Compilerconstructie

najaar 2012

`http://www.liacs.nl/home/rvvliet/coco/`

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college 8, dinsdag 13 november 2012

Code Optimization

9.1 The Principal Sources of Optimization

Causes of redundancy

- At source level
- Side effect of high-level programming language, e.g., $A[i][j]$

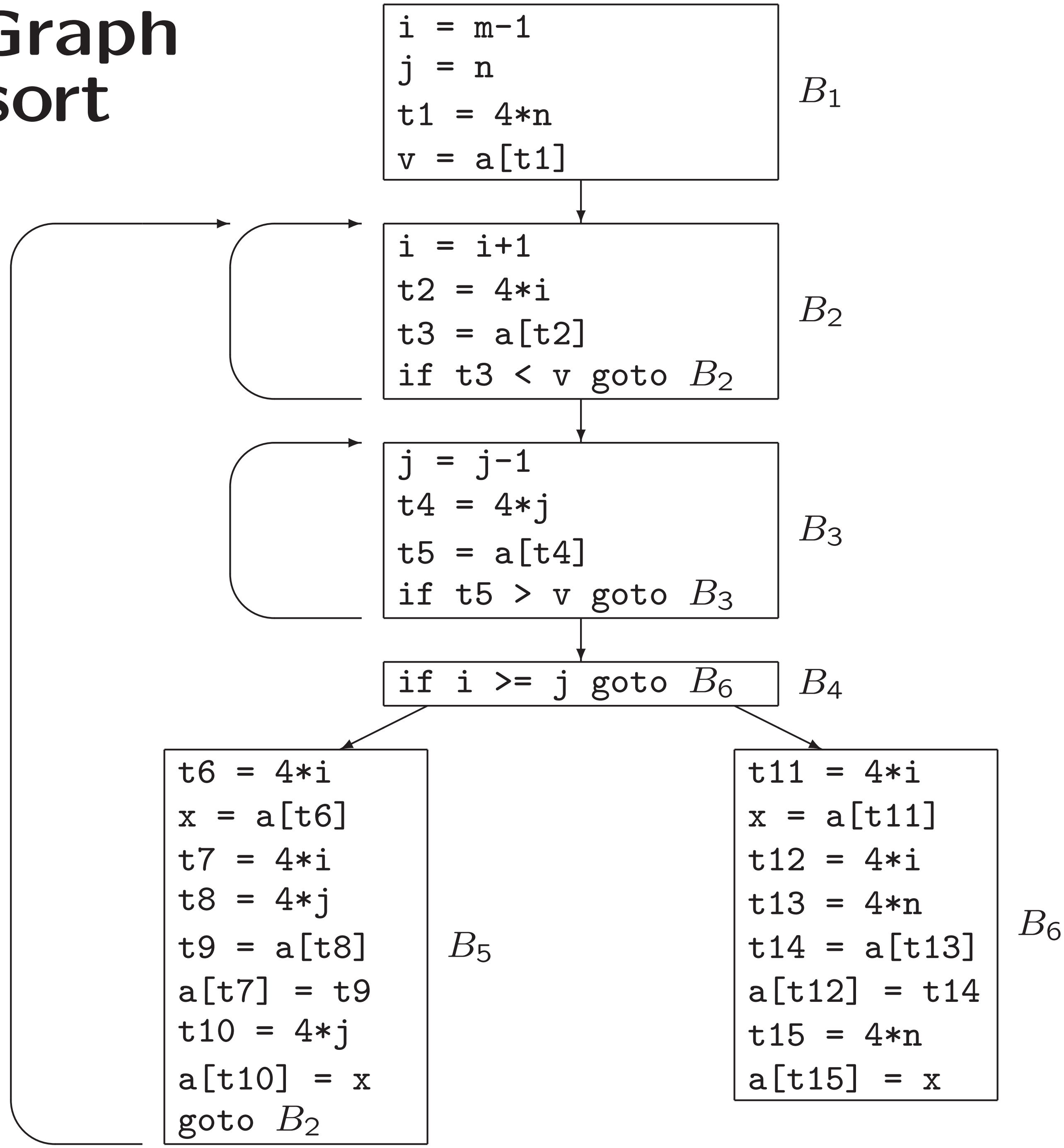
A Running Example: Quicksort

```
void quicksort (int m, int n)
    /* recursively sorts a[m] through a[n] */
{
    int i, j;
    int v, x;

    if (n <= m) return;

    i = m-1; j = n; v = a[n];
    while (1)
    {   do i = i+1; while (a[i] < v);
        do j = j-1; while (a[j] > v);
        if (i >= j) break;
        x = a[i]; a[i] = a[j]; a[j] = x; /* swap a[i], a[j] */
    }
    x = a[i]; a[i] = a[n]; a[n] = x; /* swap a[i], a[n] */

    quicksort(m,j); quicksort(i+1,n);
}
```

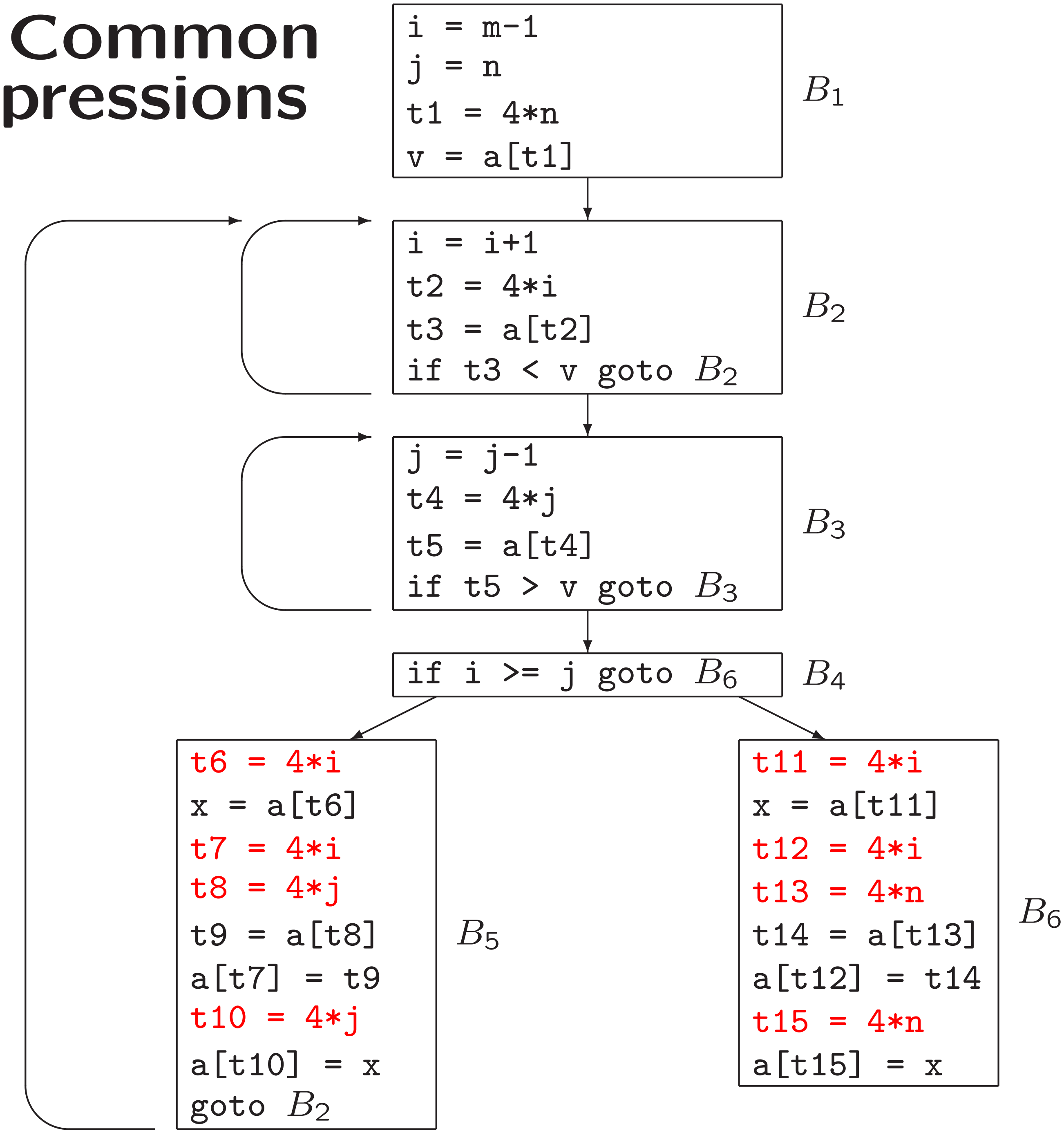
Three-Address Code Quicksort

```
→   (1)   i = m-1
    (2)   j = n
    (3)   t1 = 4*n
    (4)   v = a[t1]
→   (5)   i = i+1
    (6)   t2 = 4*i
    (7)   t3 = a[t2]
    (8)   if t3<v goto (5)
→   (9)   j = j-1
   (10)   t4 = 4*j
   (11)   t5 = a[t4]
   (12)   if t5>v goto (9)
→  (13)   if i>=j goto (23)
→  (14)   t6 = 4*i
   (15)   x = a[t6]
   (16)   t7 = 4*i
   (17)   t8 = 4*j
   (18)   t9 = a[t8]
   (19)   a[t7] = t9
   (20)   t10 = 4*j
   (21)   a[t10] = x
   (22)   goto (5)
→  (23)   t11 = 4*i
   (24)   x = a[t11]
   (25)   t12 = 4*i
   (26)   t13 = 4*n
   (27)   t14 = a[t13]
   (28)   a[t12] = t14
   (29)   t15 = 4*n
   (30)   a[t15] = x
```

