# Check-In

## Review: Abstract Interpretation

Draw the CFG for the following 3AC procedure. Indicate the IN and OUT sets for each basic block on a, b, c for a constant propagation analysis

Assume c is global and all other vars are local

```
fun_foo:    enter foo
     L1:    getarg 1 [a]
     L2:    [b] := 2
     L3:    [c] := 2
     L4:    [tmp0] := [a] LT64 3
     L5:    IFZ [tmp0] GOTO L11
     L6:    [tmp1] := [b] ADD64 7
     L7:    [b] := [tmp1]
     L8:    call bar
     L9:    [tmp3] := [c] ADD64 7
     L10:   [c] := [tmp3]
     L11:   setret [b]
     L12:    leave foo
```

# Announcements

Administrivia

- Quiz 4 Friday
- Review Session…

Drew Davidson | University of Kansas

EECS 665

# COMPILER CONSTRUCTION

## SSA

# Previously…

Abstract Interpretation

**Rounding out dataflow analysis concepts**

- Some more examples
- Considering more complex code
- Dataflow Framework

**Abstract Interpretation**

- Concepts
- Examples

**You should know**

- The saturation approach to dataflow
- Handling loops, globals, large domains

**Optimization**

# Today's Lecture Outline

SSA

**Static Single Assignment**

- Motivation
- Concept
- Importance
- Implementation

**Optimization**

# Recall Data Allocation

SSA – Motivation

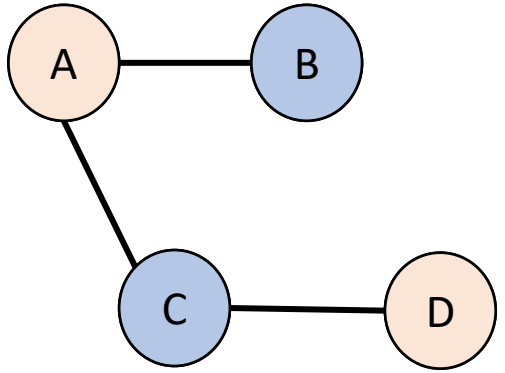
**Simplistic Interference Graph:**

- Nodes are “variables”
- Edges indicate interference

2-colorable

```
1. [A] := 1
2. [B] := 2
3. output [B]
4. [C] := 3
5. output [A]
6. [D] := 4
7. output [D]
8. output [C]
```

A live: (1, 5]
B live: (2, 3]
C live: (4, 8]
D live: (6, 7]



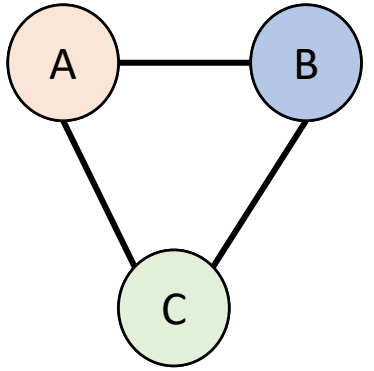
# Recall Data Allocation

## SSA – Motivation

### 3-colorable

```
1. [A] := 1
2. [B] := 2
3. output [B]
4. [C] := 3
5. output [A]
6. [B] := 4
7. output [B]
8. output [C]
```

A live: (1, 5]
B live: (2, 3] and (6,7]
C live: (4, 8]

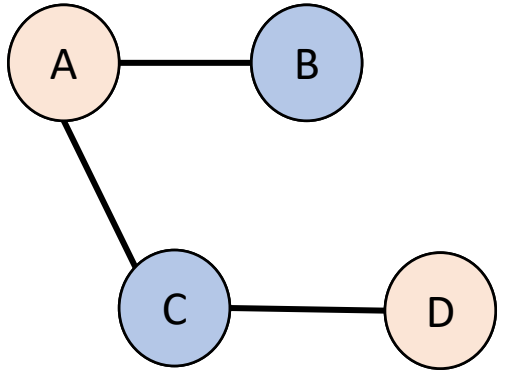



**Breaking out B into *more* variables uses *fewer* resources!**

### 2-colorable

```
1. [A] := 1
2. [B] := 2
3. output [B]
4. [C] := 3
5. output [A]
6. [D] := 4
7. output [D]
8. output [C]
```

A live: (1, 5]
B live: (2, 3]
C live: (4, 8]
D live: (6, 7]



# The Static Single Assignment Concept

*SSA*

**An additional restriction on the IR:**

- Every variable is assigned a value in *at most one* program point

**We can say 3AC is (or isn't) in *SSA form***

```
a := 1
b := a
c := a + b
```

```
a := 1
b := a
a := b * 2
c := a + b
```

**Why does that matter?**

Disentangles value use

Simplifies other analyses

```
L1: b := 7
    goto L1
```

***Ok! statically defined only once (doesn't matter that it's dynamically assigned > 1)***

# Transformation to SSA Form

*SSA*

**Basic Idea**

- Break noncompliant variables into multiple "versions"
- Preserve semantics!

**Obvious within a BBL**

- Each definition rewritten to a new variable version
- Each use rewritten to the most recently defined variable version

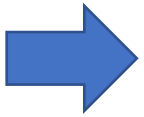
**Before**
**(not SSA form)**

[ a ] := 1

[ b ] := [ a ]

[ a ] := [ b ] * 2

[ c ] := [ a ] + [ b ]



**After**
**(is SSA form)**

[ $a_1$ ] := 1

[ b ] := [ $a_1$ ]

[ $a_2$ ] := [ b ] * 2

[ c ] := [ $a_2$ ] + [ b ]

*quick note on notation:*
*Ok to leave off the subscript*
*if there's only one "version"*

