Revisiting Out-of-SSA Translation for Correctness, Code Quality, and Efficiency

For both Static and JIT Compilation

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Laboratoire de l'Informatique du Parallélisme (LIP)
École normale supérieure de Lyon

SSA Seminar, April 27, 2009, Autrans

Context

Collaboration between Compsys team and STMicroelectronics compiler group.

- Back-end compiler: Open64 + LAO (linear assembly optimizer) with use of SSA and ψ-SSA.
- Double role: both static and just-in-time compilation for STMicro processor family.
- Applications: multimedia applications.
- Optimization objectives: compiler robustness, ease of implementation, portability, code quality, speed of compiler.
- Other collaboration themes: instruction cache optimization, register allocation.

Outline

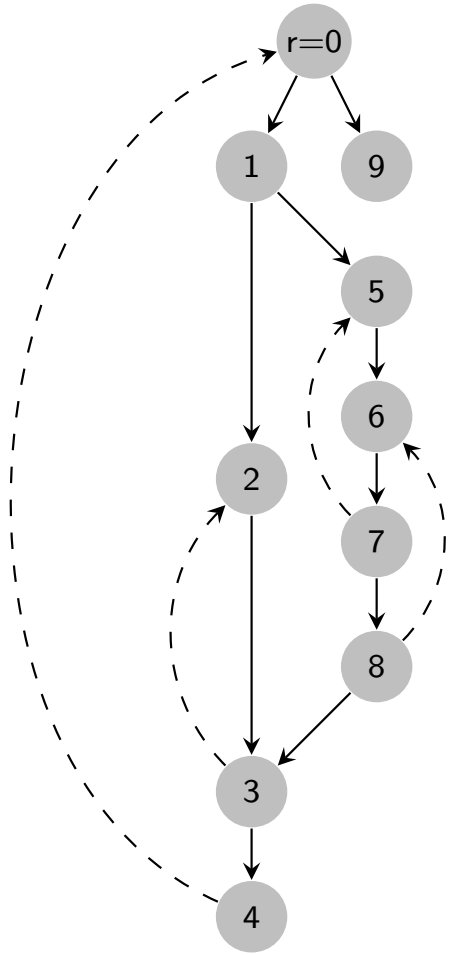
Dominance

Control Flow Graph

- one entry node r;
- every node reachable from r.

Definition (dominance)

a dominates b if every path from the root r to b contains a.



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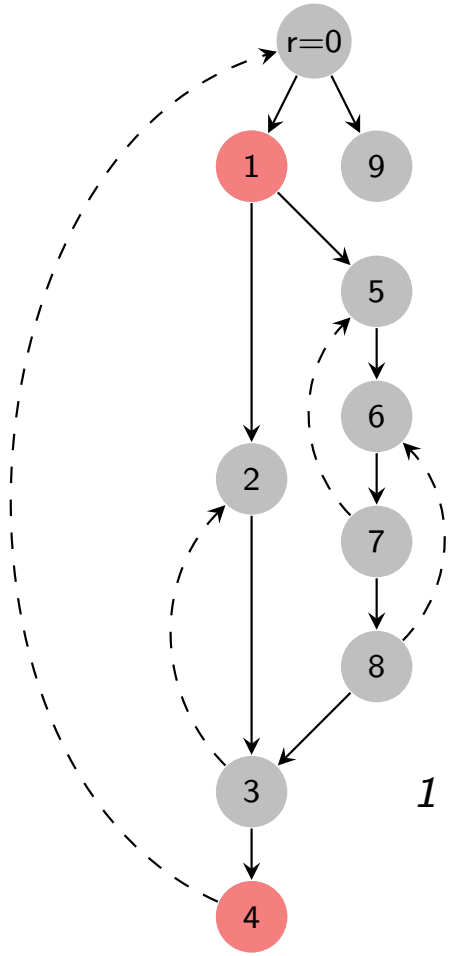

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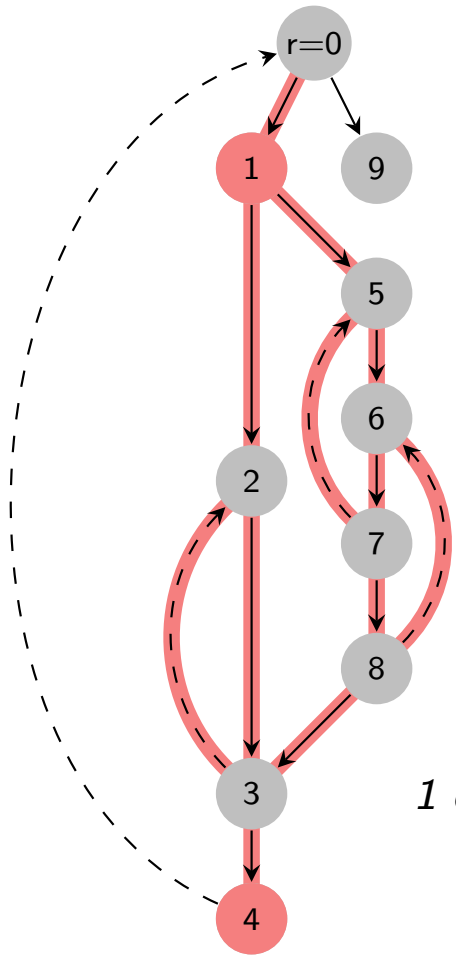

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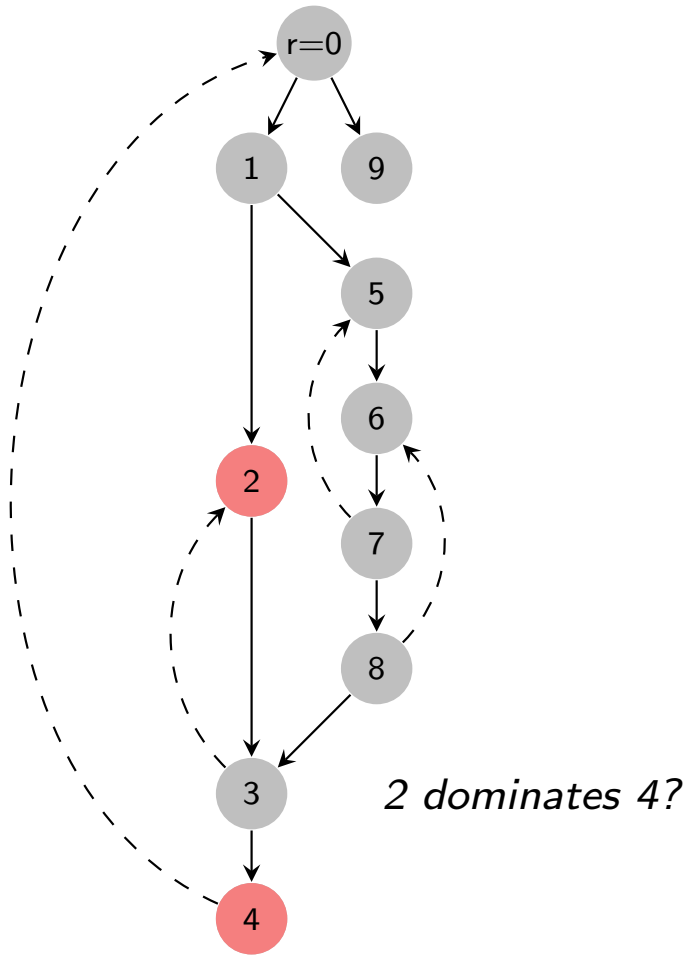

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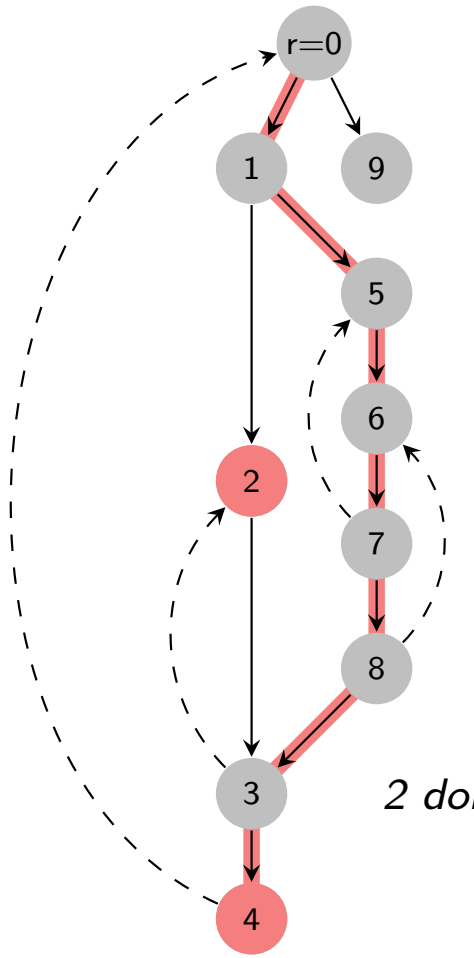

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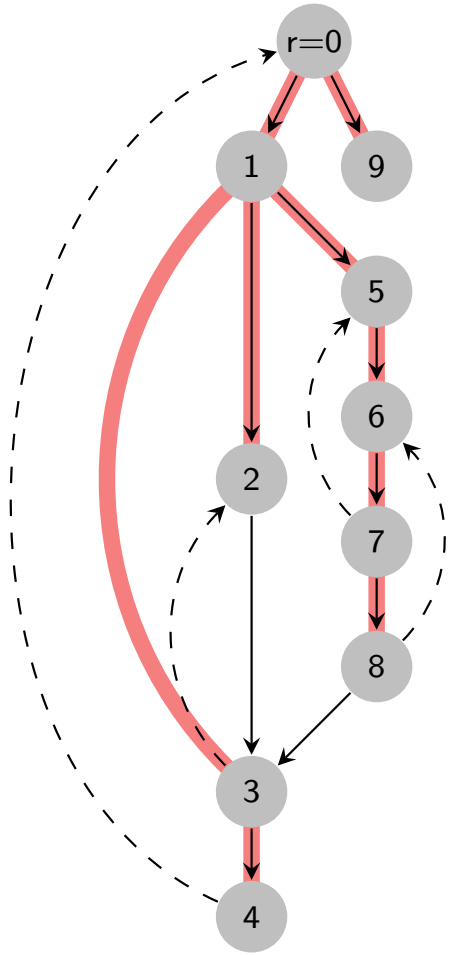
Property

The dominance relation induces a tree. ☛ With classical tree labeling, testing if a dominates b is an $O(1)$ operation.



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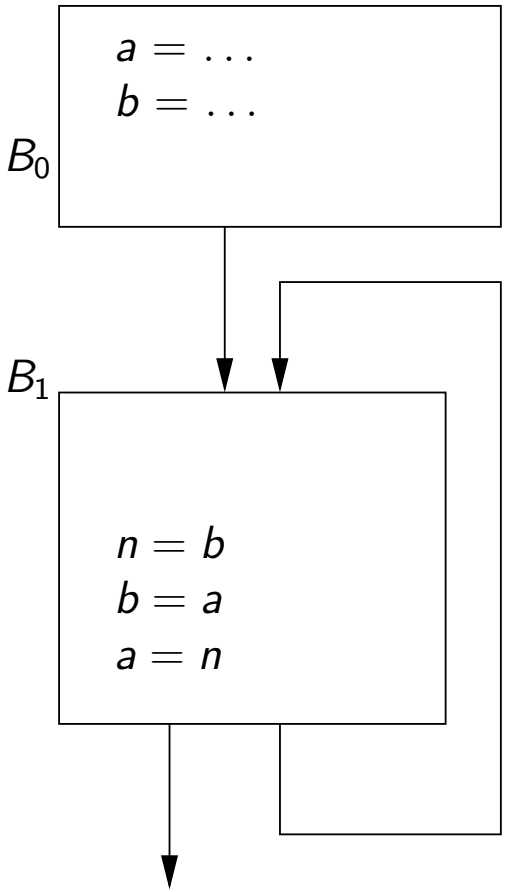

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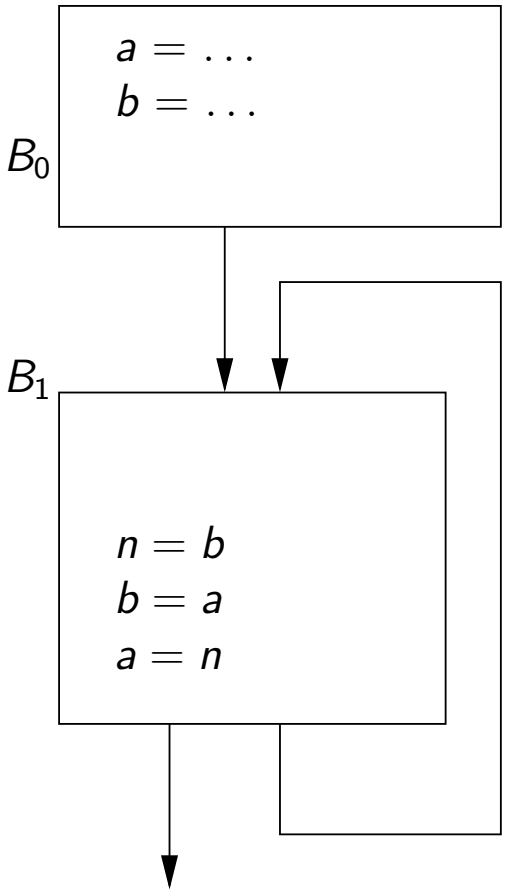

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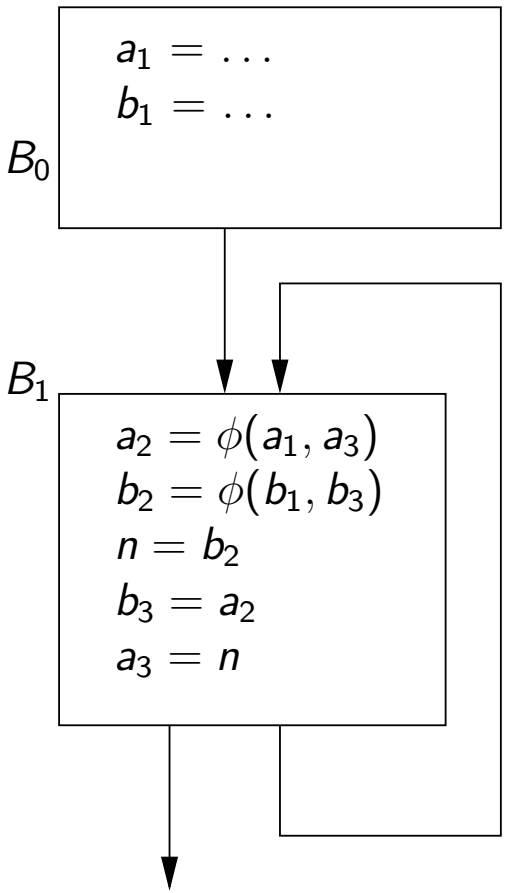

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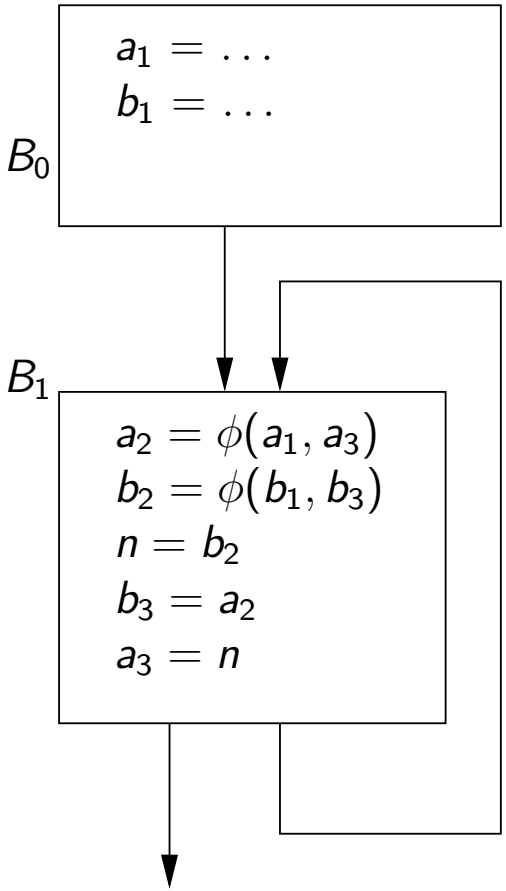

