CSE P 501 – Compilers

Dataflow Analysis

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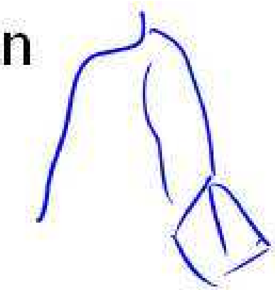
Agenda

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

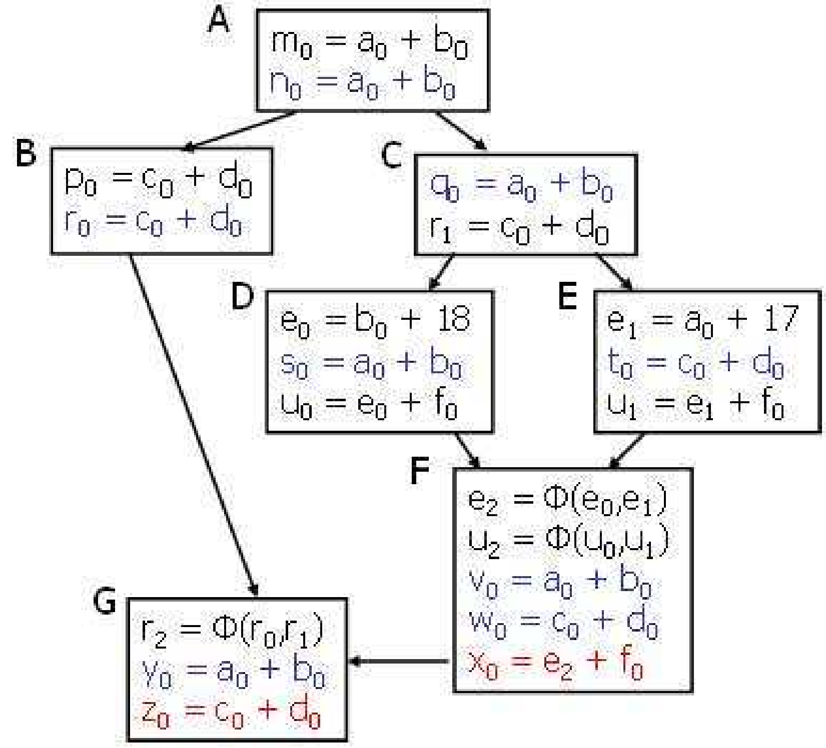
The Story So Far…

- 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)

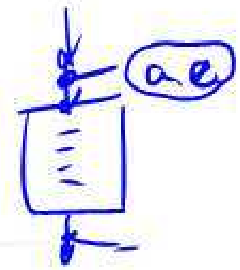


Dominator Value Numbering

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

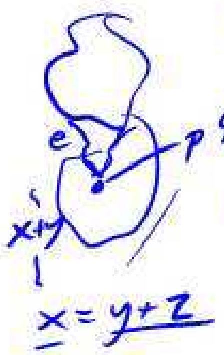


Available Expressions



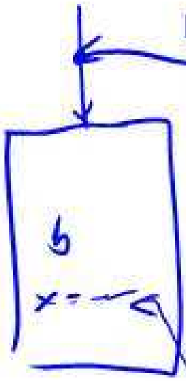
- Goal: use dataflow analysis to find common subexpressions whose range spans basic blocks
- Idea: calculate *available expressions* at beginning of each basic block
- Avoid re-evaluation of an available expression – use a copy operation

"Available" and Other Terms



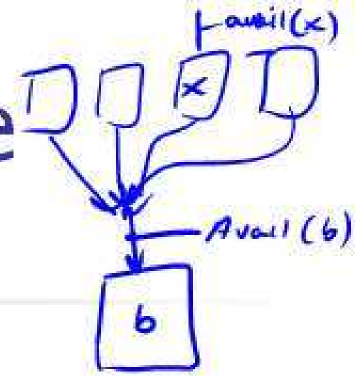
- An expression *e* is *defined* at point *p* in the CFG if its value is computed at *p*
  - Sometimes called *definition site*
- An expression *e* is *killed* at point *p* if one of its operands is defined at *p*
  - Sometimes called *kill site*
- An expression *e* is *available* at point *p* if every 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

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

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

Name Space Issues

- In previous value-numbering algorithms, we used a SSA-like renaming to keep track of versions
- In global dataflow 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 to the previously computed values

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 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)