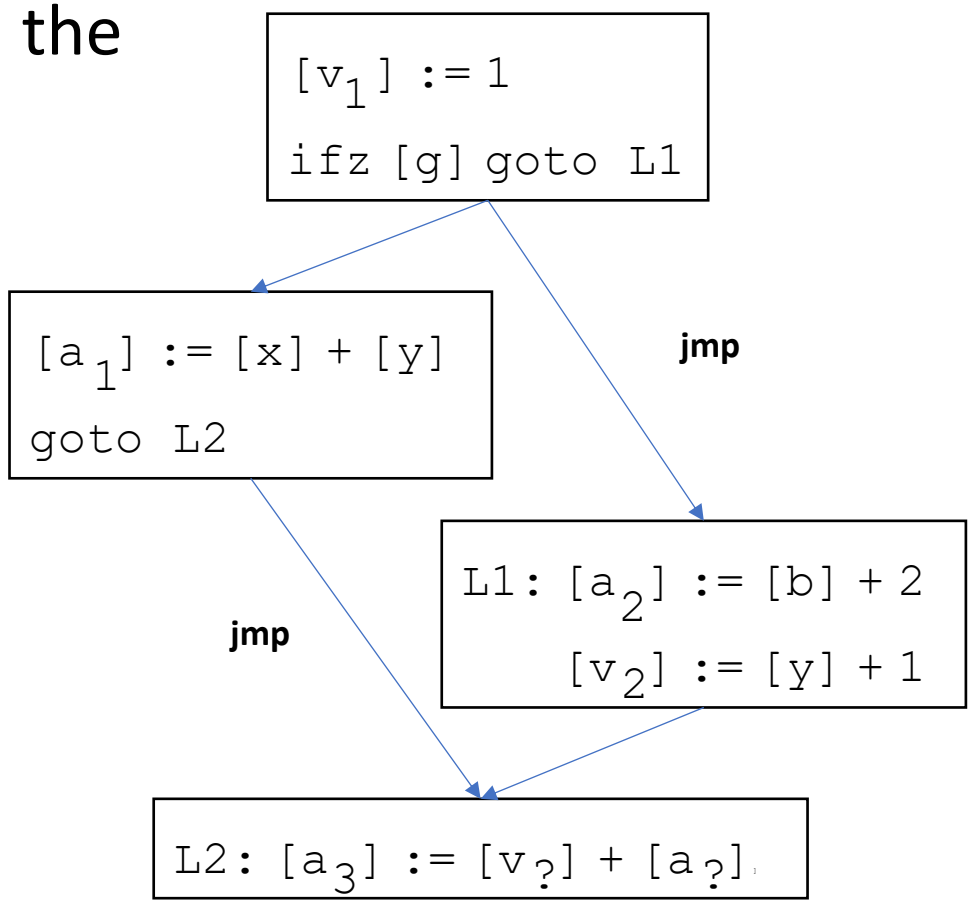
# Transformation to SSA Form

*SSA*

## Non-Obvious between BBLs

- Don't know (statically) the most recently defined variable version

```
    [v] := 1
    ifz [g] goto L1
    [a] := [x] + [y]
    goto L2
L1: [a] := [b] + 2
    [v] := [y] + 1
L2: [a] := [v] + [a]
```



# $\phi$ Functions – Notational Placeholders



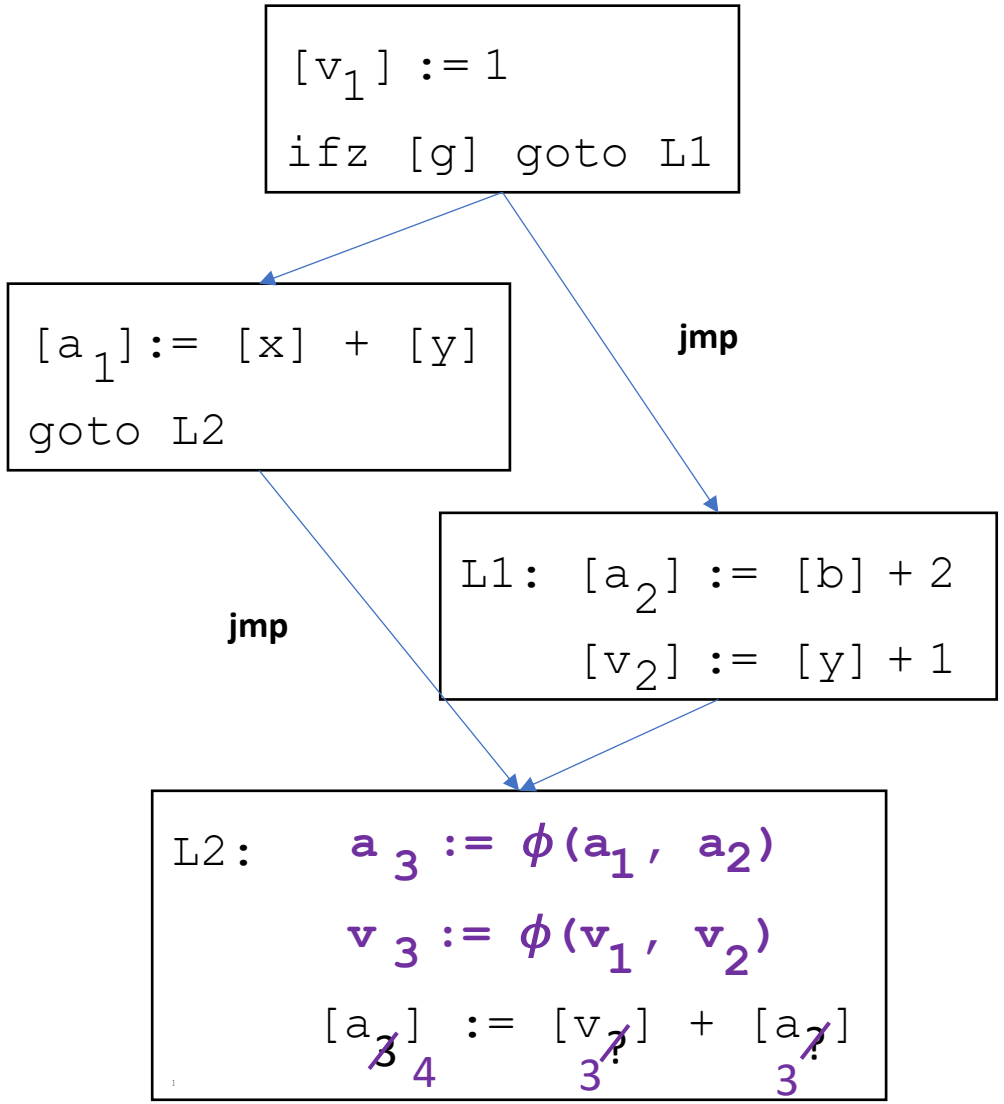
**Encapsulated the uncertainty of which version to use**

