Compiling Techniques

Lecture 14: Building SSA Form

Reminder: Static Single-Assignment (SSA) Form

> *"A program is defined to be in **Static Single-Assignment (SSA)** form if each variable is a target of exactly one assignment statement in the program text."*

- Each assignment statement defines a unique name.
- Each use refers to a single name.

Representing Control Flow

```
x = 0
if (a == 42)
    x = x + 1
else
    x = 3

y = x + 5
```

Representing Control Flow

```
x = 0
if (a == 42)
    x = x + 1
else
    x = 3

y = x + 5
```

```
x1 = 0
if (a == 42)
    x2 = x1 + 1
else
    x3 = 3

y = x? + 5
```

Representing Control Flow

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x = 0
if (a == 42)
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```

```
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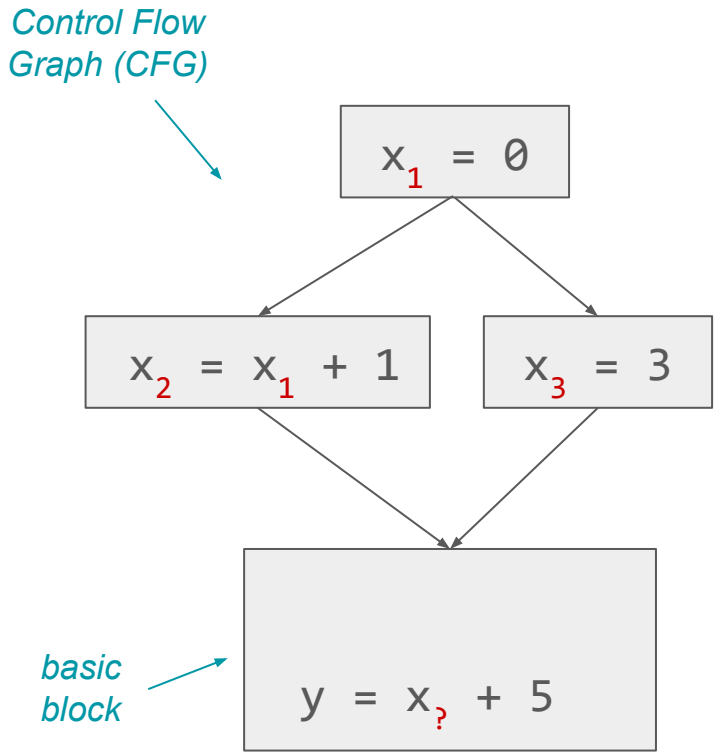
```

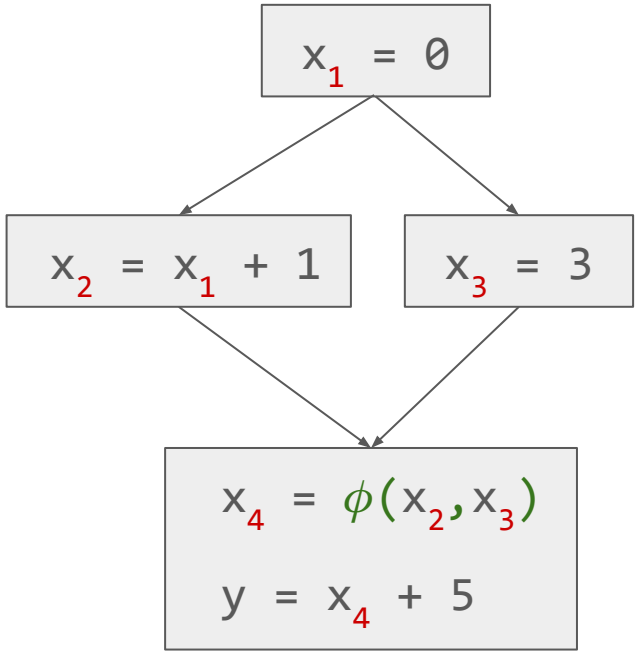


Representing Control Flow

```
x = 0
if (a == 42)
    x = x + 1
else
    x = 3

y = x + 5
```

```
x1 = 0
if (a == 42)
    x2 = x1 + 1
else
    x3 = 3
x4 = φ(x2,x3)
y = x4 + 5
```



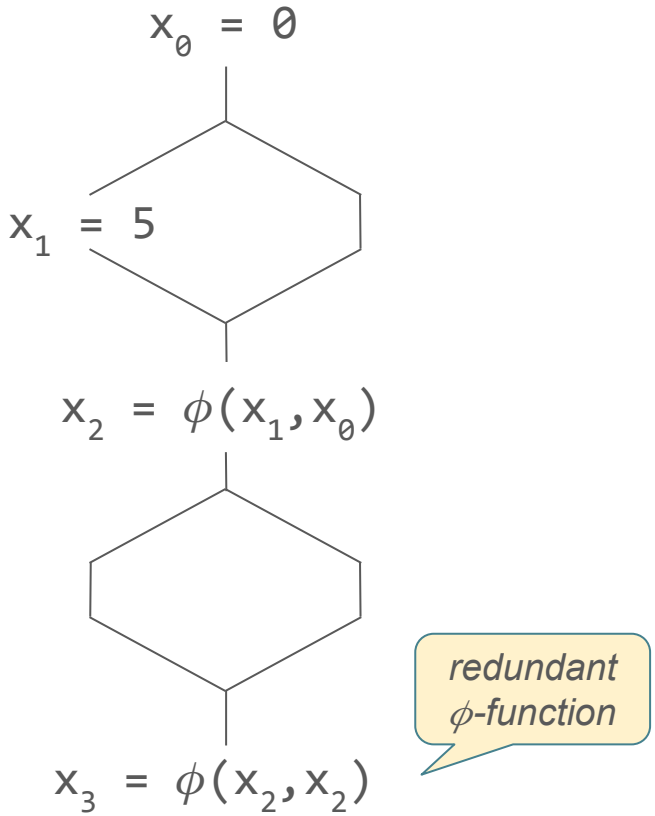
ϕ-function placement

Naive approach:

