

CSC2/455 Software Analysis and Improvement

Partial Redundancy Elimination

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Outline

Review

Partial Redundancy Elimination

Postscript

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Optimizations: Dead Code Elimination

- ▶ Find useful operations (backward analysis)
- ▶ Find useful conditional branches
 - ▶ Reverse Dominance Frontier
- ▶ Remove code, and “touch up CFG”

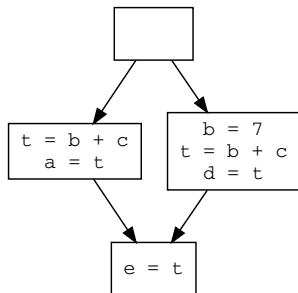
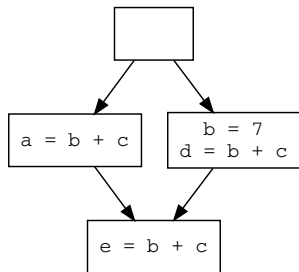
Outline

Review

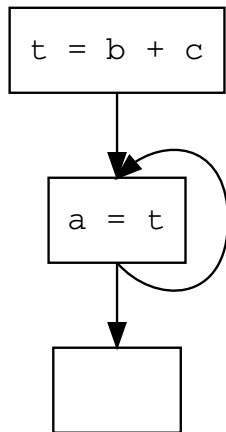
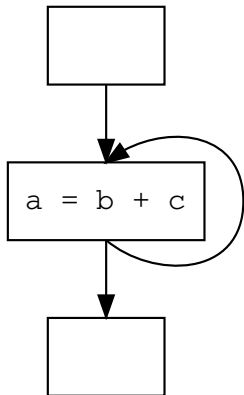
Partial Redundancy Elimination

Postscript

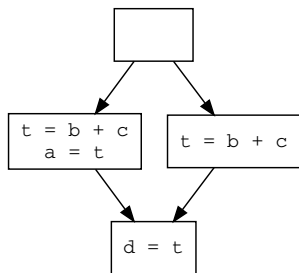
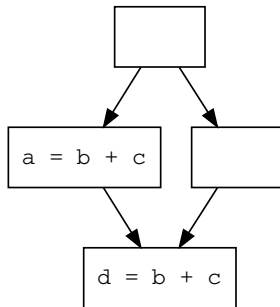
Redundancy: Fully Redundant



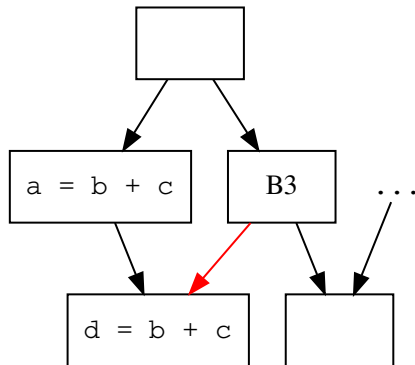
Redundancy: Loop Invariant



Redundancy: Partial Redundancy

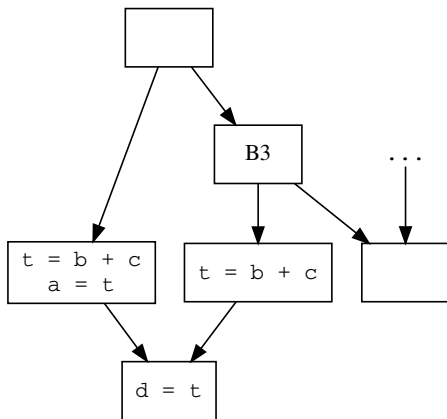


Eliminating Redundancy: Complication 1



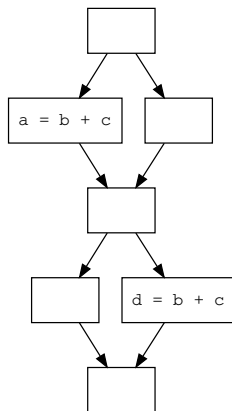
Can we insert $t = b + c$ in B_3 ?

Splitting Critical Edges



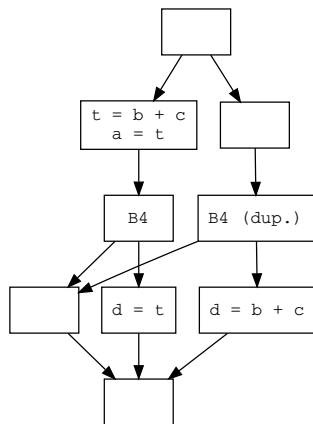
(Similar to when we were inserting minimal ϕ -functions.)

