CMPT 379
Compilers

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Code Optimization

- There is no fully optimizing compiler *O*
- Let's assume *O* exists: it takes a program P and produces output **Opt**(P) which is the *smallest* possible
- Imagine a program Q that produces no output and never terminates, then **Opt**(Q) could be:
  `L1: goto L1`
- Then to check if a program P never terminates on some inputs, check if **Opt**(P(i)) is equal to **Opt**(Q) = Solves the Halting Problem
- Full Employment Theorem for Compiler Writers, see Rice(1953)

Optimizations

- Non-Optimizations
- Correctness of optimizations
  - Optimizations must not change the meaning of the program
- Types of optimizations
  - Local optimizations
  - ~~Global dataflow analysis for optimization~~
  - Static Single Assignment (SSA) Form
- Amdahl's Law

Non-Optimizations

```
enum { GOOD, BAD };
extern int test_condition();

void check() {
 int rc;

 rc = test_condition();
 if (rc != GOOD) {
  exit(rc);
 }
}
```

```
enum { GOOD, BAD };
extern int test_condition();

void check() {
 int rc;

 if ((rc = test_condition())) {
  exit(rc);
 }
}
```

Which version of check runs faster?

Types of Optimizations

- High-level optimizations
  - function inlining
- Machine-dependent optimizations
  - e.g., peephole optimizations, instruction scheduling
- Local optimizations or Transformations
  - within basic block

Types of Optimizations

- Global optimizations or Data flow Analysis
  - across basic blocks
  - within one procedure (*intraprocedural*)
  - whole program (*interprocedural*)
  - pointers (*alias analysis*)

Maintaining Correctness

- What does this program output?

3

Not:

$ decafcc byzero.decaf

Floating exception

```
int main() {
  int x;
  if (false) {
    x = 3/(3-3);
  } else {
    x = 3;
  }
  print_int( x);
}
```

branch delay slot (cf. **load delay** slot)

Peephole Optimization

- Redundant instruction elimination
  - If two instructions perform that same function ***and*** are in the same basic block, remove one
  - Redundant loads and stores

    li $t0, 3

    li $t0, 4
  - Remove unreachable code

    li $t0, 3

    goto L2

    ... (all of this code until next label can be removed)

Peephole Optimization

- Flow control optimization

  goto L1

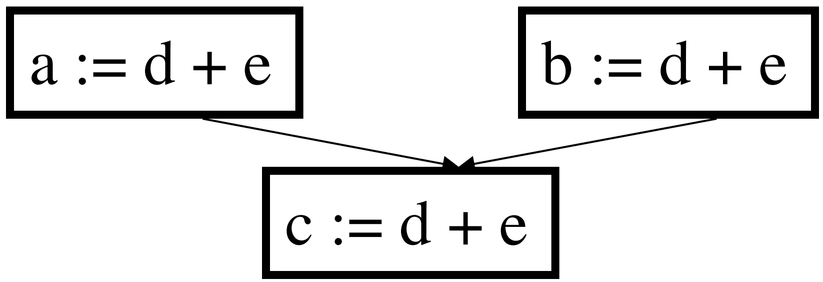
  L1: goto L2
- Algebraic simplification
- Reduction in strength
  - Use faster instructions whenever possible
- Use of Machine Idioms
- Filling delay slots

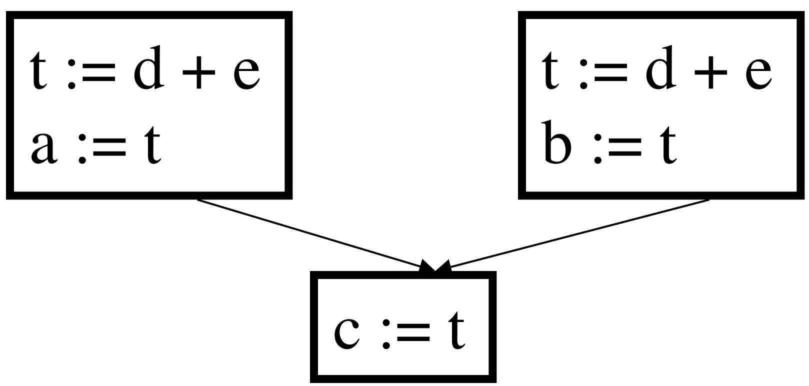
Constant folding & propagation

- Constant folding
  - compute expressions with known values at compile time
- Constant propagation
  - if constant assigned to variable, replace uses of variable with constant unless variable is reassigned

Constant folding & propagation

- Copy Propagation





Transformations

- Structure preserving transformations
- Common subexpression elimination

  a := b + c

  b := a - d

  c := b + c

  d := a - d ($\Rightarrow$ b)

Transformations

- Dead-code elimination (combines copy propogation with removal of unreachable code)

  if (debug) { f(); } /* debug := false (as a constant) */

  if (false) { f(); } /* constant folding */

  using deadcode elimination, code for f() is removed

  x := t3 x := t3

  t4 := x becomes t4 := t3

Transformations

- Renaming temporary variables

  t1 := b+c can be changed to t2 := b+c

  replace all instances of t1 with t2

- Interchange of statements

  t1 := b+c   t2 := x+y

  t2 := x+y can be converted to t1 := b+c

Transformations

- Algebraic transformations

  d := a + 0 (⇒ a)

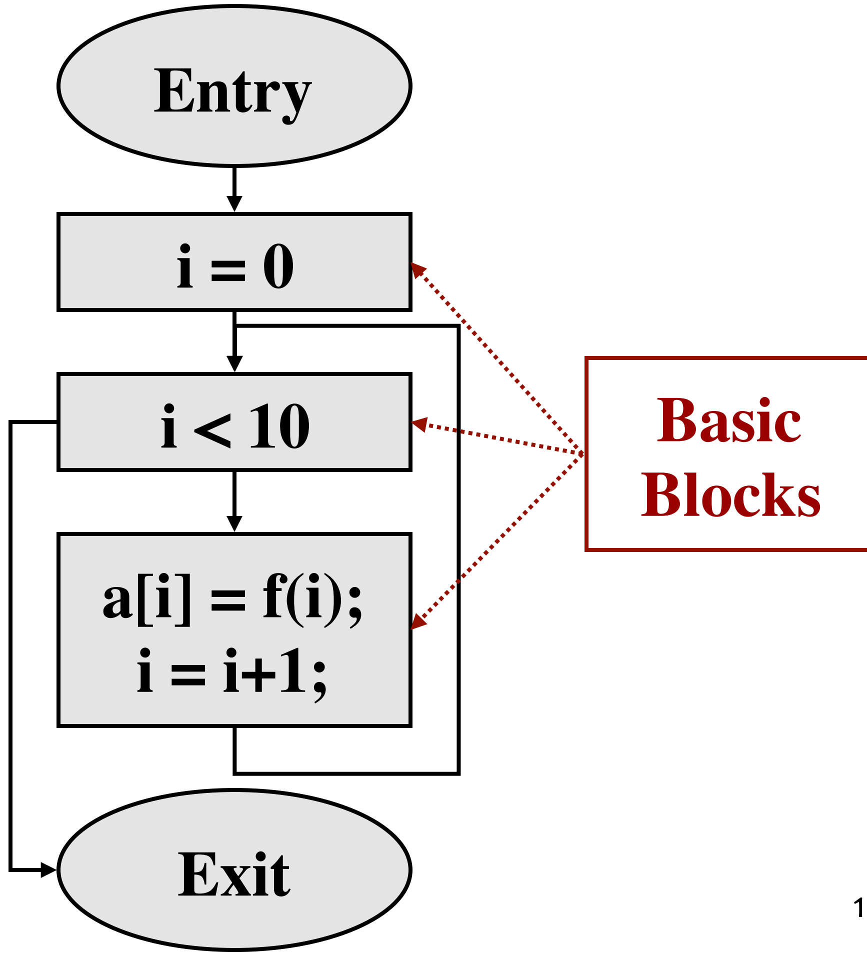
  d := d * 1 (⇒ *eliminate*)

- Reduction of strength

  d := a ** 2 (⇒ a * a)

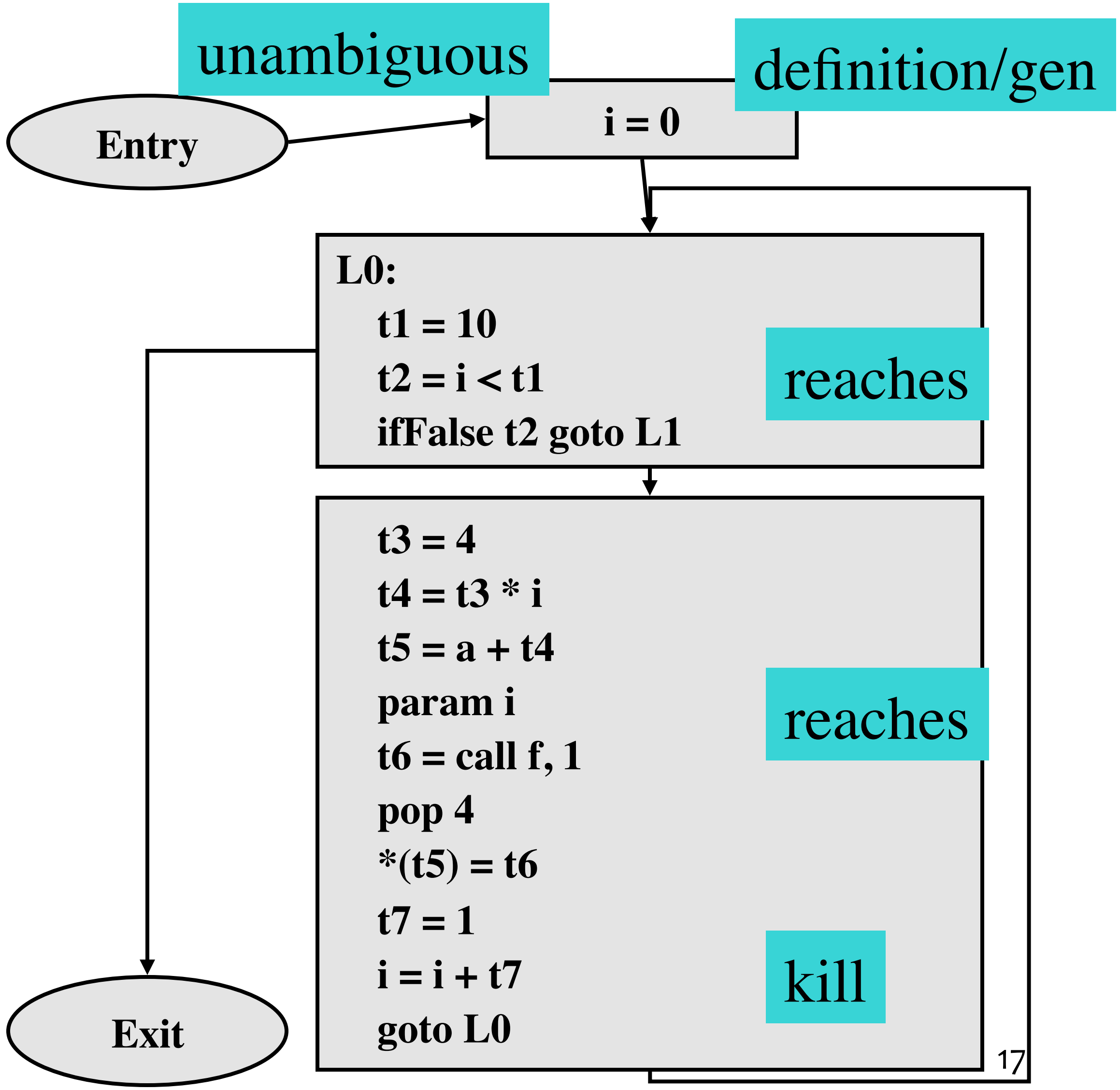
Control Flow Graph (CFG)

```
int main() {
 extern int f(int);
 int i;
 int *a;
 for (i = 0;
        i < 10;
           i = i + 1)
     { a[i] = f(i); }
}
```



Control Flow Graph in TAC

```
main:
   i = 0
L0:
   t1 = 10
   t2 = i < t1
   ifFalse t2 Goto L1
   t3 = 4
   t4 = t3 * i
   t5 = a + t4
   param i
   t6 = call f, 1
   pop 4
   *(t5) = t6
   t7 = 1
   i = i + t7
   goto L0
L1:
   return
```



SSA Form

- *def-use* chains keep track of where variables were defined and where they were used
- Consider the case where each variable has only one definition in the intermediate representation
- One static definition, accessed many times
- Static Single Assignment Form (SSA)

SSA Form

- SSA is useful because
  - Dataflow analysis and optimization is simpler when each variable has only one definition
  - If a variable has N uses and M definitions (which use N+M instructions) it takes N*M to represent def-use chains
  - Complexity is the same for SSA but in practice it is usually linear in number of definitions
  - SSA simplifies the register interference graph

SSA Form

- Original Program

a := x + y

b := a - 1

a := y + b

b := x * 4

a := a + b

- SSA Form

a1 := x + y

b1 := a1 - 1

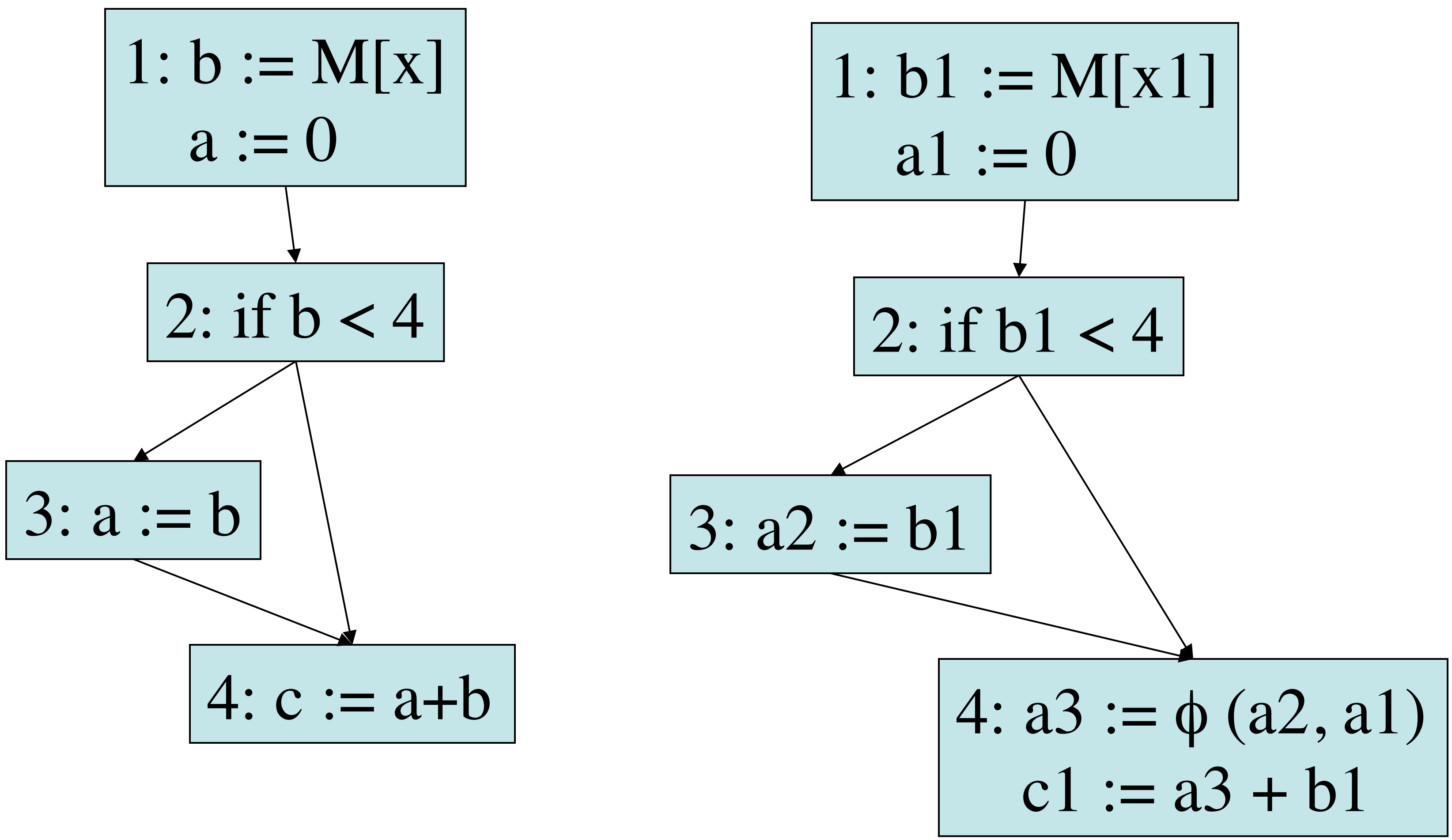
a2 := y + b1

b2 := x * 4

a3 := a2 + b2

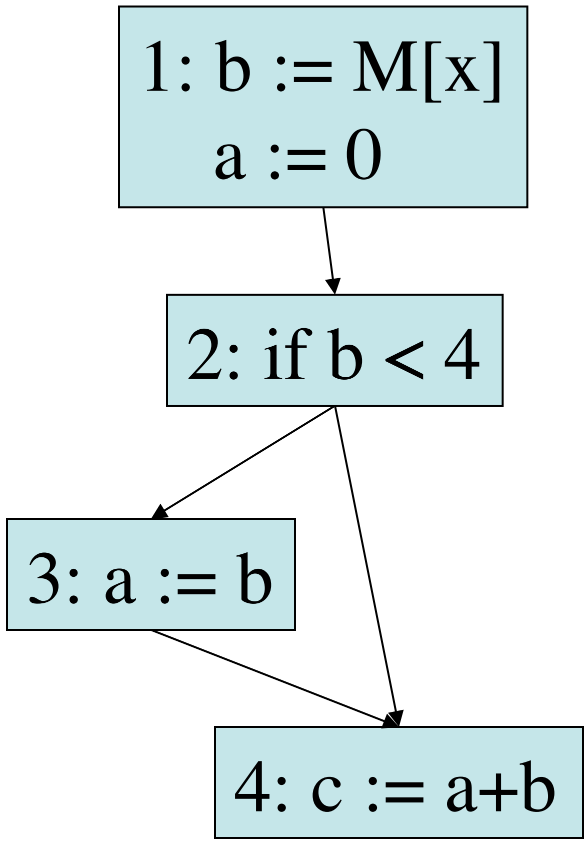
what about conditional branches?

