Lazy Code Motion

COMP 512
Rice University
Houston, Texas

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“Lazy Code Motion,” J. Knoop, O. Ruthing, & B. Steffen, in PLDI 92

“A Variation of Knoop, Ruthing, and Steffen’s Lazy Code Motion,”
K. Drechsler & M. Stadel, SIGPLAN Notices, 28(5), May 1993

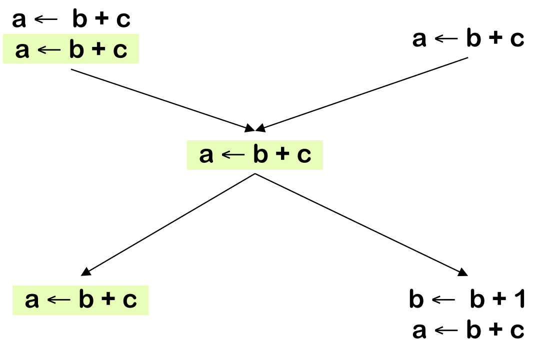
Treatment in Chapter 10 of Engineering a Compiler …

Redundant Expression

An expression is <u>redundant</u> at point *p* if, on every path to *p*

1. It is evaluated before reaching *p*, and
2. Non of its constitutent values is redefined before *p*

Example


a ← b + c
a ← b + c

a ← b + c

a ← b + c

a ← b + c

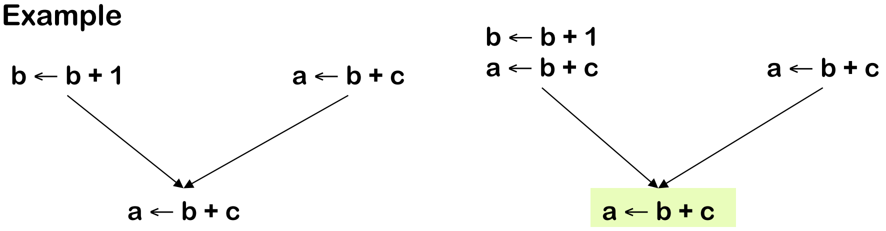
b ← b + 1
a ← b + c

Some occurrences of b+c are redundant

Partially Redundant Expression

An expression is partially redundant at *p* if it is redundant along some, but not all, paths reaching *p*

Example



Inserting a copy of "a ← b + c" after the definition of b can make it redundant

fully redundant?

Loop Invariant Expression

Another example

b+c is partially redundant here

Loop invariant expressions are partially redundant

- Partial redundancy elimination performs code motion
- Major part of the work is figuring out where to insert operations

Lazy Code Motion

The concept

- Solve data-flow problems that show opportunities & limits
- Compute INSERT & DELETE sets from solutions
- Linear pass over the code to rewrite it (using INSERT & DELETE)

The history

- Partial redundancy elimination (Morel & Renvoise, CACM, 1979)
- Improvements by Drechsler & Stadel, Joshi & Dhamdhere, Chow, Knoop, Ruthing & Steffen, Dhamdhere, Sorkin, …
- All versions of PRE optimize placement
  - Guarantee that no path is lengthened
- LCM was invented by Knoop et al. in PLDI, 1992
- We will look at a variation by Drechsler & Stadel
  - SIGPLAN Notices 28(5), May 1993

PRE and its descendants are conservative

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The intuitions

- Compute *__available expressions__*
- Compute *__anticipable expressions__*
- From AVAIL & Ant, we can compute an earliest placement for each expression
- Push expressions down the CFG until it changes behavior

LCM operates on expressions

It moves expression evaluations, not assignments

Assumptions

- Uses a lexical notion of identity (*not value identity*)
- ILOC-style code with unlimited name space
- Consistent, disciplined use of names
  - Identical expressions define the same name
  - No other expression defines that name

} Avoids copies

Result serves as proxy

Digression in Chapter 5 of EAC: “The impact of naming”

