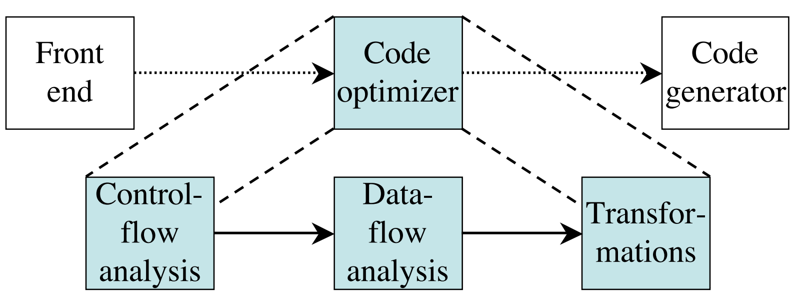
Code Optimization

Chapter 10

The Code Optimizer

- Control flow analysis: CFG (Ch. 9)
- Data-flow analysis
- Transformations



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Code Optimizations

- Local/global common subexpression elimination
- Dead-code elimination
- Instruction reordering
- Constant folding
- Algebraic transformations
- Copy propagation
- *Loop optimizations*

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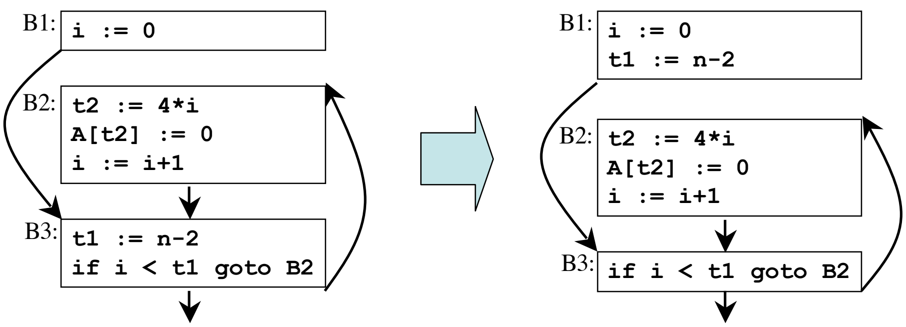
Loop Optimizations

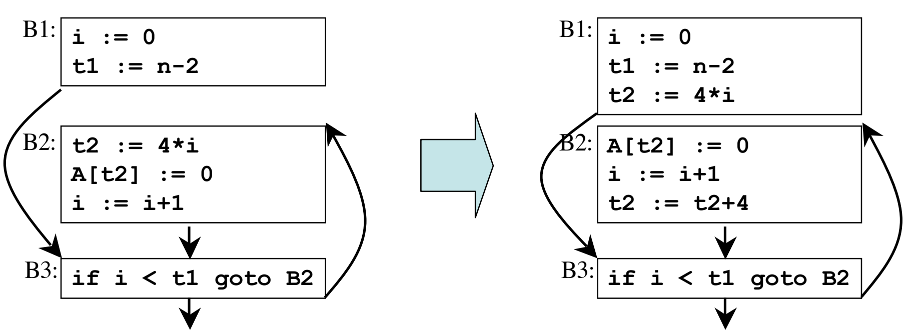
- Code motion
- Induction variable elimination
- Reduction in strength
- … lots more

Code Motion



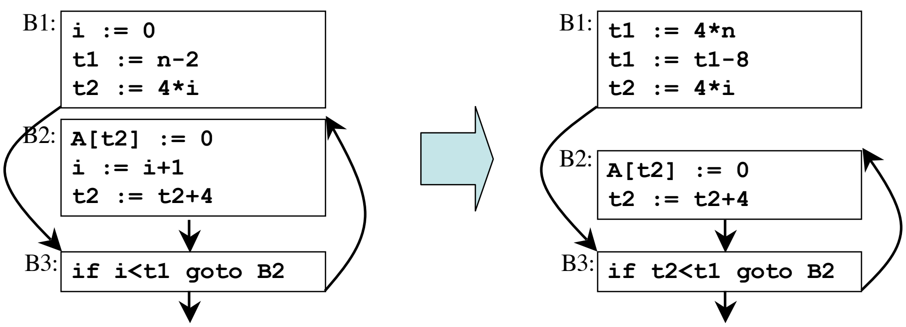
Move *loop-invariant computations* before the loop