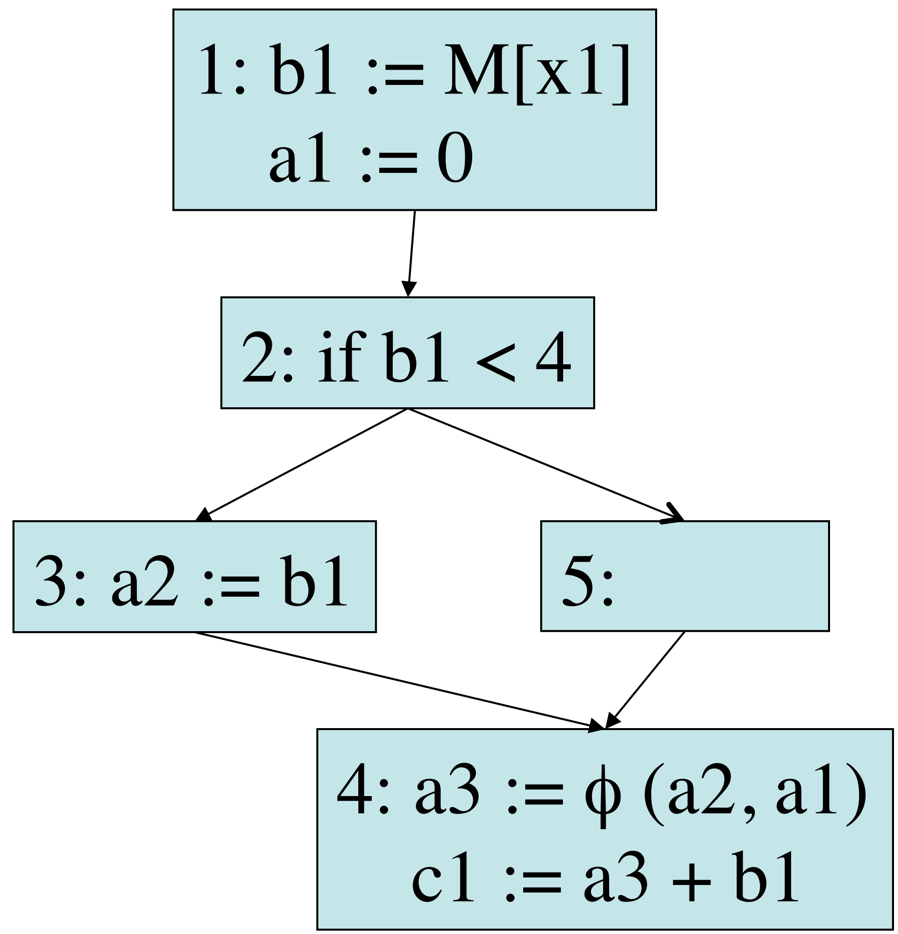
SSA Form


1: b := M[x]
a := 0
2: if b < 4
3: a := b
4: c := a+b
1: b1 := M[x1]
a1 := 0
2: if b1 < 4
3: a2 := b1
4: a3 := φ (a2, a1)
c1 := a3 + b1

Edge-split SSA Form

Unique Successor & Unique Predecessor





SSA Form

- Conversion from a Control Flow Graph (created from TAC) into SSA Form is not trivial
- SSA creation algorithms:
  - Original algorithm by Cytron et al. 1986
  - Lengauer-Tarjan algorithm (see the Tiger book by Andrew W. Appel for more details)
  - Harel algorithm

Conversion to SSA Form

- Simple idea: add a ϕ function for every variable at a join point
- A join point is any node in the control-flow graph with more than one predecessor
- But: this is wasteful and unnecessary.

Conversion to SSA

b1 is never used, stmt can be deleted

```
1: a := 0
```

```
2: b := a + 1
   c := c + b
   a := b * 2
   if a < N
```

```
3: return c
```

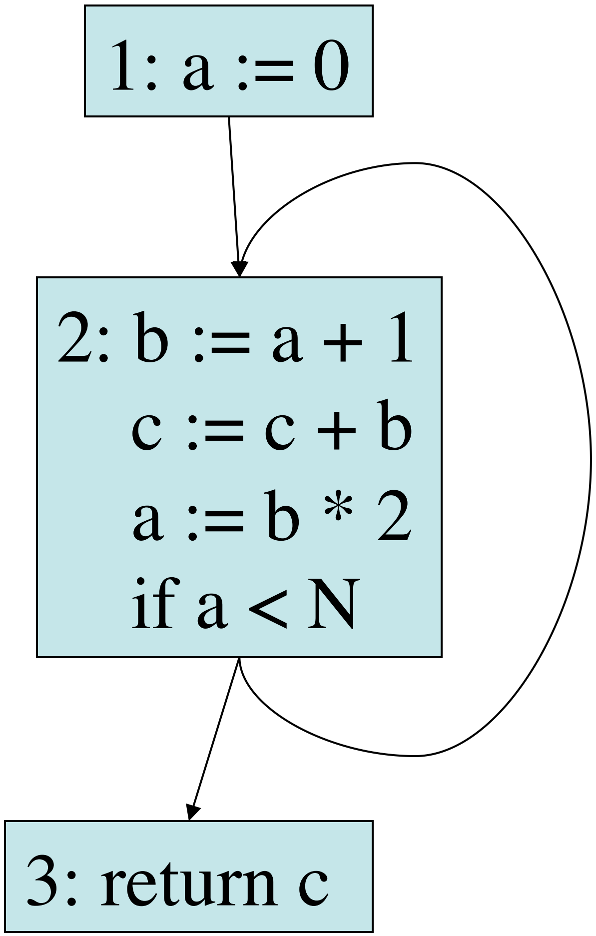
```
1: a1 := 0
```

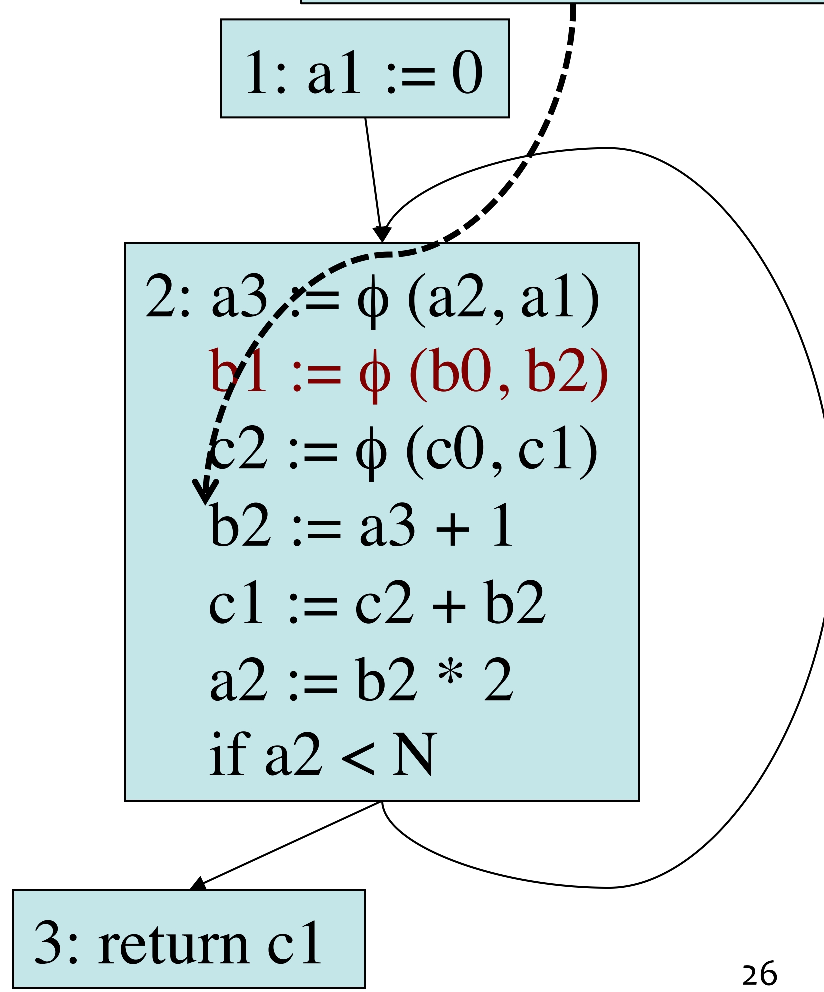
```
2: a3 := ϕ (a2, a1)
   b1 := ϕ (b0, b2)
   c2 := ϕ (c0, c1)
   b2 := a3 + 1
   c1 := c2 + b2
   a2 := b2 * 2
   if a2 < N
```

```
3: return c1
```

Conversion to SSA

b2 changes in each loop. SSA is **not** functional programming!



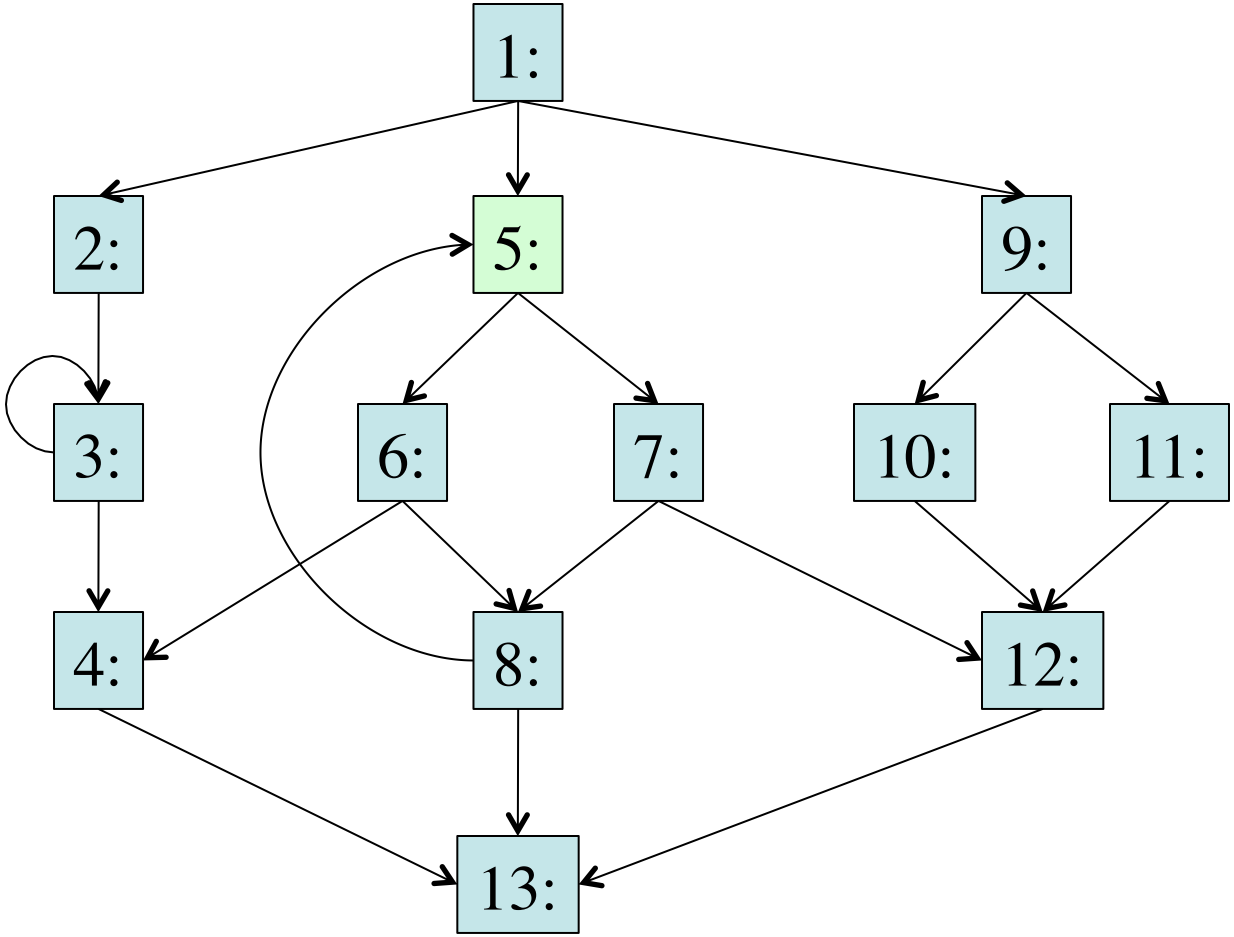


Dominance Relation

- X *dominates* Y if every path from the start node to Y goes through X
- D(X) is the set of nodes that X dominates
- X *strictly dominates* Y if X dominates Y and $X \neq Y$

Dominance Relation

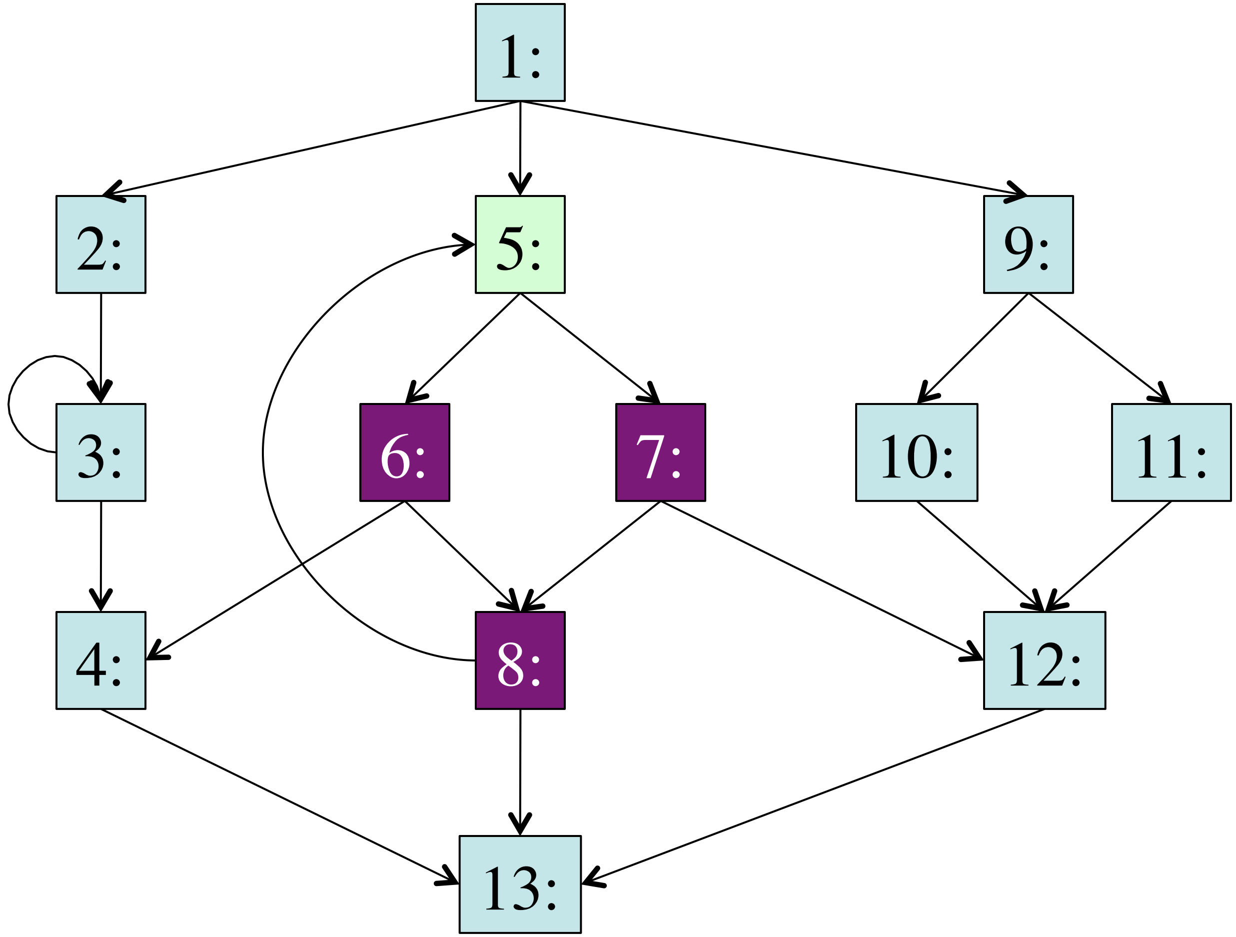
D(5)={6,7,8}



5 strictly dominates 6, 7, 8

Dominance Relation

D(5)={6,7,8}



5 strictly dominates 6, 7, 8

Dominance Property of SSA

- Essential property of SSA form is the definition of a variable must *dominate* use of the variable:
  - If X is used in a ϕ function in block n, then definition of X dominates every predecessor of n
  - If X is used in a non-ϕ statement in block n, then the definition of X dominates n.

