

CSC2/455 Software Analysis and Improvement

Dominators and SSA Form

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Outline

Review

Dominator Analysis (DOM)

SSA Form

Postscript

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Data flow analysis framework

- ▶ Live variable analysis
 - ▶ “Is there a read of this variable along any path?”
- ▶ Reaching Definitions
 - ▶ “Which definitions reach this use?”
- ▶ Available expressions
 - ▶ “Is this expression calculated previously and the result still usable?”
- ▶ Very Busy Expressions
 - ▶ “Are there expressions that can be precalculated?”
- ▶ Iterative data flow analysis
 - ▶ GEN, KILL, Transfer functions, Initialization

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Dominator Analysis (DOM)

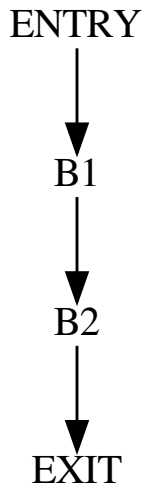
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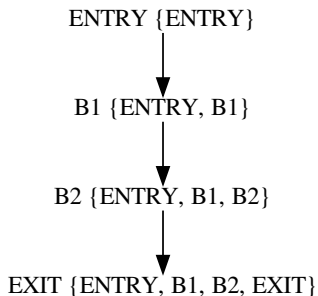
Dominators

- ▶ A node n in the CFG dominates a node m iff:
 - ▶ n is on all paths from entry to m
 - ▶ by definition, a node n always dominates itself
- ▶ Dominators are a property of graphs
 - ▶ I.e. has nothing to do with code in basic blocks

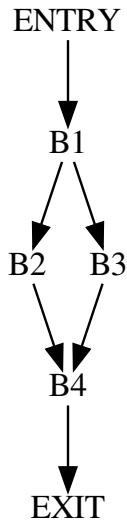
Example 1: Node with single predecessor



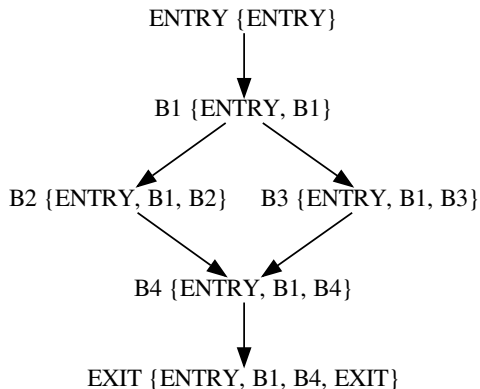
Example 1: Node with single predecessor (Answer)



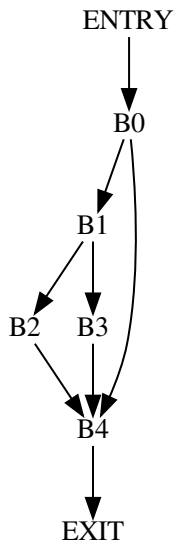
Example 2: Node with multiple predecessors



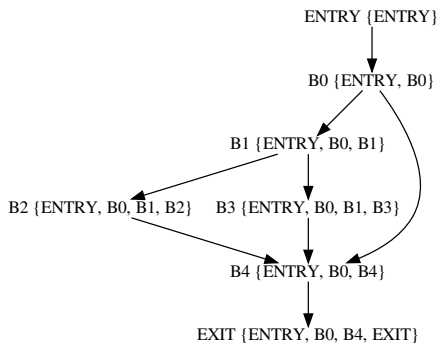
Example 2: Node with multiple predecessors (Answer)



Example 3: Slightly more involved example



Example 3: Slightly more involved example (Answer)



Today

Can we use data flow analysis to identify the dominators of a node?

Data flow analysis setup

- ▶ Domain of facts?
- ▶ GEN and KILL?
- ▶ Direction of analysis?
- ▶ Merge operator?
- ▶ Initialization?

Data flow analysis Equation

$$\text{DOM}(n) = \{n\} \cup \left(\bigcap_{m \in \text{pred}(n)} \text{DOM}(m)\right)$$

► Initialization

- (for $n \neq \text{ENTRY}$): $\text{DOM}(n) = N$ (where N is the set of all nodes)
- (for $n = \text{ENTRY}$): $\text{DOM}(n) = \text{ENTRY}$

Related concept: Post-dominators

A node m is post-dominated by a node n iif:

- ▶ n appears on every path from m to EXIT.
- ▶ n post-dominates itself, by definition

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Static Single Assignment (SSA) Form

- ▶ Intermediate Representation
 - ▶ Similar to 3 address code
- ▶ Each variable only written once
 - ▶ Static [in source] Single [once] assignment
- ▶ SSA form can be generated from 3 address code
 - ▶ Introduce ϕ functions
 - ▶ Rename variables

Example 1: Straight-line code

```
y = x + 1;  
x = 2;  
y = x + y + 2;
```

gets transformed to:

```
y_0 = x_0 + 1  
x_1 = 2;  
y_1 = x_1 + y_0 + 2;
```

From this example, when should we rename variables?