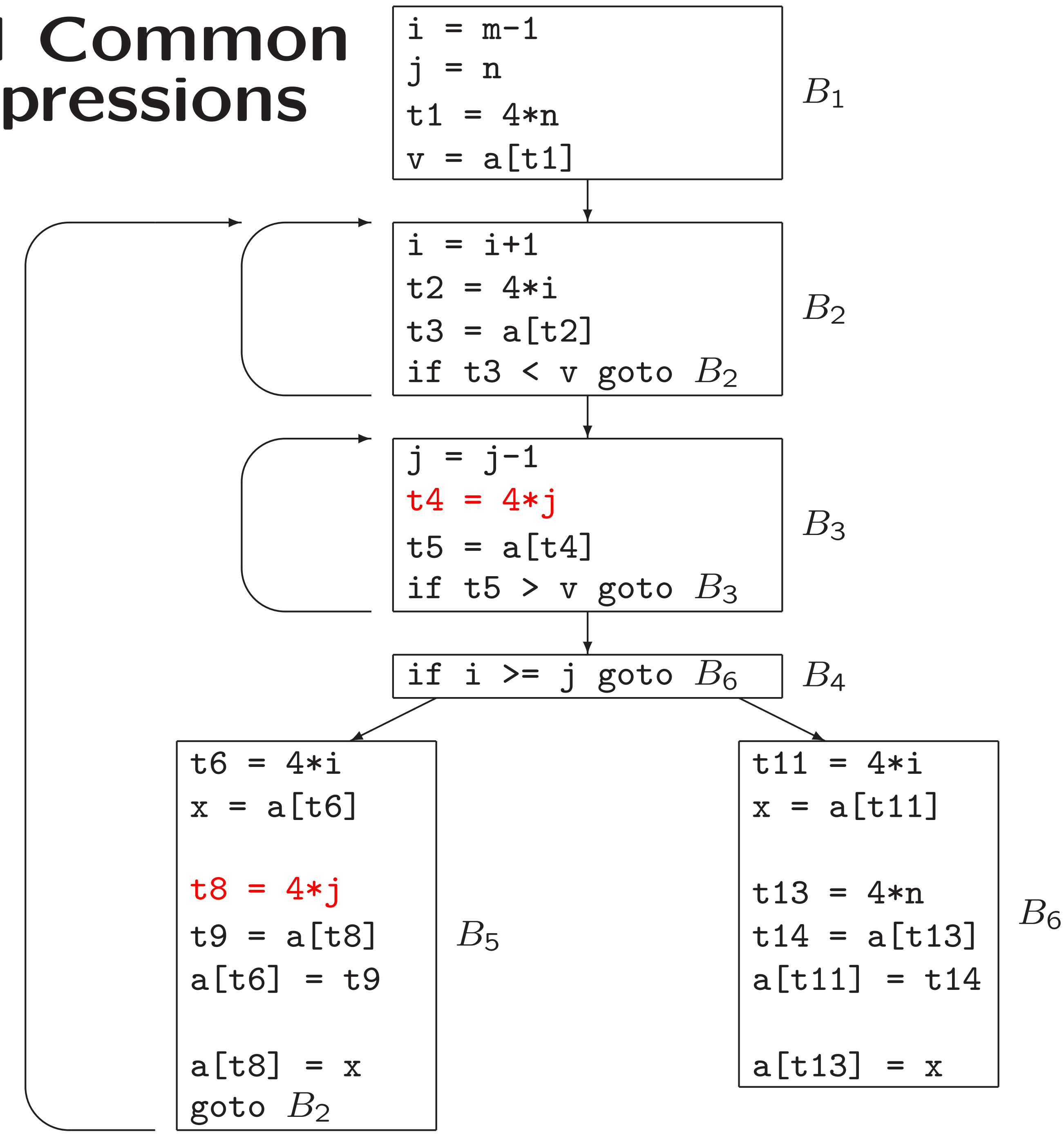
Flow Graph Quicksort



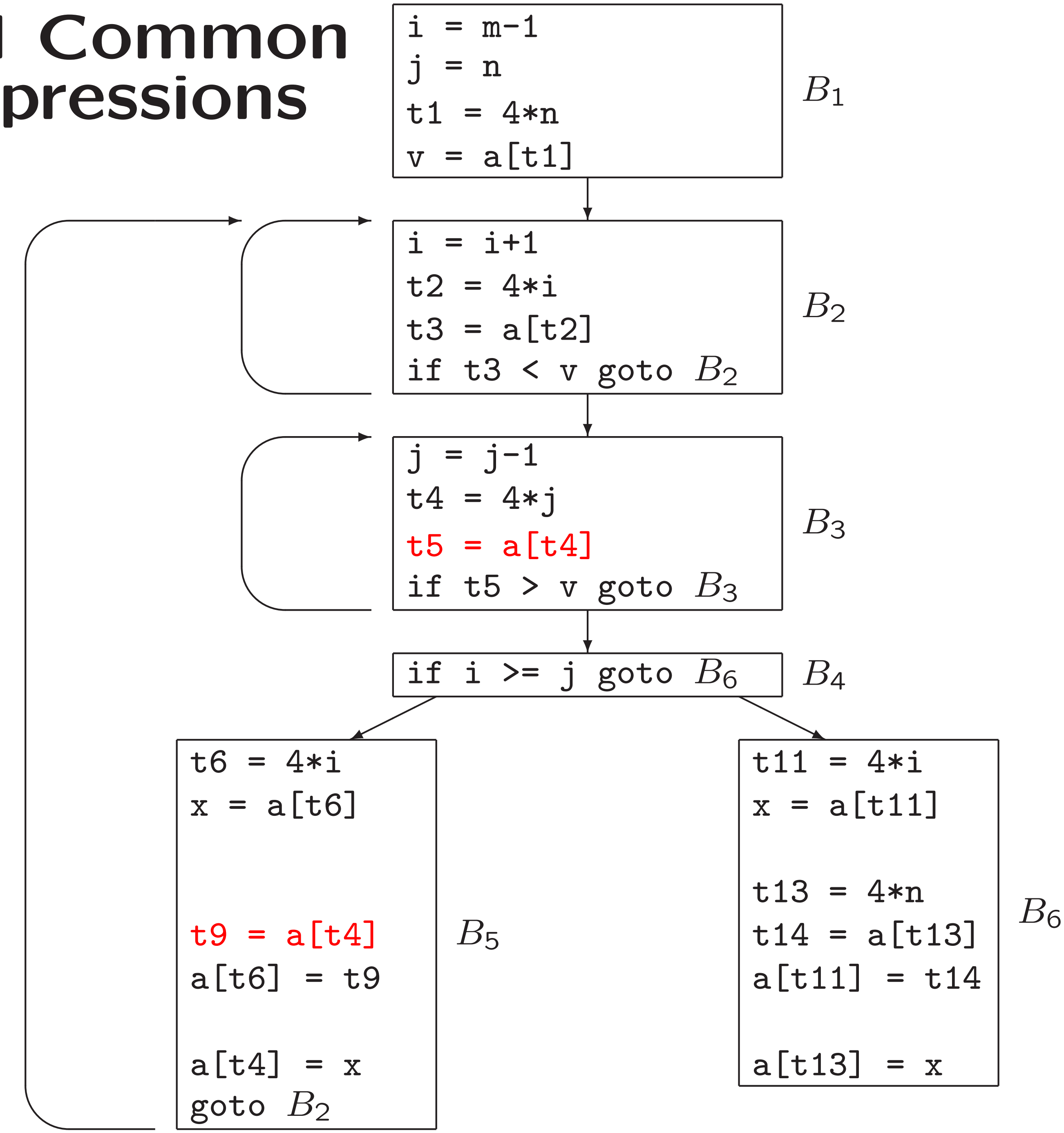
Local Common Subexpressions



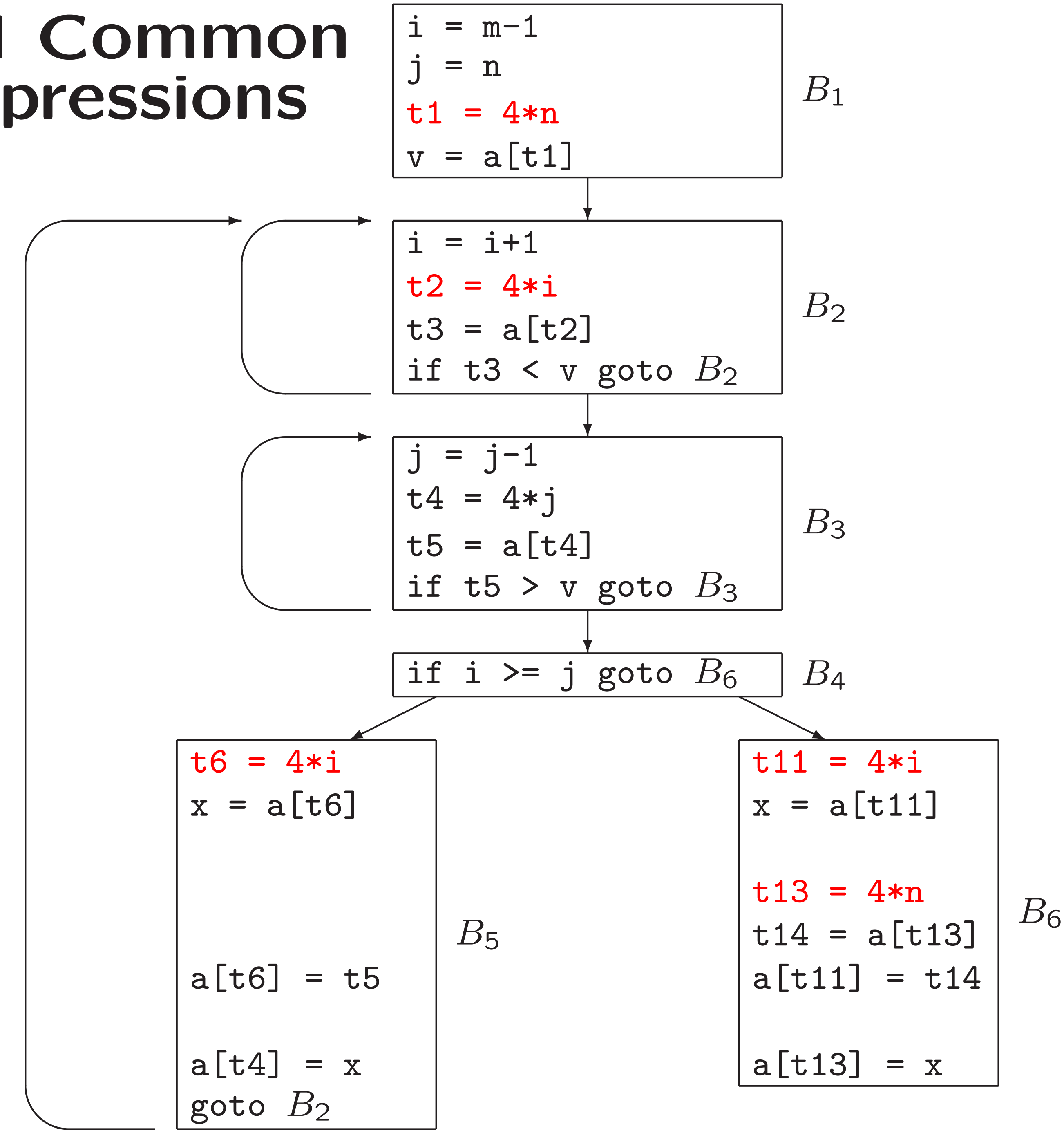
Global Common Subexpressions



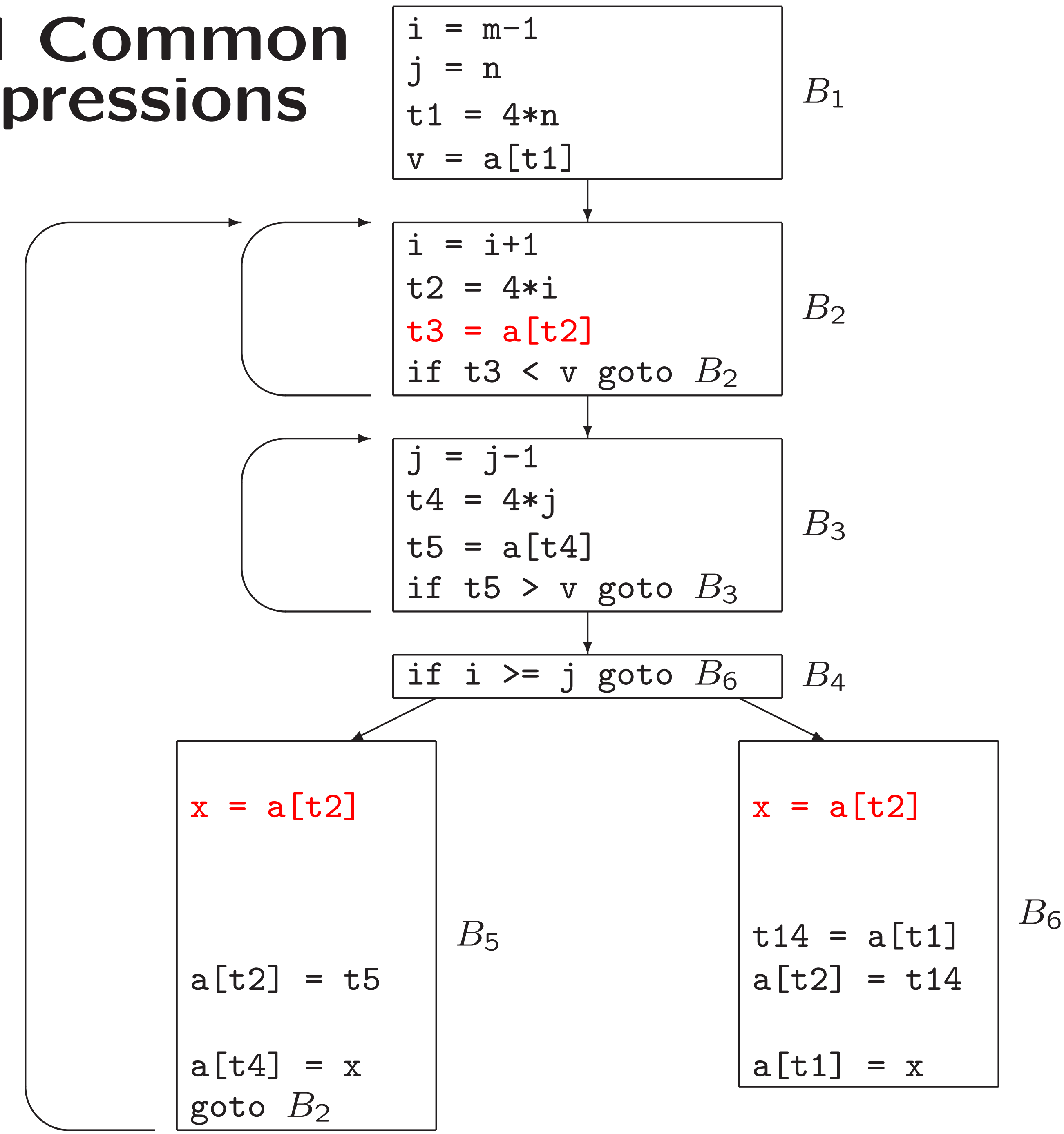
Global Common Subexpressions



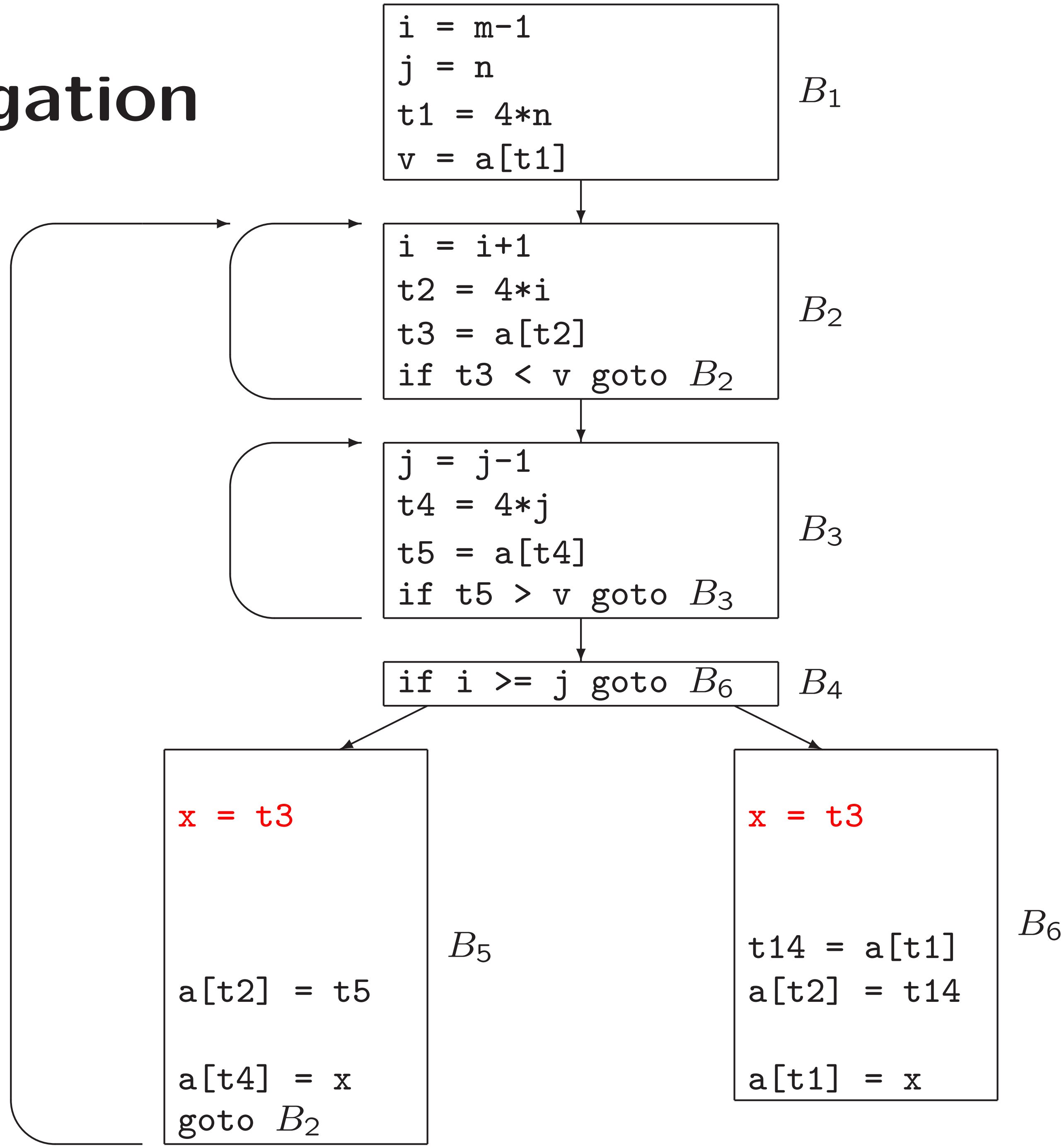
