CSE 401/M501 – Compilers

SSA
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Autumn 2018
Administrivia

- HW3 graded (at last!) Thank you for your patience

- Codegen due *tomorrow* night 😊 (not tonight)

- Compiler additions out today or tomorrow – add doubles
  - Limited: no mixed mode math, NaN, ∞, other edge cases
  - Due next Thursday
  - A chance to revisit the project and review how everything works

- Once the additions are done we’ll do an overall evaluation of your compiler, all phases, and rerun a comprehensive set of tests. This final score is *the* major part of the project grade. So you need to fix any remaining bugs, all the way back to the scanner! 🐜🐜🪒🦗
Agenda

• Overview of SSA IR
  – Constructing SSA graphs
  – Sample of SSA-based optimizations
  – Converting back from SSA form

• Sources: Appel ch. 19, also an extended discussion in Cooper-Torczon sec. 9.3, Mike Ringenburg’s CSE 401 slides
Def-Use (DU) Chains

• Common dataflow analysis problem: Find all sites where a variable is used, or find the definition site of a variable used in an expression

• Traditional solution: def-use chains – additional data structure on top of the dataflow graph
  – Link each statement defining a variable to all statements that use it
  – Link each use of a variable to its definition
Def-Use (DU) Chains

In this example, two DU chains intersect
DU-Chain Drawbacks

• Expensive: if a typical variable has $N$ uses and $M$ definitions, the total cost \textit{per-variable} is $O(N \times M)$, i.e., $O(n^2)$
  – Would be nice if cost were proportional to the size of the program

• Unrelated uses of the same variable are mixed together
  – Complicates analysis – variable looks live across all uses even if unrelated
SSA: Static Single Assignment

• IR where each variable has only one definition in the program text
  – This is a single static definition, but that definition can be in a loop, function, or other code that is executed dynamically many times
• Makes many analyses (and related optimizations) more efficient
• Separates values from memory storage locations
• Complementary to CFG/DFG – better for some things, but cannot do everything
SSA in Basic Blocks

Idea: for each original variable \( v \), create a new variable \( v_n \) at the \( n^{th} \) definition of the original \( v \). Subsequent uses of \( v \) use \( v_n \) until the next definition point.

• Original
  
  \[
  \begin{align*}
  a & := x + y \\
  b & := a - 1 \\
  a & := y + b \\
  b & := x \times 4 \\
  a & := a + b
  \end{align*}
  \]

• SSA
  
  \[
  \begin{align*}
  a_1 & := x + y \\
  b_1 & := a_1 - 1 \\
  a_2 & := y + b_1 \\
  b_2 & := x \times 4 \\
  a_3 & := a_2 + b_2
  \end{align*}
  \]
Merge Points

• The issue is how to handle merge points

if (...)  
  a = x;  
else  
  a = y;  
b = a;

if (...)  
  a₁ = x;  
else  
  a₂ = y;  
b₁ = ??;
Merge Points

• The issue is how to handle merge points

<table>
<thead>
<tr>
<th>if (...)</th>
<th>if (...)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a = x;</td>
<td>a₁ = x;</td>
</tr>
<tr>
<td>else</td>
<td>else</td>
</tr>
<tr>
<td>a = y;</td>
<td>a₂ = y;</td>
</tr>
<tr>
<td>b = a;</td>
<td>a₃ = Φ(a₁, a₂);</td>
</tr>
<tr>
<td></td>
<td>b₁ = a₃;</td>
</tr>
</tbody>
</table>

• Solution: introduce a Φ-function
  
a₃ := Φ(a₁, a₂)

• Meaning: a₃ is assigned either a₁ or a₂ depending on which control path is used to reach the Φ-function
Another Example

Original

\[
\begin{align*}
b & := M[x] \\
a & := 0 \\
\text{if } b < 4 \\
a & := b \\
c & := a + b
\end{align*}
\]

SSA

\[
\begin{align*}
b_1 & := M[x] \\
a_1 & := 0 \\
\text{if } b_1 < 4 \\
a_2 & := b_1 \\
a_3 & := \Phi(a_1, a_2) \\
c_1 & := a_3 + b_1
\end{align*}
\]
How Does $\Phi$ “Know” What to Pick?