1. At each join point insert a ϕ-function for every variable name

1. Rename adding unique subscripts

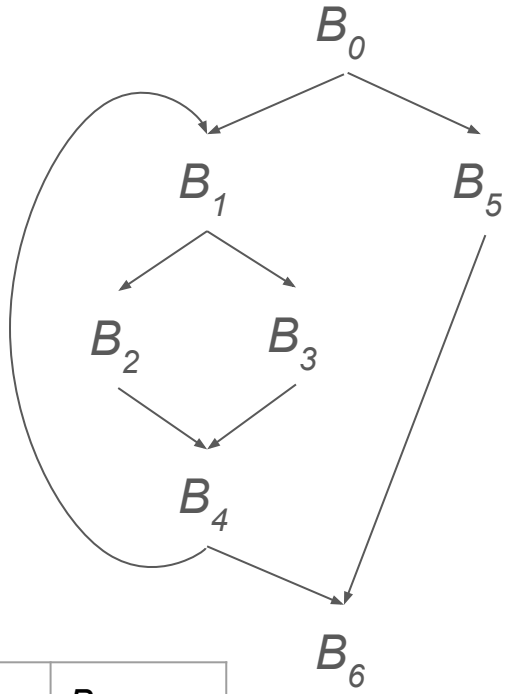
Computes *maximal SSA form*



Dominators

p dominates q (*p >> q*, *p dom q*) iff
every path from the entry node b_0 to *q* also visits *p*.

Dom(q) – set of nodes that dominate *q*.



B	B_0	B_1	B_2	B_3	B_4	B_5	B_6
DOM(B)	B_0						

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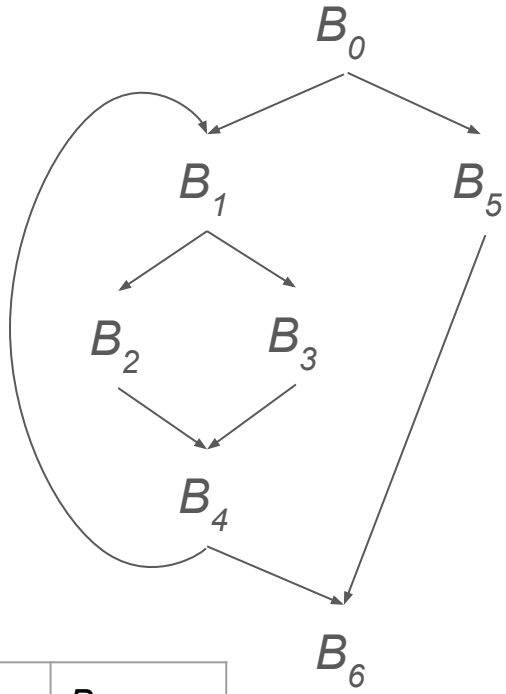

B	B_0	B_1	B_2	B_3	B_4	B_5	B_6
DOM(B)	B_0	B_0, B_1					

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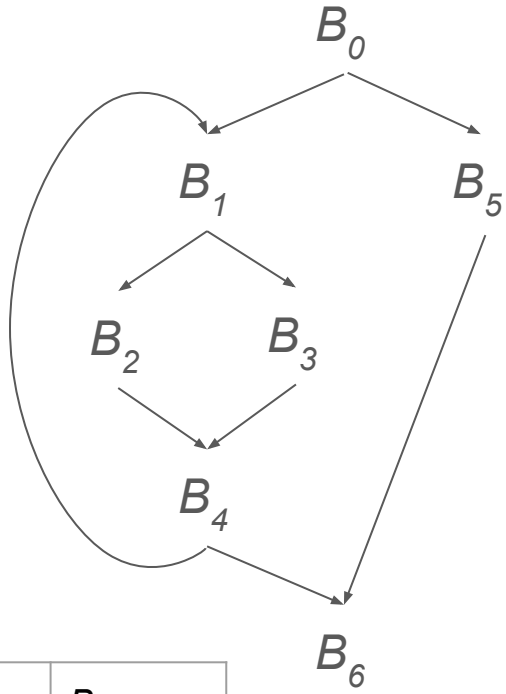

B	B_0	B_1	B_2	B_3	B_4	B_5	B_6
DOM(B)	B_0	B_0, B_1	B_0, B_1, B_2	B_0, B_1, B_3			

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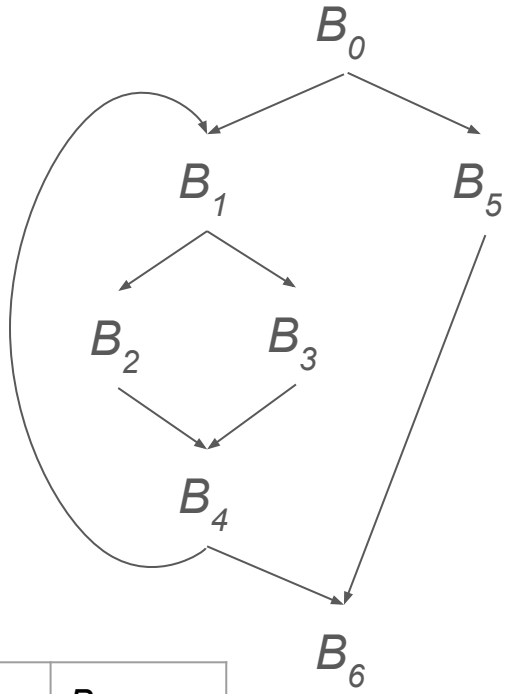