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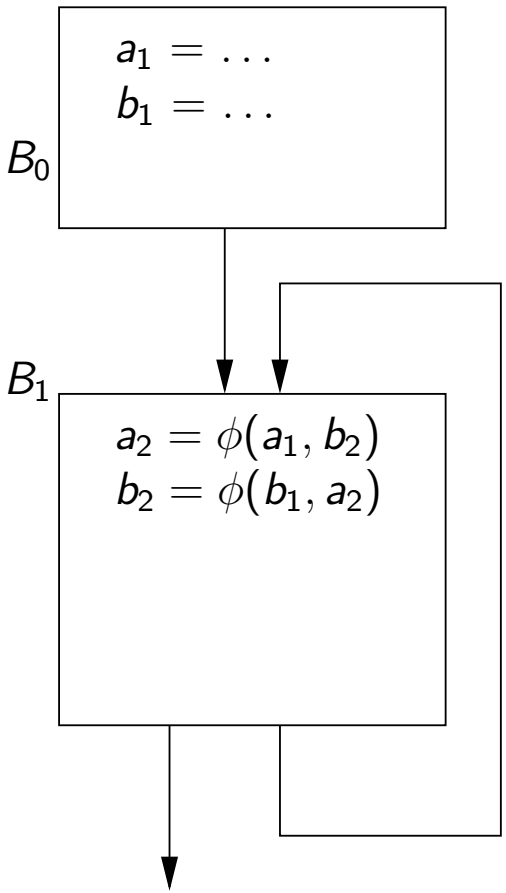

Basic dominance and SSA properties for interferences

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See work of F. Bouchez, P. Brisk, S. Hack, J. Palsberg, F. Pereira

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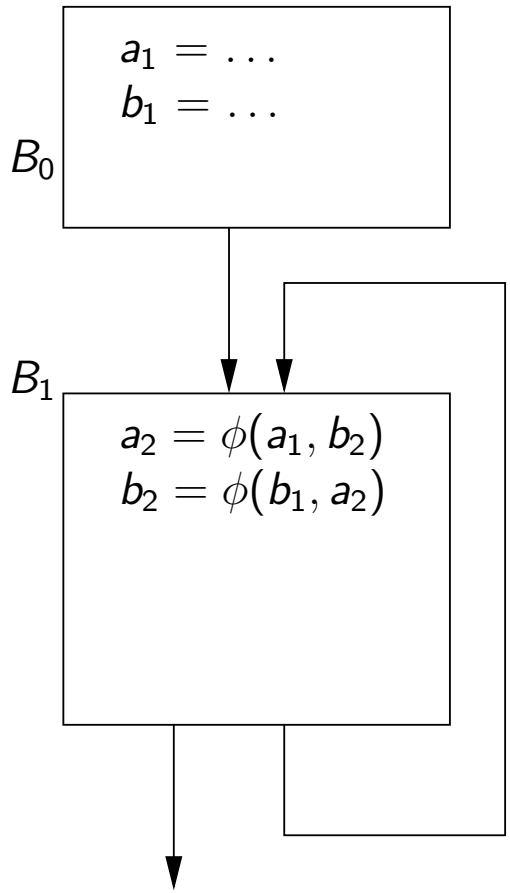
- Cytron et al. (1991): copies in predecessor basic blocks.

Swap problem



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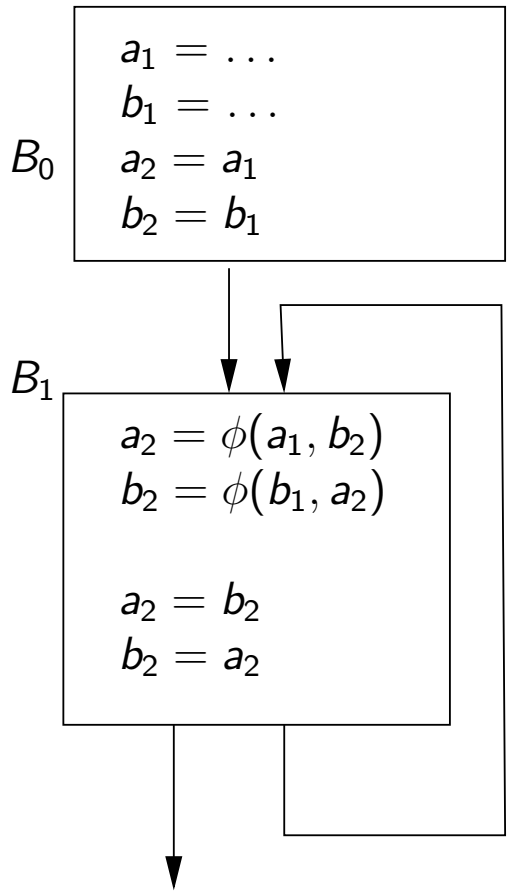

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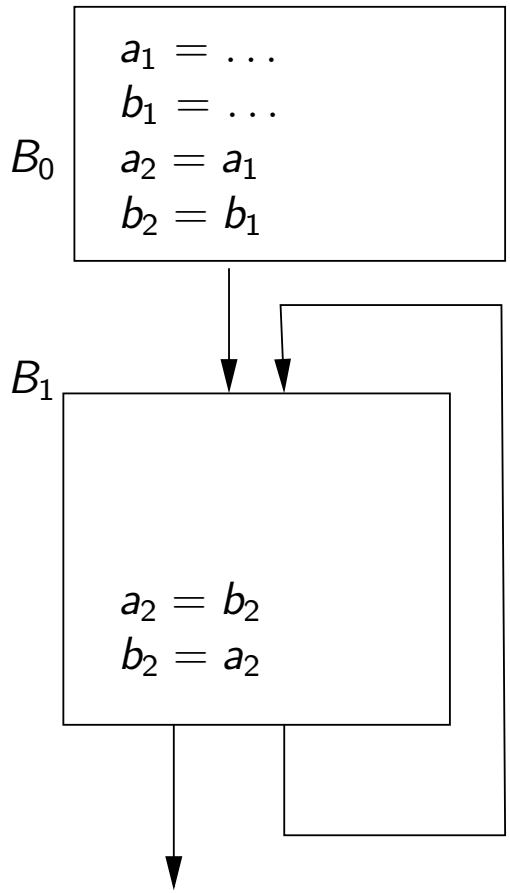

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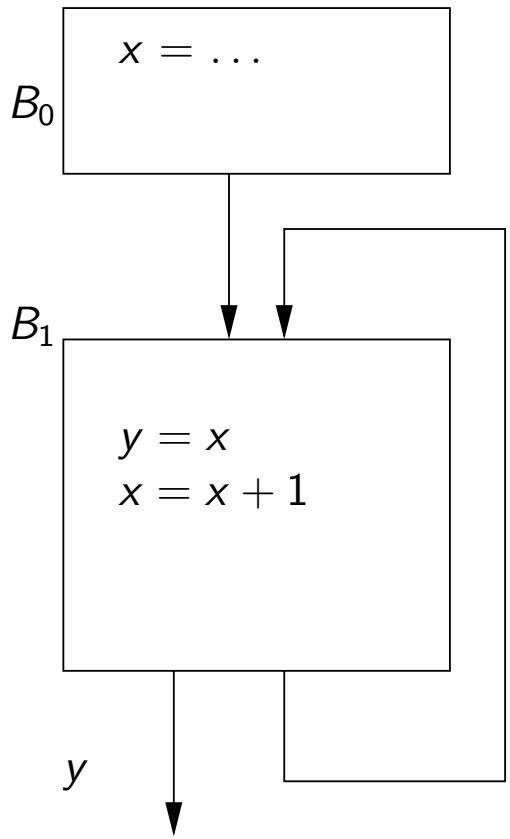

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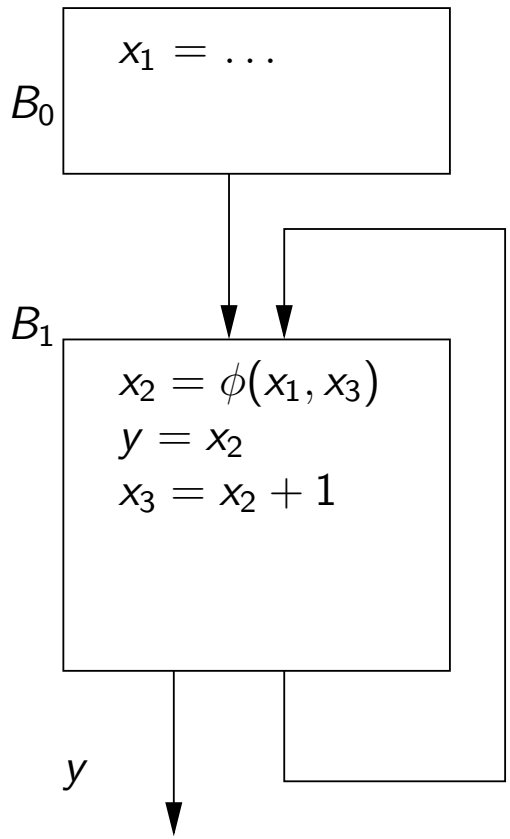

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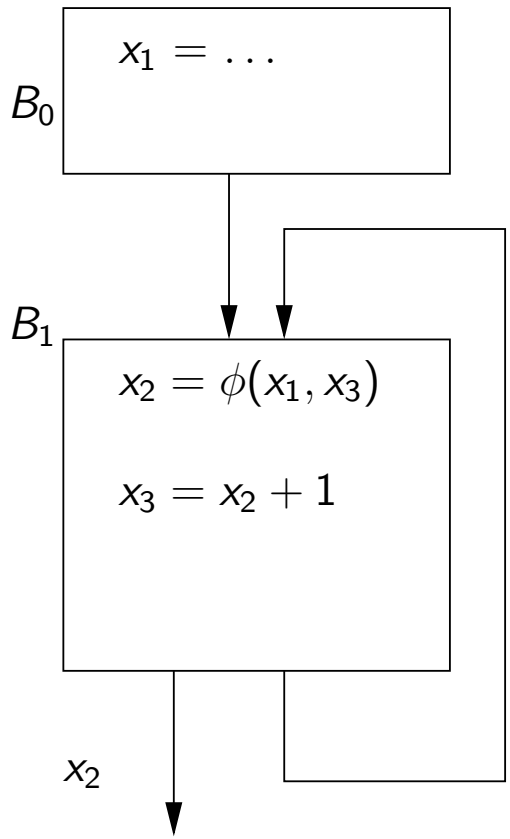

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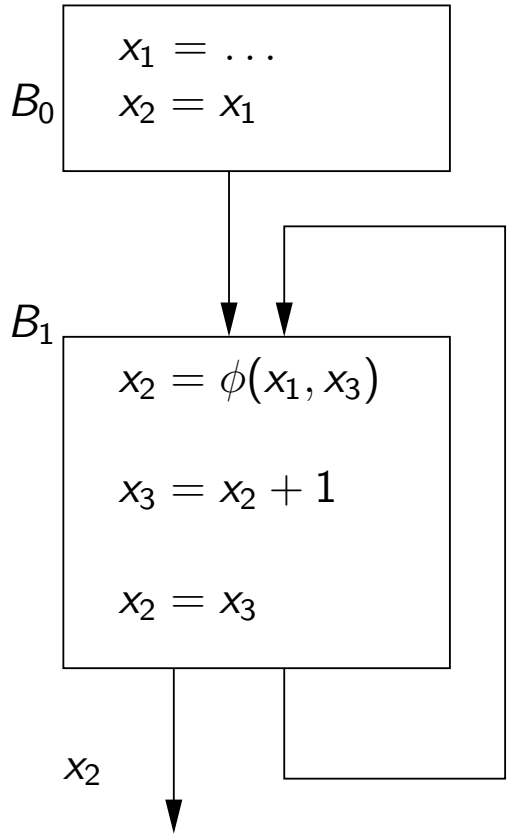

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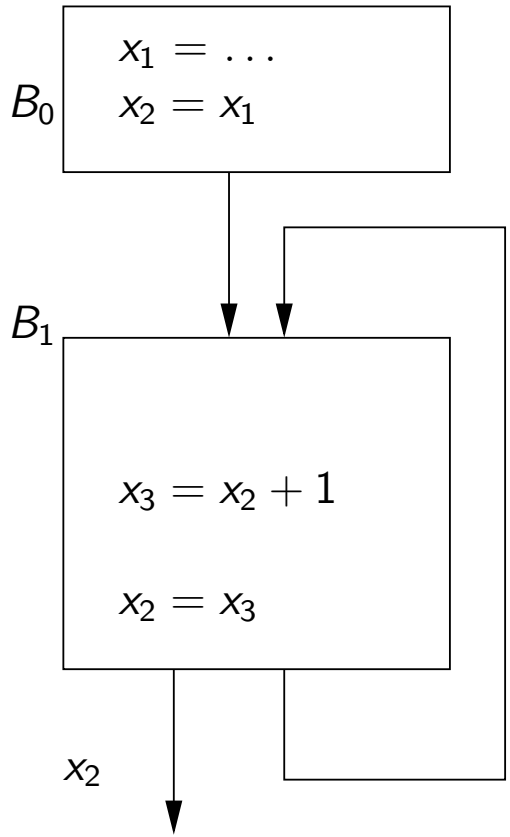

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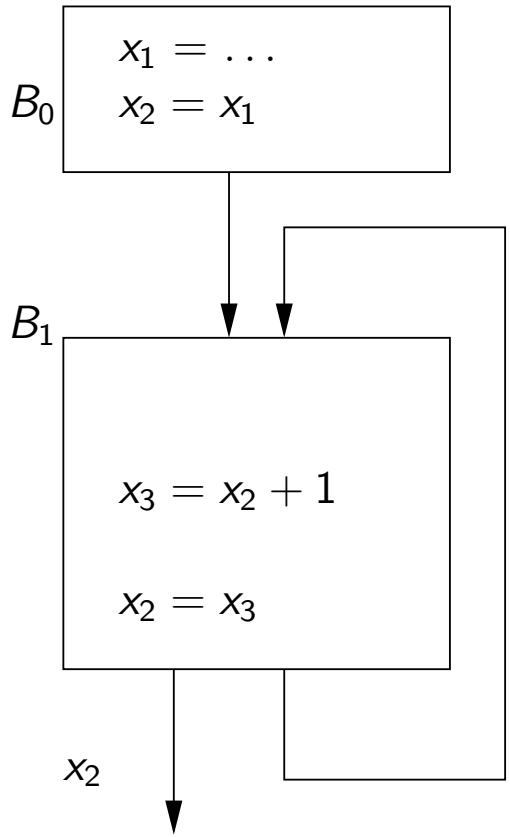

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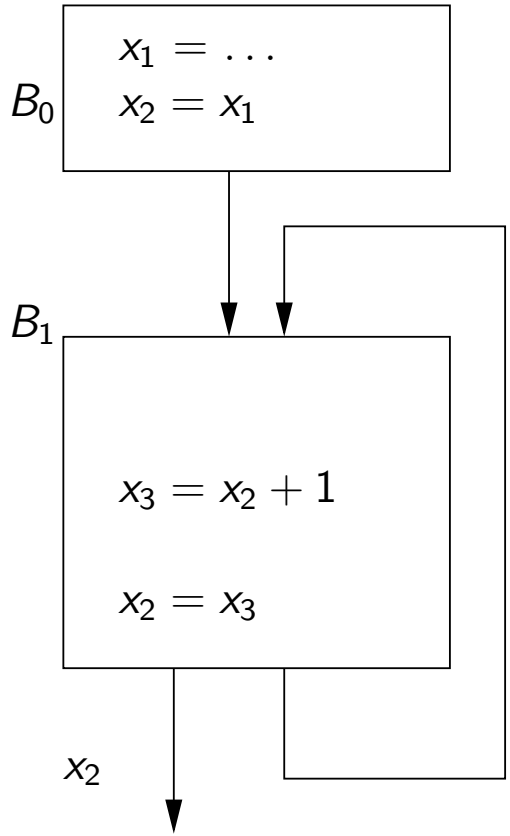

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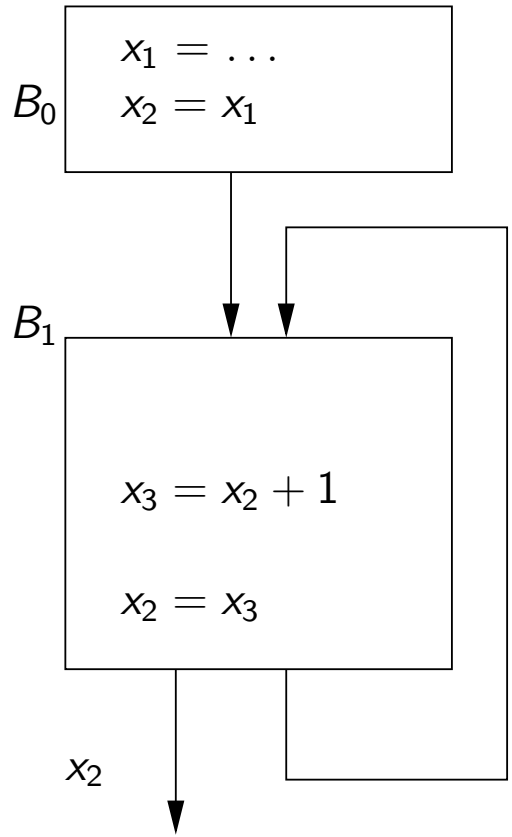

☛ Many SSA optimizations turned off in gcc and Jikes.