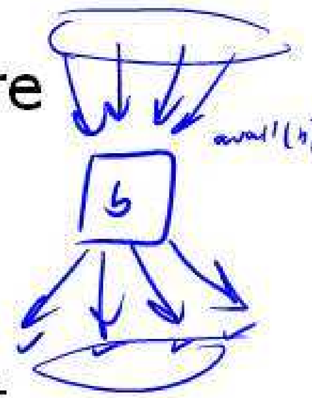
- After computing DEF and KILLED for a block b,

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

Computing Available Expressions

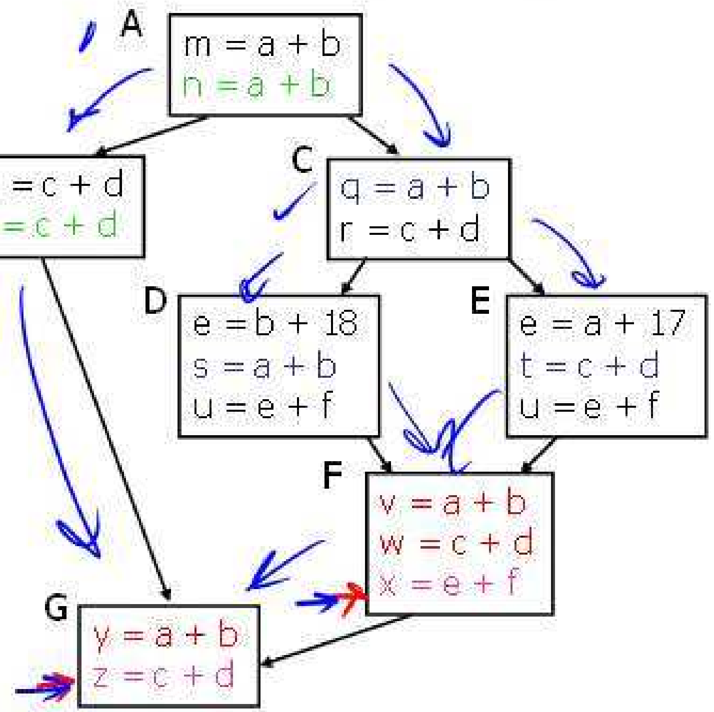
- Once DEF(b) and NKILL(b) are computed for all blocks b

```
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

$a^3 + b^6 \qquad c^3 + d^6$

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

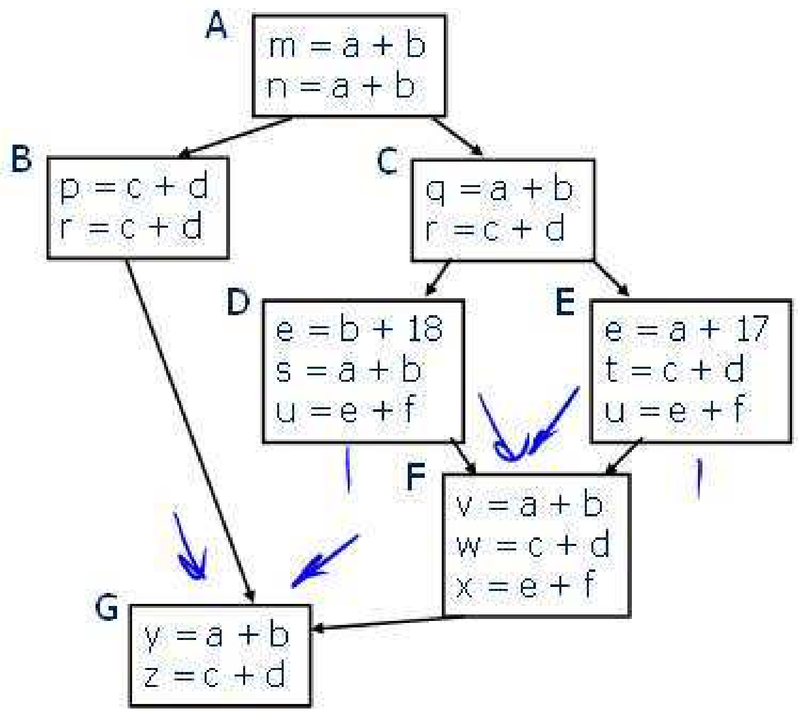
Code Replication

- Sometimes replicating code increases opportunities – modify the code to create larger regions with simple control flow
- Two examples
  - Cloning
  - Inline substitution

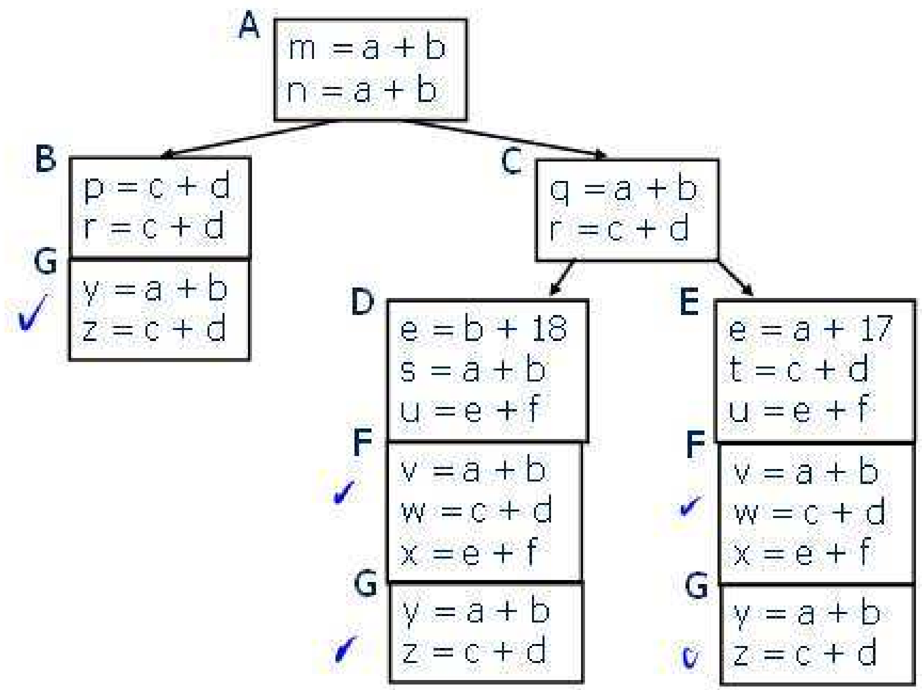
Cloning

- Idea: duplicate blocks with multiple predecessors
- Tradeoff
  - More local optimization possibilities – larger blocks, fewer branches
  - But: larger code size, may slow down if it interacts badly with cache

Original VN Example



Example with cloning



Inline Substitution

- Problem: an optimizer has to treat a procedure call as if it (could have) modified all globally reachable data
  - Plus there is the basic expense of calling the procedure
- Inline Substitution: replace each call site with a copy of the called function body

Inline Substitution Issues

- Pro
  - More effective optimization – better local context and don't need to invalidate local assumptions
  - Eliminate overhead of normal function call
- Con
  - Potential code bloat
  - Need to manage recompilation when either caller or callee changes

Dataflow analysis

- Global redundancy elimination is the first 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

Dataflow 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

Dataflow Analysis (2)

- Usually formulated as a set of *simultaneous equations* (dataflow 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

$p \equiv q$

Dataflow 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

Dataflow 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
- For scalar values we can quickly solve simple problems

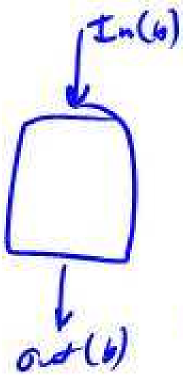
a[i] = 17
= a[j]

Example: Available Expressions

- This is the analysis we did earlier to eliminate redundant expression evaluations
- Equation:

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

Characterizing Dataflow Analysis

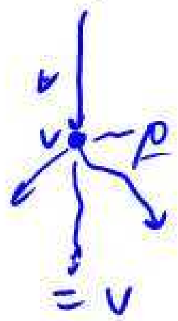


- All of these algorithms involve sets of facts about each basic block b
  - IN(b) – facts true on entry to b
  - OUT(b) – facts true on exit from b
  - GEN(b) – facts created and not killed in b
  - KILL(b) – facts killed in b
- These are related by the equation

  $$OUT(b) = GEN(b) \cup (IN(b) - KILL(b))$$

