COS320: Compiling Techniques

Zak Kincaid

April 16, 2020

Static Single Assignment form

SSA

- Each `%uid` appears on the left-hand-side of at most one assignment in a CFG

```
if (x < 0) {
  y := y - x;
} else {
  y := y + x;
}
return y
```

$\longrightarrow$

$$
\begin{array}{l}
\texttt{if } (\texttt{x}_0 < 0)\ \{ \\
\quad \texttt{y}_1 := \texttt{y}_0 - \texttt{x}_0; \\
\}\ \texttt{else}\ \{ \\
\quad \texttt{y}_2 := \texttt{y}_0 + \texttt{x}_0; \\
\} \\
\texttt{y}_3 := \phi(\texttt{y}_1, \texttt{y}_2) \\
\texttt{return } \texttt{y}_3
\end{array}
$$

  - Recall: $y_3 := \phi(y_1, y_2)$ picks either y_1 or y_2 (whichever one corresponds to the branch that is actually taken) and stores it in y_3
- Well-formedness condition: uids must be defined before they are used.

Register allocation

- SSA form reduces register pressure
  - Each variable x is replaced by potentially many "subscripted" variables x_1, x_2, x_3,...
    - (At least) one for each definition of of x
  - Each x_i can potentially be stored in a different memory location

Register allocation

- SSA form reduces register pressure
  - Each variable x is replaced by potentially many “subscripted” variables x_1, x_2, x_3,...
    - (At least) one for each definition of of x
  - Each x_i can potentially be stored in a different memory location
- Interference graphs for SSA programs are *chordal* (every cycle contains a chord)
  - Chordal graphs can be colored optimally in polytime
  - (*But* optimal translation out of SSA form is intractable)

Dead assignment elimination

Simple algorithm for eliminating assignment[1] instructions that are never used:

while *some* $\%x$ *has no uses* **do**

  Remove definition of $\%x$ from CFG;

- SSA conversion $\Rightarrow$ more assignments are eliminated

```
x := 0
x := 1
return 2 * x
```

[1] does *not* eliminate dead *stores*

Dead assignment elimination

Simple algorithm for eliminating assignment[1] instructions that are never used:

while *some* $\%x$ *has no uses* **do**

  Remove definition of $\%x$ from CFG;

- SSA conversion $\Rightarrow$ more assignments are eliminated

```
x := 0
x := 1
return 2 * x
```

SSA conversion ⇢

```
x0 := 0
x1 := 1
return 2 * x1
```

[1] does *not* eliminate dead *stores*

Dead assignment elimination

Simple algorithm for eliminating assignment[1] instructions that are never used:

while *some* $\%x$ *has no uses* **do**

  Remove definition of $\%x$ from CFG;

- SSA conversion $\Rightarrow$ more assignments are eliminated

```
x := 0
x := 1
return 2 * x
```

SSA conversion

x_0 := 0
x_1 := 1
return 2 * x_1

[1] does *not* eliminate dead *stores*

Dead assignment elimination

Simple algorithm for eliminating assignment[1] instructions that are never used:

while *some* $\%x$ *has no uses* **do**

  Remove definition of $\%x$ from CFG;

- SSA conversion $\Rightarrow$ more assignments are eliminated

```
x := 0
x := 1
return 2 * x
```

SSA conversion

```
x1 := 1
return 2 * x1
```

[1] does *not* eliminate dead *stores*

Recall: constant propagation

- The goal of constant propagation: determine at each instruction I a *constant environment*
  - A constant environment is a symbol table mapping each variable x to one of:
    - an integer n (indicating that x's value is n whenever the program is at I)
    - $\top$ (indicating that x might take more than one value at I)
    - $\bot$ (indicating that x may take no values at run-time – I is unreachable)
- Say that the assignment **IN**, **OUT** is conservative if

1. $\mathbf{IN}[s]$ assigns each variable $\top$
2. For each node *bb* $\in N$,

$$\mathbf{OUT}[bb] \sqsupseteq post_{CP}(bb, \mathbf{IN}[bb])$$

3. For each edge *src* $\rightarrow$ *dst* $\in E$,

$$\mathbf{IN}[dst] \sqsupseteq \mathbf{OUT}[src]$$

(Dense) constant propagation performance

- Memory requirements: $O(|N| \cdot |\mathit{Var}|)$
  - Constant environment has size $O(|\mathit{Var}|)$, need to track $O(1)$ per node
- Time requirements: $O(|N| \cdot |\mathit{Var}|)$
  - Processing a single node takes $O(1)$ time
  - Each node is processed $O(|\mathit{Var}|)$ times
    - Height of the abstract domain (length of longest strictly ascending sequence): $3|\mathit{Var}|$
- Can we do better?

