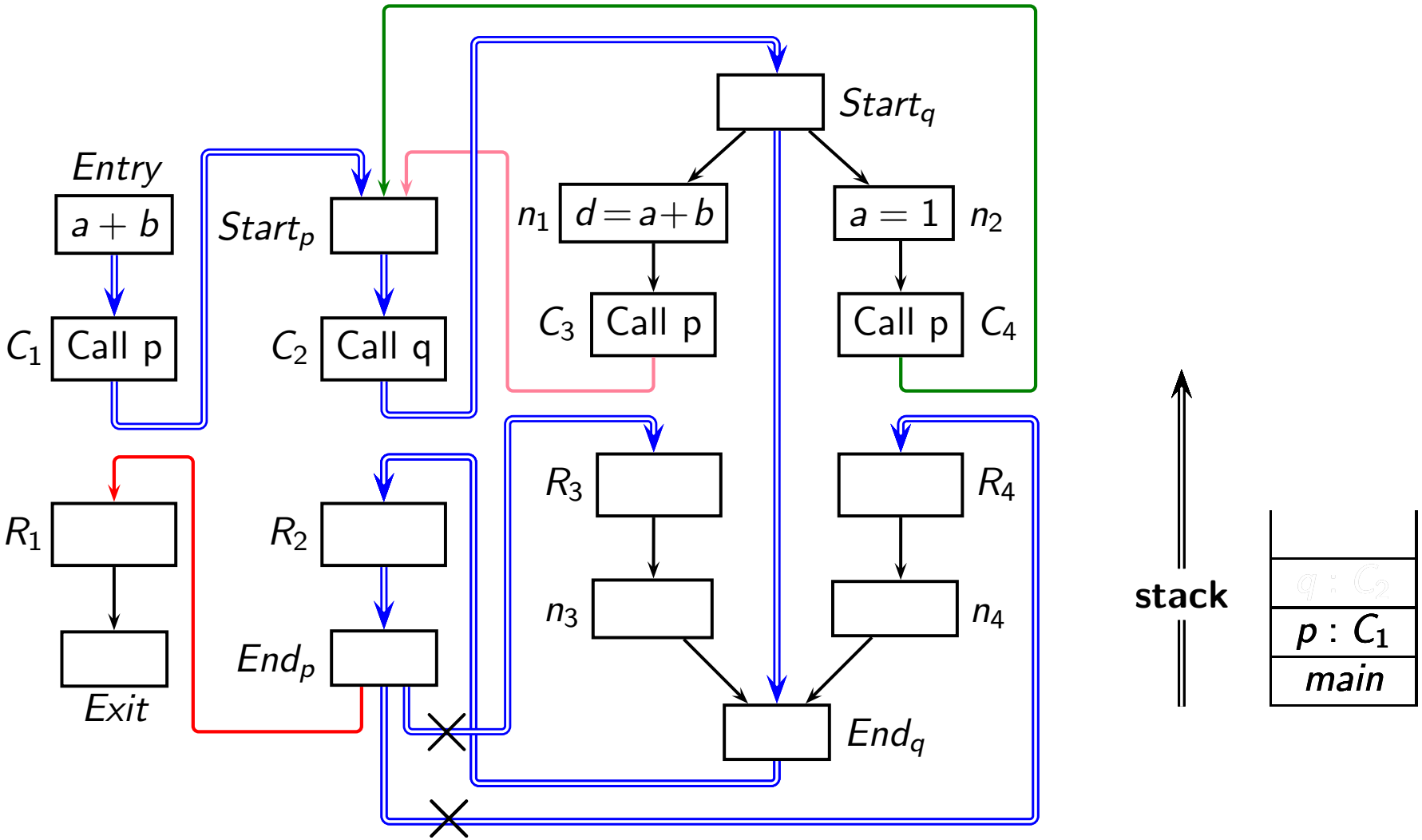

Context is defined by stack snapshot ⇒ Unbounded number of contexts

Safety, Precision, and Efficiency of Data Flow Analysis

- Data flow analysis uses static representation of programs to compute summary information along paths

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A path which represents legal control flow

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Safety, Precision, and Efficiency of Data Flow Analysis

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- *Ensuring Safety*. All valid paths must be covered
- *Ensuring Precision*. Only valid paths should be covered.
- *Ensuring Efficiency*. Only relevant valid paths should be covered.

A path which yields information that affects the summary information.

Flow and Context Sensitivity

- Flow sensitive analysis:
  Considers intraprocedurally valid paths
- Context sensitive analysis:
  Considers interprocedurally valid paths

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  Considers interprocedurally valid paths

For maximum statically attainable precision, analysis must be both flow and context sensitive.

Part 3

Classical Call Strings Approach

Call Strings Approach [Sharir and Pnueli 1981]

Most general, flow and context sensitive method

- Remember call history
  Information should be propagated *back* to the correct point

- Call string at a program point:
  - Sequence of *unfinished calls* reaching that point
  - Starting from the *Entry*

  A snap-shot of call stack in terms of call sites

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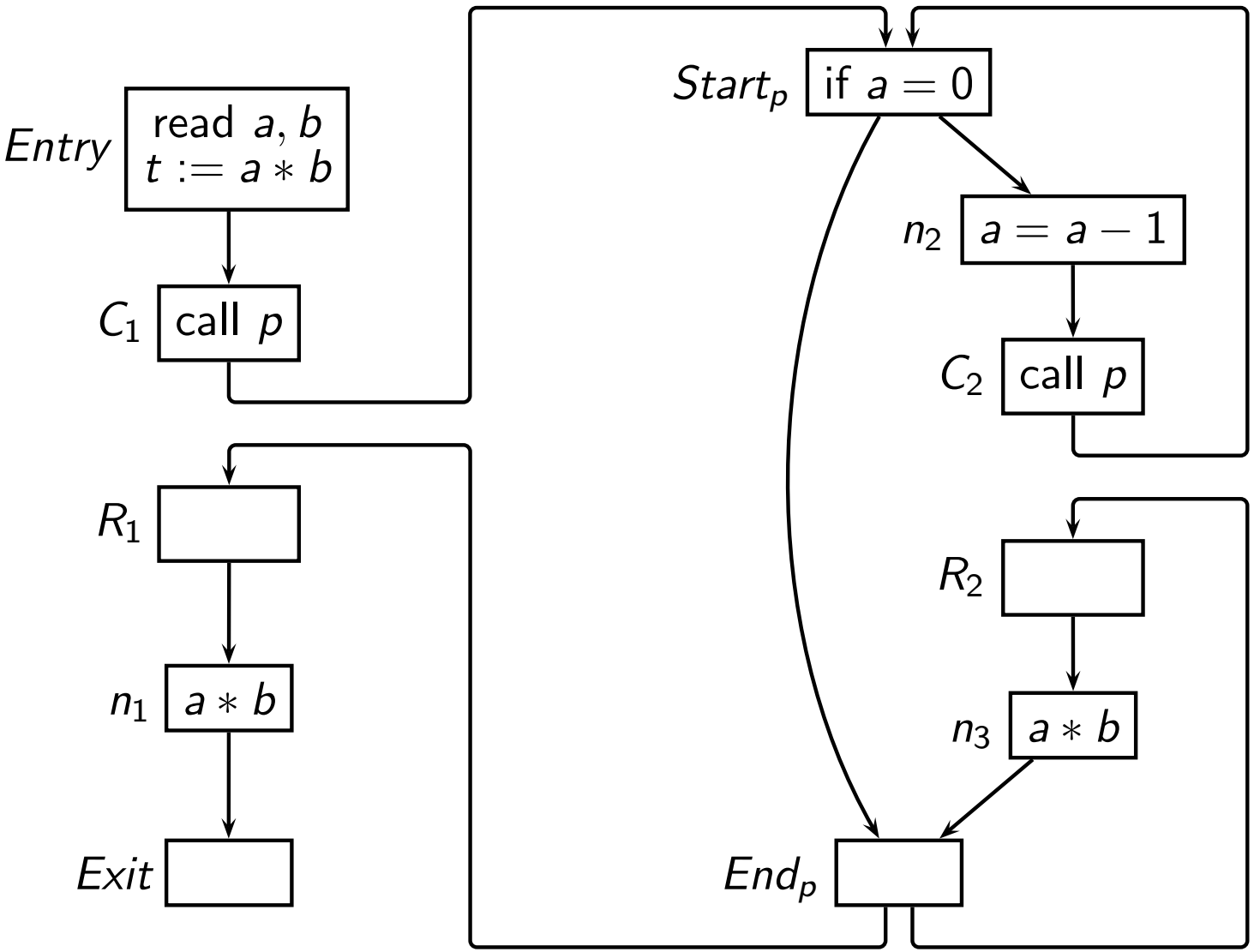
Efficiency ??

Interprocedural Data Flow Analysis Using Call Strings

- Data flow information at a program point
  $\langle$Call String : σ, Data Flow Value : $d\rangle$
- Flow functions
  - Intraprocedural edges: Manipulate data flow value d
  - Interprocedural edges: Manipulate call string σ
    - Call edge $C_i \longrightarrow s_p$ (i.e. call site c_i calling procedure p)
      append c_i to every σ reaching c_i.
    - Return edge $e_p \longrightarrow R_i$ (i.e. p returning the control to call site c_i)
      if the last call site is c_i, remove it and propagate the data flow value

Available Expressions Analysis Using Call Strings Approach



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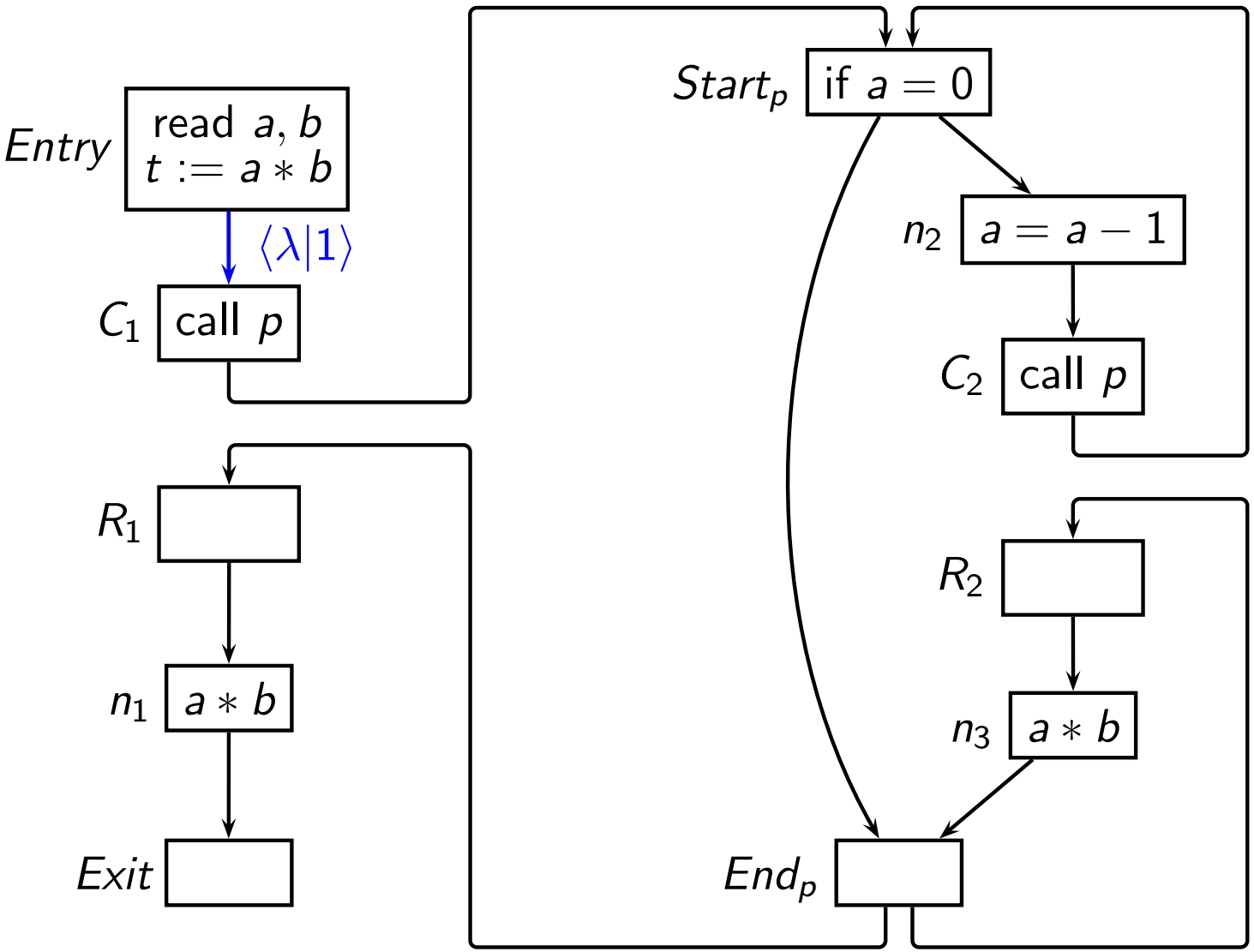

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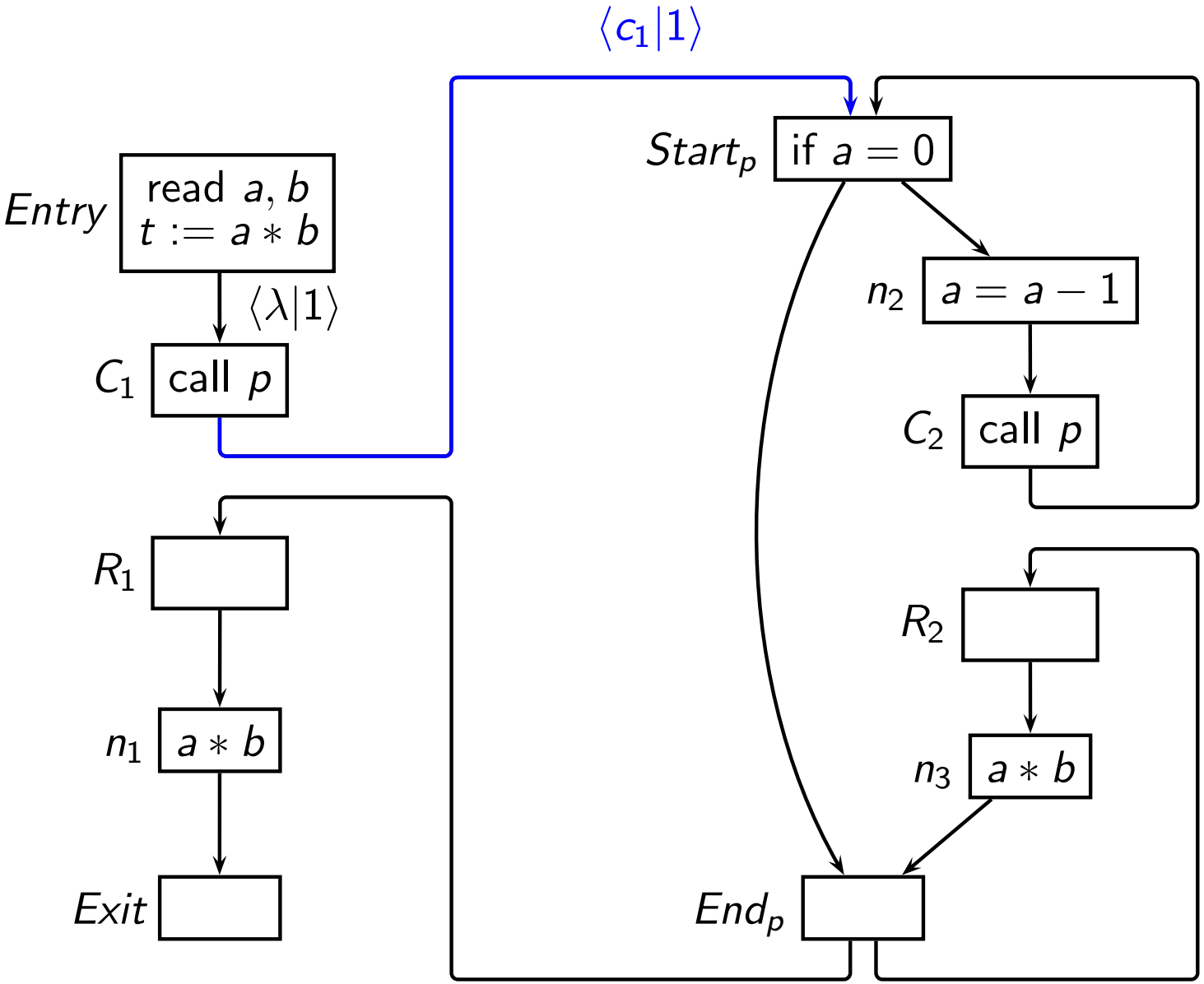

