An SSA-based Algorithm for Optimal Speculative Code Motion under an Execution Profile

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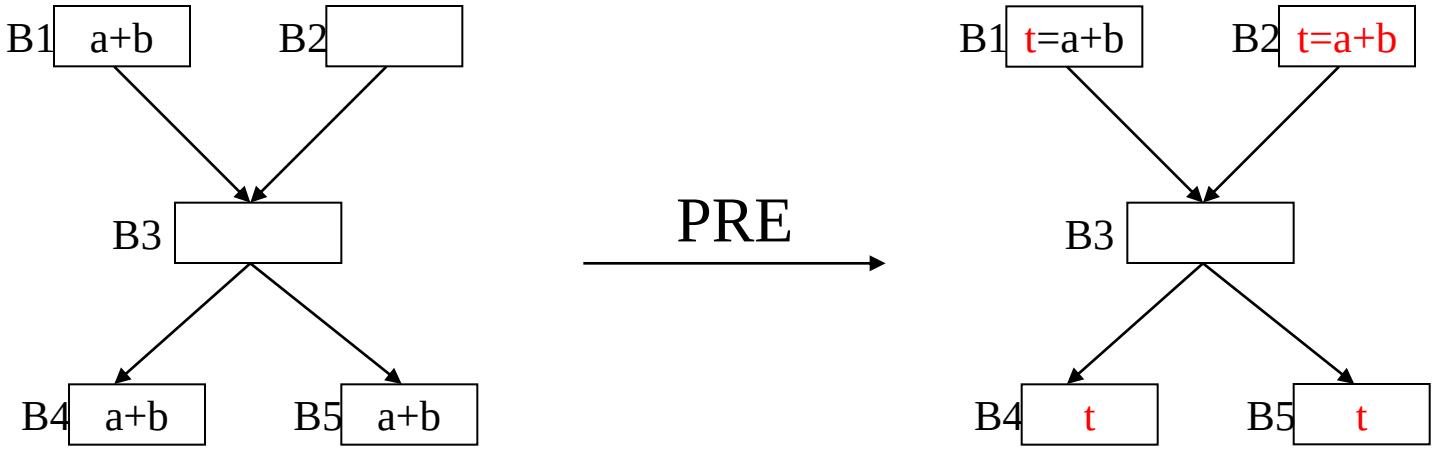
Contents

Partial Redundancy Elimination (PRE)

- Eliminates expressions redundant on some (not necessarily all) paths
- One of the most important and widely applied target-independent global optimization
- Subsumes global common subexpression and loop invariant code motion



PRE Facts

- Applied to each lexically identified expression independently
  - e.g (a+b), (a-b), (a*c)
- Formulated as a Placement problem:
  - Step 1 – Determine where to perform insertions
    - Render more computations fully redundant
  - Step 2 – Delete fully redundant computations
- Main challenge is in Step 1

The Most Popular PRE Algorithms

Lazy Code Motion (Knoop *et. al)*

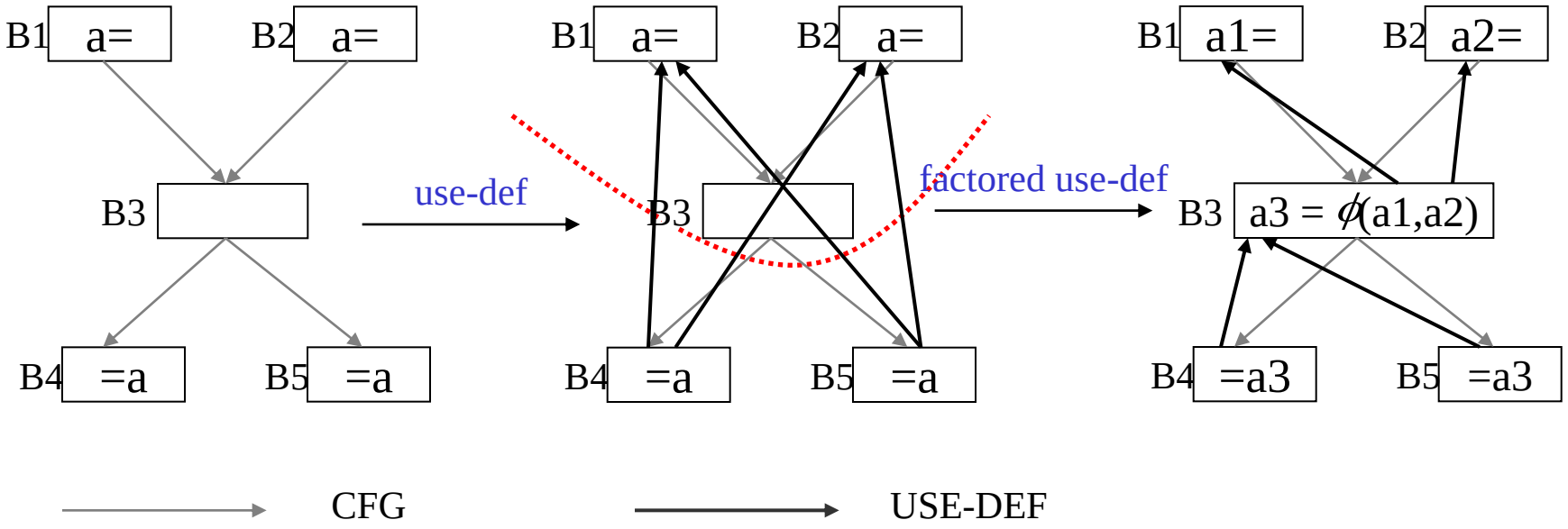
- Computationally and Life-time Optimal
- Ordinary program representation
- Bit-vector-based iterative data flow analyses

SSAPRE

- Computationally and Life-time Optimal
- SSA form of program representation
- Sparse solution of data flow properties
- Subsumes local common subexpression
  - Insensitive to basic block boundaries

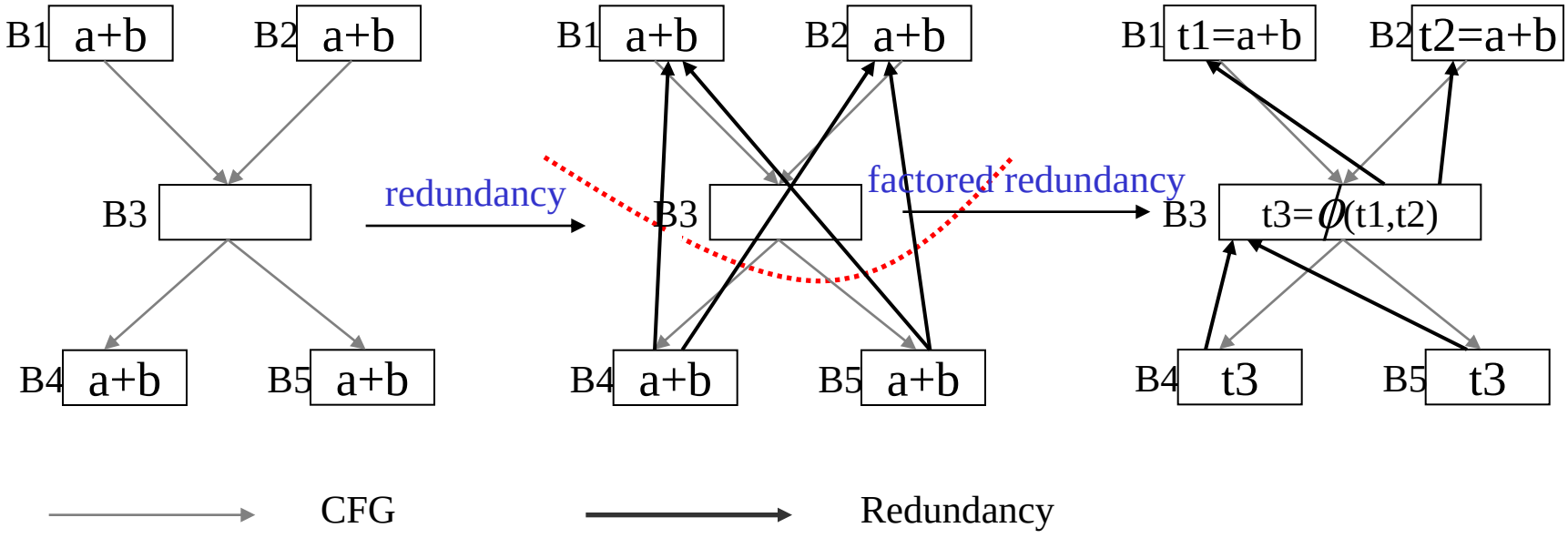
Static Single Assignment (SSA)