Dominance Frontier

- X *strictly dominates* Y if X dominates Y and $X \neq Y$
- *Dominance Frontier* (DF) of node X is the set of all nodes Y such that:
  - X dominates a predecessor of Y, AND
  - X does not strictly dominate Y

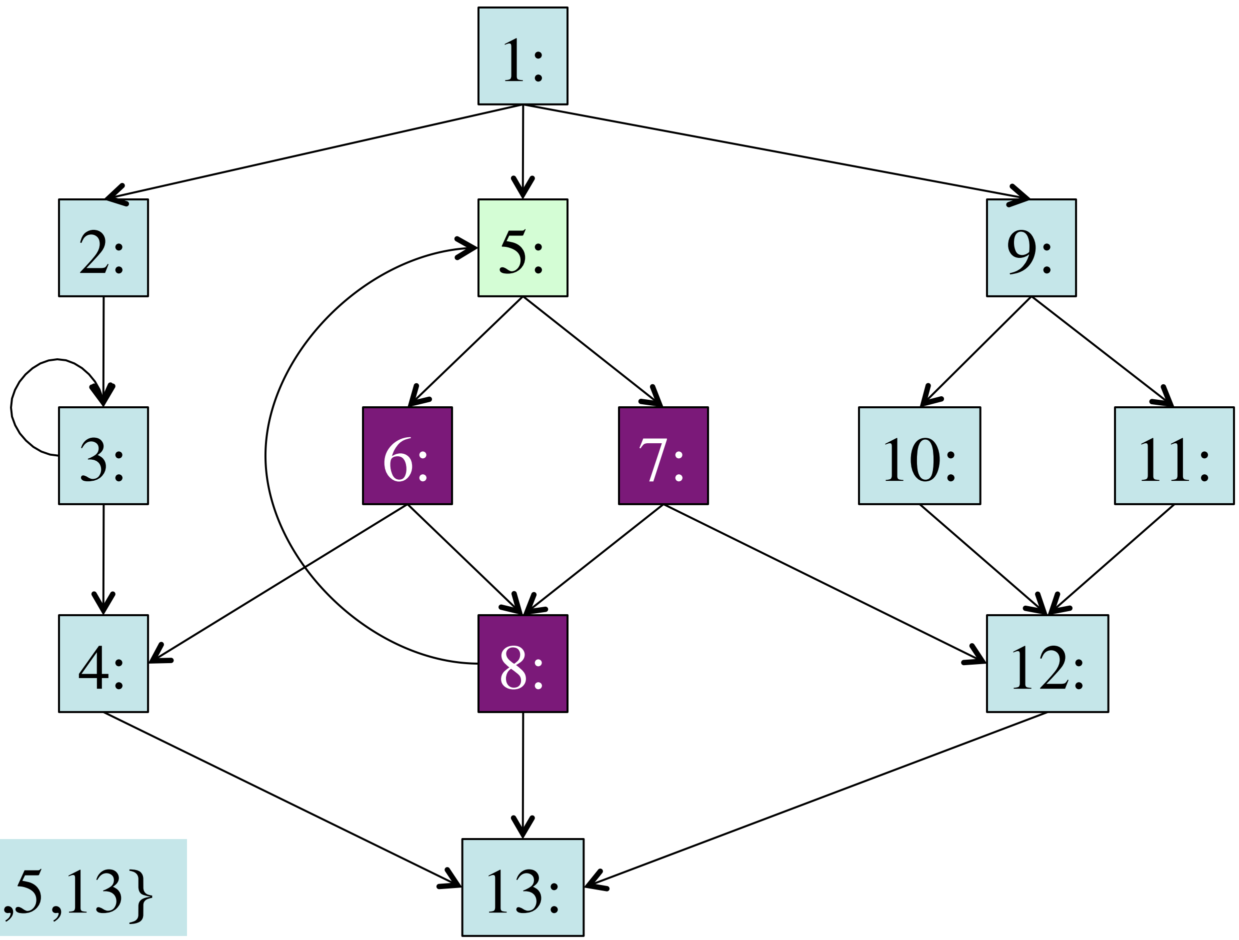
Dominance Frontier

D(5)={6,7,8}

S(6)={4,8}

S(7)={8,12}

S(8)={5,13}



DF(5) = {4,12,5,13}

Dominance Frontier

- Algorithm to compute DF(X):
  - Local(X) := set of successors of X who do not immediately dominate X
  - Up(X) := set of nodes in DF(X) that are not dominated by X's immediate dominator.
  - DF(X) := Union of Local(X) & (Union of Up(K) for all K that are children of X)

Dominance Frontier

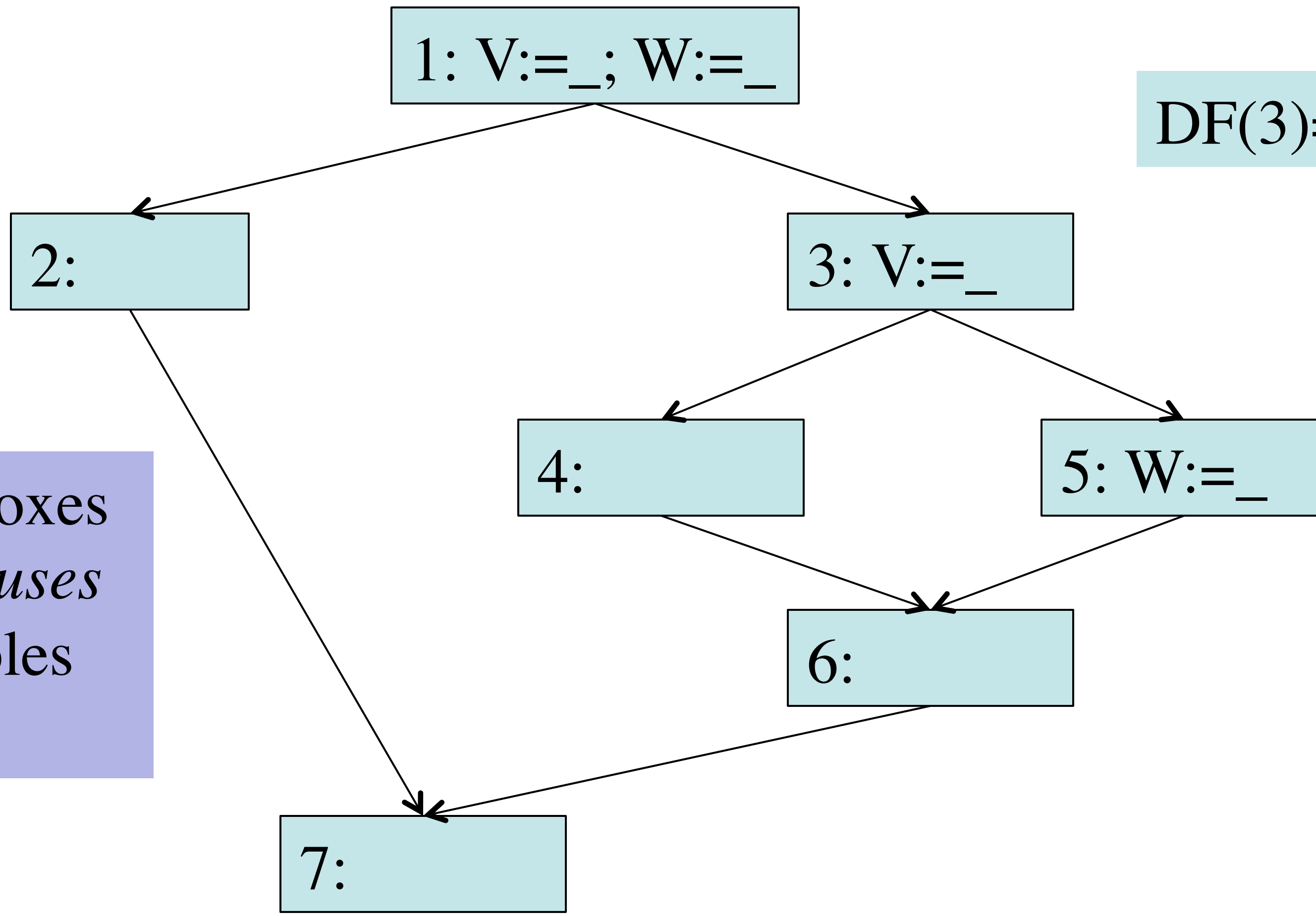
- ComputeDF(X):

```
S := {} // empty set
For each node Y in Successor(X):
    If X is not strictly dominating Y:
      S := S + {Y} // this is Local(X), + means union
For each child K of X in D(X): // X dominates K
    For each element Y in ComputeDF(K):
      If X does not dominate Y,
                S := S + {Y} // this is Up(X)
return DF(X) := S
```

Dominance Frontier

- Dominance Frontier Criterion
  - If node X contains definition of some variable *a*, then any node Y in the DF(X) needs a ϕ function for *a*.
- Iterated Dominance Frontier
  - Since a ϕ function is itself a definition of a new variable, we must iterate the DF criterion until no nodes in the CFG need a ϕ function.