B	B_0	B_1	B_2	B_3	B_4	B_5	B_6
DOM(B)	B_0	B_0, B_1	B_0, B_1, B_2	B_0, B_1, B_3	B_0, B_1, B_4		

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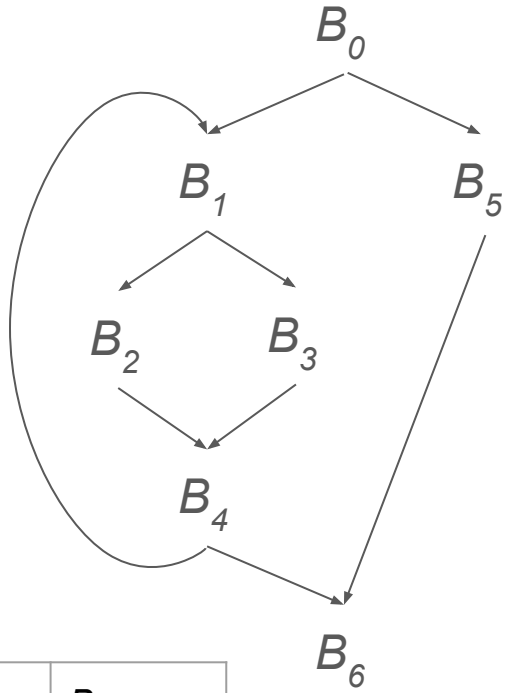

B	B_0	B_1	B_2	B_3	B_4	B_5	B_6
DOM(B)	B_0	B_0, B_1	B_0, B_1, B_2	B_0, B_1, B_3	B_0, B_1, B_4	B_0, B_5	

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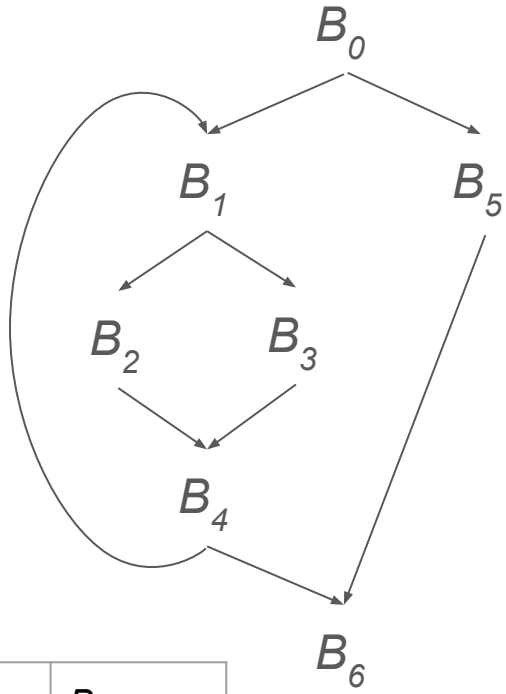


B	B_0	B_1	B_2	B_3	B_4	B_5	B_6
DOM(B)	B_0	B_0, B_1	B_0, B_1, B_2	B_0, B_1, B_3	B_0, B_1, B_4	B_0, B_5	B_0, B_6

dom Relation

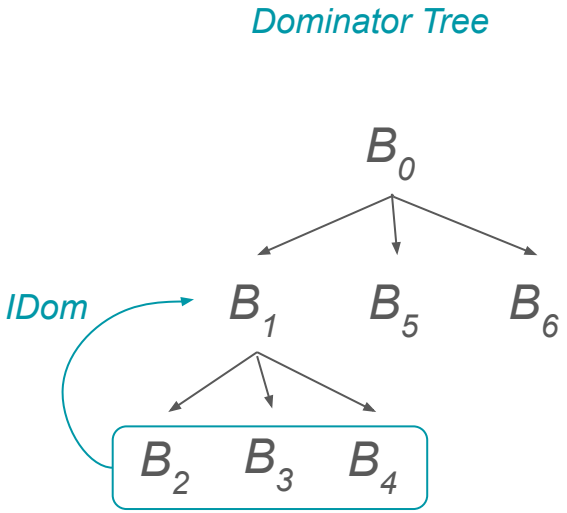
- reflexive

  $a \text{ dom } a$
- antisymmetric

  $a \text{ dom } b \land b \text{ dom } a \Rightarrow a = b$
- transitive

  $a \text{ dom } b \land b \text{ dom } c \Rightarrow a \text{ dom } c$

i.e. it's a *partial order*



Dominance frontier

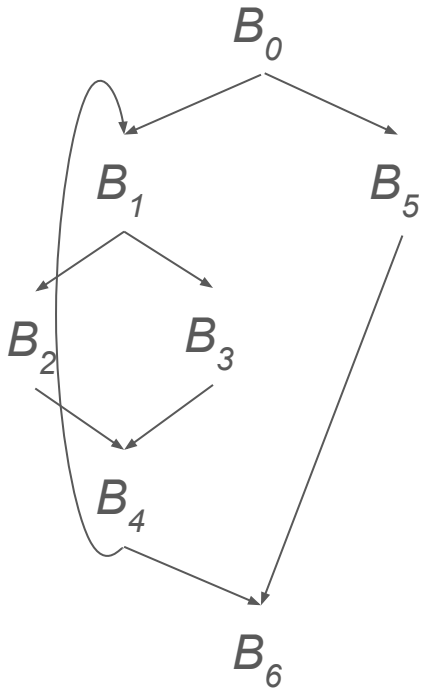
p strictly dominates q iff

p dominates *q* and $p \neq q$.

q is in *dominance frontier* of *p* iff

- *p* domitates a predecessor of *q*.
- *p* does not strictly dominate *q*.