- Program representation with *built-in* use-def information
- Use-def edges factored at join points in CFG
- Use-def implicitly represented via unique names
- Each renamed variable has only one definition



Factored Redundancy Graph (FRG)

- Used in SSAPRE to represent redundant relationships among occurrences of the same expression via edges
- The redundancy edges are factored as in SSA
- Can view as SSA applied to expressions
  - Effectively put the *t* storing the expression after PRE in SSA form



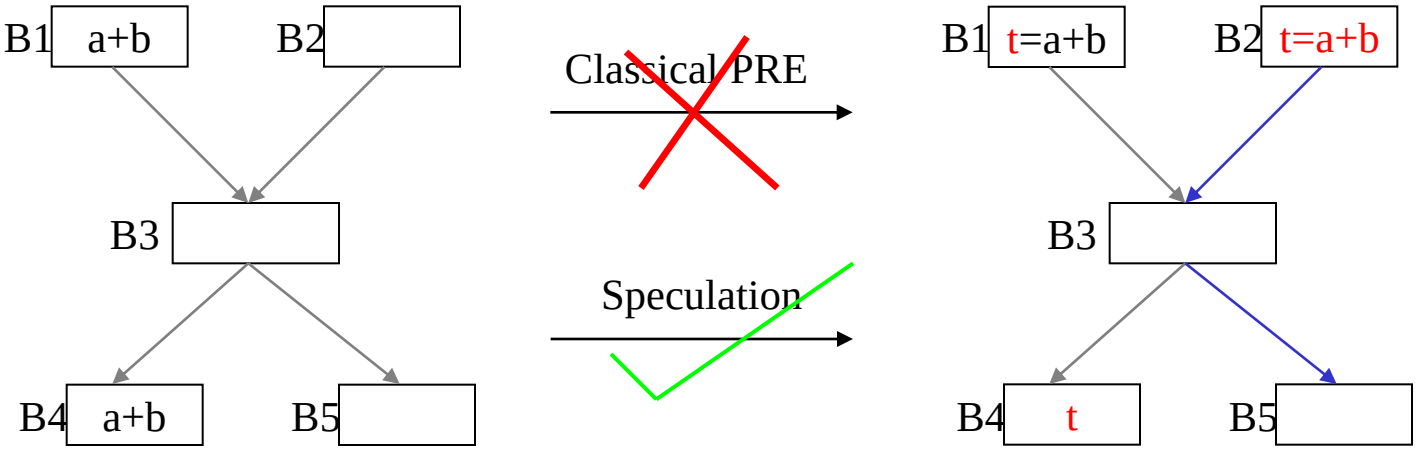
Speculative Code Motion

Classical PRE only inserts at places where the expression is anticipated (down-safe)

- Many redundant computations cannot be eliminated

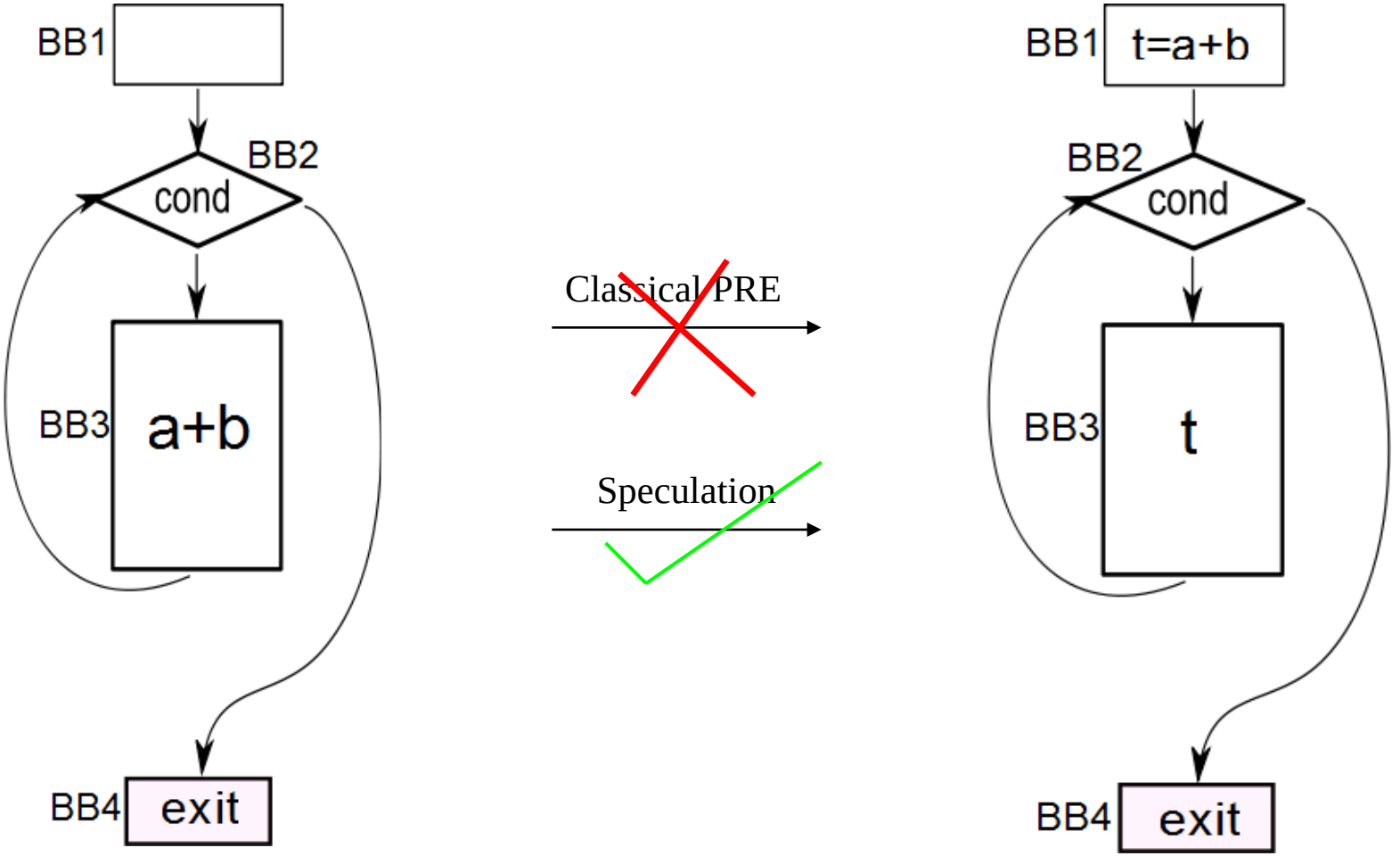
Speculative code motion *ignores* safety constraint