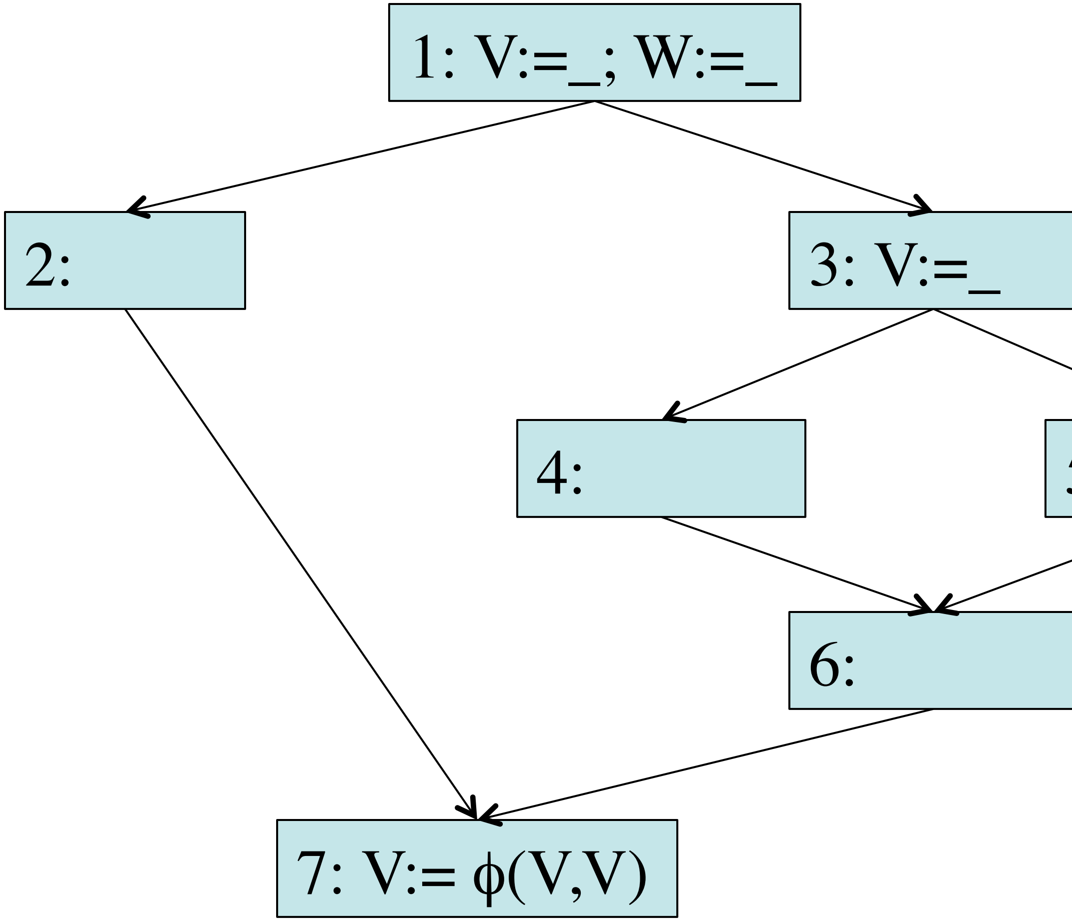
Placing ϕ Functions



DF(3)={7}

Empty boxes indicate *uses* of variables V, W

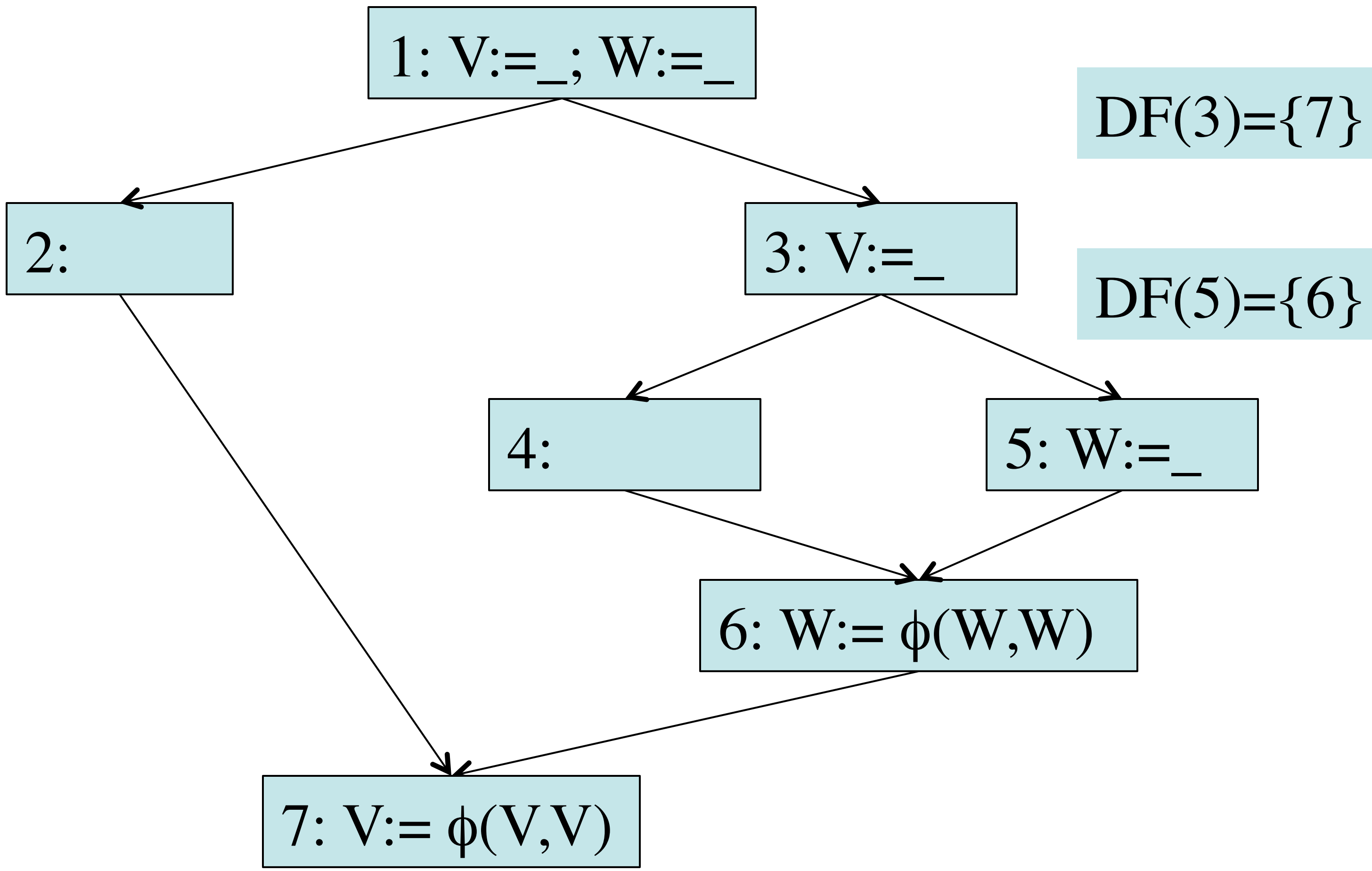
Placing ϕ Functions



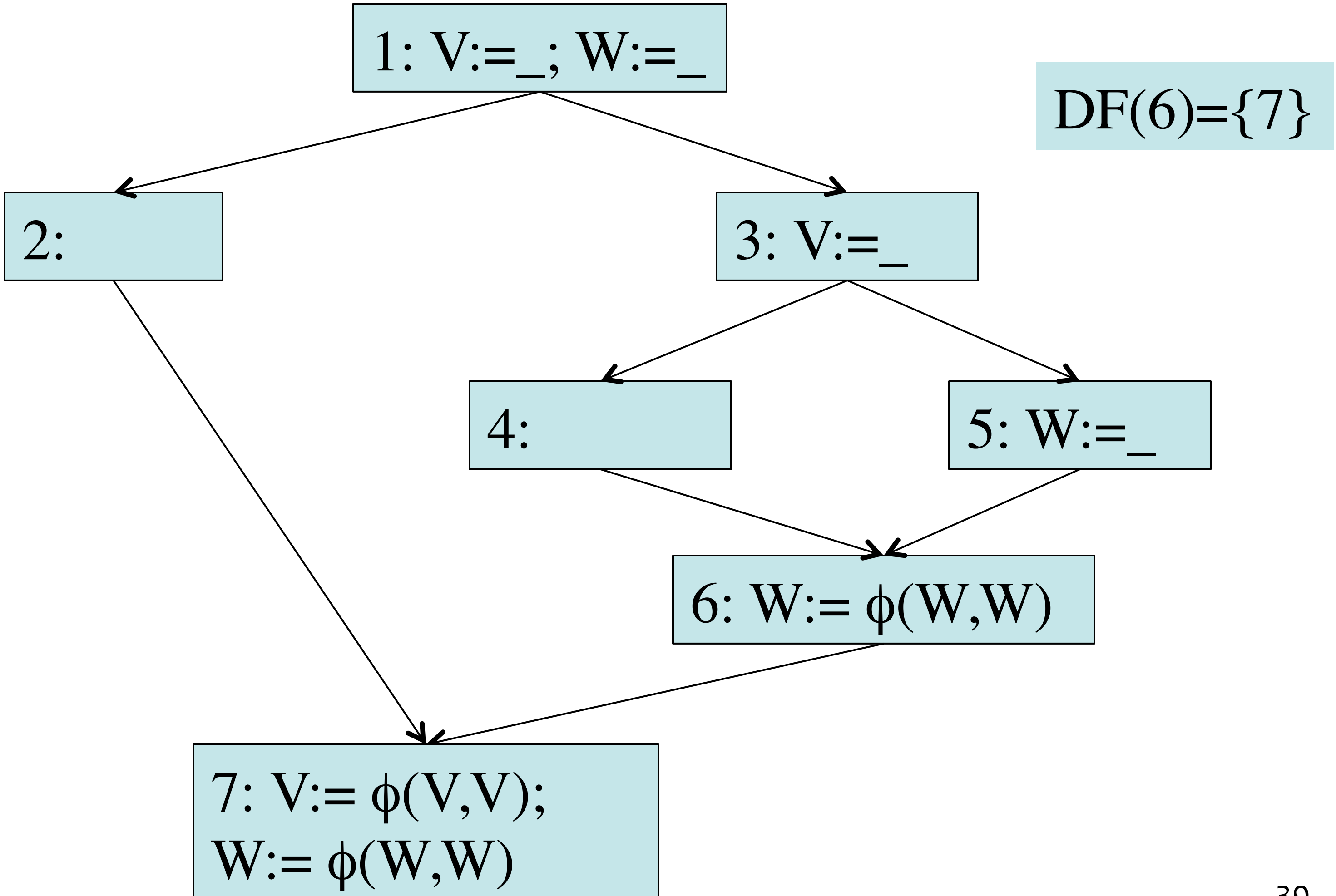
DF(3)={7}

DF(5)={6}

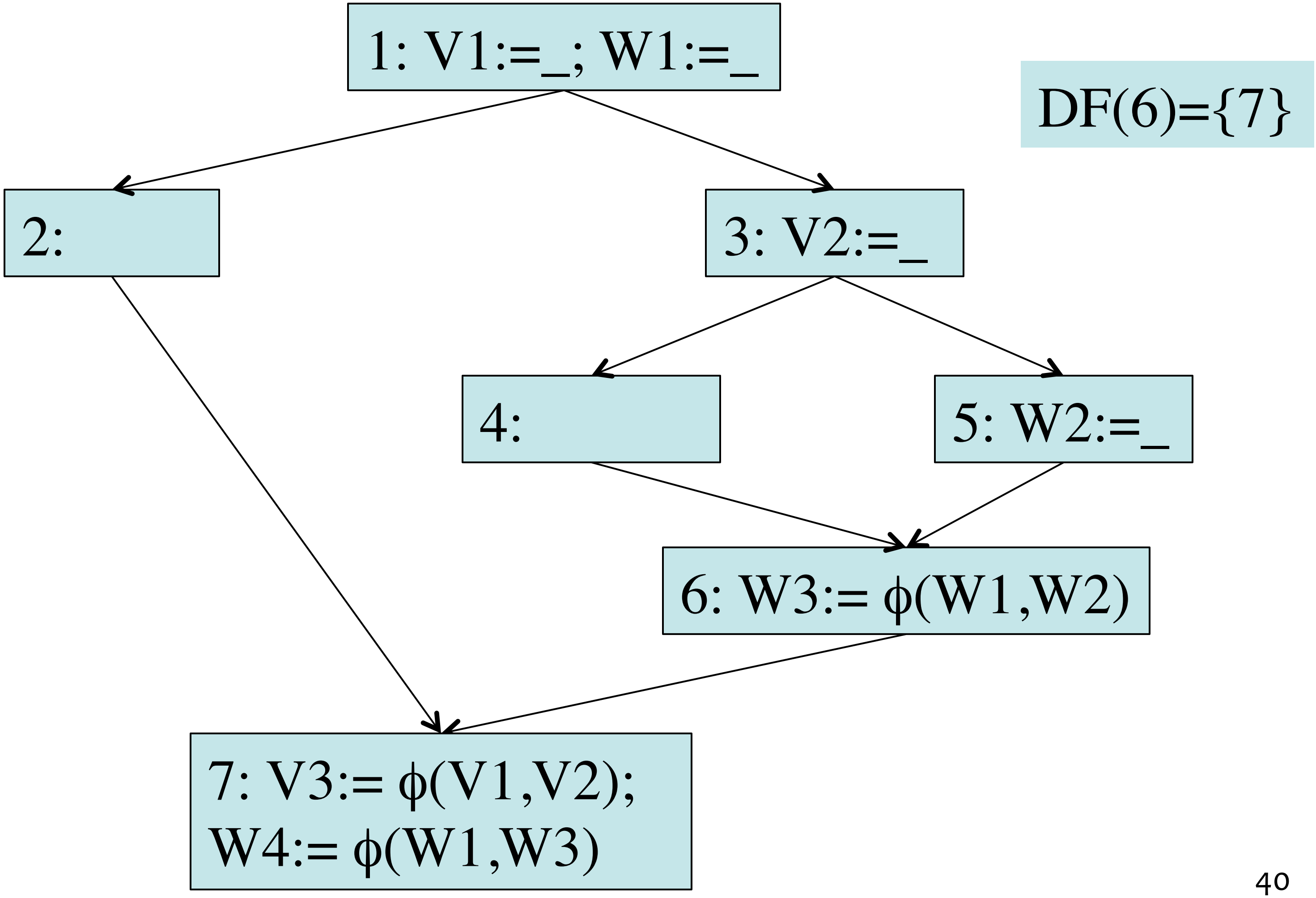
Placing ϕ Functions



Placing ϕ Functions



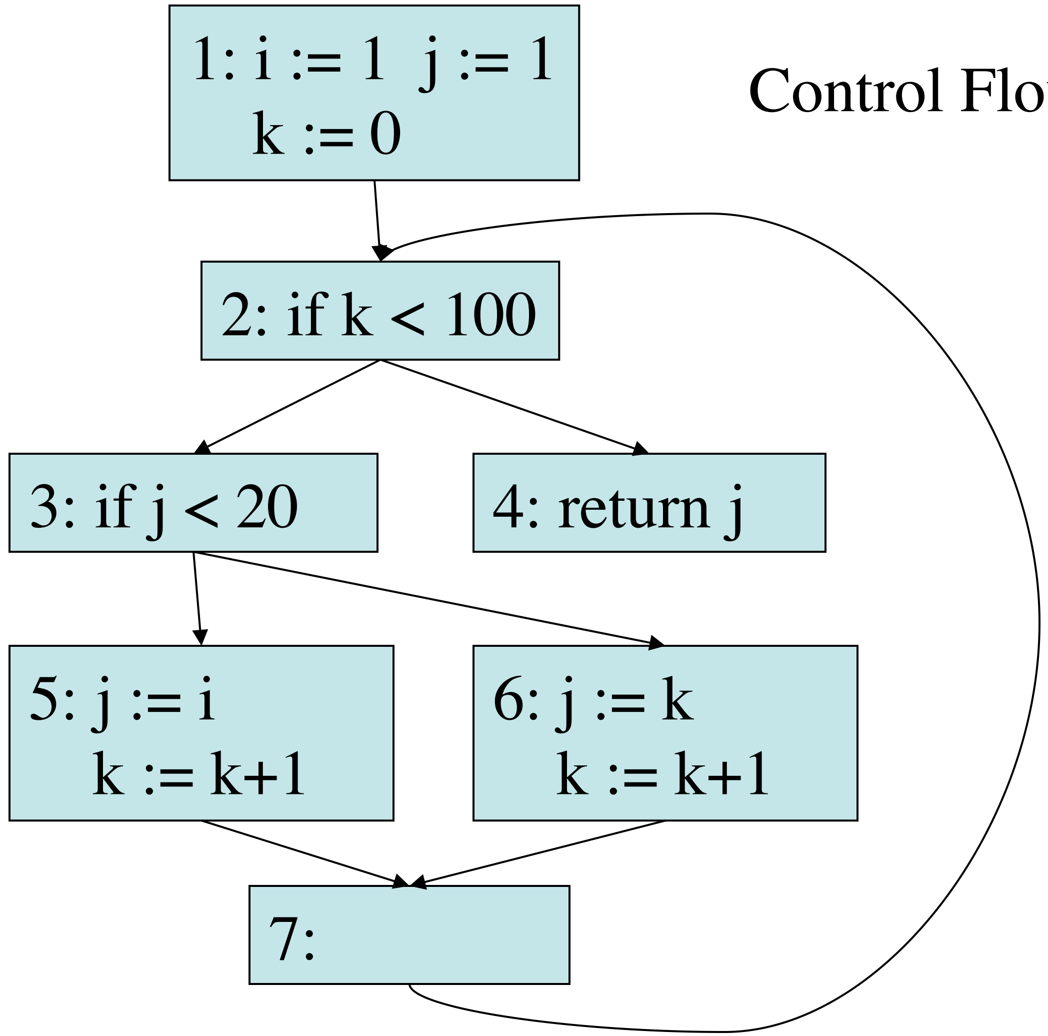
Rename Variables



Converting to SSA Form

Program

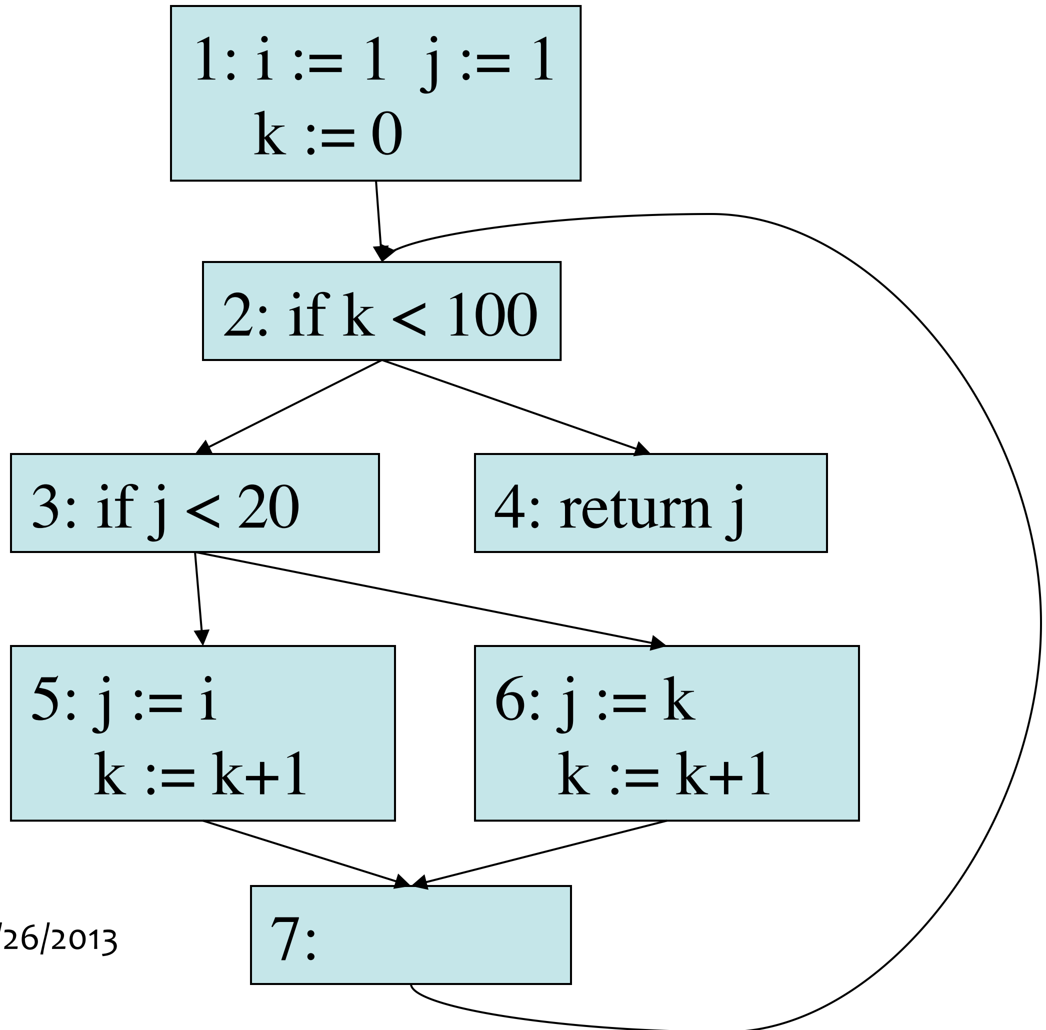
```
i:=1
j:=1
k:=0
while k<100:
    if j < 20:
        j:=i
        k:=k+1
    else:
        j:=k
        k:=k+1
return j
```



