6. Intermediate Representation

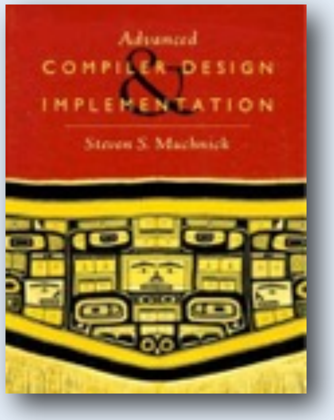
Oscar Nierstrasz

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
- SSA generation
- Dominance and SSA generation
- Applications of SSA
- Φ-congruence and SSA removal



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

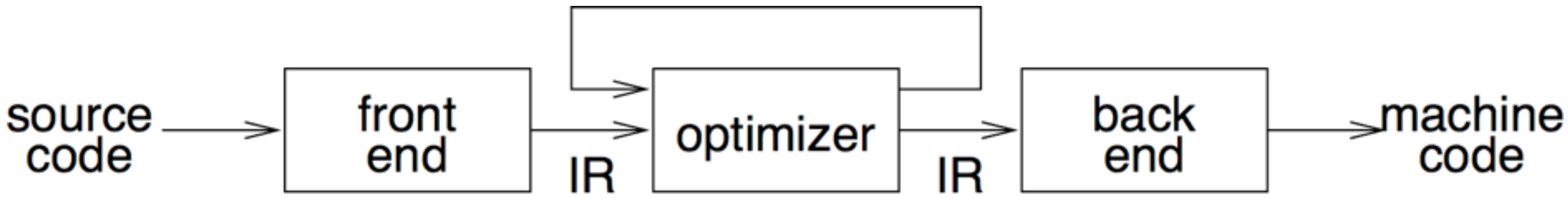
Roadmap

> **Intermediate representations**
> Static Single Assignment
> SSA generation
> Dominance and SSA generation
> Applications of SSA
> Φ-congruence and SSA removal

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

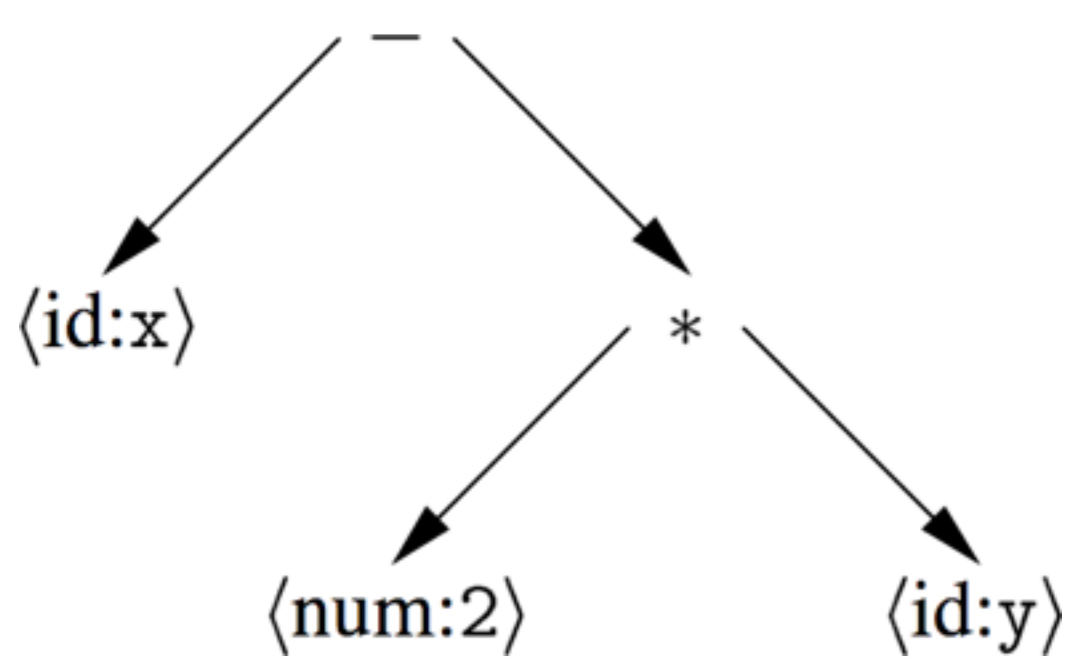
Subtle design decisions in the IR can have far-reaching effects on the speed and effectiveness of the compiler!

➔ *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!



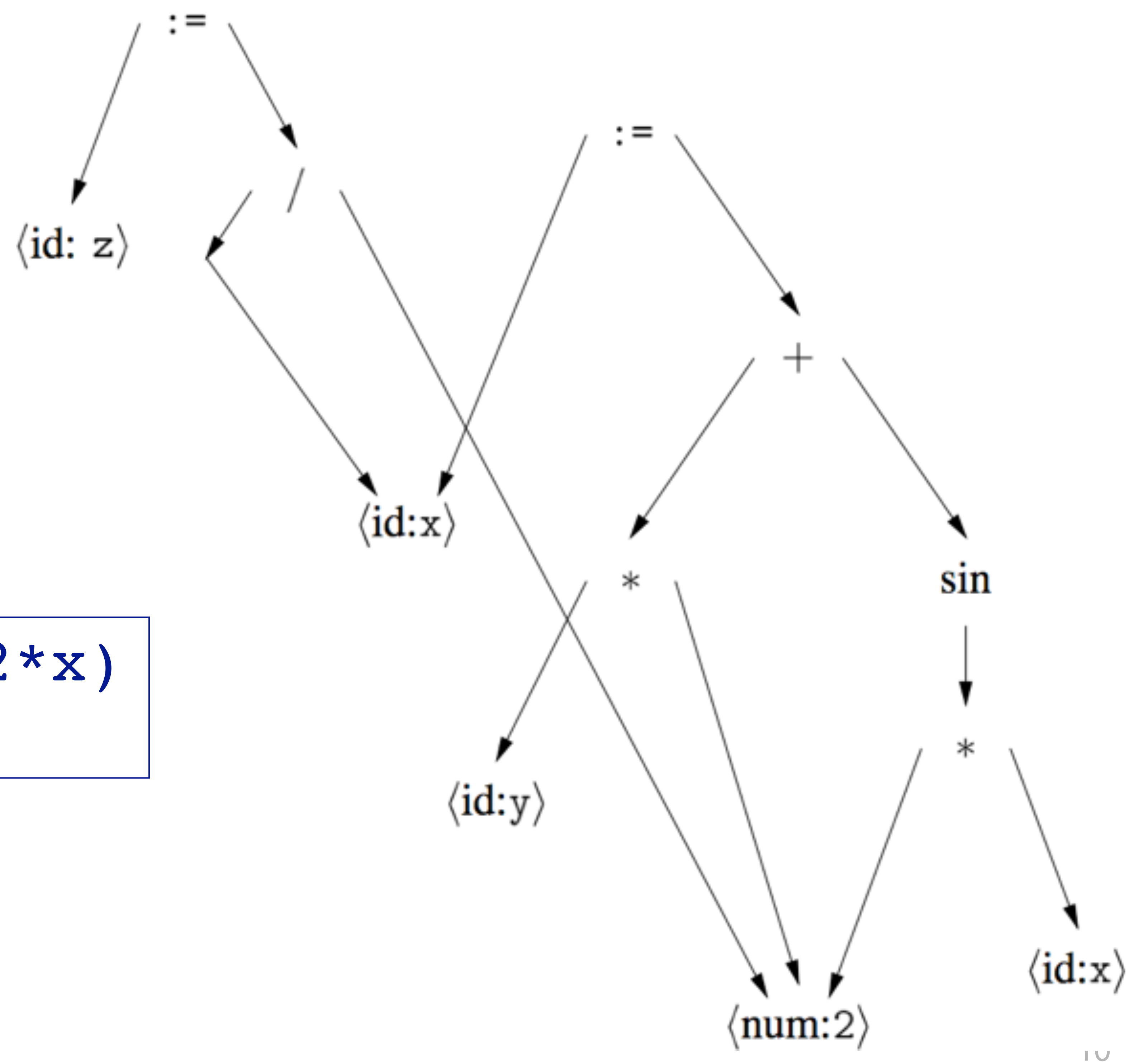
A linear operator form of this tree (postfix) would be:

```
x 2 y * -
```