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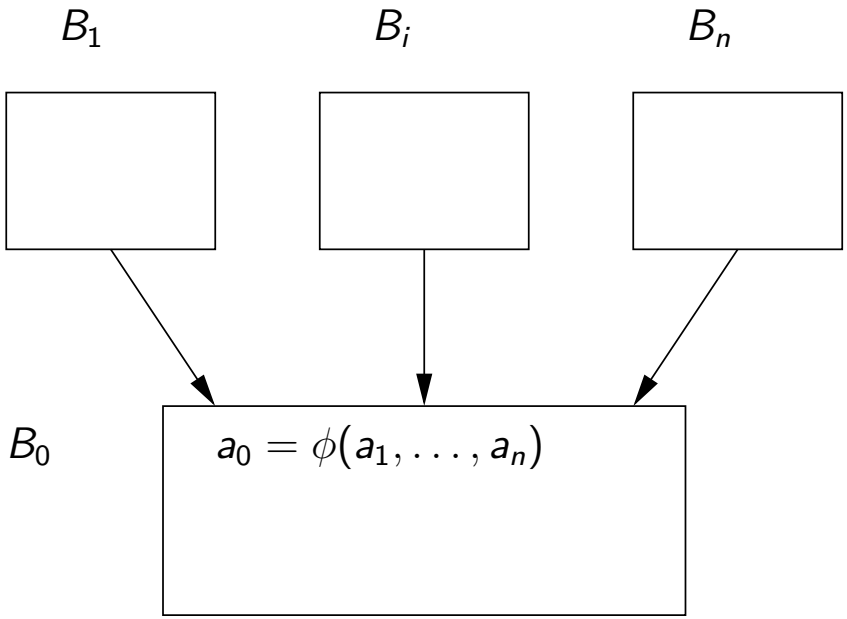
CSSA: if variables can be renamed, without changing program semantics, so that, for all ϕ-function $a_0 = \phi(a_1, \ldots, a_n)$, $a_0, \ldots, a_n$ have the same name.

From SSA to CSSA



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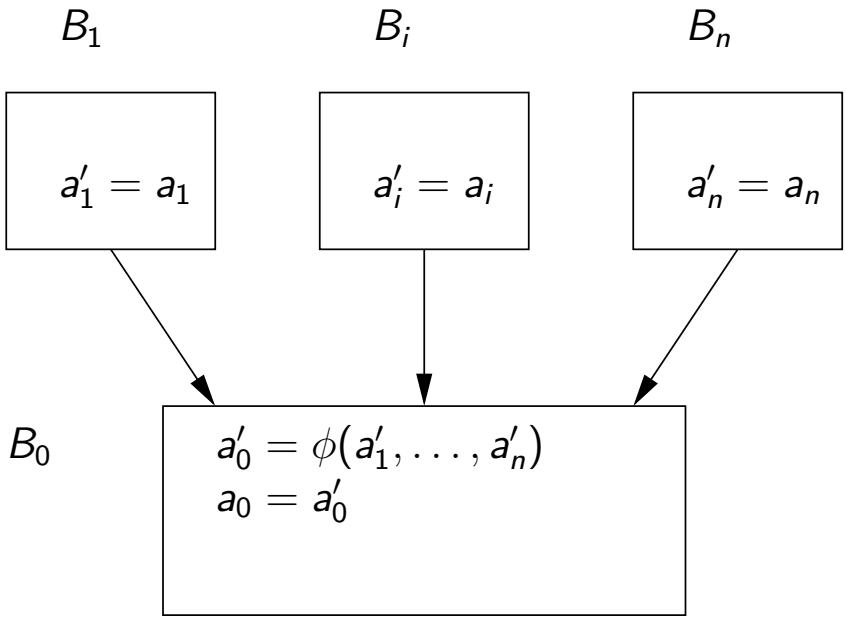

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Code quality

Aggressive coalescing can remove useless copies. But better use accurate notion of interferences.

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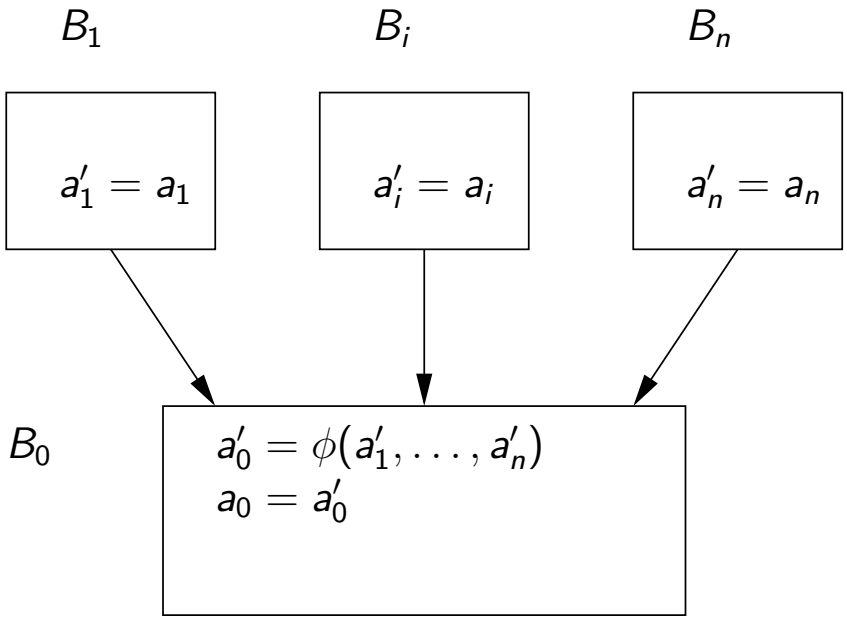
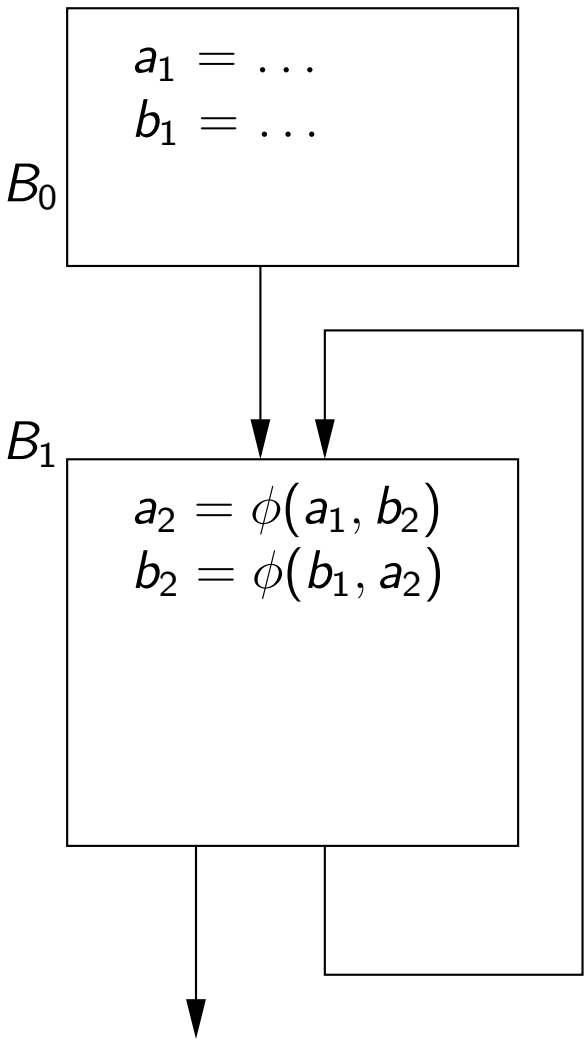
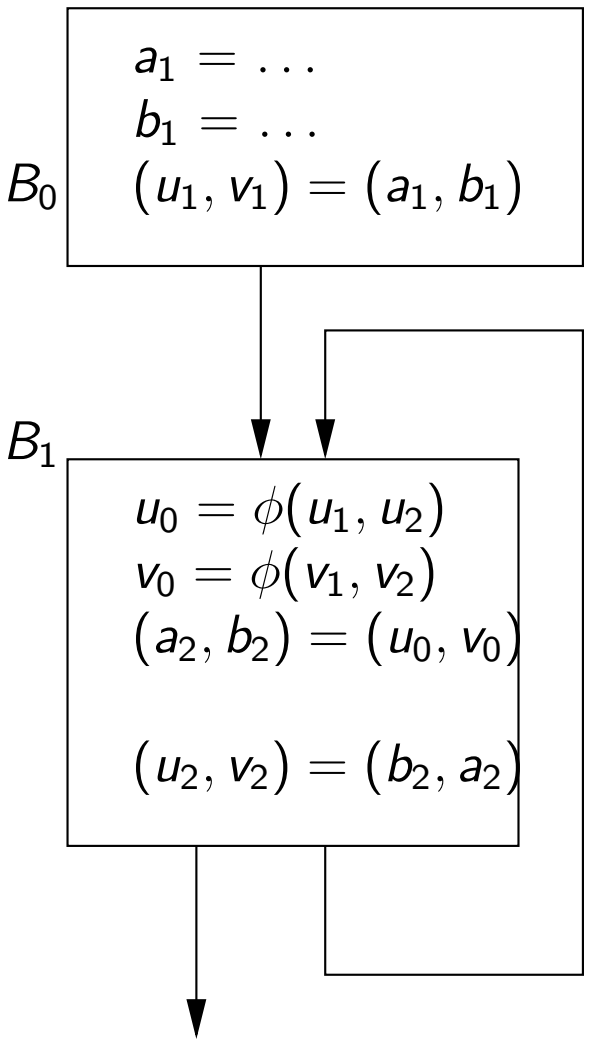


"Liveness of ϕ" defined by the a'_i.

✝ Be careful with potential bugs due to conditional branches that use or define variables.

Coalesced example: the swap problem





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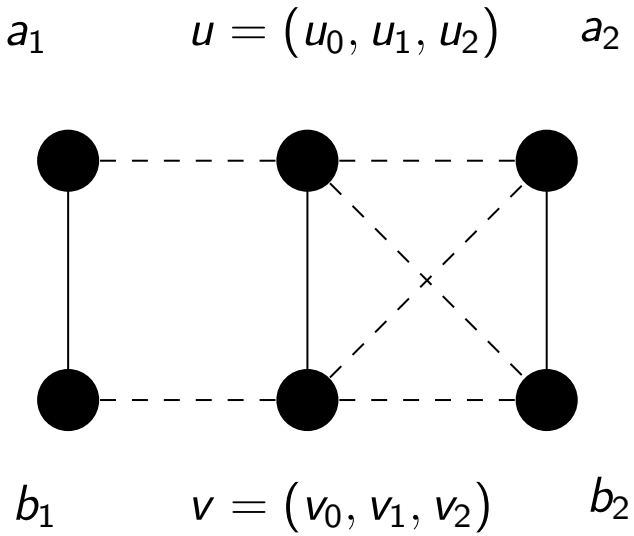

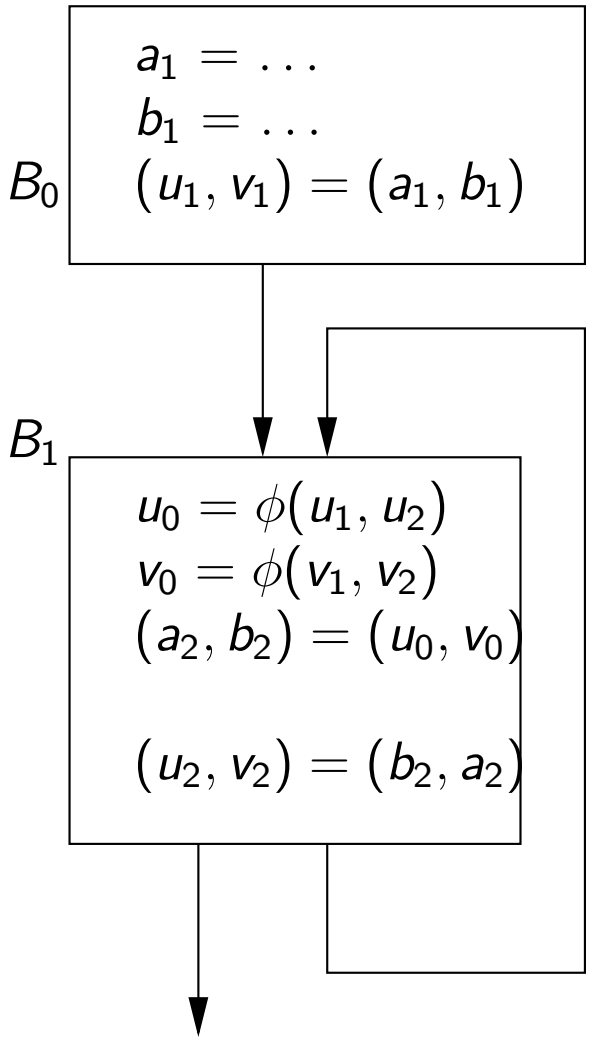

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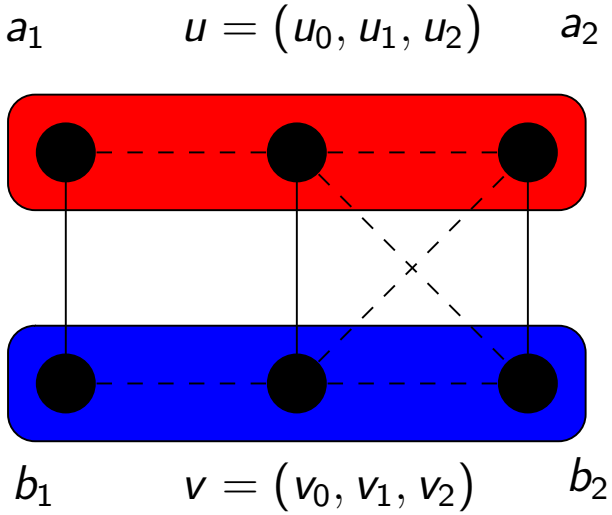

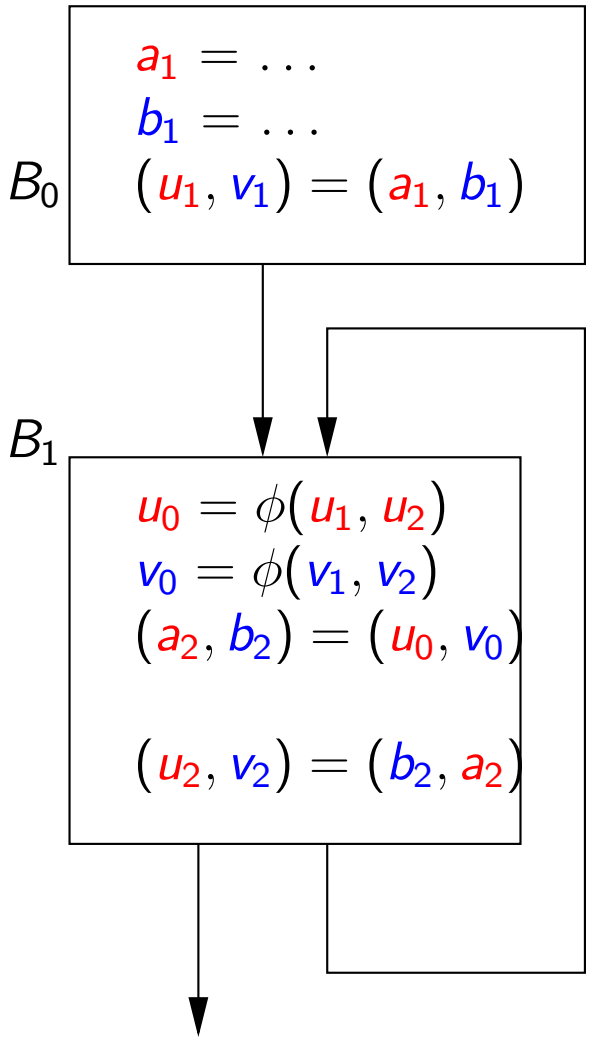

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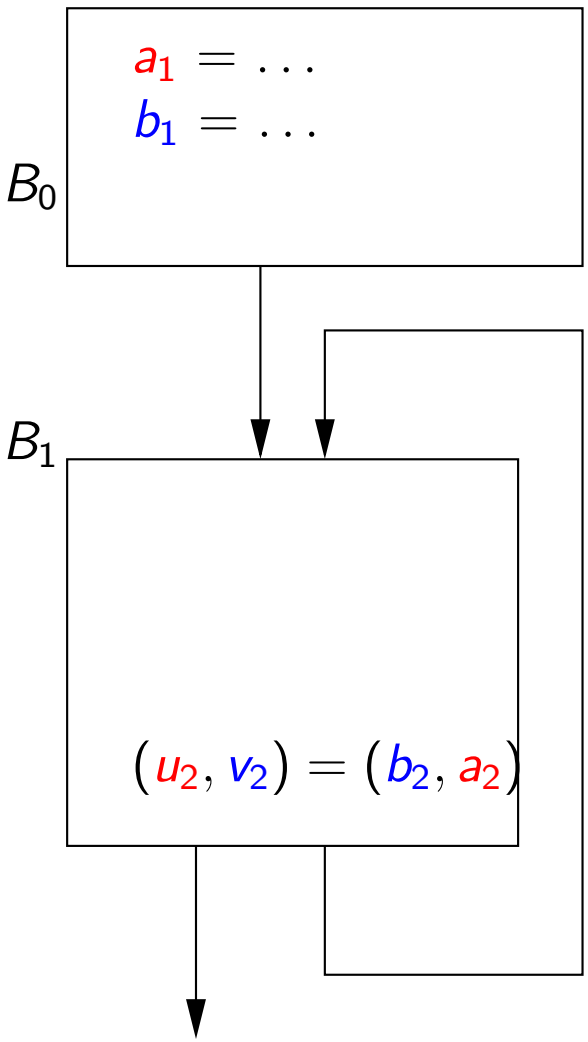

