UNIVERSITÄT BERN

# 6. Intermediate Representation

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Thanks to Jens Palsberg and Tony Hosking for their kind permission to reuse and adapt the CS132 and CS502 lecture notes.
http://www.cs.ucla.edu/~palsberg/
http://www.cs.purdue.edu/homes/hosking/

SSA lecture notes by Marcus Denker

# Roadmap


> Intermediate representations
> Static Single Assignment

See, *Modern compiler implementation in Java* (Second edition), chapters 7-8.

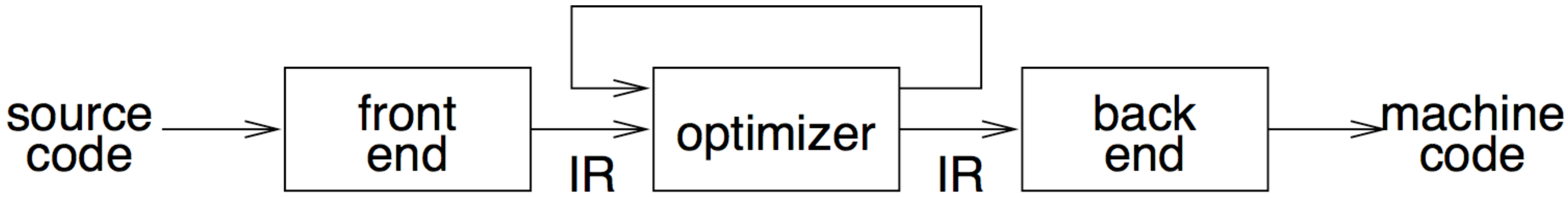
# Roadmap

- > **Intermediate representations**
- > Static Single Assignment

# Why use intermediate representations?

1. Software engineering principle
   — break compiler into manageable pieces
2. Simplifies retargeting to new host
   — isolates back end from front end
3. Simplifies support for multiple languages
   — different languages can share IR and back end
4. Enables machine-independent optimization
   — general techniques, multiple passes

# IR scheme




- front end produces IR
- optimizer transforms IR to more efficient program
- back end transforms IR to target code

# Kinds of IR

- Abstract syntax trees (AST)
- Linear operator form of tree (e.g., postfix notation)
- Directed acyclic graphs (DAG)
- Control flow graphs (CFG)
- Program dependence graphs (PDG)
- Static single assignment form (SSA)
- 3-address code
- Hybrid combinations

# Categories of IR

- Structural
  - graphically oriented (trees, DAGs)
  - nodes and edges tend to be large
  - heavily used on source-to-source translators
- Linear
  - pseudo-code for abstract machine
  - large variation in level of abstraction
  - simple, compact data structures
  - easier to rearrange
- Hybrid
  - combination of graphs and linear code (e.g. CFGs)
  - attempt  to achieve best of both worlds

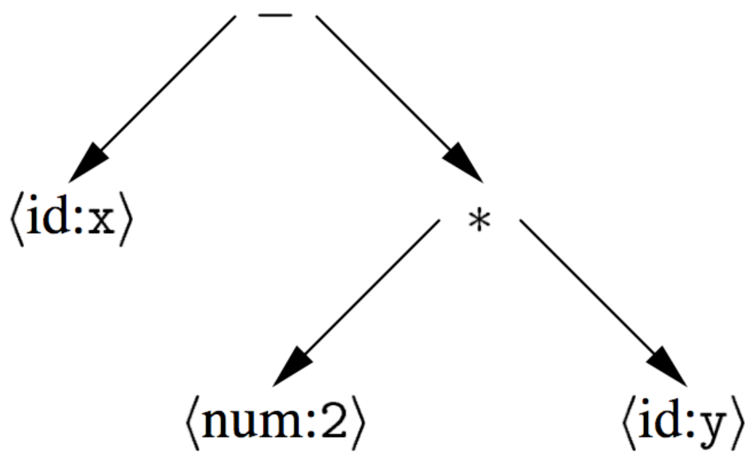
# Important IR properties

- Ease of generation
- Ease of manipulation
- Cost of manipulation
- Level of abstraction
- Freedom of expression (!)
- Size of typical procedure
- Original or derivative

Subtle design decisions in the IR can have far-reaching effects on the speed and effectiveness of the compiler!
➔ *Degree of exposed detail can be crucial*

# Abstract syntax tree

An AST is a parse tree with nodes for most non-terminals removed.




*Since the program is already parsed, non-terminals needed to establish precedence and associativity can be collapsed!*

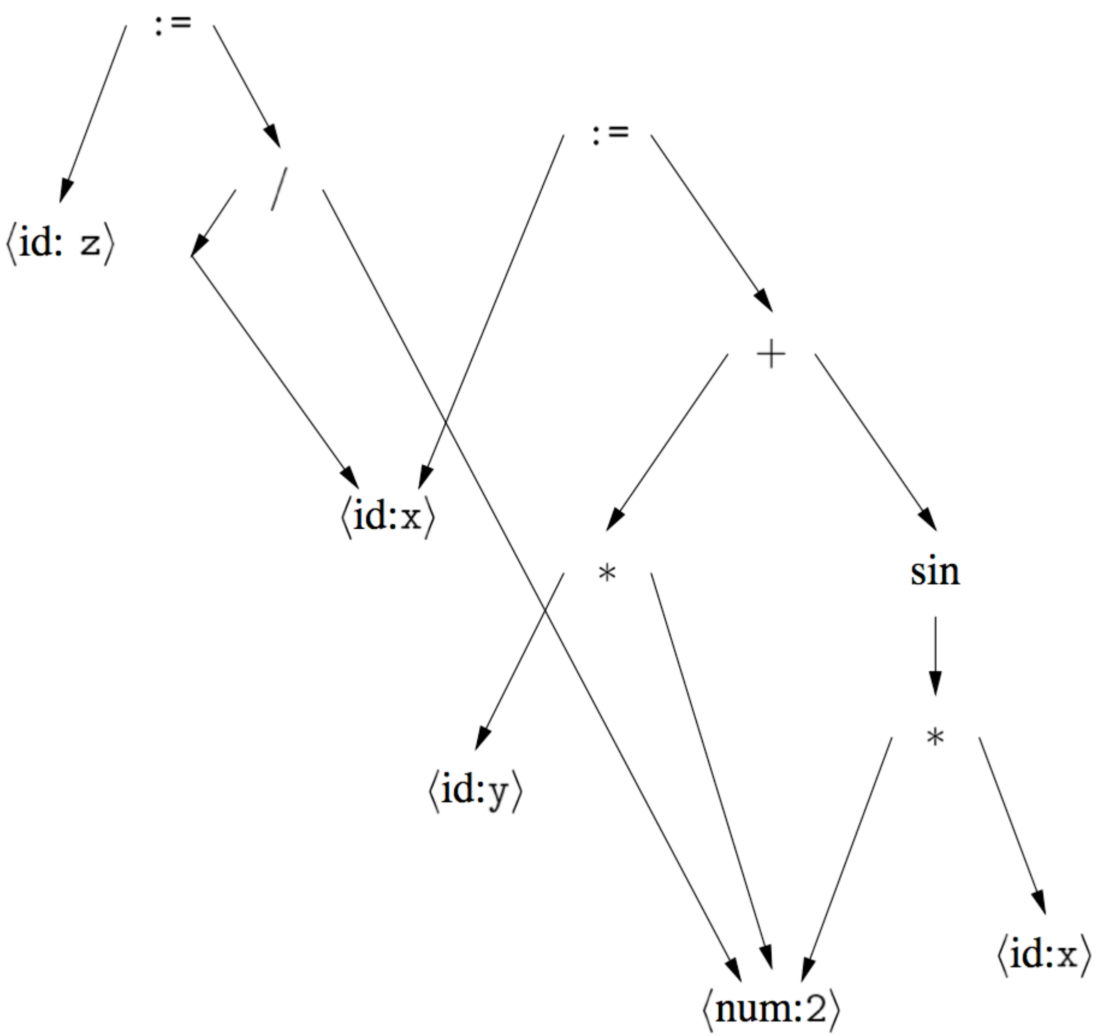
A linear operator form of this tree (postfix) would be:

```
x 2 y * -
```

# Directed acyclic graph

A DAG is an AST with unique, shared nodes for each value.

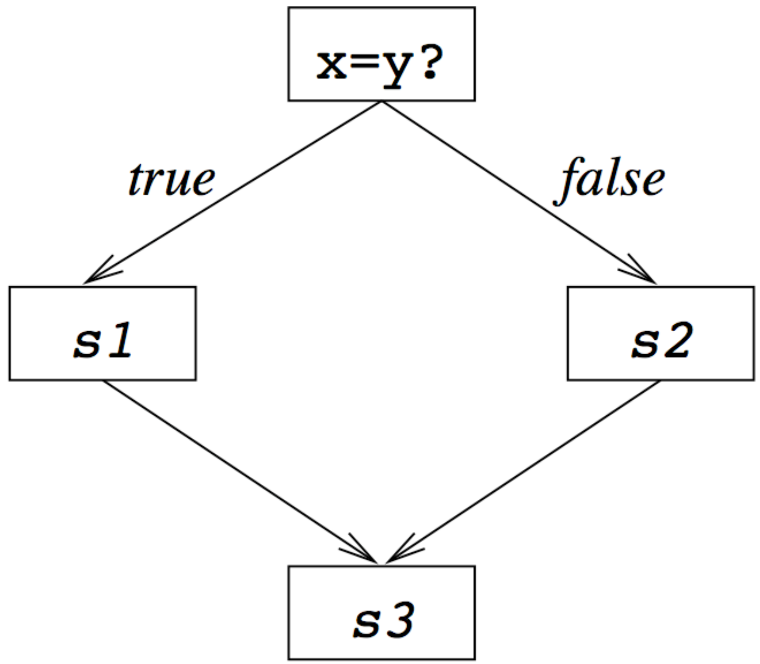
```
x := 2 * y + sin(2*x)
z := x / 2
```