Sparse constant propagation

- Idea: SSA connects variable *definitions* directly to their *uses*
  - Don’t need to store the value of *every* variable at *every* program point
  - Don’t need to propagate changes through irrelevant blocks

Sparse constant propagation

- Idea: SSA connects variable *definitions* directly to their *uses*
  - Don't need to store the value of *every* variable at *every* program point
  - Don't need to propagate changes through irrelevant blocks
- Can think of SSA as a graph, where edges correspond to *data flow* rather than *control flow*
  - Define *rhs*$(\%x)$ to be the right hand side of the **unique** assignment to $\%x$
  - Define *succ*$(\%x) = \{\%y :$ *rhs*$(\%y)$ *reads* $\%x\}$

Sparse constant propagation

- Idea: SSA connects variable *definitions* directly to their *uses*
  - Don't need to store the value of *every* variable at *every* program point
  - Don't need to propagate changes through irrelevant blocks
- Can think of SSA as a graph, where edges correspond to *data flow* rather than *control flow*
  - Define *rhs*$(\%x)$ to be the right hand side of the **unique** assignment to $\%x$
  - Define *succ*$(\%x) = \{\%y :$ *rhs*$(\%y)$ ***reads*** $\%x\}$
- Local specification for constant propagation:
  - *scp* is the smallest function *Uid* $\rightarrow \mathbb{Z} \cup \{\top, \bot\}$ such that
    - If G contains no assignments to *%x*, then *scp*$(\%x) = \top$
    - For each instruction *%x* = ***e***, *scp*$(\%x) = eval(e,$ ***scp***$)$

Worklist algorithm

$$\textit{scp}(\%x) = \begin{cases} \bot & \text{if } \%x \text{ has an assignment} \\ \top & \text{otherwise} \end{cases}$$

$\textit{work} \leftarrow \{\%x \in \textit{Uid} : \%x \text{ is defined}\};$

while $\textit{work} \neq \emptyset$ **do**

  Pick some $\%x$ from work;

  $\textit{work} \leftarrow \textit{work} \setminus \{\%x\}$;

  if $\textit{rhs}(\%x) = \phi(\%y, \%z)$ **then**

    $v \leftarrow \textit{scp}(\%y) \sqcup \textit{scp}(\%z)$

  else

    $v \leftarrow \textit{eval}(\textit{rhs}(\%x), \textit{scp})$

  if $v \neq \textit{scp}(\%x)$ **then**

    $\textit{scp}(\%x) \leftarrow v;$

    $\textit{work} \leftarrow \textit{work} \cup \textit{succ}(\%x)$

Computational complexity of constant propagation

	Dense	Sparse
Memory	$O(\|N\| \cdot \|\mathit{Var}\|)$	$O(\|N\|) = O(\|\mathit{Var}\|)$
Time	$O(\|N\| \cdot \|\mathit{Var}\|)$	$O(\|N\|) = O(\|\mathit{Var}\|)$

- *However*, observe that we only find constants for uids, not stack slots.
  - Again, advantageous to use uids to represent variable whenever possible

Computing SSA

(High-level) SSA conversion

- Replace each definition $x = e$ with a $x_i = e$ for some unique subscript i
- Replace each *use* of a variable y with y_i, where the ith definition of y is the unique reaching definition

(High-level) SSA conversion

- Replace each definition $x = e$ with a $x_i = e$ for some unique subscript i
- Replace each *use* of a variable y with y_i, where the ith definition of y is the unique reaching definition
- If multiple definitions reach a single use, then they must be merged using a ϕ (phi) statement

```
y := 0;
while (x >= 0) {
  x := x - 1;
  y := y + x;
}
return y
```

$\rightarrow$

```
y0 := 0;
while (true) {
  x2 = φ(x0, x1)
  y2 = φ(y0, y1)
  if (x2 < 0) break;
  x1 := x2 - 1;
  y1 := y2 + x1;
}
return y2
```

Placing ϕ statements

- Easy, inefficient solution: place a ϕ statement for each variable locaction at each *join point*
    - A *join point* is a node in the CFG with more than one predecessor

[2] The entry node of the CFG is considered to be an implicit definition of every variable