Control Flow Graph

Converting to SSA Form

Control Flow Graph



Dominance Relations

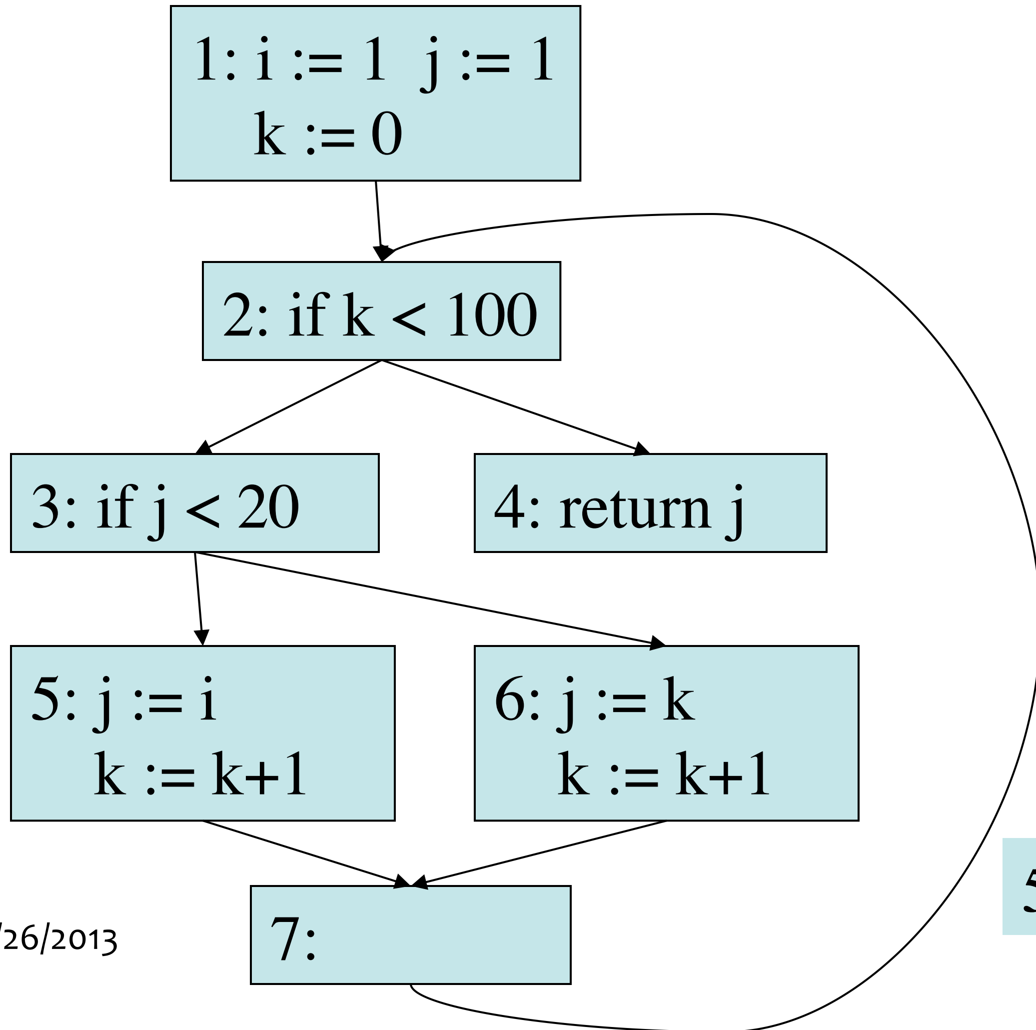
- D(1) = {2,3,4,5,6,7}
- D(2) = {3,4,5,6,7}
- D(3) = {5,6,7}
- D(4) = {}
- D(5) = {}
- D(6) = {}
- D(7) = {}