# Control flow graph

> A CFG models *transfer of control* in a program
  — nodes are *basic blocks* (straight-line blocks of code)
  — edges represent *control flow* (loops, if/else, goto …)

```
if x = y then
   S1
else
   S2
end
S3
```



# 3-address code

- Statements take the form: `x = y op z`
  - single operator and at most three names

```
x – 2 * y
```

→

```
t1 = 2 * y
t2 = x – t1
```

- Advantages:
  - compact form
  - names for intermediate values

# Typical 3-address codes

| | |
|---|---|
| *assignments* | `x = y op z` |
| | `x = op y` |
| | `x = y[i]` |
| | `x = y` |
| *branches* | `goto L` |
| *conditional branches* | `if x relop y goto L` |
| *procedure calls* | `param x`<br>`param y`<br>`call p` |
| *address and pointer assignments* | `x = &y`<br>`*y = z` |

# 3-address code — two variants

*Quadruples*

x - 2 * y

| | | | | |
|---|---|---|---|---|
| (1) | load | t1 | y | |
| (2) | loadi | t2 | 2 | |
| (3) | mult | t3 | t2 | t1 |
| (4) | load | t4 | x | |
| (5) | sub | t5 | t4 | t3 |

- simple record structure
- easy to reorder
- explicit names

*Triples*

x - 2 * y

| | | | |
|---|---|---|---|
| (1) | load | y | |
| (2) | loadi | 2 | |
| (3) | mult | (1) | (2) |
| (4) | load | x | |
| (5) | sub | (4) | (3) |

- table index is implicit name
- only 3 fields
- harder to reorder

# IR choices

- Other hybrids exist
  - combinations of graphs and linear codes
  - CFG with 3-address code for basic blocks
- Many variants used in practice
  - no widespread agreement
  - compilers may need several different IRs!

- Advice:
  - choose IR with right level of detail
  - keep manipulation costs in mind

# Roadmap


> Intermediate representations
> **Static Single Assignment**

# Static Single Assignment Form

> Goal: simplify procedure-global optimizations

> *Definition:*

Program is in SSA form if every variable is only assigned once

# Static Single Assignment (SSA)

Ron Cytron, et al., *"Efficiently computing static single assignment form and the control dependence graph,"* ACM TOPLAS., 1991. doi:10.1145/115372.115320

- Each assignment to a temporary is given a unique name
  - All uses reached by that assignment are renamed
  - Compact representation
  - Useful for many kinds of compiler optimization …

```
x := 3;
x := x + 1;
x := 7;
x := x*2;
```

➔

$$
\begin{aligned}
x_1 &:= 3; \\
x_2 &:= x_1 + 1; \\
x_3 &:= 7; \\
x_4 &:= x_3 * 2;
\end{aligned}
$$

http://en.wikipedia.org/wiki/Static_single_assignment_form

# Why *Static*?

- Why Static?
  - *We only look at the static program*
  - *One assignment per variable in the program*

- At runtime variables are assigned multiple times!

# Example: Sequence

*Easy to do for sequential programs:*

**Original**

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

**SSA**

$$
\begin{aligned}
a_1 &:= b_1 + c_1 \\
b_2 &:= c_1 + 1 \\
d_1 &:= b_2 + c_1 \\
a_2 &:= a_1 + 1 \\
e_1 &:= a_2 + b_2
\end{aligned}
$$

# Example: Condition

*Conditions: what to do on control-flow merge?*

Original

```
if B then
  a := b
else
  a := c
end
  … a …
```

SSA

```
if B then
  a1 := b
else
  a2 := c
End

  … a? …
```

# Solution: Φ-Function

*Conditions: what to do on control-flow merge?*

Original

```
if B then
   a := b
else
   a := c
end
   … a …
```

SSA

```
if B then
   a1 := b
else
   a2 := c
End
a3 := Φ(a1,a2)
   … a3 …
```

# The Φ-Function

- Φ-functions are always at the beginning of a basic block
- Select between values depending on control-flow
- $a_1 := \Phi(a_1 \ldots a_k)$: the block has k preceding blocks

*PHI-functions are evaluated simultaneously within a basic block.*

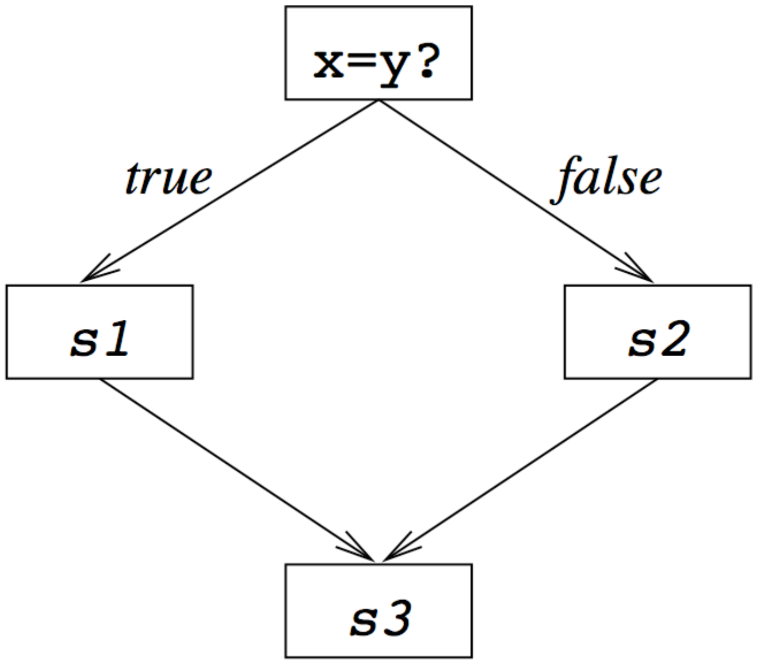
# SSA and CFG

- SSA is normally used for control-flow graphs (CFG)
- Basic blocks are in 3-address form

# Recall: Control flow graph

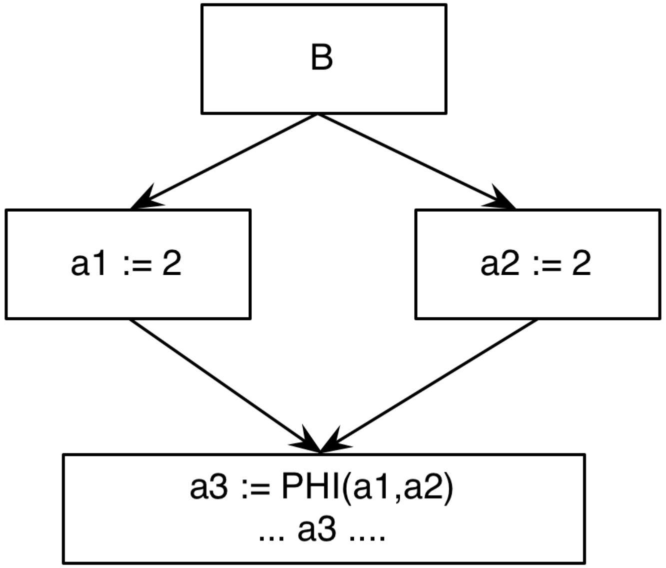
> A CFG models *transfer of control* in a program
  — nodes are *basic blocks* (straight-line blocks of code)
  — edges represent *control flow* (loops, if/else, goto …)

```
if x = y then
   S1
else
   S2
end
S3
```

