Dead Code Elimination & Constant Propagation on SSA Form

Slides mostly based on Keith Cooper's set of slides (COMP 512 class at Rice University, Fall 2002). Used with kind permission.

Dead Code Elimination on SSA Form

Dead code elimination

- Conceptually similar to mark-sweep garbage collection
  - Mark *useful* operations
  - Everything not marked is useless
- Need an efficient way to find and to mark useful operations
  - Start with critical operations
  - Work back up SSA edges to find their antecedents

Operations defined as critical

- I/O statements, linkage code (*entry & exit blocks*), return values, calls to other procedures

Algorithm will use post-dominators & reverse dominance frontiers

Dead Code Elimination on SSA Form

```
Mark
  for each op i
    clear i's mark
    if i is critical then
      mark i
      add i to WorkList
  while (Worklist ≠ Ø)
    remove i from WorkList
      (i has form "x←y op z")
    if def(y) is not marked then
      mark def(y)
      add def(y) to WorkList
    if def(z) is not marked then
      mark def(z)
      add def(z) to WorkList
    for each b ∈ RDF(block(i))
      mark the block-ending
        branch in b
      add it to WorkList
```

```
Sweep
  for each op i
    if i is not marked then
      if i is a branch then
        rewrite with a jump to
          i's nearest useful
          post-dominator
      if i is not a jump then
        delete i
```

Notes:

- Eliminates some branches
- Reconnects dead branches to the remaining live code
- Find useful post-dominator by walking post-dominator tree
  - Entry & exit nodes are useful

Useless Control Flow Elimination

Handling Branches

- When is a branch useful?
  - When a useful operation depends on its existence

In the CFG, *j* is control dependent on *i* if

1. ∃ a non-null path *p* from *i* to *j* ∍ *j* post-dominates every node on *p* after *i*
2. *j* does not strictly post-dominate *i*

- *j* control dependent on *i* ⇒ one path from *i* leads to *j*, one doesn't
- This is the reverse dominance frontier of *j* (RDF(j))

Algorithm uses RDF(*n*) to mark branches as live

Dead Code Elimination on SSA Form

What's left?

- Algorithm eliminates useless definitions & some useless branches
- Algorithm leaves behind empty blocks & extraneous control-flow

Algorithm from: Cytron, Ferrante, Rosen, Wegman, & Zadeck, *Efficiently Computing Static Single Assignment Form and the Control Dependence Graph*, ACM TOPLAS 13(4), October 1991

with a correction due to Rob Shillner

Two more issues

- Simplifying control-flow
- Eliminating unreachable blocks

Both are CFG transformations (no need for SSA)

Constant Propagation

Safety

- Proves that name always has known value
- Specializes code around that value
  - Moves some computations to compile time (⇒ *code motion*)
  - Exposes some unreachable blocks (⇒ *dead code*)

Opportunity

- Value ≠ ⊥ signifies an opportunity

Profitability

- Compile-time evaluation is cheaper than run-time evaluation
- Branch removal may lead to block coalescing (CLEAN)
  - If not, it still avoids the test & makes branch predictable

Sparse Constant Propagation on SSA Form

$\forall$ expression, e
Value(e) $\leftarrow$ { TOP if its value is unknown; c_i if its value is known; BOT if its value is known to vary }
WorkList $\leftarrow \emptyset$

$\forall$ SSA edge s = <u,v>
 if Value(u) $\neq$ TOP then
  add s to WorkList

while (WorkList $\neq \emptyset$)
 remove s = <u,v> from WorkList
 let o be the operation that uses v
 if Value(o) $\neq$ BOT then
  t $\leftarrow$ result of evaluating o
  if t $\neq$ Value(o) then
   $\forall$ SSA edge <o,x>
    add <o,x> to WorkList

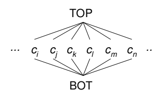
i.e., o is "a$\leftarrow$b op v" or "a $\leftarrow$v op b"

Evaluating a Φ-node:
$\Phi(x_1,x_2,x_3, \ldots x_n)$ is
 Value(x_1) $\wedge$Value(x_2) Value(x_3)
 $\wedge \ldots \wedge$ Value(x_n)
Where
 TOP $\wedge$ x = x $\forall$ x
 $c_i \wedge c_j = c_i$ if $c_i = c_j$
 $c_i \wedge c_j$ = BOT if $c_i \neq c_j$
 BOT $\wedge$ x = BOT $\forall$ x

Same result, fewer $\wedge$ operations
Performs $\wedge$ only at Φ nodes

Sparse Constant Propagation on SSA Form

How long does this algorithm take to halt?