Strength Reduction



Replace expensive computations with *induction variables*

Reduction Variable Elimination

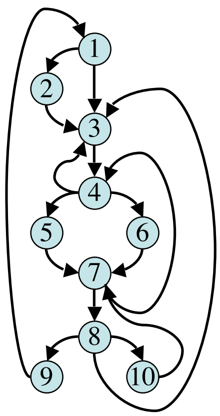


Replace induction variable in expressions with another

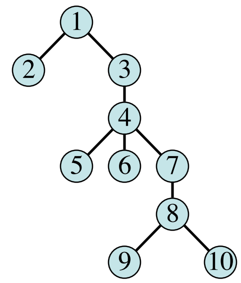
Determining Loops in Flow Graphs: Dominators

- Dominators: *d dom n*
  - Node *d* of a CFG *dominates* node *n* if *every* path from the initial node of the CFG to *n* goes through *d*
  - The loop entry dominates all nodes in the loop
- The *immediate dominator m* of a node *n* is the last dominator on the path from the initial node to *n*
  - If $d \neq n$ and *d dom n* then *d dom m*

Dominator Trees



CFG



Dominator tree

Natural Loops

- A *back edge* is is an edge $a \rightarrow b$ whose head b dominates its tail a
- Given a back edge $n \rightarrow d$
  - The *natural loop* consists of d plus the nodes that can reach n without going through d
  - The *loop header* is node d
- Unless two loops have the same header, they are disjoint or one is nested within the other
  - A nested loop is an *inner loop* if it contains no other loops

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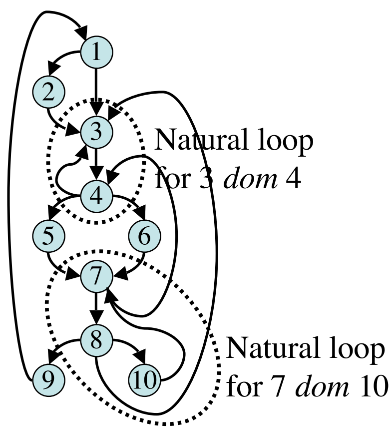
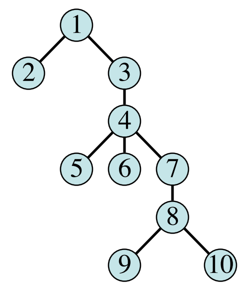
Natural (Inner) Loops Example



CFG



Dominator tree

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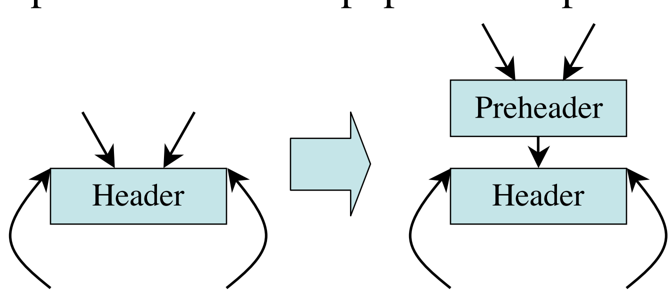
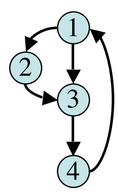
Pre-Headers

- To facilitate loop transformations, a compiler often adds a *preheader* to a loop
- Code motion, strength reduction, and other loop transformations populate the preheader

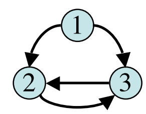


Reducible Flow Graphs

- *Reducible graph* = disjoint partition in forward and back edges such that the forward edges form an acyclic (sub)graph



Example of a reducible CFG

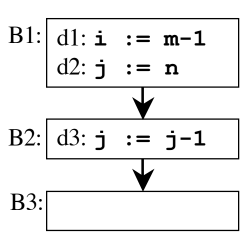


Example of a nonreducible CFG

Global Data-Flow Analysis

- To apply global optimizations on basic blocks, *data-flow information* is collected by solving systems of *data-flow equations*
- Suppose we need to determine the *reaching definitions* for a sequence of statements S

  $out[S] = gen[S] \cup (in[S] - kill[S])$



$out[B1] = gen[B1] = \{d1, d2\}$
$out[B2] = gen[B2] \cup \{d1\} = \{d1, d3\}$

d1 reaches B2 and B3 and
d2 reaches B2, but not B3
because d2 is killed in B2

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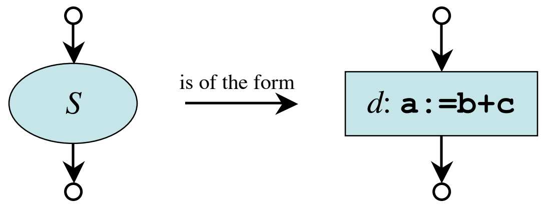
Reaching Definitions



Then, the data-flow equations for S are:

$gen[S]$	$= \{d\}$
$kill[S]$	$= D_{\mathbf{a}} - \{d\}$
$out[S]$	$= gen[S] \cup (in[S] - kill[S])$

where $D_{\mathbf{a}}$ = all definitions of **`a`** in the region of code

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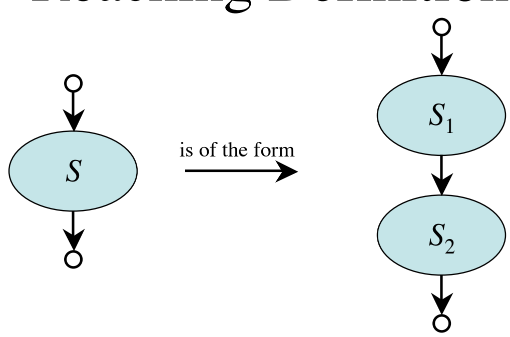
Reaching Definitions



$gen[S]$	$= gen[S_2] \cup (gen[S_1] - kill[S_2])$
$kill[S]$	$= kill[S_2] \cup (kill[S_1] - gen[S_2])$
$in[S_1]$	$= in[S]$
$in[S_2]$	$= out[S_1]$
$out[S]$	$= out[S_2]$

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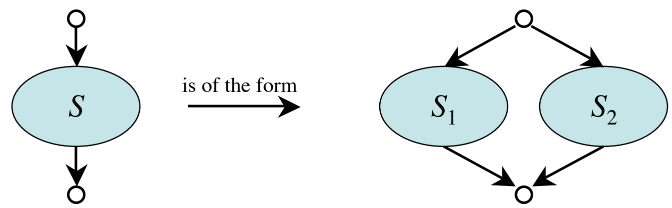
Reaching Definitions



$gen[S] = gen[S_1] \cup gen[S_2]$
$kill[S] = kill[S_1] \cap kill[S_2]$
$in[S_1] = in[S]$
$in[S_2] = in[S]$
$out[S] = out[S_1] \cup out[S_2]$

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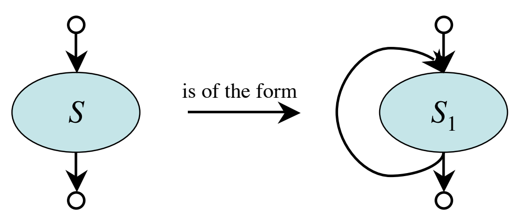
Reaching Definitions



$gen[S] = gen[S_1]$
$kill[S] = kill[S_1]$
$in[S_1] = in[S] \cup gen[S_1]$
$out[S] = out[S_1]$

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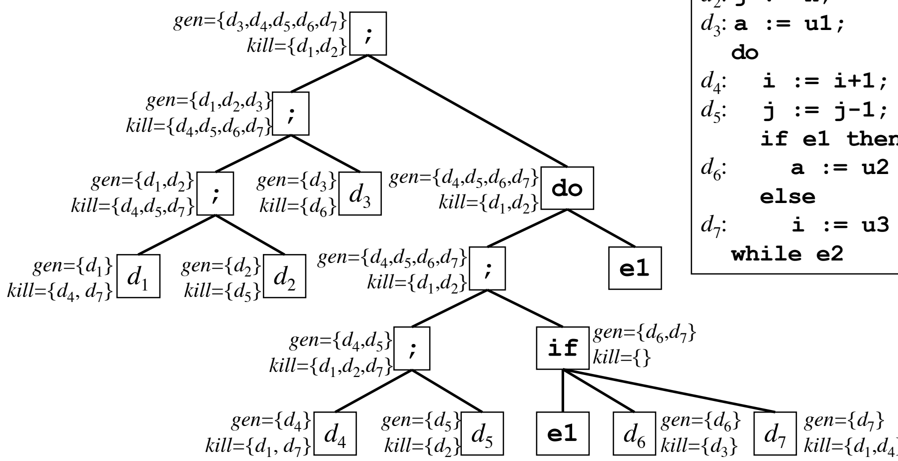
Example Reaching Definitions




```
d1: i := m-1;
d2: j := n;
d3: a := u1;
    do
d4:   i := i+1;
d5:   j := j-1;
      if e1 then
d6:     a := u2
      else
d7:     i := u3
    while e2
```