Directed acyclic graph

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

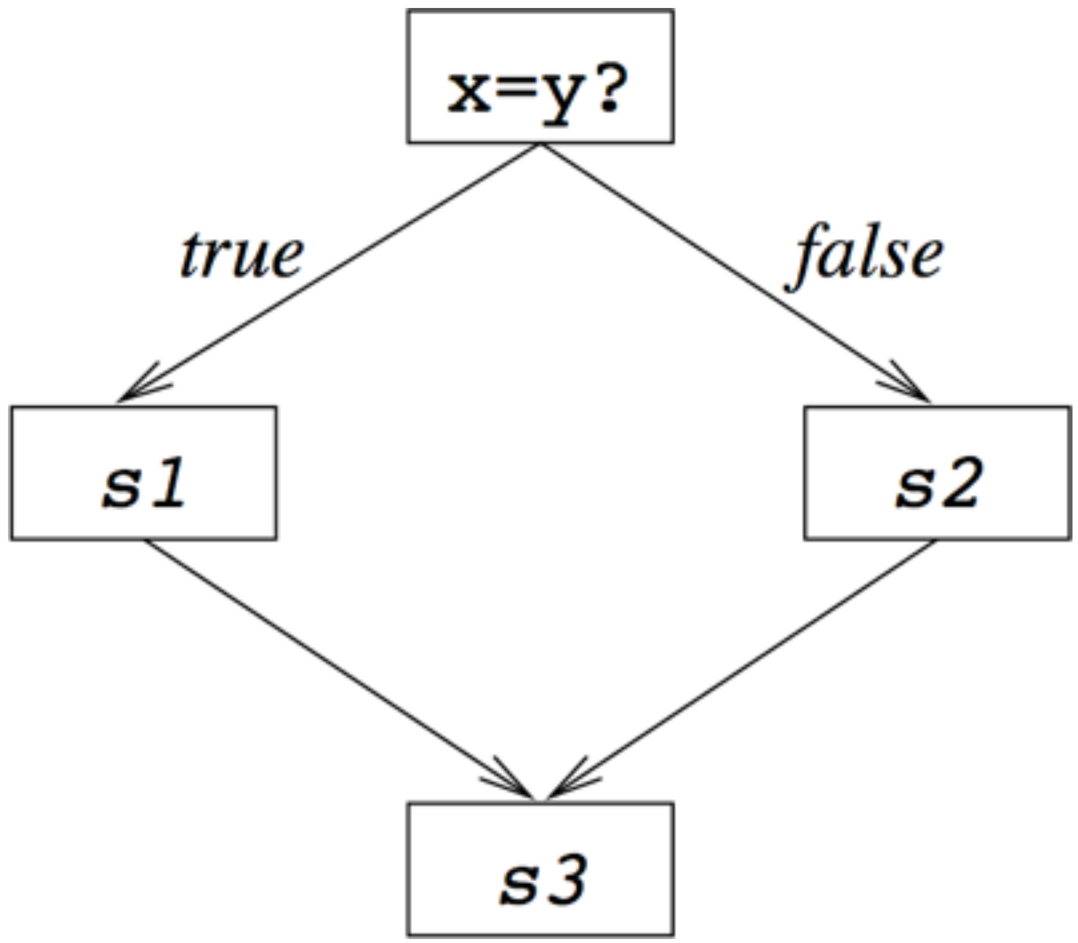
```
x := 2 * y + sin(2*x)
z := x / 2
```



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`
	`param y`
	`call p`

address and pointer assignments	`x = &y` `*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

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- **Static Single Assignment**
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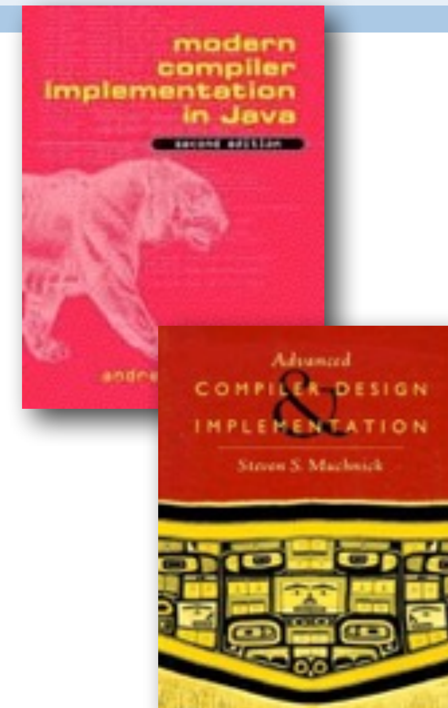
SSA: Literature

Books:

- SSA Chapter in Appel

- Chapter 8.11 Muchnik



SSA Creation:

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

Φ-Removal: Sreedhar et at. *Translating out of Static Single Assignment Form* (SAS, 1999)

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)