Example 2: Branches

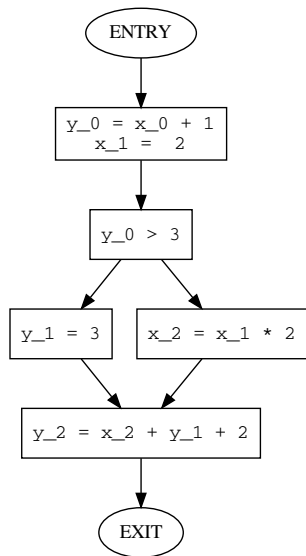
```
y = x + 1;  
x = 2;  
  
if(y > 3)  
    y = 3;  
else  
    x = x * 2;  
  
y = x + y + 2;
```

gets transformed to:

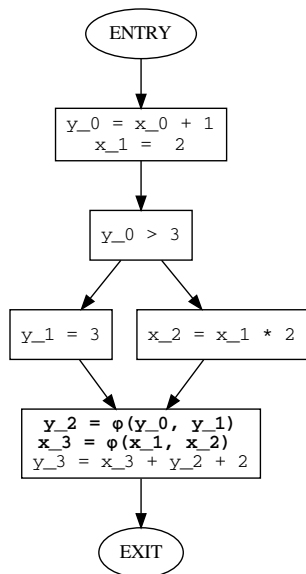
```
y_0 = x_0 + 1  
x_1 = 2;  
  
if(y_0 > 3)  
    y_1 = 3;  
else  
    x_2 = x_1 * 2;  
  
y_2 = x_2 + y_1 + 2;
```

Is this renaming correct?

Example 2: The CFG



Example 2: Fix using ϕ functions



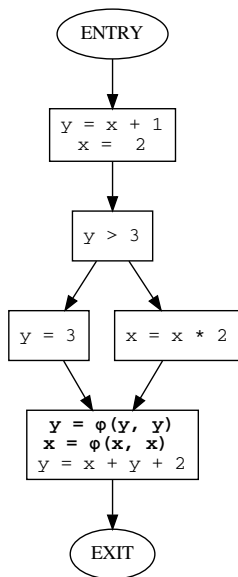
Simple Algorithm for constructing SSA form: 1

- ▶ Insert ϕ functions
 - ▶ In which nodes of CFG?
 - ▶ For which variables?
- ▶ Rename variables
 - ▶ To what?
 - ▶ Helps to think of LHS (definition) renames and RHS (use) renames

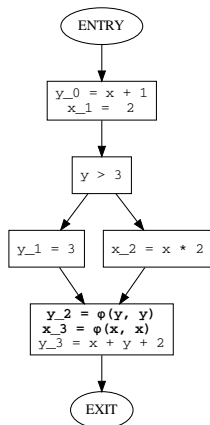
Simple Algorithm for constructing SSA form: 2

- ▶ Insert ϕ functions
 - ▶ In join nodes, before all other code
 - ▶ For *all* variables defined or used in procedure
 - ▶ Each ϕ function has one argument per incoming edge
 - ▶ Use $y = \phi(y, y)$ form for variable y
- ▶ Rename variables
 - ▶ To what?
 - ▶ Helps to think of LHS (definition) renames and RHS (use) renames

Simple Algorithm for constructing SSA form: 3



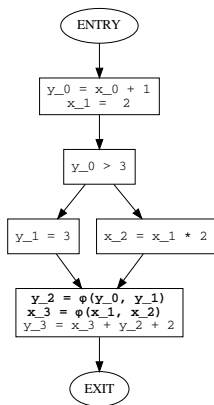
Simple Algorithm for constructing SSA form: Rename LHS



Simple Algorithm for constructing SSA form: Rename RHS

- ▶ Note that in SSA form, only one definition reaches a use (except the uses in ϕ)
- ▶ The arguments to ϕ are the definitions that reach it

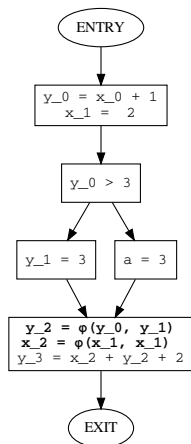
Simple Algorithm for constructing SSA form: Rename RHS



Simple Algorithm for constructing SSA form: Renaming

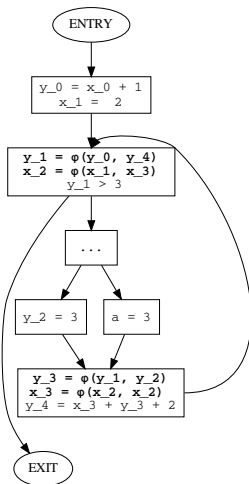
- ▶ In actual compilers, renaming LHS and RHS can be done by simply calculating reaching definitions
 - ▶ Remember we had to track each definition there too (recall $y \neq 0$)
- ▶ This construction is called the *maximal SSA form*
 - ▶ Simple to construct
 - ▶ Wasteful, can introduce too many ϕ functions (not in our example)

Example: Redundant ϕ functions



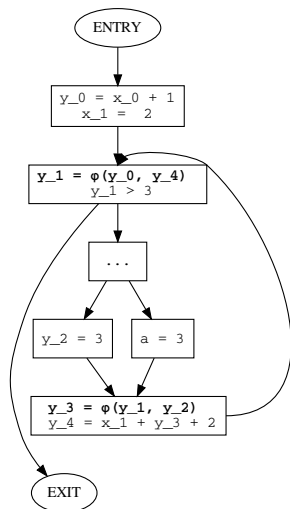
Here, our method constructs a redundant ϕ function for x_2 .

Example: Redundant ϕ functions (now with loops)



Here, x_3 is redundant, and its removal makes x_2 redundant.

Example: Non-redundant ϕ functions



This gets rid of the redundant ϕ functions.

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References

- ▶ Chapter 9 of Cooper and Turczon
 - ▶ Section 9.2.1
 - ▶ Section 9.3