Global Common Subexpressions



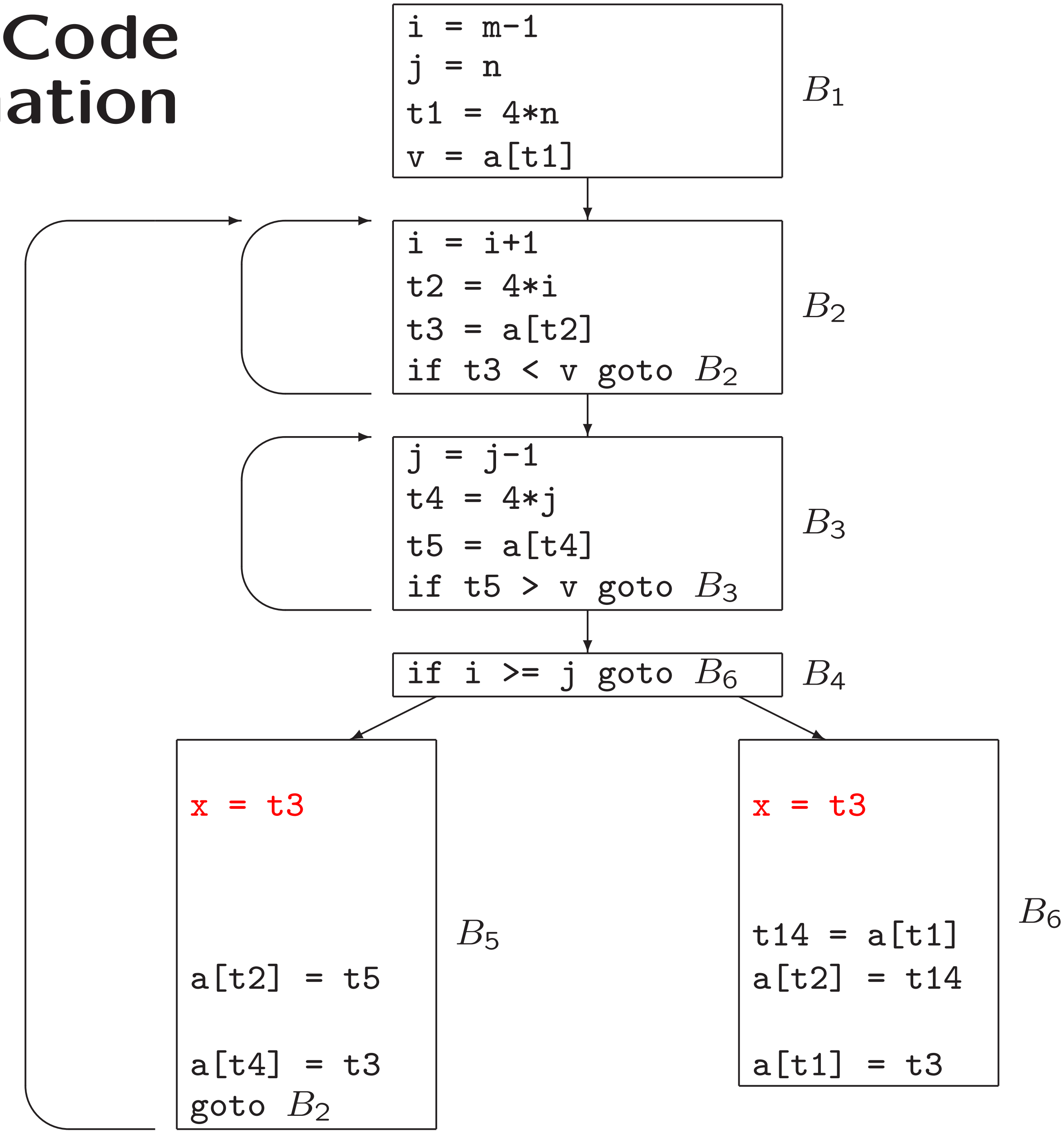
Global Common Subexpressions



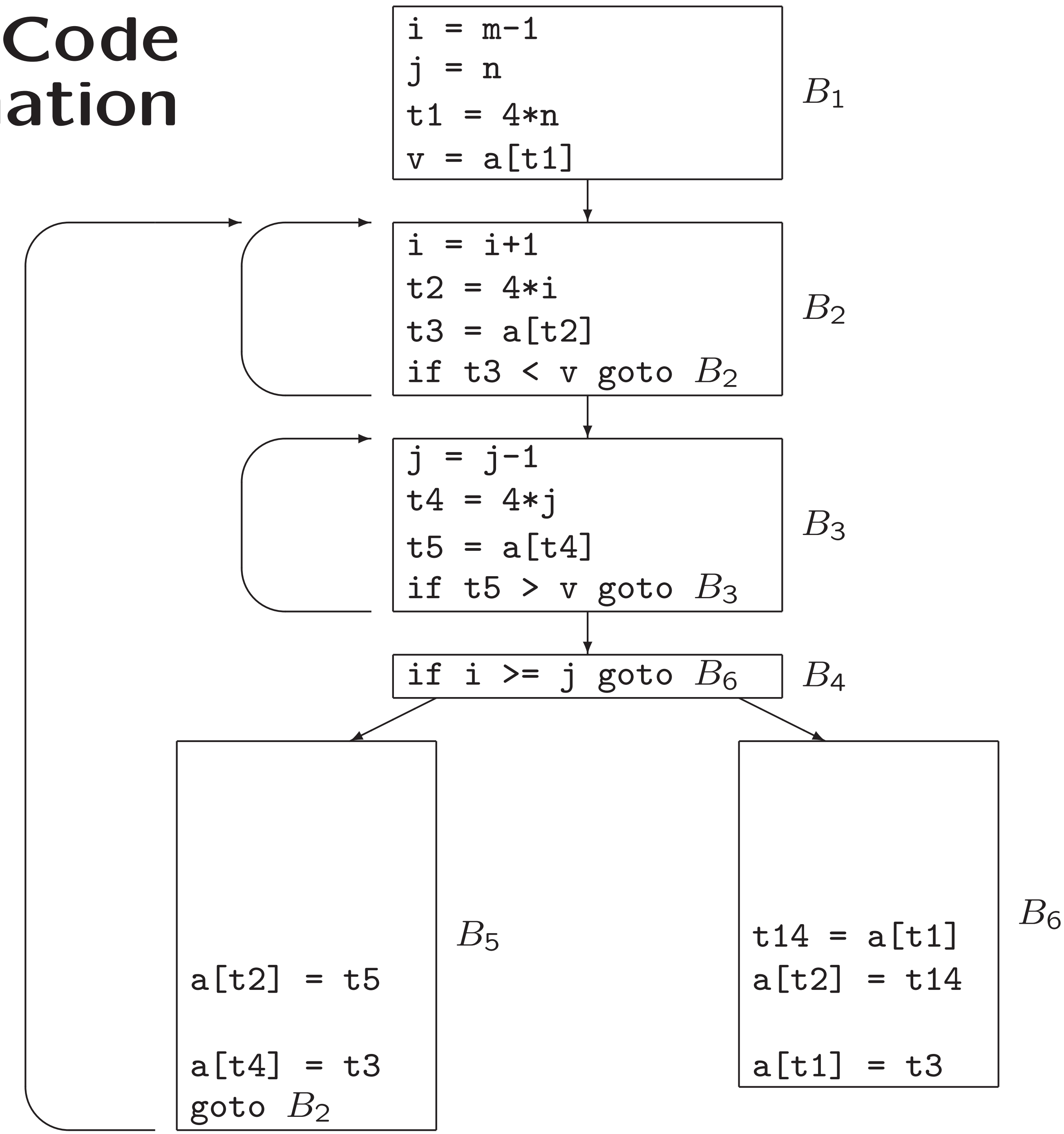
Copy Propagation



Dead-Code Elimination



Dead-Code Elimination



Code Motion

- loop-invariant computation
- compute before loop
- Example:

```
while (i <= limit-2)  /* statement does not change limit */