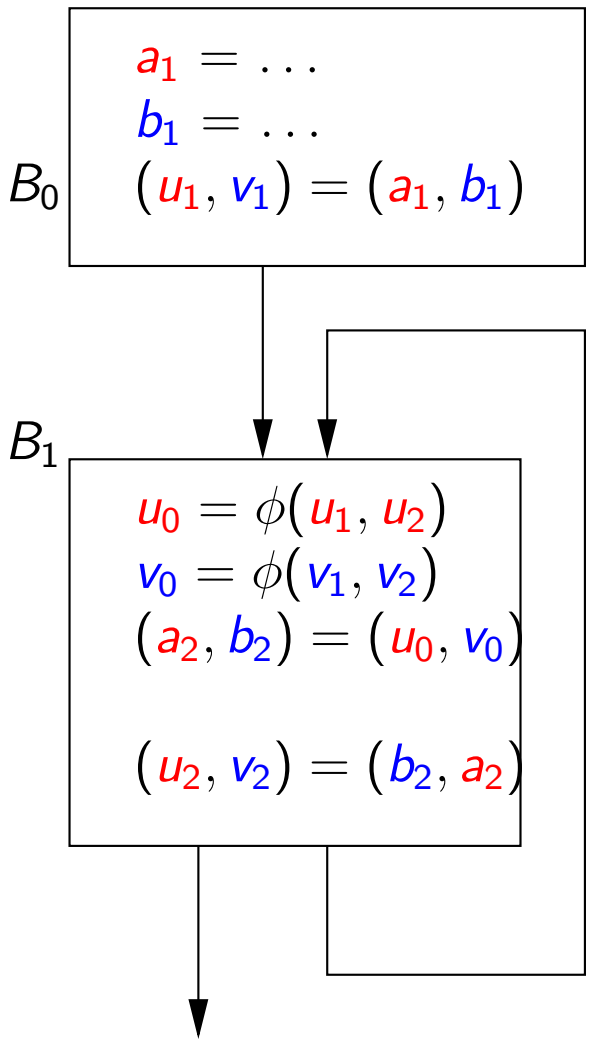

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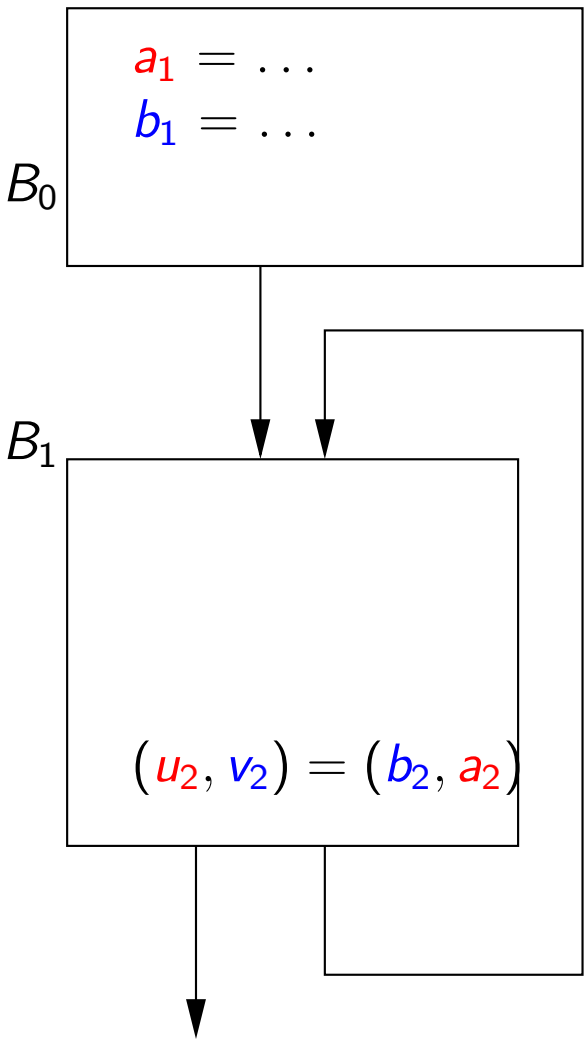

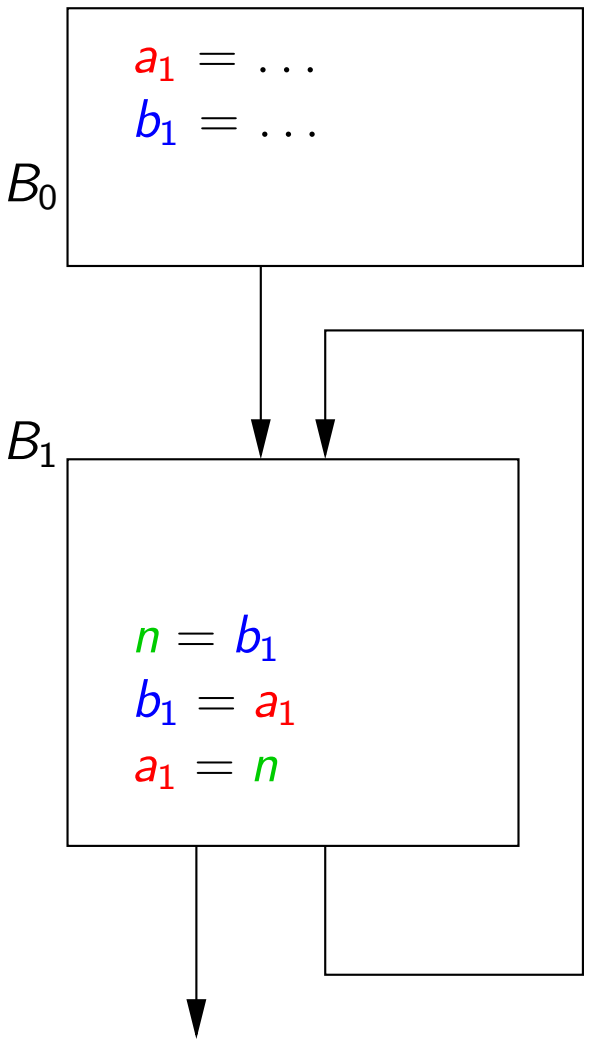

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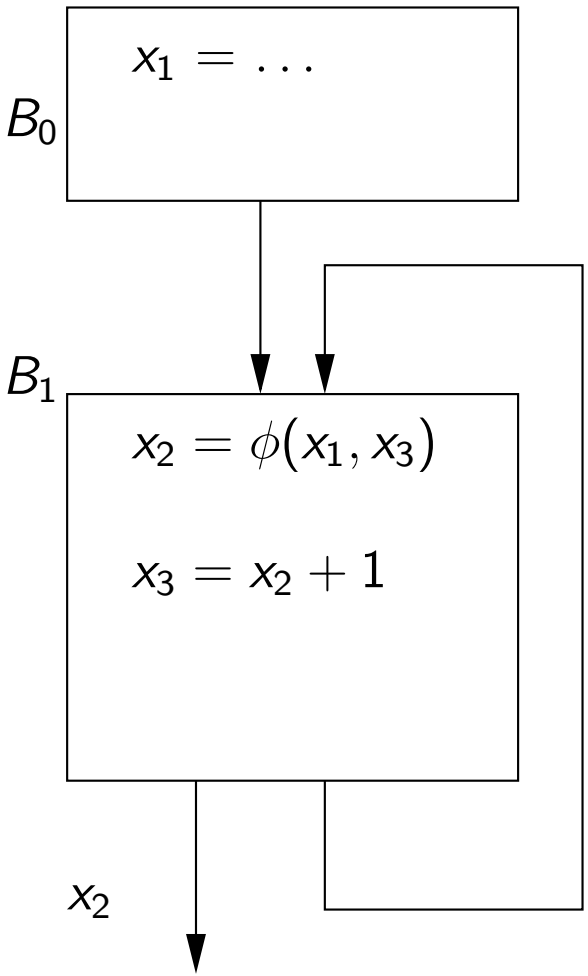

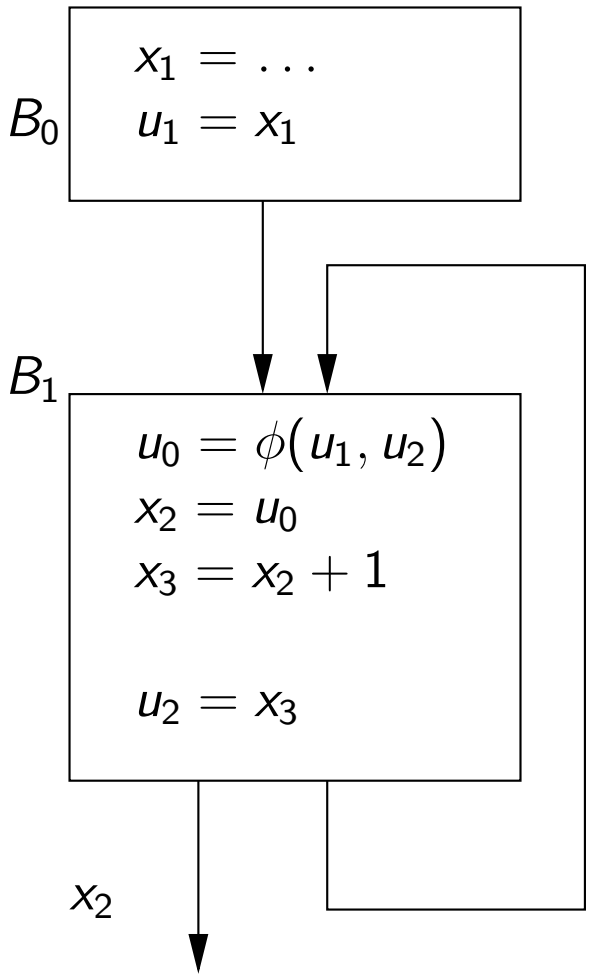

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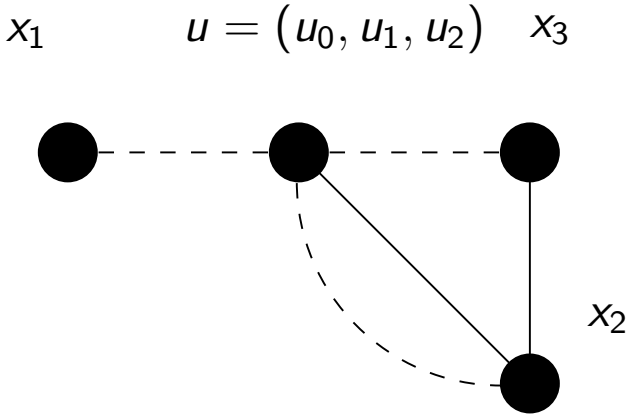

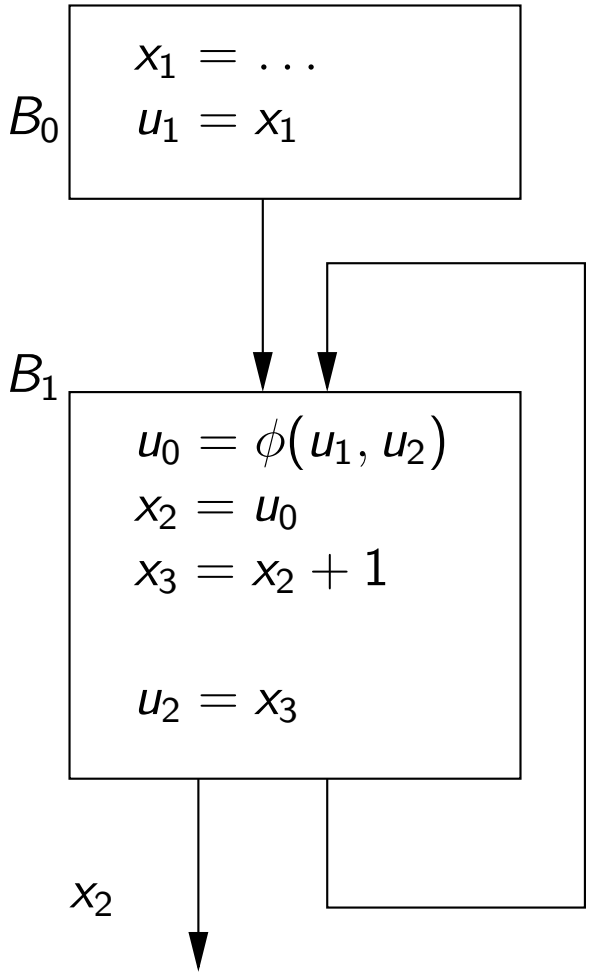

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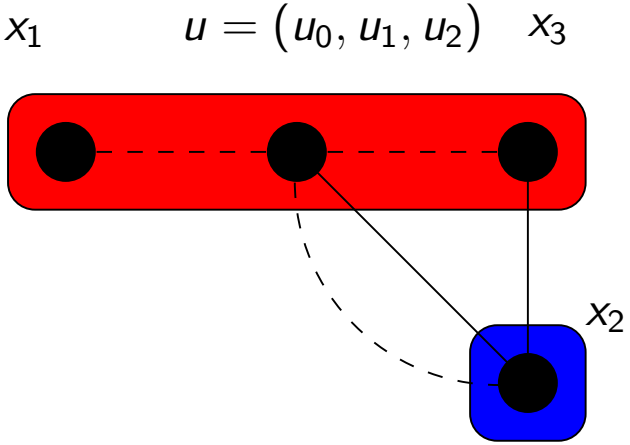