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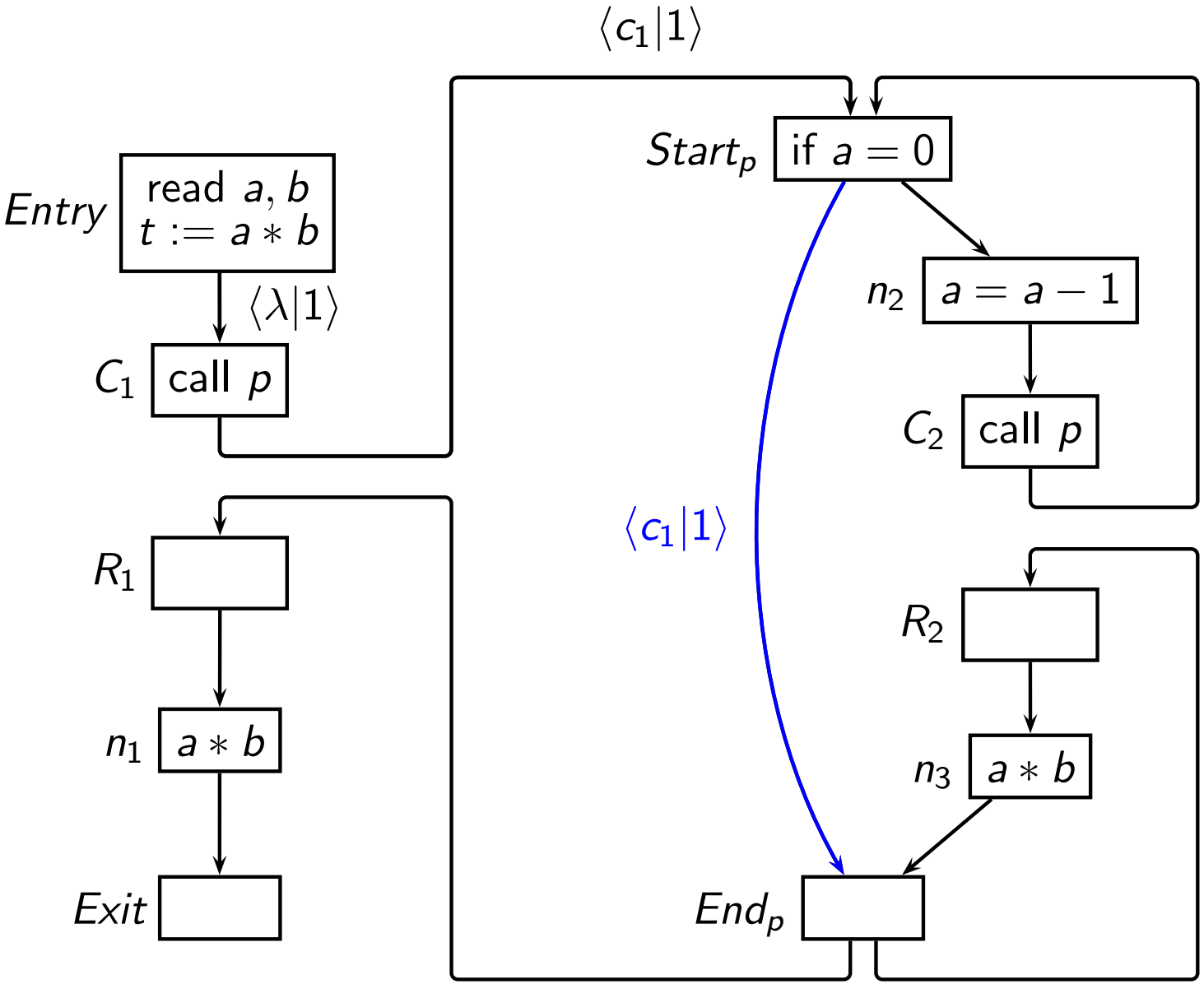

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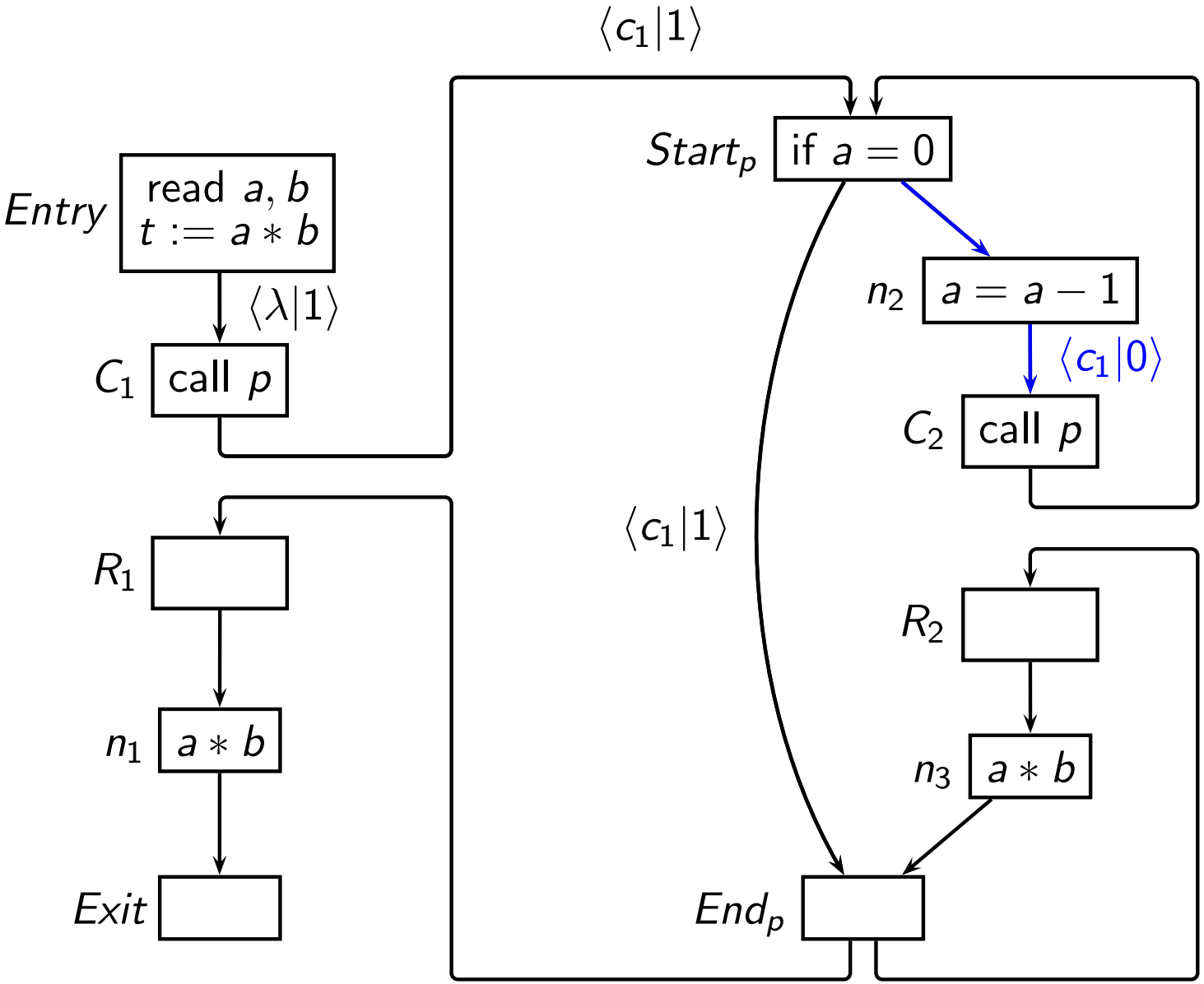

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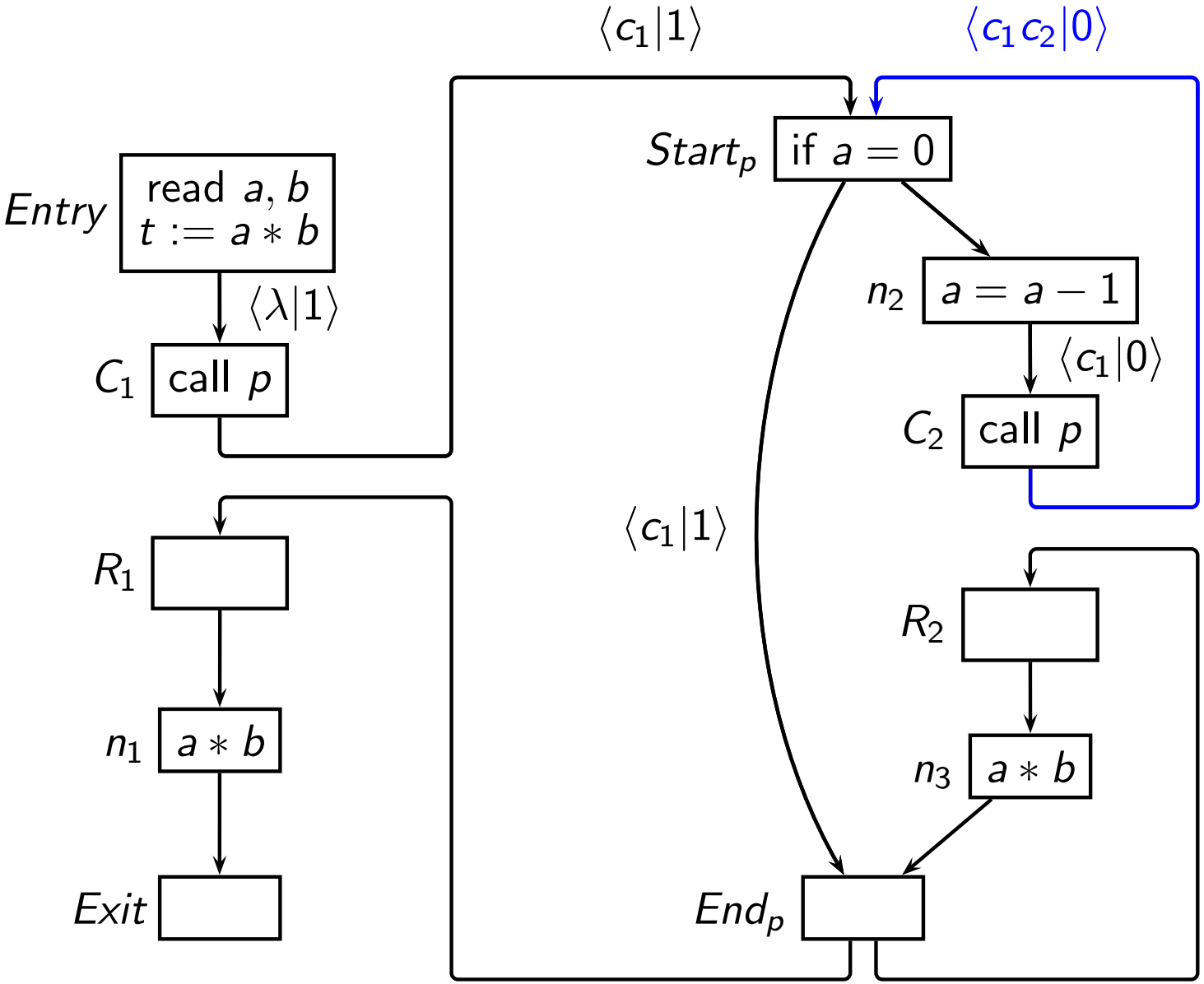

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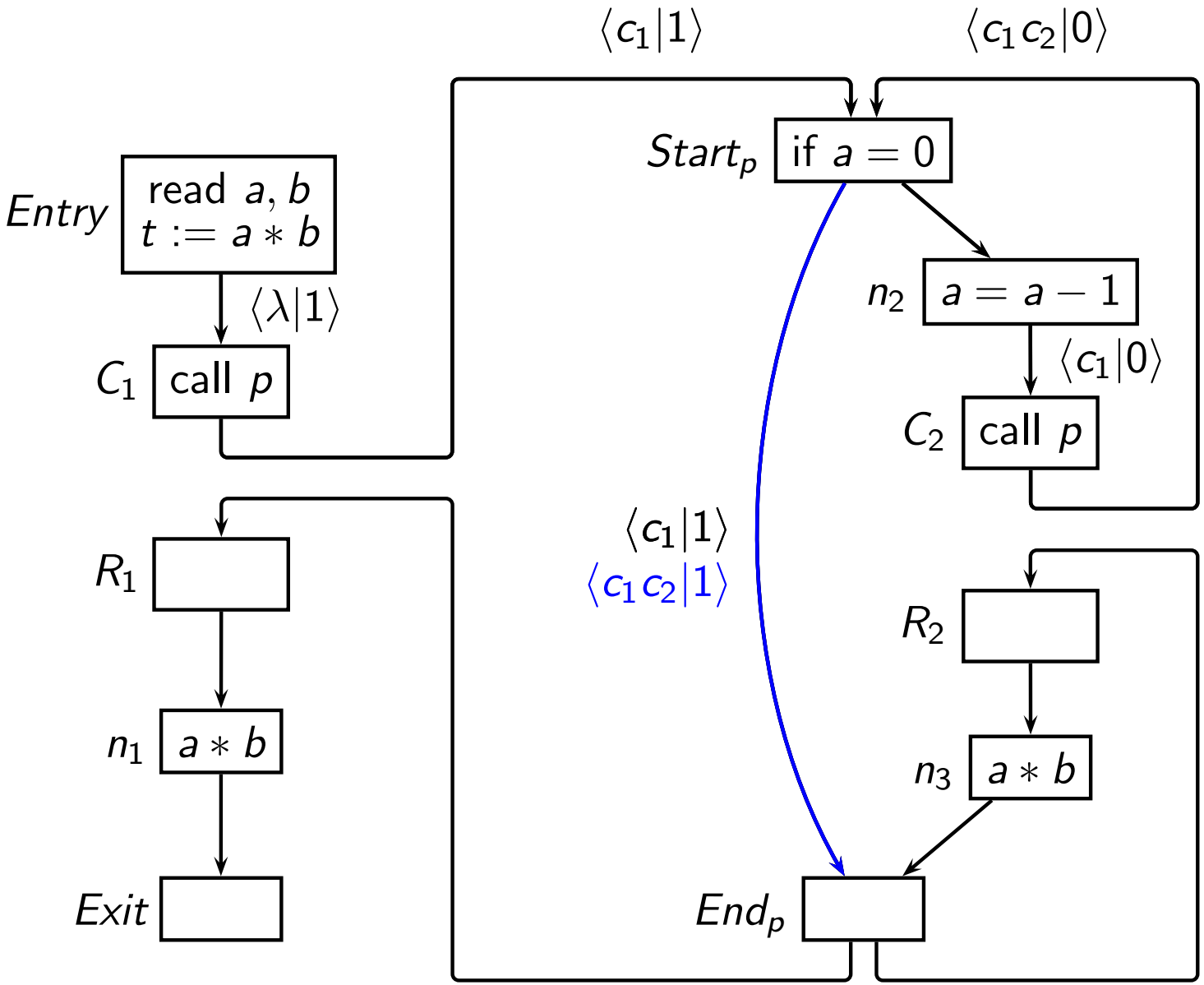