- Can remove more redundancies
- Not applicable to computations that may trigger runtime exceptions



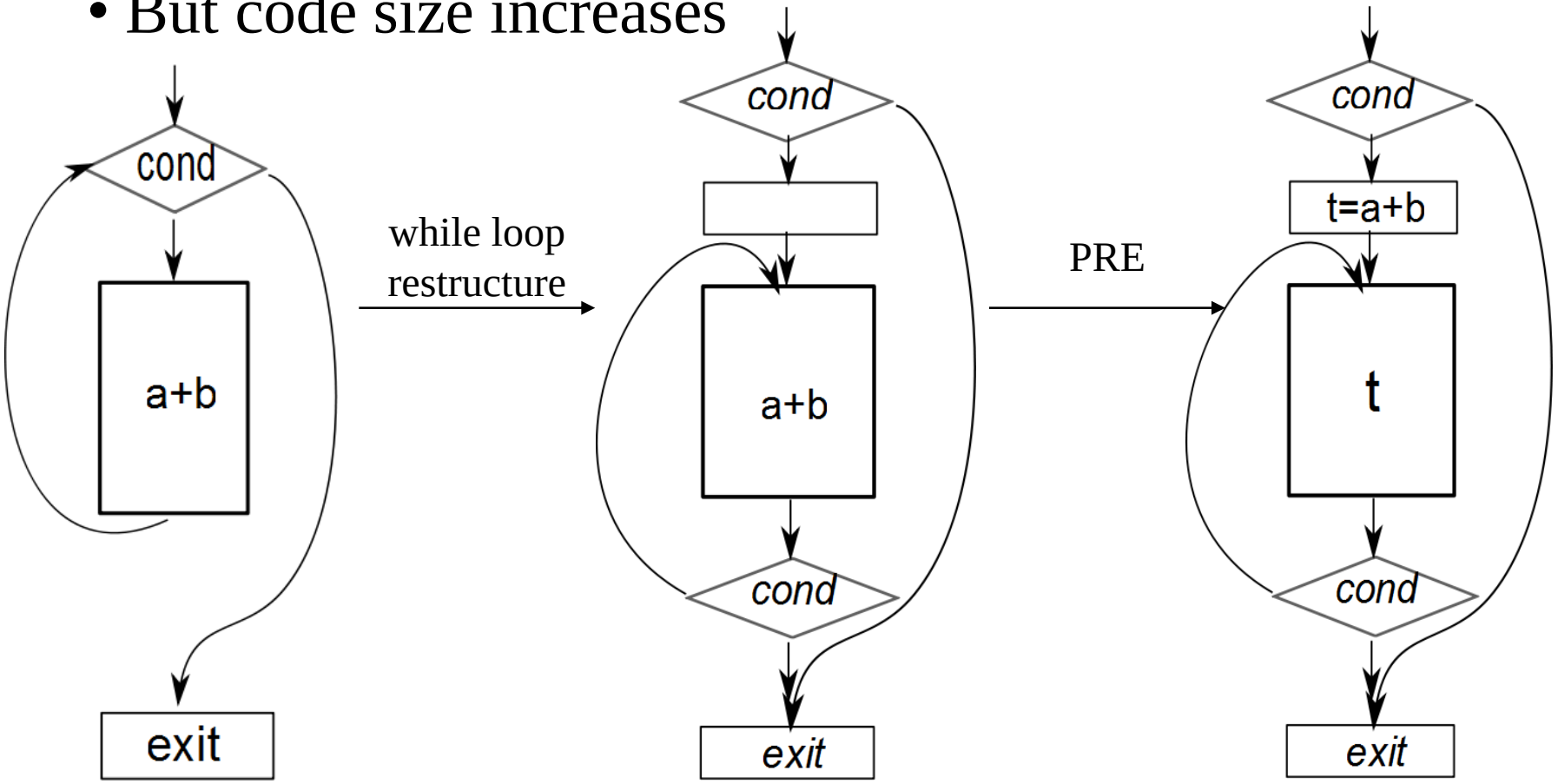
While Loop Example

Invariant code motion involves speculation



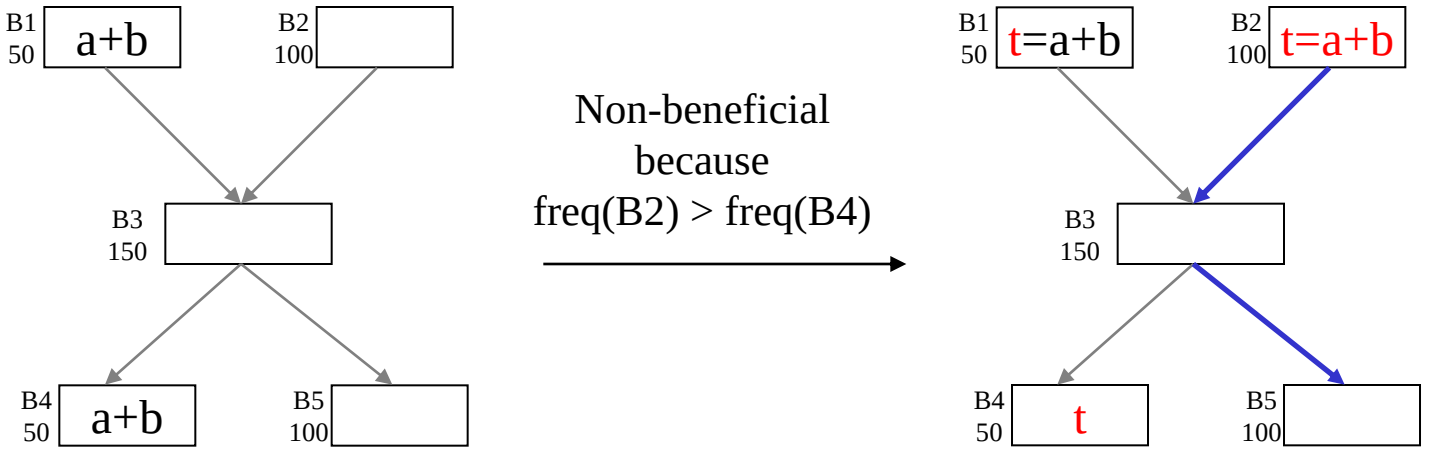
While Loop Restructuring

- The common solution
- Speculation no longer necessary
- But code size increases



Speculation not always beneficial

- Useless computations introduced for some paths
- Beneficial only if removed computations executed more frequently than inserted computations
- Requires execution frequency information



Problem Statement

How to minimize the dynamic execution count of an expression under an execution profile

- A more aggressive form of PRE
  - Classical PRE beneficial regardless of execution frequencies
- Cai and Xue (2003, 2006) first to apply min-cut to solve this problem optimally
  - Algorithm called MC-PRE
  - Uses bit-vector-based data flow analyses
  - Min-cut applied to CFG
- No SSA-based technique exists yet

Topic of this Paper

MC-SSAPRE – a new algorithm that yields optimal code placement under the SSAPRE framework

Overview:

- Form a essential flow graph (EFG) out of the FRG
- Map the BB execution frequencies to the EFG nodes
- Apply min-cut to the EFG

Algorithm Steps

SSAPRE Steps

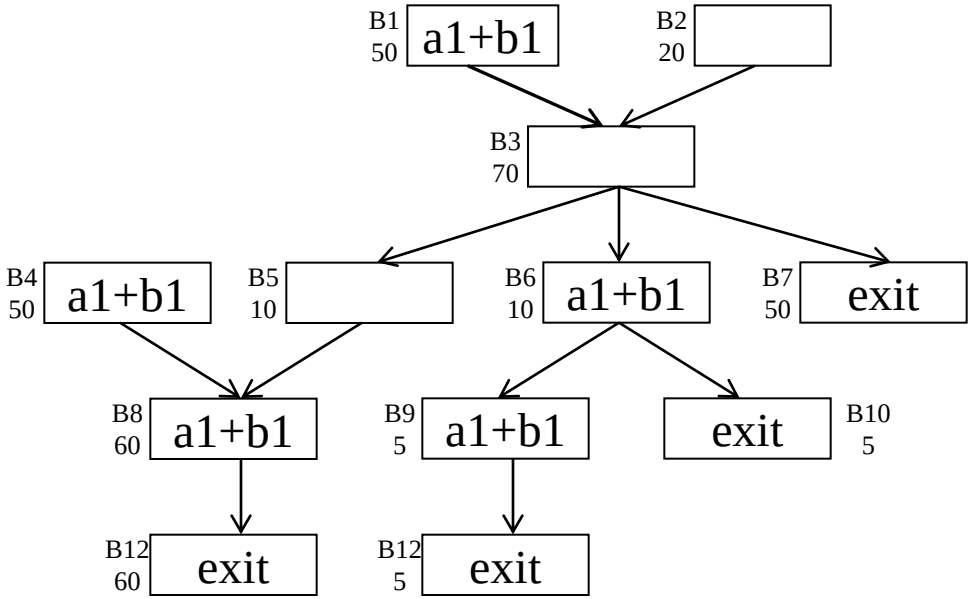
- Construct FRG
  - Φ insertion
  - Rename
- Data Flow Attributes
  - DownSafety
  - WillBeAvail
- Book-keeping
  - Finalize
  - CodeMotion

MC-SSAPRE Steps

- Construct FRG
  - Φ insertion
  - Rename
- Form EFG and perform min-cut
  - Data flow
  - Graph reduction
  - Single source
  - Single sink
  - Minimum cut
  - WillBeAvail
- Book-keeping
  - Finalize
  - CodeMotion

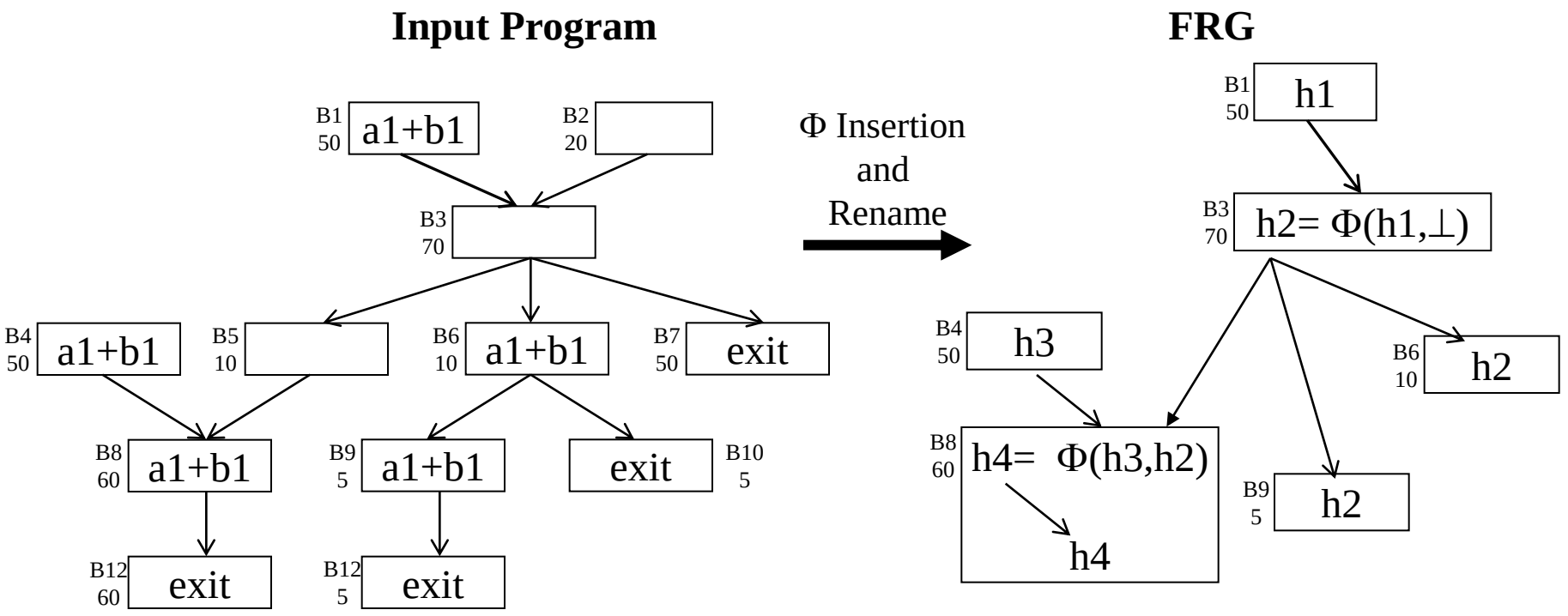
Running example in SSA Form

Input Program



FRG for Running Example

Introduce *h* so the FRG can be viewed from an SSA perspective



Roles of Factored Redundancy Graph

- Insertions need to be considered only at Φ's
  - associated with the Φ operands
- Medium to compute data flow properties to disqualify more Φ's from being insertion candidates
- SSA form for *t* (temporary to store the computed value) will be carved out of the FRG
- Three kinds of nodes:
  1. Real occurrences in original program
     - Def – always non-redundant
     - Use – partially redundant (including fully redundant)
  2. Φ (def)
  3. Φ operand (use) – can be ⊥

Data Flow Properties for MC-SSAPRE

Fully available

- Insertions at these Φ's always unnecessary because the computed values are available

Partially anticipated

- Insertions should only be at these Φ's
- otherwise, the inserted computation would have no use

