CSE P 501 – Compilers

Data-flow Analysis

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Agenda

- Initial example: data-flow analysis for common subexpression elimination
- Other analysis problems that work in the same framework

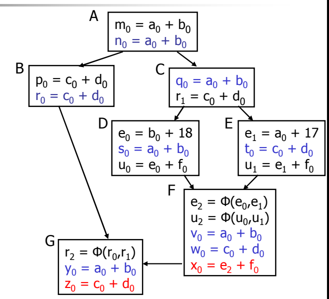
- Credits: Largely based on Keith Cooper's slides from Rice University

The Story So Far…

- Redundant expression elimination
  - Local Value Numbering
  - Superlocal Value Numbering
    - Extends VN to EBBs
    - SSA-like namespace
  - Dominator VN Technique (DVNT)
- All of these propagate along forward edges
- None are global
  - In particular, can't handle back edges (loops)

Dominator Value Numbering

- Most sophisticated algorithm so far
- Still misses some opportunities
- Can't handle loops



Available Expressions

- Goal: use data-flow analysis to find common subexpressions whose range spans basic blocks
- Idea: calculate *available expressions* at beginning of each basic block
- Avoid re-evaluation of an available expression – use a copy operation

"Available" and Other Terms

- An expression *e* is *defined* at point *p* in the CFG if its value is computed at *p*
  - Sometimes called *definition site*
- An expression *e* is *killed* at point *p* if one of its operands is defined at *p*
  - Sometimes called *kill site*
- An expression *e* is *available* at point *p* if every path leading to *p* contains a prior definition of *e* and *e* is not killed between that definition and *p*

Available Expression Sets

- For each block *b*, define
  - AVAIL(b) – the set of expressions available on entry to *b*
  - NKILL(b) – the set of expressions <u>not killed</u> in *b*
  - DEF(b) – the set of expressions defined in *b* and not subsequently killed in *b*

Computing Available Expressions

- AVAIL(b) is the set

  $$\text{AVAIL(b)} = \cap_{x \in \text{preds(b)}} (\text{DEF(x)} \cup (\text{AVAIL(x)} \cap \text{NKILL(x)}))$$

  - preds(b) is the set of b's predecessors in the control flow graph
- This gives a system of simultaneous equations – a data-flow problem

Name Space Issues

- In previous value-numbering algorithms, we used a SSA-like renaming to keep track of versions
- In global data-flow problems, we use the original namespace
  - The KILL information captures when a value is no longer available

GCSE with Available Expressions

- For each block b, compute DEF(b) and NKILL(b)
- For each block b, compute AVAIL(b)
- For each block b, value number the block starting with AVAIL(b)
- Replace expressions in AVAIL(b) with references

Replacement Issues

- Need a unique name for each expression in AVAIL(b)
- Several possibilities; all workable

Global CSE Replacement

- After analysis and before transformation, assign a global name to each expression *e* by hashing on *e*
- During transformation step
  - At each evaluation of *e*, insert copy
    name(*e*) = *e*
  - At each reference to *e*, replace *e* with *name*(*e*)

Analysis

- Main problem – inserts extraneous copies at all definitions and uses of every *e* that appears in any AVAIL(b)
  - But the extra copies are dead and easy to remove
  - Useful copies often coalesce away when registers and temporaries are assigned
- Common strategy
  - Insert copies that might be useful
  - Let dead code elimination sort it out later

Computing Available Expressions

- Big Picture
  - Build control-flow graph
  - Calculate initial local data – DEF(b) and NKILL(b)
    - This only needs to be done once
  - Iteratively calculate AVAIL(b) by repeatedly evaluating equations until nothing changes
    - Another fixed-point algorithm

Computing DEF and NKILL (1)

- For each block *b* with operations $o_1, o_2, \ldots, o_k$

```
KILLED = ∅
DEF(b) = ∅
for i = k to 1
   assume o_i is "x = y + z"
   if (y ∉ KILLED and z ∉ KILLED)
      add "y + z" to DEF(b)
   add x to KILLED
…
```


Computing DEF and NKILL (2)

- After computing DEF and KILLED for a block b,

```
NKILL(b) = { all expressions }
for each expression e
   for each variable v ∈ e
      if v ∈ KILLED then
         NKILL(b) = NKILL(b) - e
```

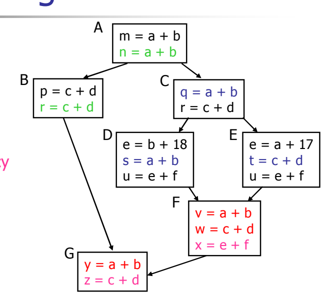

Computing Available Expressions

- Once DEF(b) and NKILL(b) are computed for all blocks b

```
Worklist = { all blocks b_i }
while (Worklist ≠ ∅)
   remove a block b from Worklist
   recompute AVAIL(b)
   if AVAIL(b) changed
      Worklist = Worklist ∪ successors(b)
```


Comparing Algorithms

- LVN – Local Value Numbering
- SVN – Superlocal Value Numbering
- DVN – Dominator-based Value Numbering
- GRE – Global Redundancy Elimination



Comparing Algorithms (2)

- LVN => SVN => DVN form a strict hierarchy – later algorithms find a superset of previous information
- Global RE finds a somewhat different set
  - Discovers e+f in F (computed in both D and E)
  - Misses identical values if they have different names (e.g., a+b and c+d when a=c and b=d)
    - Value Numbering catches this