Converting to SSA

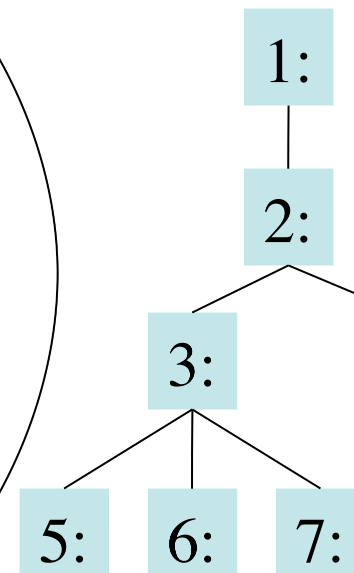
Dominance Relations

- D(1) = {2,3,4,5,6,7}
- D(2) = {3,4,5,6,7}
- D(3) = {5,6,7}
- D(4) = {}
- D(5) = {}
- D(6) = {}
- D(7) = {}

Control Flow Graph

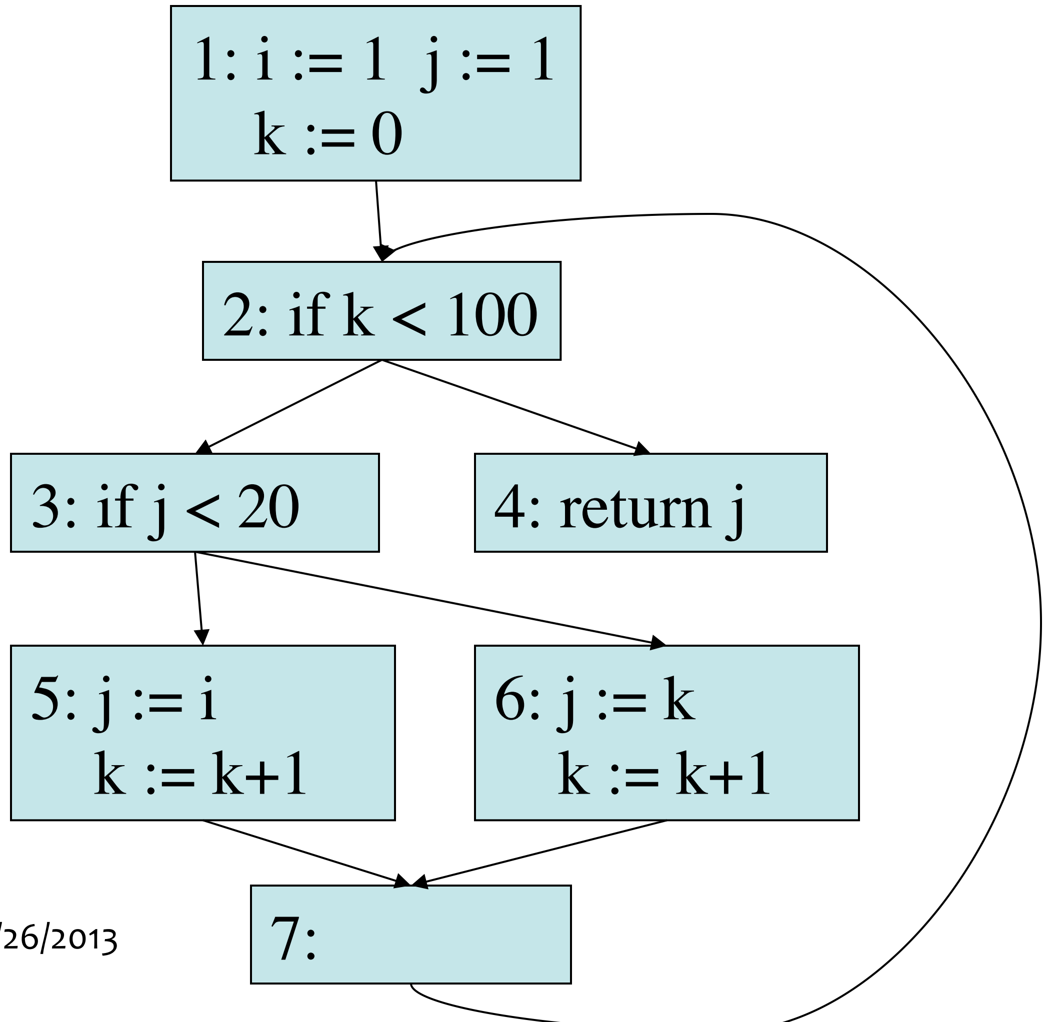


Dominator Tree



Converting to SSA

Control Flow Graph



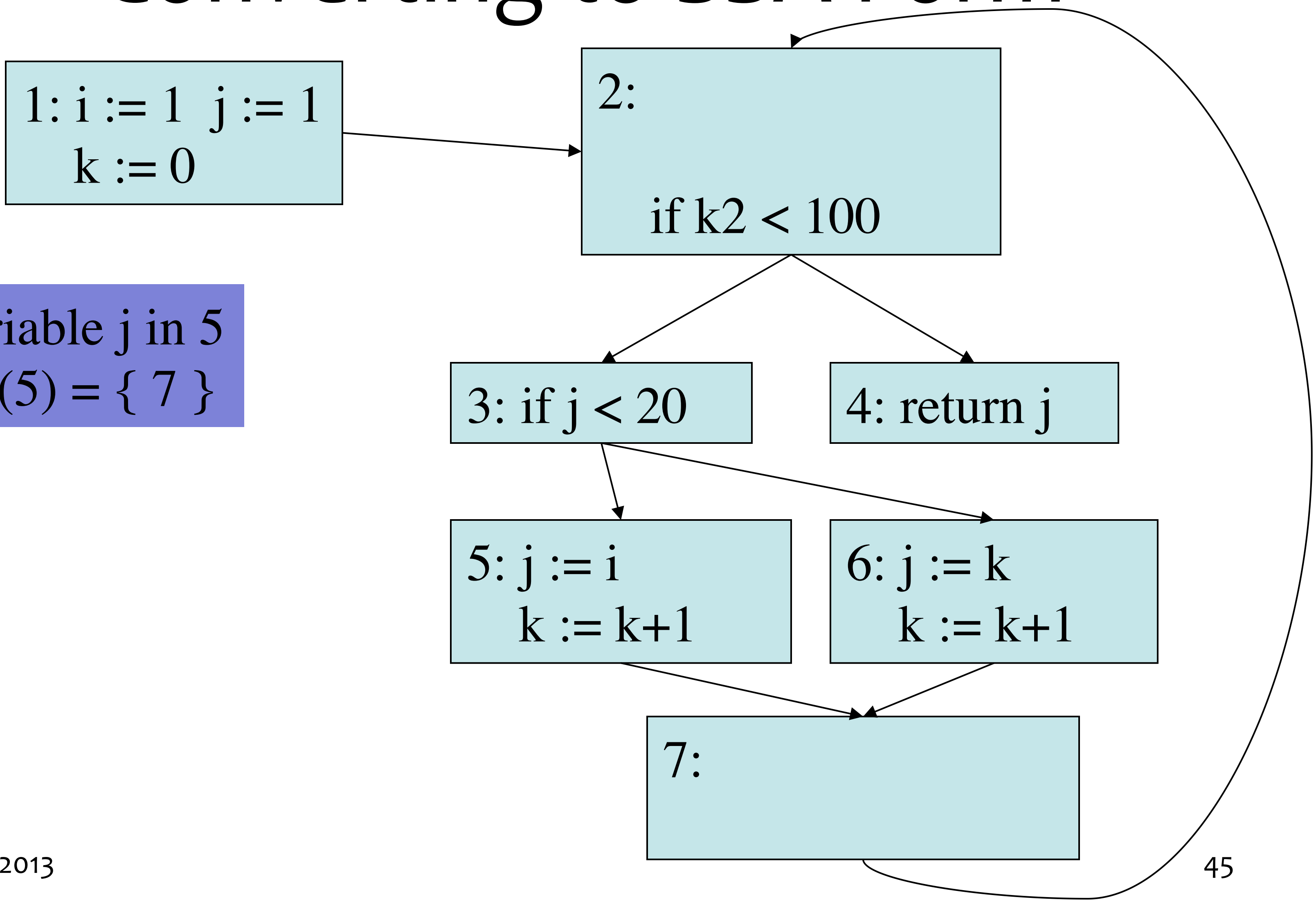
Dominance Relations

- D(1) = {2,3,4,5,6,7}
- D(2) = {3,4,5,6,7}
- D(3) = {5,6,7}
- D(4) = {}
- D(5) = {}
- D(6) = {}
- D(7) = {}

Dominance Frontier

- DF(1) = {}
- DF(2) = {2}
- DF(3) = {2}
- DF(4) = {}
- DF(5) = {7}
- DF(6) = {7}
- DF(7) = {2}

Converting to SSA Form

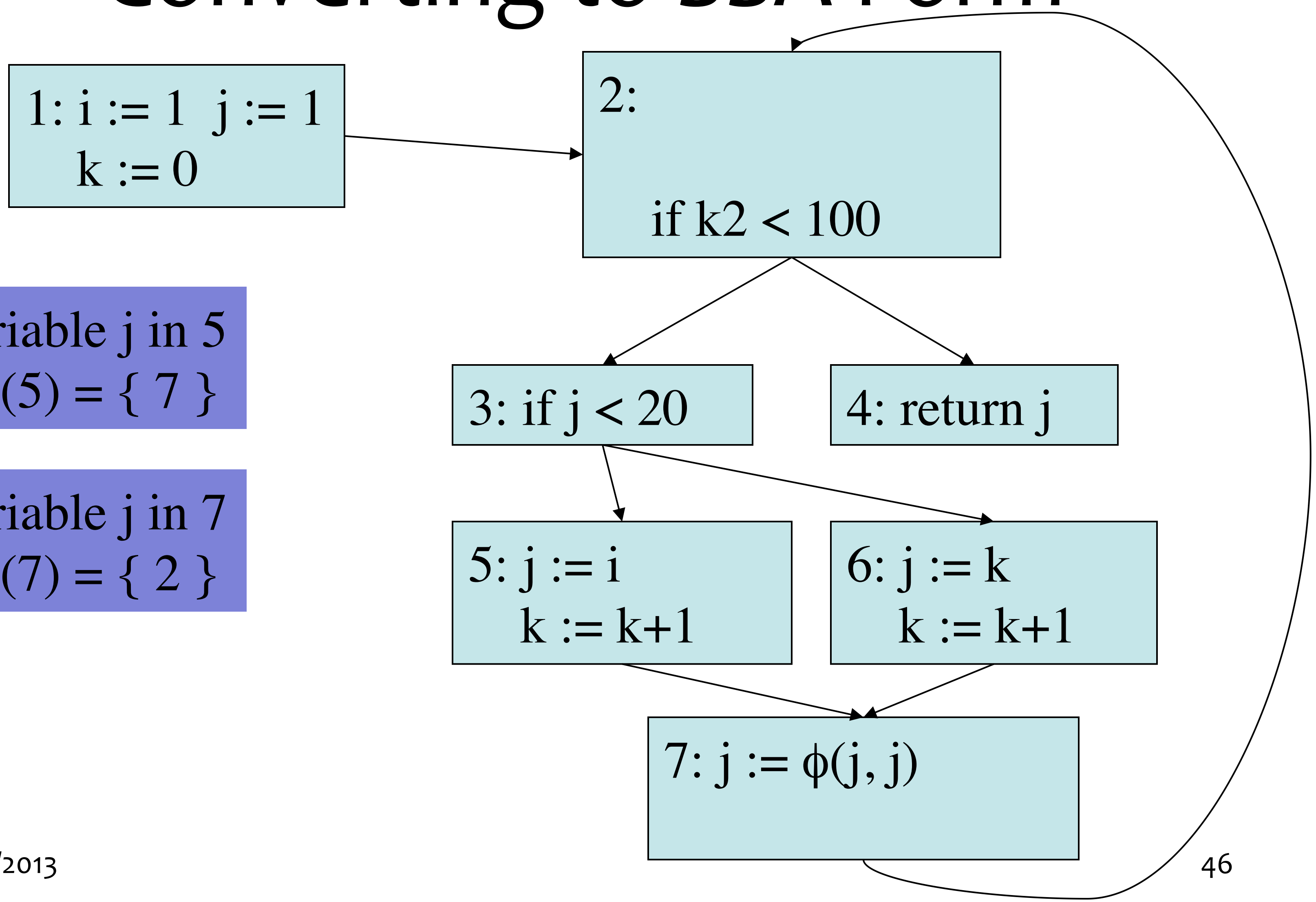


Variable j in 5
DF(5) = { 7 }

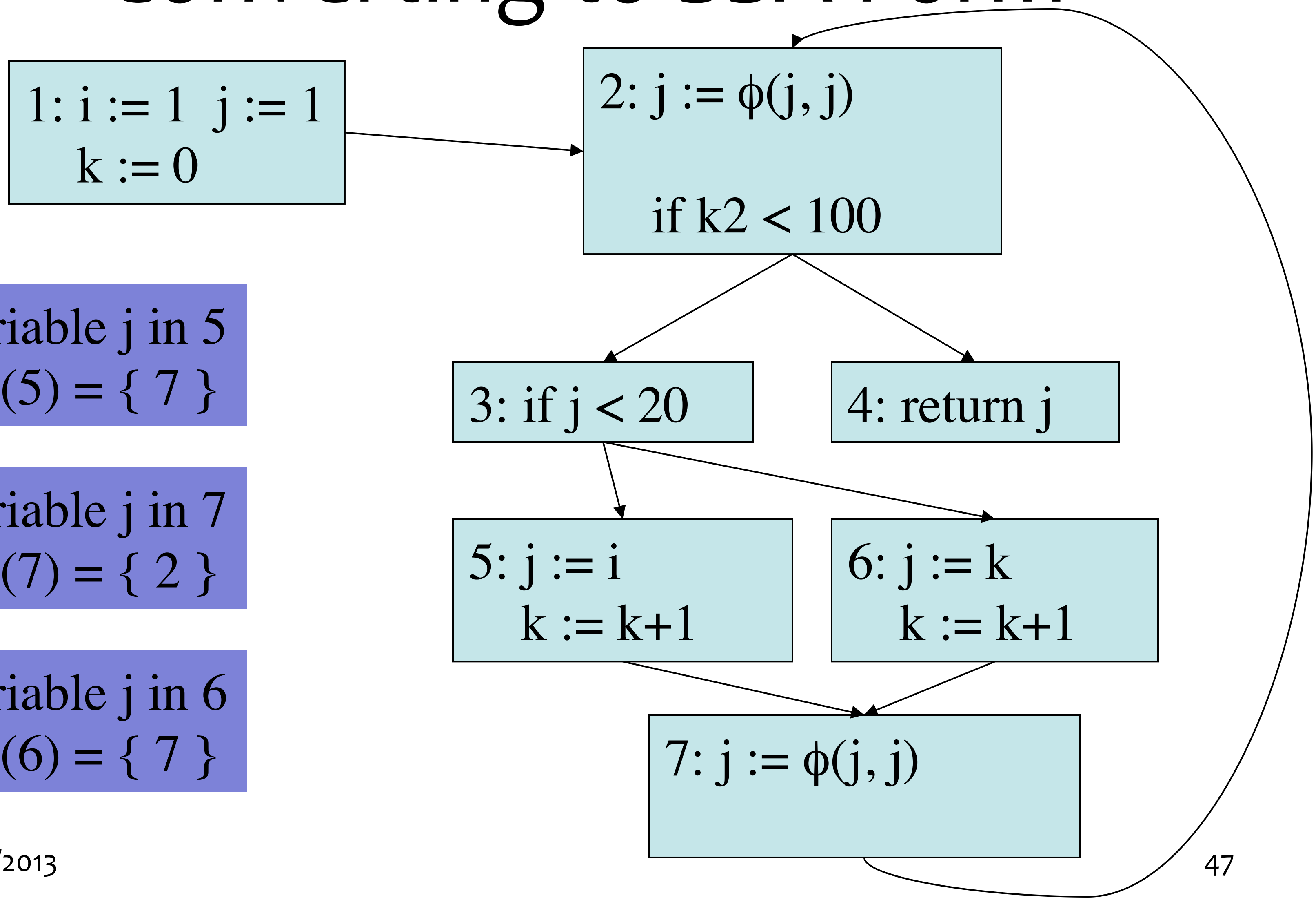
Converting to SSA Form

Variable j in 5
DF(5) = { 7 }

Variable j in 7
DF(7) = { 2 }



Converting to SSA Form



Variable j in 5
DF(5) = { 7 }

Variable j in 7
DF(7) = { 2 }

Variable j in 6
DF(6) = { 7 }

Converting to SSA Form

1: i := 1 j := 1
k := 0

2: j := ϕ(j, j)
k := ϕ(k,k)
if k2 < 100

3: if j < 20

4: return j

5: j := i
k := k+1

6: j := k
k := k+1

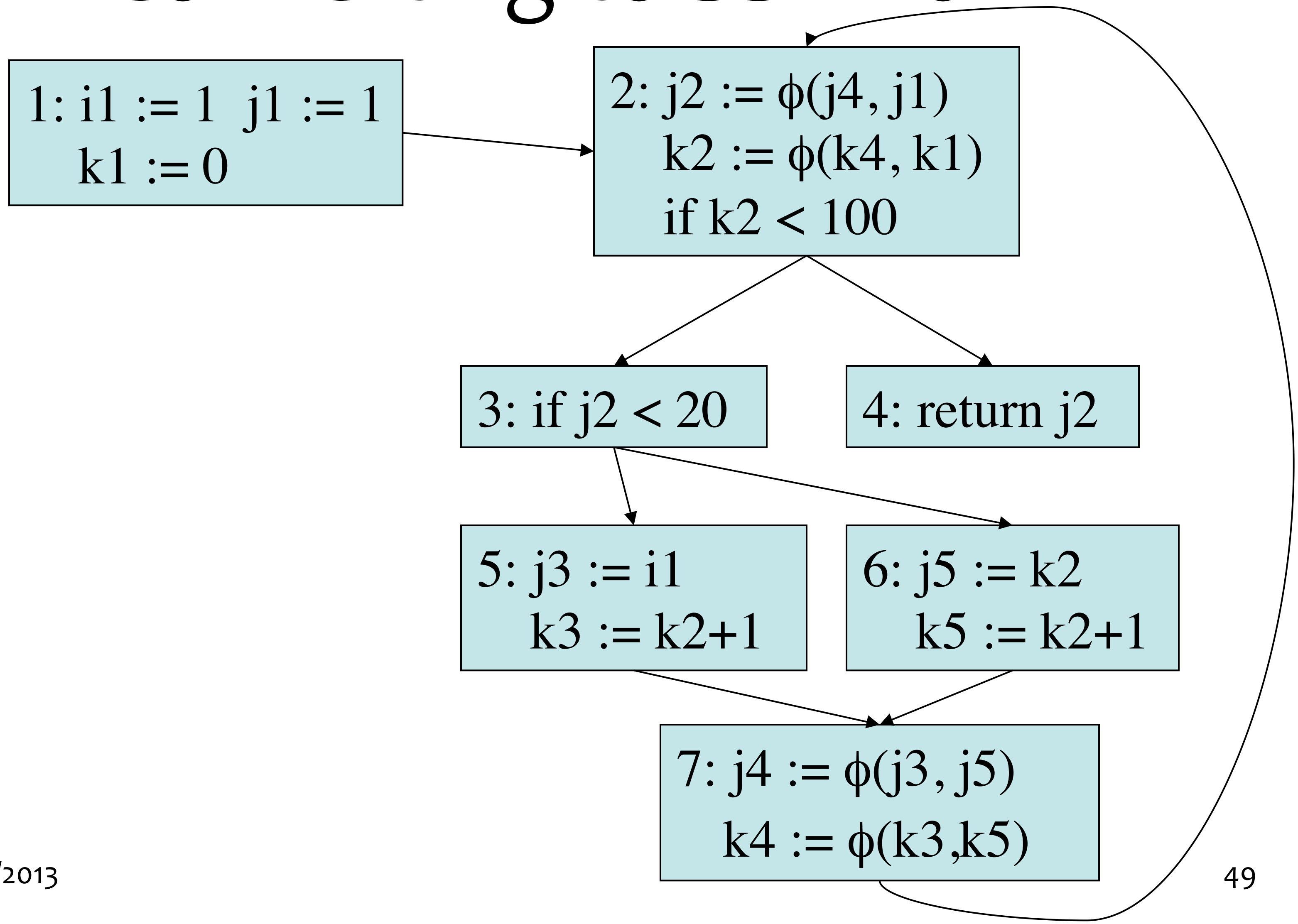
7: j := ϕ(j, j)
k := ϕ(k,k)

Variable k in 5
DF(5) = { 7 }

Variable k in 7
DF(7) = { 2 }

Variable k in 6
DF(6) = { 7 }

Converting to SSA Form



Optimizations using SSA

- SSA form contains *statements*, *basic blocks* and *variables*
- Dead-code elimination
  - if there is a variable *v* with no *uses* and *def* of *v* has no side-effects, delete statement defining *v*
  - if $z := \phi(x, y)$ then eliminate this stmt if no *defs* for *x*,*y*

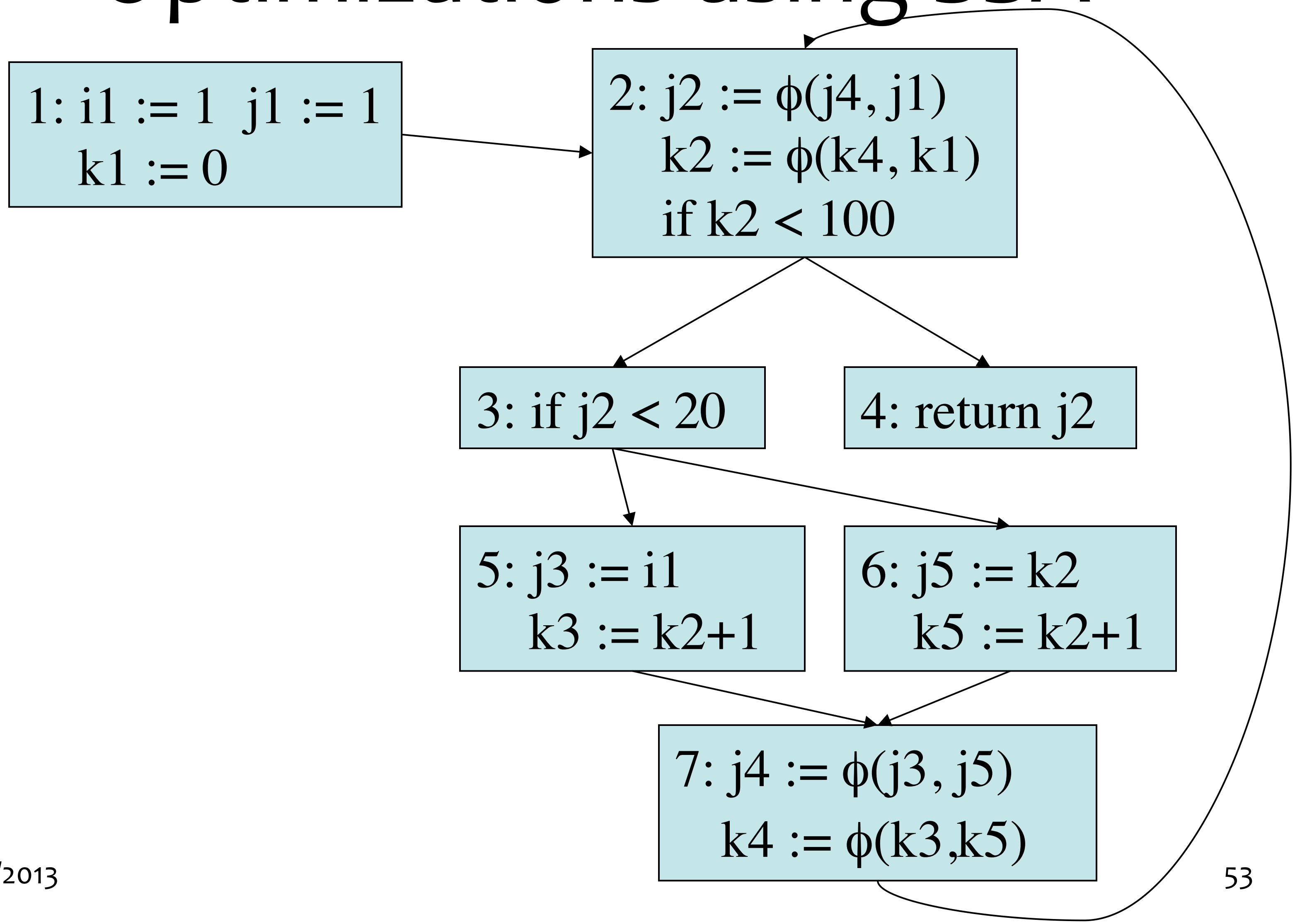
Optimizations using SSA

- Constant Propagation
  - if $v := c$ for some constant c then replace v with c for all uses of v
  - $v := \phi\,(c1, c2, \ldots, cn)$ where all c_i are equal to c can be replaced by $v := c$

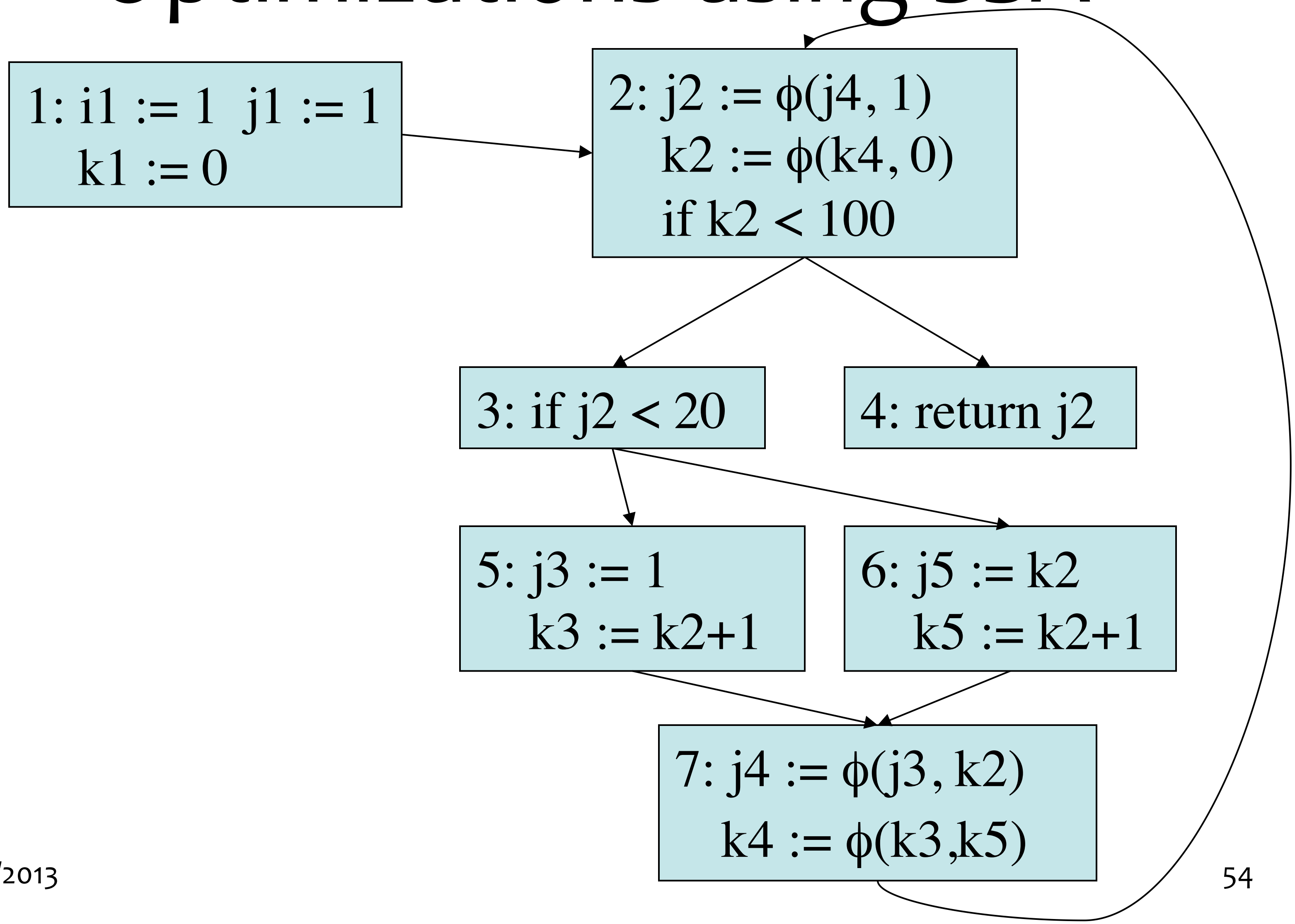
Optimizations using SSA

- Conditional Constant Propagation
  - In previous flow graph, is j always equal to 1?
  - If j = 1 always, then block 6 will never execute and so j := i and j := 1 always
  - If j > 20 then block 6 will execute, and j := k will be executed so that eventually j > 20
  - Which will happen? Using SSA we can find the answer.