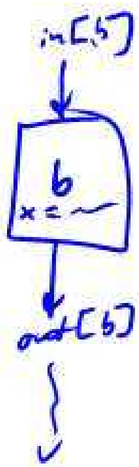
  - Solve this iteratively for all blocks
  - Sometimes information propagates forward; sometimes backward

Example: Live Variable Analysis



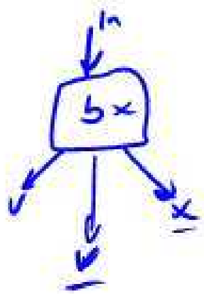
- A variable *v* is *live* at point *p* iff there is *any* path from *p* to a use of *v* along which *v* is not redefined
- Uses
  - Register allocation – only live variables need a register (or temporary)
  - Eliminating useless stores
  - Detecting uses of uninitialized variables
  - Improve SSA construction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

Liveness Analysis Sets



- For each block b, define
  - use[b] = variable used in b before any def
  - def[b] = variable defined in b & not killed
  - in[b] = variables live on entry to b
  - out[b] = variables live on exit from b

Equations for Live Variables



- Given the preceding definitions, we have
  - $in[b] = use[b] \cup (out[b] - def[b])$
  - $out[b] = \cup_{s \in succ[b]} in[s]$
- Algorithm
  - Set $in[b] = out[b] = \emptyset$
  - Update in, out until no change

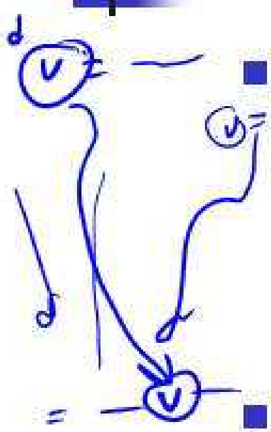
Equations for Live Variables v2

- Many problems have more than one formulation. For example, 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

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

Example: Reaching Definitions



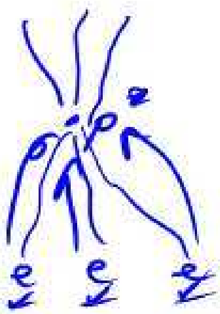
- A definition *d* of some variable *v* *reaches* operation *i* iff *i* reads the value of *v* and there is a path from *d* to *i* that does not define *v*
- Uses
  - Find all of the possible definition points for a variable in an expression

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

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

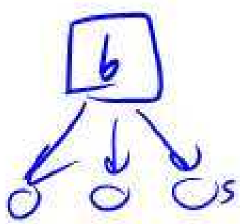
Example: Very Busy Expressions



- 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

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

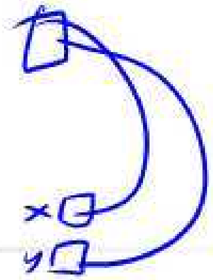
Efficiency of Dataflow Analysis

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

$f(t,t)$

Aliases

$f(x,y)$



- A variable or memory location may have multiple names or *aliases*
  - Call-by-reference parameters
  - Variables whose address is taken (&x)
  - Expressions that dereference pointers (p.x, *p)
  - Expressions involving subscripts (a[i])
  - Variables in nested scopes

*p = 10 — *p

Aliases vs Optimizations

- Example:

  p.x := 5; q.x := 7; a := p.x;

  5

  - Does reaching definition analysis show that the definition of p.x reaches a?
  - (Or: do p and q refer to the same variable/object?)
  - (Or: *can* p and q refer to the same thing?)

Aliases vs Optimizations

- Example