Data-flow Analysis (1)

- A collection of techniques for compile-time reasoning about run-time values
- Almost always involves building a graph
  - Trivial for basic blocks
  - Control-flow graph or derivative for global problems
  - Call graph or derivative for whole-program problems

Data-flow Analysis (2)

- Usually formulated as a set of *simultaneous equations* (data-flow problem)
  - Sets attached to nodes and edges
  - Need a lattice (or semilattice) to describe values
    - In particular, has an appropriate operator to combine values and an appropriate "bottom" or minimal value

Data-flow Analysis (3)

- Desired solution is usually a *meet over all paths* (MOP) solution
  - "What is true on every path from entry"
  - "What can happen on any path from entry"
  - Usually relates to safety of optimization

Data-flow Analysis (4)

- Limitations
  - Precision – "up to symbolic execution"
    - Assumes all paths taken
  - Sometimes cannot afford to compute full solution
  - Arrays – classic analysis treats each array as a single fact
  - Pointers – difficult, expensive to analyze
    - Imprecision rapidly adds up
- Summary: for scalar values we can quickly solve simple problems

Scope of Analysis

- Larger context (EBBs, regions, global, interprocedural) sometimes helps
  - More opportunities for optimizations
- But not always
  - Introduces uncertainties about flow of control
  - Usually only allows weaker analysis
  - Sometimes has unwanted side effects
    - Can create additional pressure on registers, for example

Some Problems (1)

- Merge points often cause loss of information
  - Sometimes worthwhile to clone the code at the merge points to yield two straight-line sequences

Some Problems (2)

- Procedure/function/method calls are problematic
  - Have to assume anything could happen, which kills local assumptions
  - Calling sequence and register conventions are often more general than needed
- One technique – inline substitution
  - Allows caller and called code to be analyzed together; more precise information
  - Can eliminate overhead of function call, parameter passing, register save/restore
  - But… Creates dependency in compiled code on specific version of procedure definition – need to avoid trouble (inconsistencies) if (when?) the definition changes.

Other Data-Flow Problems

- The basic data-flow analysis framework can be applied to many other problems beyond redundant expressions
- Different kinds of analysis enable different optimizations

Characterizing Data-flow Analysis

- All of these involve sets of facts about each basic block b
  - IN(b) – facts true on entry to b
  - OUT(b) – facts true on exit from b
  - GEN(b) – facts created and not killed in b
  - KILL(b) – facts killed in b
- These are related by the equation

  $OUT(b) = GEN(b) \cup (IN(b) - KILL(b))$
  - Solve this iteratively for all blocks
  - Sometimes information propagates forward; sometimes backward

Efficiency of Data-flow Analysis

- The algorithms eventually terminate, but the expected time needed can be reduced by picking a good order to visit nodes in the CFG
  - Forward problems – reverse postorder
  - Backward problems - postorder

Example:Live Variable Analysis

- A variable *v* is *live* at point *p* iff there is *any* path from *p* to a use of *v* along which *v* is not redefined
- Uses
  - Register allocation – only live variables need a register (or temporary)
  - Eliminating useless stores
  - Detecting uses of uninitialized variables
  - Improve SSA construction – only need Φ-function for variables that are live in a block

Equations for Live Variables

- Sets
  - USED(b) – variables used in b before being defined in b
  - NOTDEF(b) – variables not defined in b
  - LIVE(b) – variables live on *exit* from b
- Equation

  LIVE(b) = $\cup_{s \in succ(b)}$ USED(s) $\cup$ (LIVE(s) $\cap$ NOTDEF(s))

Example: Available Expressions

- This is the analysis we did earlier to eliminate redundant expression evaluation (i.e., compute AVAIL(b))

Example: Reaching Definitions

- A definition *d* of some variable *v* *reaches* operation *i* iff *i* reads the value of *v* and there is a path from *d* to *i* that does not define *v*
- Uses
  - Find all of the possible definition points for a variable in an expression

Equations for Reaching Definitions

- Sets
  - DEFOUT(b) – set of definitions in b that reach the end of b (i.e., not subsequently redefined in b)
  - SURVIVED(b) – set of all definitions not obscured by a definition in b
  - REACHES(b) – set of definitions that reach b
- Equation

  REACHES(b) = $\cup_{p \in preds(b)}$ DEFOUT(p) $\cup$ (REACHES(p) $\cap$ SURVIVED(p))

Example: Very Busy Expressions

- An expression *e* is considered *very busy* at some point *p* if *e* is evaluated and used along every path that leaves *p*, and evaluating *e* at *p* would produce the same result as evaluating it at the original locations
- Uses
  - Code hoisting – move *e* to *p* (reduces code size; no effect on execution time)

Equations for Very Busy Expressions

- Sets
  - USED(b) – expressions used in b before they are killed
  - KILLED(b) – expressions redefined in b before they are used
  - VERYBUSY(b) – expressions very busy on exit from b
- Equation

  VERYBUSY(b) = $\cap_{s \in succ(b)}$ USED(s) $\cup$ (VERYBUSY(s) - KILLED(s))

Summary

- Dataflow analysis gives a framework for finding global information
- Key to enabling most optimizing transformations