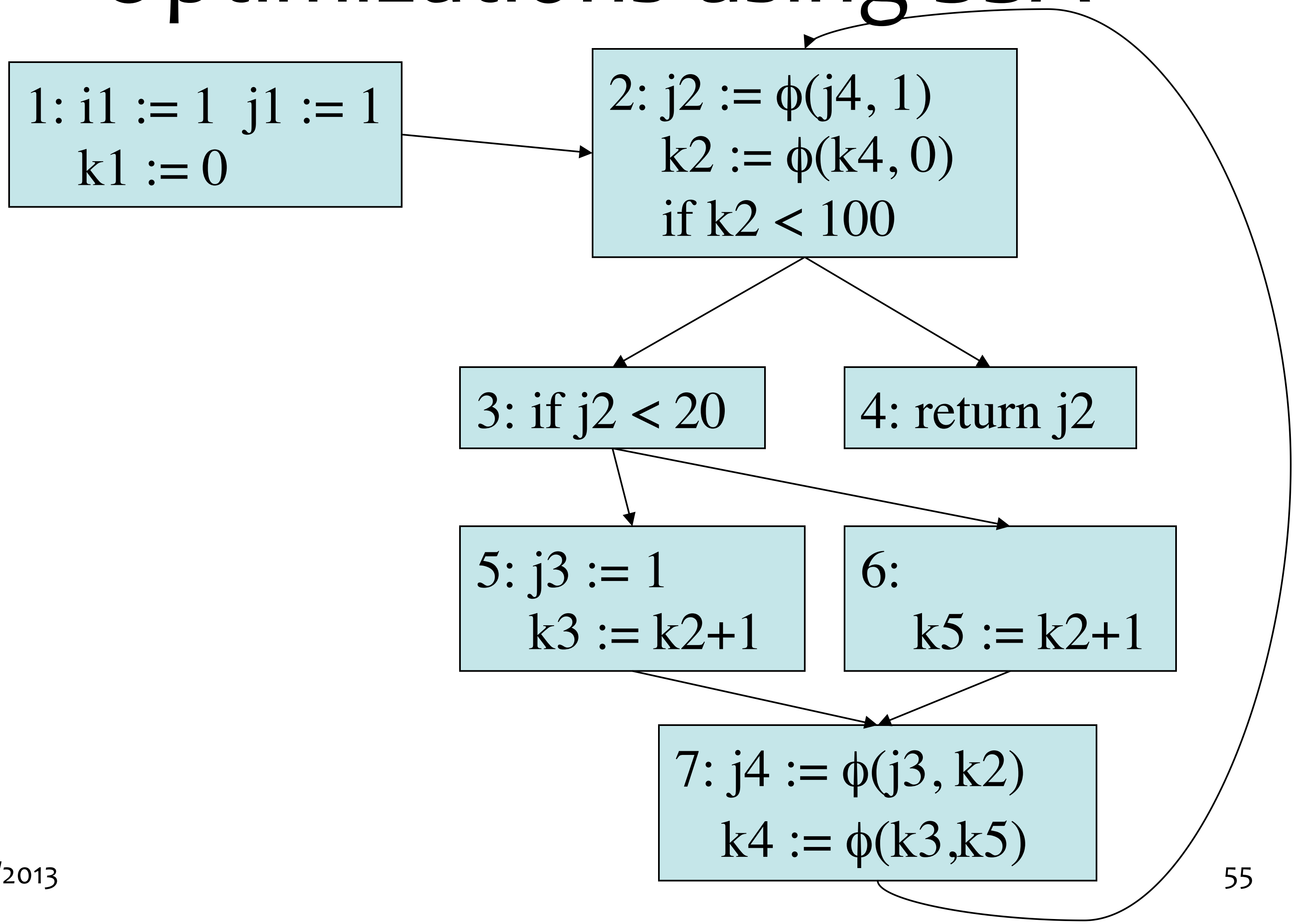
Optimizations using SSA



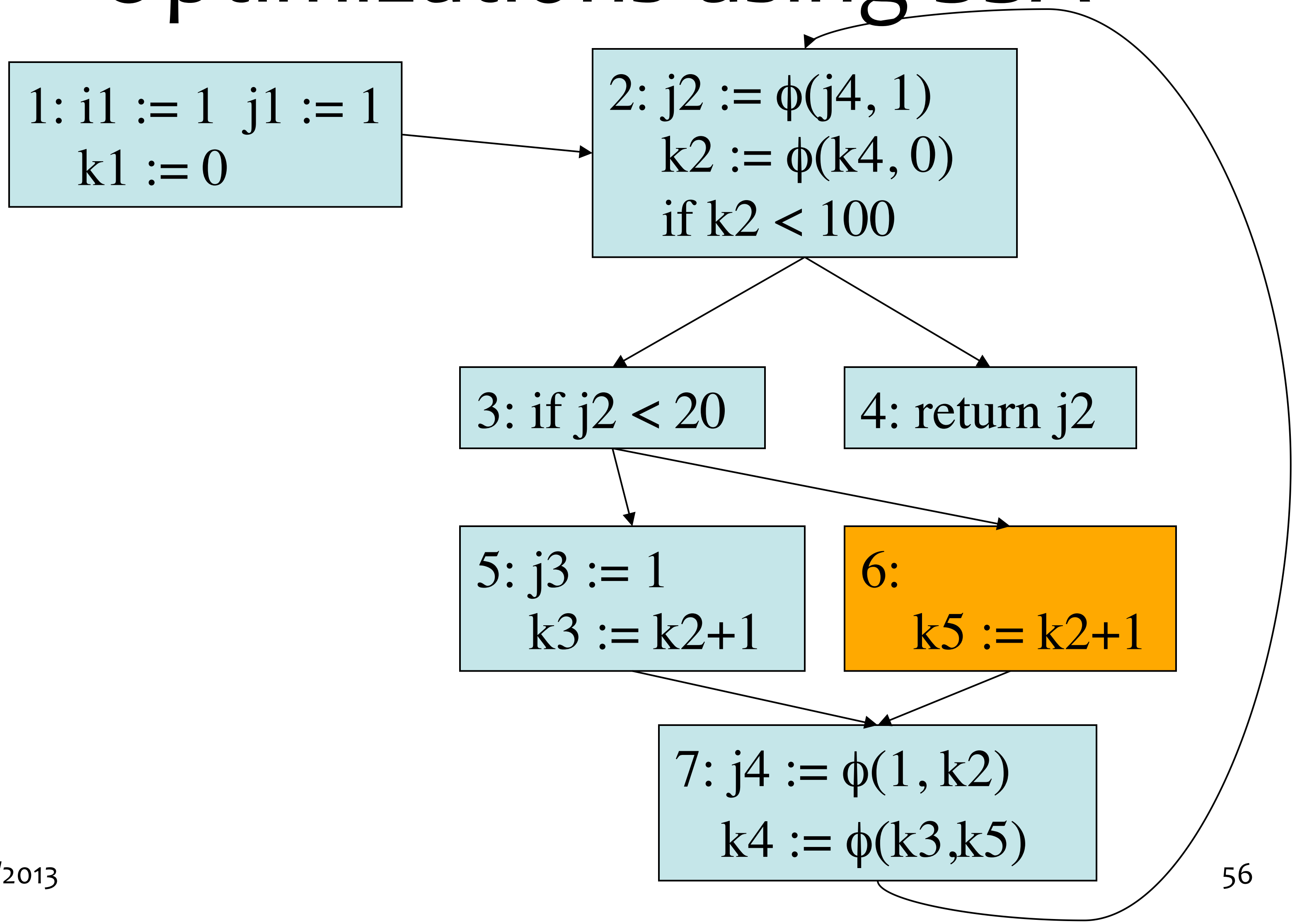
Optimizations using SSA



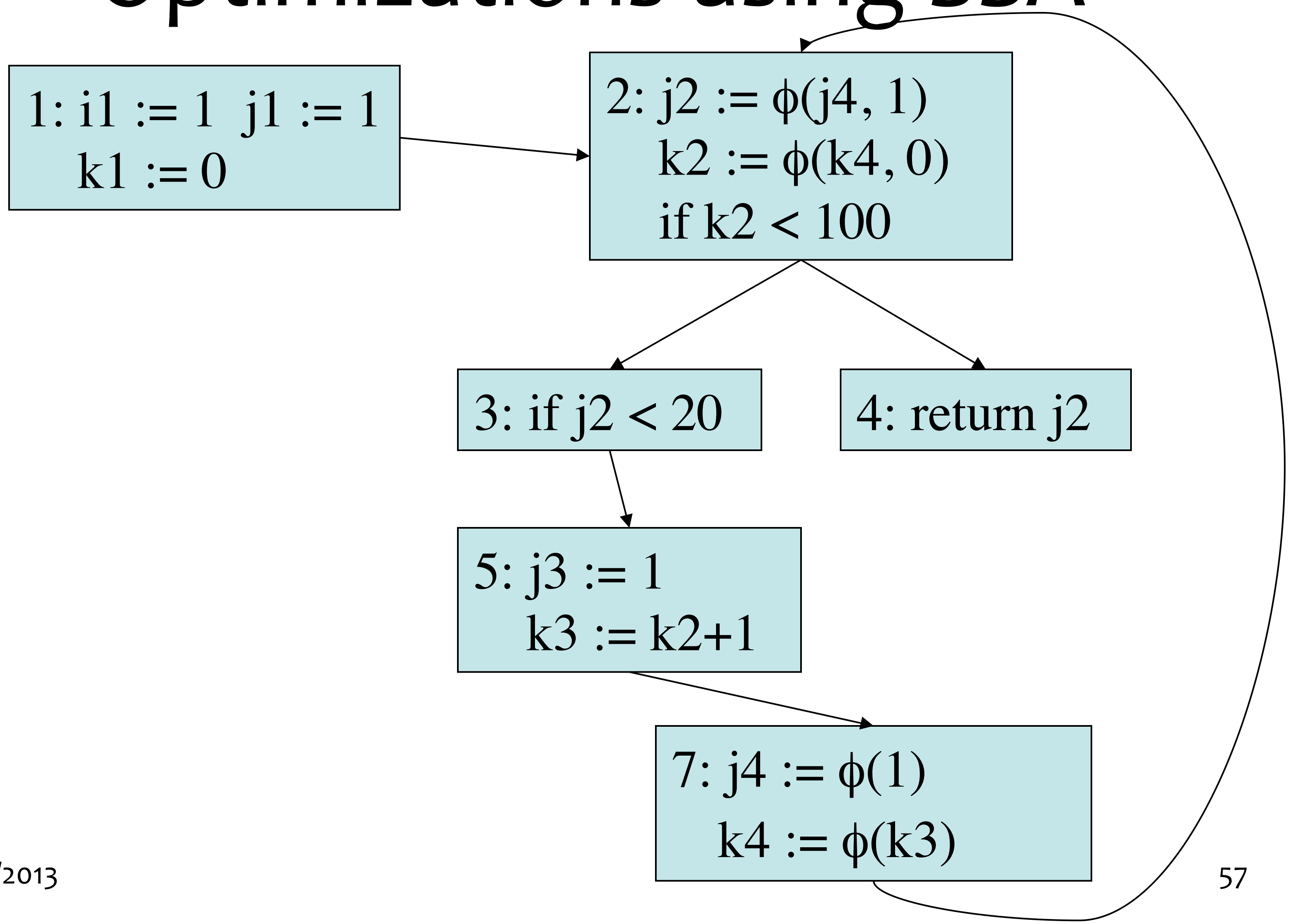
Optimizations using SSA



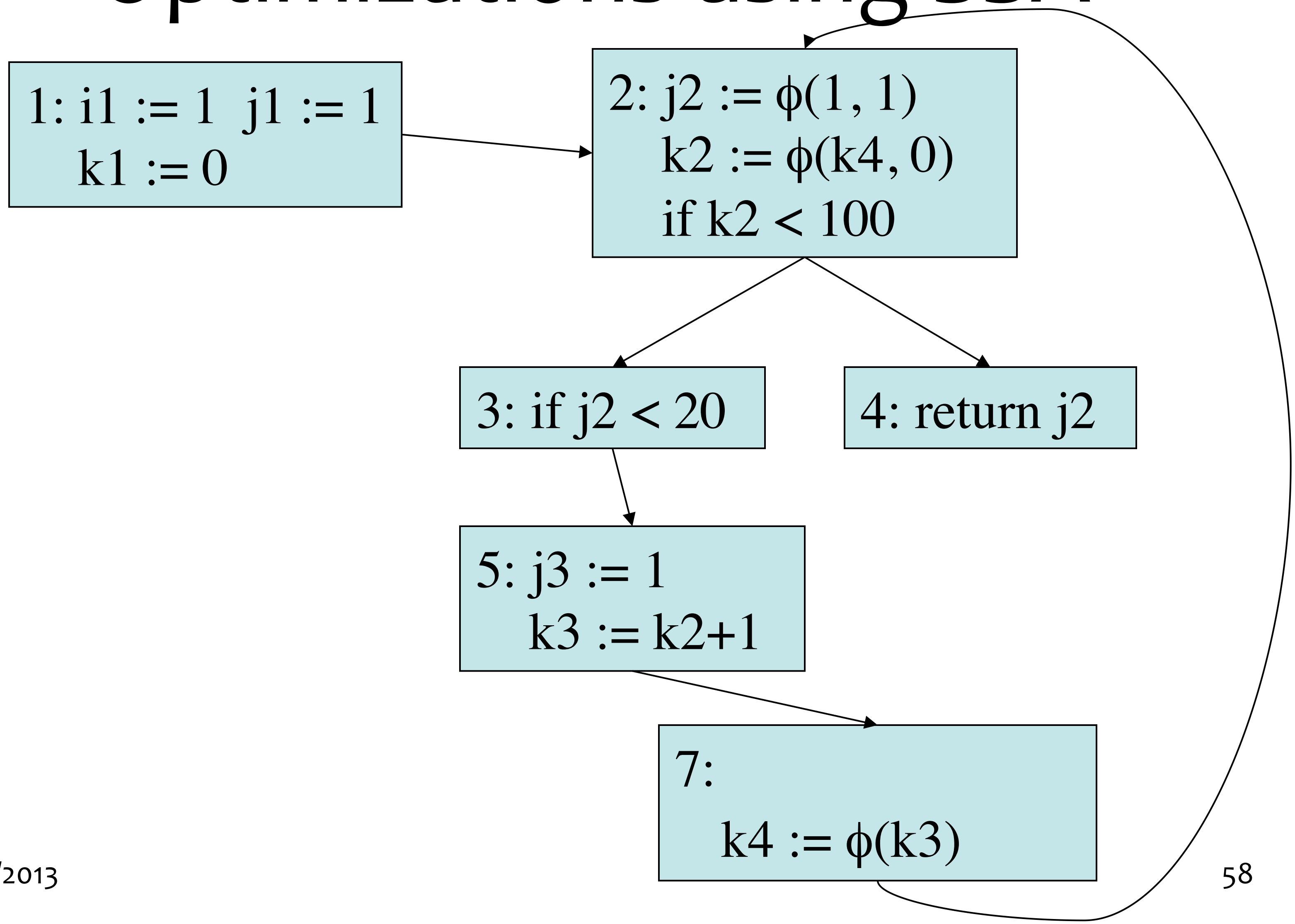
Optimizations using SSA



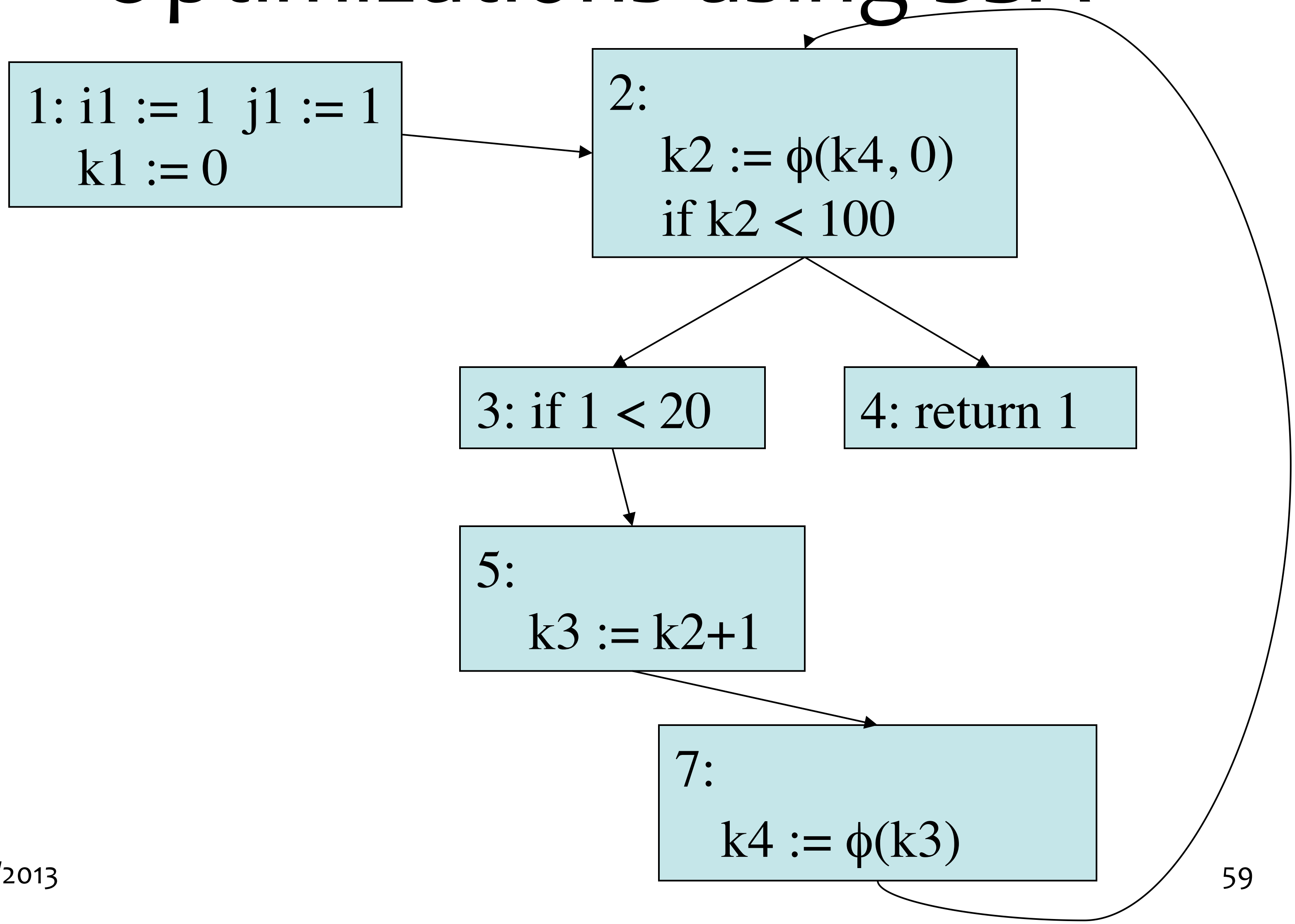
Optimizations using SSA



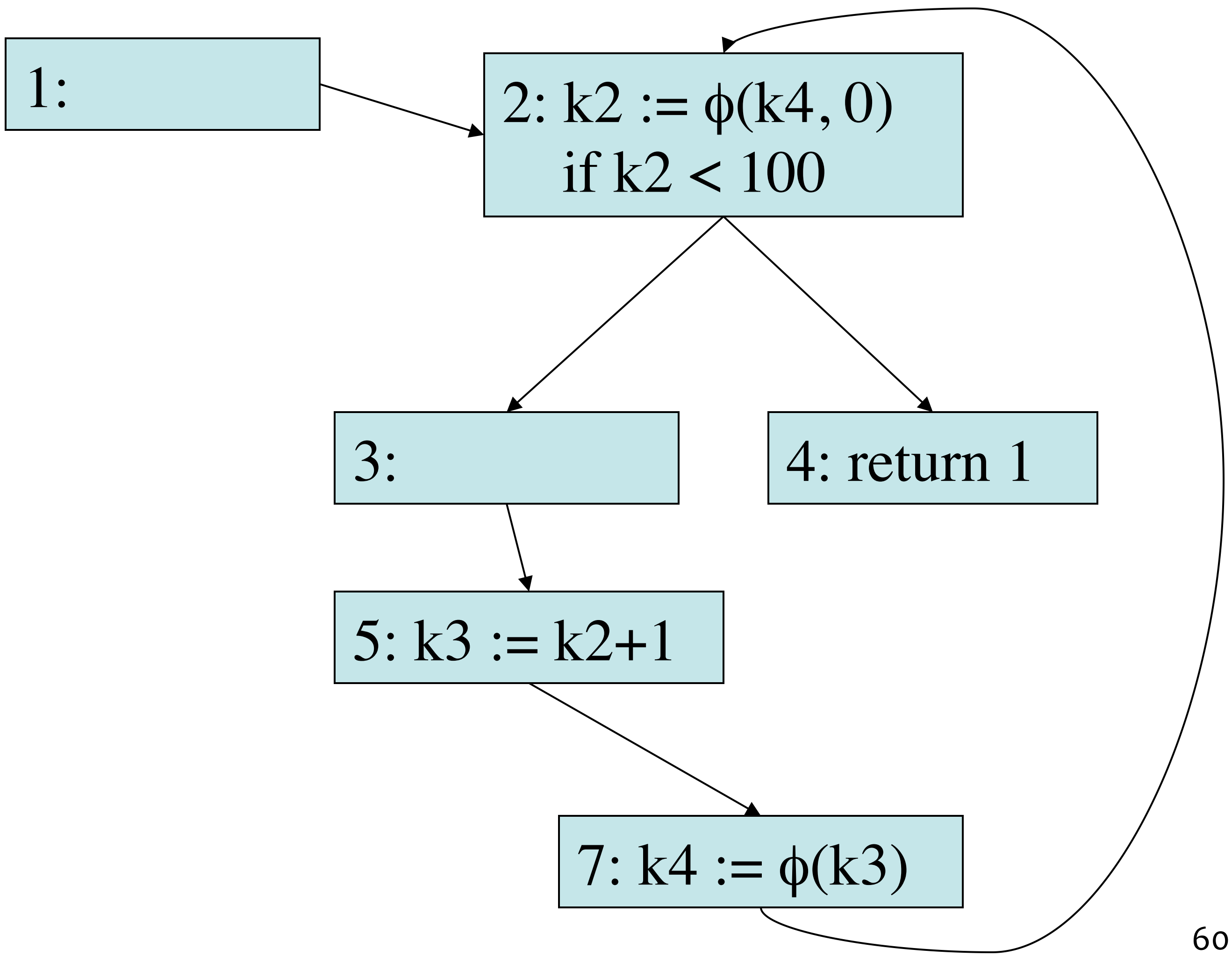
Optimizations using SSA



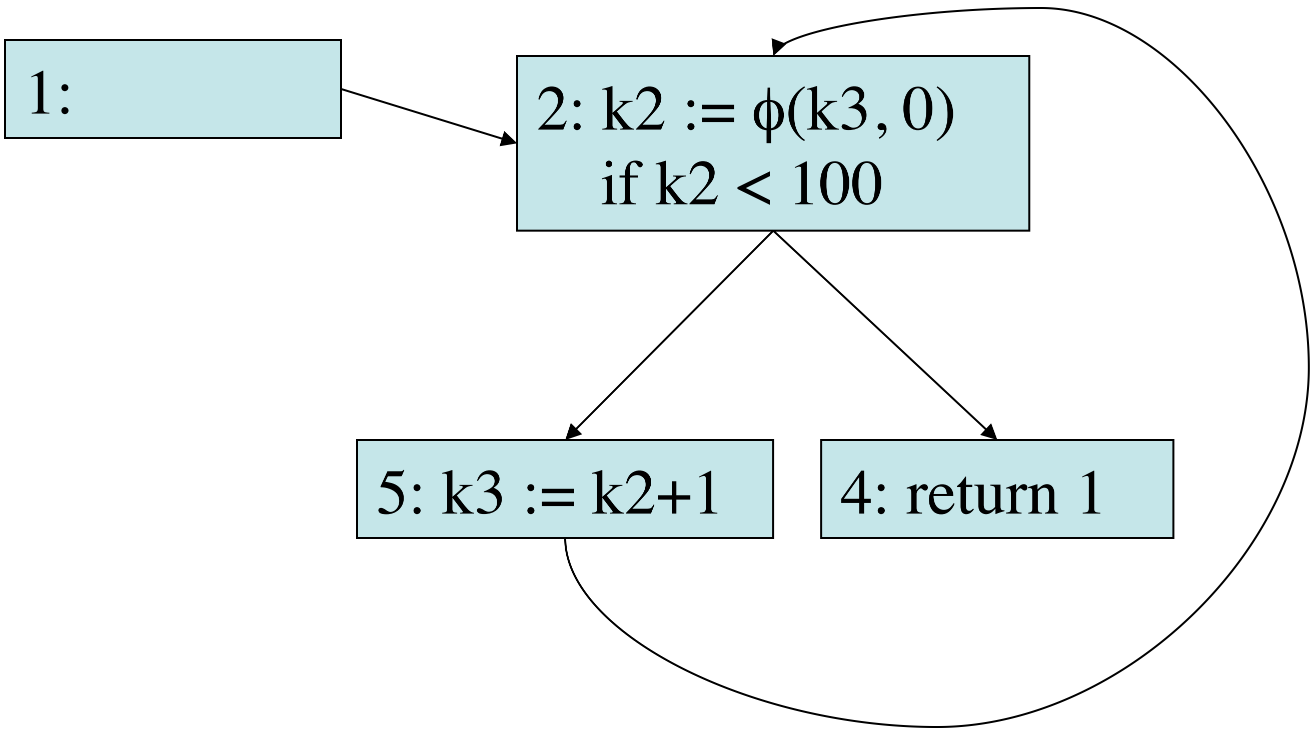
Optimizations using SSA



Optimizations using SSA



Optimizations using SSA



Optimizations using SSA

- Arrays, Pointers and Memory
  - For more complex programs, we need *dependencies*: how does statement B depend on statement A?
  - **Read after write**: A defines variable *v*, then B uses *v*
  - **Write after write**: A defines *v*, then B defines *v*
  - **Write after read**: A uses *v*, then B defines *v*
  - **Control**: A controls whether B executes

Optimizations using SSA

- Memory dependence

  M[i] := 4

  x := M[j]

  M[k] := j

- We cannot tell if *i*, *j*, *k* are all the same value which makes any optimization difficult
- Similar problems with Control dependence
- SSA does not offer an easy solution to these problems

More on Optimization

- *Advanced Compiler Design and Implementation* by Steven S. Muchnick

- Control Flow Analysis
- Data Flow Analysis