DF(p) – dominance frontier of *p*.



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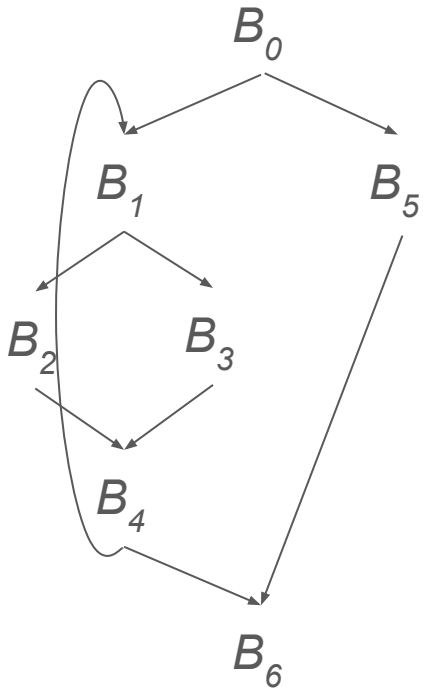

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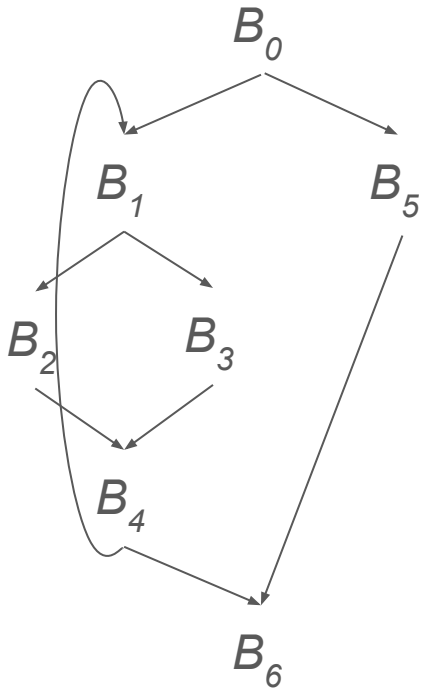

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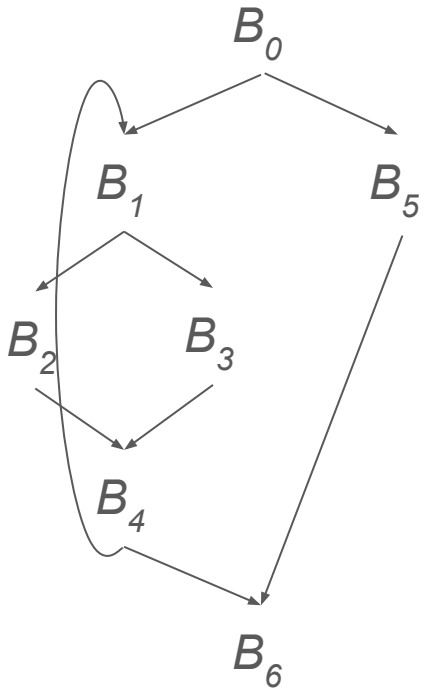

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DF(B)	∅	B_1, B_6	B_4	B_4			

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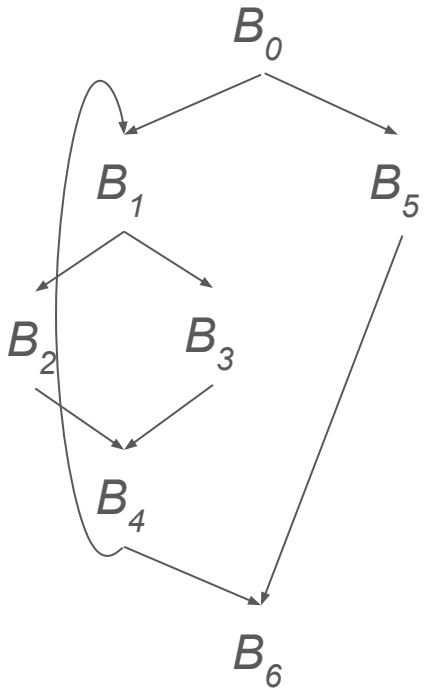

B	B_0	B_1	B_2	B_3	B_4	B_5	B_6
DF(B)	∅	B_1, B_6	B_4	B_4	B_1, B_6		

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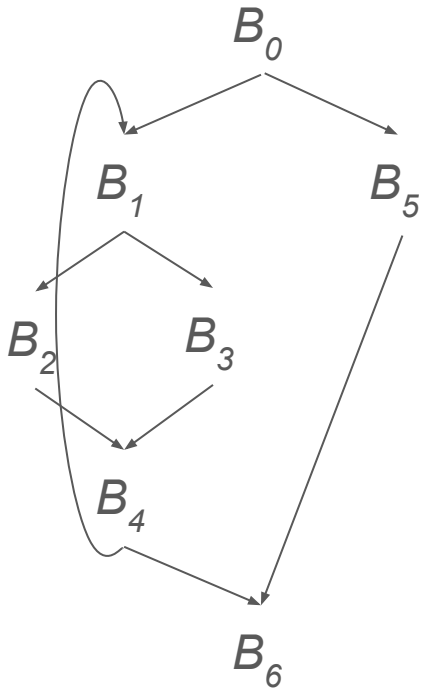