- 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;
```

→

x_1 := 3;
x_2 := x_1 + 1;
x_3 := 7;
x_4 := x_3*2;

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

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

$a_1 := b_1 + c_1$
$b_2 := c_1 + 1$
$d_1 := b_2 + c_1$
$a_2 := a_1 + 1$
$e_1 := a_2 + b_2$

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
- Selects between values depending on control-flow
- $a_{k+1} := \Phi(a_1 \ldots a_k)$: the block has k preceding blocks

Φ-functions are evaluated simultaneously within a basic block.

SSA and CFG

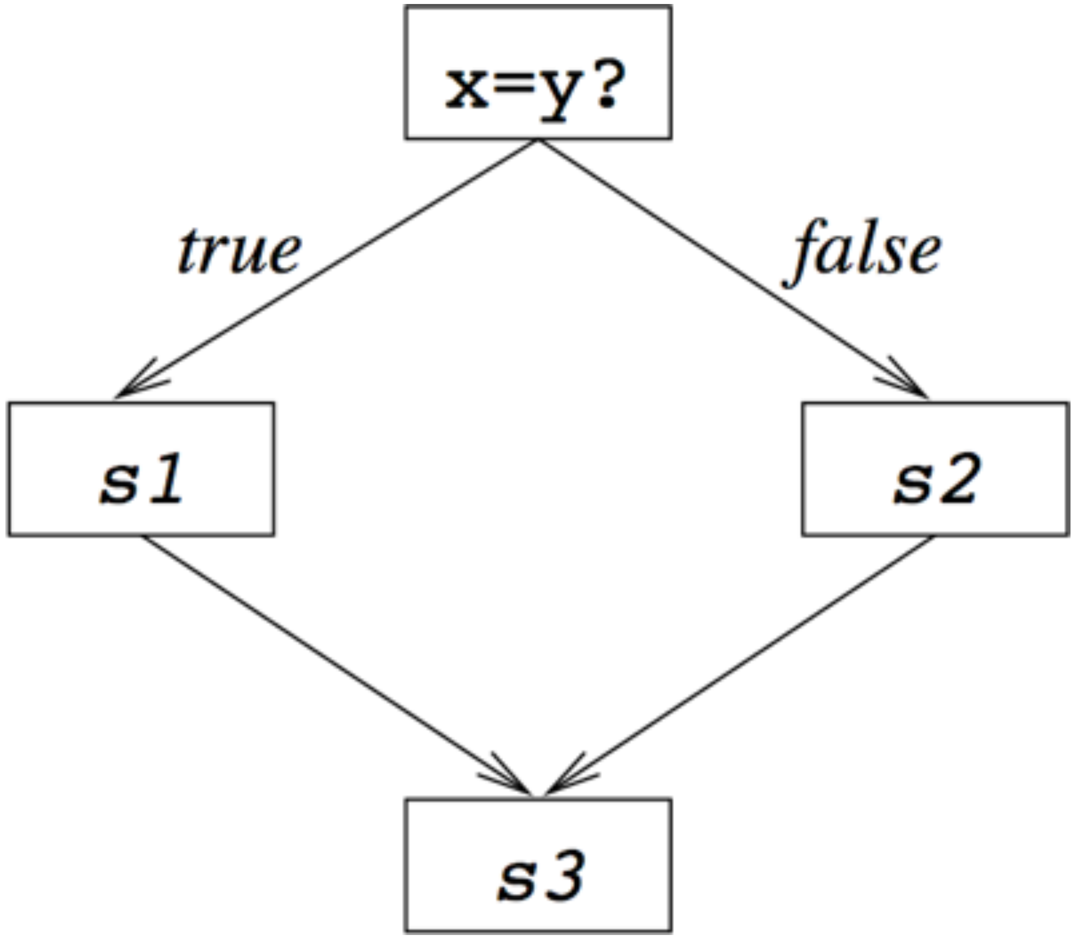
> SSA is normally used for control-flow graphs (CFG)

> Basic blocks are in 3-address form

