RICE

COMP 412
FALL 2010

Code Optimization, Part III
Global Methods

Comp 412

The Story So Far …

Introduced scope of optimization

- Local — a single basic block
- Regional — a subset of the blocks in a procedure
- Global — an entire procedure — Intraprocedural
- Whole Program — multiple procedures — Interprocedural

Some example optimizations

- Local Value Numbering
- Superlocal Value Numbering
- Loop Unrolling
- Data-analysis & an application
- Procedure Placement

Finding Uninitialized Variables

We can use global data-flow analysis to find variables that might be used before they are ever defined

A variable v is live at point p iff ∃ a path in the CFG from p to a use of v along which v is not redefined.

Any variable that is live in the entry block of a procedure may be used before it is defined

- Represents a potential logic error in the code
- Compiler should discover and report this condition

We are looking at this issue because it gives us an opportunity to introduce the computation of *liveness*

- Compiler builds a CFG and computes LIVEOUT(*n*) ∀ node *n*
- LIVEOUT is a classic problem in data-flow analysis

Data-flow analysis is a form of compile-time reasoning about the runtime flow of values.

Live Variables

Data-flow problems are expressed with a set of simultaneous equations over sets associated with nodes in a graph

$$\mathrm{LIVEOUT}(n_f) = \emptyset$$

$$\mathrm{LIVEOUT}(n) = \bigcup_{m \in succ(n)} (\mathrm{UEVAR}(m) \cup (\mathrm{LIVEOUT}(m) \cap \overline{\mathrm{VARKILL}(m)}))$$

Where

- UEVAR(n) is the set of names used before being defined in the block that corresponds to node n in the CFG
- VARKILL(n) is the set of names defined in the block that corresponds to node n in the CFG

These equations annotate each CFG node n with a LIVEOUT set

Live Variables

To compute live information for a procedure

- Build the CFG
- Compute UEVAR and VARKILL sets
- Use an iterative fixed-point solver to compute LiveOut sets

N ← number of blocks

for i = 0 to N-1
*   LIVEOUT(i) ← Ø*

changed ← true

while(changed)

*   changed ← false*

*   for i ← 0 to N-1*

*   recompute LIVEOUT(i)*

*   if LIVEOUT(i) changed*
*   then changed ← true*

Iterative fixed-point solver

- LIVEOUT ⊆ 2^{Names}
- UEVAR, VARKILL are constants
- Equation is monotone increasing
- Finite sets + monotone equations ⇒ algorithm must halt

Theory of data-flow analysis assures us that this equation has a unique fixed point solution

In EaC1e, see § 9.2.1; in EaC2e, see § 8.6.1

Live Variables

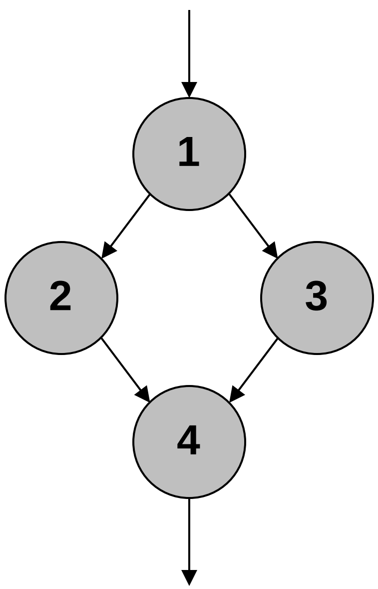
A couple more points

- Can use LIVEOUT sets to find uninitialized variables
  - $x \in$ LIVEOUT(n_0) means x is uninitialized at some use
- Can use LIVEOUT sets to eliminate unnecessary stores
  - Build LIVE at each operation
  - $x \notin$ Live at a store means that the value is never reloaded
- The LIVEOUT equations have a unique fixed-point solution
  - ⇒ *The algorithm finds a fixed-point solution; since the fixed-point solution is unique, it finds the correct solution*
- Order of computation determines speed of convergence
  - ⇒ *Choose an order that reaches fixed point quickly*

Data-Flow Analysis

The order of computation affects speed of convergence

- Live is a backward data-flow problem
  - Sets for node *n* are computed from sets at *n's* CFG *successors*



Example CFG

LIVEOUT(1) is computed from LIVEOUT(2) and LIVEOUT(3), which depend on LIVEOUT(4)

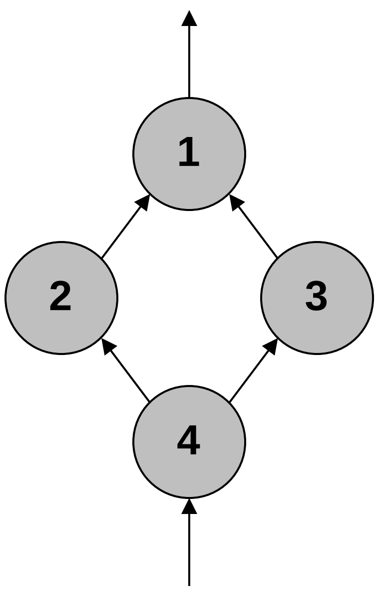
- Solver should visit 2 & 3 before 1
- Solver should visit 4 before 2 & 3
- Update as many "sources" as possible before visiting a given node

General idea is to let a change in the LiveOut set flow as far in the CFG as it can in a single "pass" of the while loop

Data-Flow Analysis

Code optimization is intimately tied to graph theory

- LIVEOUT is computed, conceptually, on the reverse CFG
- Order for solver is defined by the reverse CFG



Reverse CFG

Propagation Order for Backward Problem

- Want to visit 4, then {2,3}, then 1
- PostOrder of RCFG would be 1, {2, 3}, 4
- Desired order is reverse of postorder
  - → RPO(i) = |N| + 1 - PO(i)
- Reverse PostOrder would be 4, {3, 2}, 1
  - → We don't care about order of 2 & 3

Forward problem ⇒ RPO on the CFG
Backward problem ⇒ RPO on the reverse CFG
RPO on RFG is not reverse preorder on CFG

Recap of Live Variables

Define the problem

A variable v is live at point p iff ∃ a path in the CFG from p to a use of v along which v is not redefined.

Solve the equations for LIVEOUT

$$\text{LIVEOUT}(n_f) = \emptyset$$

$$\text{LIVEOUT}(n) = \bigcup_{m \in succ(n)} (\text{UEVAR}(m) \cup (\text{LIVEOUT}(m) \cap \overline{\text{VARKILL}(m)}))$$

Use an iterative fixed-point solver

- Theory guarantees unique solution to this problem
- Choose an order that produces efficient solution

Use the sets to identify uninitialized variables, or to eliminate useless stores, or to find live ranges, or to …

EaC1e has material on Live in § 9.2

Chapter 9 of EaC contains more examples of data-flow problems