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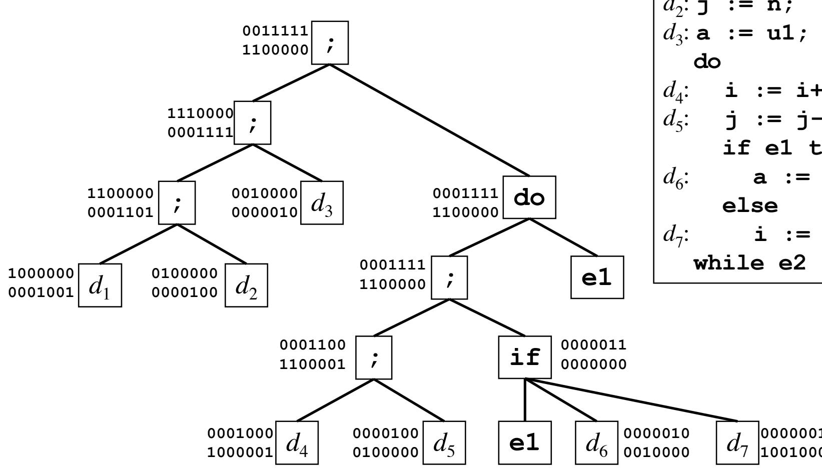
Using Bit-Vectors to Compute Reaching Definitions

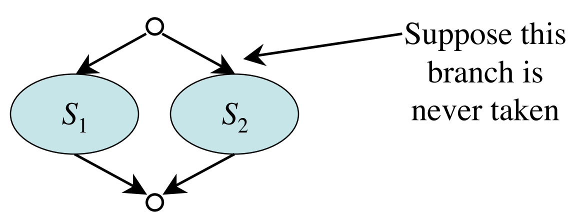
```
d1: i := m-1;
d2: j := n;
d3: a := u1;
    do
d4:   i := i+1;
d5:   j := j-1;
      if e1 then
d6:     a := u2
      else
d7:     i := u3
    while e2
```



Accuracy, Safeness, and Conservative Estimations

- *Conservative*: refers to making safe assumptions when insufficient information is available at compile time, i.e. the compiler has to guarantee not to change the meaning of the optimized code
- *Safe*: refers to the fact that a superset of reaching definitions is safe (some may be have been killed)
- *Accuracy*: the larger the superset of reaching definitions, the less information we have to apply code optimizations

Reaching Definitions are a Conservative (Safe) Estimation



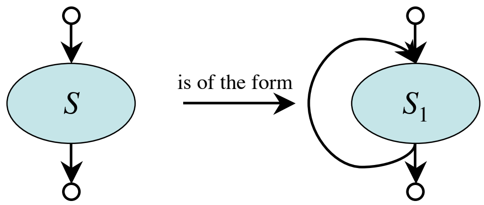
Estimation:

$gen[S] = gen[S_1] \cup gen[S_2]$
$kill[S] = kill[S_1] \cap kill[S_2]$

Accurate:

$gen'[S] = gen[S_1] \subseteq gen[S]$
$kill'[S] = kill[S_1] \supseteq kill[S]$

Reaching Definitions are a Conservative (Safe) Estimation



Why *gen*?

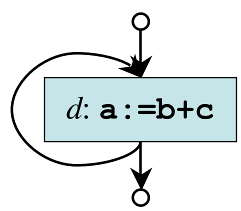
$in[S_1] = in[S] \cup gen[S_1]$

The problem is that

$$in[S_1] = in[S] \cup out[S_1]$$

makes more sense, but we cannot solve this directly, because $out[S_1]$ depends on $in[S_1]$

Reaching Definitions are a Conservative (Safe) Estimation



We have:

(1) $in[S_1] = in[S] \cup out[S_1]$

(2) $out[S_1] = gen[S_1] \cup (in[S_1] - kill[S_1])$

Solve $in[S_1]$ and $out[S_1]$ by estimating $in^1[S_1]$ using safe but approximate $out[S_1]=\varnothing$, then re-compute $out^1[S_1]$ using (2) to estimate $in^2[S_1]$, etc.

$$
\begin{aligned}
in^1[S_1] &=_{(1)} in[S] \cup out[S_1] = in[S] \\
out^1[S_1] &=_{(2)} gen[S_1] \cup (in^1[S_1] - kill[S_1]) = gen[S_1] \cup (in[S] - kill[S_1]) \\
in^2[S_1] &=_{(1)} in[S] \cup out^1[S_1] = in[S] \cup gen[S_1] \cup (in[S] - kill[S_1]) = in[S] \cup gen[S_1] \\
out^2[S_1] &=_{(2)} gen[S_1] \cup (in^2[S_1] - kill[S_1]) = gen[S_1] \cup (in[S] \cup gen[S_1] - kill[S_1]) \\
&= gen[S_1] \cup (in[S] - kill[S_1])
\end{aligned}
$$

Because $out^1[S_1] = out^2[S_1]$, and therefore $in^3[S_1] = in^2[S_1]$, we conclude that

$in[S_1] = in[S] \cup gen[S_1]$