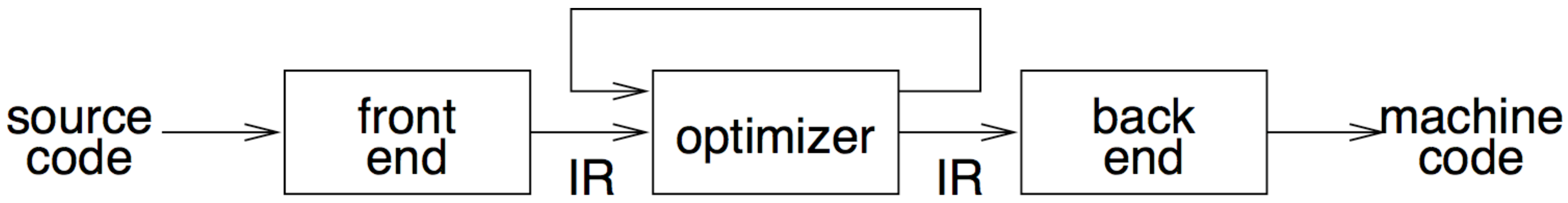


# SSA: a Simple Example

```
if B then
   a1 := 1
else
   a2 := 2
End
a3 := PHI(a1,a2)
   … a3 …
```

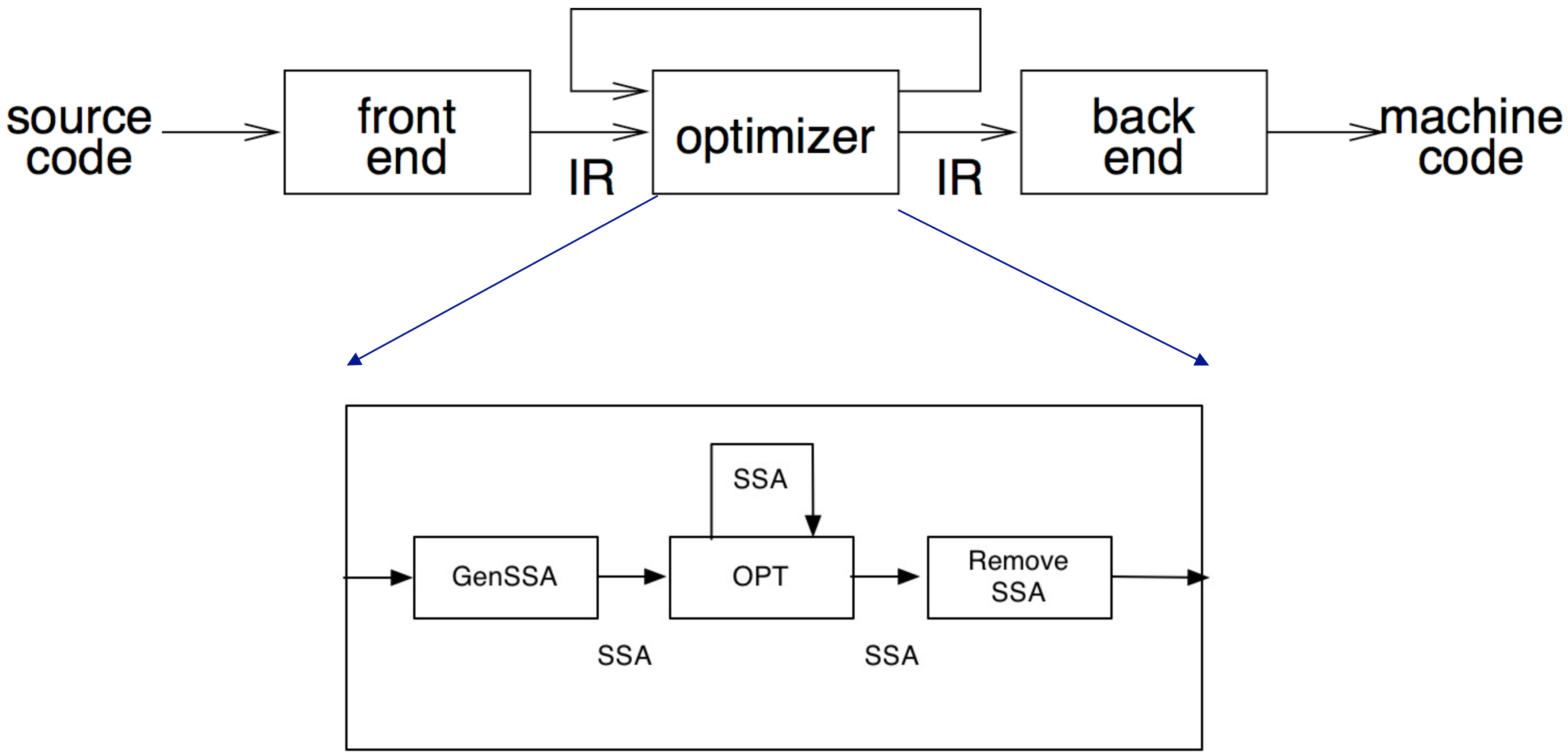


# Recall: IR




- front end produces IR
- optimizer transforms IR to more efficient program
- back end transform IR to target code

# SSA as IR


source
code
front
end
IR
optimizer
IR
back
end
machine
code
SSA
GenSSA
OPT
Remove
SSA
SSA
SSA

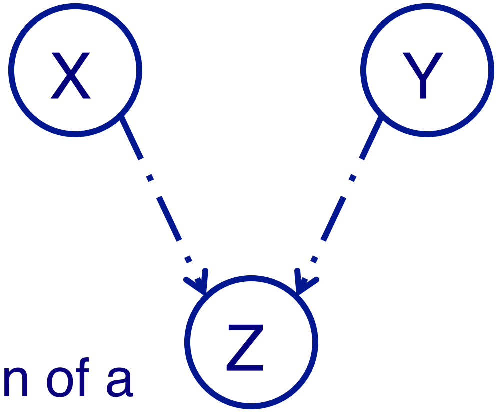
# Transforming to SSA

- ***Problem: Performance / Memory***
  - Minimize number of inserted $\Phi$-functions
  - Do not spend too much time
- ***Many relatively complex algorithms***
  - We do not go too much into detail
  - See literature!

# Minimal SSA

- Two steps:
  - Place $\Phi$-functions
  - Rename Variables
- Where to place $\Phi$-functions?
- We want minimal amount of needed $\Phi$
  - *Save memory*
  - *Algorithms will work faster*

# Path Convergence Criterion




> There should be a $\Phi$ for a at node Z if:

1. There is a block X containing a definition of a
2. There is a block Y (Y ≠ X) containing a definition of a
3. There is a nonempty path $P_{xz}$ of edges from X to Z
4. There is a nonempty path $P_{yz}$ of edges from Y to Z
5. Path $P_{xz}$ and $P_{yz}$ do not have any nodes in common other than Z
6. The node Z does not appear within both $P_{xz}$ and $P_{yz}$ prior to the end (although it may appear in one or the other)

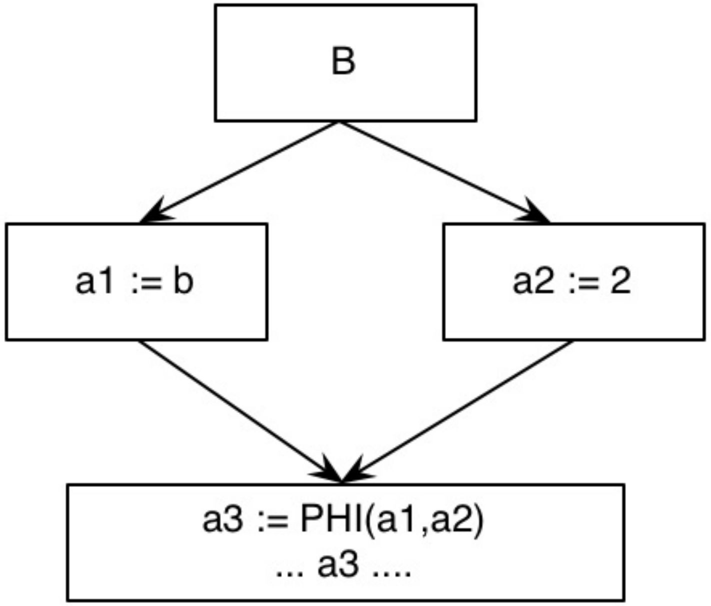
# Iterated Path-Convergence

> Inserted $\Phi$ is itself a definition!

```
While there are nodes X,Y,Z satisfying conditions 1-5
   and Z does not contain a phi-function for a
 do
    insert PHI at node Z.
```

*A bit slow, other algorithms used in practice*

# Example (Simple)




1. *block X contains a definition of a*
2. *block Y (Y ≠ X) contains a definition of a.*
3. *path $P_{xz}$ of edges from X to Z.*
4. *path $P_{yz}$ of edges from Y to Z.*
5. *Path $P_{xz}$ and $P_{yz}$ do not have any nodes in common other than Z*
6. *Node Z does not appear within both $P_{xz}$ and $P_{yz}$ prior to the end*

# Dominance Property of SSA

> Dominance: node *D* *dominates* node *N* if every path from the start node to *N* goes through *D*.

("strictly dominates": D ≠ N)

**Dominance Property of SSA:**

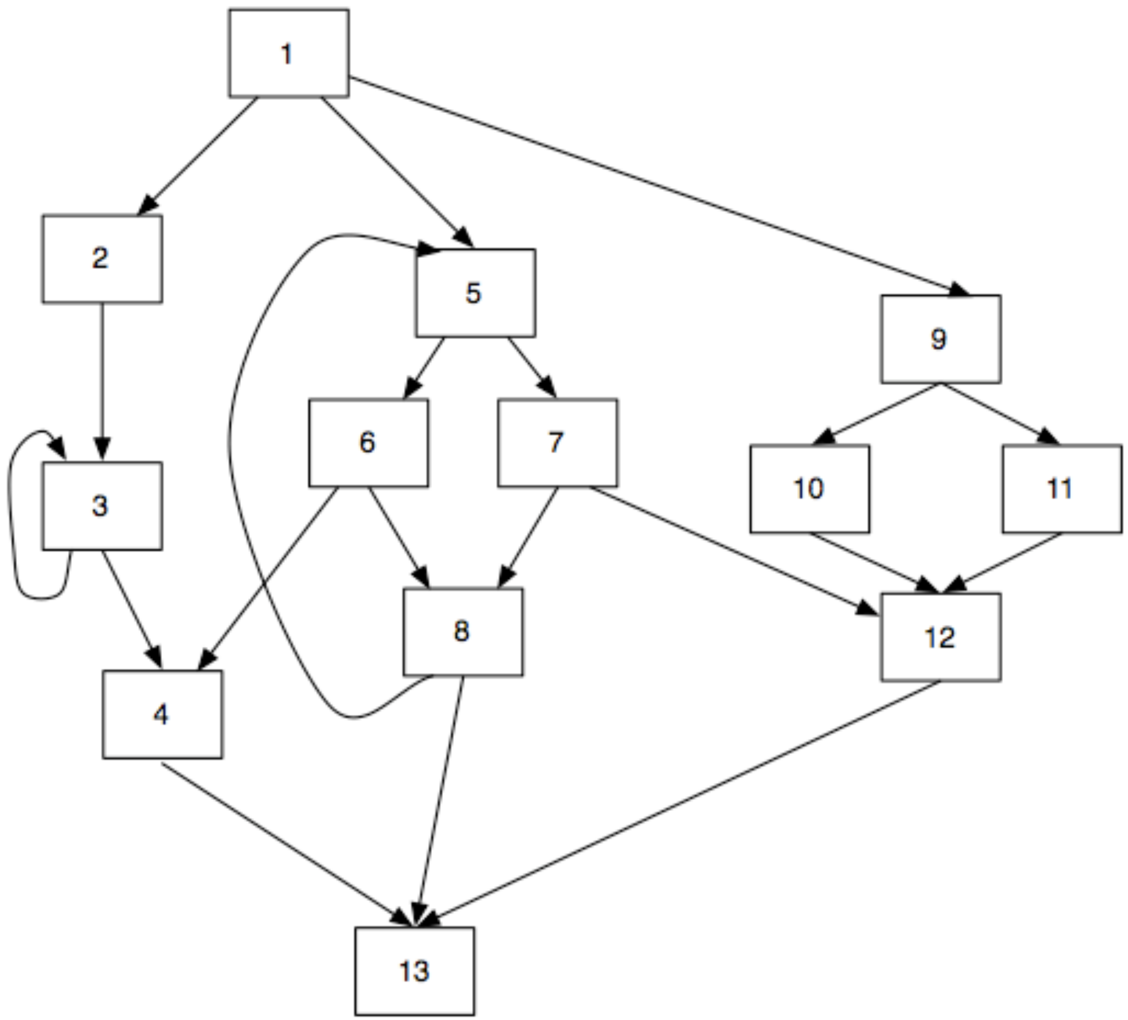
1. If x is used in a Phi-function in block N, then the node defining x dominates every predecessor of N.
2. If x is used in a non-Phi statement in N, then the node defining x dominates N