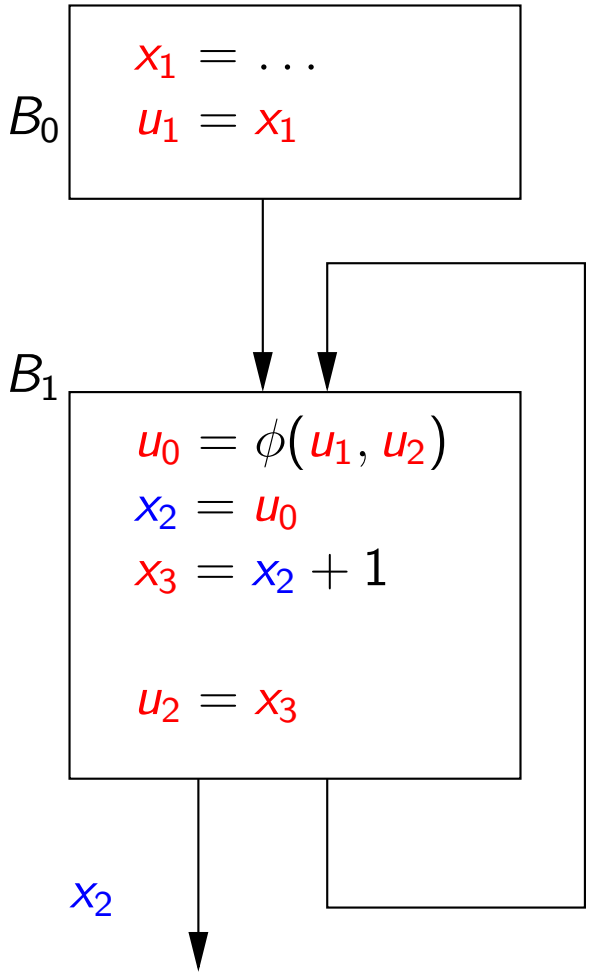

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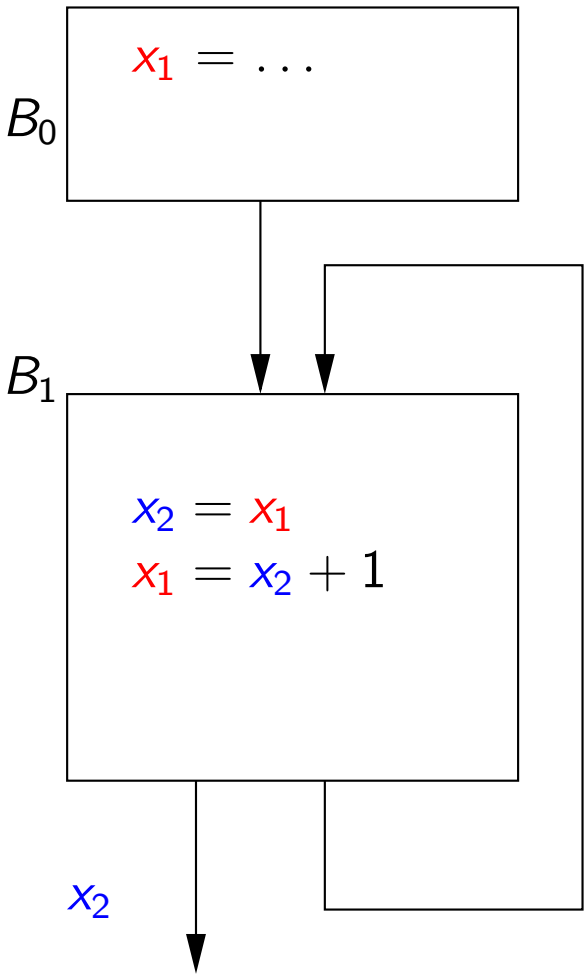
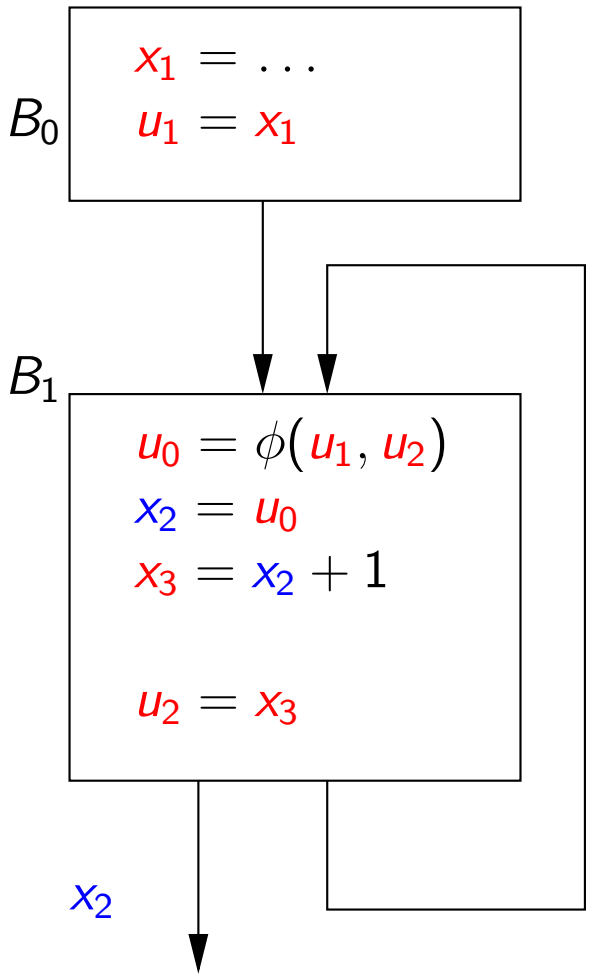
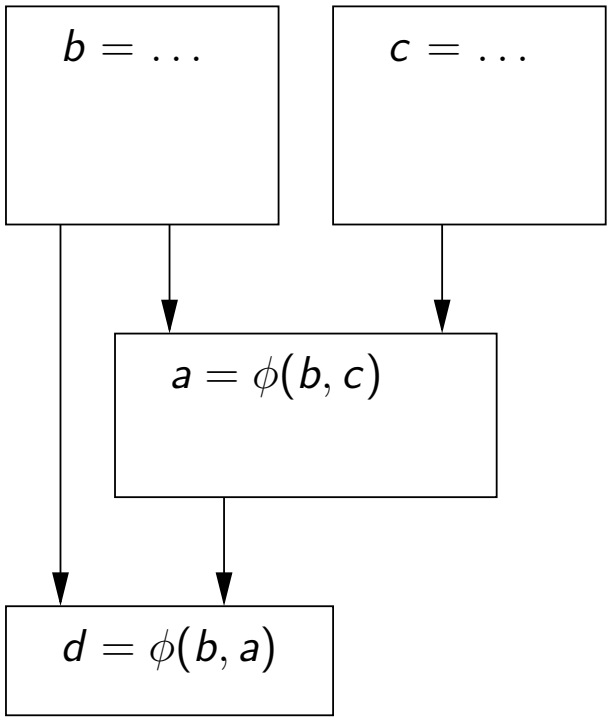




Exploiting SSA: value-based interferences

Definition (Chaitin interference)

Two variables interfere if one is live at the definition of the other, which is not a copy of the first.



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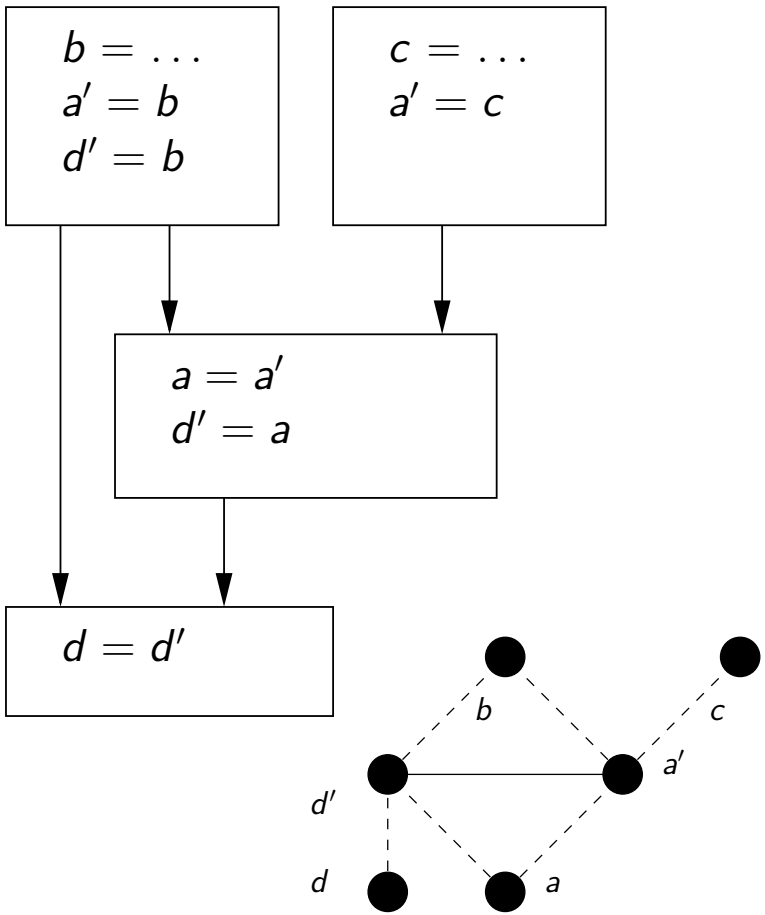

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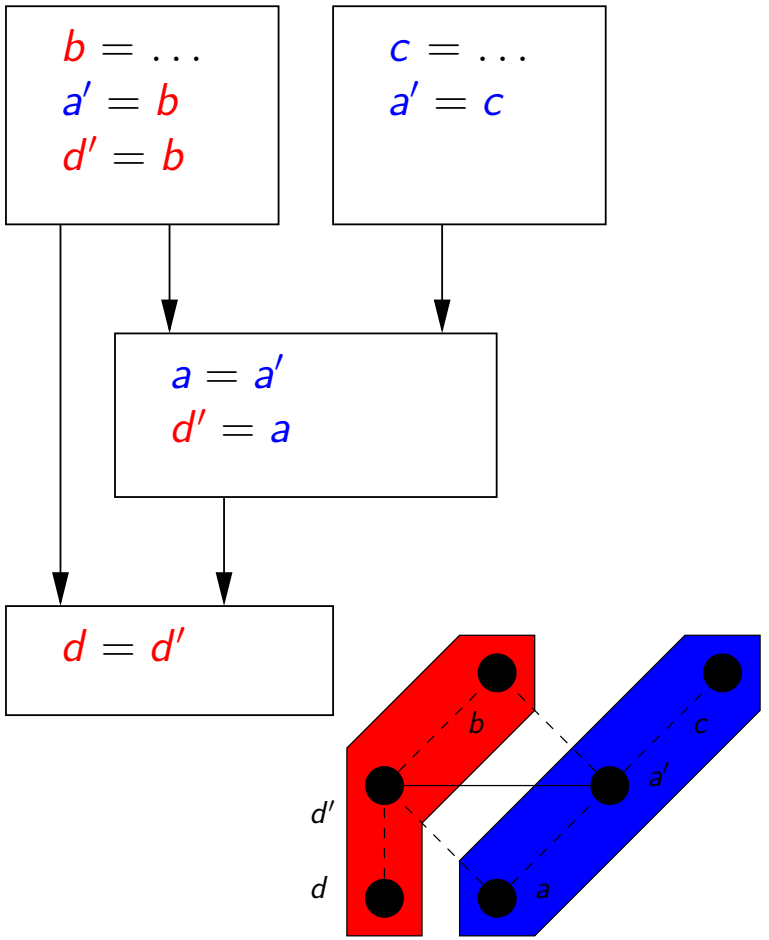

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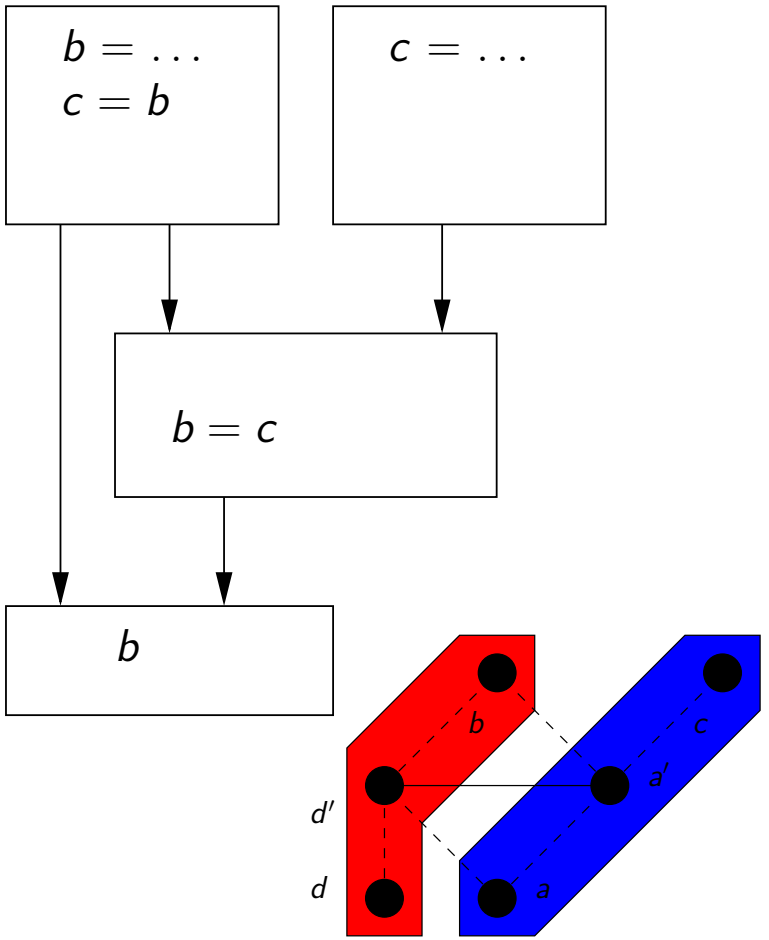

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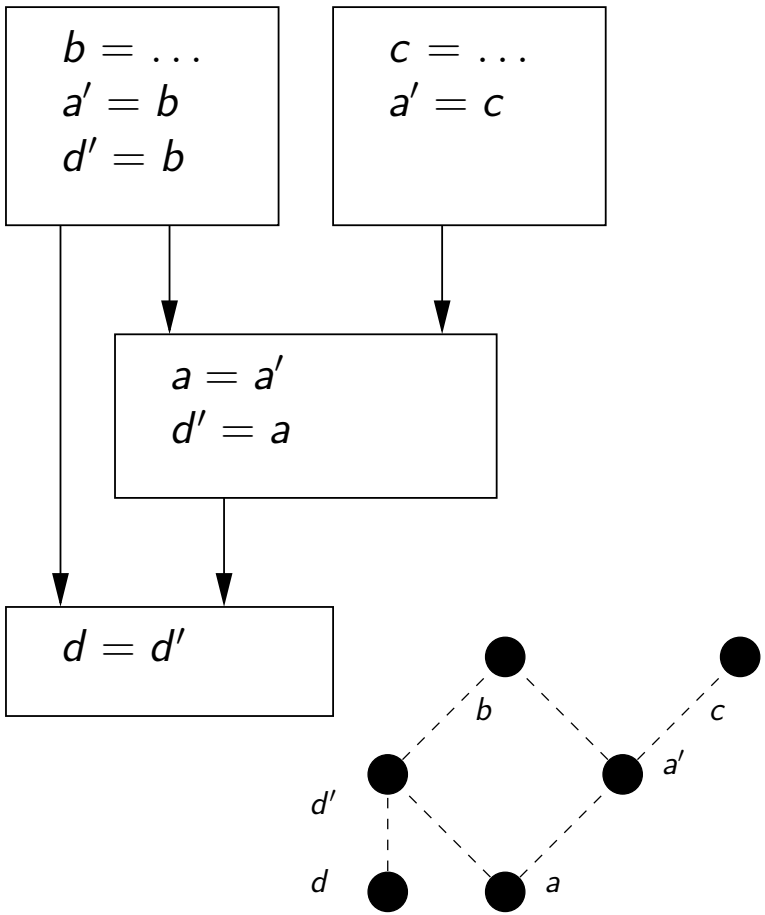
For a copy $\mathtt{b} = \mathtt{a}$, $V(\mathtt{b}) = V(\mathtt{a})$ (traversal of dominance tree).

Value-based interference

a and b interfere if $V(\mathtt{a}) \neq V(\mathtt{b})$ and Live-range(a) $\cap$ Live-range(b) $\neq \emptyset$.



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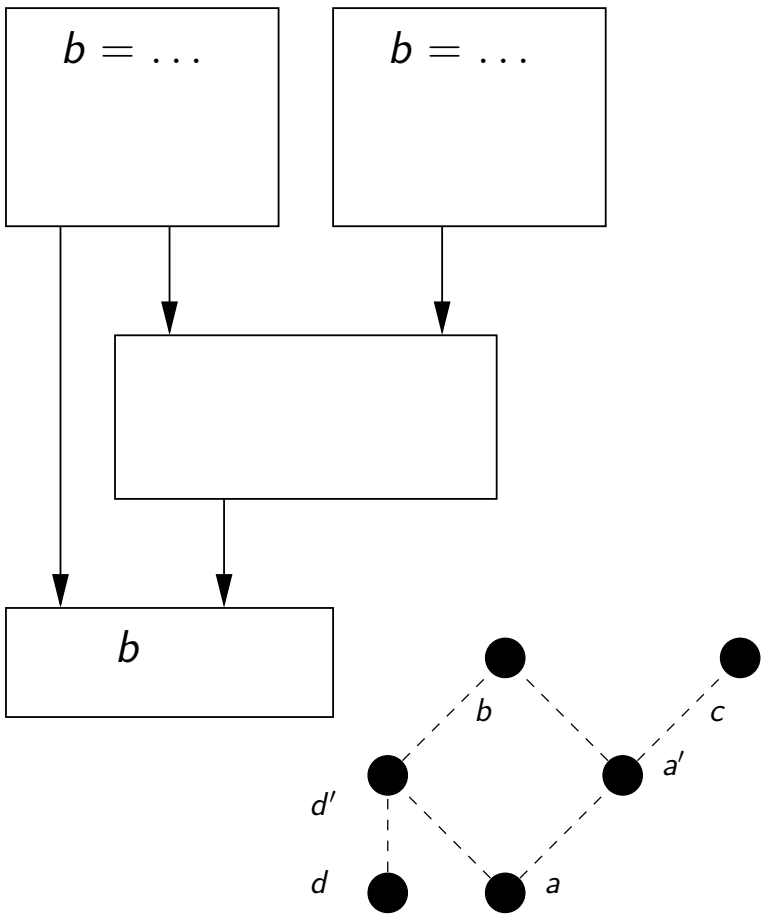

Using parallel copies instead of sequential copies

Parallel copy semantics

In $(a_1, \ldots, a_n) = (b_1, \ldots, b_n)$, all copies $a_i = b_i$ are simultaneous.