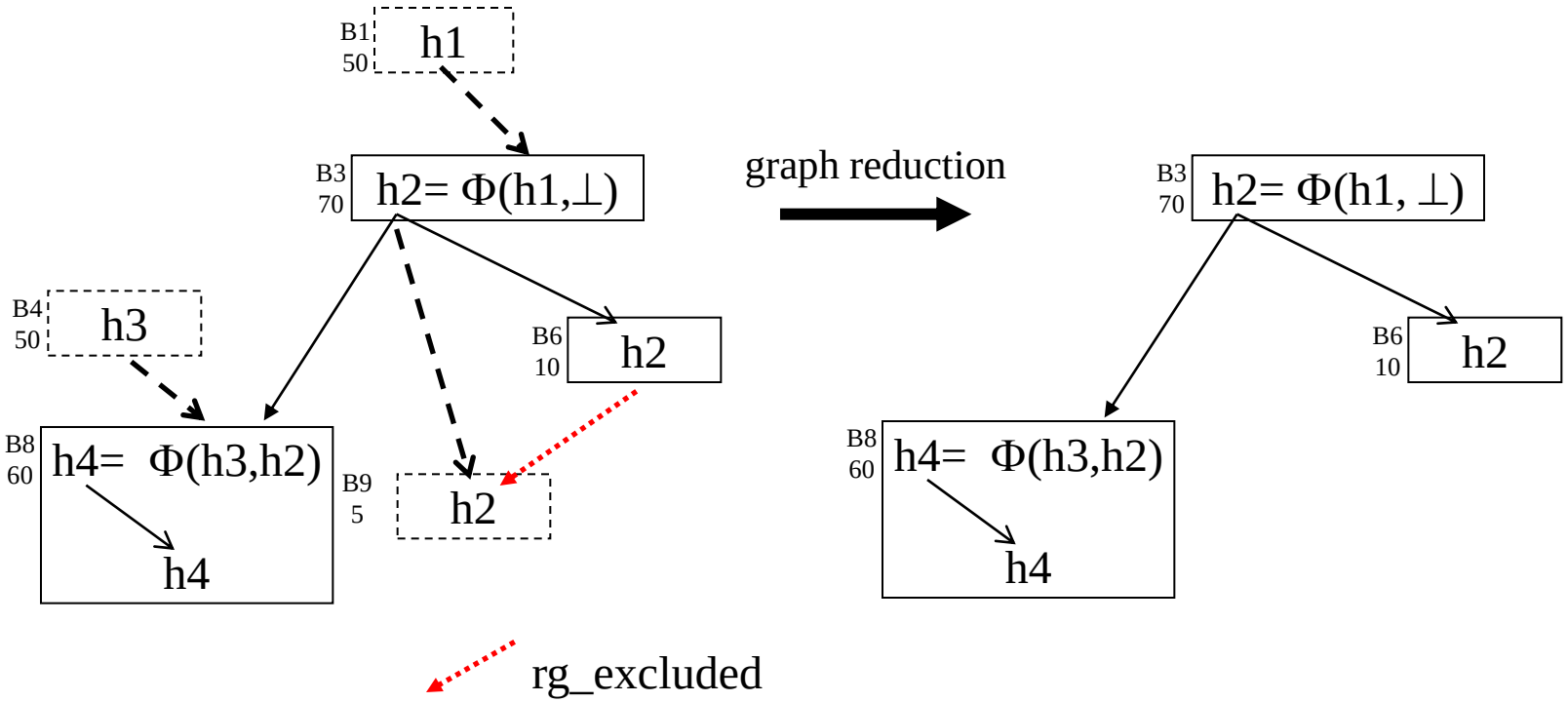
Graph Reduction

Use computed data flow properties to further narrow down the Φ candidates for insertion

Delete:

- Φ's that are fully available
- Φ's that are not partial anticipated
- Use nodes (real occurrences or Φ operands) that are fully redundant
- Edges from/to above nodes

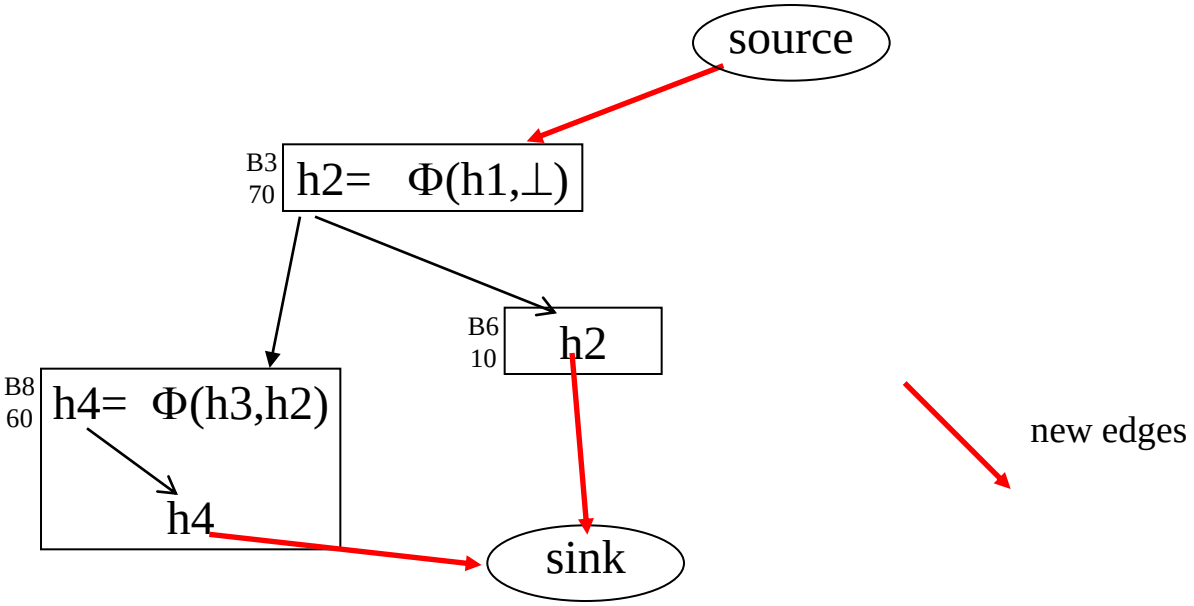
Graph Reduction for Running Example



rg_excluded – fully redundant occurrences determined during Renaming

Form Essential Flow Graph (EFG)

- Introduce a virtual source node
  - Add an edge from it to each $\perp$ Φ operand
- Introduce a virtual sink node
  - Add an edge from each real occurrence to it
- Result is a complete flow network



Edges in EFG

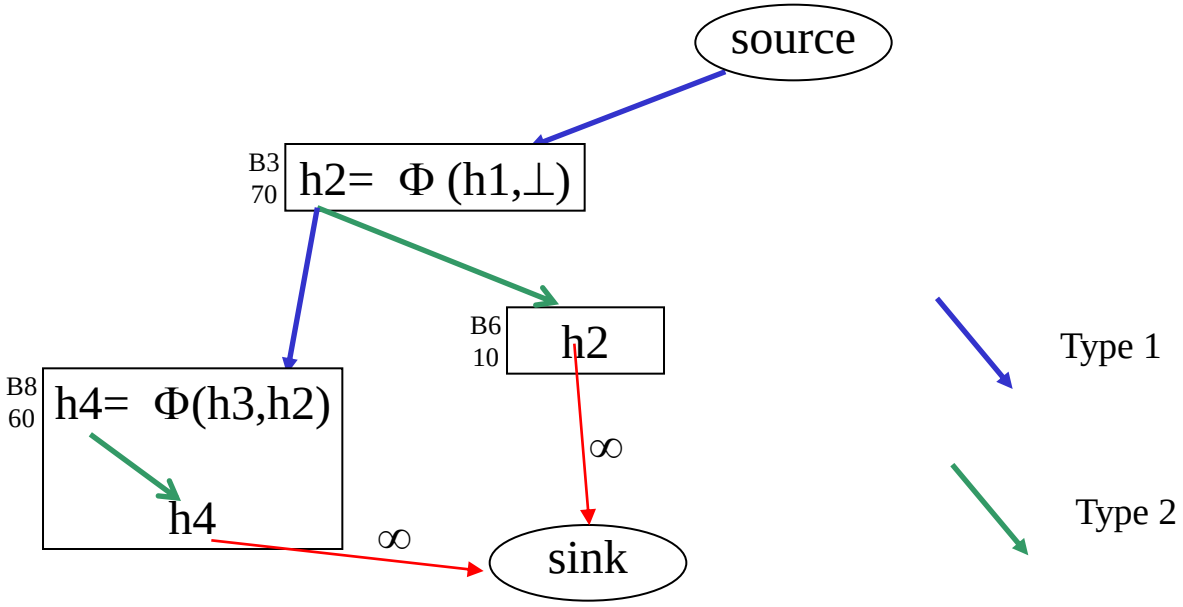
Edges to the sink are never insertion candidate