$$a_4 := \phi(a_1, a_2, a_3)$$

means that $a_4$ will hold whichever version of **a** was defined most recently

# $\phi$ Functions – Resolving "Conflicts"

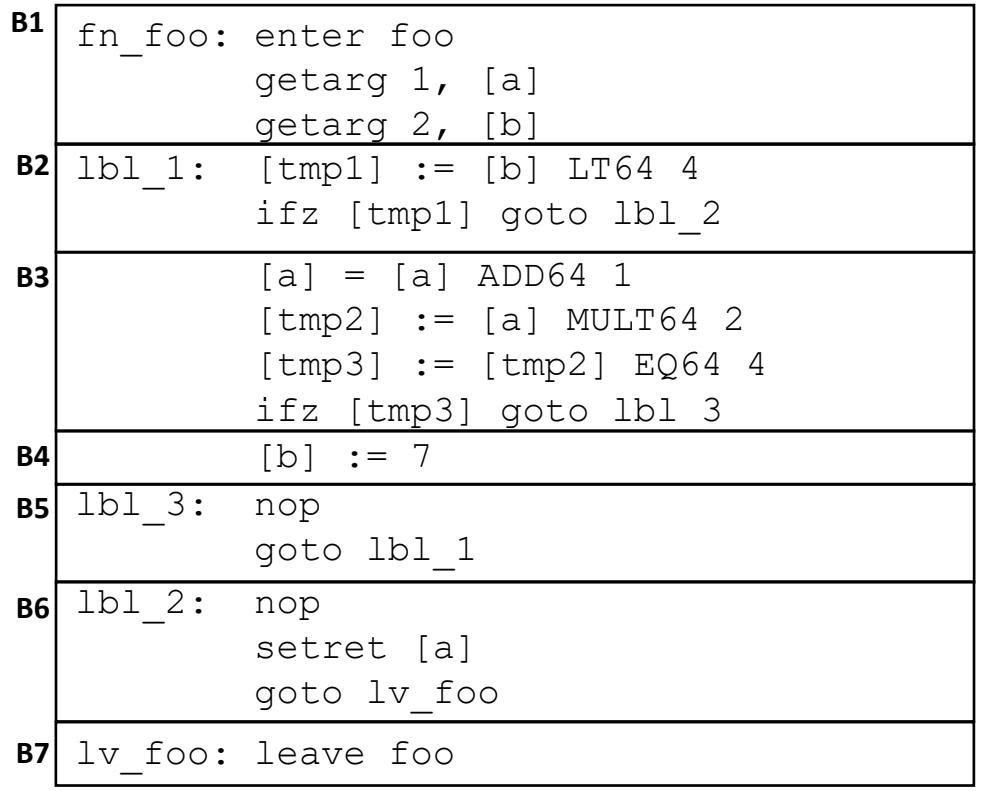




# Example Time – Transform to SSA Form

SSA – $\phi$ Functions

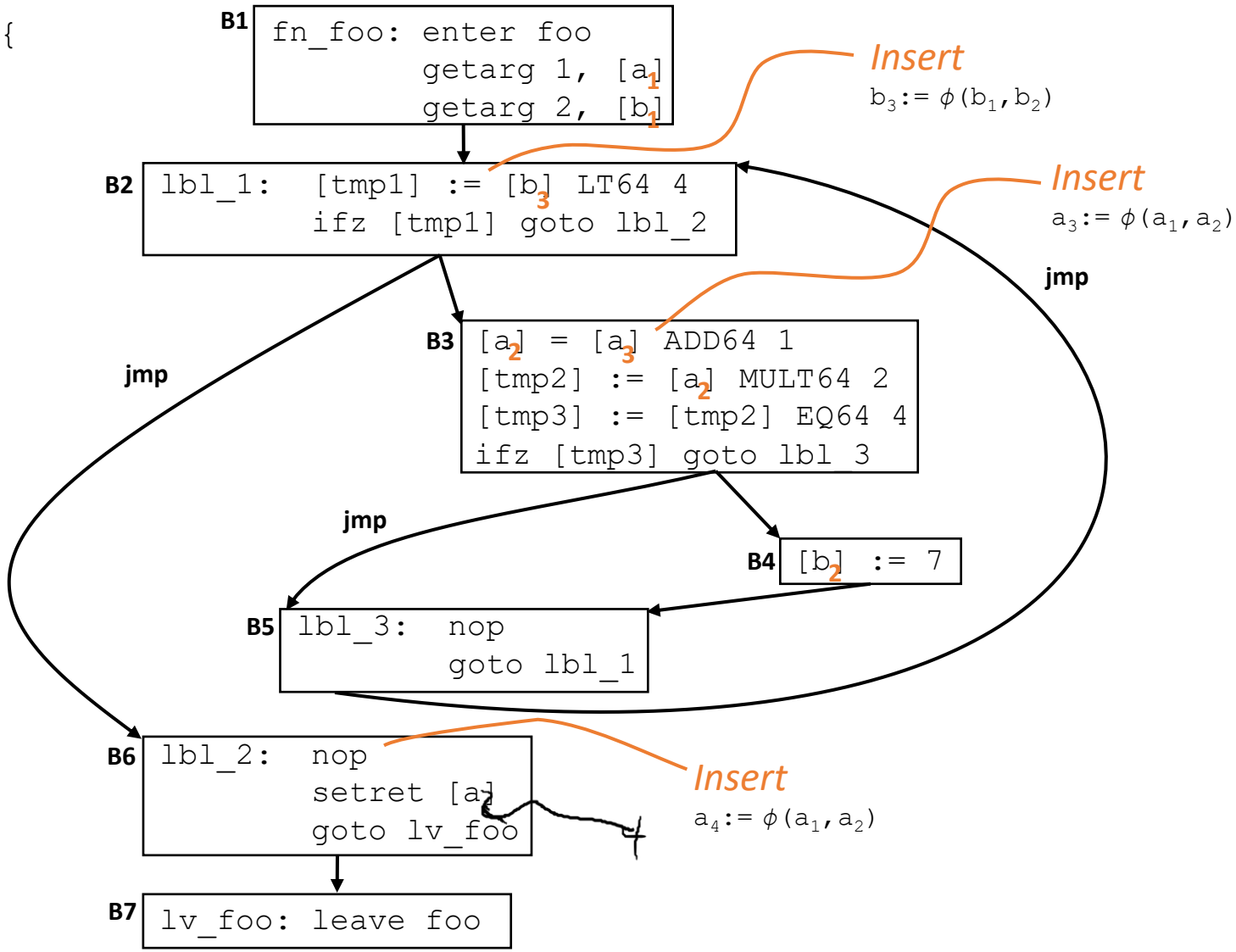
```
int foo(int a, int b){
  while(b < 4){
    a += 1;
    if ( a * 2 == 4){
      b = 7;
    }
  }
  return a;
}
```