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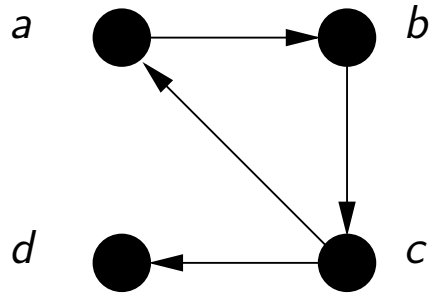
Particular copy structure

Directed graph with edges $b_i \rightarrow a_i$.

- Directed trees with roots=circuits.
- Insert copies for the leaves first.

$$(a, b, c, d) = (c, a, b, c)$$



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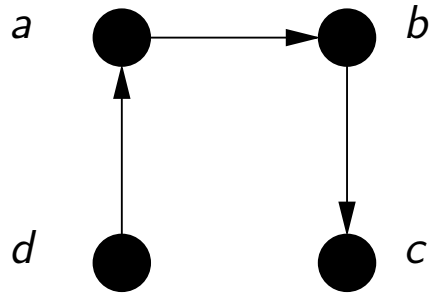
$d = c$
$(a, b, c) = (d, a, b)$



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d &= c \\
c &= b \\
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a &= d
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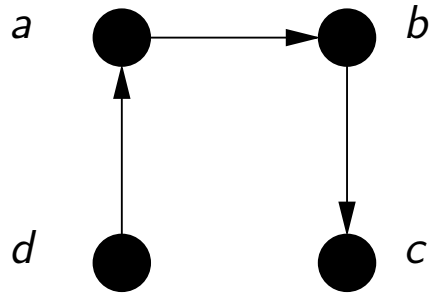
$$



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Directed graph with edges $b_i \rightarrow a_i$.

- Directed trees with roots=circuits.
- Insert copies for the leaves first.
- Simple circuit: one more copy.

$$
\begin{aligned}
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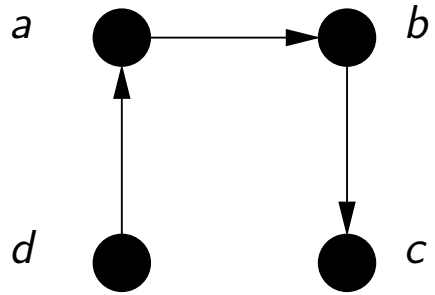
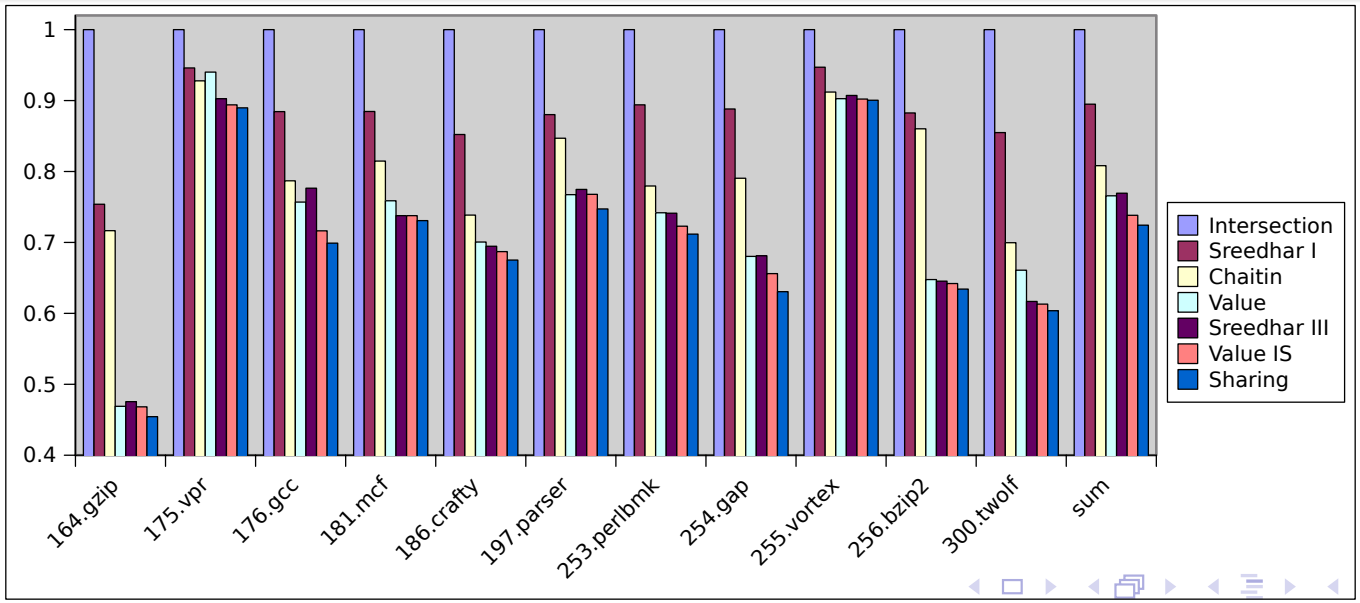


Qualitative experiments with SPEC CINT2000

Key points of the out-of-SSA translation

- Copy insertion (to go to CSSA and to handle register renaming constraints) followed by coalescing.
- Value-based interferences ☛ coalescing is improved and independent of virtualization (i.e., as in Sreedhar III).
- Parallel copies followed by sequentialization.



Outline

How to coalesce variables?

Two alternatives

- Use a working interference graph where, in case of coalescing, corresponding vertices are merged. $O(1)$ interference query.
- Manipulate congruence classes, i.e., sets of coalesced variables. Interferences must be tested between sets.

Chaitin, Sreedhar, Budimlić use congruence classes. Also useful to avoid interference graph. Naive algorithm: quadratic complexity.

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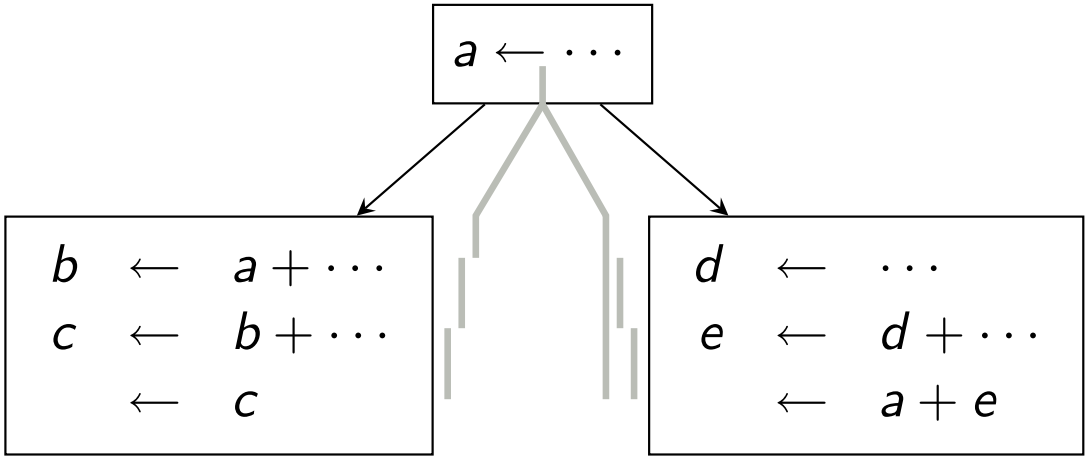
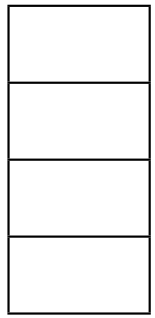
Key properties for linear-complexity live range intersection

- 2 variables intersect if one is live at the definition of the other.
- In this case, the first definition dominates the second one.
- Budimlić: a set contains 2 intersecting variables if it contains a variable that intersects its "parent dominating" variable.

Fast interference test for a set of variables





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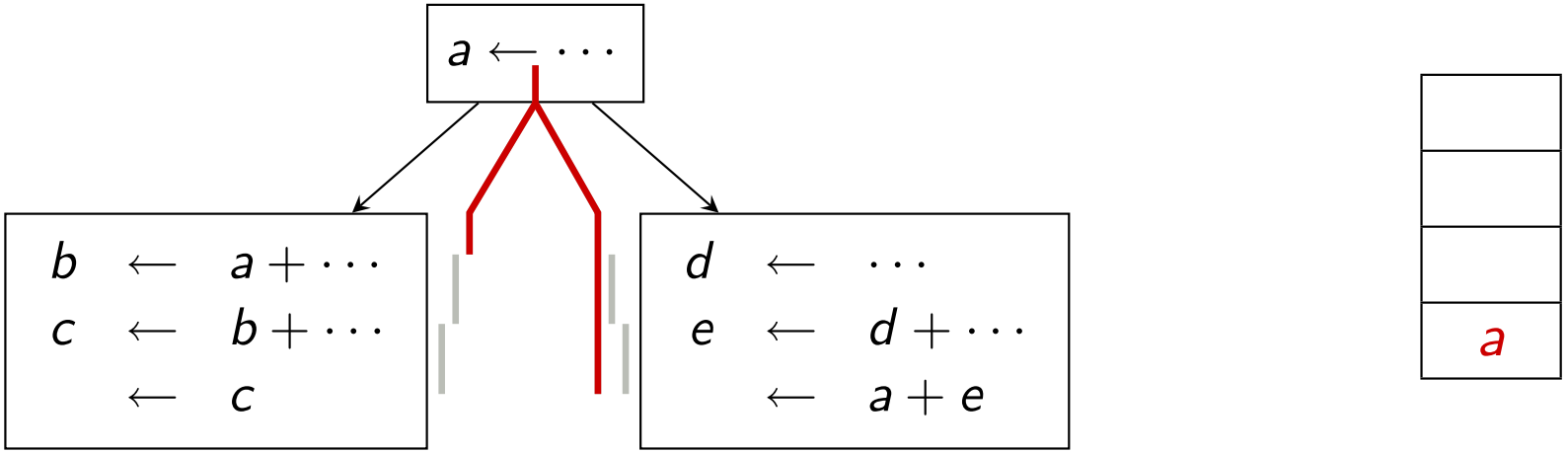

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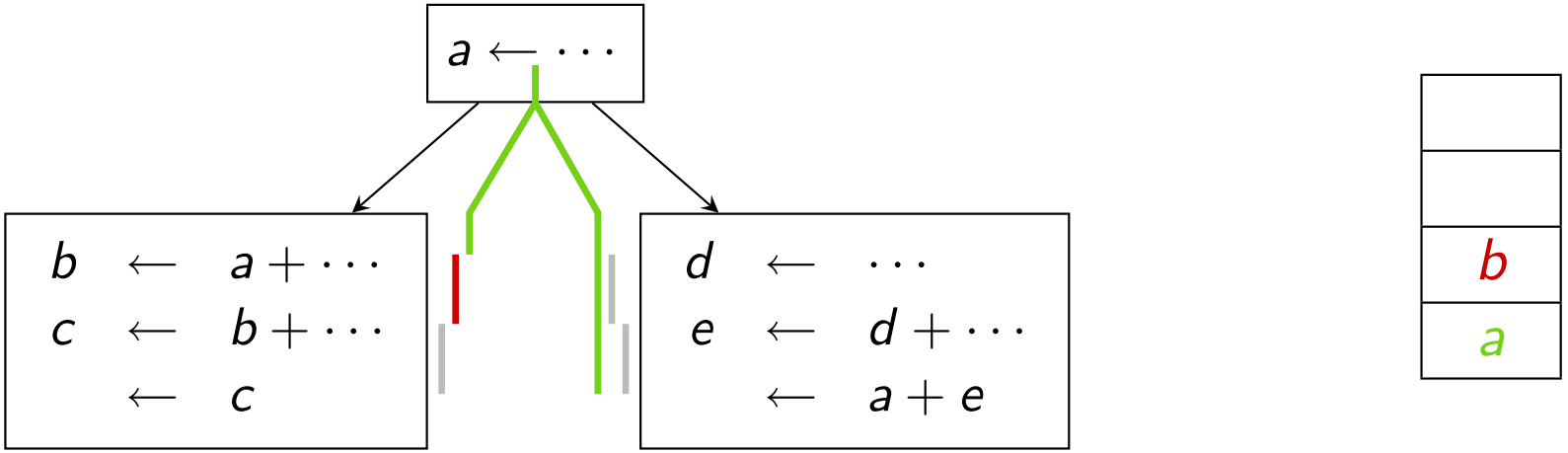

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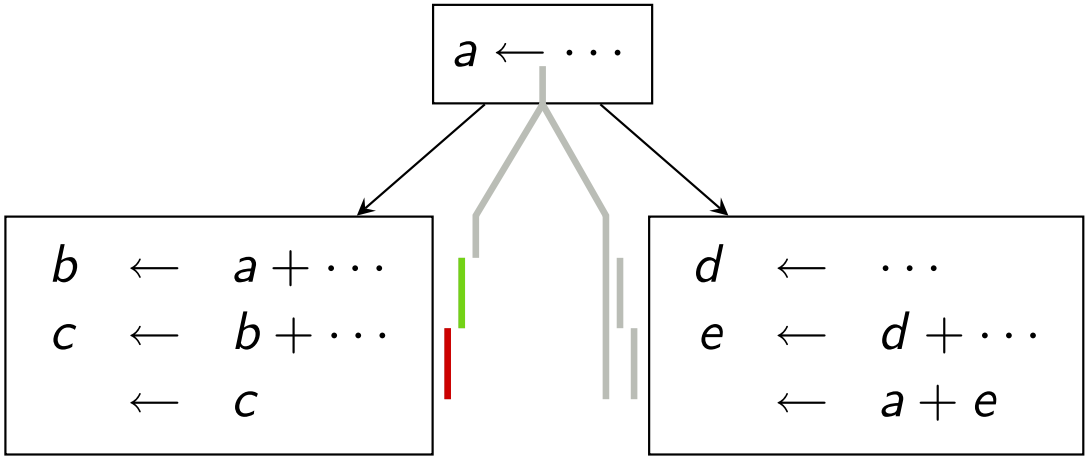

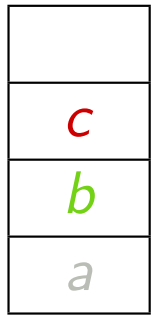

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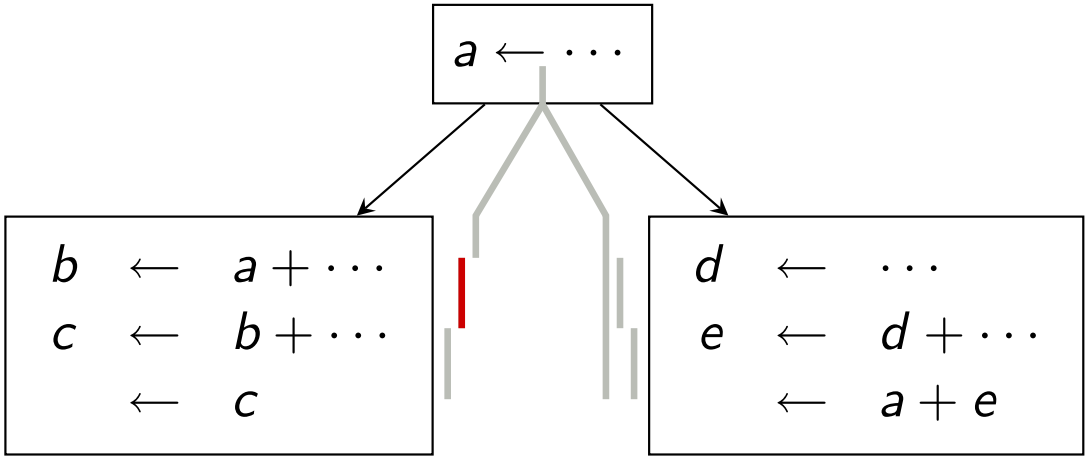