Eliminating Redundancy: Complication 2



Note that there is no block where $t = b + c$ can be introduced without introducing computations not in the original program.

CFG duplication



(Possibility of exponential blowup.)

The Lazy Code Motion Algorithm

- ▶ Eliminate all expressions when it will not duplicate code
- ▶ Do not perform computations not in original program
 - ▶ Although where the computation is performed can change
- ▶ Delay computation for as long as possible
 - ▶ “Lazy”
 - ▶ Helps lower resource (esp. register) usage

Setup

For all blocks B in CFG, compute:

- ▶ e_use_B : set of expressions used in a block
- ▶ e_kill_B : set of expressions killed in block
 - ▶ usually by redefining subcomponents

Also, split all critical edges, inserting empty blocks.

Anticipable Expressions

Recall *very busy expressions*. An expression e is anticipable at block p if:

- ▶ ?

Anticipable Expressions

Recall *very busy expressions*. An expression e is anticipable at block p if:

- ▶ e is used/computed on all paths leading out of p
- ▶ And it is not killed before the use
- ▶ Implies that p can compute e and all paths could use this result

Anticipable Expressions Analysis

- ▶ Direction: Backwards
- ▶ Values: Expressions in programs
- ▶ Meet: \cap
- ▶ Transfer Function
 - ▶ $f_B(x) = e_use_B \cup (x - e_kill_B)$
- ▶ Equations:
 - ▶ $OUT[B] = \bigwedge_{S \in succ(B)} IN[S]$
 - ▶ $IN[B] = f_B(OUT[B])$
- ▶ $\top = U$
- ▶ $IN[EXIT] = \emptyset$

Available Expressions

An expression is available at a program point p if:

- ▶ it has been computed along all paths leading into p
- ▶ it has not been killed since being computed until p
- ▶ (NEW) it is anticipated at p
 - ▶ we could make it available if it is anticipated

Available Expressions Analysis

- ▶ Direction: Forwards
- ▶ Meet: \cap
- ▶ Transfer function
 - ▶ $f_B(x) = (e_use_B \cup anticipable[B].in) \cup (x - e_kill_B)$
- ▶ Equations
 - ▶ $IN[B] = \bigwedge_{P \in pred(B)} OUT[P]$
 - ▶ $OUT[B] = f_B(IN[B])$
- ▶ $\top = U$
- ▶ $OUT[ENTRY] = \emptyset$

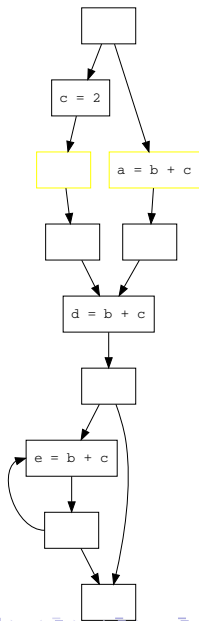
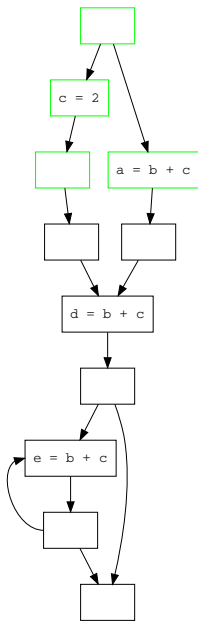
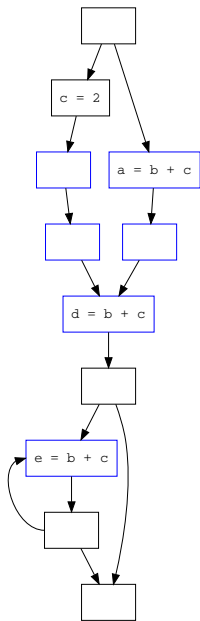
Positioning Expressions

- ▶ When is the earliest an expression can be evaluated?
- ▶ When is the latest an expression can be evaluated?