Placing ϕ statements

- Easy, inefficient solution: place a ϕ statement for each variable locaction at each *join point*
  - A *join point* is a node in the CFG with more than one predecessor
- Better solution: place a ϕ statement for variable x at location n exactly when the following **path convergence criterion** holds: there exist a pair of non-empty paths P_1, P_2 ending at n such that
  1. The start node of both P_1 and P_2 defines x[2]
  2. The only node shared by P_1 and P_2 is n

[2] The entry node of the CFG is considered to be an implicit definition of every variable

Placing ϕ statements

- Easy, inefficient solution: place a ϕ statement for each variable locaction at each *join point*
  - A *join point* is a node in the CFG with more than one predecessor
- Better solution: place a ϕ statement for variable x at location n exactly when the following **path convergence criterion** holds: there exist a pair of non-empty paths P_1, P_2 ending at n such that
  1. The start node of both P_1 and P_2 defines x[2]
  2. The only node shared by P_1 and P_2 is n
- The path convergence criterion can be implemented using the concept of *iterated dominance frontiers*

[2] The entry node of the CFG is considered to be an implicit definition of every variable

Dominance

- Let $G = (N, E, s)$ be a control flow graph
- We say that a node $d \in N$ *dominates* a node $n \in N$ if every path from s to n contains d
  - Every node dominates itself
  - d *strictly dominates* n if d is not n
  - d *immediately dominates* n if d strictly dominates n and but does not strictly dominate any strict dominator of n.

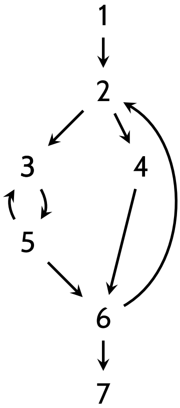
Dominance

- Let $G = (N, E, s)$ be a control flow graph
- We say that a node $d \in N$ *dominates* a node $n \in N$ if every path from s to n contains d
  - Every node dominates itself
  - d *strictly dominates* n if d is not n
  - d *immediately dominates* n if d strictly dominates n and but does not strictly dominate any strict dominator of n.
- Observe: dominance is a partial order on N
  - Every node dominates itself (reflexive)
  - If n_1 dominates n_2 and n_2 dominates n_3 then n_1 dominates n_3 (transitive)
  - If n_1 dominates n_2 and n_2 dominates n_1 then n_1 must be n_2 (anti-symmetric)

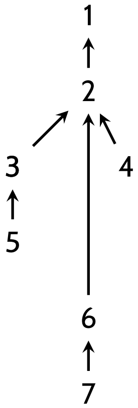
If we draw an edge from every node to its immediate dominator, we get a data structure called the *dominator tree*.

- (Essentially the Haase diagram of the dominated-by order)

Control Flow Graph



Dominator tree



Dominance and SSA

- SSA well-formedness criteria
  - If $\%x$ is the ith argument of a ϕ function in a block n, then the definition of $\%x$ must dominate the ith predecessor of n.
  - If $\%x$ is used in a non-ϕ statement in block n, then the definition of $\%x$ must dominate n

Dominator analysis

- Let $G = (N, E, s)$ be a control flow graph.
- Define *dom* to be a function mapping each node $n \in N$ to the set *dom*$(n) \subseteq N$ of nodes that dominate it

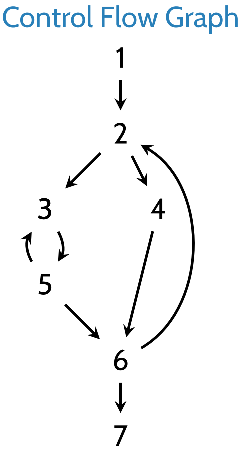
Dominator analysis

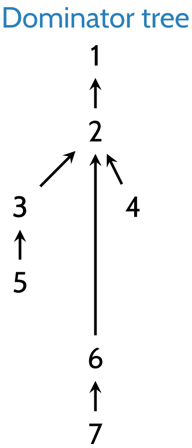
- Let $G = (N, E, s)$ be a control flow graph.
- Define *dom* to be a function mapping each node $n \in N$ to the set *dom*$(n) \subseteq N$ of nodes that dominate it
- *Local specification*: *dom* is the largest (equiv. least in superset order) function such that
  - $dom(s) = \{s\}$
  - For each $p \to n \in E$, *dom*$(n) \subseteq \{n\} \cup$ *dom*(p)