- It doesn’t
- $\Phi$-functions don’t actually exist at runtime
  - When we’re done using the SSA IR, we translate back out of SSA form, removing all $\Phi$-functions
    - Basically by adding code to copy all SSA $x_i$ values to the single, non-SSA variable $x$
  - For analysis, all we typically need to know is the connection of uses to definitions – no need to “execute” anything
Example With a Loop

Original

\[
\begin{align*}
  a &:= 0 \\
  b &:= a + 1 \\
  c &:= c + b \\
  a &:= b \times 2 \\
  \text{if } a < N &\text{ return } c
\end{align*}
\]

SSA

\[
\begin{align*}
  a_1 &:= 0 \\
  a_3 &:= \Phi(a_1, a_2) \\
  b_1 &:= \Phi(b_0, b_2) \\
  c_2 &:= \Phi(c_0, c_1) \\
  b_2 &:= a_3 + 1 \\
  c_1 &:= c_2 + b_2 \\
  a_2 &:= b_2 \times 2 \\
  \text{if } a_2 < N &\text{ return } c_1
\end{align*}
\]

Notes:
- Loop-back edges are also merge points, so require $\Phi$-functions
- $a_0, b_0, c_0$ are initial values of $a, b, c$ on block entry
- $b_1$ is dead – can delete later
- $c$ is live on entry – either input parameter or uninitialized
What does SSA “buy” us?

• No need for DU or UD chains – implicit in SSA

• Compact representation

• SSA is “recent” (i.e., 80s)

• Prevalent in real compilers for { } languages
Converting To SSA Form

• Basic idea
  – First, add $\Phi$-functions
  – Then, rename all definitions and uses of variables by adding subscripts
Inserting $\Phi$-Functions

• Could simply add $\Phi$-functions for every variable at every join point(!)
• Called “maximal SSA”
• But
  – Wastes way too much space and time
  – Not needed in many cases
Path-convergence criterion

• Insert a $\Phi$-function for variable $a$ at point $z$ when:
  – There are blocks $x$ and $y$, both containing definitions of $a$, and $x \neq y$
  – There are nonempty paths from $x$ to $z$ and from $y$ to $z$
  – These paths have no common nodes other than $z$
Details

• The start node of the flow graph is considered to define every variable (even if “undefined”)

• Each $\Phi$-function itself defines a variable, which may create the need for a new $\Phi$-function
  – So we need to keep adding $\Phi$-functions until things converge

• How can we do this efficiently?
  Use a new concept: dominance frontiers
Dominators

• Definition: a block $x$ dominates a block $y$ iff every path from the entry of the control-flow graph to $y$ includes $x$

• So, by definition, $x$ dominates $x$

• We can associate a Dom(inator) set with each CFG node $x$ – set of all blocks dominated by $x$
  $|\text{Dom}(x)| \geq 1$

• Properties:
  – Transitive: if $a$ dom $b$ and $b$ dom $c$, then $a$ dom $c$
  – There are no cycles, thus can represent the dominator relationship as a tree
Example

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Dominators and SSA

• One property of SSA is that definitions dominate uses; more specifically:
  – If $x := \Phi(\ldots, x_i, \ldots)$ is in block $b$, then the definition of $x_i$ dominates the $i^{th}$ predecessor of $b$
  – If $x$ is used in a non-$\Phi$ statement in block $b$, then the definition of $x$ dominates block $b$
Dominance Frontier (1)

- To get a practical algorithm for placing Φ-functions, we need to avoid looking at all combinations of nodes leading from x to y
- Instead, use the dominator tree in the flow graph
Dominance Frontier (2)

• Definitions
  – x *strictly dominates* y if x dominates y and x \( \neq y \)
  – The *dominance frontier* of a node x is the set of all nodes w such that x dominates a predecessor of w, but x does not strictly dominate w
    • This means that x can be in *it’s own* dominance frontier! That can happen if there is a back edge to x (i.e., x is the head of a loop)

• Essentially, the dominance frontier is the border between dominated and undominated nodes
Example

= \text{x}

= \text{DomFrontier}(x)

= \text{StrictDom}(x)
Example

= x

= DomFrontier(x)