```

After code-motion

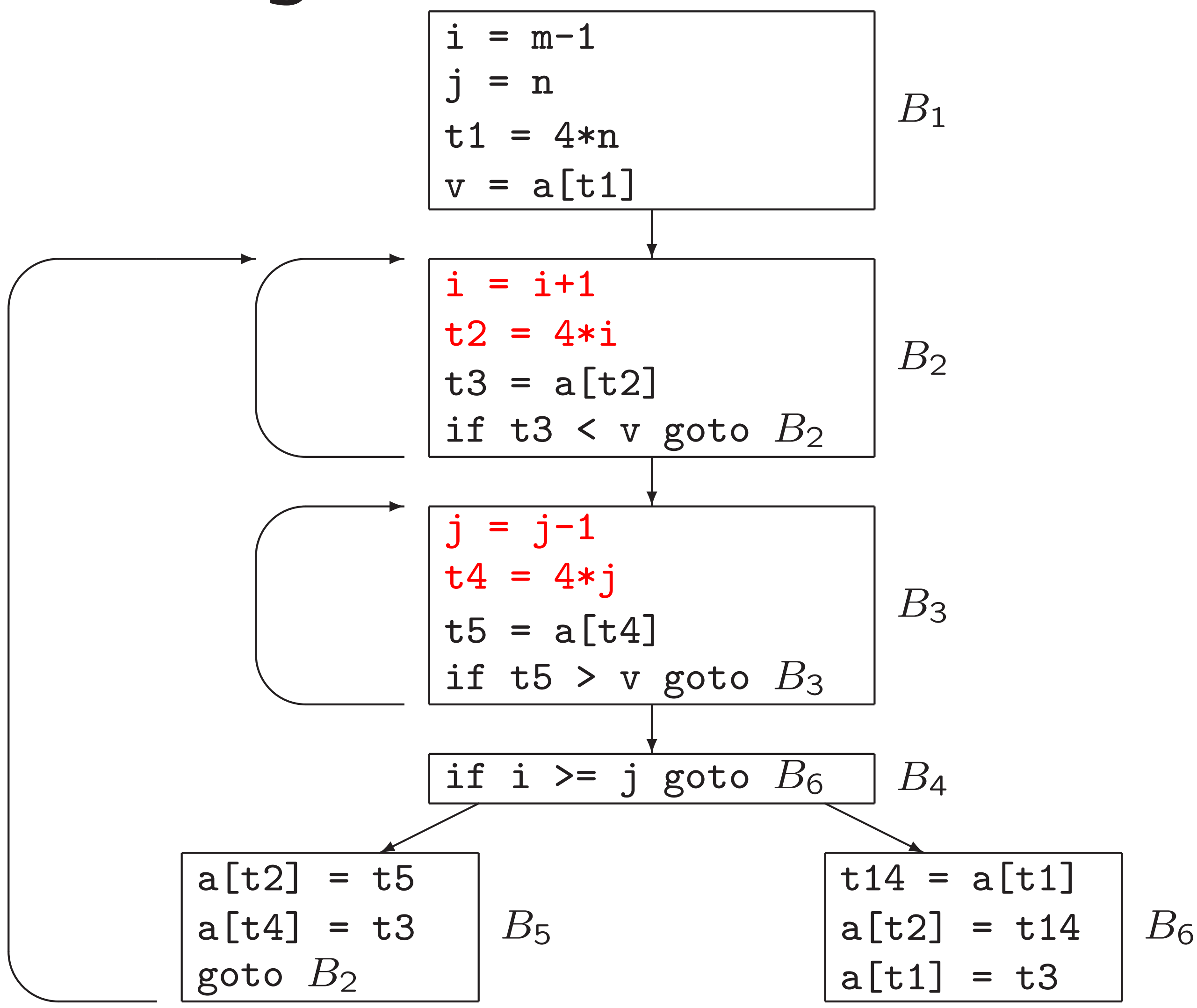
```
t = limit-2
while (i <= t)  /* statement does not change limit or t */
```

Induction Variables and Reduction in Strength

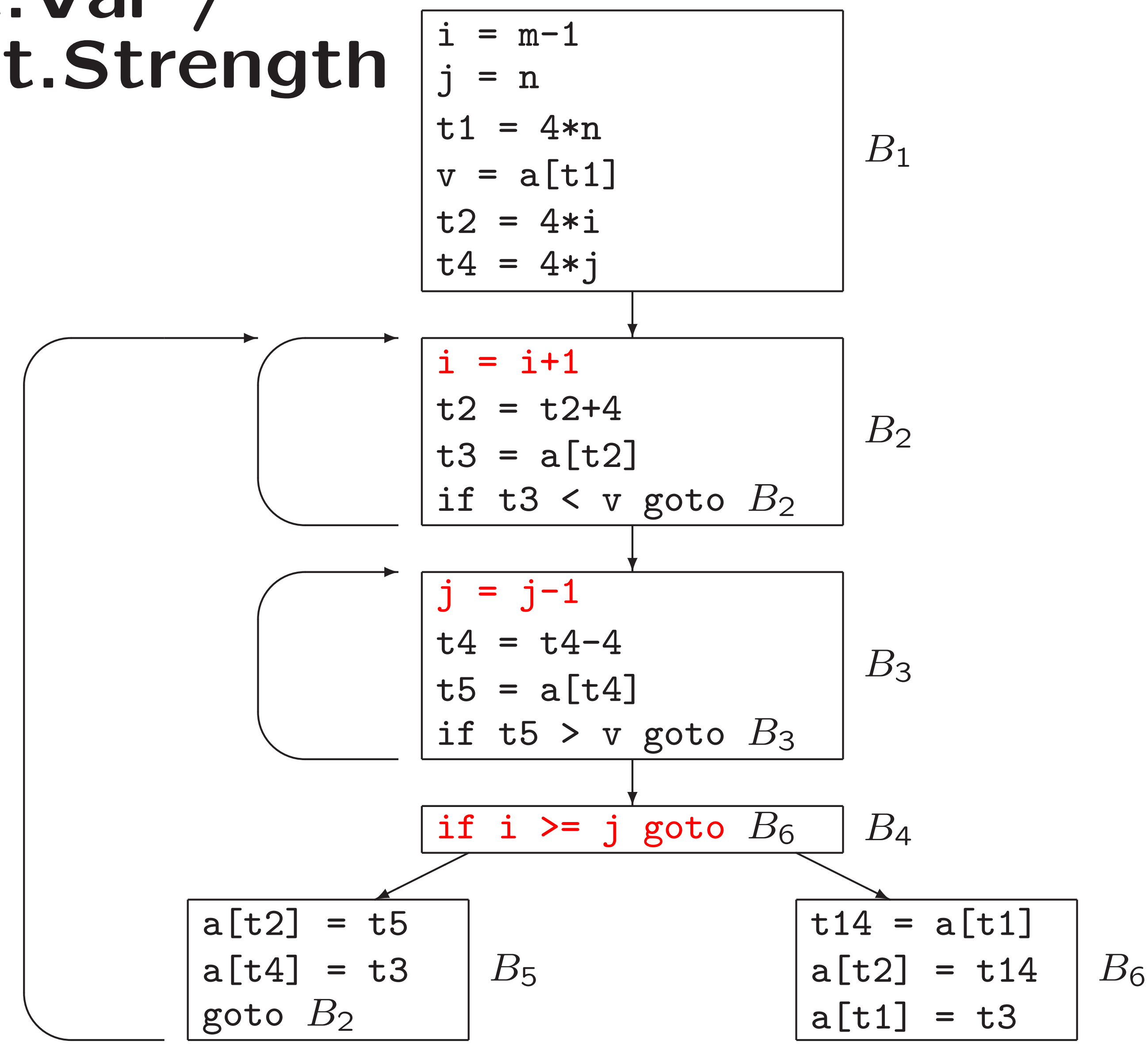
- Induction variable: each assignment to x of form $x = x + c$