- Mark with ∞ frequency

Other edges are:

Type 1 edge – Edges ending at a Φ operand

Type 2 edge – Edges from a Φ to a real occurrence

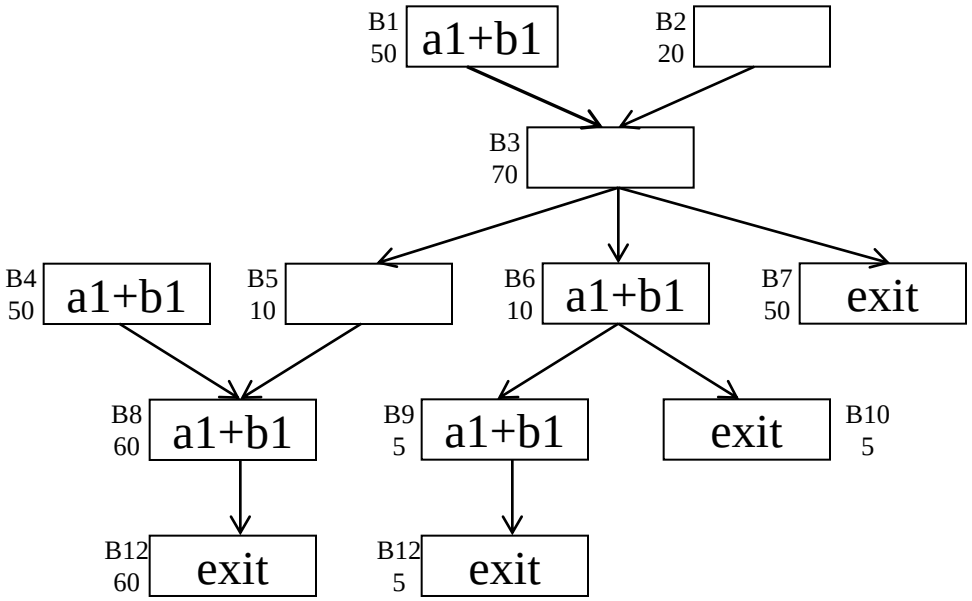


Mapping Frequencies to EFG Edges

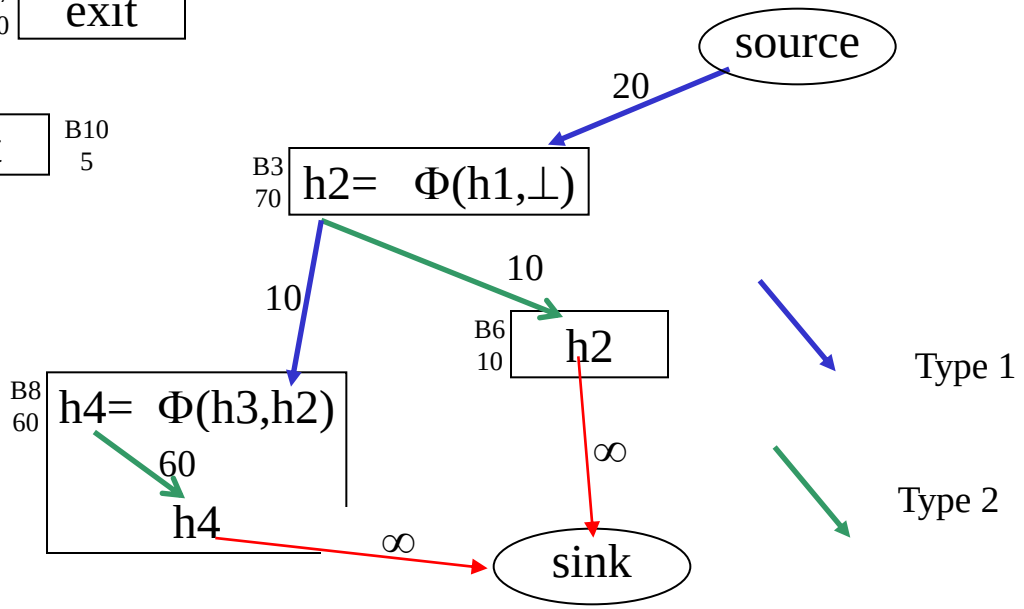
- Model insertion at a Type 1 edge by inserting at exit of the predecessor BB corresponding to the Φ operand
  - Annotate the Type 1 edge by the node frequency of that predecessor BB
- Insertion at a Type 2 edge means performing the computation *in place*
  - Annotate the Type 2 edge by the frequency of the real occurrence

EFG annotated with Frequencies

Original Program



Final EFG



Performing Minimum Cut

A minimum cut

- *separates the flow network into two halves, such that*
- *the sum of the weights of the cut edges is minimized*

By performing insertions at the cut edges, the number of execution of the computation is minimized