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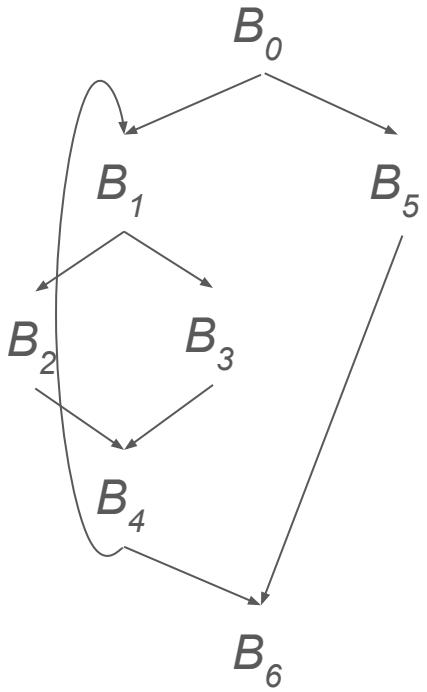


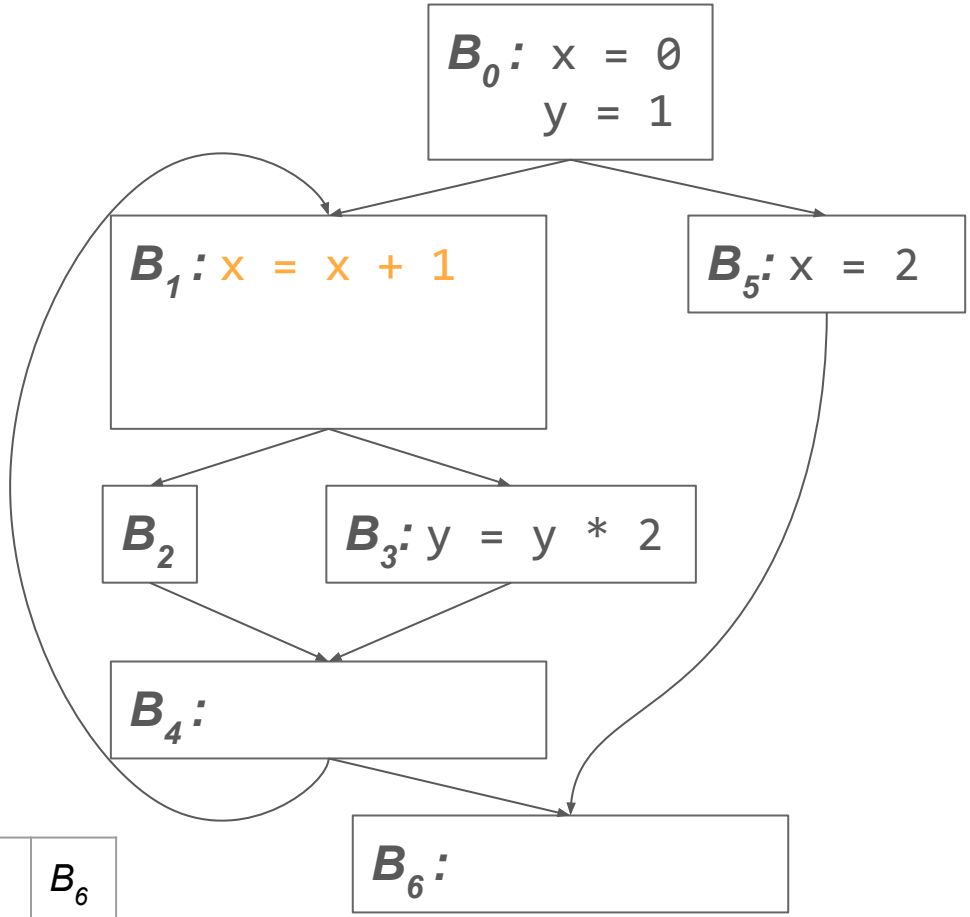
B	B_0	B_1	B_2	B_3	B_4	B_5	B_6
DF(B)	∅	B_1, B_6	B_4	B_4	B_1, B_6	B_6	∅

Minimal SSA

Idea

an assignment to x in the node *B* introduces a ϕ-function in every node from DF(B)