- Reduction in strength: replace expensive operation by cheaper one

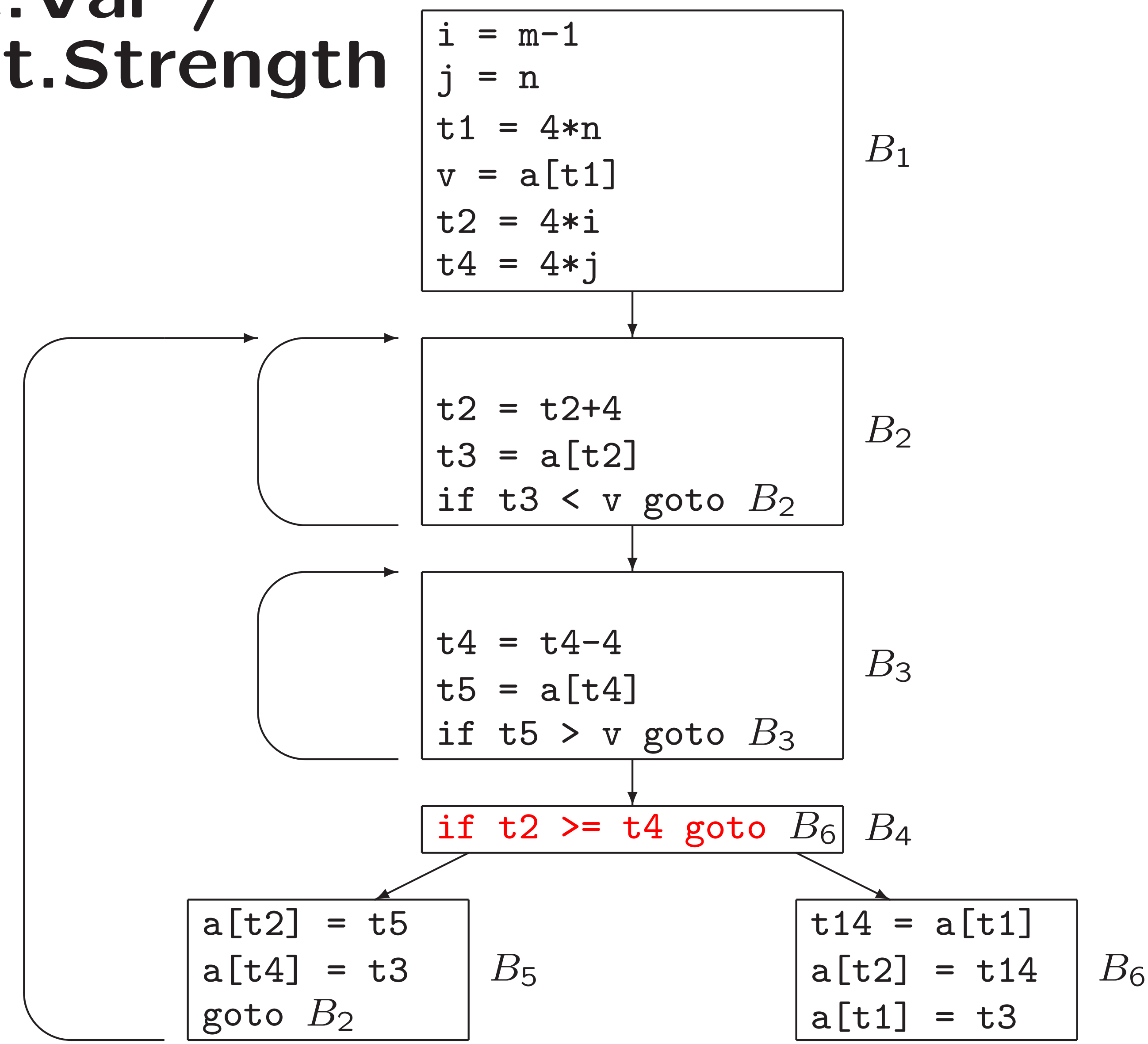
Induct.Var / Reduct.Strength



Induct.Var / Reduct.Strength



Induct.Var / Reduct.Strength



9.2 Introduction to Data-Flow Analysis

- Optimizations depend on data-flow analysis, e.g.,
  - Global common subexpression elimination
  - Dead-code elimination
- Execution path yields program state
- Extract information from program state for data-flow analysis
- Usually infinite number of execution paths / program states
- Different analyses extract different information

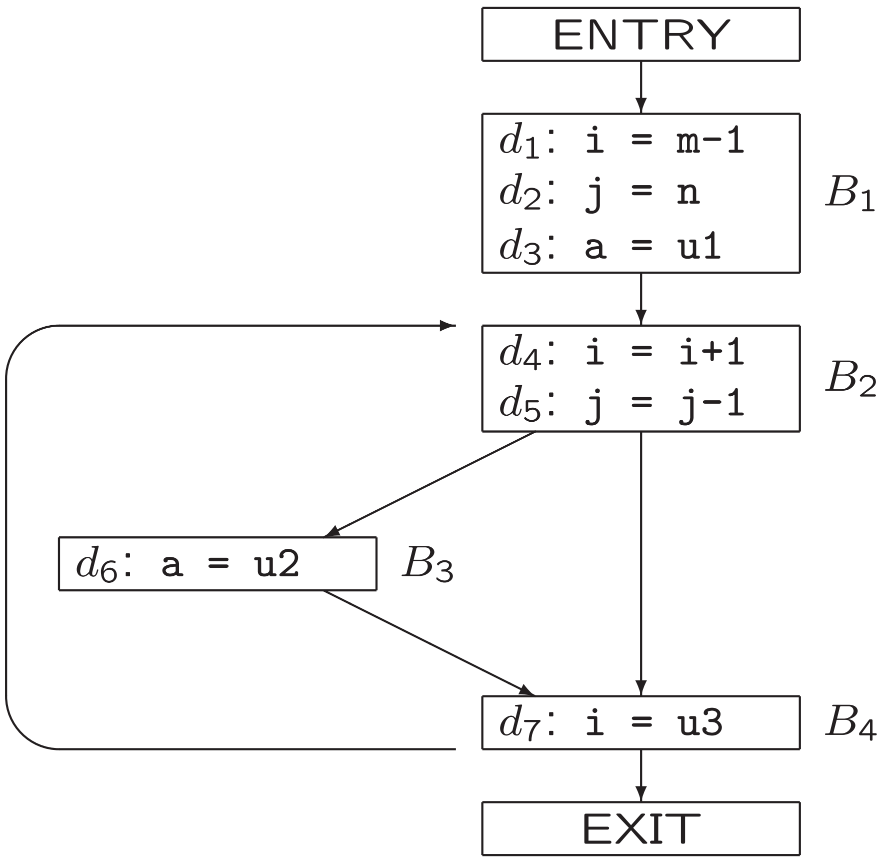
Data-Flow Analysis (Examples)

Extract information from program states at program point

- Reaching definitions: which definitions (assignments of values) of variable a reach program point?

- Can variable x only have one constant value at program point?
  Useful for constant folding

Computing Reaching Definitions



Reaching definitions

- Before B_1: $\emptyset$
- After B_1: $\{d_1, d_2, d_3\}$
- Before B_2: ...

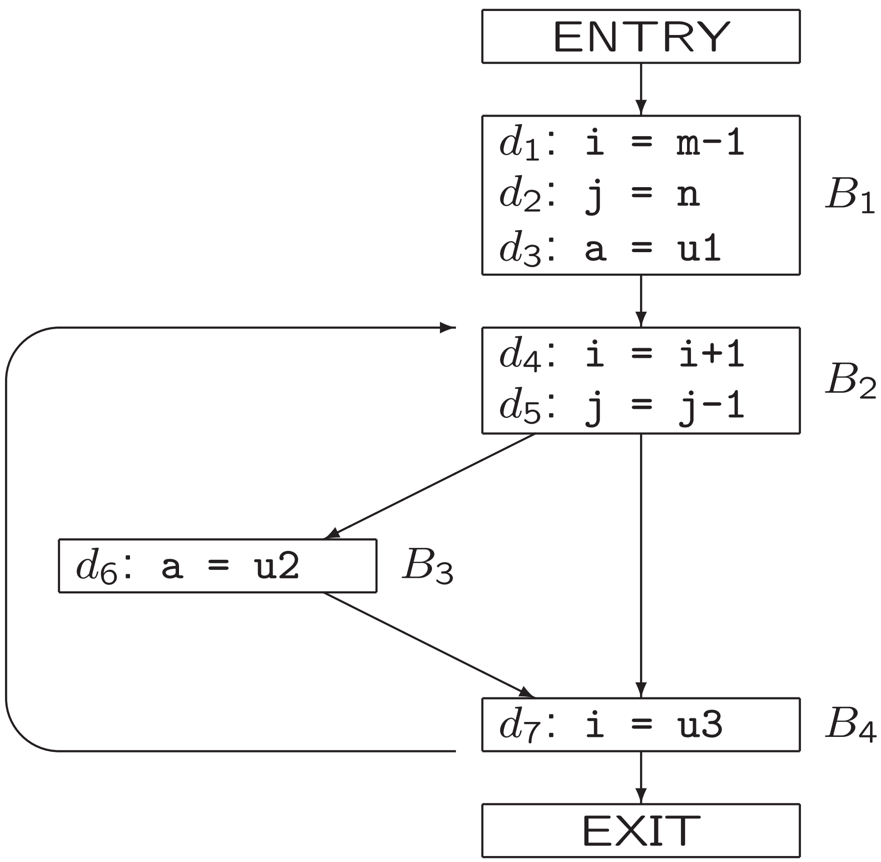
Computing Reaching Definitions

- Effect of single definition $d : u = v$ *op* w:
  - $gen_d = \{d\}$
  - $kill_d = \{$all other definitions of u in program$\}$

- Effect of block B, with definitions $1, 2, \ldots, n$:

$$
\begin{aligned}
gen_B &= \{n, n-1, \ldots, 1\} - \{\text{ definitions killed afterwards }\} \\
&= gen_n \cup (gen_{n-1} - kill_n) \cup (gen_{n-2} - kill_{n-1} - kill_n) \ldots \\
kill_B &= kill_1 \cup kill_2 \cup \ldots \cup kill_n
\end{aligned}
$$

Computing Reaching Definitions



$gen_{B_1} = \{d_1, d_2, d_3\}$
$kill_{B_1} = \{d_4, d_5, d_6, d_7\}$

$gen_{B_2} = \{d_4, d_5\}$
$kill_{B_2} = \{d_1, d_2, d_7\}$

$gen_{B_3} = \{d_6\}$
$kill_{B_3} = \{d_3\}$

$gen_{B_4} = \{d_7\}$
$kill_{B_4} = \{d_1, d_4\}$

Iterative Algorithm for Computing Reaching Definitions

$\text{OUT[ENTRY]} = \emptyset$
for each basic block B other than ENTRY
    $\text{OUT}[B] = \emptyset$

while (changes to any OUT occur)
    for each basic block B other than ENTRY
    $\{$ $\text{IN}[B] = \cup_{\text{predecessors } P \text{ of } B} \text{OUT}[P]$

        $\text{OUT}[B] = \textit{gen}_B \cup (\text{IN}[B] - \textit{kill}_B)$
    $\}$

Typical form of algorithm for forward data-flow analysis

Example with $B = B_1, B_2, B_3, B_4, \text{EXIT} \ldots$

Implementation of Iterative Algorithm for Computing Reaching Definitions

With bit vectors

Block B	$\text{OUT}[B]^0$	$\text{IN}[B]^1$	$\text{OUT}[B]^1$	$\text{IN}[B]^2$	$\text{OUT}[B]^2$
B_1	000 0000	000 0000	111 0000	000 0000	111 0000
B_2	000 0000	111 0000	001 1100	111 0111	001 1110
B_3	000 0000	001 1100	000 1110	001 1110	000 1110
B_4	000 0000	001 1110	001 0111	001 1110	001 0111
EXIT	000 0000	000 0000	001 0111	001 0111	001 0111

Live-Variable Analysis

- Variable x is live at program point p,
  if value of x at p could be used later along *some* path