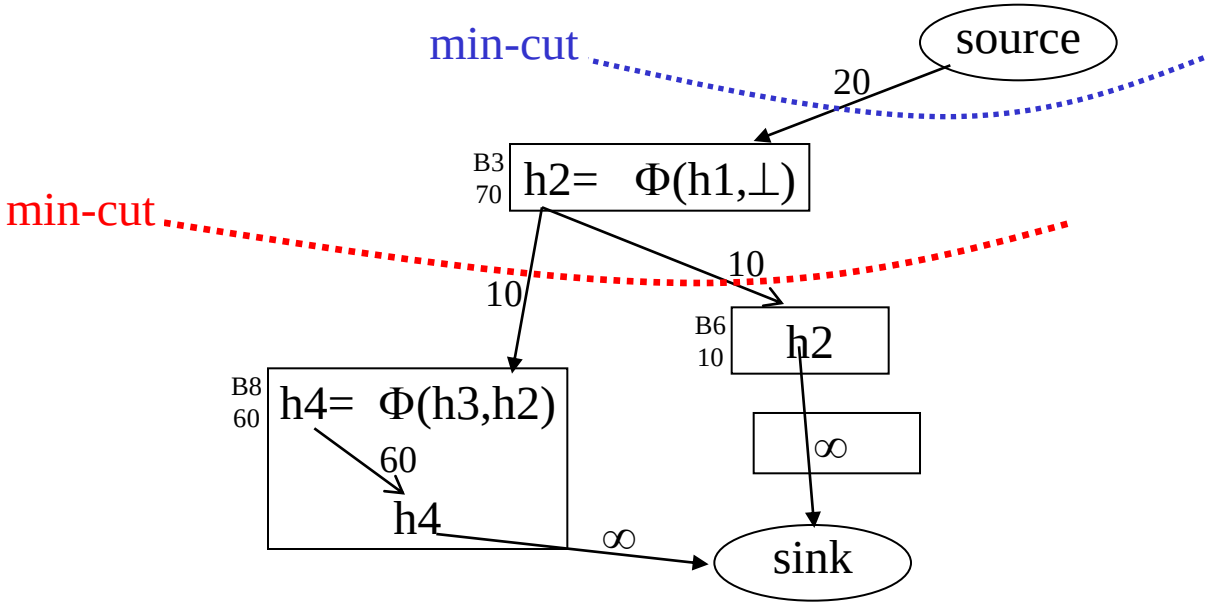
  – Implies computational optimality

If min-cut not unique, choose the cut nearest the sink

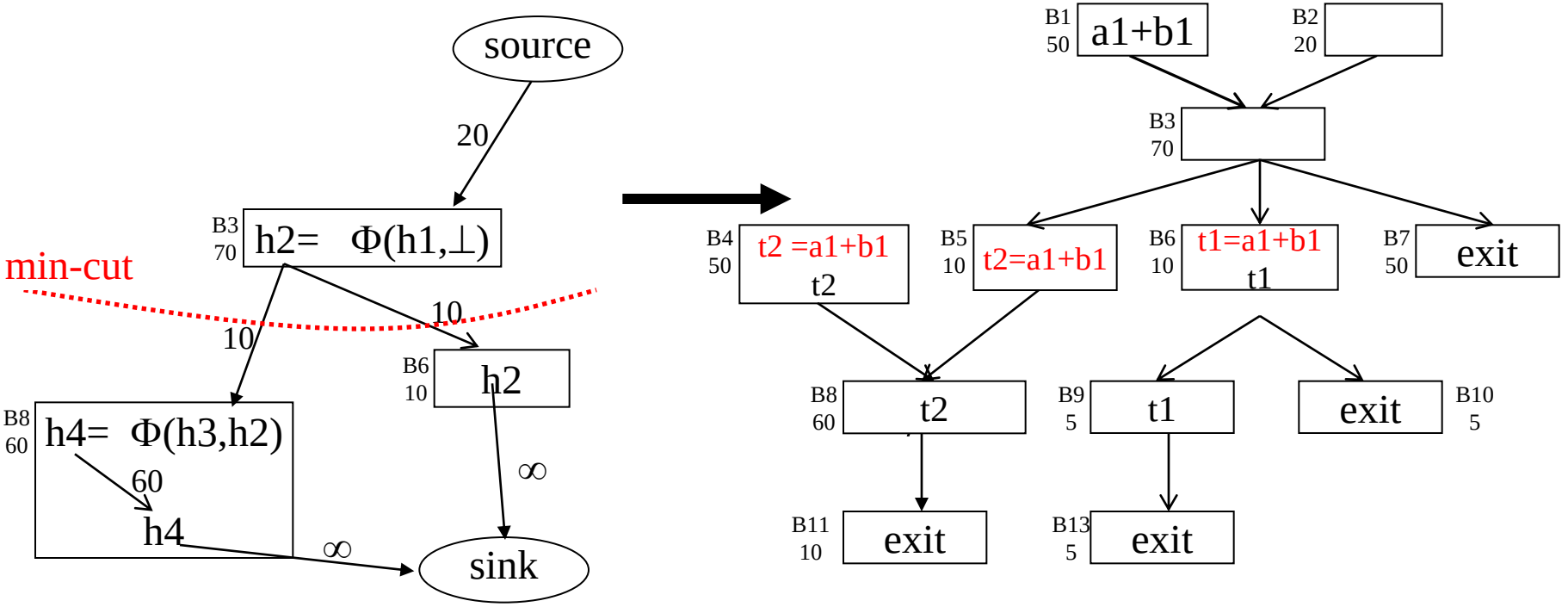
  – Induces life-time optimality

Our Example

- Two possible min-cuts
- Pick later red one



Final Result



Complexity of MC-SSAPRE

MC-SSAPRE Steps

- Construct FRG
  - Φ insertion
  - Rename
- Form EFG and perform min-cut
  - Data flow
  - Graph reduction
  - Single source
  - Single sink
  - Minimum cut
  - WillBeAvail
- Book-keeping
  - Finalize
  - CodeMotion

V – number of FRG nodes

E – number of FRG edges

- Except the minimum cut step, all the steps are $O(V+E)$
- Performing minimum cut is $O(V^2\sqrt{E})$
- In general,

$$V_{cfg} > V_{frg} > V_{efg}$$

Our Implementation

- Implemented MC-SSAPRE in the open source Path64 compiler, a descendent of the compiler with the original SSAPRE
- Leveraged existing SSAPRE infrastructure
- Resulting compiler will perform:
  - SSAPRE when no profile available
    - Perform speculation for loop-invariant computations
  - MC-SSAPRE with profile data
- Compiler always restructures **while** loops

Setup of Experiment 1

- Target is Intel Core™ i7-970 at 2.67GHz with 8MB cache
- Ubuntu 9.10
- With 6GB on board memory
- Compare run-time performances of all of SPEC CPU2006 (29 benchmarks)
- The 3 runs:

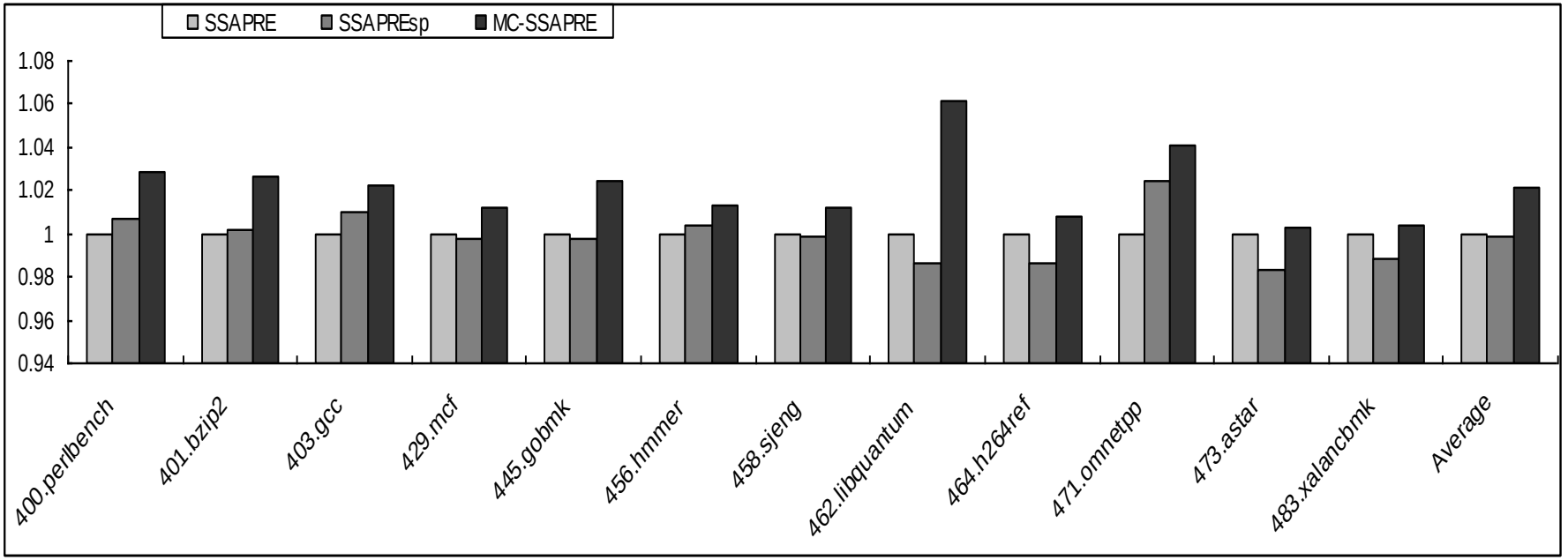
  SSAPRE – no speculation, no profile data