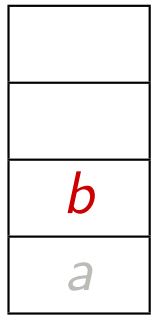

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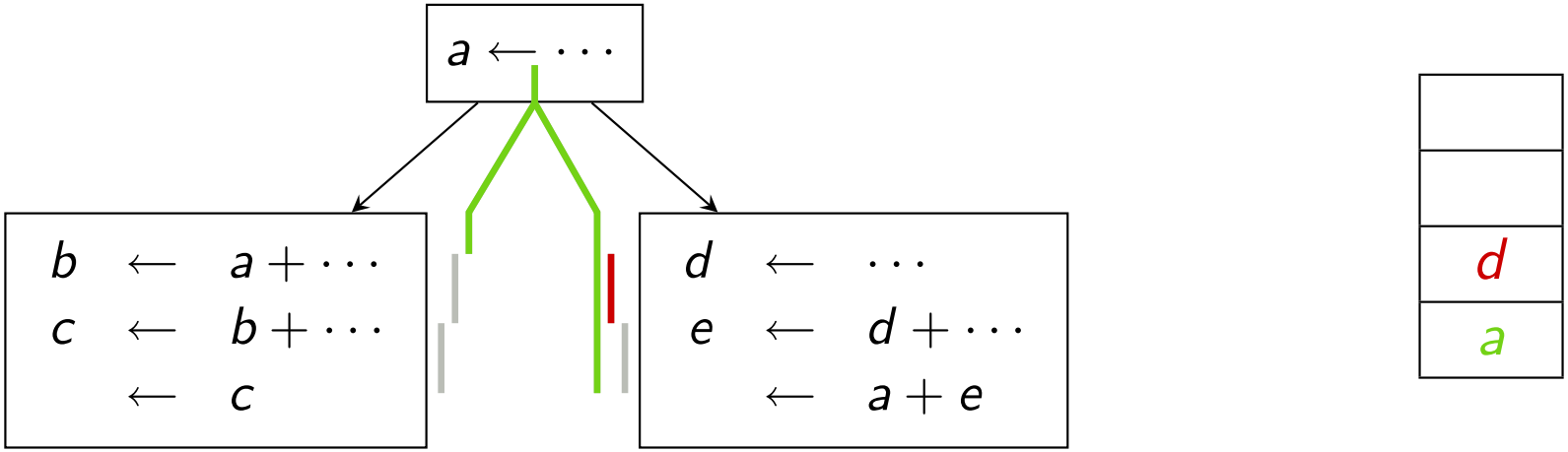

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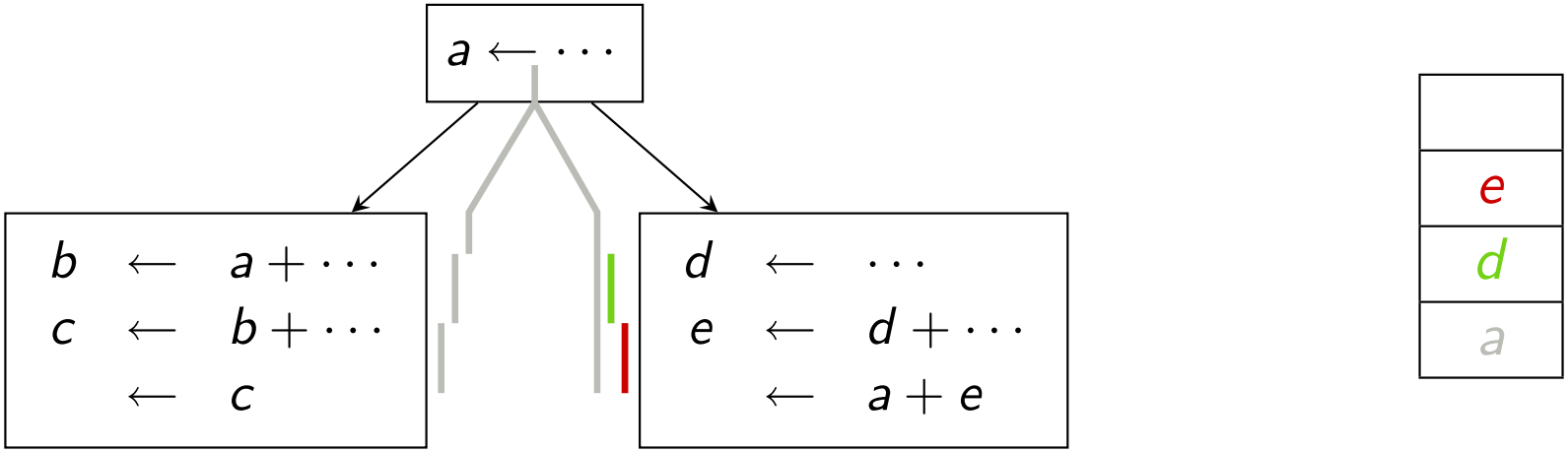

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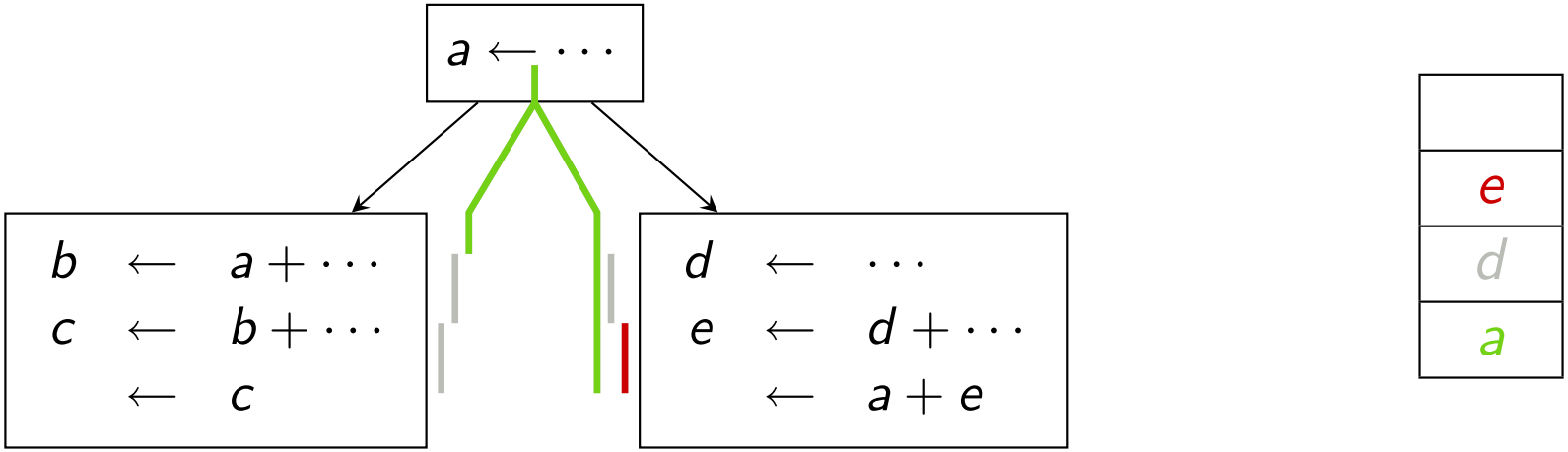

Algorithm 1: Check intersection in a set of variables

Data: `list` sorted according to a pre-DFS order of the dominance tree
Output: Returns TRUE if the list contains an interference

```
1  dom ← empty_stack ; i ← 0  ;                          /* stack of the traversal */
2  while i < list.size() do
3      current ← list(i++) ;
4      other ← dom.top() ;                               /* NULL if dom is empty */
5      while (other ≠ NULL) and dominate(other, current) = FALSE do
6          dom.pop() ;                                   /* not the desired parent, remove */
7          other ← dom.top() ;                           /* consider next one */
8      parent ← other ;
9      if (parent ≠ NULL) and (intersect(current, parent) = TRUE) then
       return TRUE ;                                     /* intersection detected */
10     dom.push(current) ;                               /* otherwise, keep checking */
11 return FALSE ;
```

Linear interference test of two congruence classes

Generalization to interference test of two sets

- Emulate a stack-based DFS traversal of dominance tree, for two sorted sets instead of one ☛ linear number of tests. Also no need to test intersection of variables in the same set.
- Take values into account for value-based interference: need links of "equal ancestors", which may increase complexity.
- Sort in linear time the resulting set, in case of coalescing.

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Fewer intersection tests ☛ possible now to use more expensive queries for intersection and liveness and avoid interference graph:

- Budimlić intersection test, still using liveness sets.
- Fast liveness checking of Boissinot et al. (CGO'08).

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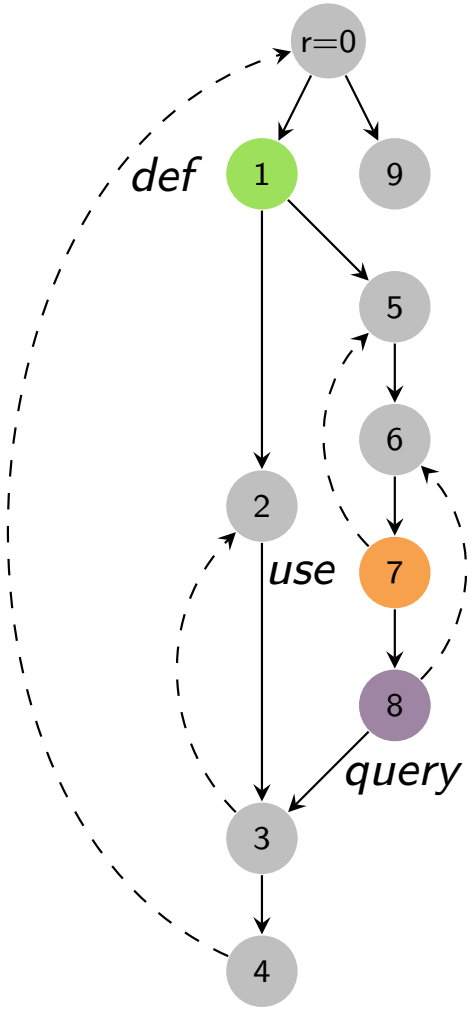
Definition (Liveness)

Variable a is live-in at q if there is a path from q to a *use* of a, that does not contain its *def*.



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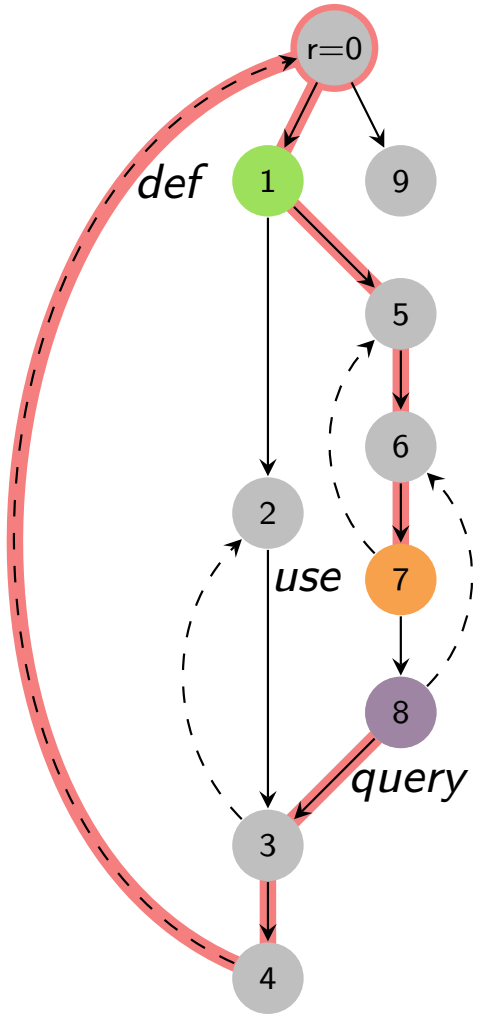

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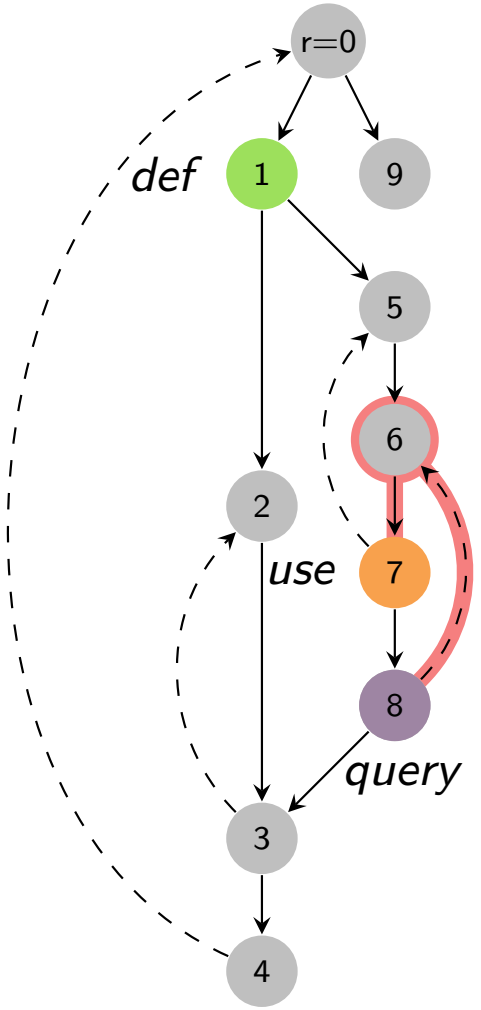

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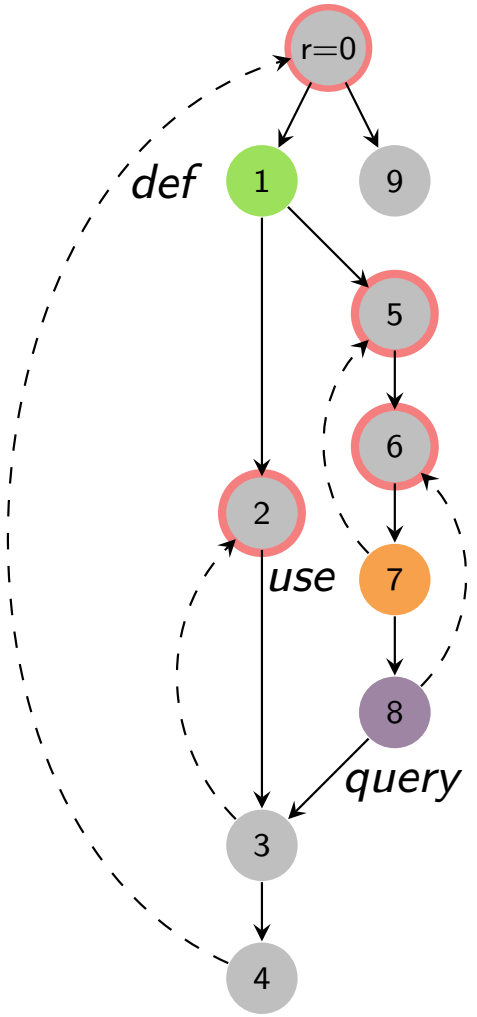
Precomputation:

- Compute transitive closure of G', the CFG without DFS back edges;
- For each q, compute a set T_q of back-edge targets reached from q.