*"Definition dominates use"*

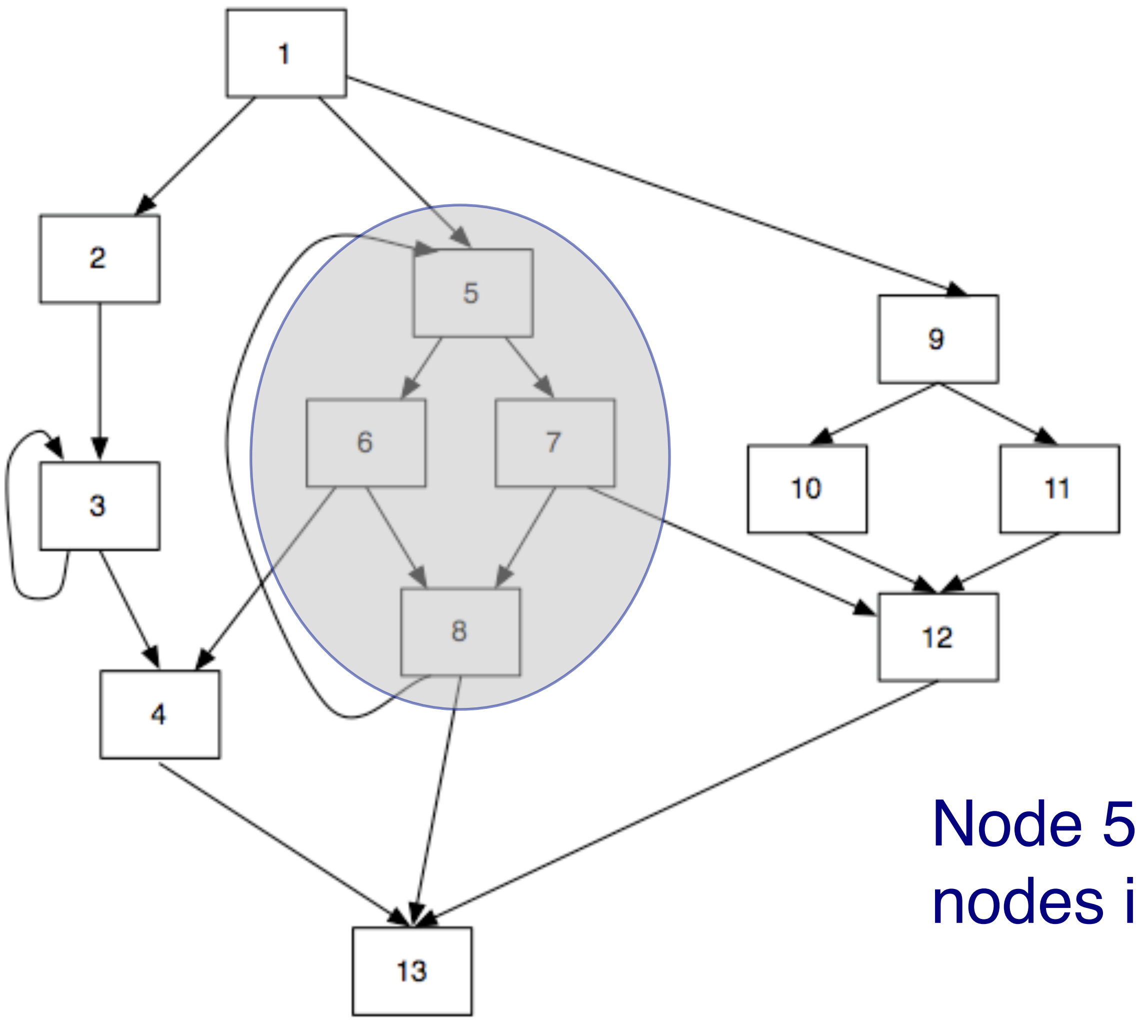
# Dominance and SSA Creation

- Dominance can be used to efficiently build SSA
- Φ-Functions are placed in all basic blocks of the *Dominance Frontier*
  - DF(D) = the set of all nodes N such that D dominates an immediate predecessor of N but does not strictly dominate N.

