CS738: Advanced Compiler Optimizations

Static Single Assignment (SSA)

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Agenda

- ► SSA Form
- Constructing SSA form
- Properties and Applications

SSA Form

- ▶ Developed by Ron Cytron, Jeanne Ferrante, Barry K. Rosen, Mark N. Wegman, and F. Kenneth Zadeck,
 - ▶ in 1980s while at IBM.
- Static Single Assignment A variable is assigned only once in program text
 - May be assigned multiple times if program is executed

What is SSA Form?

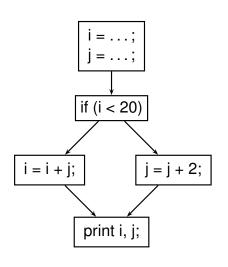
- ► An Intermediate Representation
- Sparse representation
 - ▶ Definitions sites are directly associated with use sites
- Advantage
 - Directly access points where relevant data flow information is available

SSA IR

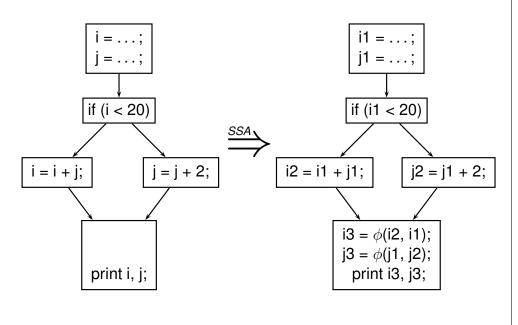
- ► In SSA Form
 - ► Each variable has exactly one definition
 - ⇒ A use of a variable is reached by exactly one definition
- Control flow like traditional programs
- ► Some *magic* is needed at *join* nodes

Example

SSA Example



SSA Example



SSA Example

The *magic*: ϕ function

- \blacktriangleright ϕ is used for selection
 - ► One out of multiple values at join nodes
- ightharpoonup Not every join node needs a ϕ
 - Needed only if multiple definitions reach the node
- ► Examples?

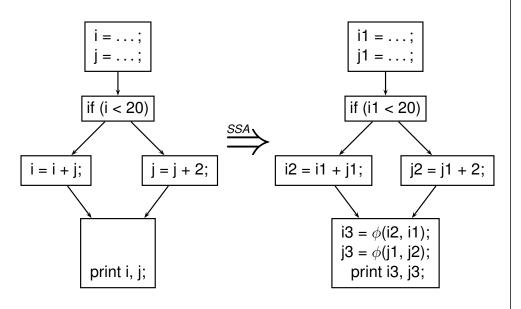
But...What is ϕ ?

- \blacktriangleright What does ϕ operation mean in a machine code?
- $ightharpoonup \phi$ is a conceptual entity
- Statically equivalent to choosing one of the arguments "non-deterministicly"
- ▶ No direct translation to machine code
 - typically mimicked using "copy" in predecessors
 - Inefficient
 - Practically, the inefficiency is compensated by dead code elimination and register allocation passes

Properties of ϕ

- ► Placed only at the entry of a join node
- \blacktriangleright Multiple ϕ -functions could be placed
 - ▶ for multiple variables
 - \blacktriangleright all such ϕ functions execute concurrently
- ightharpoonup n-ary ϕ function at n-way join node
- gets the value of *i*-th argument if control enters through *i*-th edge
 - \blacktriangleright Ordering of ϕ arguments according to the edge ordering is important

SSA Example (revisit)



Construction of SSA Form

Assumptions

- ► Only scalar variables
 - ► Structures, pointers, arrays could be handled
 - ► Refer to publications

Dominators

- ► Nodes *x* and *y* in flow graph
- x dominates y if every path from Entry to y goes through x
 - $\triangleright x \text{ dom } y$
 - partial order?
- ightharpoonup x strictly dominates y if x dom y and $x \neq y$
 - ➤ *x* sdom *y*