- Otherwise x is dead at p

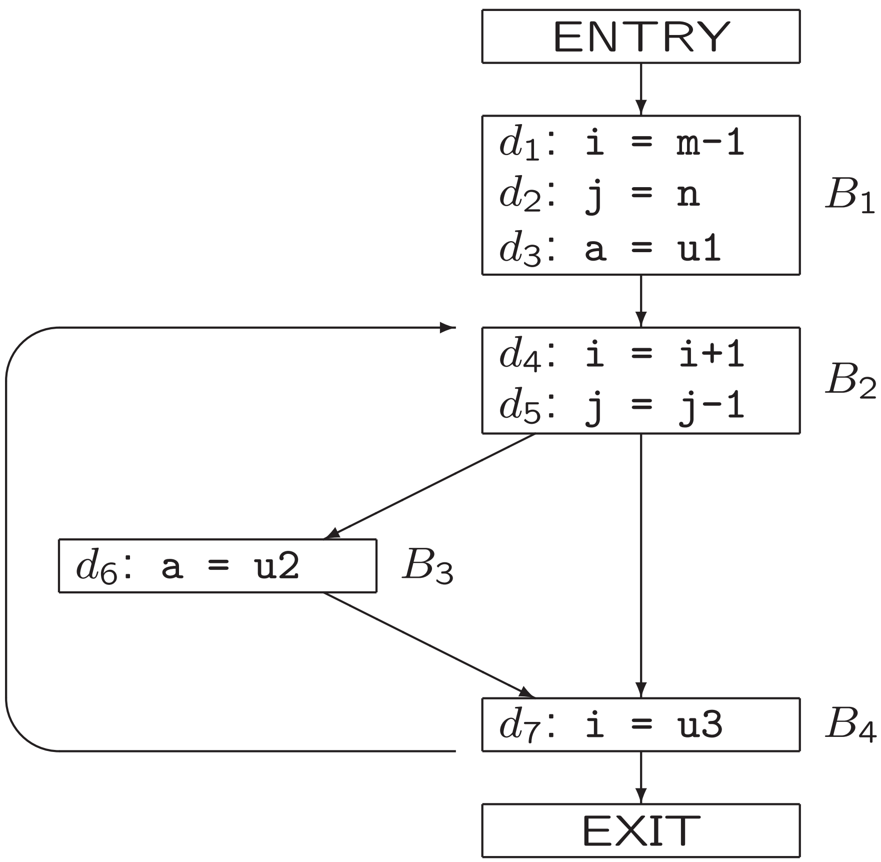
- Information useful for register allocation (see college 7)

- Information about later use must be propagated backwards

Live-Variable Analysis

- Effect of block B on live variables
  - *def*$_B$: variables *defined* in B
  - *use*$_B$: variables that may be *used* in B prior to any definition in B

Computing Liveness



$def_{B_1} = \{i, j, a\}$
$use_{B_1} = \{m, n, u1\}$

$def_{B_2} = \{i, j\}$
$use_{B_2} = \{i, j\}$

$def_{B_3} = \{a\}$
$use_{B_3} = \{u2\}$

$def_{B_4} = \{i\}$
$use_{B_4} = \{u3\}$

Iterative Algorithm for Computing Liveness

IN[EXIT] = $\emptyset$
for each basic block B other than EXIT
    IN[B] = $\emptyset$

while (changes to any IN occur)
    for each basic block B other than EXIT
    { OUT[B] = $\cup_{\text{successors } S \text{ of } B}$ IN[S]

        IN[B] = $use_B \cup$ (OUT[B] $-$ def_B)
    }

Typical form of algorithm for backward data-flow analysis

Available expressions

- Is (value of) expression x *op* y available?
- Useful for global common subexpression elimination
- Can be decided with data-flow analysis (not for exam)

Efficient Iterative Data-Flow Analysis

Example: computing reaching definitions

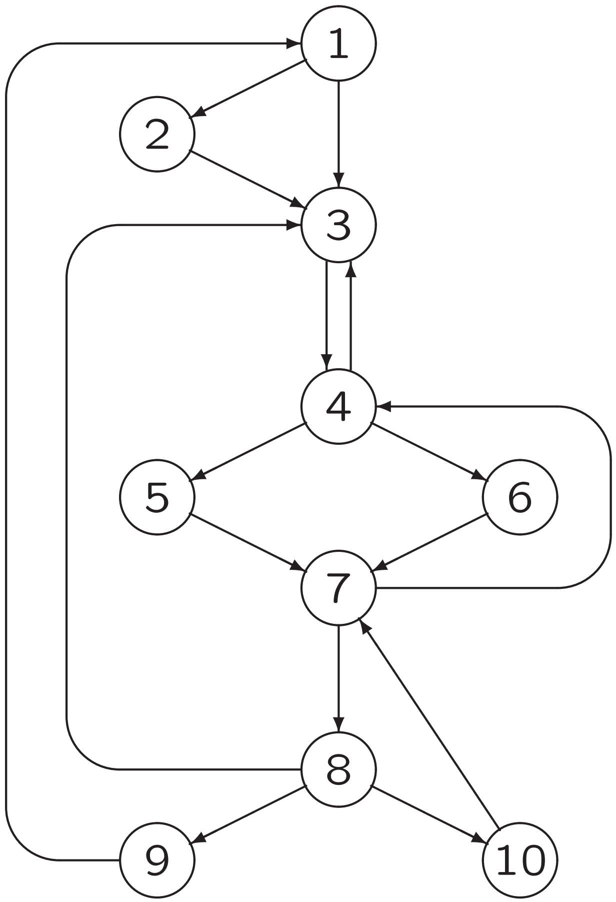
OUT[ENTRY] $= \emptyset$
for each basic block B other than ENTRY
    OUT[B] $= \emptyset$

while (changes to any OUT occur)
    for each basic block B other than ENTRY
    $\{$ IN[B] $= \cup_{\text{predecessors } P \text{ of } B}$ OUT[P]

        OUT[B] $=$ $gen_B \cup$ (IN[B] $-$ $kill_B$)
    $\}$

Order of blocks in second for-loop matters

Efficient Iterative Data-Flow Analysis



Order of blocks in second for-loop matters

9.6 Loops in Flow Graphs

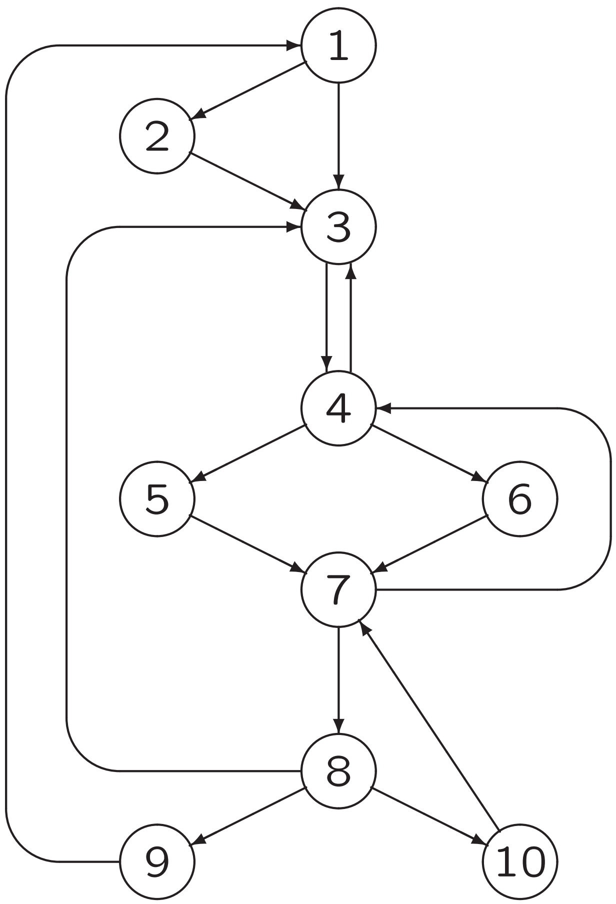
- Optimizations of loops have significant impact

- Essential to identify loops

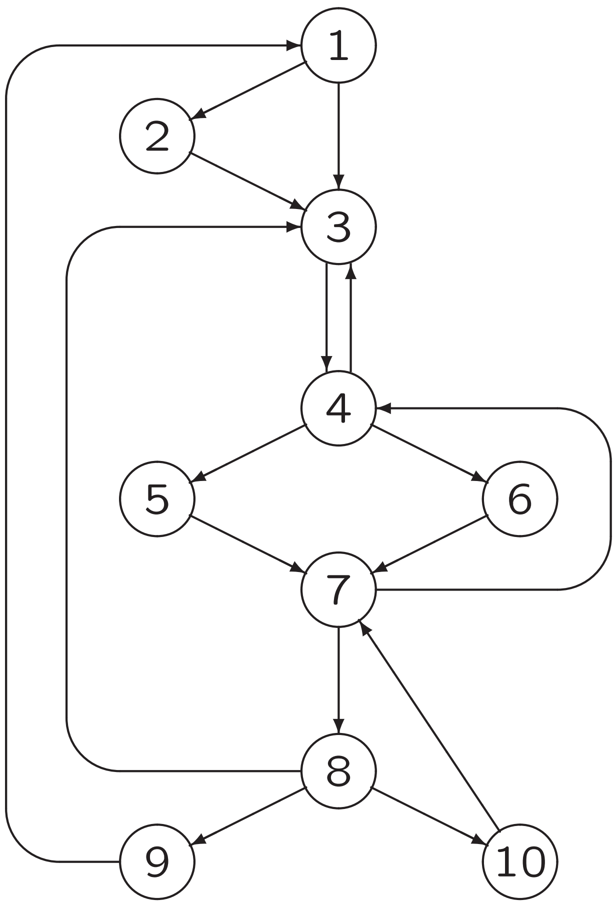
Dominators

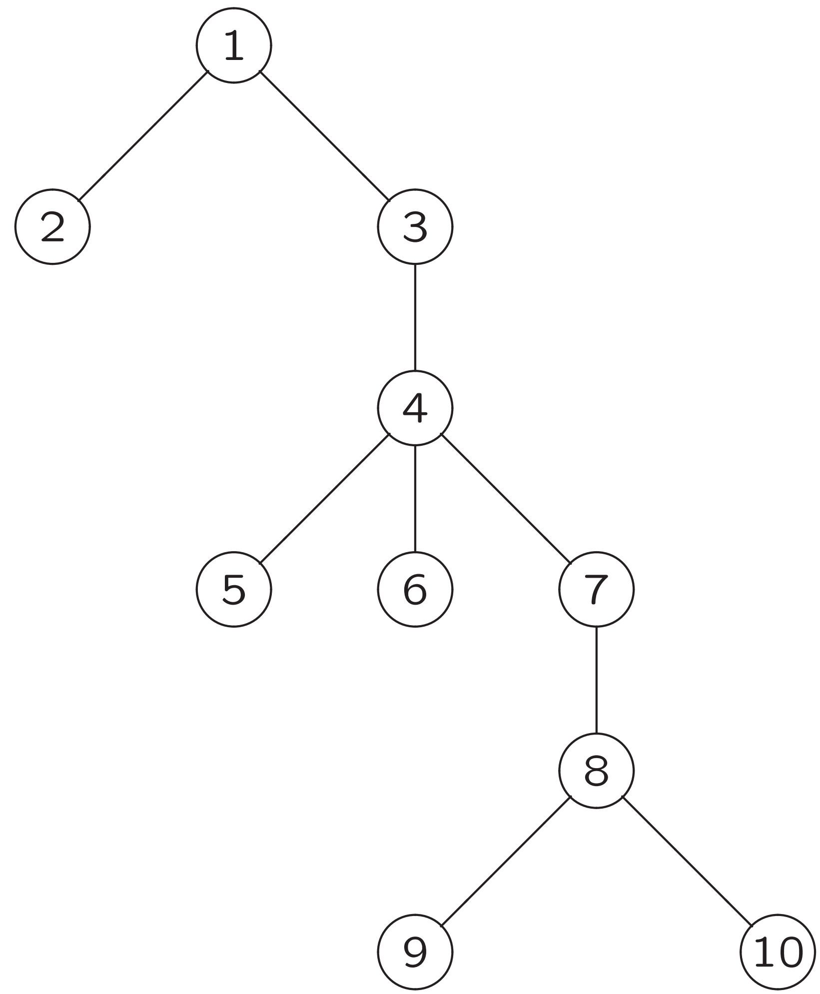
- Dominators:
  - Node d dominates node n if every path from ENTRY node to n goes through d: d *dom* n
  - Node n dominates itself
  - Loop entry dominates all nodes in loop
- Immediate dominator m of n:
  last dominator on (any) path from ENTRY node to n
  - if $d \neq n$ and d *dom* n, then d *dom* m