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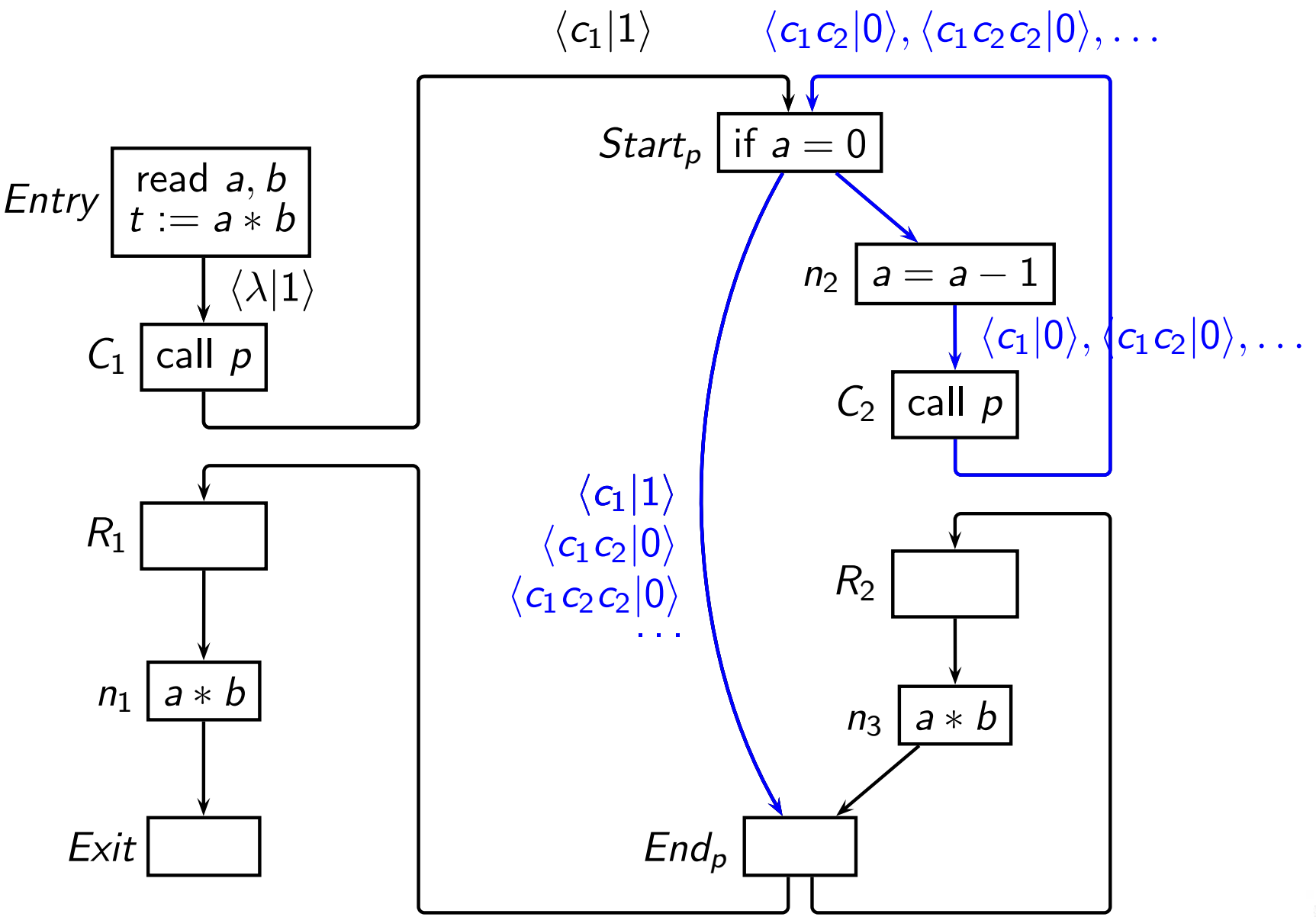

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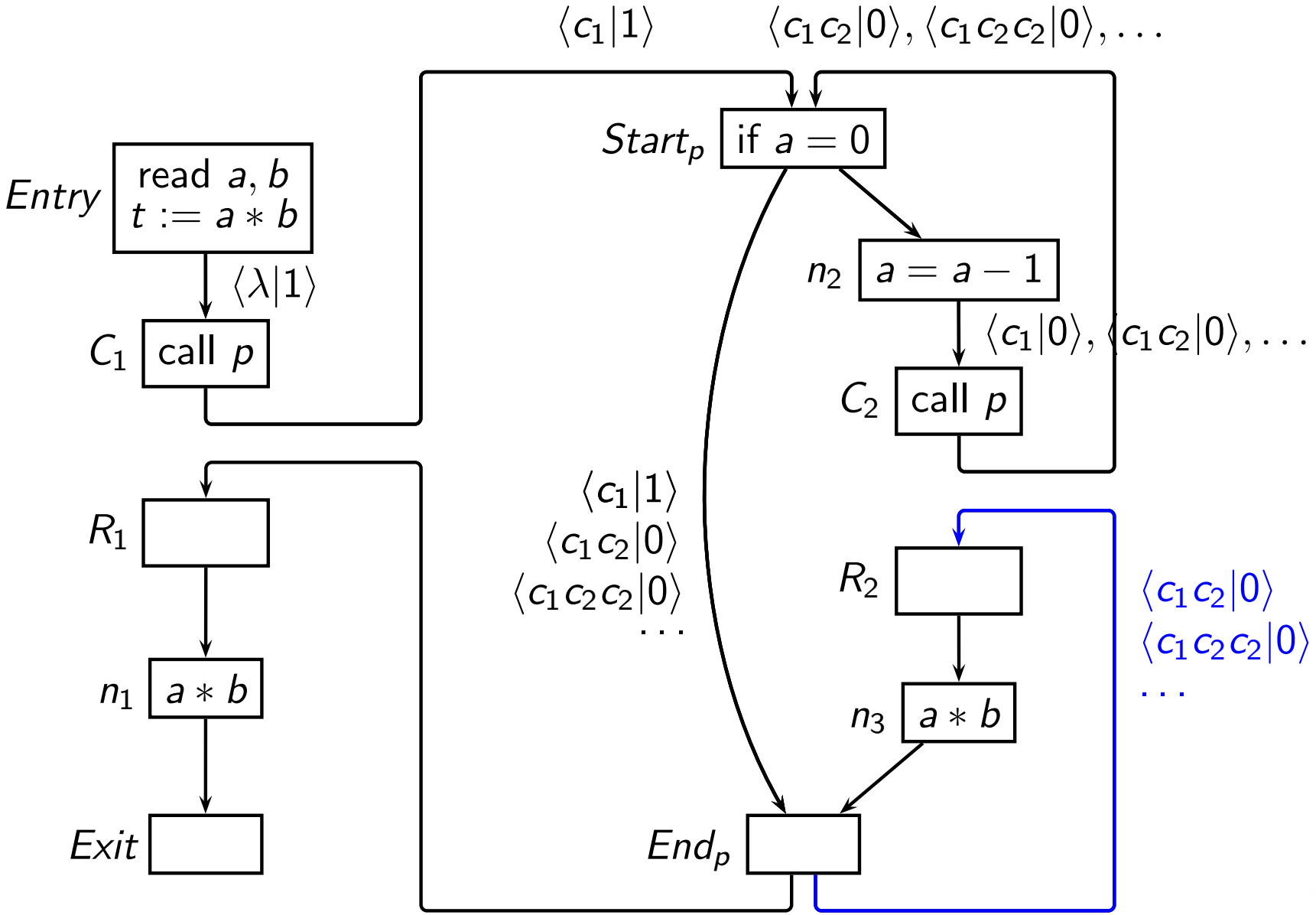

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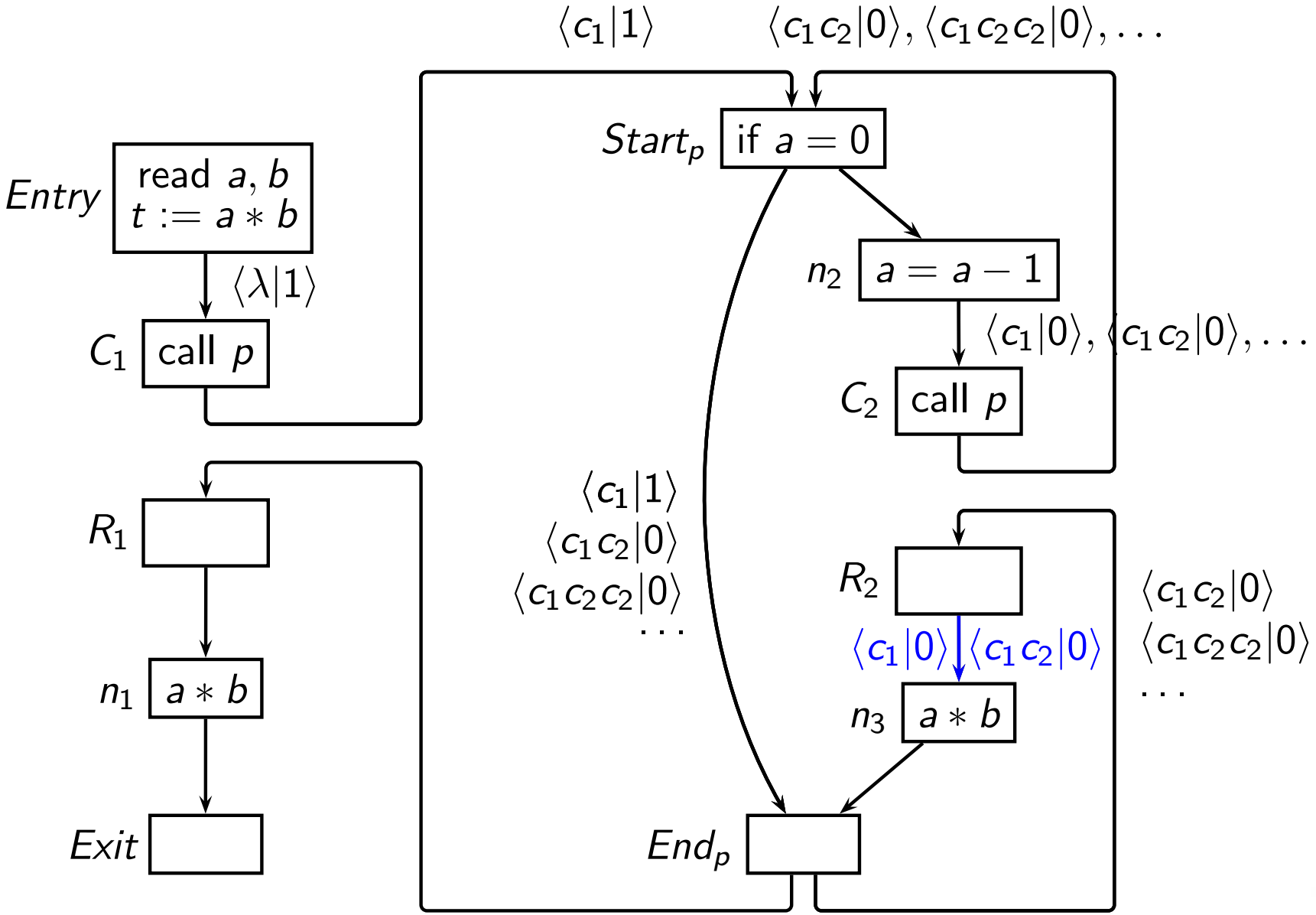

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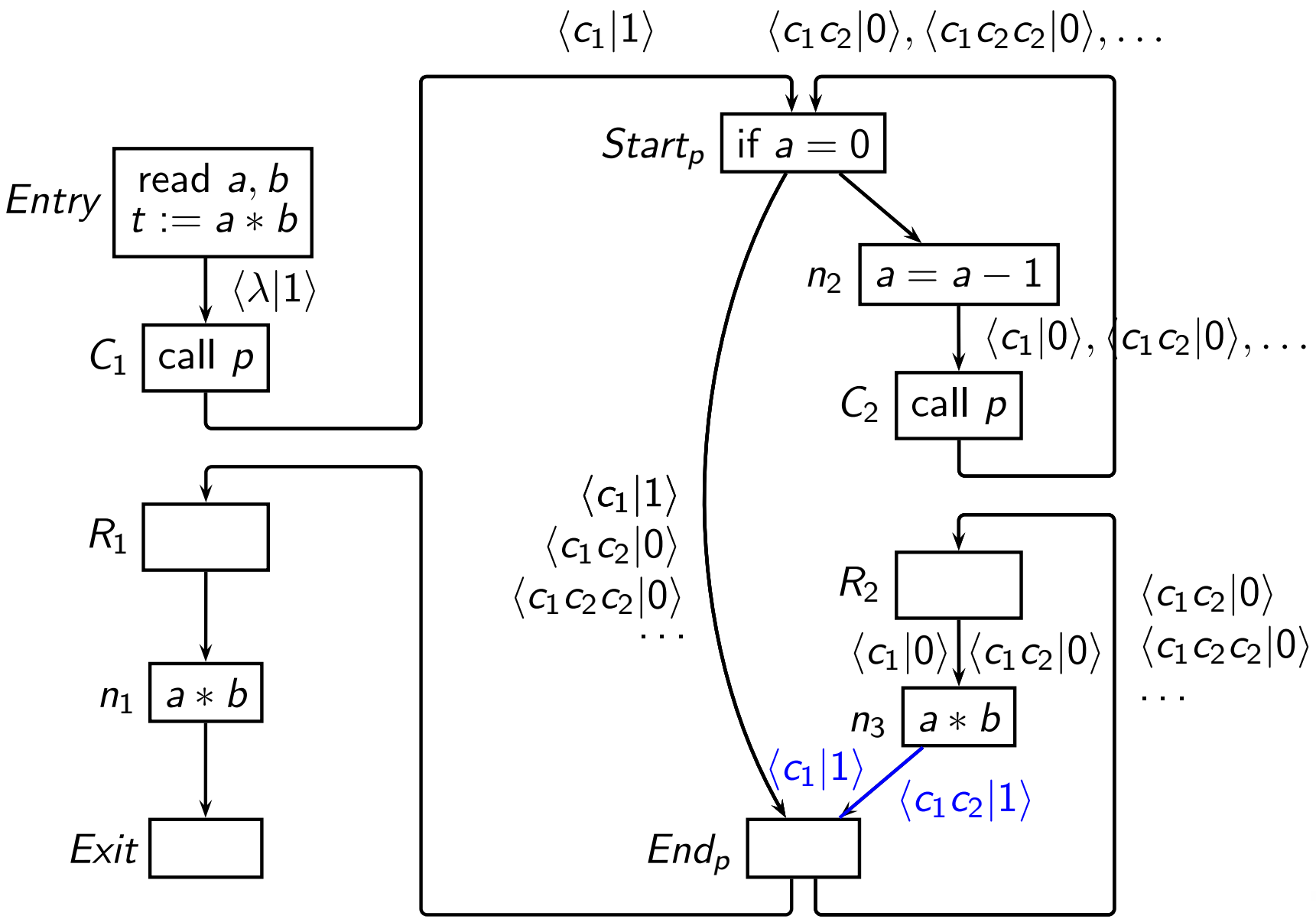