# Dominance and SSA Creation

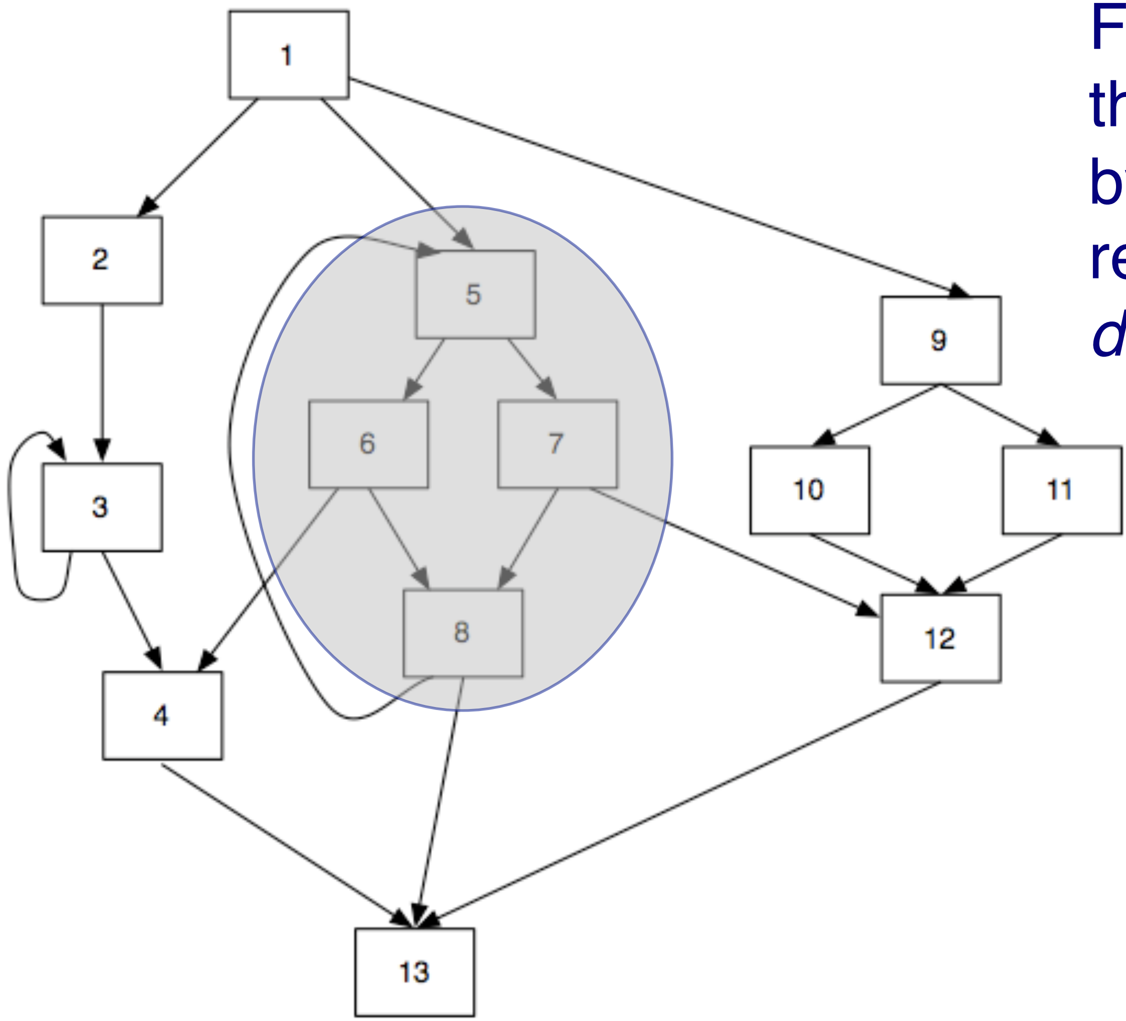


# Dominance and SSA Creation




Node 5 dominates all nodes in the gray area

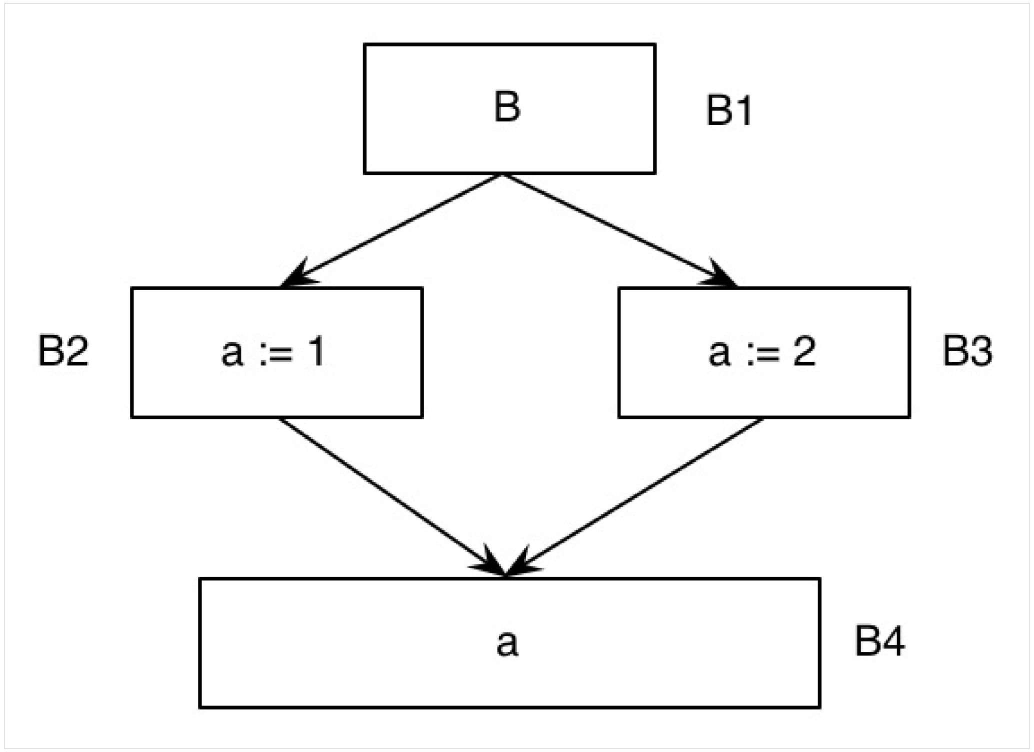
# Dominance and SSA Creation




Follow edges leaving the region dominated by node 5 to the region not *strictly dominated by 5.*