1. **ϕ-function placement**
2. renaming



B	B_0	B_1	B_2	B_3	B_4	B_5	B_6
DF(B)	∅	B_1, B_6	B_4	B_4	B_1, B_6	B_6	∅

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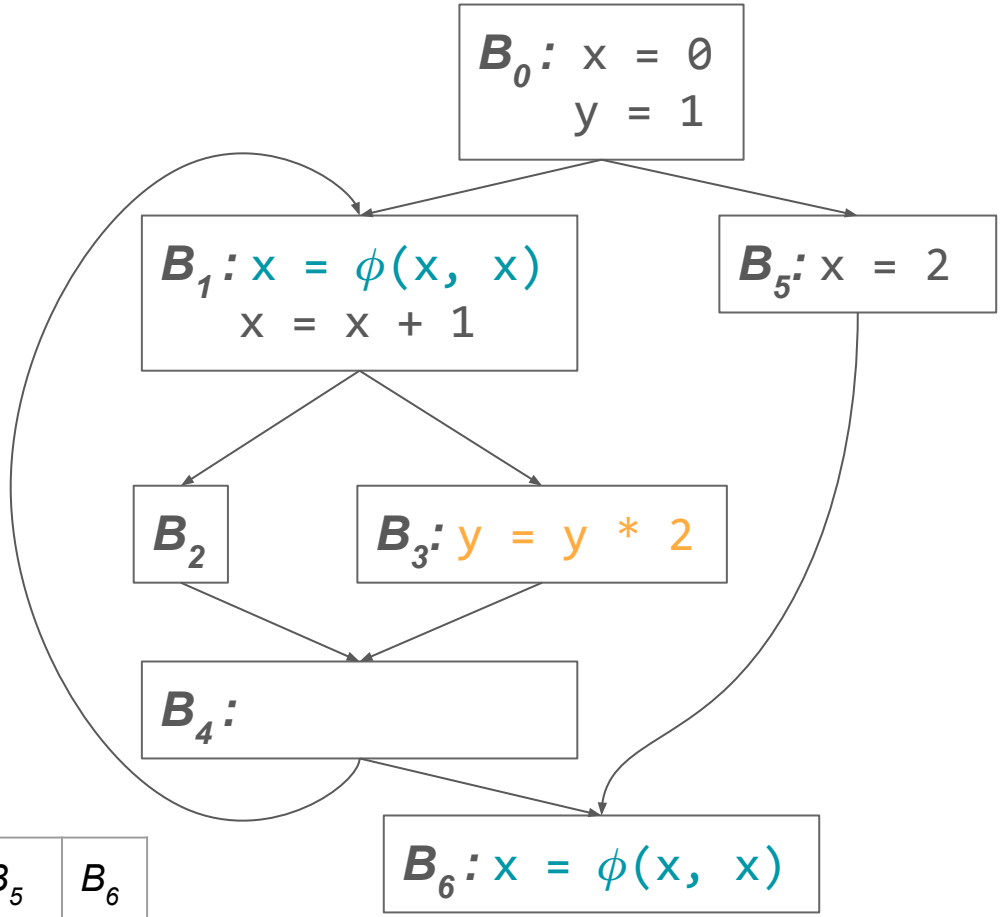

B	B_0	B_1	B_2	B_3	B_4	B_5	B_6
DF(B)	∅	B_1, B_6	B_4	B_4	B_1, B_6	B_6	∅

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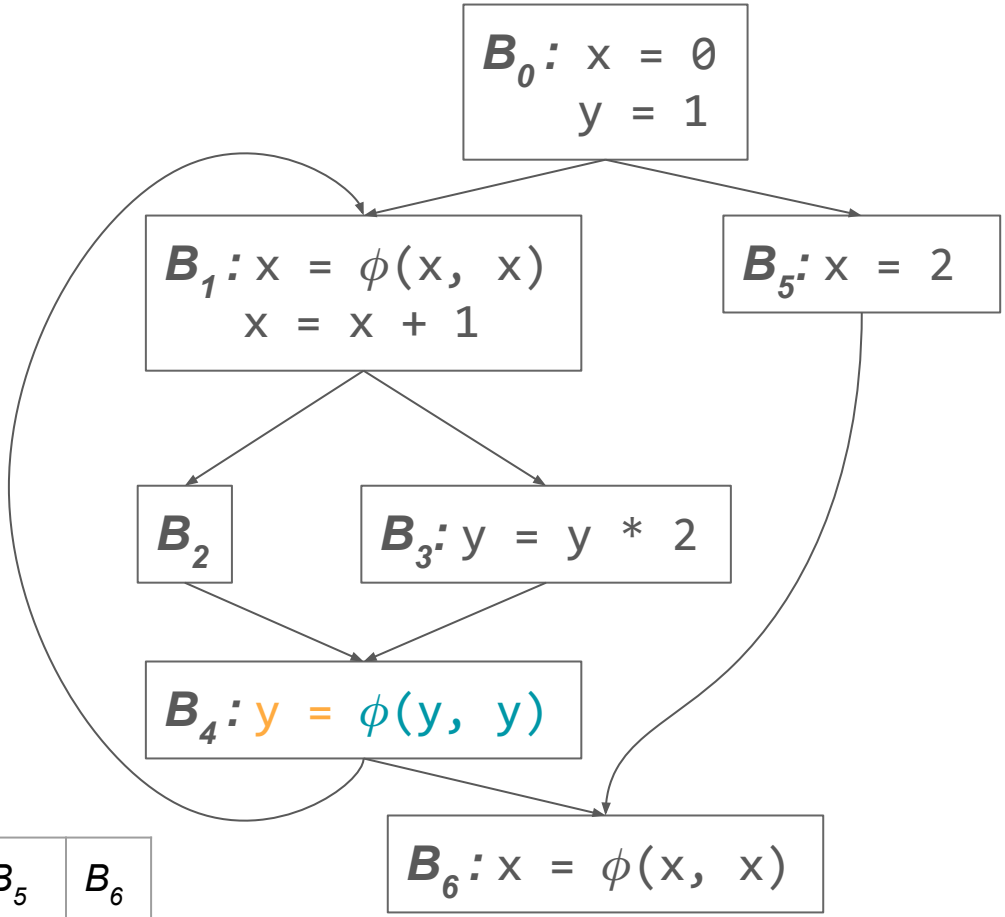

B	B_0	B_1	B_2	B_3	B_4	B_5	B_6
DF(B)	∅	B_1, B_6	B_4	B_4	B_1, B_6	B_6	∅

Minimal SSA

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an assignment to x in the node *B* introduces a ϕ-function in every node from DF(B)