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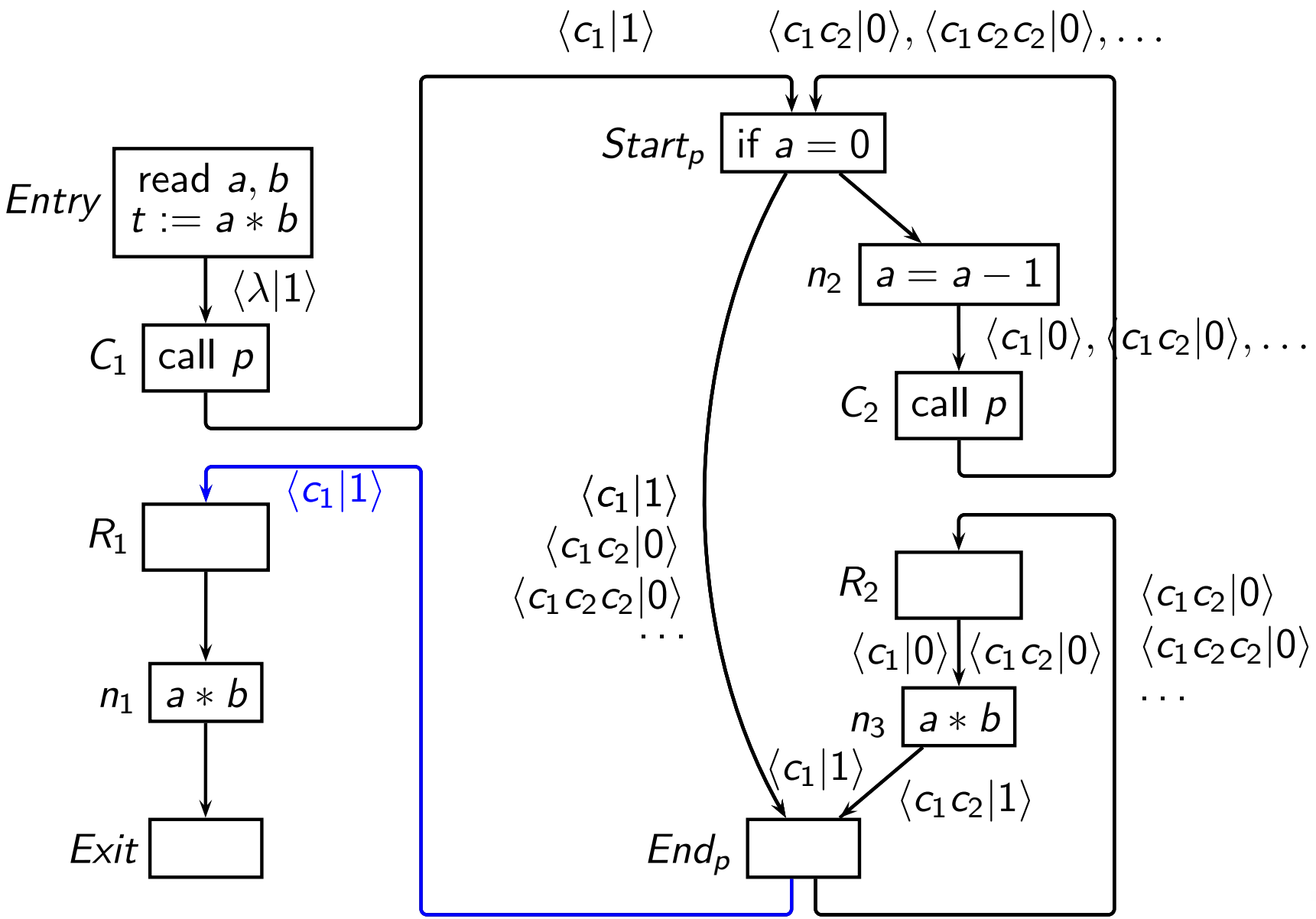

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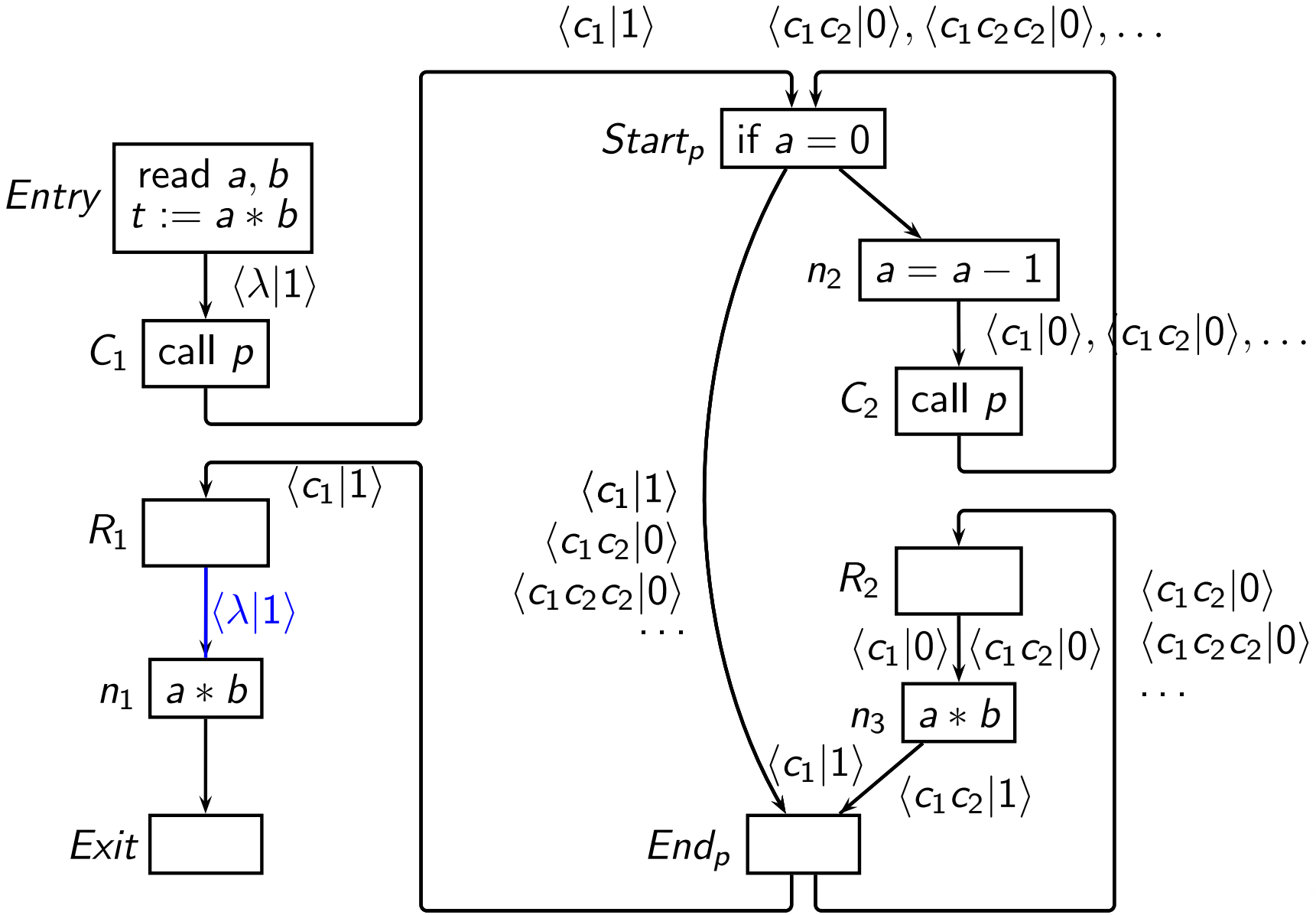

Terminating Call String Construction

- For non-recursive programs: Number of call strings is finite
- For recursive programs: Number of call strings could be infinite

  Fortunately, the problem is decidable for finite lattices.
  - All call strings with the length
    - $K \cdot (|L| + 1)^2$ for general bounded frameworks
      (L is the overall lattice of data flow values)
    - $K \cdot (|\widehat{L}| + 1)^2$ for separable bounded frameworks
      (L is the component lattice for an entity)
    - $K \cdot 3$ for bit vector frameworks

    must be constructed

  $\Rightarrow$ Large number of long call strings

Intuition Behind the Classical Call String Length

- Consider call and return nodes C_i and R_i
- Let the value at C_i x_i and the value at R_i be z_i.

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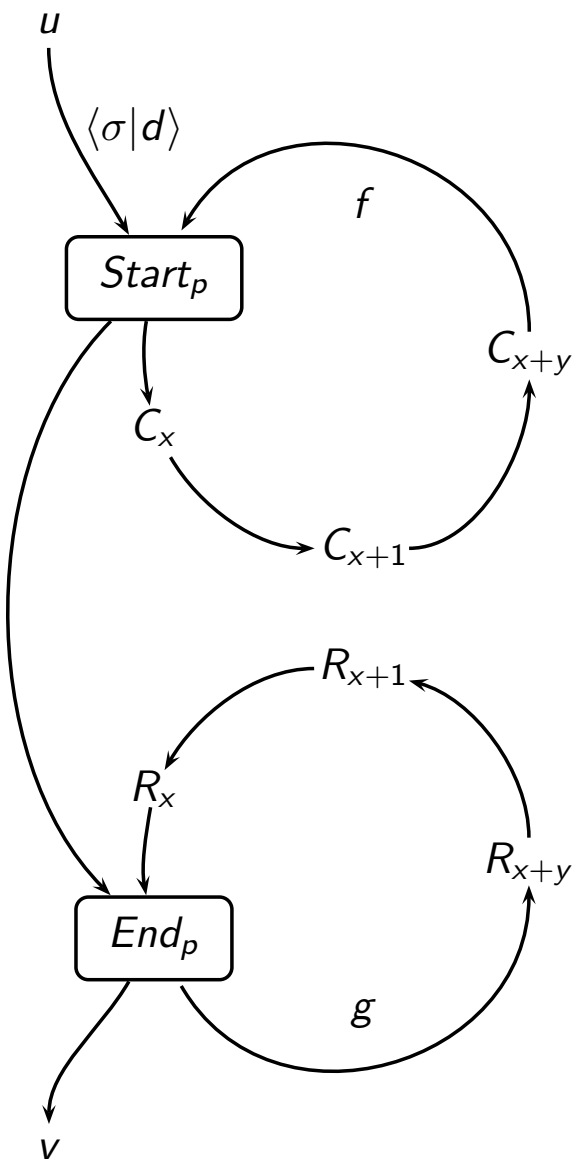
- Thus c_i can appear $(|L| + 1)^2$ times in a call string
- Since there are K call sites, it is sufficient to construct call strings of length $K \cdot (|L| + 1)^2$

Part 4

The Proposed Variant

Call Strings for Recursive Contexts



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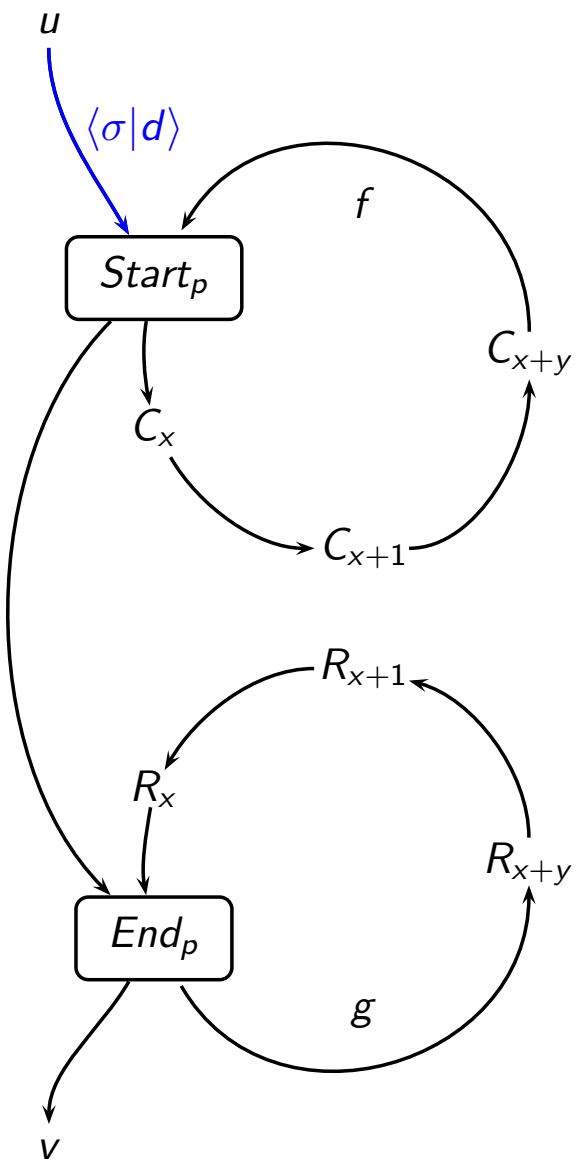

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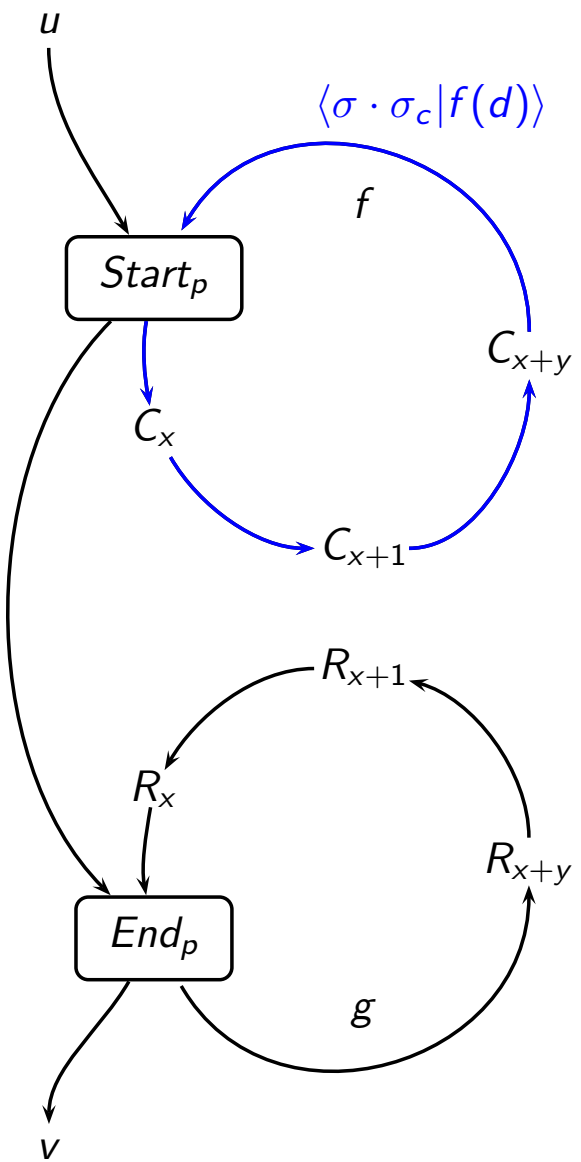