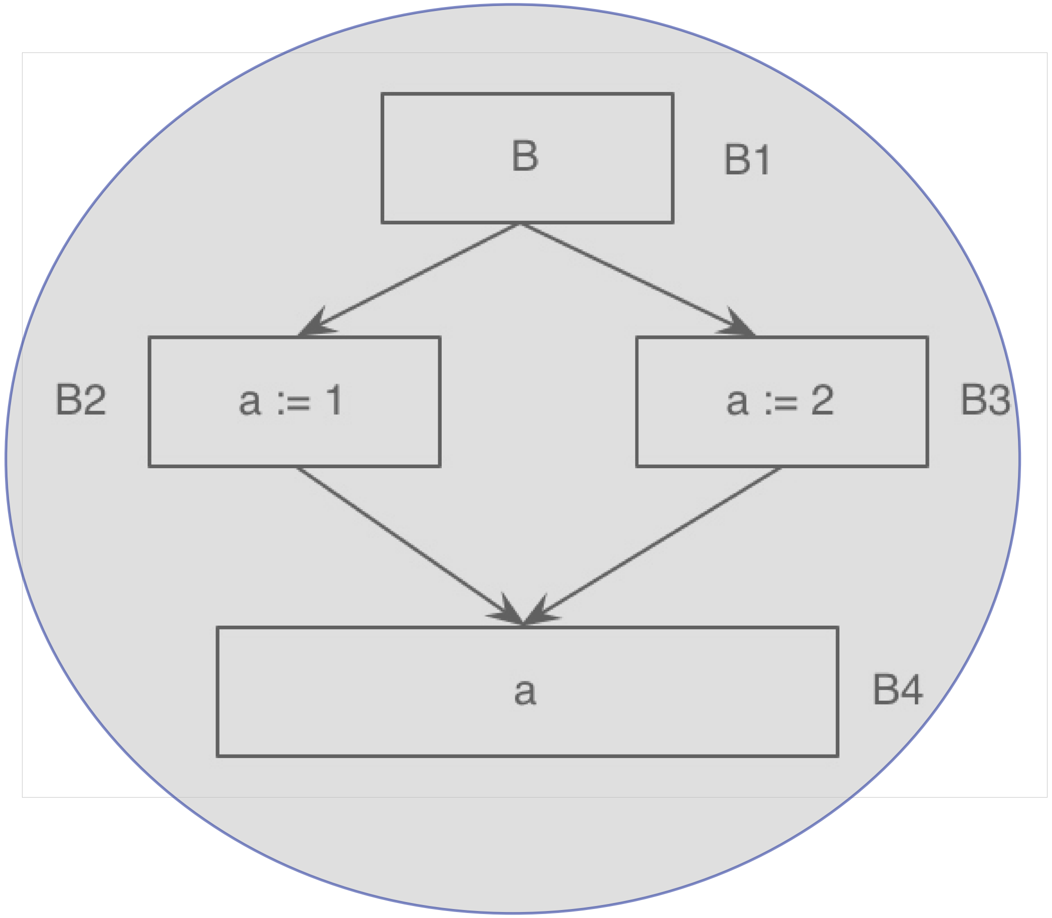
DF(5)= {4, 5, 12, 13}

# Simple Example



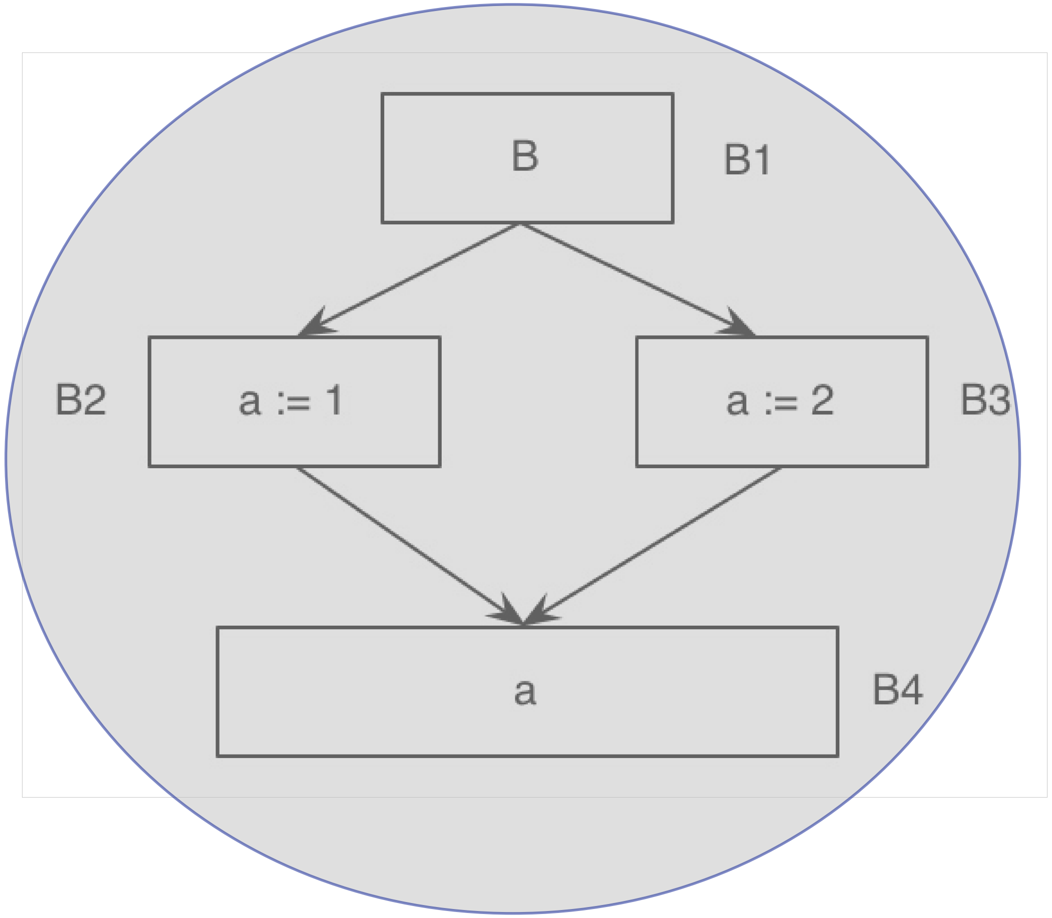

DF(B1)=
DF(B2)=
DF(B3)=
DF(B4)=

# Simple Example



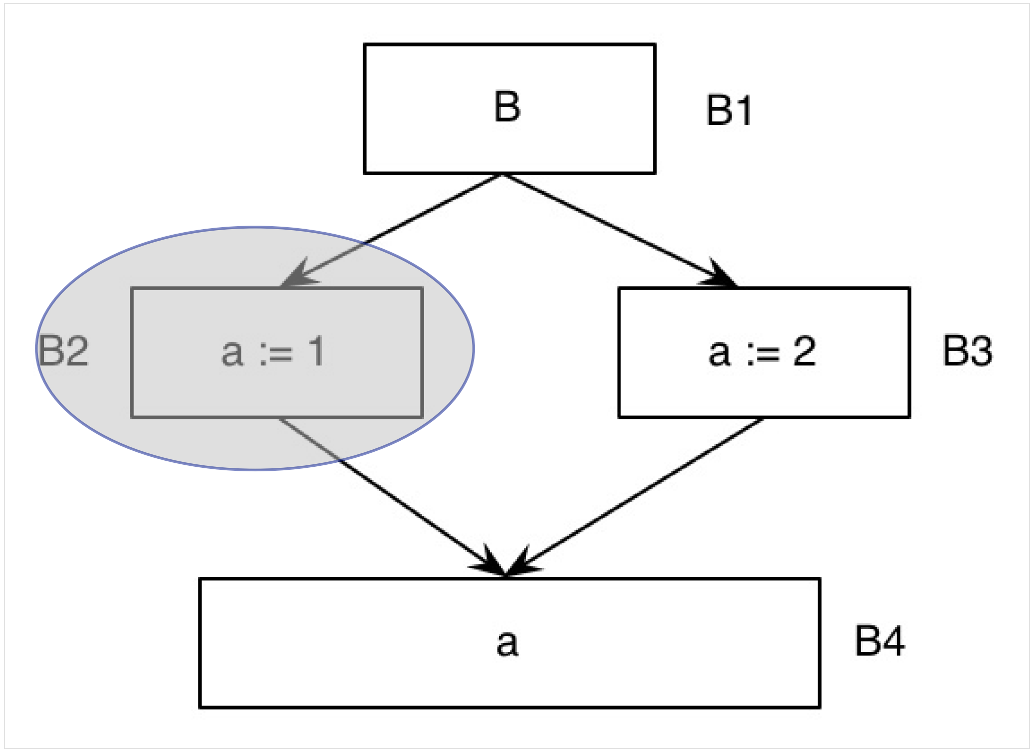

DF(B1)={?}
DF(B2)=
DF(B3)=
DF(B4)=

# Simple Example



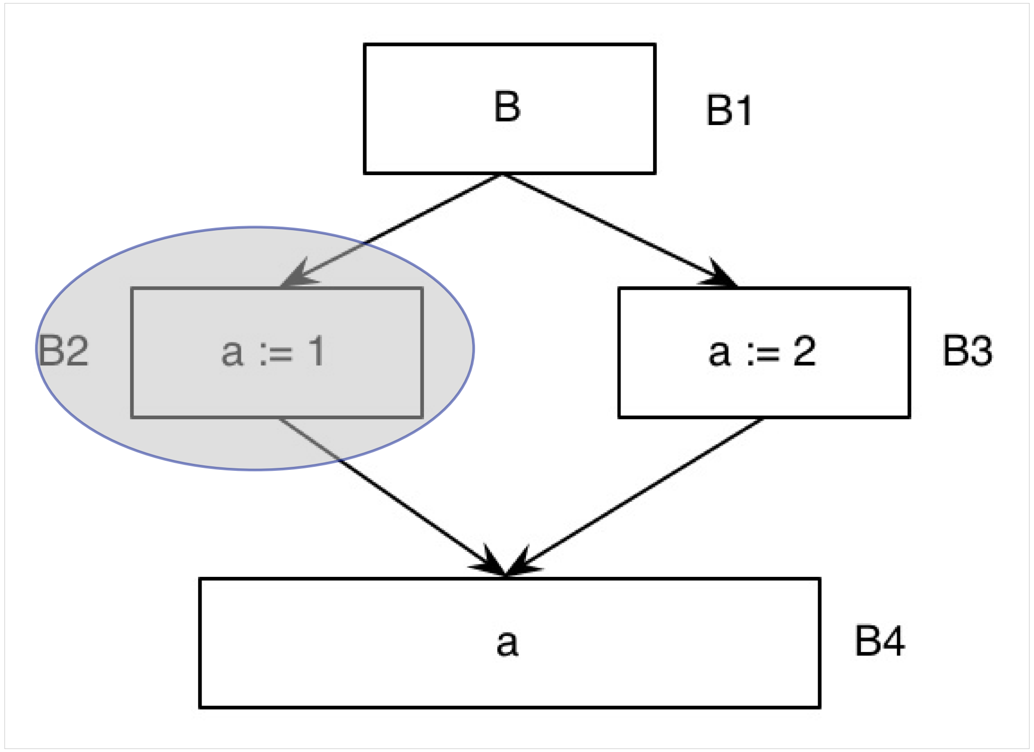

DF(B1)={}
DF(B2)=
DF(B3)=
DF(B4)=

# Simple Example



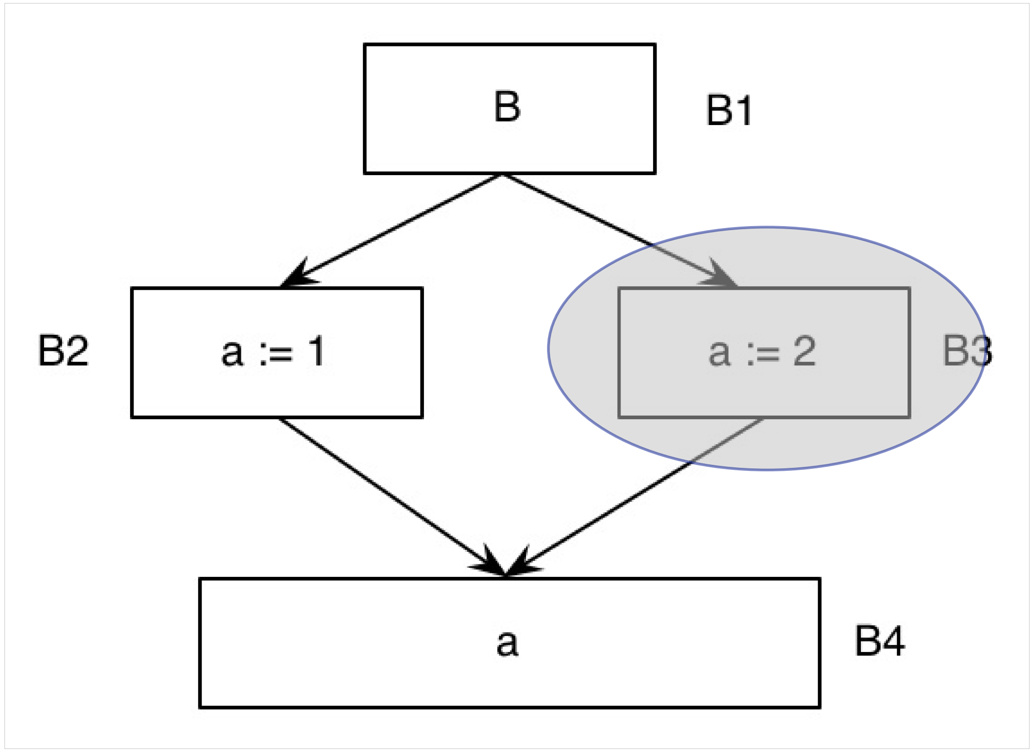

DF(B1)={}
DF(B2)={?}
DF(B3)=
DF(B4)=

# Simple Example



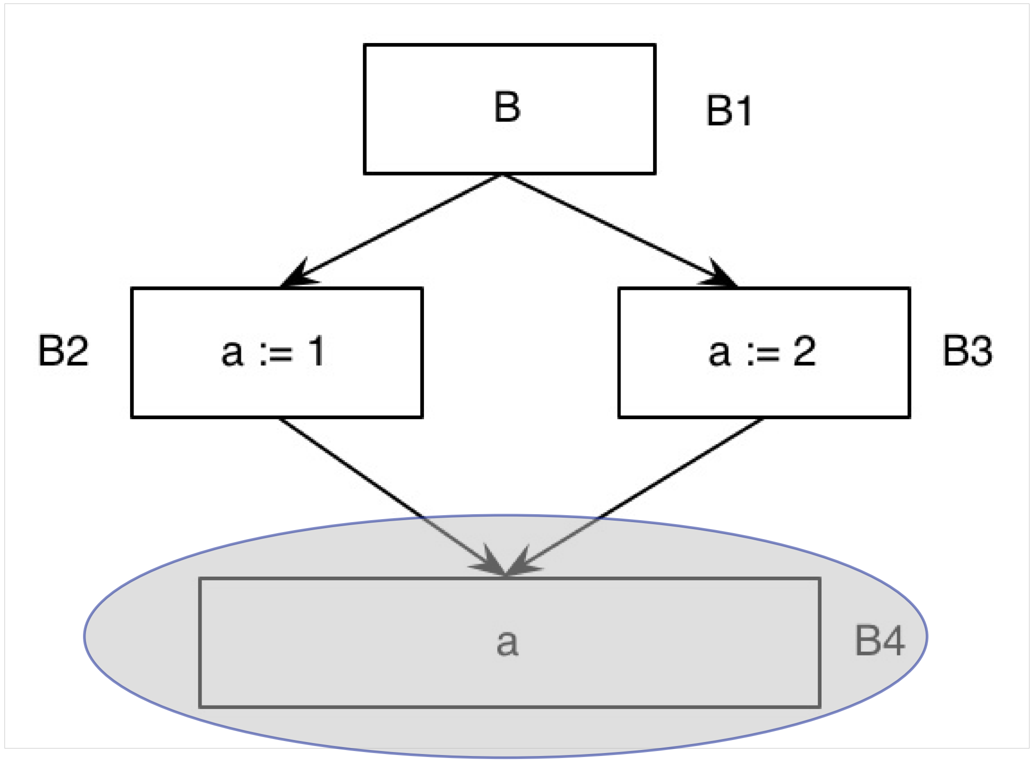

DF(B1)={}
DF(B2)={B4}
DF(B3)=
DF(B4)=

# Simple Example



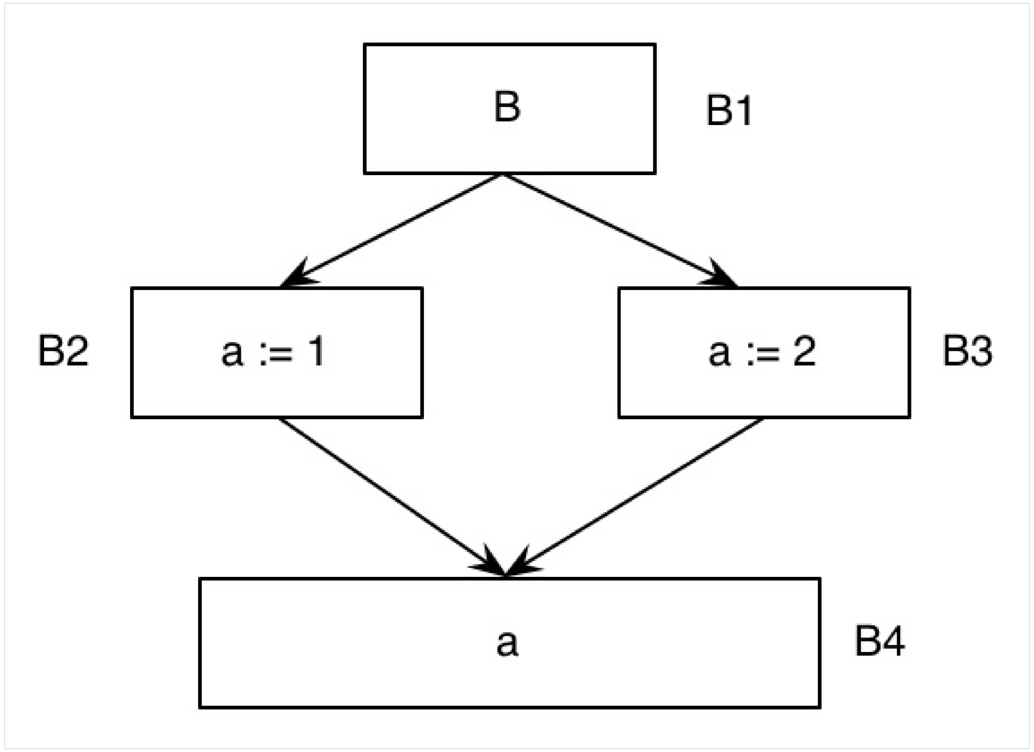

DF(B1)={}
DF(B2)={B4}
DF(B3)={B4}
DF(B4)=

# Simple Example




DF(B1)={}
DF(B2)={B4}
DF(B3)={B4}
DF(B4)={}

# Simple Example




DF(B1)={}
DF(B2)={B4}
DF(B3)={B4}
DF(B4)={}

*PHI-Function needed in B4 (for a)*

# Properties of SSA

- Simplifies many optimizations
  - *Every variable has only one definition*
  - *Every use knows its definition, every definition knows its uses*
  - *Unrelated variables get different names*

- *Examples:*
  - *Constant propagation*
  - *Value numbering*
  - *Invariant code motion and removal*
  - *Strength reduction*