Recall: Control flow graph

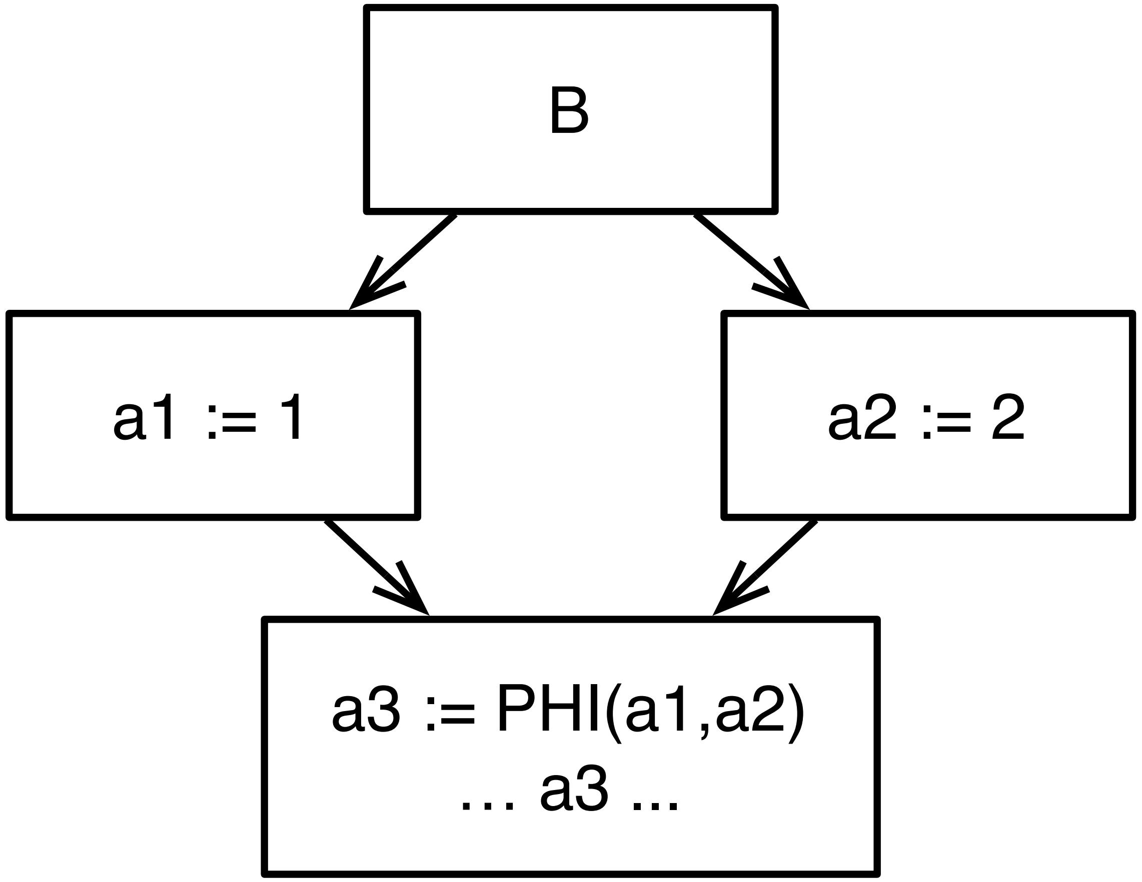
> A CFG models *transfer of control* in a program
  - —nodes are *basic blocks* (straight-line blocks of code)
  - —edges represent *control flow* (loops, if/else, goto …)

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



SSA: a Simple Example

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



Roadmap

- Intermediate representations
- Static Single Assignment
- **SSA generation**
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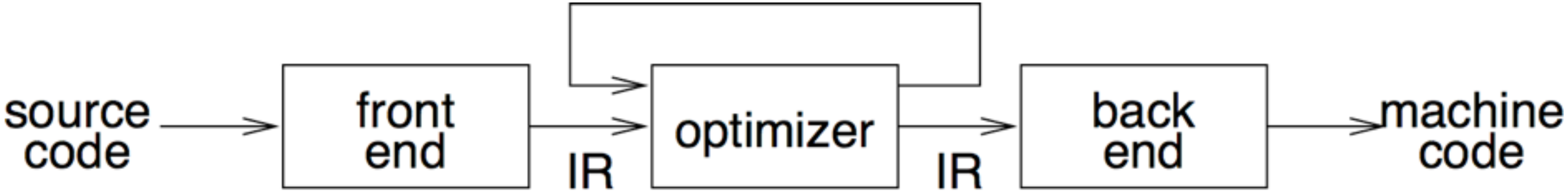
Recall: IR



- front end produces IR
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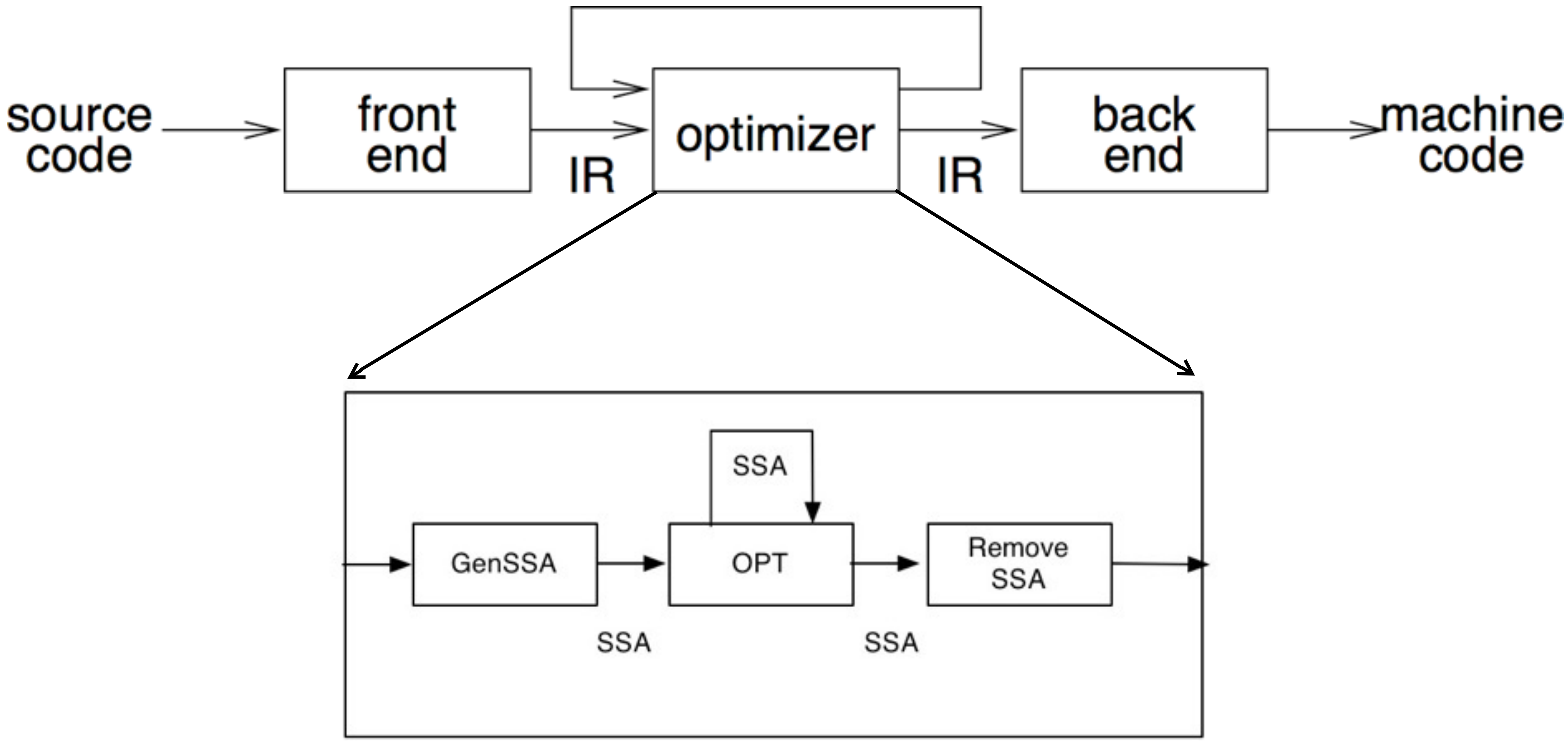
SSA as IR