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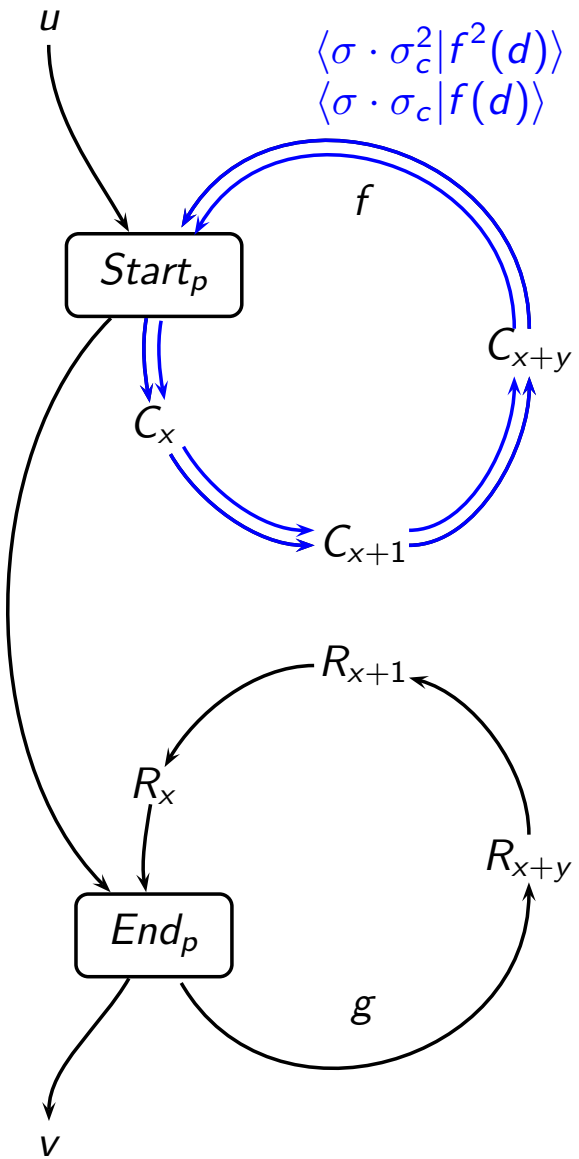

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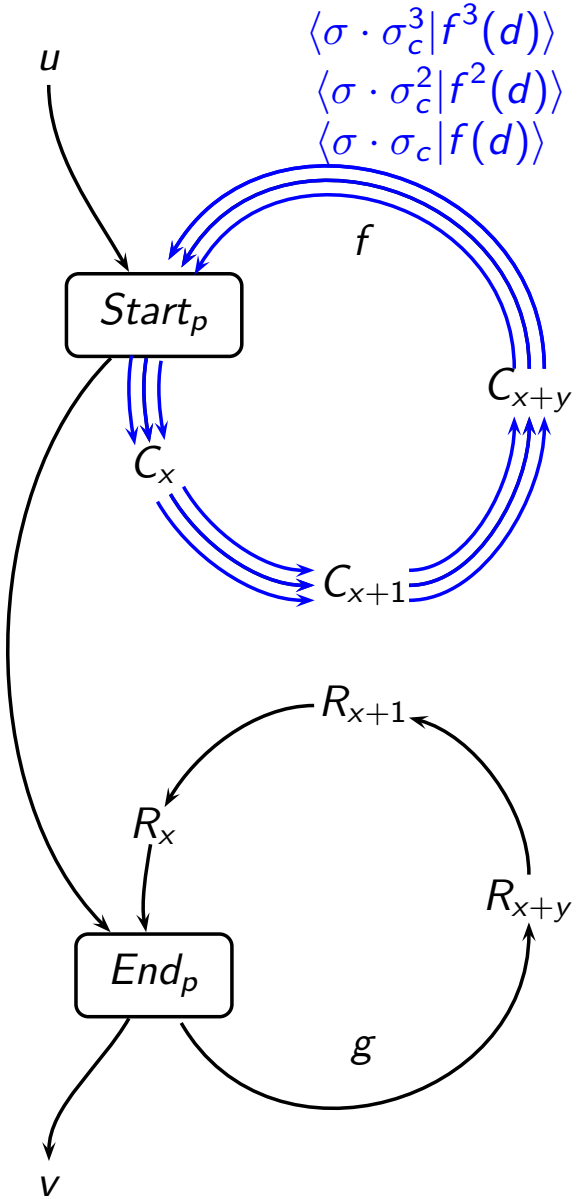

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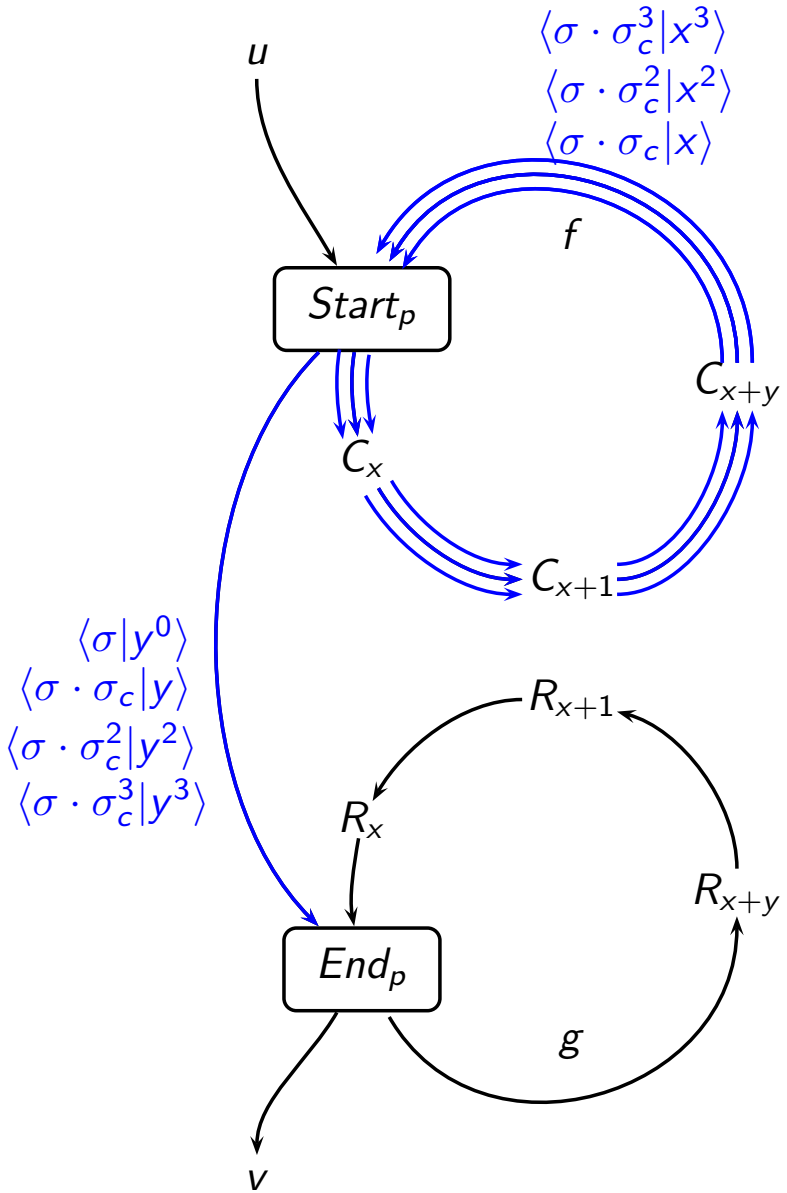

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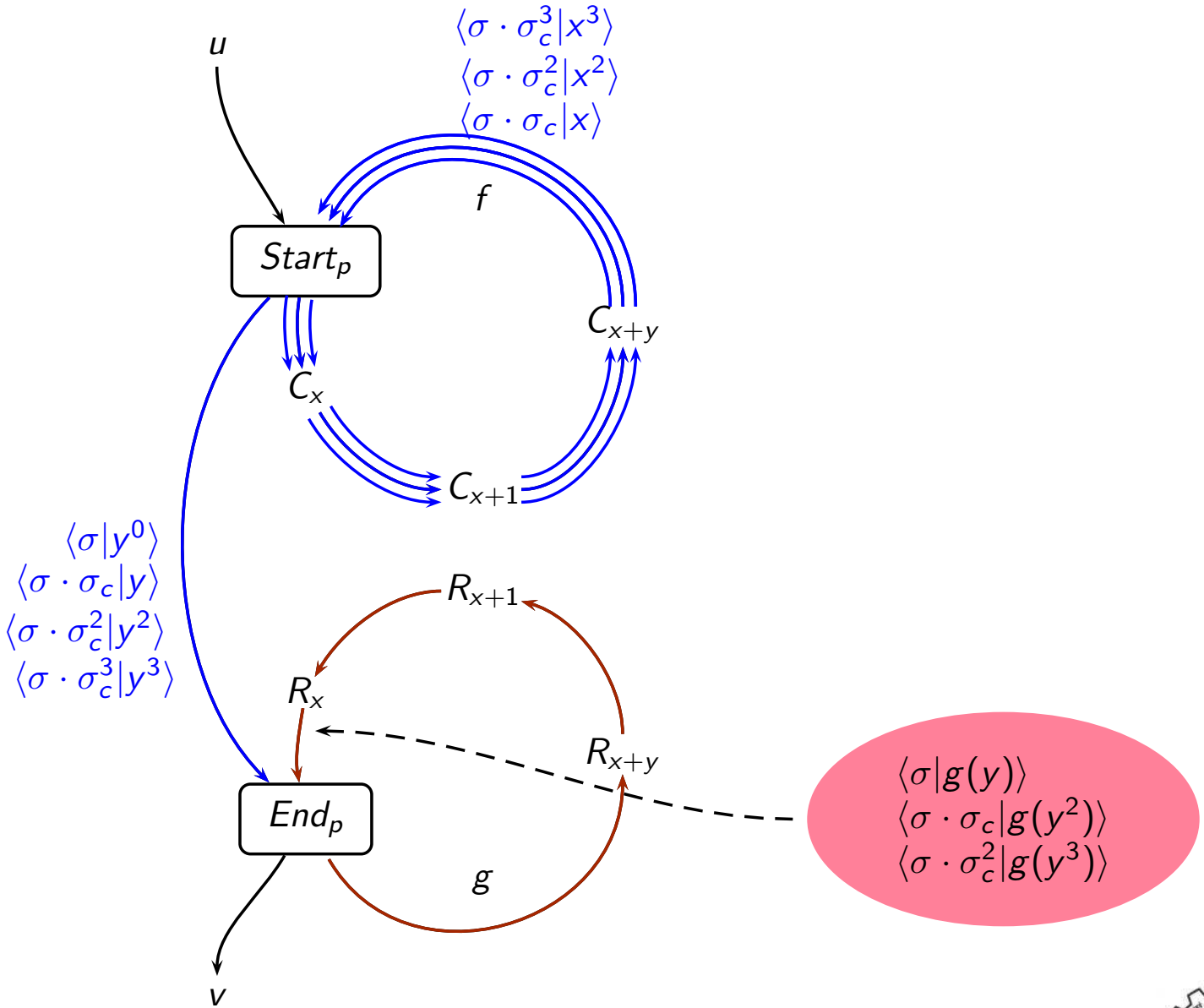

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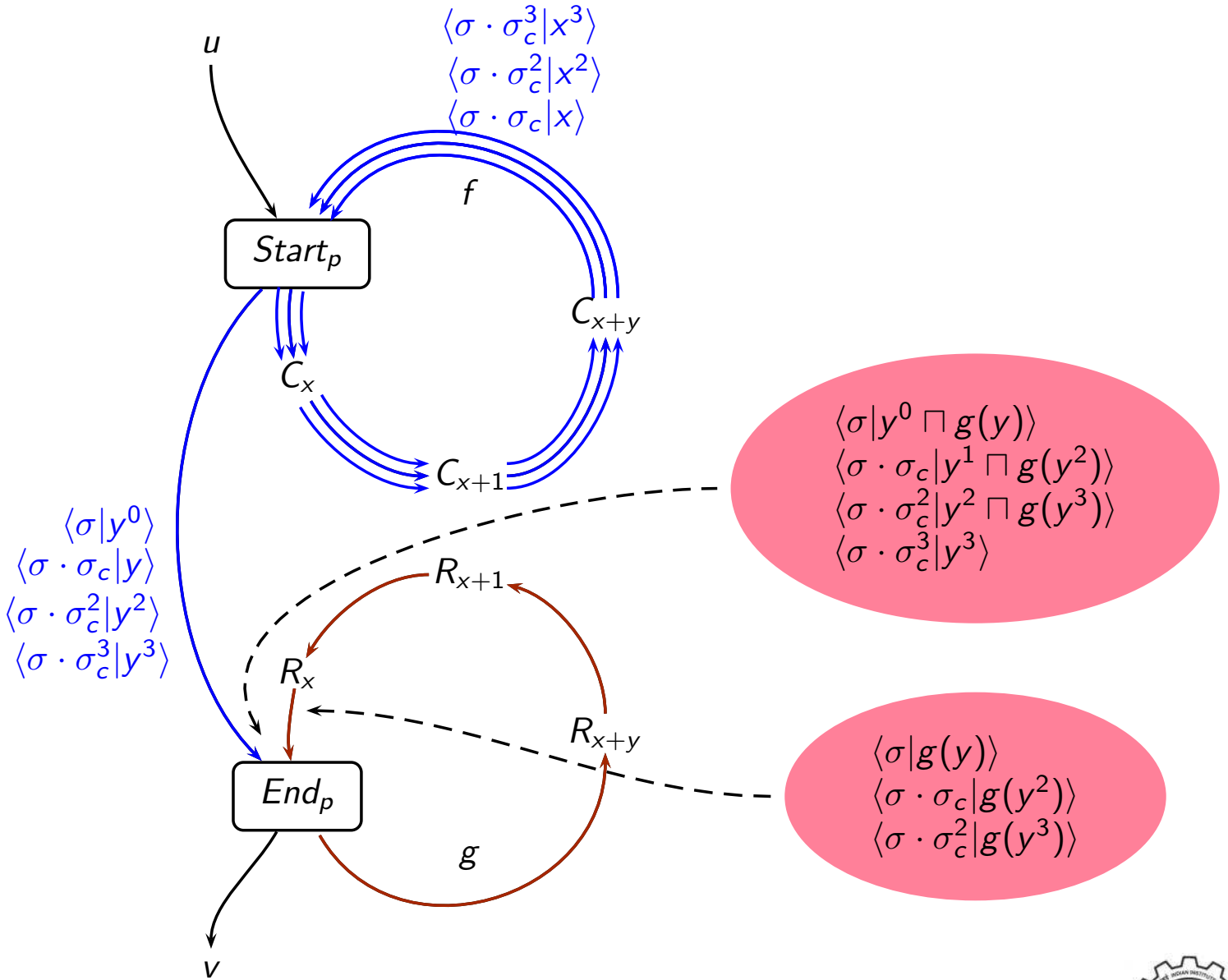