# Example Time – Transform to SSA Form

SSA – $\phi$ Functions

```
int foo(int a, int b){
  while(b < 4){
    a += 1;
    if ( a * 2 == 4){
      b = 7;
    }
  }
  return a;
}
```



# $\phi$ Functions – A "Magical" Placeholder



**Why rely on a function we cannot compute?**

We can remove the $\phi$s later

- Easy solution: make sure that all arguments to the $\phi$ share a common memory location


*Image Credit: Avyst e-forms wizard*

$a_3 := \phi(a_1, a_2)$

*-24(%rbp)*

*-24(%rbp)*

# $\phi$ Functions are Costly!

SSA – Placing $\phi$s

**Rolls back our sub-variable resource goals**

- Consider a naïve algorithm to place $\phi$s:
  - Place $\phi$ for every defined version of the variable

# What Points Actually Require $\phi$?

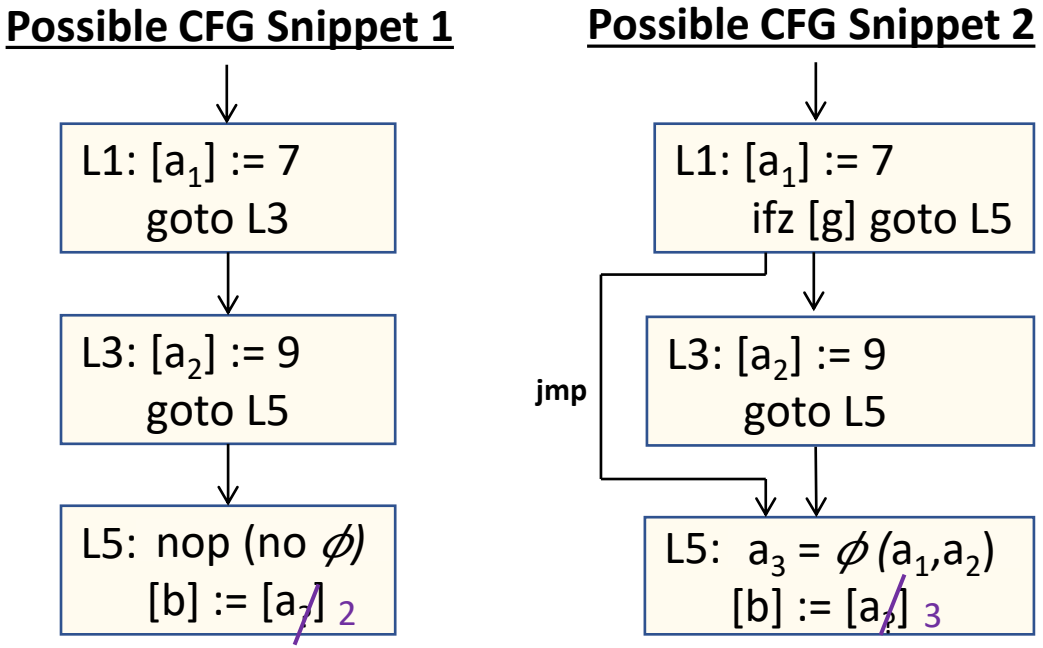
SSA – Placing $\phi$s

**One sufficient condition for Avoiding $\phi$ nodes:**

*(wlog, assume Block A defines x and Block B uses x)*

- Block B has an *unambiguous variable definition* if you're guaranteed to go through block A on any path to B