- Initialization is two passes
  - |ops| + 2 x |ops| edges
- Value(x) can take on 3 values
  - TOP, c_i, BOT
  - Each use can be on WorkList twice
  - 2 x |args| = 4 x |ops| evaluations, WorkList pushes & pops

This is an optimistic algorithm:
- Initialize all values to TOP, unless they are known constants
- Every value becomes BOT or c_i, unless its use is uninitialized

Sparse Conditional Constant Propagation

Optimism

12 $i_0 \leftarrow 12$
  while (…)
TOP $i_1 \leftarrow \Phi(i_0,i_3)$
TOP $x \leftarrow i_1 * 17$
TOP $j \leftarrow i_1$
TOP $i_2 \leftarrow \ldots$
  …
TOP $i_3 \leftarrow j$

Optimistic initializations

Leads to:
 $i_1 \equiv 12 \wedge \text{TOP} \equiv 12$
 $x \equiv 12 * 17 \equiv 204$
 $j \equiv 12$
 $i_3 \equiv 12$
 $i_1 \equiv 12 \wedge 12 \equiv 12$

Optimism
- This version of the algorithm is an *optimistic* formulation
- Initializes values to TOP
- Prior version used $\perp$ (*implicit*)

In general
- Optimism helps inside loops
- Largely a matter of initial value

M.N. Wegman & F.K. Zadeck, Constant propagation with conditional branches, ACM TOPLAS, 13(2), April 1991, pages 181–210.

Sparse Conditional Constant Propagation

What happens when it propagates a value into a branch?
- TOP $\Rightarrow$ we gain no knowledge
- BOT $\Rightarrow$ either path can execute
- TRUE or FALSE $\Rightarrow$ only one path can execute

} But, the algorithm does not use this ...

Working this into the algorithm
- Use two worklists: SSAWorkList & CFGWorkList
  - SSAWorkList determines values
  - CFGWorkList governs reachability
- Don't propagate into operation until its block is reachable

Sparse Conditional Constant Propagation

SSAWorkList $\leftarrow \emptyset$
CFGWorkList $\leftarrow n_0$
$\forall$ block b
 clear b's mark
 $\forall$ expression e in b
  Value(e) $\leftarrow$ TOP

Initialization Step

To evaluate a branch
 if arg is BOT then
  put both targets on CFGWorklist
 else if arg is TRUE then
  put TRUE target on CFGWorkList
 else if arg is FALSE then
  put FALSE target on CFGWorkList
To evaluate a jump
 place its target on CFGWorkList

while ((CFGWorkList $\cup$ SSAWorkList) $\neq \emptyset$)
 while(CFGWorkList $\neq \emptyset$)
  remove b from CFGWorkList
  mark b
  evaluate each Φ-function in b
  evaluate each op in b, *in order*
 while(SSAWorkList $\neq \emptyset$)
  remove s = <u,v> from WorkList
  let o be the operation that contains v
  t $\leftarrow$ result of evaluating o
  if t $\neq$ Value(o) then
   Value(o) $\leftarrow$ t
   $\forall$ SSA edge <o,x>
    if x is marked, then
     add <o,x> to WorkList

Propagation Step

Sparse Conditional Constant Propagation

There are some subtle points
- Branch conditions should not be TOP when evaluated
  - Indicates an upwards-exposed use (*no initial value*)
  - Hard to envision compiler producing such code
- Initialize all operations to TOP
  - Block processing will fill in the non-top initial values
  - Unreachable paths contribute TOP to Φ-functions
- Code shows CFG edges first, then SSA edges
  - Can intermix them in arbitrary order (*correctness*)
  - Taking CFG edges first may help with speed (*minor effect*)

Sparse Conditional Constant Propagation

More subtle points

- TOP * BOT → TOP
  - If TOP becomes 0, then 0 * BOT → 0
  - This prevents non-monotonic behavior for the result value
  - Uses of the result value might go irretrievably to
  - Similar effects with any operation that has a "zero"
- Some values reveal simplifications, rather than constants
  - BOT * c_i → BOT, but might turn into shifts & adds (c_i = 2, BOT ≥ 0)
  - Removes commutativity (*reassociation*)
  - BOT**2 → BOT * BOT (*vs. series or call to library*)
- cbr TRUE → L_1,L_2 becomes br → L_1
  - Method discovers this; it must rewrite the code, too!

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Sparse Conditional Constant Propagation

Unreachable Code

```
17     i ← 17
       if (i > 0) then
10        j1 ← 10
       else
20 TOP    ~~j2 ← 20~~
10     j3 ← Φ(j1, j2)
170 ⊥  k ← j3 * 17
```

All paths execute

With SCC marking blocks

Optimism

- Initialization to TOP is still important
- Unreachable code keeps TOP
- ∧ with TOP has desired result

Cannot get this any other way

- DEAD code cannot test (i > 0)
- DEAD marks j_2 as useful

In general, combining two optimizations can lead to answers that cannot be produced by any combination of running them separately.

This algorithm is one example of that general principle.

Combining register allocation & instruction scheduling is another ...

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Using SSA Form for Optimizations

In general, using SSA conversion prior to optimization leads to

- Cleaner formulations
- Better results
- Faster algorithms

We've seen two SSA-based optimization algorithms

- Dead-code elimination
- Sparse conditional constant propagation

There are many more…

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