- Dependence Analysis
- Alias Analysis
- Early Optimizations
- Redundancy Elimination
- Loop Optimizations
- Procedure Optimizations
- Code Scheduling (pipelining)
- Low-level Optimizations
- Interprocedural Analysis
- Memory Hierarchy

Amdahl's Law

- $\text{Speedup}_{\text{total}} = ((1 - \text{Time}_{\text{Fractionoptimized}}) + \text{Time}_{\text{Fractionoptimized}} / \text{Speedup}_{\text{optimized}})^{-1}$
- Optimize the common case, 90/10 rule
- Requires quantitative approach
  - Profiling + Benchmarking
- Problem: Compiler writer doesn't know the application beforehand

Summary

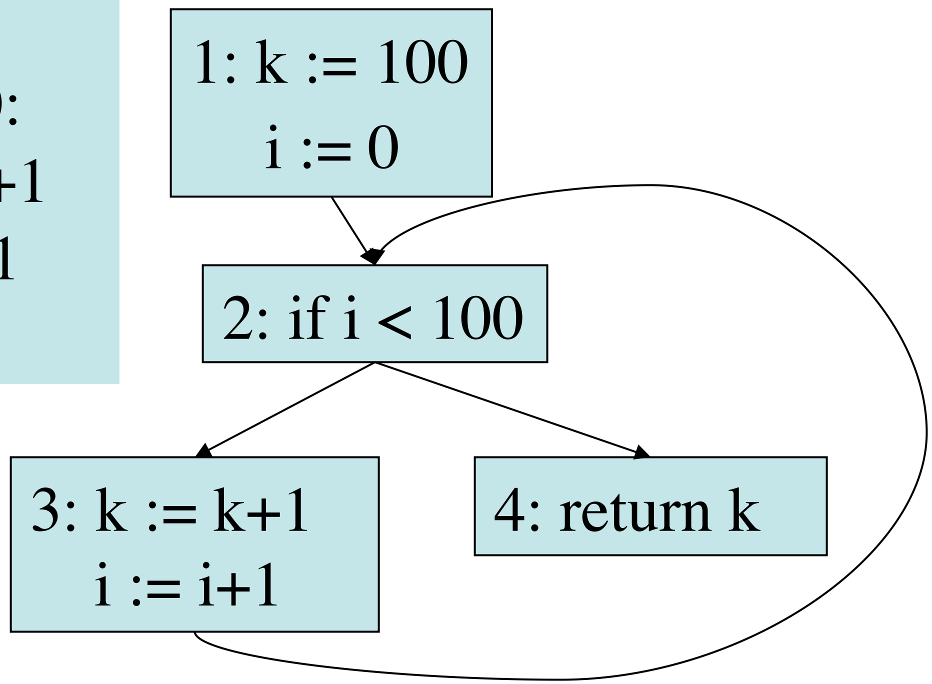
- Optimizations can improve speed, while maintaining correctness
- Various early optimization steps
- Static Single-Assignment Form (SSA)
- Optimization using SSA Form

Converting to SSA Form

Program

```
k:=100
i:=0
if i<100:
    k:=k+1
    i:=i+1
return k
```

Control Flow Graph



Dominance Relations

- D(1) = {2,3,4}
- D(2) = {3,4}
- D(3) = {}
- D(4) = {}

Dominance Frontier

- DF(1) = {}
- DF(2) = {2}
- DF(3) = {2}
- DF(4) = {}

Variable i,k in 1
DF(1) = {}

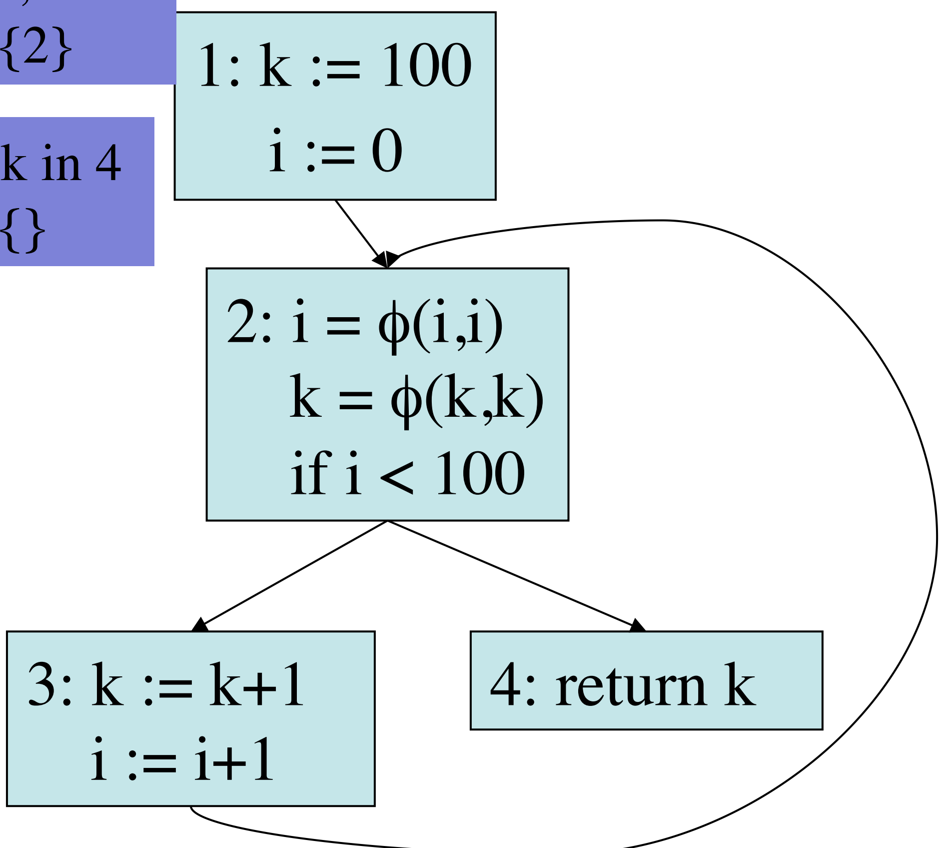
Variable i in 2
DF(2) = {2}

Variable i,k in 3
DF(3) = {2}

Variable k in 4
DF(4) = {}

Converting to SSA Form

Control Flow Graph



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Converting to SSA Form