***There's a name for this constraint…***




Domination

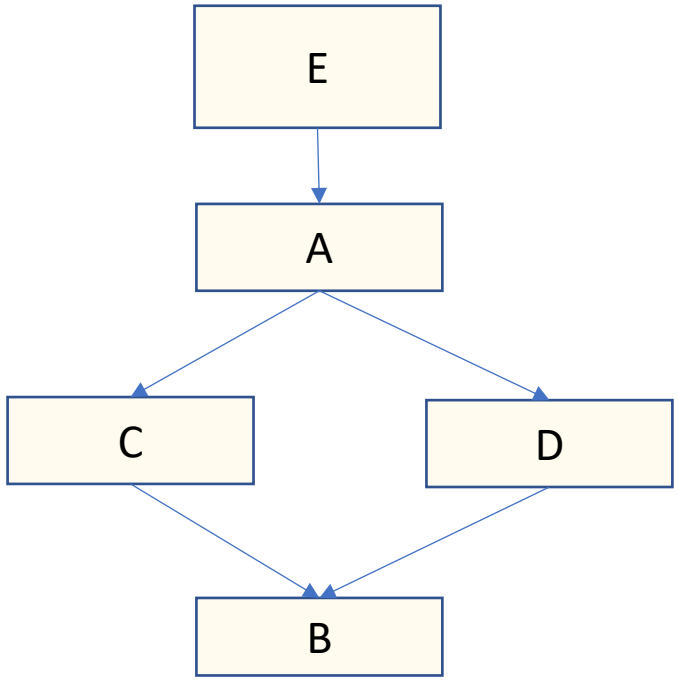
# Domination Examples

SSA – Placing $\phi$s

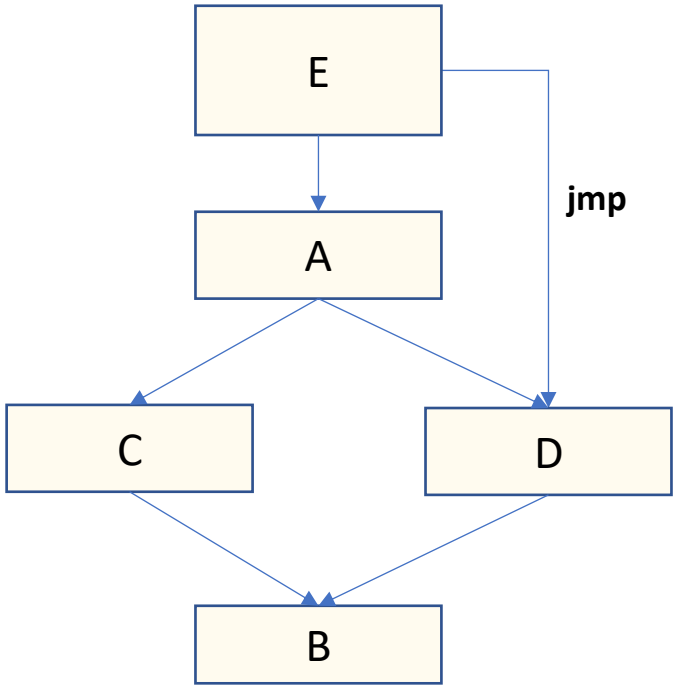
Block X **dominates** block Y if all paths to Y must pass through X

**Examples** *(what does A dominate?)*

A **dominates** A, D, C, B




A **dominates** A and C only



# Domination Vocabulary

SSA – Placing $\phi$s

**X DOM Y –** *X dominates Y*

- All paths to Y go through X
- (Reflexive - X DOM X)

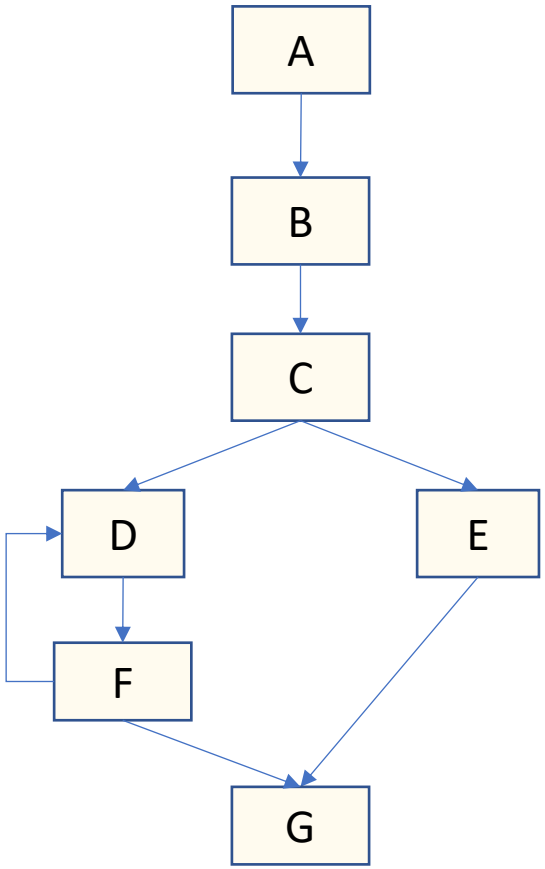
**X SDOM Y –** *X strictly dominates Y*

- Non-reflexive domination
- Formally: X DOM Y and X != Y

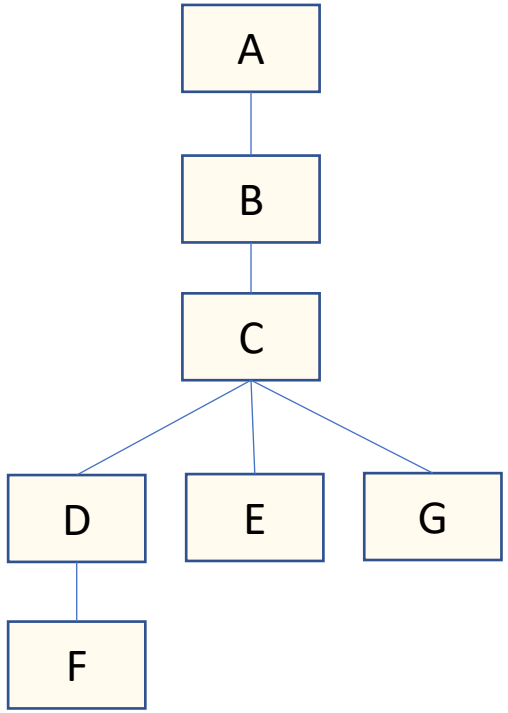
**X IDOM Y –** *X immediately dominates Y*

- "Closest" strict dominator
- Formally: X SDOM Y and Z SDOM Y ⇒ Z = X

**Control-Flow Graph**




**Dominator Tree**



# What Good is Domination?

SSA – Placing $\phi$s

**Provides guarantees about execution (sorta-kinda like a looser version of statements being in the same basic block)**

- A given block can rely on statements in a dominator to always have happened before the block is executed
- Similarly, a given block cannot rely on statements in non-dominators to always have happened before the block is executed