Dominator analysis

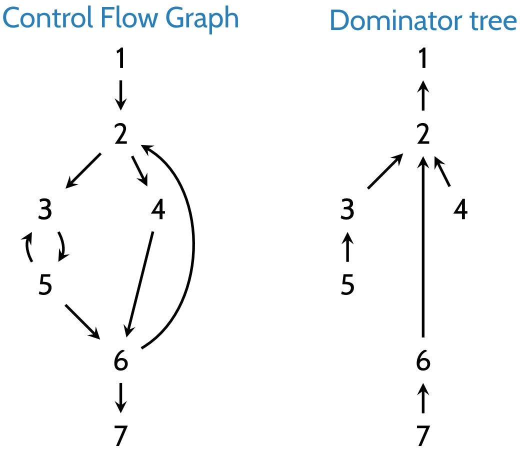
- Let $G = (N, E, s)$ be a control flow graph.
- Define *dom* to be a function mapping each node $n \in N$ to the set *dom*$(n) \subseteq N$ of nodes that dominate it
- *Local specification*: *dom* is the largest (equiv. least in superset order) function such that
  - $dom(s) = \{s\}$
  - For each $p \to n \in E$, *dom*$(n) \subseteq \{n\} \cup$ *dom*(p)
- Can be solved using dataflow analysis techniques
  - In practice: nearly linear time algorithm due to Lengauer & Tarjan

- The *dominance frontier* of a node n is the set of all nodes m such that n dominates a *predecessor* of m, but does not strictly dominate m itself.
  - $DF(n) = \{m : (\exists p \in Pred(m).n \in dom(p)) \wedge (m = n \vee n \notin dom(m))\}$
- Whenever a node n contains a definition of some uid $\%x$, then any node m in the dominance frontier of n needs a ϕ function for $\%x$.

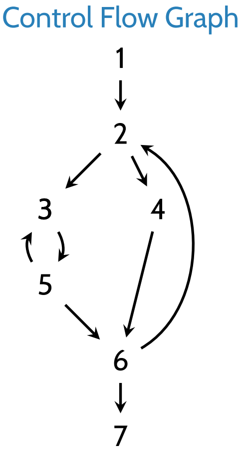


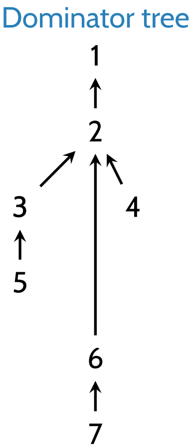


- $DF(1) = \emptyset$

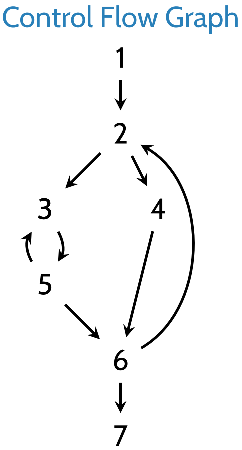


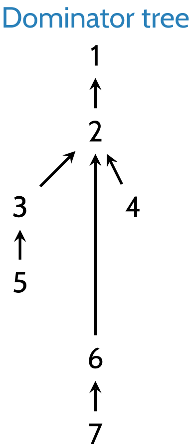
- $DF(1) = \emptyset$
- $DF(2) = \{2\}$





- $DF(1) = \emptyset$
- $DF(2) = \{2\}$
- $DF(3) = \{3, 6\}$

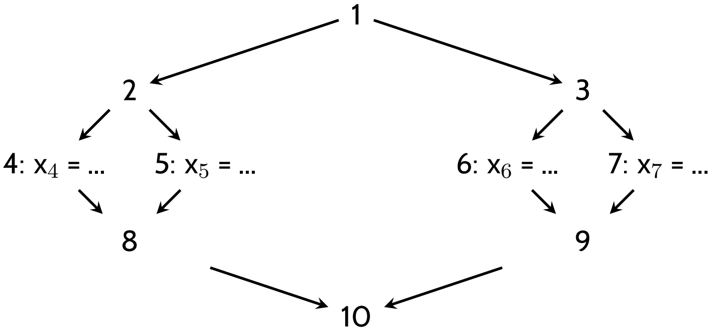




- $DF(1) = \emptyset$
- $DF(2) = \{2\}$
- $DF(3) = \{3, 6\}$
- $DF(4) = \{6\}$
- $DF(5) = \{3, 6\}$
- $DF(6) = \{2\}$