  - *Partial redundancy elimination*

*Next Week!*

# SSA in the Real World

- Invented end of the 80s, a lot of research in the 90s

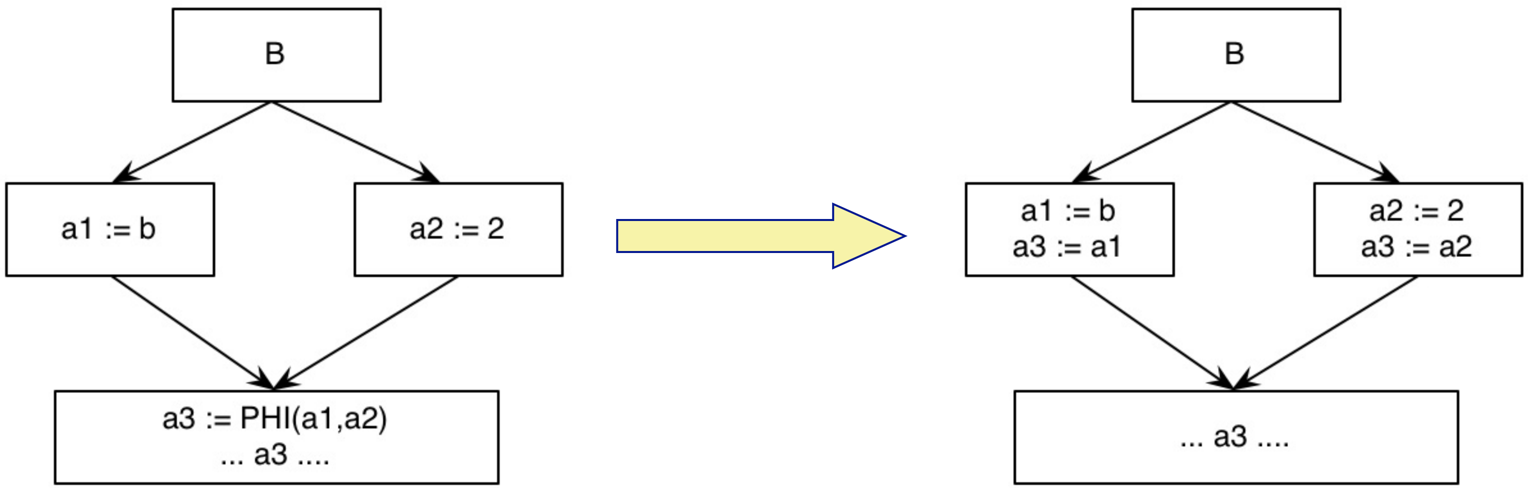
- Used in many modern compilers
  - *ETH Oberon 2*
  - *LLVM*
  - *GNU GCC 4*
  - *IBM Jikes Java VM*
  - *Java Hotspot VM*
  - *Mono*
  - *Many more…*

# Transforming out-of SSA

- Processor cannot execute Φ-Function

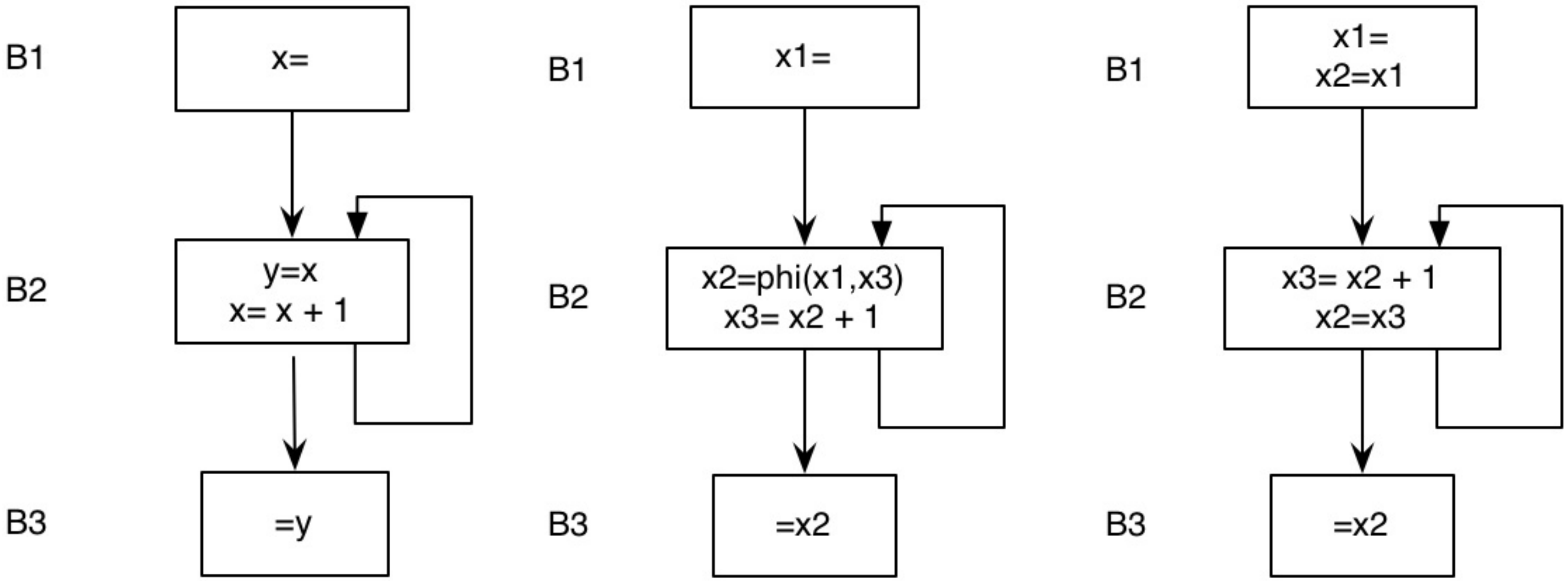
- How do we remove it?

# Simple Copy Placement



# Problems

- *Copies need to be removed*
- *Wrong in some cases after reordering of code*




Original

SSA with opt

Φ removed

# Φ-Congruence

***Idea:*** transform program so that all variables in Φ are the same:

$$a1 = \Phi(a1, a1) \Rightarrow a1 = a1$$

- Insert Copies
- Rename Variables

# Φ-Congruence: Definitions

**Φ-connected(x):**

a3 = Φ(**a1**, a2)
a5 = Φ(a3, **a4**)

a1, a4 are connected

**Φ-congruence-class:**

Transitive closure of Φ-connected(x).

# Φ-Congruence Property

**Φ-congruence property:**

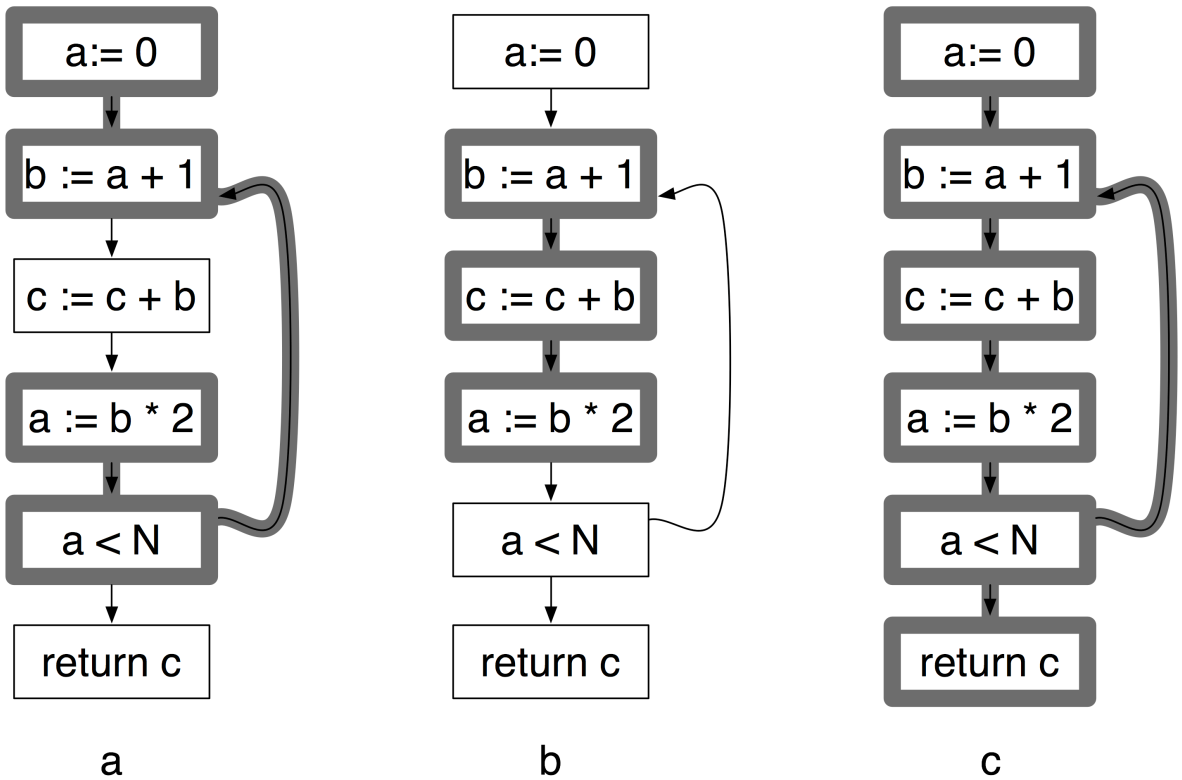
All variables of the same congruence class can be replaced by one representative variable without changing the semantics.