***The boundary has interesting properties for SSA***

# Detour: Using Dominators for $\phi$s

SSA – Placing $\phi$s

# Domination Vocabulary

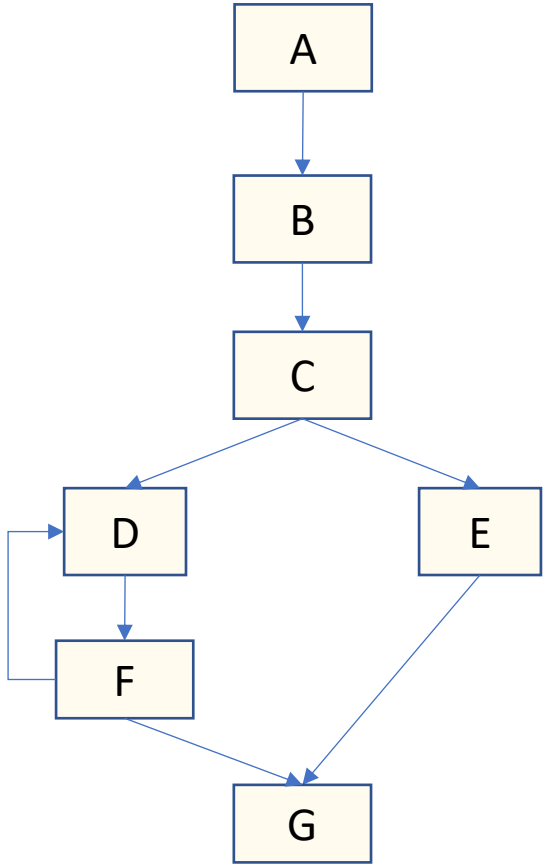
SSA – Placing $\phi$s


**Dominator Frontier of X:**

The set of nodes $k_i$

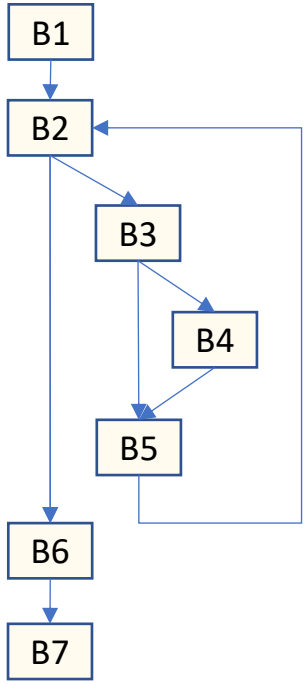
that X does not strictly dominate,

but X dominates an immediate predecessor of $k_i$



# Example Time – Compute Dom Frontier

SSA – $\phi$ Functions



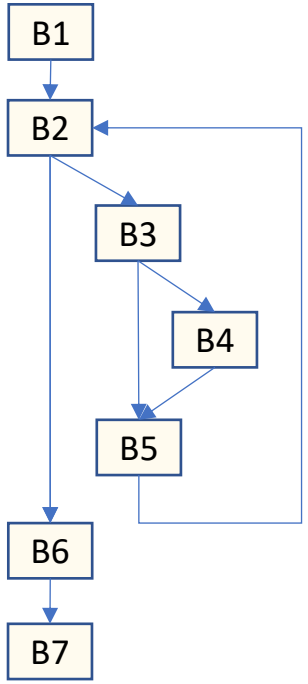

**Dominator Frontier of X:**
The set of nodes $k_i$
! X SDOM $k_i$
X DOM Y and Y IPRED $k_i$

B1 What does B1 dominate? B1 B2 B3 B4 B5 B6 B7
What do these precede? ~~B2~~ ~~B3~~ ~~B6~~ ~~B4~~ ~~B5~~ ~~B2~~ ~~B7~~
Disqualify if B1 SDOMs

| BBL | IPRED | DOM | SDOM | DF |
|---|---|---|---|---|
| B1 | B2 | (all) | B2,B3,B4,B5,B6,B7 | {} |
| B2 | B3, B6 | B2,B3,B4,B5,B6,B7 | B3,B4,B5,B6,B7 | |
| B3 | B4,B5 | B3, B4,B5 | B4,B5 | |
| B4 | B5 | B4 | {} | |
| B5 | B2 | B5 | {} | |
| B6 | B7 | B6,B7 | B7 | |
| B7 | {} | B7 | {} | |

# Example Time – Compute Dom Frontier

SSA – $\phi$ Functions

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What do these precede? ~~B2~~ ~~B3~~ ~~B6~~ ~~B4~~ ~~B5~~ ~~B2~~ ~~B7~~
Disqualify if B1 SDOMs

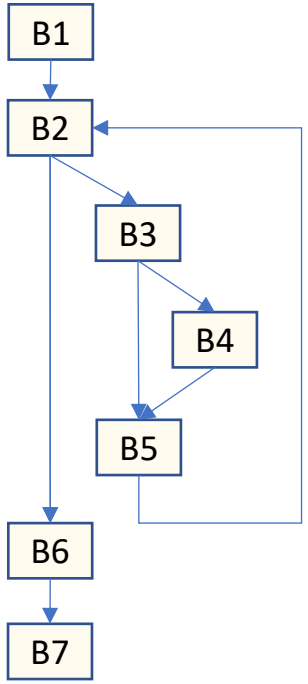
B2 What does B2 dominate? B2 B3 B4 B5 B6 B7
What do these precede? ~~B3~~ ~~B6~~ ~~B4~~ ~~B5~~ ~~B5~~ B2 ~~B7~~
Disqualify if B2 SDOMs

B3 What does B3 dominate? B3 B4 B5
What do these precede? ~~B4~~ ~~B5~~ ~~B5~~ B2
Disqualify if B3 SDOMs

| BBL | IPRED | DOM | SDOM | DF |
|---|---|---|---|---|
| B1 | B2 | (all) | B2,B3,B4,B5,B6,B7 | {} |
| B2 | B3, B6 | B2,B3,B4,B5,B6,B7 | B3,B4,B5,B6,B7 | B2 |
| B3 | B4,B5 | B3, B4,B5 | B4,B5 | B2 |
| B4 | B5 | B4 | {} | |
| B5 | B2 | B5 | {} | |
| B6 | B7 | B6,B7 | B7 | |
| B7 | {} | B7 | {} | |

# Example Time – Compute Dom Frontier

SSA – $\phi$ Functions

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| BBL | IPRED | DOM | SDOM | DF |
|---|---|---|---|---|
| B1 | B2 | (all) | B2,B3,B4,B5,B6,B7 | {} |
| B2 | B3, B6 | B2,B3,B4,B5,B6,B7 | B3,B4,B5,B6,B7 | B2 |
| B3 | B4,B5 | B3, B4,B5 | B4,B5 | B2 |
| B4 | B5 | B4 | {} | B5 |
| B5 | B2 | B5 | {} | B2 |
| B6 | B7 | B6,B7 | B7 | |
| B7 | {} | B7 | {} | |