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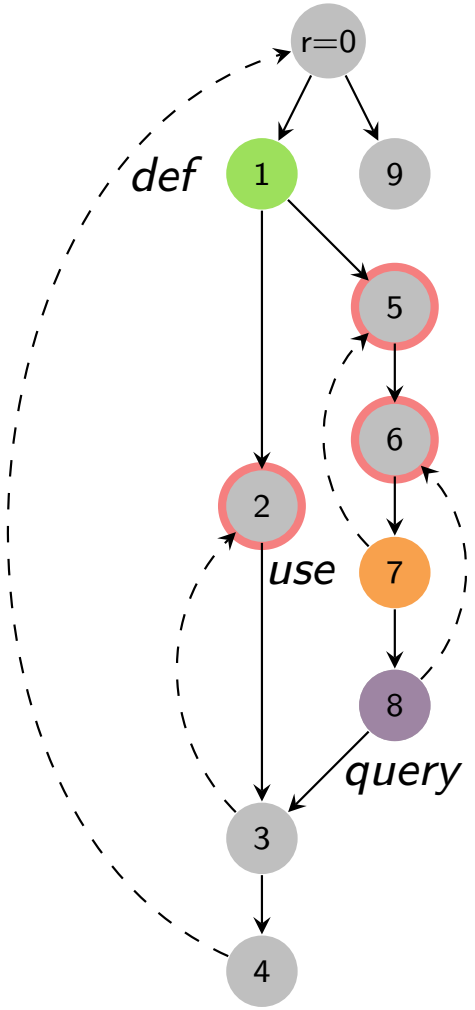

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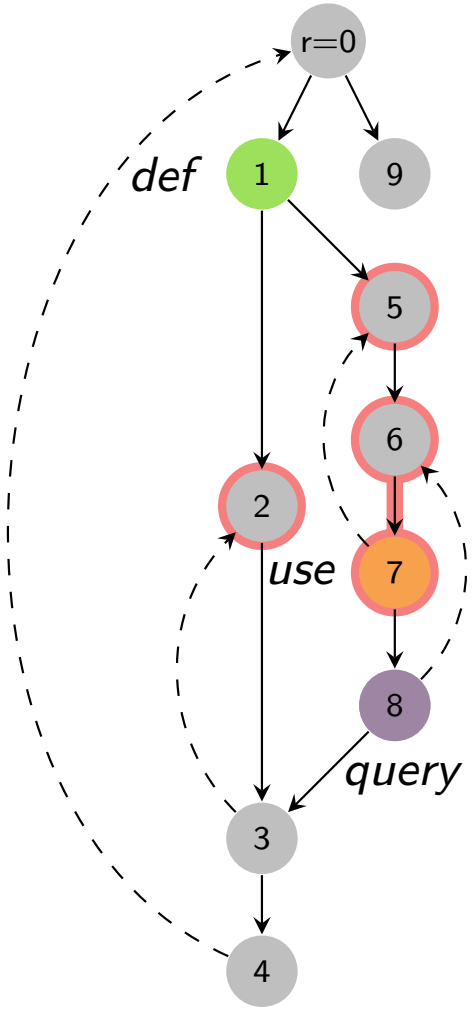


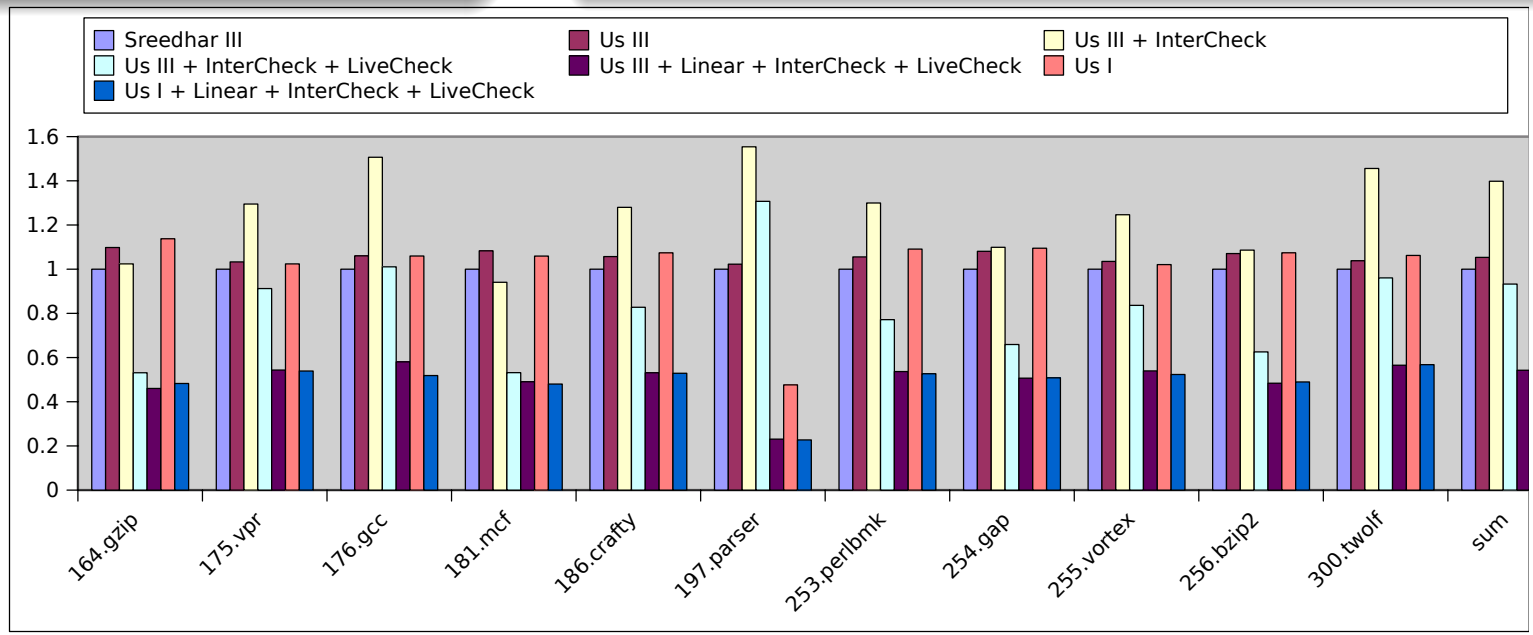
Speed-up for SPEC CINT2000: x2

General scheme

- `Sreedhar III`: w. virtualization.
- `Us I`, `Us III`: our proposal, w.o./w. virtualization.

Interference checks

- Default: liveness sets + interference graph.
- `InterCheck`: Budimlić with liveness sets.
- `LiveCheck`: Fast liveness checking.
- `Linear`: Linear check instead of quadratic.

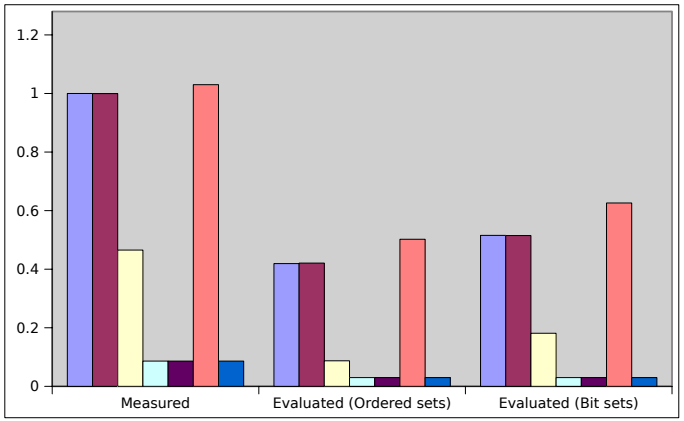


Memory footprint reduction for SPEC CINT2000: x10

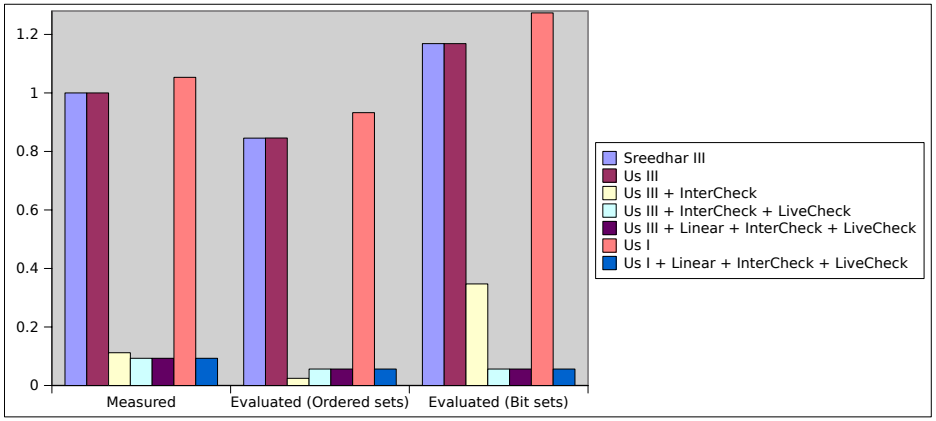
- Interference graph: half-size bit matrix.
- Liveness sets: enumerated sets. Does not count construction.
- Livenesss check: bit sets. Construction taken into account.

Data structures grow during virtualization. "Perfect memory" evaluated, with both enumerated/bit sets for liveness sets.

Sum of memory footprint



Max of memory footprint



Outline

General framework

- Correctness clarified even for complex cases
- Two-phases solution, based on coalescing

Results

- Value-based interferences, for free, as good as Sreedhar III
- Fast algorithm: Speed-up x2, memory reduction x10.

Implementation

- No need to virtualize (at least for us)
- Simpler implementation

The End

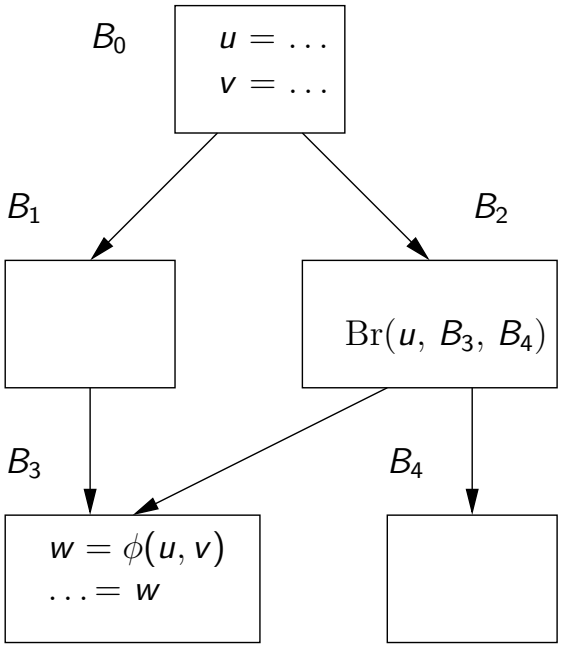
Thank you!

Bug tracking RVM-254 of Jikes RVM

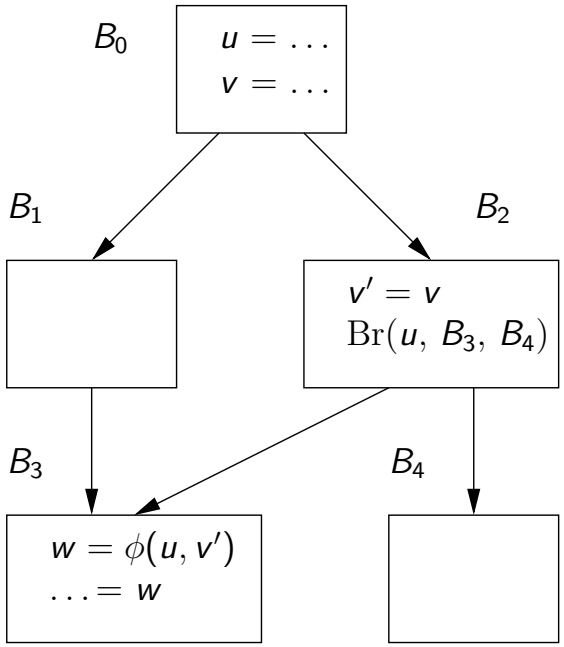
Problems with SSA form: lack of loop unrolling breaks VM

This problem is probably one of the most serious in the RVM currently. When loop unrolling is disabled and SSA enabled the created IR is corrupt. The error has in the past look like we were suffering from the "lost copy" problem, but implementing a naive solution to this didn't solve the problem. Their is sound logic behind the code so we need to identify a small test case where things are broken and then reason about what's wrong in leave SSA. This has been attempted once (with the code that removes an element from the live set) but the problem no longer appears to surface here. Currently these optimizations are disabled but by RVM 3.0 they should be re-enable and this bug cured.

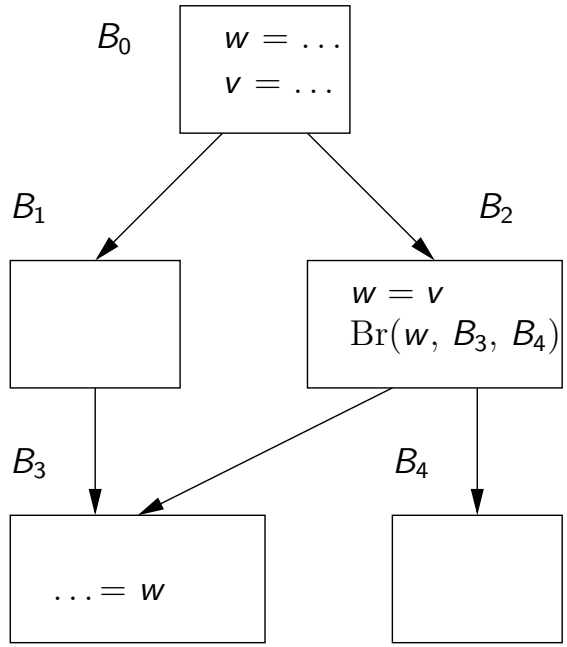
Potential bugs with conditional branches



Initial code

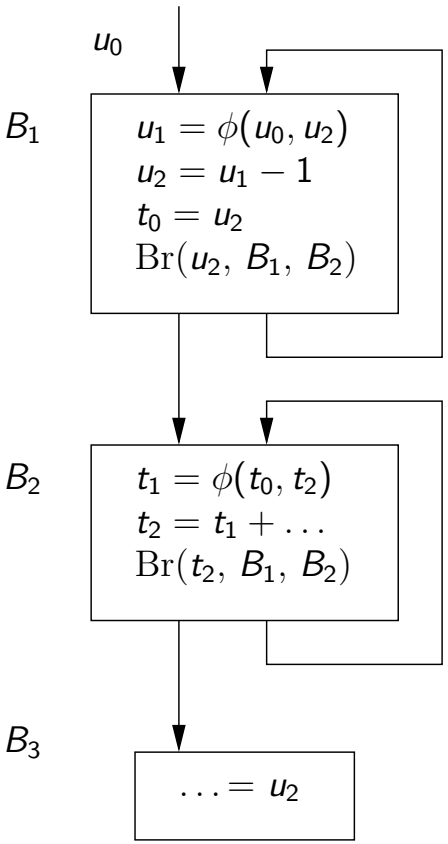


"Blind" Sreedhar III

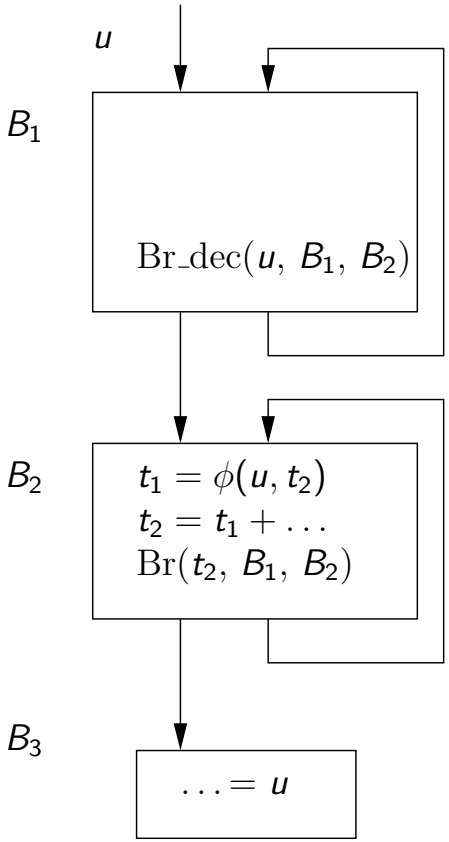


Wrong output code

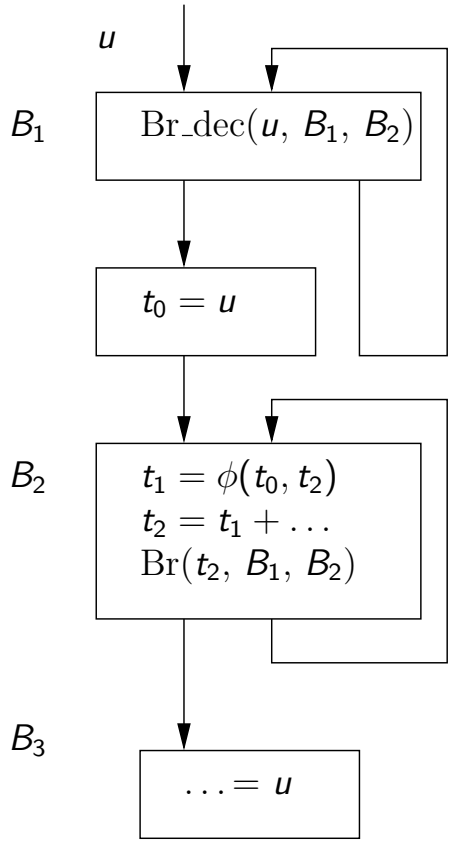
Unfeasible out-of-SSA translation example



Initial code



After optimization



Needs edge splitting