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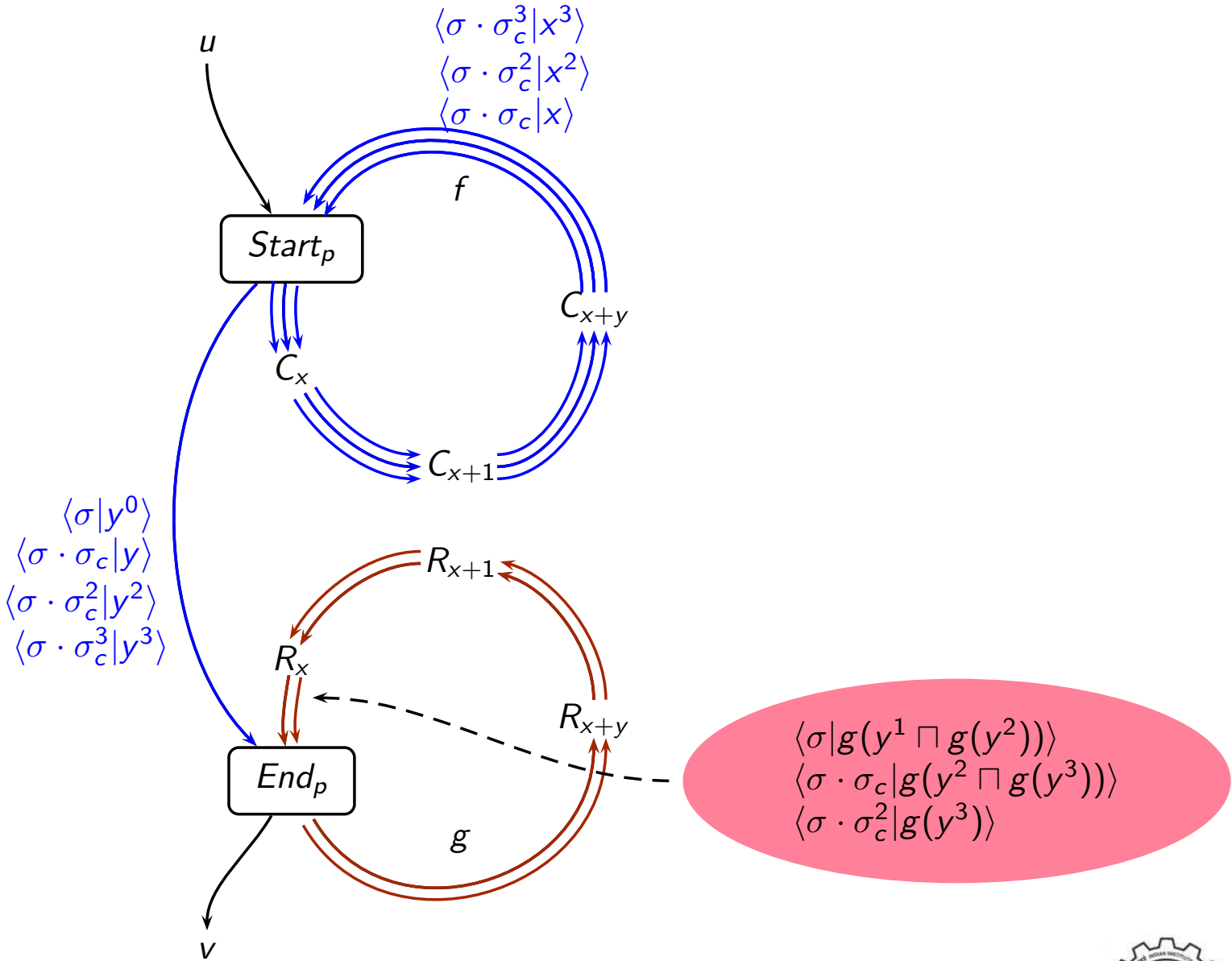

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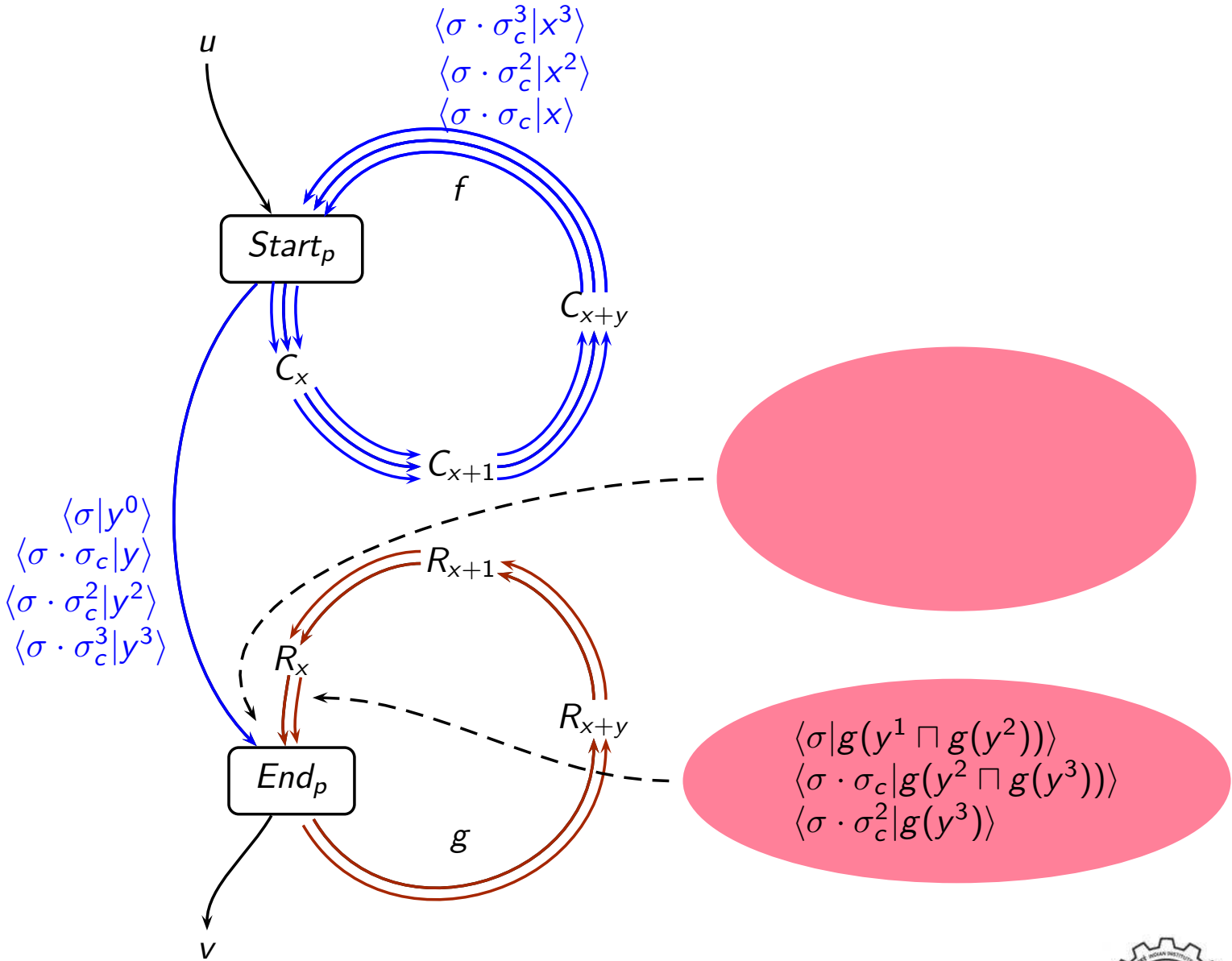

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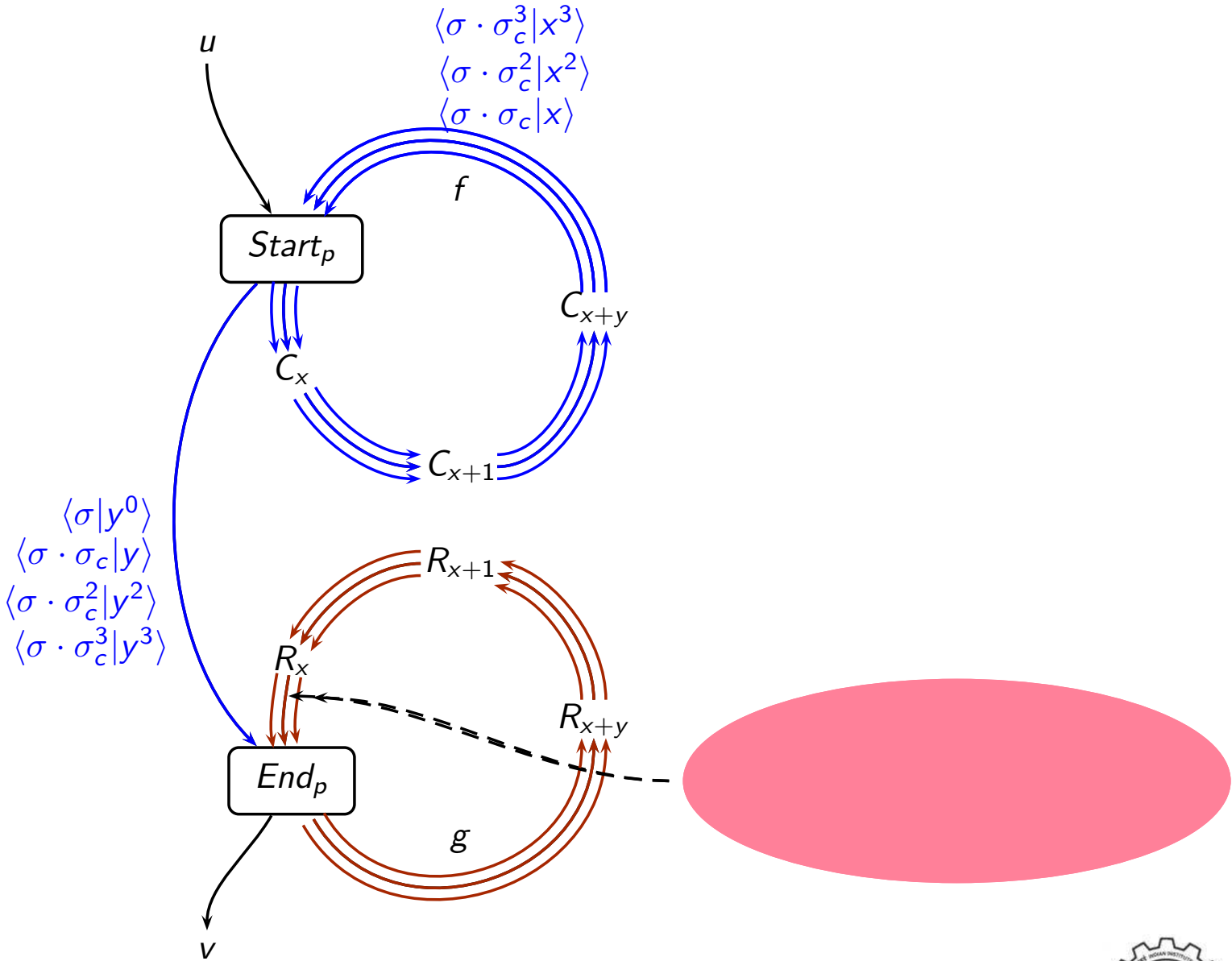

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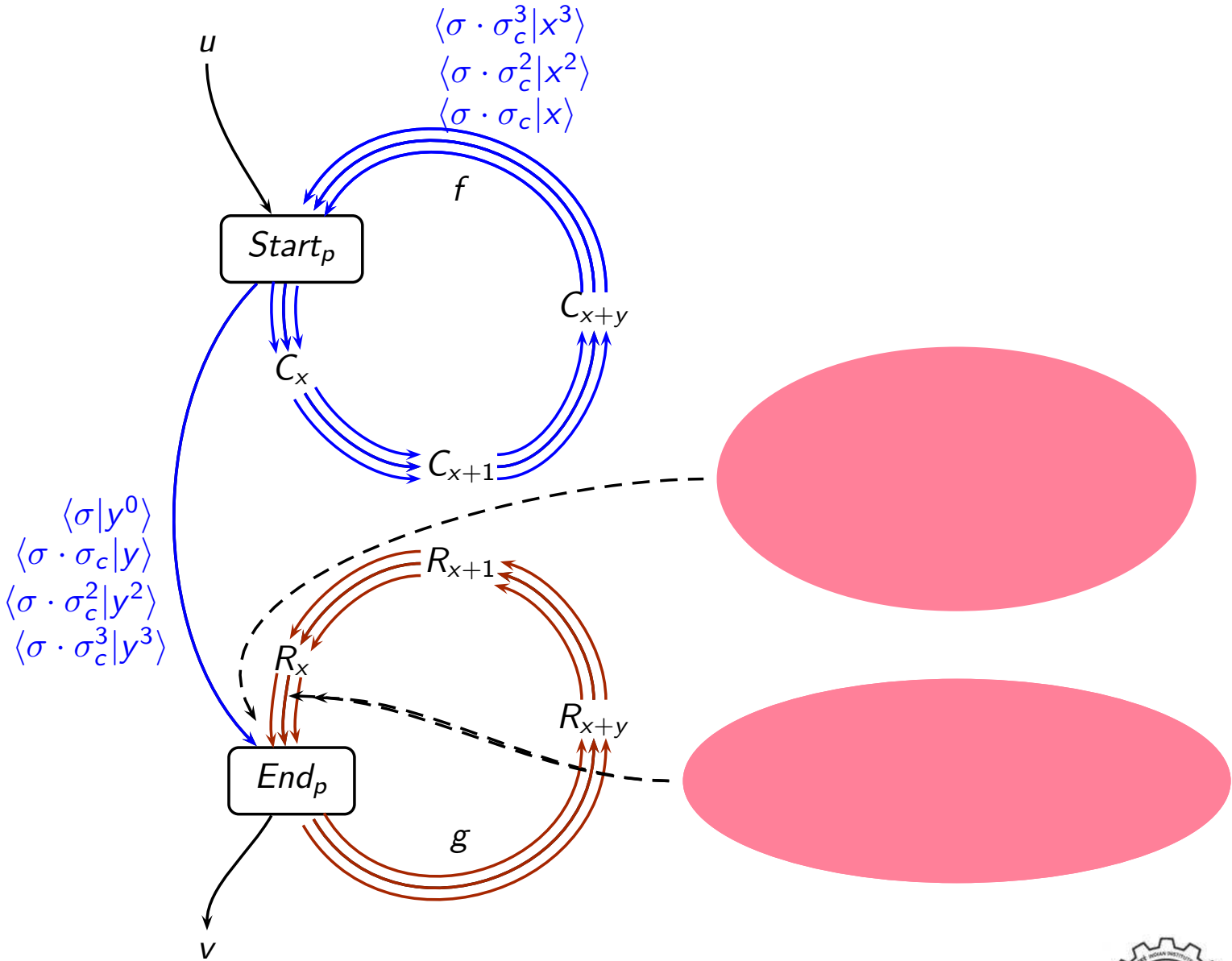
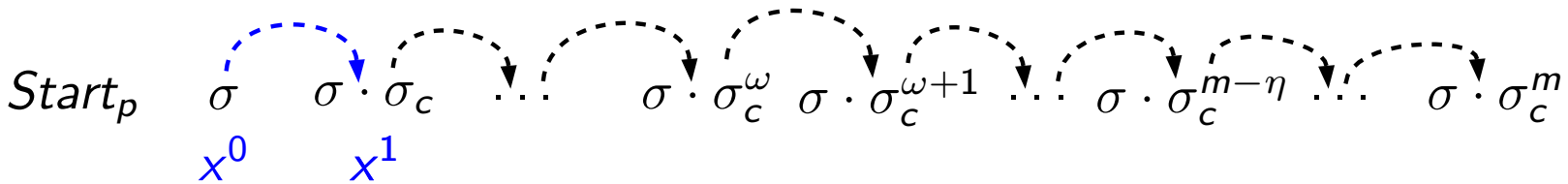


The Moral of the Story

- In the cyclic call sequence, the computation begins from the first call string and influences successive call strings.
- In the cyclic return sequence, the computation begins from the last call string and influences the preceding call strings.