**SSA without optimizations has Φ-congruence property**

Variables of the congruence class never live at the same time (by construction)

# Liveness

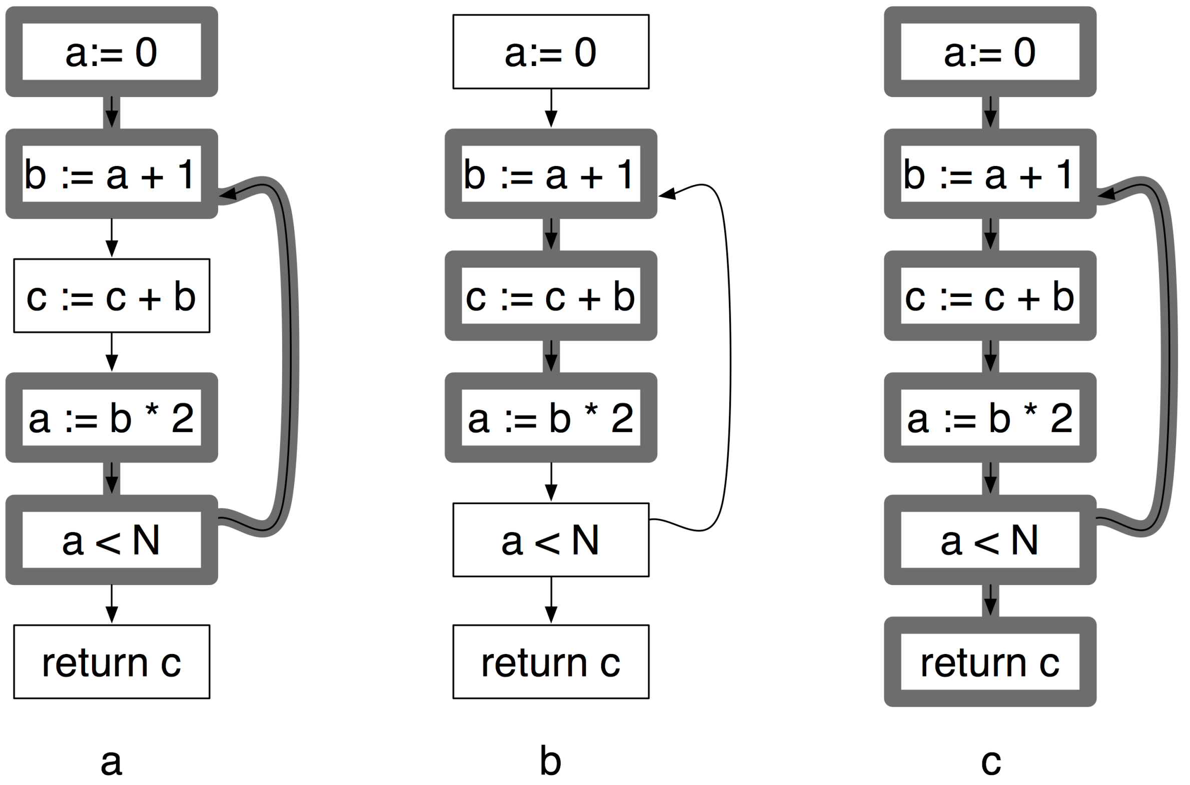
A variable *v* is *live* on edge *e* if there is a path from *e* to a use of *v* not passing through a definition of *v*




*a and b are never live at the same time, so two registers suffice to hold a, b and c*

# Interference

*a, c live at the same time: interference*



# Φ-Removal: Big picture

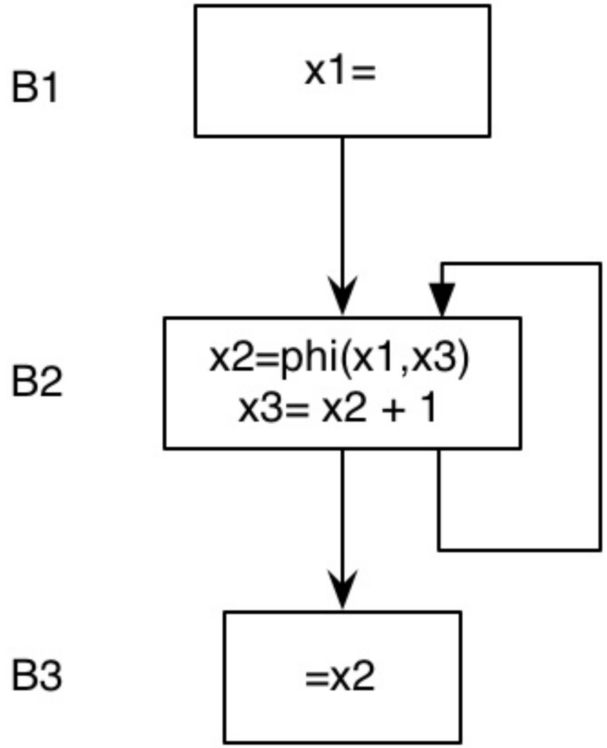
> CSSA: SSA with Φ-congruence-property.
> — *directly after SSA generation*
> — *no interference*

> TSSA: SSA without Φ-congruence-property.
> — after optimizations
> — Interference

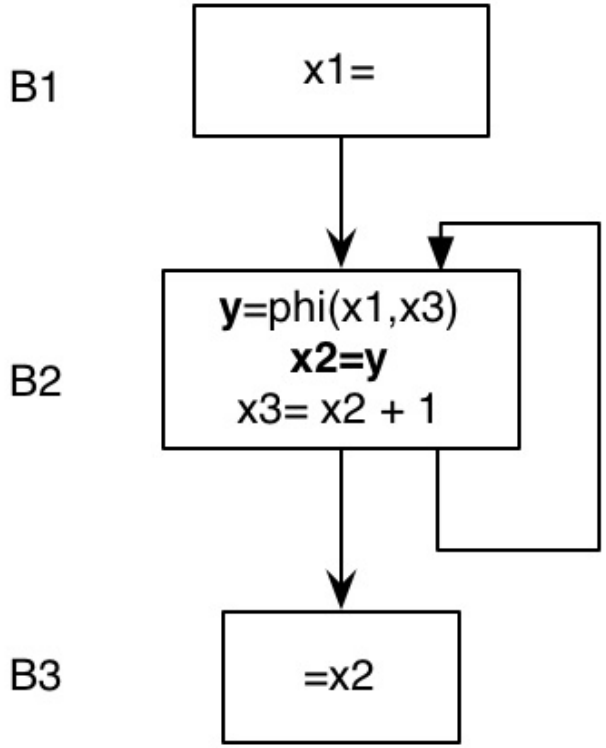
1. Transform TSSA into CSSA (fix interference)
2. Rename Φ-variables
3. Delete Φ

# Example: Problematic case

X2 and X3 interfere




Solution: Break up



# SSA and Register Allocation

> Idea: remove Φ as late as possible

> Variables in Φ-function never live at the same time!
  — *Can be stored in the same register*

> Do register allocation on SSA!

# SSA: Literature

**Books:**

- SSA Chapter in Appel
  Modern Compiler Impl. In Java
- Chapter 8.11 Muchnik:
  Advanced Compiler Construction

**SSA Creation:**

Cytron et. al: *Efficiently computing Static Single Assignment Form and the Control Dependency Graph* (TOPLAS, Oct 1991)

**PHI-Removal:** Sreedhar et at. *Translating out of Static Single Assigment Form* (LNCS 1694)

# Summary

- SSA, what it is and how to create it
  - Where to place $\Phi$-functions?
- Transformation out of SSA
  - Placing copies
  - Remove $\Phi$

Next Week: Optimizations

# *What you should know!*

- ✎ *Why do most compilers need an intermediate representation for programs?*
- ✎ *What are the key tradeoffs between structural and linear IRs?*
- ✎ *What is a "basic block"?*
- ✎ *What are common strategies for representing case statements?*
- ✎ *When a program has SSA form.*
- ✎ *What is a $\Phi$-function.*
- ✎ *When do we place $\Phi$-functions*
- ✎ *How to remove $\Phi$-functions*

# *Can you answer these questions?*

- ✎ *Why can't a parser directly produced high quality executable code?*
- ✎ *What criteria should drive your choice of an IR?*
- ✎ *What kind of IR does JTB generate?*
- ✎ *Why can we not directly generate executable code from SSA?*
- ✎ *Why do we use 3-adress code and CFG for SSA?*

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