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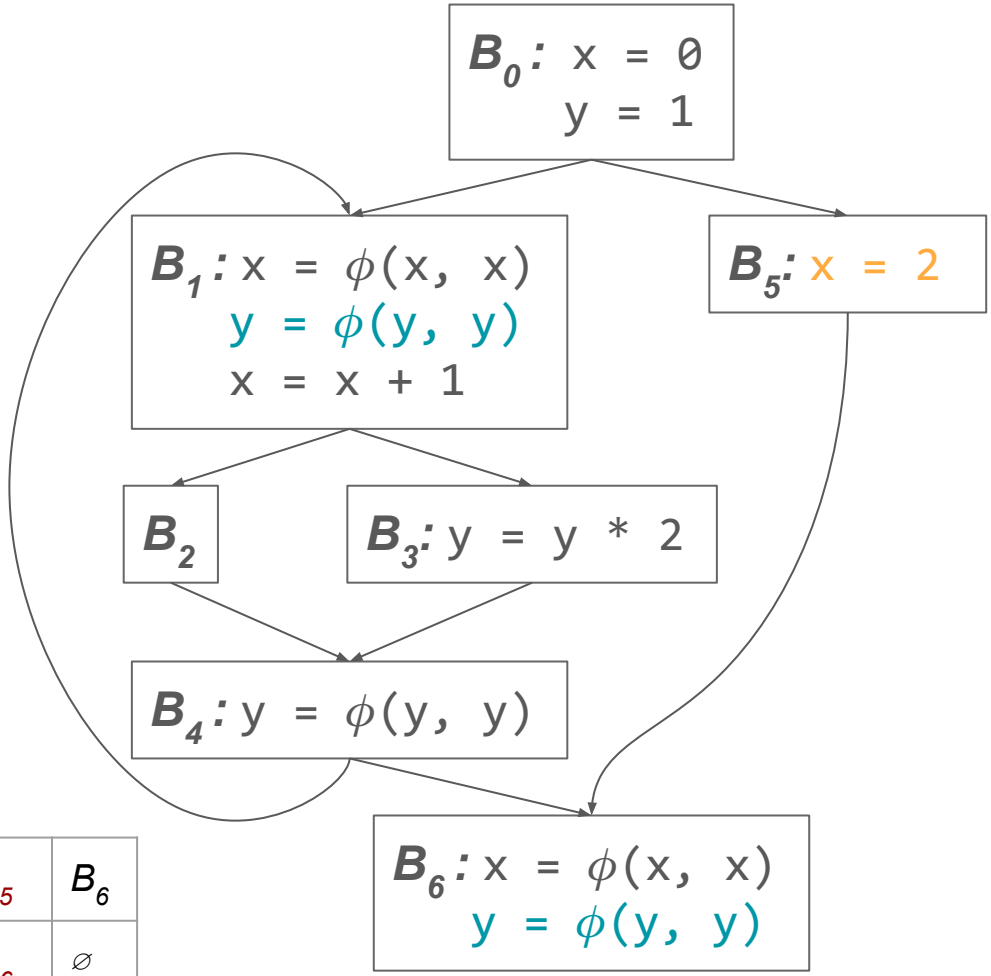

B	B_0	B_1	B_2	B_3	B_4	B_5	B_6
DF(B)	∅	B_1, B_6	B_4	B_4	B_1, B_6	B_6	∅

Minimal SSA

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an assignment to x in the node *B* introduces a ϕ-function in every node from DF(B)

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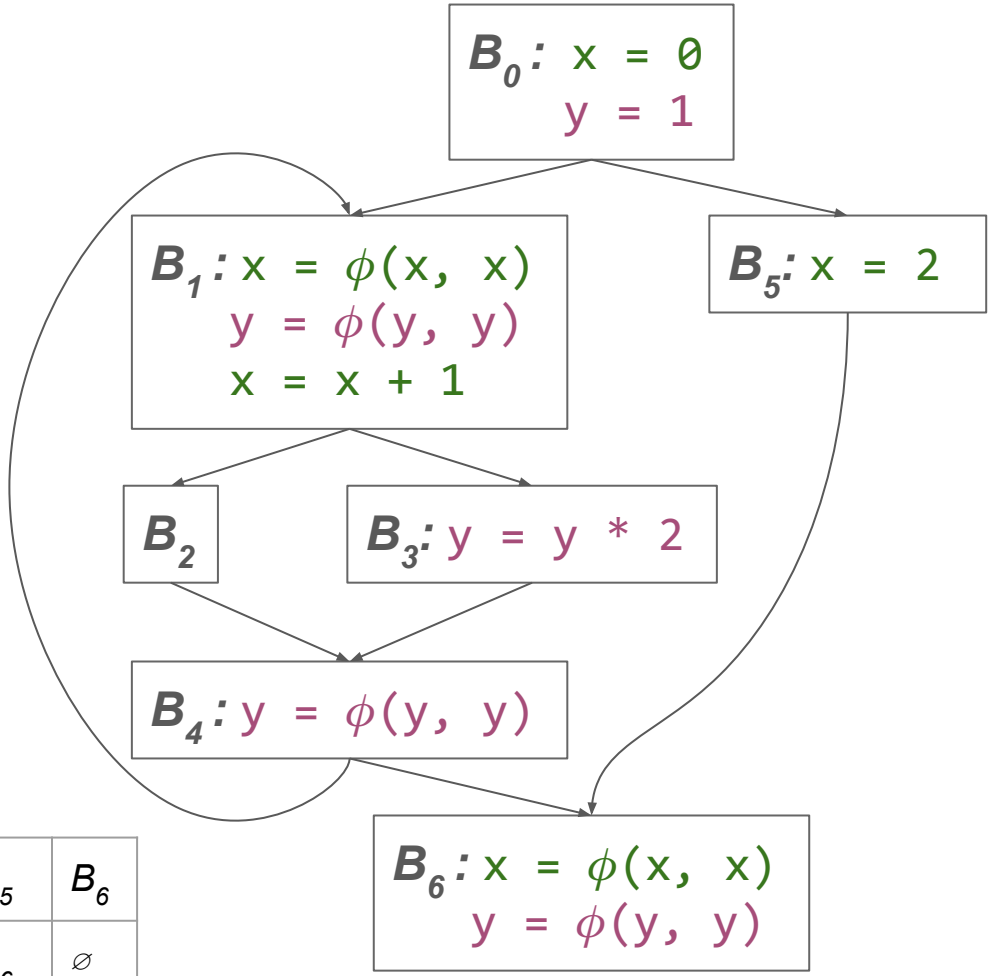