Dominators (Example)



Dominator Trees (Example)





Finding Dominators

Forward data-flow analysis

N is set of all nodes

OUT[ENTRY] $= \{$ENTRY$\}$
for each node n other than ENTRY
    OUT[n] $= N$

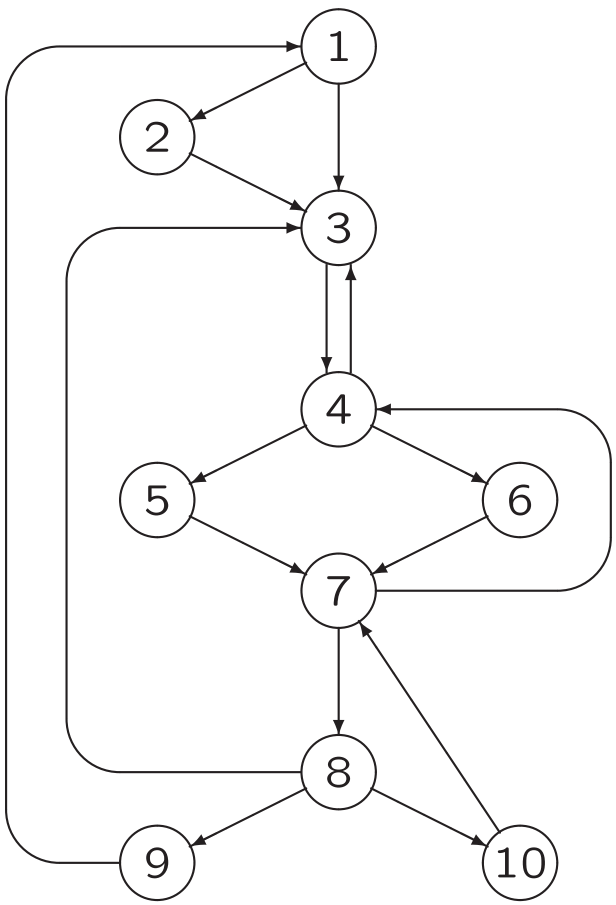
while (changes to any OUT occur)
    for each node n other than ENTRY
    $\{$ IN[n] $= \cap_{\text{predecessors } m \text{ of } n}$ OUT[m]

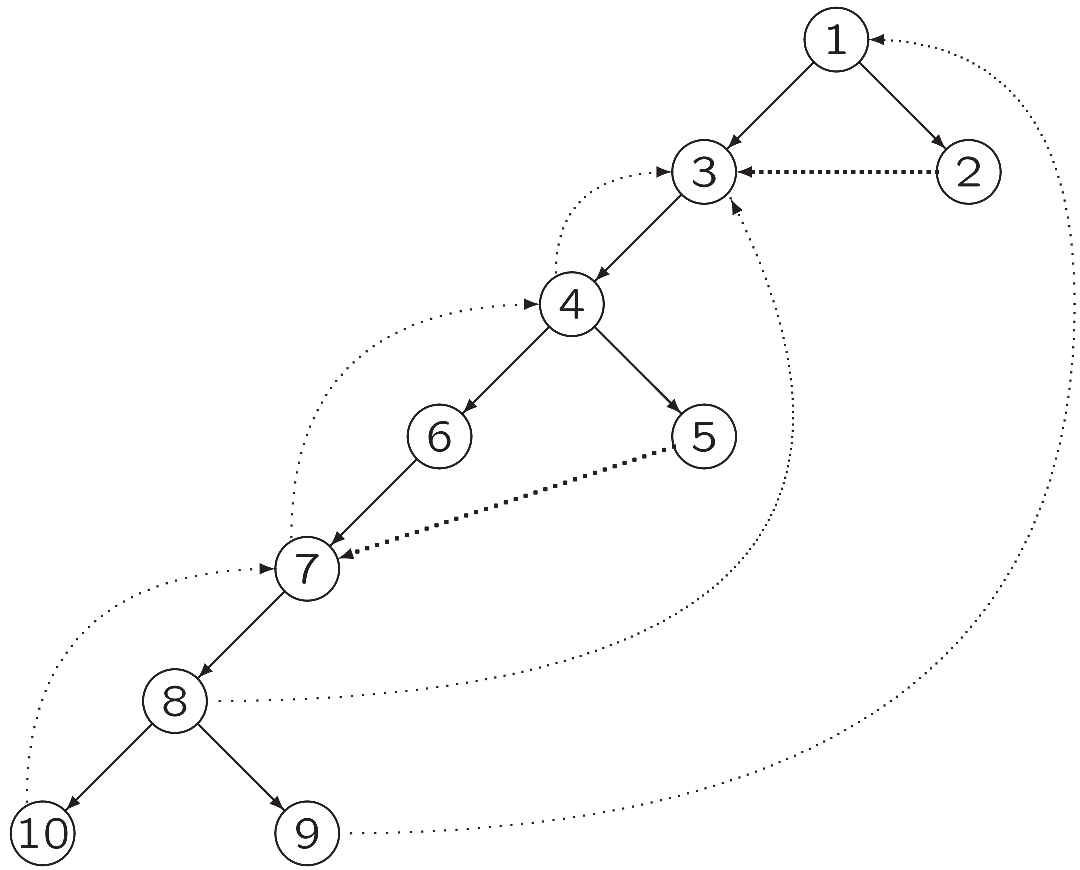
        OUT[n] $=$ IN[n] $\cup \{n\}$
    $\}$

Depth-First Traversal

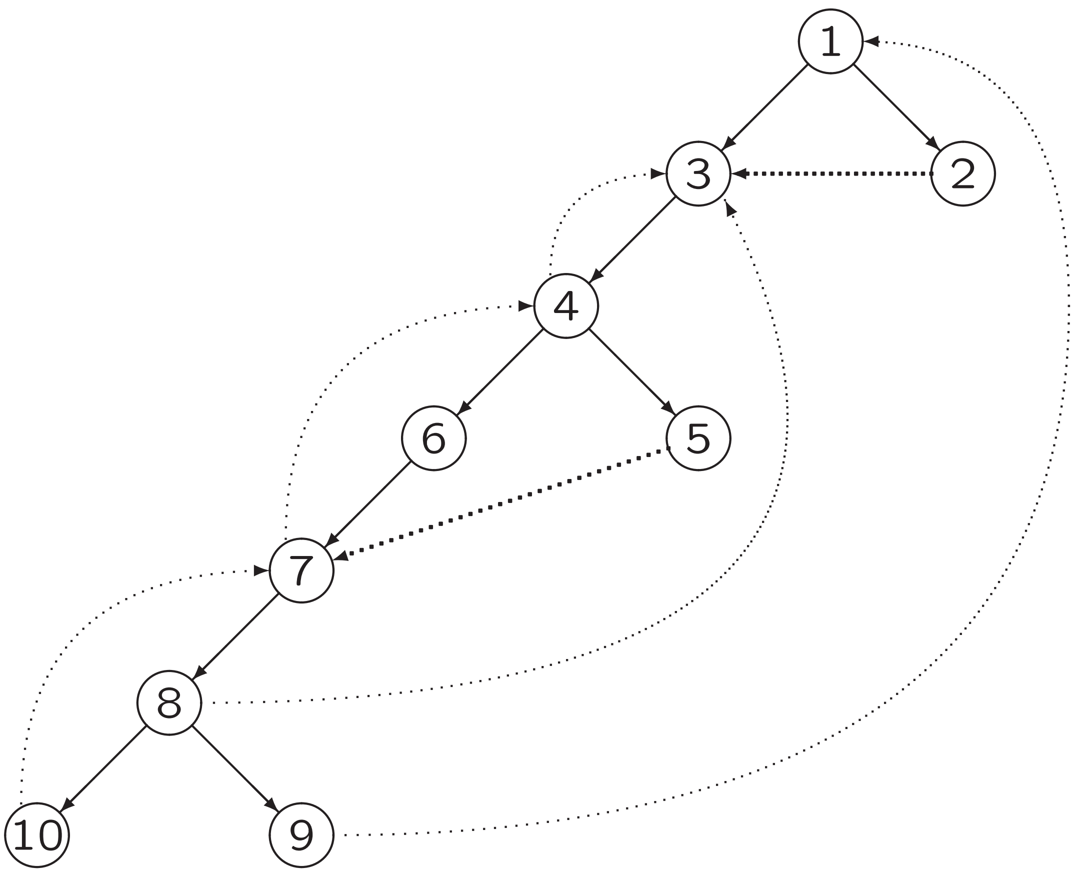
- Depth-first traversal of graph
  - Start from entry node
  - Recursively visit neighbours (in any order)
  - Hence, visit nodes far away from the entry node as quickly as it can (DF)

A Depth-First Spanning Tree





A Depth-First Spanning Tree



- Advancing edges
- Retreating edges
- Cross edges
- Back edge $a \to b$, if b dominates a (regardless of DFST)
- Each back edge is retreating edge in DFST
- Flow graph is reducible, if each retreating edge in any DFST is back edge

(Non)Reducible flow graphs

- In practice, almost every flow graph is reducible

- Example of nonreducible flow graph
  (with advancing edges)

- To decide on reducibility:

  1. Remove back edges

  2. Is remaining graph acyclic?

Natural loops

- If loop has single-entry node, then compiler can assume initial certain conditions