B1 What does B1 dominate? B1 B2 B3 B4 B5 B6 B7
What do these precede? ~~B2~~ ~~B3~~ ~~B6~~ ~~B4~~ ~~B5~~ ~~B2~~ ~~B7~~
Disqualify if B1 SDOMs

B2 What does B2 dominate? B2 B3 B4 B5 B6 B7
What do these precede? ~~B3~~ ~~B6~~ ~~B4~~ ~~B5~~ ~~B5~~ B2 ~~B7~~
Disqualify if B2 SDOMs

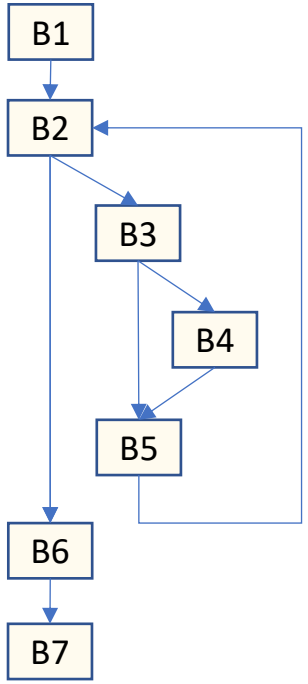
B3 What does B3 dominate? B3 B4 B5
What do these precede? ~~B4~~ ~~B5~~ ~~B5~~ B2
Disqualify if B3 SDOMs

B4 What does B4 dominate? B4
What do these precede? B5
Disqualify if B4 SDOMs

B5 What does B5 dominate? B5
What do these precede? B2
Disqualify if B5 SDOMs

# Example Time – Compute Dom Frontier

SSA – $\phi$ Functions




**Dominator Frontier of X:**
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| B2 | B3, B6 | B2,B3,B4,B5,B6,B7 | B3,B4,B5,B6,B7 | B2 |
| B3 | B4,B5 | B3, B4,B5 | B4,B5 | B2 |
| B4 | B5 | B4 | {} | B5 |
| B5 | B2 | B5 | {} | B2 |
| B6 | B7 | B6,B7 | B7 | {} |
| B7 | {} | B7 | {} | {} |

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What do these precede? ~~B2~~ ~~B3~~ ~~B6~~ ~~B4~~ ~~B5~~ ~~B2~~ ~~B7~~
Disqualify if B1 SDOMs

B2 What does B2 dominate? B2 B3 B4 B5 B6 B7
What do these precede? ~~B3~~ ~~B6~~ ~~B4~~ ~~B5~~ ~~B5~~ B2 ~~B7~~
Disqualify if B2 SDOMs

B3 What does B3 dominate? B3 B4 B5
What do these precede? ~~B4~~ ~~B5~~ ~~B5~~ B2
Disqualify if B3 SDOMs

B4 What does B4 dominate? B4
What do these precede? B5
Disqualify if B4 SDOMs

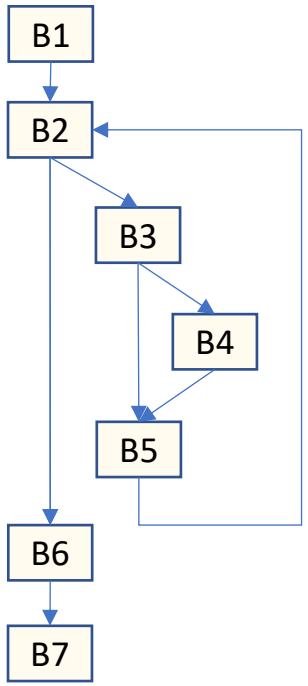
B7 What does B7 dominate? B7
What do these precede? {}

B5 What does B5 dominate? B5
What do these precede? B2
Disqualify if B5 SDOMs

B6 What does B6 dominate? B6 B7
What do these precede? ~~B7~~
Disqualify if B6 SDOMs

# Example Time – Compute Dom Frontier

SSA – $\phi$ Functions




**Dominator Frontier of X:**

The set of nodes $k_i$

! X SDOM $k_i$

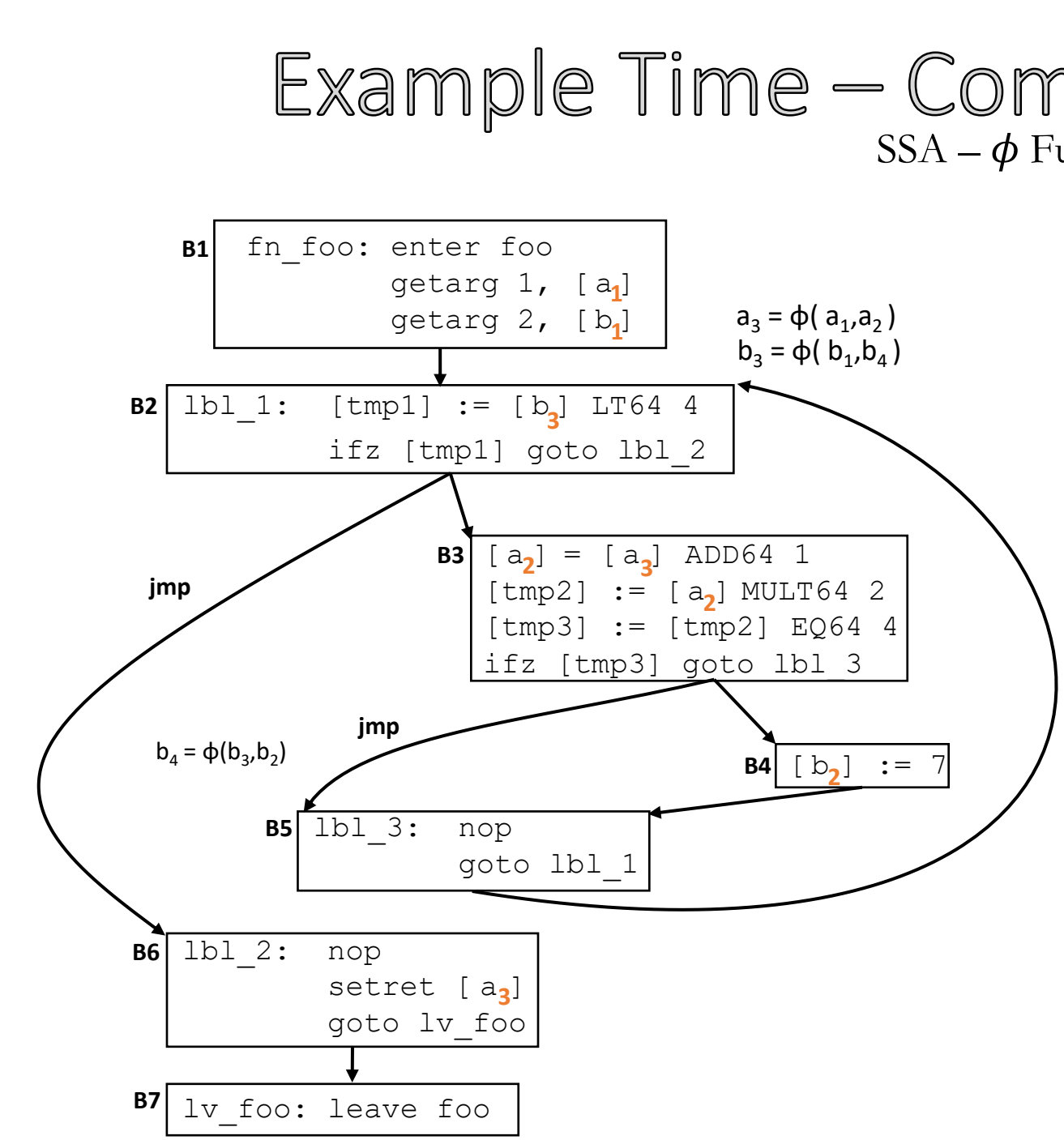
X DOM Y and Y IPRED $k_i$

```
for v in vars:
   for d in DefBBLs[v]:
     for block in DF[d]:
       Add a ϕ-node to block,
         unless we have done so already.
       Add block to DefBBLs[v]
         unless it's already in there.
```