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 Φ-functions
—Do not spend too much time

> ***Many relatively complex algorithms***
—We do not go too much into detail
—See literature!

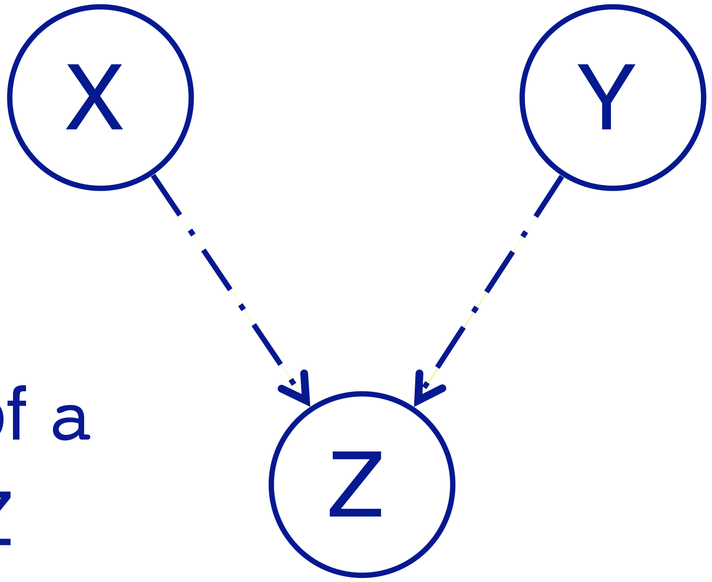
Minimal SSA

- Two steps:
  - —Place Φ-functions
  - —Rename Variables

- Where to place Φ-functions?

- We want minimal amount of needed Φ
  - —*Save memory*
  - —*Algorithms will work faster*

Path Convergence Criterion



- There should be a Φ 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)

- *I.e., Z is the first place where two definitions of a collide*

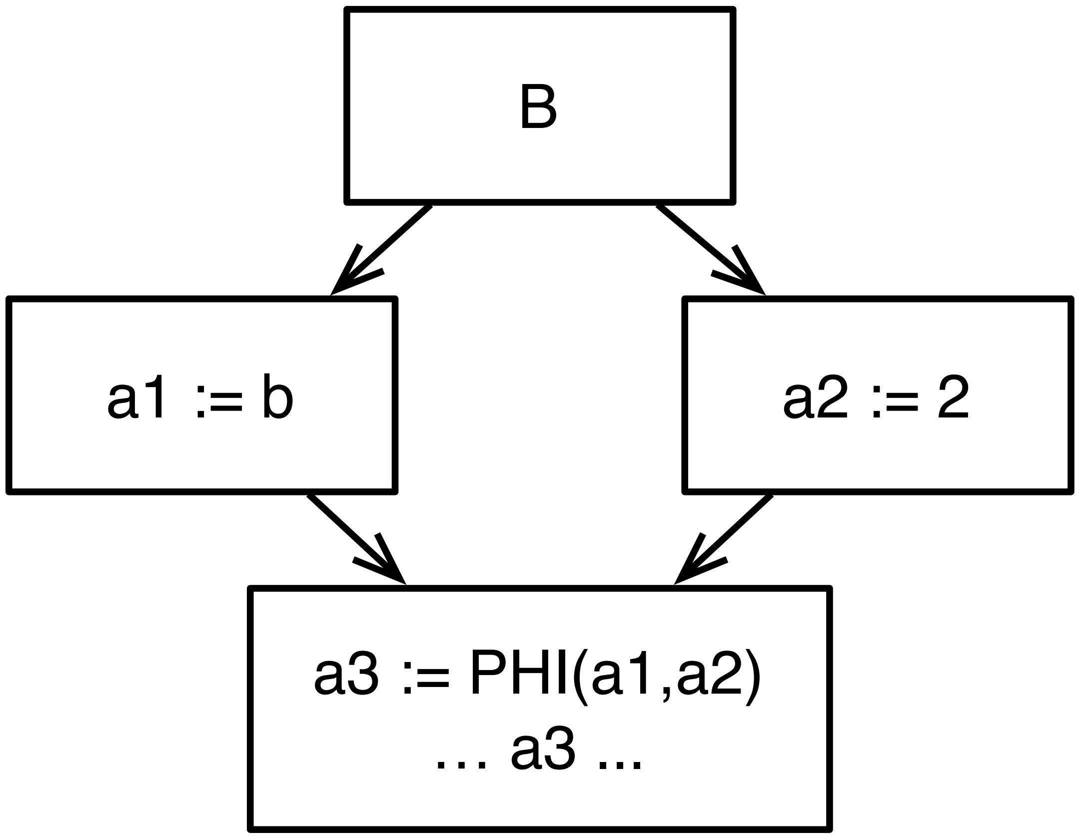
Iterated Path-Convergence

> Inserted Φ is itself a definition!