Positioning Expressions: Earliest

- ▶ When is the earliest an expression can be evaluated?
 - ▶ When it anticipated, but not available
- ▶ $earliest[B] = anticipable[B].in - available[B].in$
 - ▶ Observe notation for results of different analyses

Anticipable + (Not) Available = Earliest



Positioning Expressions: Latest

- ▶ When is the latest an expression can be evaluated?
 - ▶ When it can no longer be postponed
- ▶ “Postponed”: expression pushed down from earliest placement
 - ▶ When can we push down an expression into the next block?

Postponable Expressions

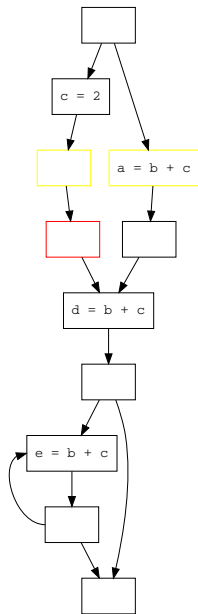
An expression e is postponable to a block p if:

- ▶ e could be placed in block b before p (earliest is before p)
- ▶ Such that it is available on all paths leading to p from ENTRY
- ▶ But e is not used after block b (and before p)

Postponable Expressions Analysis

- ▶ Direction: Forwards
- ▶ Values: Expressions
- ▶ Meet: \cap
- ▶ Transfer functions
 - ▶ $f_B(x) = (\text{earliest}[B] \cup x) - e_use_B$
- ▶ Equations
 - ▶ $OUT[B] = f_B(IN[B])$
 - ▶ $IN[B] = \bigwedge_{P \in \text{pred}(B)} OUT[P]$
- ▶ $\top = U$
- ▶ $OUT[ENTRY] = \emptyset$

Postponable



Postponement Frontier

A block p is on the *postponement frontier* for an expression e if

- ▶ e can be postponed to p
- ▶ e cannot be placed at entry to a successor s of p
 - ▶ e is used in p
 - ▶ e is not postponable from some predecessor of s
 - ▶ e is not in $earliest[S]$

$$latest[B] = (earliest[B] \cup postponable[B].in) \cap (e_use_B \cup (\bigcap_{S \in succ(B)} (earliest[S] \cup postponable[S].in)))^c)$$

(Note: A^c means the complement of set A)

Used Expressions

An expression e in block p is used if:

- ▶ Some block q uses e
- ▶ There exists a path from p to q that does not invalidate e
 - ▶ I.e. recompute e or invalidate its operands

Used Expressions Analysis

- ▶ Direction: Backwards
- ▶ Values: Expressions
- ▶ Meet: \cup
- ▶ Transfer function
 - ▶ $f_B(x) = (x \cup e_use_B) - latest[B]$
- ▶ Equations
 - ▶ $IN[B] = f_B(OUT[B])$
 - ▶ $OUT[B] = \wedge_{S \in succ(B)} IN[S]$
- ▶ $\top = \emptyset$
- ▶ $IN[EXIT] = \emptyset$

Putting it all together - I

- ▶ Compute *anticipable*[*B*].*in*, *available*[*B*].*in*
- ▶ Compute *earliest*[*B*]
- ▶ Compute *postponable*[*B*].*in*
- ▶ Compute *latest*[*B*]
- ▶ Compute *used*[*B*].*out*

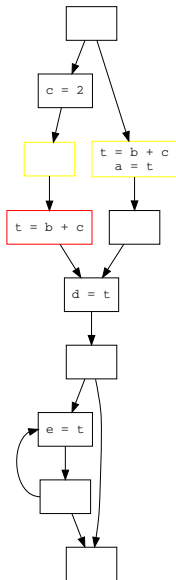
Putting it all together - II

For each expression $x + y$ in program:

- ▶ Create $t = x + y$ (where t is a unique temporary)
- ▶ Place $t = x + y$ at the beginning of all blocks B such that
 - ▶ $x + y$ is in $latest[B] \cap used[B].out$
 - ▶ i.e. B is the last block where $x + y$ can be placed, and $x + y$ is used after B
- ▶ Replace all $x + y$ with t in all block B where:
 - ▶ $x + y \in (e_use_B \cap (latest[B]^G \cup used[B].out))$
 - ▶ i.e., $x + y$ is in e_use_B , and
 - ▶ $x + y$ is NOT in $latest[B]$, or
 - ▶ $x + y$ is in $used[B].out$

Algorithm 9.36 in the Dragon Book.

Final result



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References

- ▶ Chapter 9 of the Dragon Book
 - ▶ Section 9.5