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The Name Space

- $r_i + r_j \rightarrow r_k$, always, with both $i < k$ and $j < k$ (*hash to find k*)
- We can refer to $r_i + r_j$ by r_k (*bit-vector sets*)
- Variables must be set by copies
  - No consistent definition for a variable
  - Break the rule for this case, but require $r_{source} < r_{destination}$
  - To achieve this, assign register names to variables first

Without this name space

- LCM must insert copies to preserve redundant values
- LCM must compute its own map of expressions to unique ids

LCM operates on expressions

It moves expression evaluations, not assignments

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Local Predicates

- DEExpr(b) contains expressions defined in b that survive to the end of b *(downward exposed expressions)*

  $e \in$ DEExpr(b) $\Rightarrow$ evaluating e at the end of b produces the same value for e

- UEExpr(b) contains expressions defined in b that have upward exposed arguments (both args) *(upward exposed expressions)*

  $e \in$ UEExpr(b) $\Rightarrow$ evaluating e at the start of b produces the same value for e

- ExprKill(b) contains those expressions that have one or more arguments defined (*killed*) in b *(killed expressions)*

  $e \notin$ ExprKill(b) $\Rightarrow$ evaluating e produces the same result at the start and end of b

We have seen all three of these previously.

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Availability

$$\text{AVAILIN}(n) = \bigcap_{m \in preds(n)} \text{AVAILOUT}(m), \qquad n \neq n_0$$

$$\text{AVAILOUT}(m) = \text{DEEXPR}(m) \cup (\text{AVAILIN}(m) \cap \overline{\text{EXPRKILL}(m)})$$

Initialize AVAILIN(n) to the set of all names, except at n_0

Set AVAILIN(n_0) to Ø

Interpreting AVAIL

- e $\in$ AVAILOUT(b) $\Leftrightarrow$ evaluating e at end of b produces the same value for e. AVAILOUT tells the compiler how far forward e can move
- This differs from the way we *talk* about AVAIL in global redundancy elimination; the equations, however, are unchanged.

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Anticipability is identical to VeryBusy expressions

Anticipability

$$\text{ANTOUT}(n) = \bigcap_{m \in succs(n)} \text{ANTIN}(m), \qquad n \text{ not an exit block}$$

$$\text{ANTIN}(m) = \text{UEEXPR}(m) \cup (\text{ANTOUT}(m) \cap \overline{\text{EXPRKILL}(m)})$$

Initialize ANTOUT(n) to the set of all names, except at exit blocks

Set ANTOUT(n) to Ø, for each exit block n

Interpreting ANTOUT

- e $\in$ ANTIN(b) $\Leftrightarrow$ evaluating e at start of b produces the same value for e. ANTIN tells the compiler how far backward e can move
- This view shows that anticipability is, in some sense, the inverse of availablilty (& explains the new interpretation of AVAIL)

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The intuitions

Available expressions

- $e \in \text{AVAILOUT}(b) \Rightarrow$ evaluating e at exit of b gives same result
- $e \in \text{AVAILIN}(b) \Rightarrow$ e is available from every predecessor of b

  ⇒ an evaluation at entry of b is redundant

Anticipable expressions

- $e \in \text{ANTIN}(b) \Rightarrow$ evaluating e at entry of b gives same result
- $e \in \text{ANTOUT}(b) \Rightarrow$ e is anticipable from every successor of b

  ⇒ evaluation at exit of b would a later evaluation redundant, on every path, so exit of b is a profitable place to insert e

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Earliest placement on an edge

$$\text{EARLIEST}(i,j) = \text{ANTIN}(j) \cap \overline{\text{AVAILOUT}(i)} \cap (\text{EXPRKILL}(i) \cup \overline{\text{ANTOUT}(i)})$$

Can move e to head of j & it is not redundant from i

and

Either killed in i or would not be busy at exit of i

$$\text{EARLIEST}(n_0,j) = \text{ANTIN}(j) \cap \overline{\text{AVAILOUT}(n_0)}$$

⇒ insert e on the edge

EARLIEST is a predicate

- Computed for edges rather than nodes (*placement*)
- $e \in$ EARLIEST(i,j) if
  - It can move to head of j, (ANTIN(j))
  - It is not available at the end of i and (EXPRKILL(i))
  - either it cannot move to the head of i or another edge leaving i prevents its placement in i ($\overline{\text{ANTOUT}(i)}$)