```
while there are nodes X,Y,Z satisfying conditions 1-5
  and Z does not contain a Φ-function for a
 do
   insert Φ 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

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Dominance Property of SSA

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

("strictly dominates": $D \neq N$)

Dominance Property of SSA:

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

"Definition dominates use"

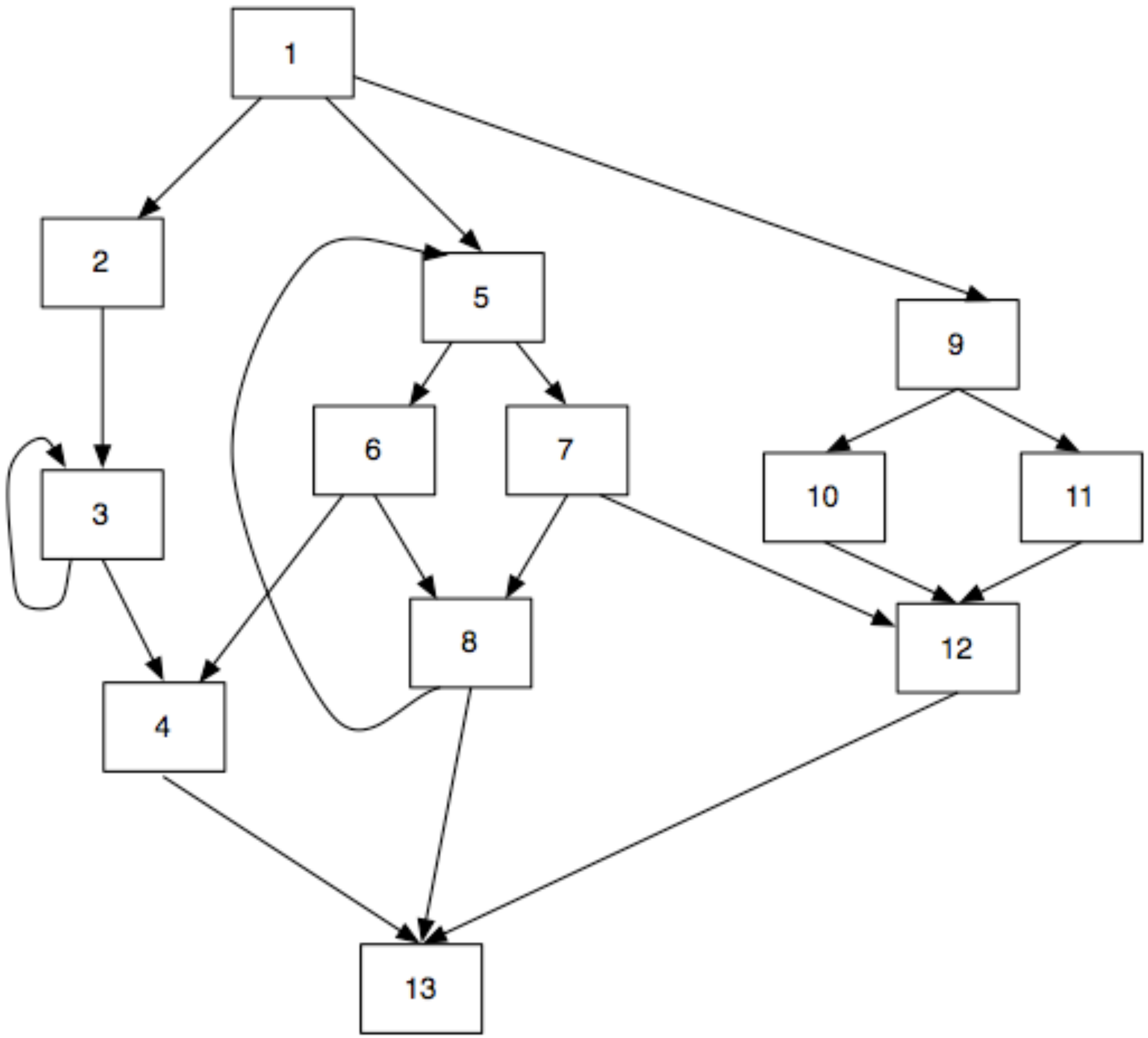
Dominance and SSA Creation

> Dominance can be used to efficiently build SSA

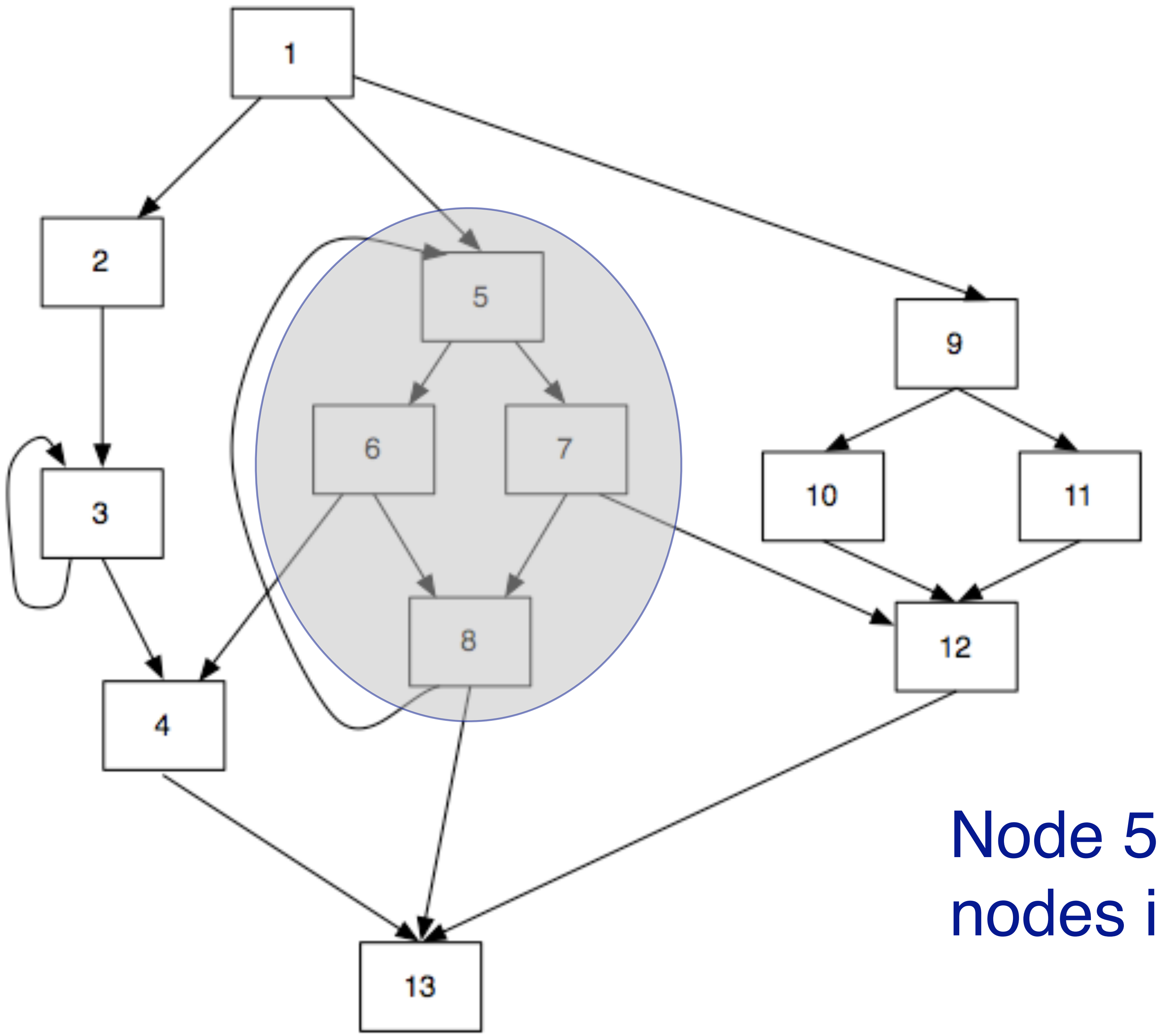
> Φ-Functions are placed in all basic blocks of the *Dominance Frontier*

—DF(D) = the set of all nodes N such that D dominates an immediate predecessor of N but does not strictly dominate N.