```
void f(int *p, int *q) {
  *p = 1; *q = 2;
  return *p;
}
```

  - How do we account for the possibility that p and q might refer to the same thing?
  - Safe approximation: since it's possible, assume it is true (but rules out a lot)

Types and Aliases (1)

int *p
struct ~ *q

- In Java, ML, MiniJava, and others, if two variables have incompatible types they cannot be names for the same location
  - Also helps that programmer cannot create arbitrary pointers to storage in these languages

Types and Aliases (2)

- Strategy: Divide memory locations into *alias classes* based on type information (every type, array, record field is a class)
- Implication: need to propagate type information from the semantics pass to optimizer
  - Not normally true of a minimally typed IR
- Items in different alias classes cannot refer to each other

p = malloc(—)
s
q = p

Aliases and Flow Analysis

- Idea: Base alias classes on points where a value is created
  - Every new/malloc and each local or global variable whose address is taken is an alias class
  - Pointers can refer to values in multiple alias classes (so each memory reference is to a set of alias classes)
  - Use to calculate "may alias" information (e.g., p "may alias" q at program point s)

Using “may-alias” information

- Treat each alias class as a “variable” in dataflow analysis problems
- Example: framework for available expressions
  - Given statement s: M[a]:=b,
    - gen[s] = { }
    - kill[s] = { M[x] | a may alias x at s }

May-Alias Analysis

- Without alias analysis, #2 kills M[t] since x and t might be related
- If analysis determines that "x may-alias t" is false, M[t] is still available at #3; can eliminate the common subexpression and use copy propagation

- Code

```
1: u := M[t]
2: M[x] := r
3: w := M[t]
4: b := u+w
```

And so forth…

- We now have machinery for discovering some interesting facts.
- Next: what can we do with that information?