| BBL | IPRED | DOM | SDOM | DF |
|---|---|---|---|---|
| B1 | B2 | (all) | B2,B3,B4,B5,B6,B7 | {} |
| B2 | B3, B6 | B2,B3,B4,B5,B6,B7 | B3,B4,B5,B6,B7 | B2 |
| B3 | B4,B5 | B3, B4,B5 | B4,B5 | B2 |
| B4 | B5 | B4 | {} | B5 |
| B5 | B2 | B5 | {} | B2 |
| B6 | B7 | B6,B7 | B7 | {} |
| B7 | {} | B7 | {} | {} |

# Example Time – Compute Dom Frontier

SSA – $\phi$ Functions




```
for v in vars:
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     for block in DF[d]:
       Add a ϕ-node to block,
         unless we have done so already.
       Add block to DefBBLs[v]
         unless it's already in there.
```

| var | DefBBLs | Φ Blocks |
|---|---|---|
| a | B1 B3 B2 | B2 |
| b | B1 B4 B5 B2 | B5 B2 |

| BBL | IPRED | DOM | SDOM | DF |
|---|---|---|---|---|
| B1 | B2 | (all) | B2,B3,B4,B5,B6,B7 | {} |
| B2 | B3, B6 | B3,B4,B5,B6,B7 | B3,B4,B5,B6,B7 | B2 |
| B3 | B4,B5 | B3, B4,B5 | B4,B5 | B2 |
| B4 | B5 | B4 | {} | B5 |
| B5 | B2 | B5 | {} | B2 |
| B6 | B7 | B6,B7 | B7 | {} |
| B7 | {} | B7 | {} | {} |

# End Detour: Using Dominators for $\phi$s

SSA – Placing $\phi$s

# Dominance: Summary

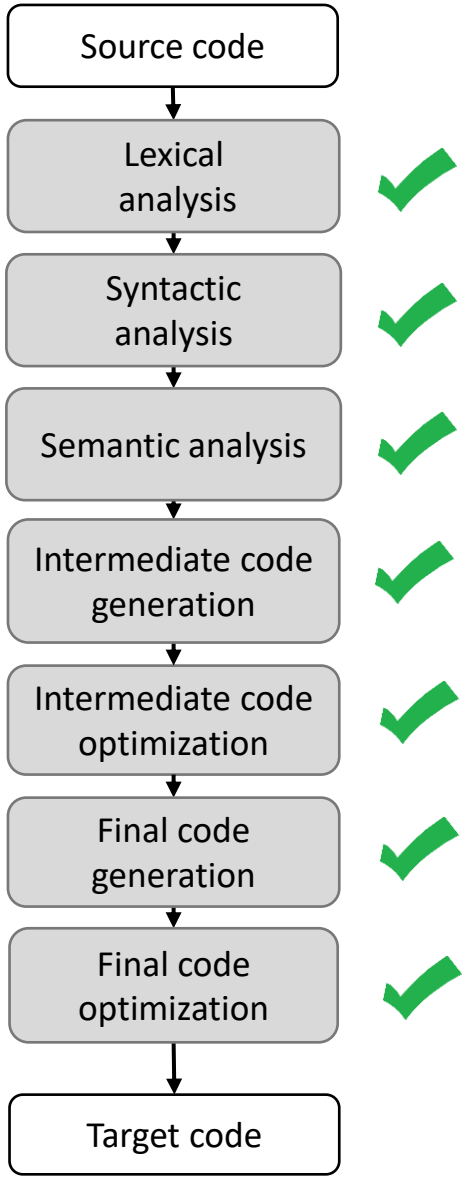
SSA – Placing $\phi$s

**Summary:**

- Dominators can be computed efficiently
- Dominance can be used to aid in efficient SSA
- SSA aids in efficient program optimization and future analysis

# Oh Hey, We Built a Compiler!

Underview




COMPILER
Machine Codegen
Optimization
Code Generation
Intermediate Representation
Semantic Analysis
Syntactic Definition
Parsing
Syntax-Dir Translation
Regular Languages
Lexical Analysis

# What Next?

Underview

**Practical Applications**

*Why does this class matter?*

- "So you can do compilers": Practical skills for language implementation / reasoning
- "What you do with compilers is useful outside doing compilers"