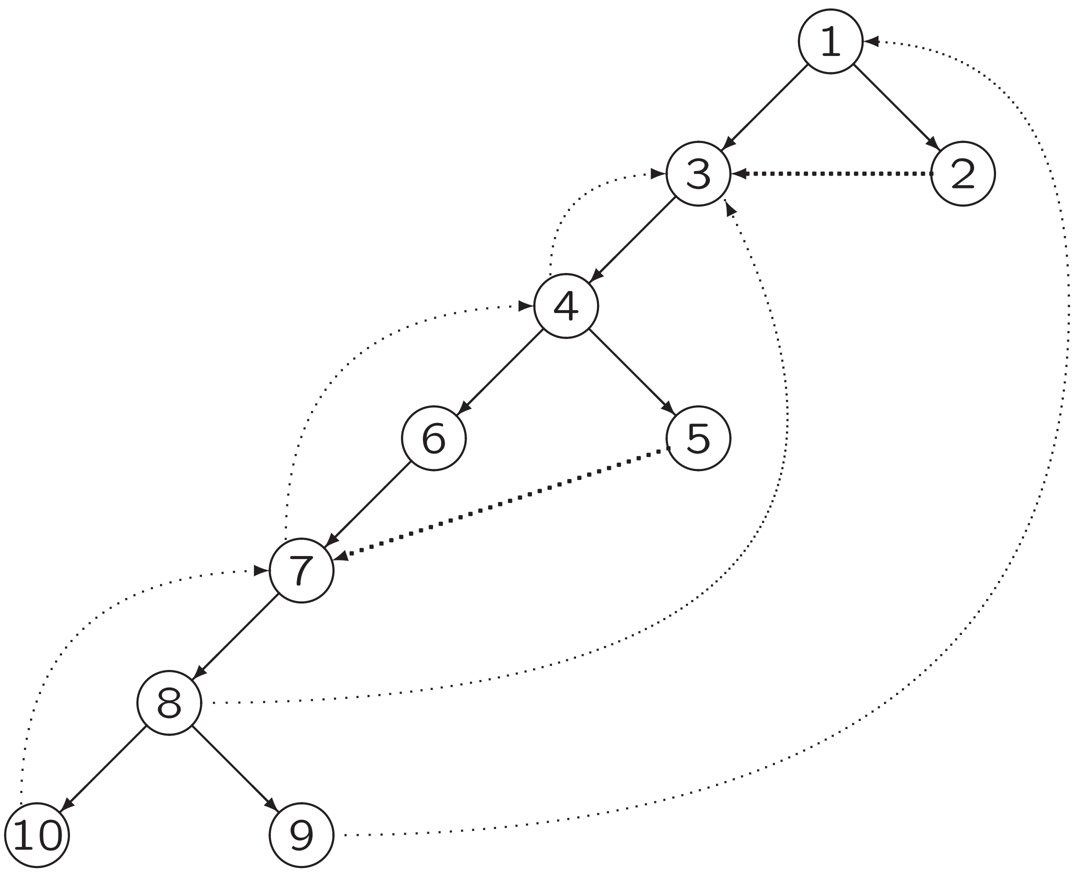
- Natural loop

  1. Has single-entry node: header
  2. Has back edge to header

- Each back edge $n \to d$ determines natural loop, consisting of
  - d
  - all nodes that can reach n without going through d

- Constructing natural loop of back edge...

Natural Loops (Example)



No Natural Loops

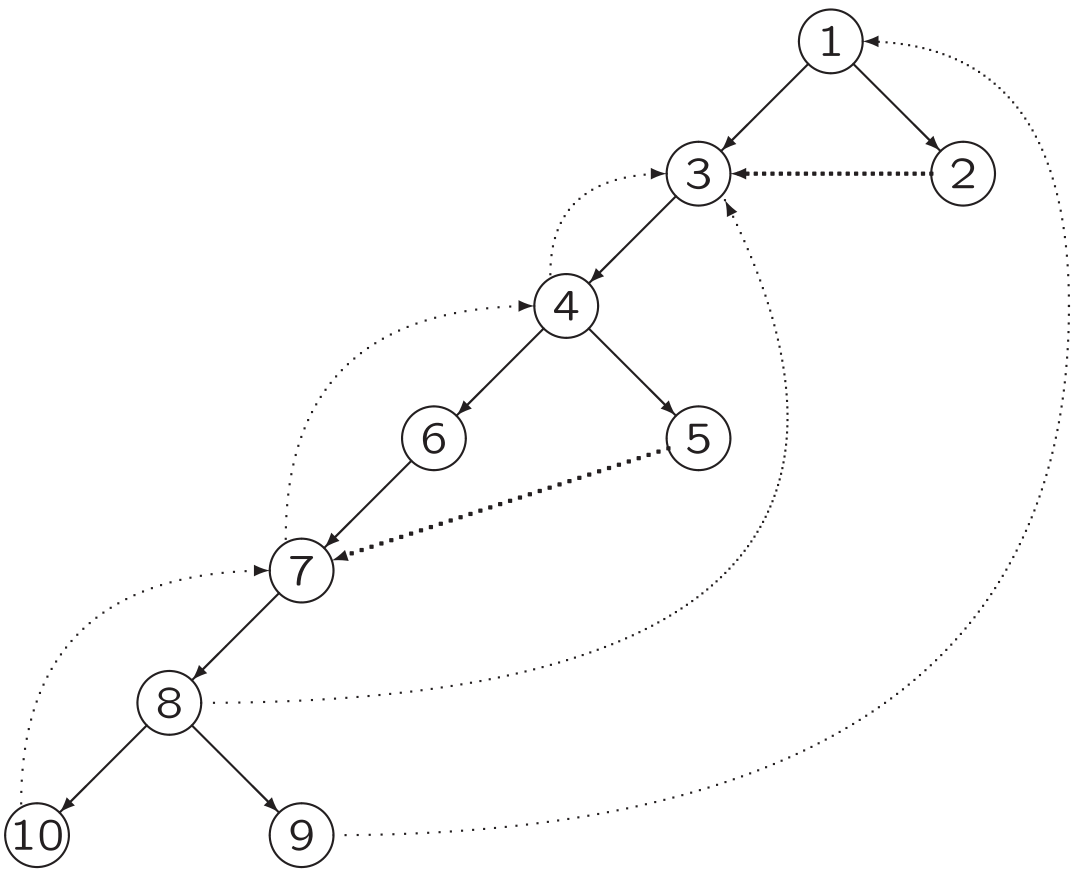
Natural Loops

- Useful property: unless two natural loops have same header
  - either they are disjoint
  - or one is nested within other

  Allows for inside-out optimization

- Assumption: if necessary, combine natural loops with same header. . .

A Depth-First Ordering

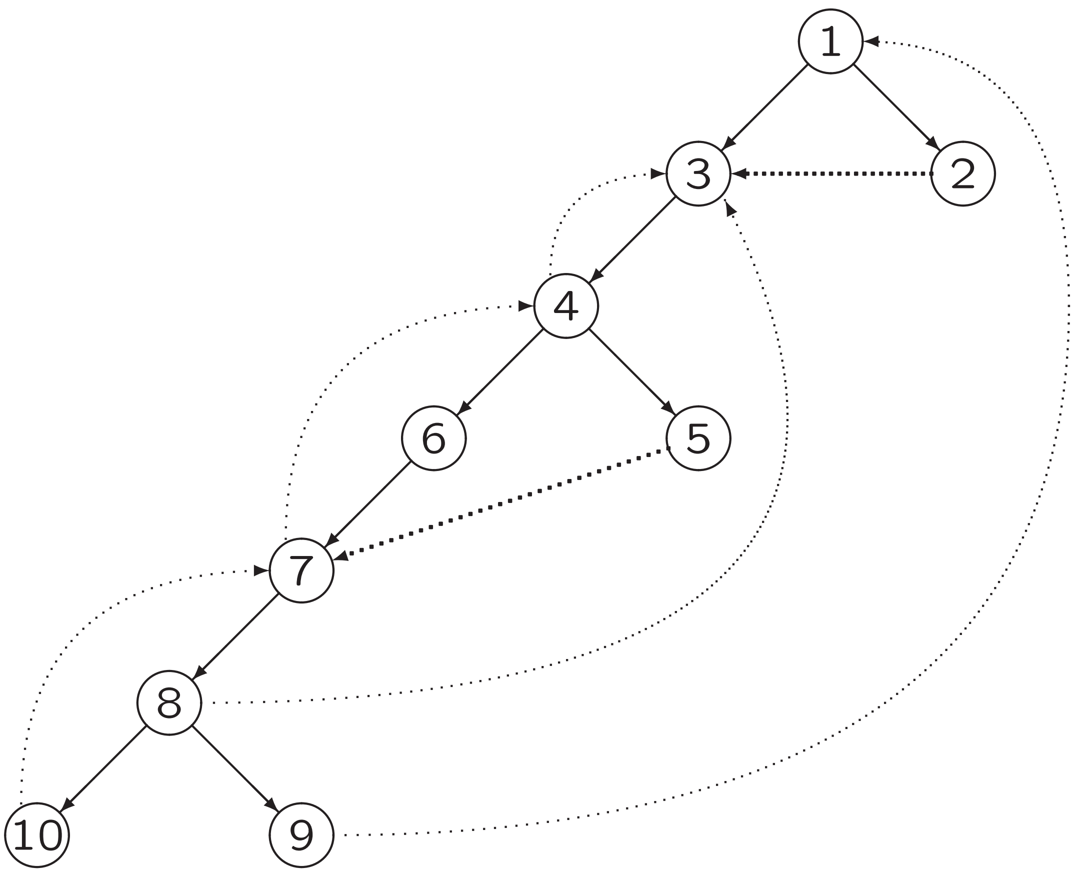


- Depth-First Ordering: nodes in DFST in WRL order ≈ reverse of postorder
- Example: 1,2,3,4,5,6,7,8,9,10
- Edge $m \rightarrow n$ is retreating, if and only if n comes before m in depth-first ordering

Depth of Flow Graph

- Depth of DFST is largest number of retreating edges on any cycle-free path
- If flow graph is reducible, then depth is independent of DFST: depth of flow graph
- Depth $\leq$ depth of loop nesting in flow graph

Depth of Flow Graph (Example)



Depth is 3, because of path
$10 \to 7 \to 4 \to 3$

Speed of Convergence of Iterative Data-Flow Algorithms

In data-flow analysis, can significant events be propagated to node along acyclic path?

- Yes for
  - Reaching definitions
  - Live-variable analysis
  - Available expressions
- No for
  - Copy propagation

If yes, then fast convergence possible

Efficient Iterative Data-Flow Analysis

Example: computing reaching definitions

```
OUT[ENTRY] = ∅
for each basic block B other than ENTRY
    OUT[B] = ∅

while (changes to any OUT occur)
    for each basic block B other than ENTRY
    {   IN[B] = ∪_{predecessors P of B} OUT[P]

        OUT[B] = gen_B ∪ (IN[B] − kill_B)
    }
```

Order of blocks in second for-loop matters

Fast Convergence

- Forward data-flow problem: visit nodes in depth-first-order
- Recall: edge $m \to n$ is retreating, if and only if n comes before m in depth-first ordering
- Example: path of propagation of definition d:

$$3 \to 5 \to 19 \to 35 \to 16 \to 23 \to 45 \to 4 \to 10 \to 17$$

- Number of iterations: $1 +$ depth ($+$ 1)
- Typical flow graphs have depth 2.75
- Backward data-flow problem: visit nodes in reverse of depth-first-order

En verder. . .

- Maandag 19 november: inleveren opdracht 3
- Dinsdag 20 november: practicum over opdracht 4
- Eerst naar 403, daarna naar 302/304
- Inleveren 10 december
- Dinsdag 27 november: werkcollege in 403
  (dus geen hoorcollege over Daedalus)
- Dinsdag 4 december: practicum over opdracht 4

Compiler constructie

college 8
Code Optimization

Chapters for reading:
9.intro, 9.1, 9.2–9.2.5, 9.6