CSE 401 – Compilers

Dataflow Analysis

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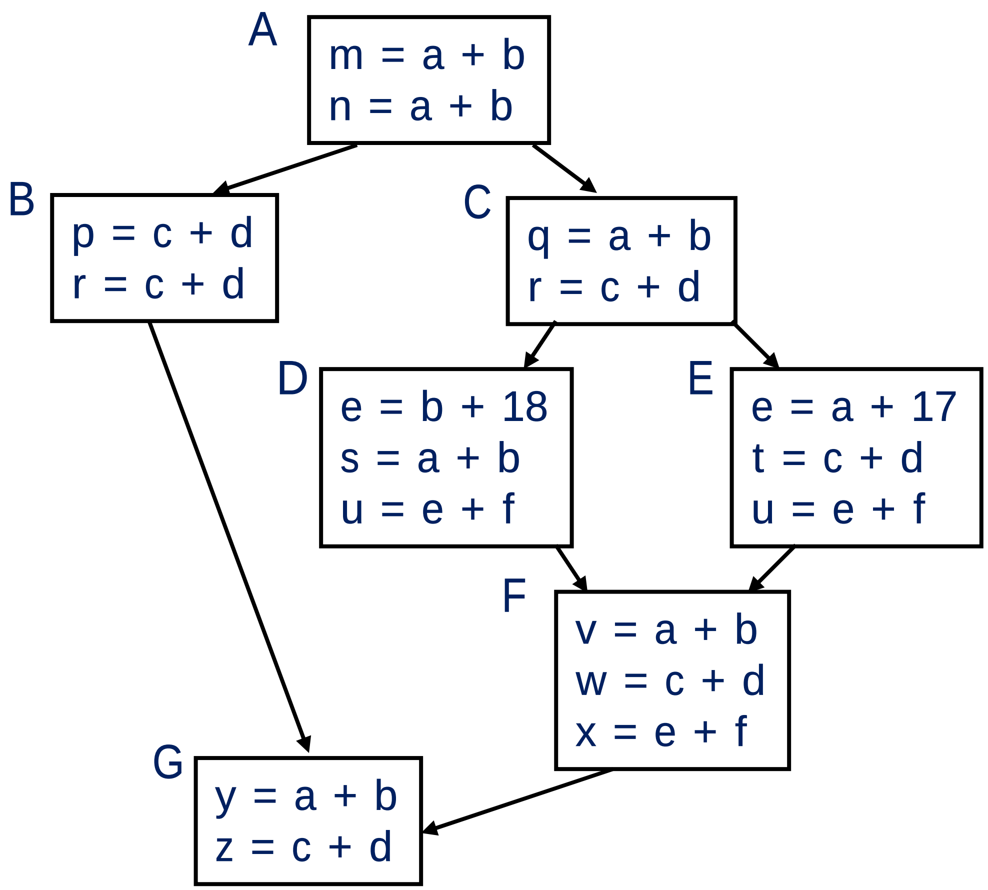
Agenda

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

Available Expressions

- Goal: use dataflow analysis to find common subexpressions
- Idea: calculate *available expressions* at beginning of each basic block
- Avoid re-evaluation of an available expression – use a copy operation
  - Simple inside a single block; more complex dataflow analysis used across bocks



"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

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

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

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 $o_1, o_2, \ldots, o_k$

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KILLED = ∅
DEF(b) = ∅
for i = k to 1
    assume oi 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 $v \in$ e

          if $v \in$ 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 $\neq \emptyset$)

remove a block b from Worklist

recompute AVAIL(b)

if AVAIL(b) changed

Worklist = Worklist $\cup$ successors(b)

Dataflow analysis

- Available expressions are an example of a *dataflow analysis* problem
- Many similar problems can be expressed in a similar framework
- Only the first part of the story – once we've discovered facts, we then need to use them to improve code

Characterizing Dataflow Analysis

- All of these algorithms 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 Dataflow 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: Available Expressions

- This is the analysis we did to detect redundant expression evaluation
- Equation:

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

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

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

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

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

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

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

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

And so forth...

- General framework for discovering facts about programs
  - Although not the only possible story
- And then: facts open opportunities for code improvement

- To be continued...
  - CSE 501!