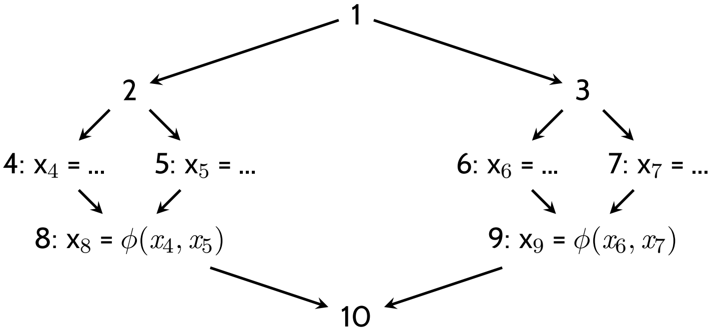
Dominance frontier is not enough!

- Whenever a node n contains a definition of some uid $\%x$, then any node m in the dominance frontier of n needs a ϕ statement for $\%x$.
- *But*, that is not the only place where ϕ statements are needed



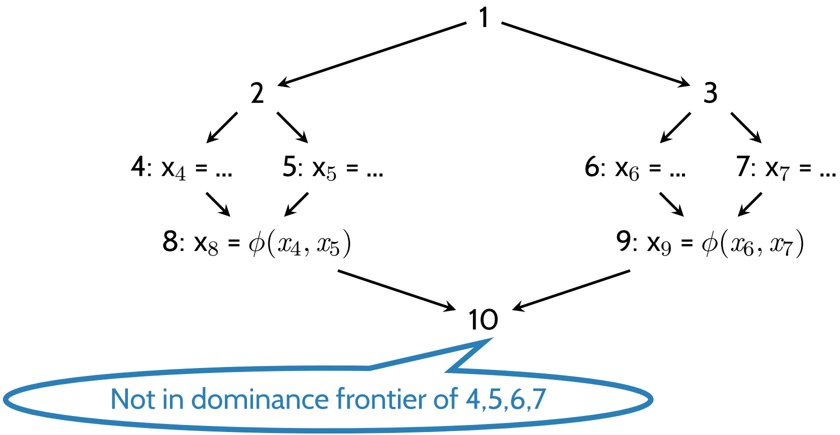
Dominance frontier is not enough!

- Whenever a node n contains a definition of some uid $\%x$, then any node m in the dominance frontier of n needs a ϕ statement for $\%x$.
- *But*, that is not the only place where ϕ statements are needed



Dominance frontier is not enough!

- Whenever a node n contains a definition of some uid $\%x$, then any node m in the dominance frontier of n needs a ϕ statement for $\%x$.
- *But*, that is not the only place where ϕ statements are needed



SSA construction

- Extend dominance frontier to sets of nodes by letting $DF(M) = \bigcup_{m \in M} DF(m)$
- Define the *iterated dominance frontier IDF*$(M) = \bigcup_i IDF_i(M)$, where
  - $IDF_0(M) = DF(M)$
  - $IDF_{i+1}(M) = IDF_i(M) \cup IDF(IDF_i(M))$

SSA construction

- Extend dominance frontier to sets of nodes by letting $DF(M) = \bigcup_{m \in M} DF(m)$
- Define the *iterated dominance frontier IDF*$(M) = \bigcup_i IDF_i(M)$, where
  - $IDF_0(M) = DF(M)$
  - $IDF_{i+1}(M) = IDF_i(M) \cup IDF(IDF_i(M))$
- For any node x, let *Def*(x) be the set of nodes that define x
- *Finally*, we can characterize ϕ statement placement

Insert a ϕ statement for x at every node in $IDF($***Def***$(x))$

Transforming out of SSA

- The ϕ statement is not executable, so it must be removed in order to generate code

Transforming out of SSA

- The ϕ statement is not executable, so it must be removed in order to generate code
- For each ϕ statement $\%x = \phi(\%x_1, ..., \$x_k)$ in block n, n must have exactly k predecessors $p_1, ...p_k$
- Insert a new block along each edge $p_i \to n$ which executes $\%x = \%x_i$ (program no longer satisfies SSA property!)

Transforming out of SSA

- The ϕ statement is not executable, so it must be removed in order to generate code
- For each ϕ statement $\%x = \phi(\%x_1, ..., \$x_k)$ in block n, n must have exactly k predecessors $p_1, ...p_k$
- Insert a new block along each edge $p_i \to n$ which executes $\%x = \%x_i$ (program no longer satisfies SSA property!)
- Using a graph coalescing register allocator, often possible to eliminate the resulting move instructions