Computing Dominators

Equation

$$DOM(n) = \{n\} \cup \left(\bigcap_{m \in PRED(n)} DOM(m)\right),$$
$$\forall n \in N$$

► Initial Conditions:

$$DOM(n_{Entry}) = \{n_{Entry}\}$$
$$DOM(n) = N, \forall n \in N - \{n_{Entry}\}$$

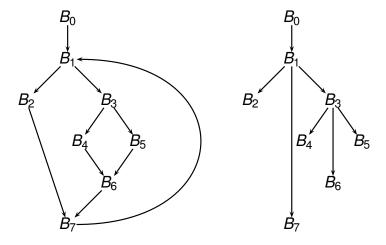
where N is the set of all nodes, n_{Entry} is the node corresponding to the Entry block.

▶ Note that efficient methods exist for computing dominators

Immediate Dominators and Dominator Tree

- x is immediate dominator of y if x is the closest strict dominator of y
 - unique, if it exists
 - denoted idom[y]
- Dominator Tree
 - ► A tree showing all immediate dominator relationships

Dominator Tree Example



Dominance Frontier: DF

- ▶ Dominance Frontier of *x* is set of all nodes *y* s.t.
 - x dominates a predecessor of y AND
 - x does not strictly dominate y
- ▶ Denoted DF(x)
- \blacktriangleright Why do you think DF(x) is important for any x?
 - ▶ Think about the information originated in *x*.

Computing DF

- PARENT(x) denotes parent of node x in the dominator tree.
- CHILDERN(x) denotes children of node x in the dominator tree.
- PRED and SUCC from CFG.

$$\mathsf{DF}(x) = \mathsf{DF}_{\mathsf{local}}(x) \cup \left(\bigcup_{z \in \mathsf{CHILDERN}(x)} \mathsf{DF}_{\mathsf{up}}(z)\right)$$

$$\begin{array}{lcl} \mathsf{DF}_{\mathsf{local}}(x) & = & \{y \in \mathsf{SUCC}(x) \mid \mathsf{idom}[y] \neq x \} \\ \mathsf{DF}_{\mathsf{up}}(z) & = & \{y \in \mathsf{DF}(z) \mid \mathsf{idom}[y] \neq \mathsf{PARENT}(z) \} \end{array}$$

Iterated Dominance Frontier

- ► Transitive closure of Dominance frontiers on a set of nodes
- ► Let S be a set of nodes

$$DF(S) = \bigcup_{x \in S} DF(x)$$

$$DF^{1}(S) = DF(S)$$

$$DF^{i+1}(S) = DF(S \cup DF^{i}(S))$$

ightharpoonup DF⁺(S) is the fixed point of DFⁱ computation.

Minimal SSA Form Construction

- ► Compute DF⁺ set for each flow graph node
- \blacktriangleright Place trivial ϕ -functions for each variable in the node

n-times

- trivial ϕ -function at n-ary join: $x = \phi(\overbrace{x, x, \dots, x})$
- ► Rename variables
- ► Why DF⁺? Why not only DF?

Inserting ϕ -functions

```
foreach variable V { S = Entry \cup \{B_n \mid v \text{ defined in } B_n\} Compute \mathsf{DF}^+(S) foreach n in \mathsf{DF}^+(S) { insert \phi-function for V at the start of B_n }
```

Renaming Variables (Pseudo Code)

- ► Rename from the *Entry* node recursively
 - For each variable x, maintain a rename stack of $x \mapsto x_{\text{version}}$ mapping
- ► For node n
 - For each assignment (x = ...) in n
 - ▶ If non- ϕ assignment, rename any use of x with the Top mapping of x from the rename stack
 - ▶ Push the mapping $x \mapsto x_i$ on the rename stack
 - \triangleright Replace lhs of the assignment by x_i
 - i = i + 1
- For the successors of *n*
 - ightharpoonup Rename ϕ operands through SUCC edge index
- ▶ Recursively rename all child nodes in the dominator tree
- For each assignment (x = ...) in n
 - ▶ Pop $x \mapsto \dots$ from the rename stack