Bounding the Call String Length



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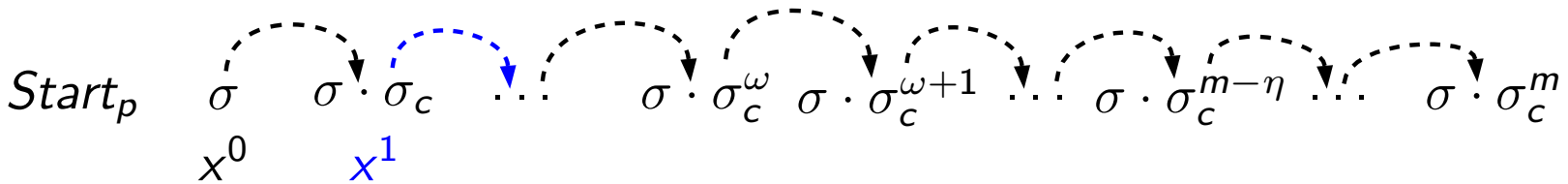

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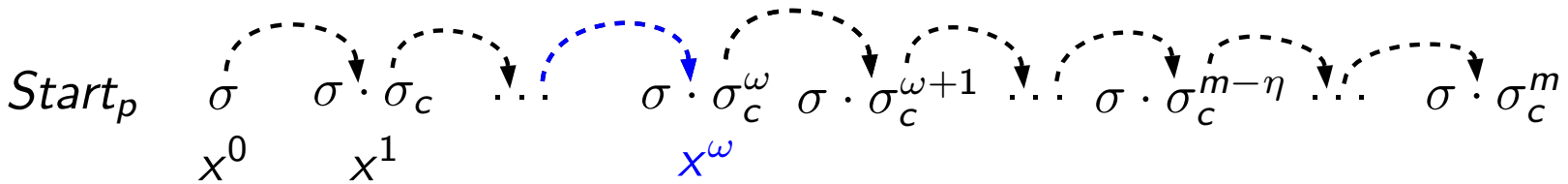

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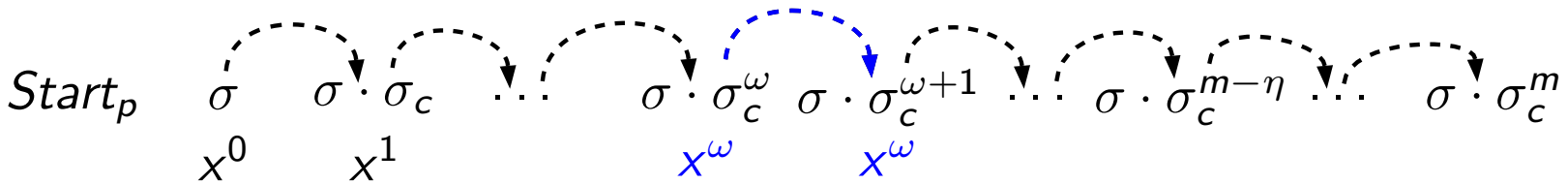

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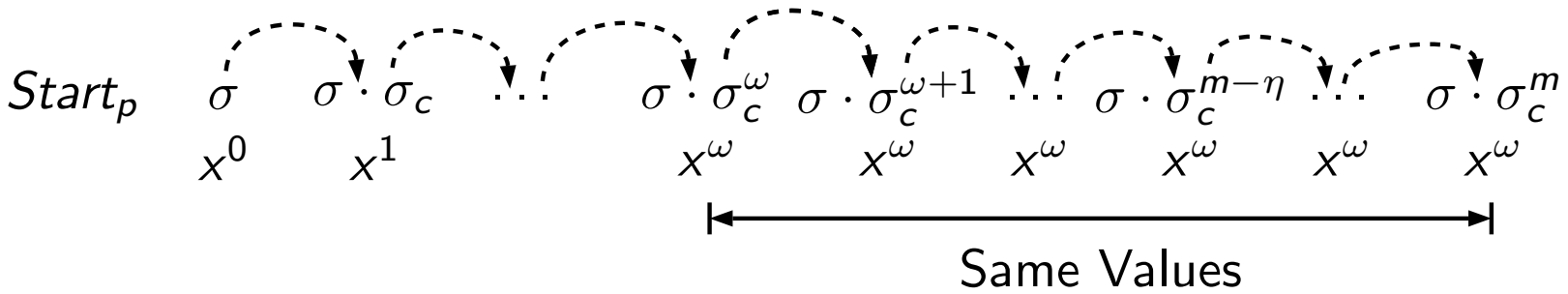

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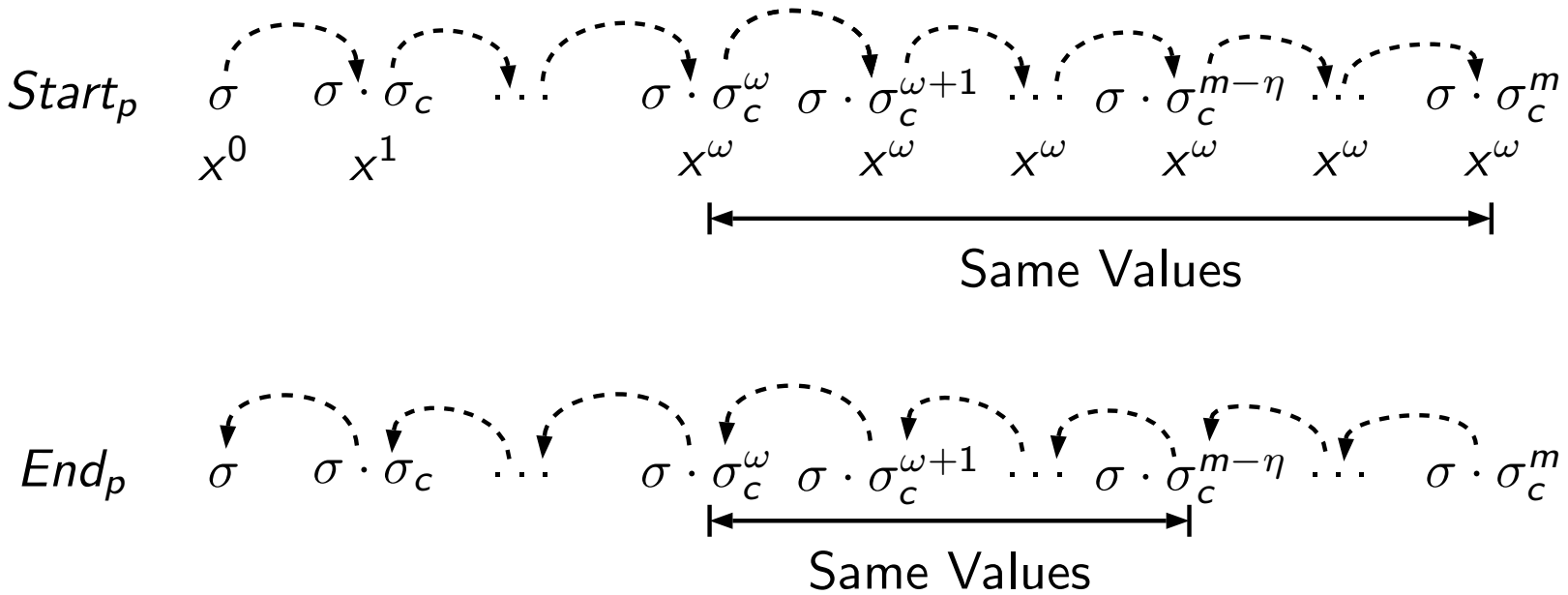

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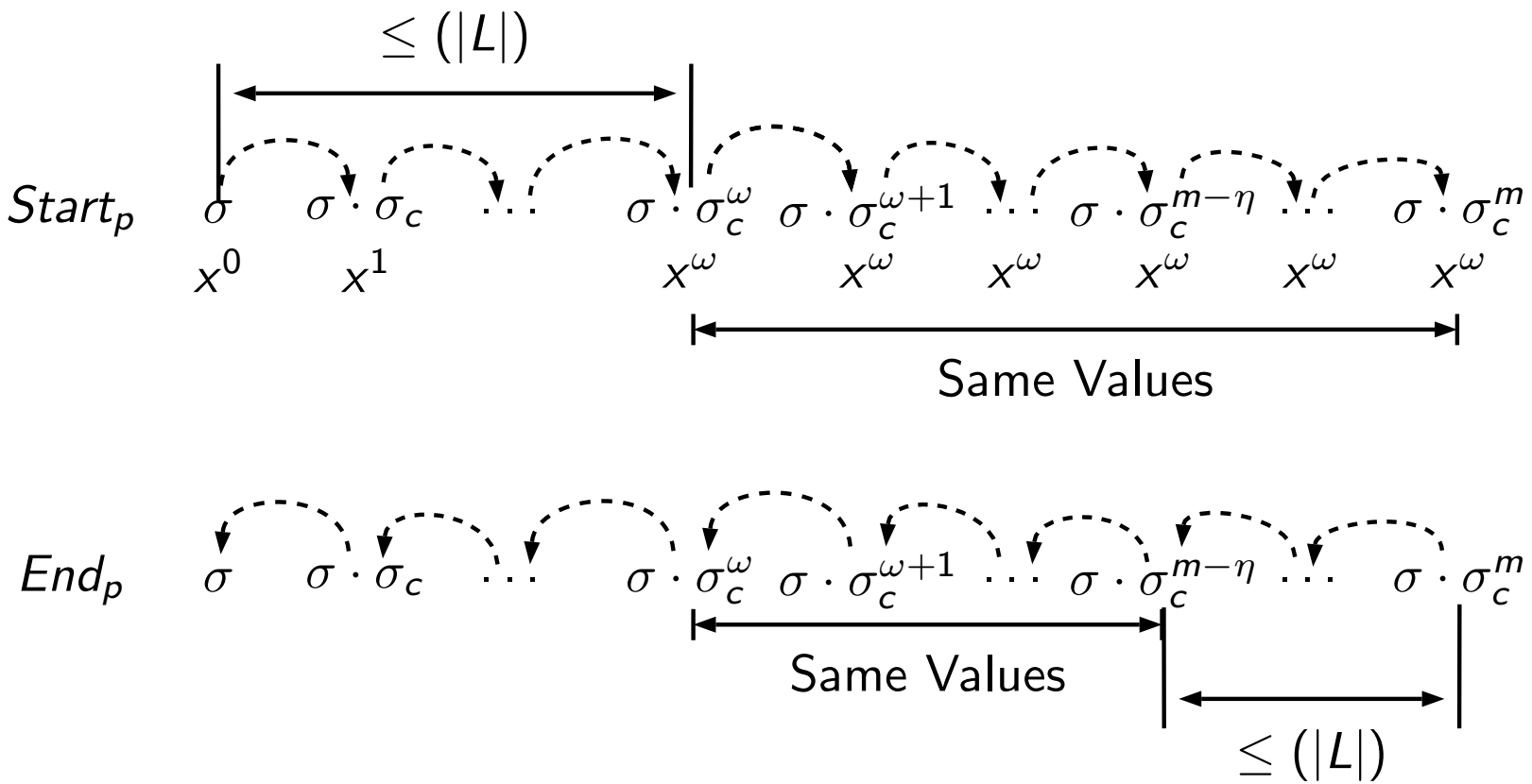

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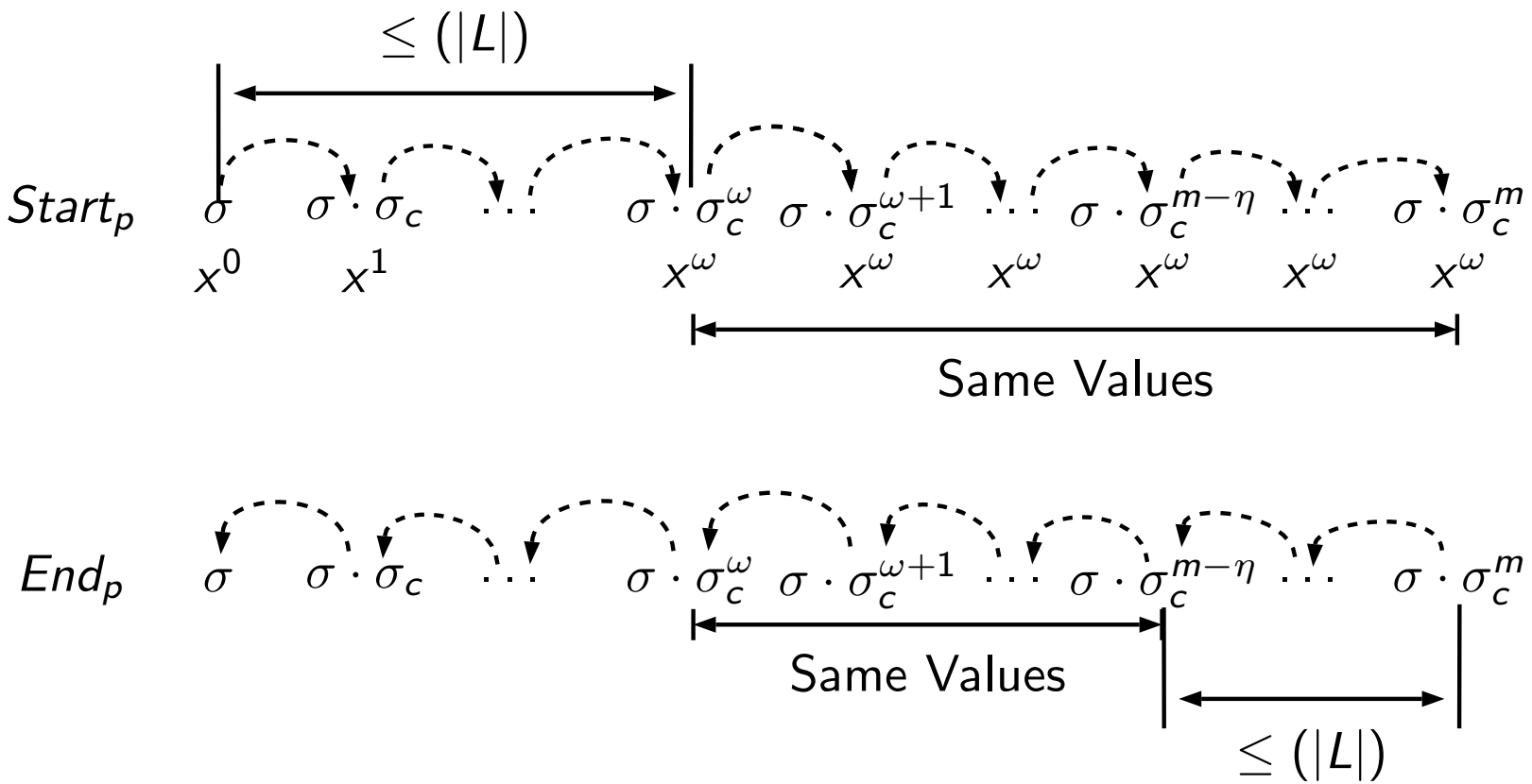
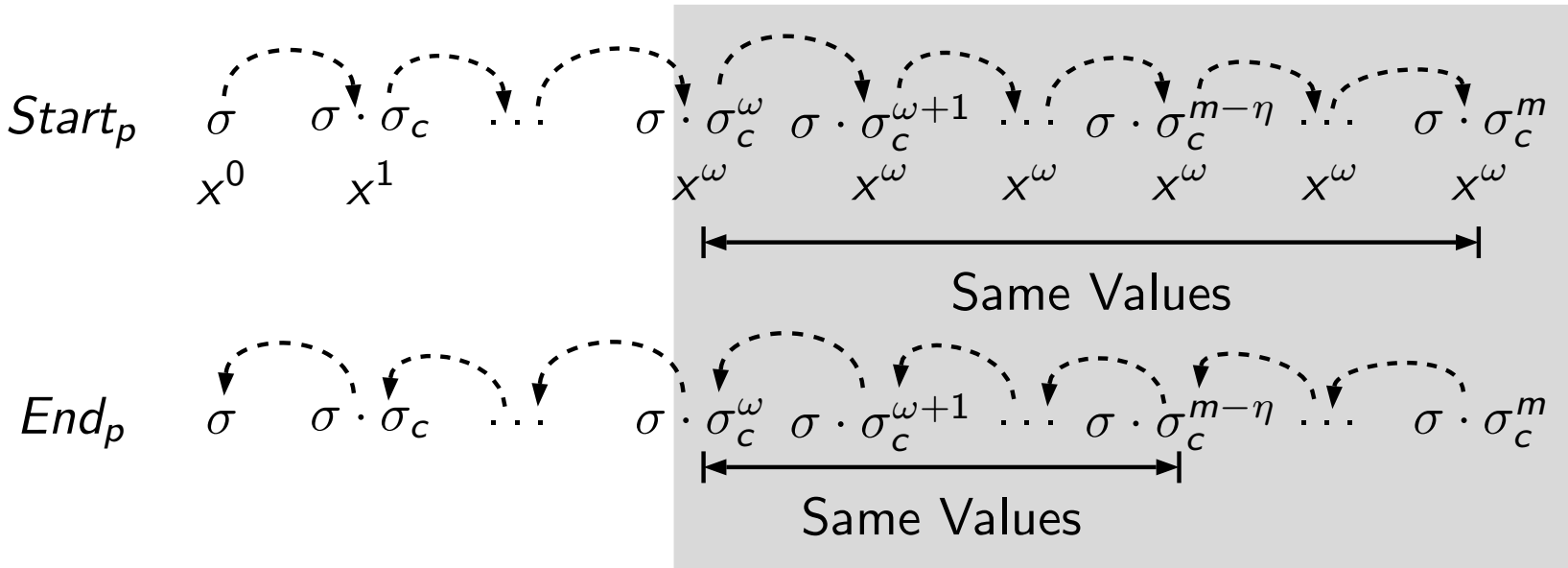


- m must be $>= 2 \cdot |L|$
- Since there could be K call sites in σ_c, call strings of length $K \cdot 2 \cdot |L|$ are sufficient.