  $SSAPRE_{sp}$ – loop-based speculation, no profile data

  MC-SSAPRE – speculation based on profile data

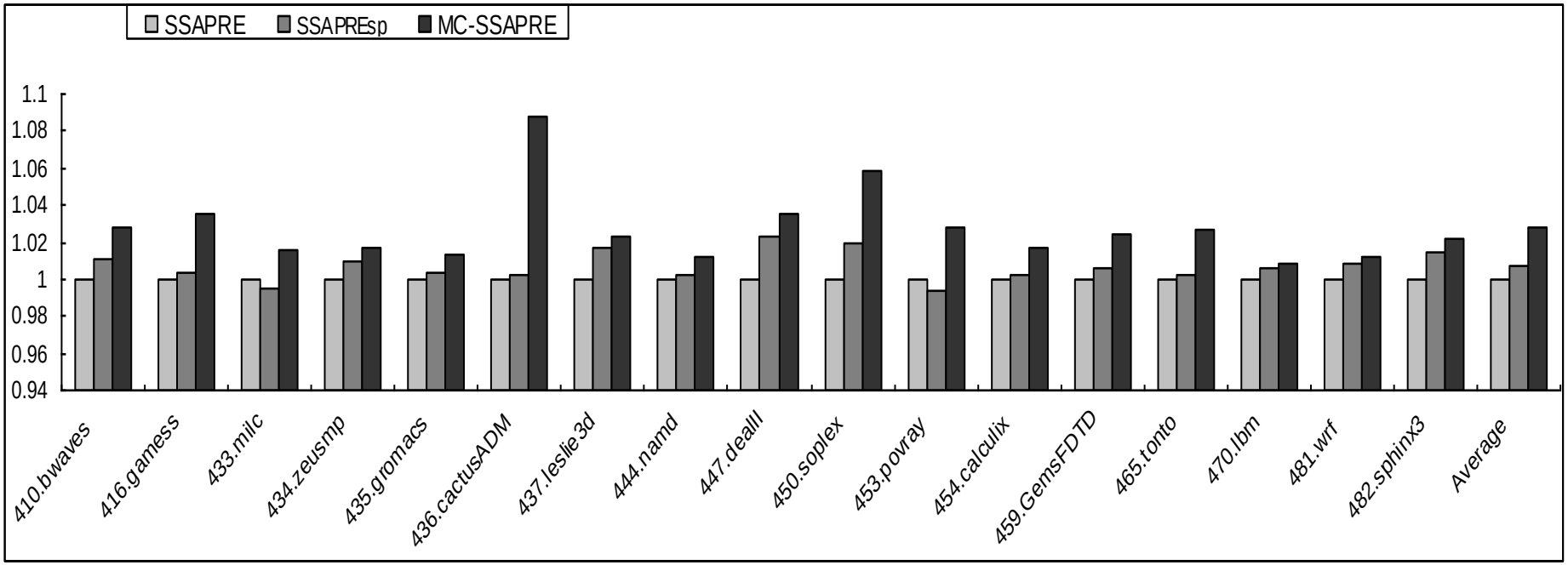
Experimental Results – CINT2006

- Average speedup of 2.13% over SSAPRE
- Average speedup of 2.25% over $SSAPRE_{sp}$



Experimental Results – CFP2006

- Average speedup of 2.76% over SSAPRE
- Average speedup of 1.96% over $SSAPRE_{sp}$

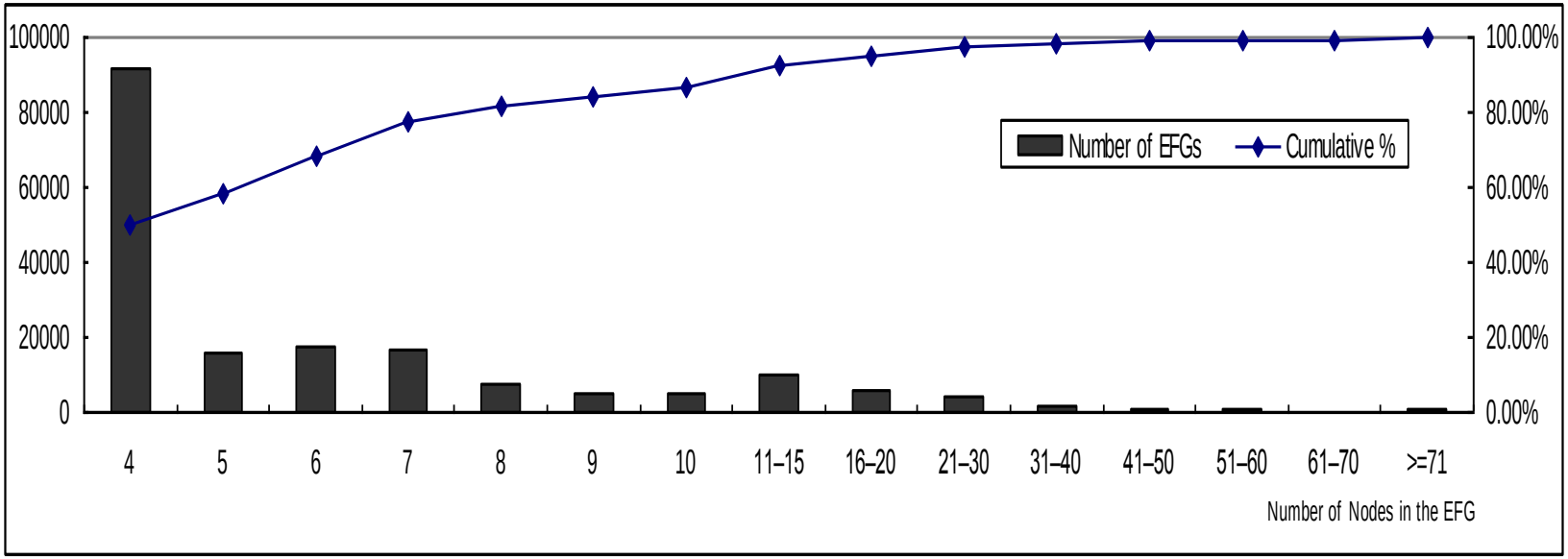


Setup of Experiment 2

- Calculate size of EFGs formed during MC-SSAPRE
- Same 29 SPEC CPU2006 benchmarks
- Target-independent
- Show
  - Optimization overhead in MC-SSAPRE
  - Impact of sparse approach
- Exclude empty EFGs
- Smallest EFG is 4 nodes:
  - Source, sink, Φ, real occurrence

Sizes of EFGs

- 183152 EFGs in the 29 SPEC CPU2006 benchmarks
- Near 50% of EFGs are only 4 nodes
- 86.5% of EFGs are less than 10 nodes
- 99.0% of EFGs are less than 50 nodes
- 24 EFGs larger than 300 nodes (largest size is 805)



Conclusion

- The minimum-cut technique for flow networks can effectively be applied to SSA graphs
- SSA-based compilers can apply MC-SSAPRE to achieve optimal speculative code motion under an execution profile
- The sparse approach is effective in reducing the problem sizes
- The polynomial time complexity of Min-cut only has limited effect on MC-SSAPRE's optimization efficiency
- MC-SSAPRE always improves program performance over SSAPRE

Questions?