= StrictDom(x)
Example

\[ x = \text{DomFrontier}(x) \]

\[ x = \text{StrictDom}(x) \]
Example

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Example

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= StrictDom(x)
Example

= x

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= StrictDom(x)
Dominance Frontier Criterion for Placing Φ-Functions

• If a node x contains the definition of variable a, then every node in the dominance frontier of x needs a Φ-function for a
  – Idea: Everything dominated by x will see x’s definition of a. The dominance frontier represents the first nodes we could have reached via an alternative path, which will have an alternate reaching definition (recall we say the entry node defines everything)
    • Why is this right for loops? Hint: strict dominance...
      – Since the Φ-function itself is a definition, this placement rule needs to be iterated until it reaches a fixed-point
  • Theorem: this algorithm places exactly the same set of Φ-functions as the path convergence criterion (above)
Placing $\Phi$-Functions: Details

- See the book for the full construction, but the basic steps are:
  1. Compute the dominance frontiers for each node in the flowgraph
  2. Insert just enough $\Phi$-functions to satisfy the criterion. Use a worklist algorithm to avoid reexamining nodes unnecessarily
  3. Walk the dominator tree and rename the different definitions of each variable $a$ to be $a_1, a_2, a_3, \ldots$
SSA Optimizations

• Why go to the trouble of translating to SSA?
• The advantage of SSA is that it makes many optimizations and analyses simpler and more efficient
  – We’ll give a couple of examples
• But first, what do we know? (i.e., what information is stored in the SSA graph?)
SSA Data Structures

For each ...

• Statement: links to containing block, next and previous statements, variables defined, variables used.

• Variable: link to its (single) definition statement and (possibly multiple) use sites

• Block: List of contained statements, ordered list of predecessor(s) & successor(s) blocks
Dead-Code Elimination

• A variable is live iff its list of uses is not empty(!)
  – That’s it! Nothing further to compute

• Algorithm to delete dead code:
  
  while there is some variable v with no uses
  
  if the statement that defines v has no other side effects, then delete it
  
  – Need to remove this statement from the list of uses for its operand variables – which may cause those variables to become dead
Simple Constant Propagation

• If c is a constant in v := c, any use of v can be replaced by c
  – Then update every use of v to use constant c
• If the c_i’s in v := Φ(c_1, c_2, ..., c_n) are all the same constant c, we can replace this with v := c
• Can also incorporate copy propagation, constant folding, and others in the same worklist algorithm
Simple Constant Propagation

\[ W := \text{list of all statements in SSA program} \]
\[ \text{while } W \text{ is not empty} \]
\[ \quad \text{remove some statement } S \text{ from } W \]
\[ \quad \text{if } S \text{ is } v := \Phi(c, c, ..., c), \text{ replace } S \text{ with } v := c \]
\[ \quad \text{if } S \text{ is } v := c \]
\[ \quad \quad \text{delete } S \text{ from the program} \]
\[ \quad \text{for each statement } T \text{ that uses } v \]
\[ \quad \quad \text{substitute } c \text{ for } v \text{ in } T \]
\[ \quad \text{add } T \text{ to } W \]
Converting Back from SSA

• Unfortunately, real machines do not include a $\Phi$ instruction
• So after analysis, optimization, and transformation, need to convert back to a “$\Phi$-less” form for execution
  – (and sometimes for different kinds of analysis or transformation)
Translating \( \Phi \)-functions

• The meaning of \( x := \Phi(x_1, x_2, ..., x_n) \) is “set \( x := x_1 \) if arriving on edge 1, set \( x := x_2 \) if arriving on edge 2, etc.”

• So, for each \( i \), insert \( x := x_i \) at the end of predecessor block \( i \)

• Rely on copy propagation and coalescing in register allocation to eliminate redundant copy instructions
SSA Wrapup

• More details needed to fully and efficiently implement SSA, but these are the main ideas
  – See recent compiler books (but not the Dragon book!)
• SSA is used in most modern optimizing compilers (LLVM is based on it) and has been retrofitted into many older ones (gcc is a major example)
• Not a silver bullet – some optimizations still need non-SSA forms – but very effective for many