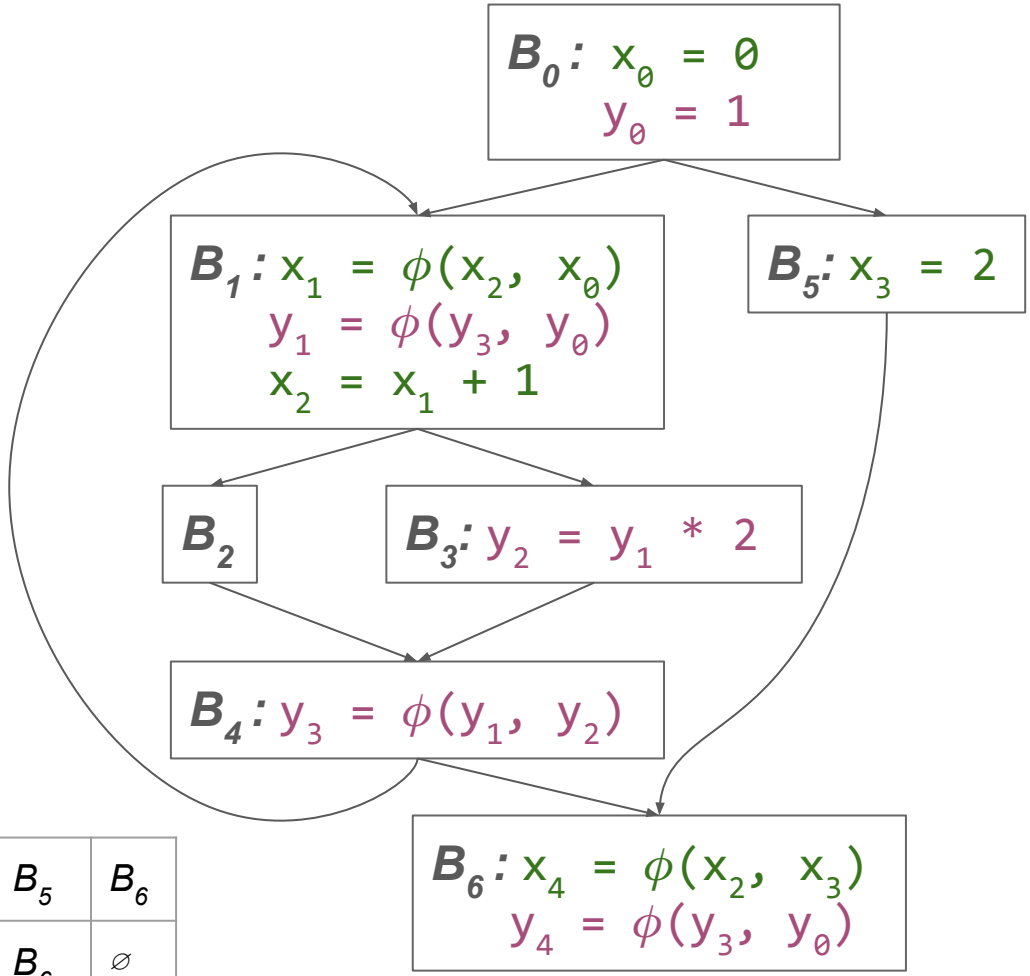
B	B_0	B_1	B_2	B_3	B_4	B_5	B_6
DF(B)	∅	B_1, B_6	B_4	B_4	B_1, B_6	B_6	∅

Minimal SSA

Idea

an assignment to x in the node *B* introduces a ϕ-function in every node from DF(B)

1. ϕ-function placement
2. **renaming**



B	B_0	B_1	B_2	B_3	B_4	B_5	B_6
DF(B)	∅	B_1, B_6	B_4	B_4	B_1, B_6	B_6	∅

SSA forms

- **Maximal SSA**
  Introduce a ϕ-function at every join node for every variable

- **Minimal SSA**
  Introduce a ϕ-function at every join node for every variable where two distinct definitions of the same name meet

- **Pruned SSA**
  Same as minimal SSA, but don't insert ϕ-functions if its result is not *live*.

- **Semipruned SSA**
  Same as minimal SSA, but don't insert ϕ-functions for names that are not live across a block boundary

Block Arguments

Instead of using ϕ-nodes (like LLVM), xDSL and MLIR use block arguments to represent control flow – dependent values.

```
func.func @simple(i64, i1) -> i64 {
^bb0(%a: i64, %cond: i1): // Code dominated by ^bb0 may refer to %a
  cf.cond_br %cond, ^bb1, ^bb2

^bb1:
  cf.br ^bb3(%a: i64)    // Branch passes %a as the argument

^bb2:
  %b = arith.addi %a, %a : i64
  cf.br ^bb3(%b: i64)    // Branch passes %b as the argument

// ^bb3 receives an argument, named %c, from predecessors
// and passes it on to bb4 along with %a. %a is referenced
// directly from its defining operation and is not passed through
// an argument of ^bb3.
^bb3(%c: i64):
  cf.br ^bb4(%c, %a : i64, i64)

^bb4(%d : i64, %e : i64):
  %0 = arith.addi %d, %e : i64
  return %0 : i64   // Return is also a terminator.
}
```

https://mlir.llvm.org/docs/LangRef/#blocks