Dominance frontier

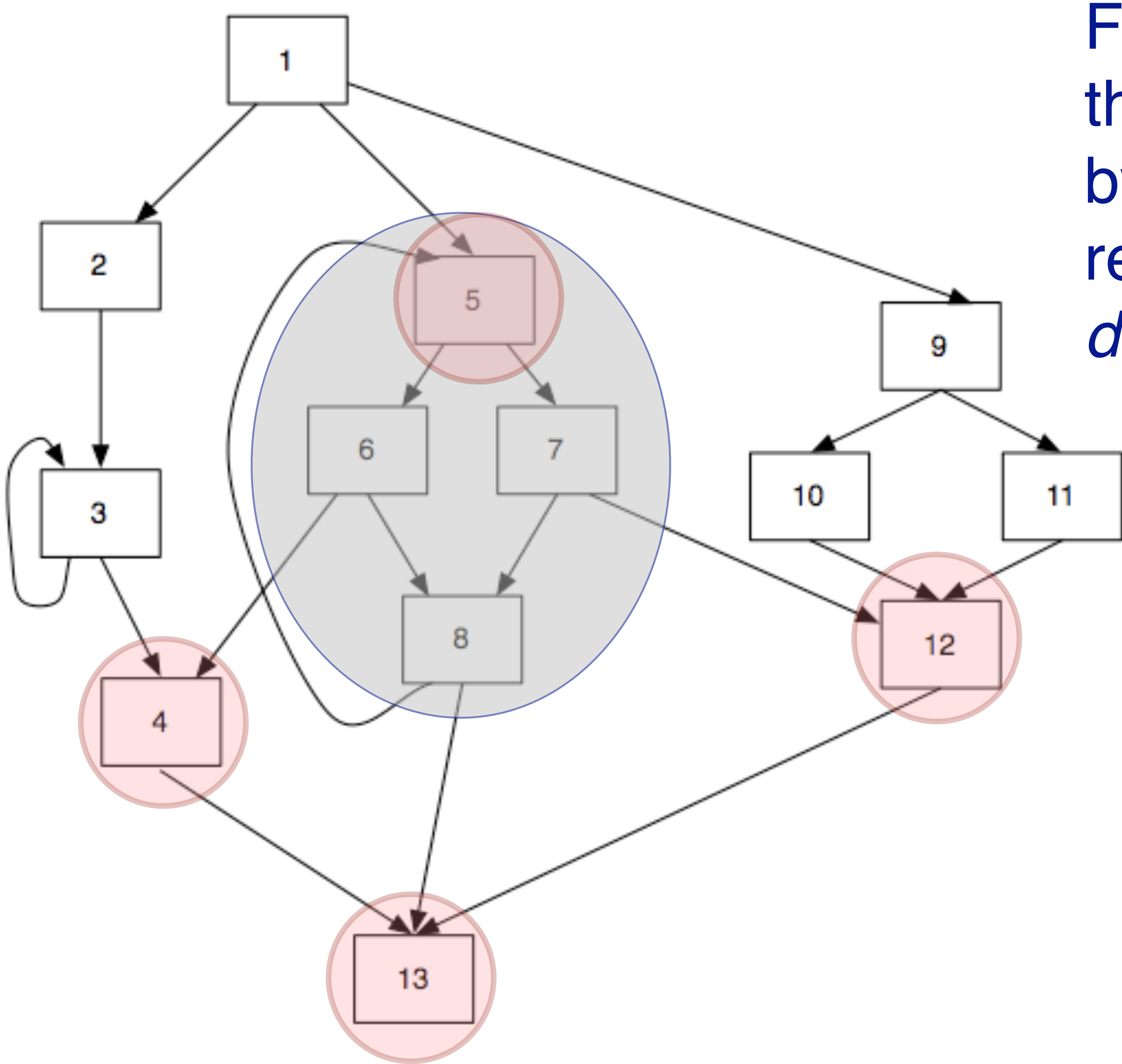


Dominance frontier



Node 5 dominates all nodes in the gray area

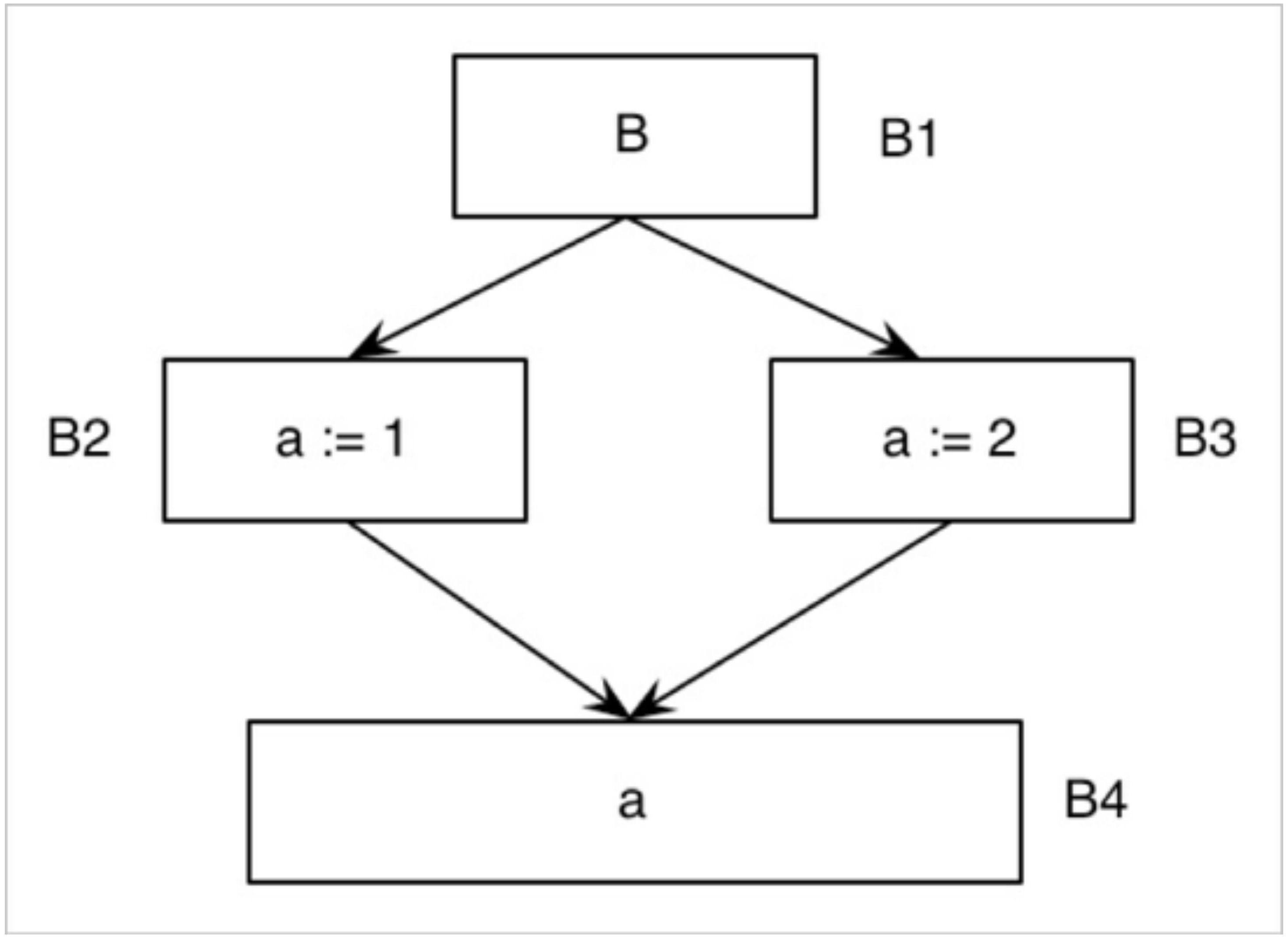
Dominance frontier