Using Data Flow Values to Bound Call Strings



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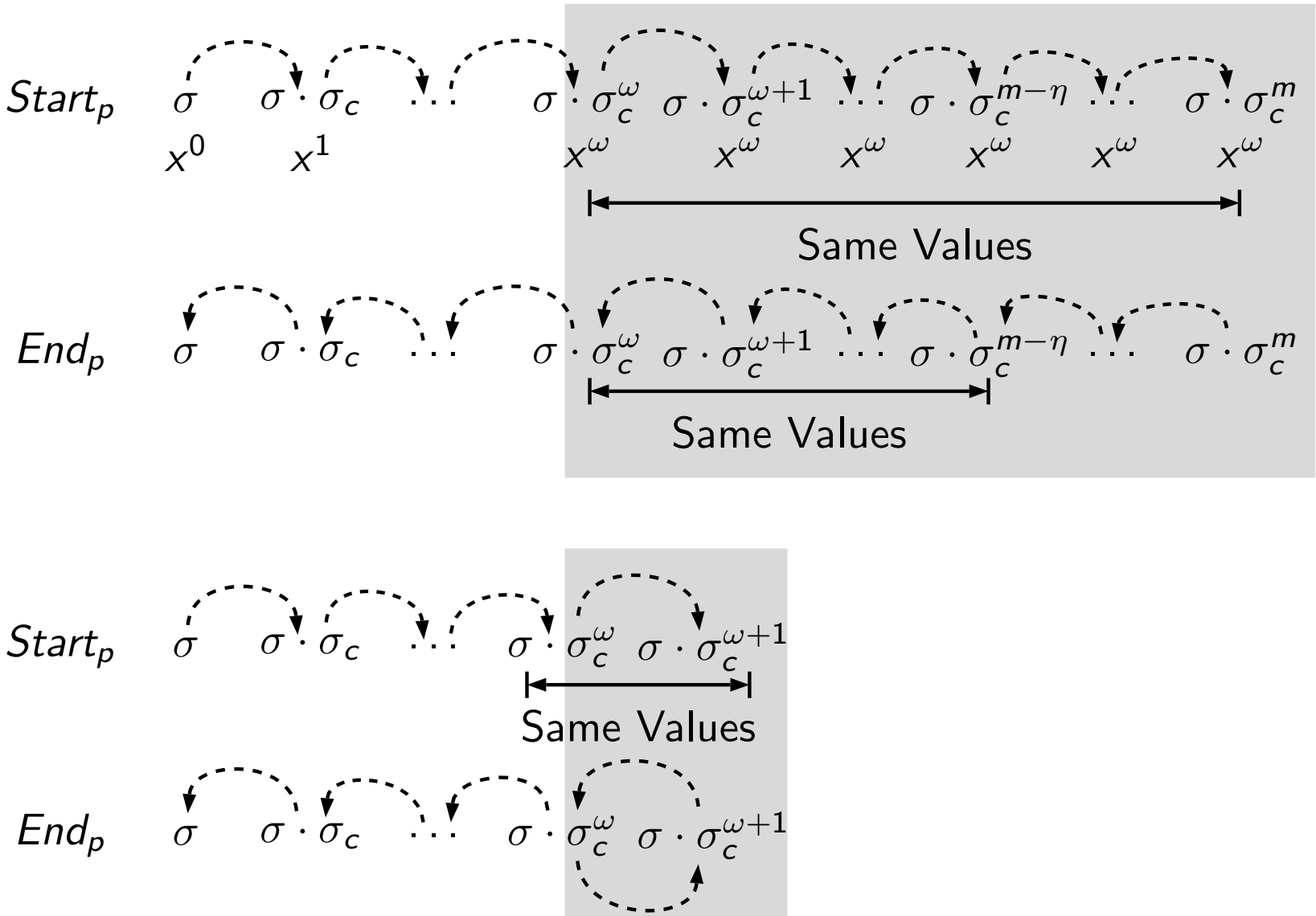

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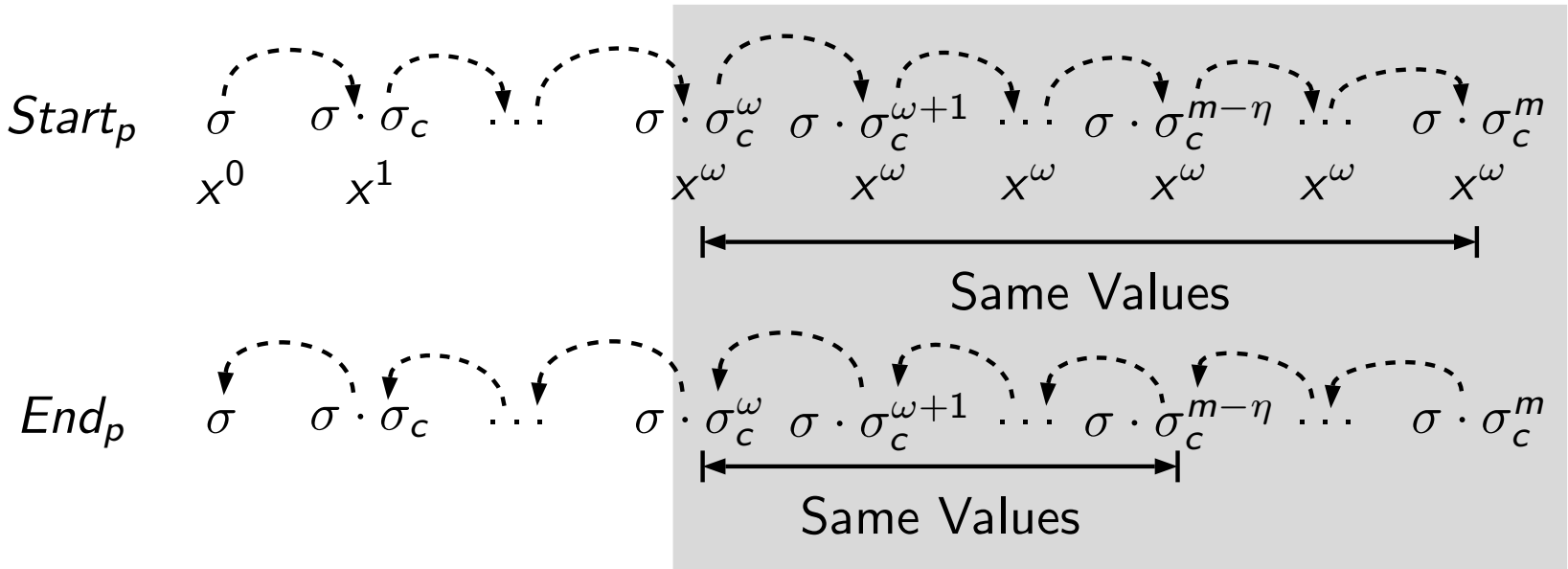

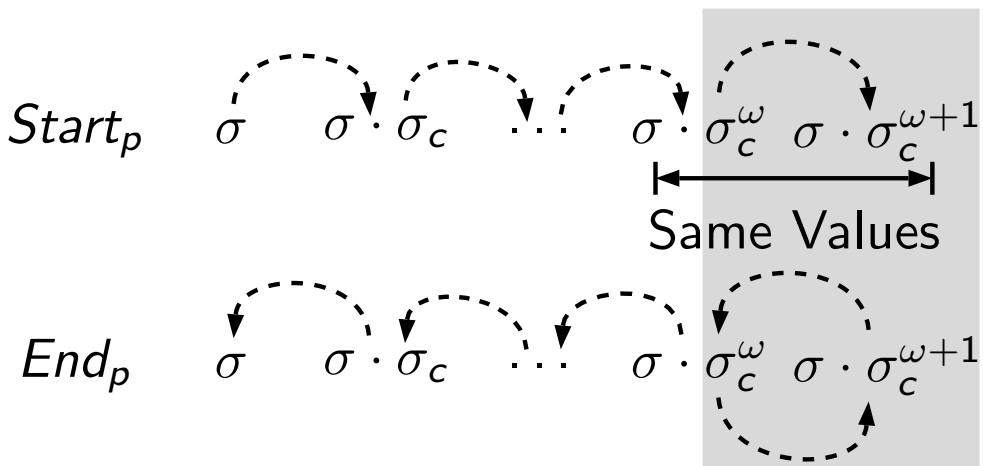

$\omega \leq |L| \Rightarrow$

- at most $|L| + 1$ occurrences of σ_c.
- call string length is at most $K \cdot (|L| + 1)$

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The Final Algorithm

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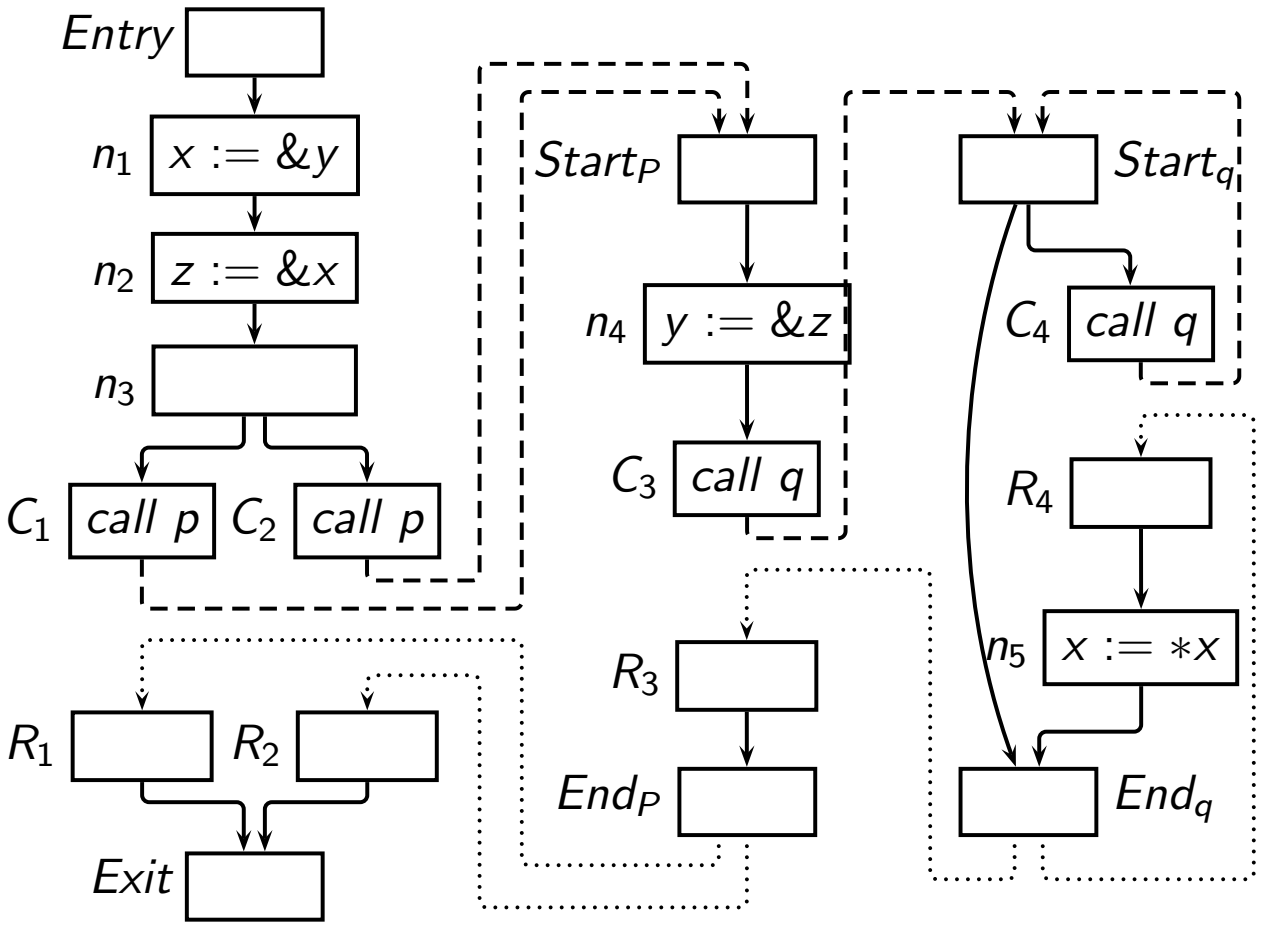
  - Then, since σ_1 and σ_2 are transformed in the same manner by traversing the same set of paths,
  - The values associated with them will also be transformed in the same manner and will continue to remain equal at End_p.

Implementing the Required Change

Let $shortest(\sigma, u)$ denote the shortest call string which has the same value as σ at u.

$$
\begin{aligned}
represent(\langle \sigma, d \rangle, Start_p) &= \langle shortest(\sigma, Start_p), d \rangle \\
regenerate(\langle \sigma, d \rangle, End_p) &= \{\langle \sigma', d \rangle \mid \sigma \text{ and } \sigma' \text{ have the same value at } Start_p\}
\end{aligned}
$$

Points-To Analysis



- $|L| = 512$, $K = 3$.
- The classical method requires 789507 call strings
- We need 5 call strings!

Approximate Version

- For framework with infinite lattices, a fixed point for cyclic call sequence may not exist.
- Use a demand driven approach:
  After a dynamically definable limit, start merging the values and associate them with the last call string.
  Assumption: Height of the lattice is finite.

Part 5

Empirical Measurements

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.

Part 6

Conclusions

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All this is achieved by a simple change without compromising on the precision, simplicity, and generality of the classical method.

Conclusions

- Compromising on precision may not be necessary for efficiency.
- Separating the necessary information from redundant information is much more significant.
- A precise modelling of the process of analysis is often an eye opener.

Future Work

- Implementing for points-to analysis.
- Modelling parameters and return values.
- Applying it to Heap Reference Analysis [TOPLAS, Nov 2007]
- Machine independent optimizer generator in GCC.

Reference

- To appear in CC 2008.

Acknowledgement

- Implementation was carried out by Seema Ravandale.

Last but not the least ...

Thank You!