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Later (than earliest) placement

$$\text{LATERIN}(j) = \cap_{i \in pred(j)} \text{LATER}(i,j), \qquad j \neq n_0$$

$$\text{LATER}(i,j) = \text{EARLIEST}(i,j) \cup (\text{LATERIN}(i) \cap \overline{\text{UEEXPR}(i)})$$

Initialize LATERIN(n_0) to Ø

x ∈ LATERIN(k) ⇔ every path that reaches k has x ∈ EARLIEST(i,j) for some edge (i,j) leading to x, and the path from the entry of j to k is x-clear & does not evaluate x

⇒ the compiler can move x through k without losing any benefit

x ∈ LATER(i,j) ⇔ <i,j> is its earliest placement, or it can be moved forward from i (LATER(i)) and placement at entry to i does not anticipate a use in i (*moving it across the edge exposes that use*)

Propagate forward until a block kills it (U$\overline{\text{UEXPR}}$)

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Rewriting the code

$$\text{INSERT}(i,j) = \text{LATER}(i,j) \cap \overline{\text{LATERIN}(j)}$$

Can go on the edge but not in j ⇒ no later placement

$$\text{DELETE}(k) = \text{UEEXPR}(k) \cap \overline{\text{LATERIN}(k)}, \; k \neq n_0$$

Upward exposed (so we will cover it) & not an evaluation that might be used later

INSERT & DELETE are predicates

Compiler uses them to guide the rewrite step

- x ∈ INSERT(i,j) ⇒ insert x at start of j, end of i, or new block
- x ∈ DELETE(k) ⇒ delete first evaluation of x in k

If local redundancy elimination has already been performed, only one copy of x exists. Otherwise, remove all upward exposed copies of x

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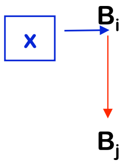
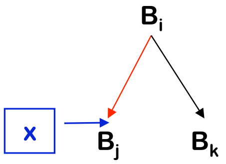
Edge placement

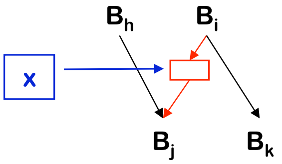
- $x \in$ INSERT(i,j)



|*succs*(i)| = 1



|*preds*(j)| = 1



|*succs*(i) > 1

|*preds*(j)| > 1

A "Critical" Edge

Three cases

- |*succs*(i)| = 1 ⇒ insert at end of i
- | *succs*(i)| > 1, but |*preds*(j)| = 1⇒ insert at start of j
- | *succs*(i)| > 1, & |*preds*(j)| > 1 ⇒ create new block in <i,j> for x

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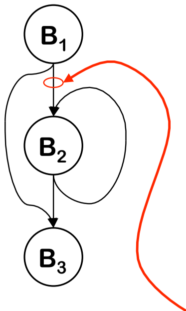
Example

B_1: $r_1 \leftarrow 1$
$r_2 \leftarrow r_0 + @m$
if $r_1 < r_2 \rightarrow B_2, B_3$
B_2: …
$r_{20} \leftarrow r_{17} * r_{18}$
…
$r_4 \leftarrow r_1 + 1$
$r_1 \leftarrow r_4$
if $r_1 < r_2 \rightarrow B_2, B_3$
B_3: …



	B1	B2
DEEXPR	r1,r2	r1,r4,r20
UEEXPR	r1,r2	r4,r20
NotKilled	r17,r18,r20	r2,r17,r18,r20

	B1	B2
AvailIn	r17,r18	r1,r2,r17,r18
AvailOut	r1,r2,r17,r18	r1,r2,r4,r17,r18,r20
AntIn	{ }	r20
AntOut	{ }	{ }

	1,2	1,3	2,2	2,3
Earliest	r20	{ }	{ }	{ }

Critical edge rule will create landing pad when needed, as on edge (B_1,B_2)

Example is too small to show off Later
Insert(1,2) = { r_{20} }
Delete(2) = { r_{20} }