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

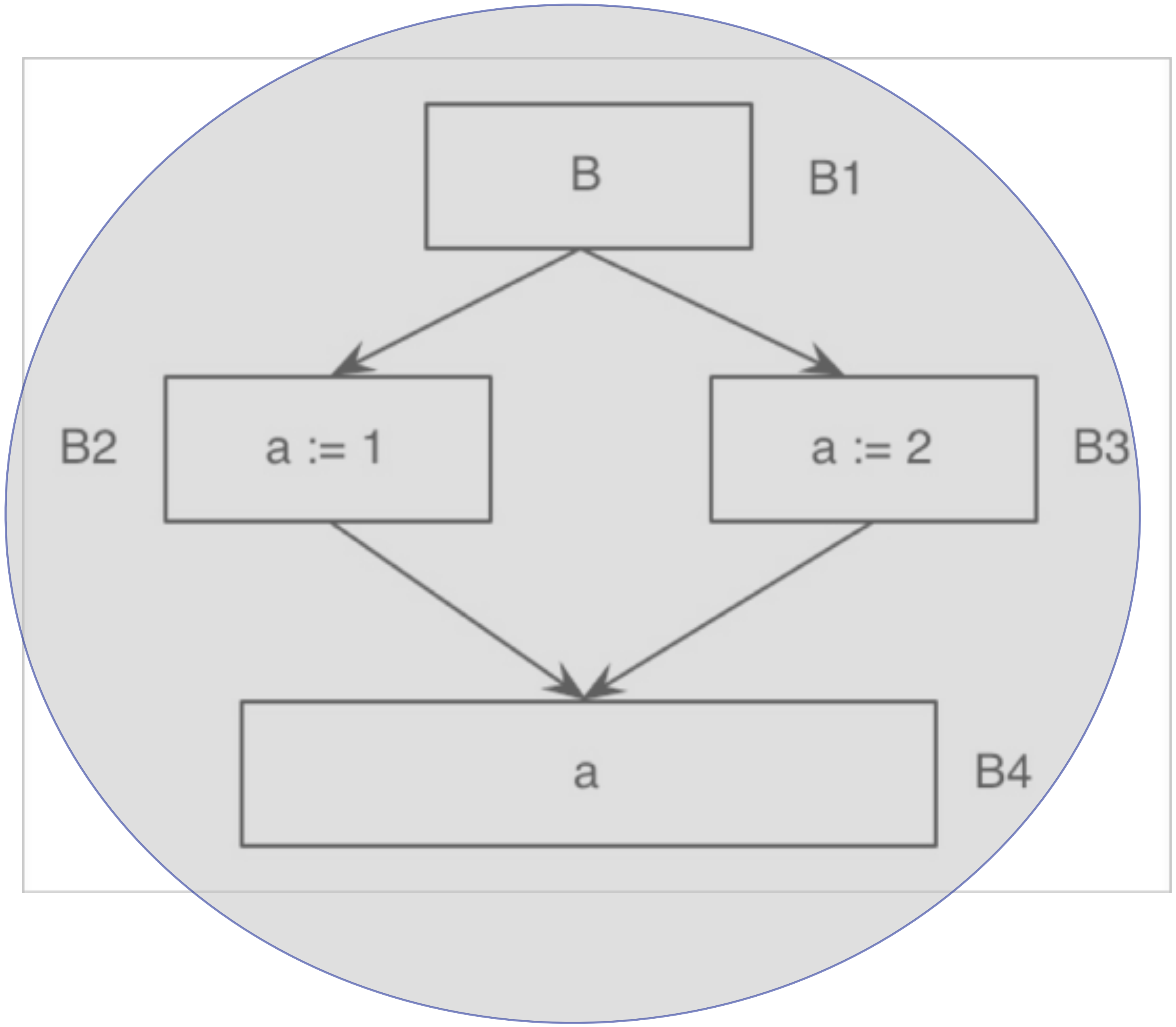
DF(5)= {4, 5, 12, 13}

Simple Example



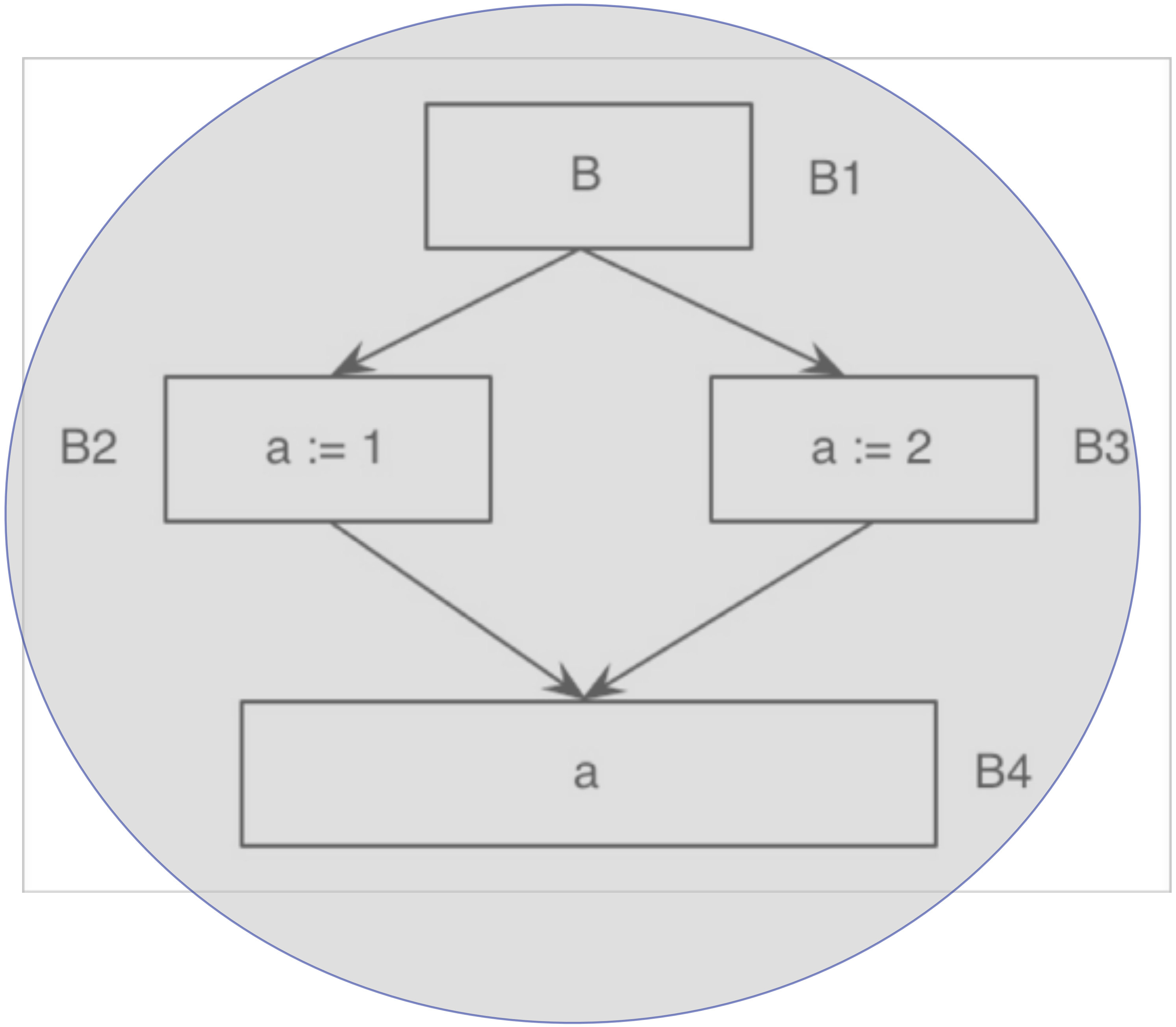
DF(B1)=
DF(B2)=
DF(B3)=
DF(B4)=

Simple Example



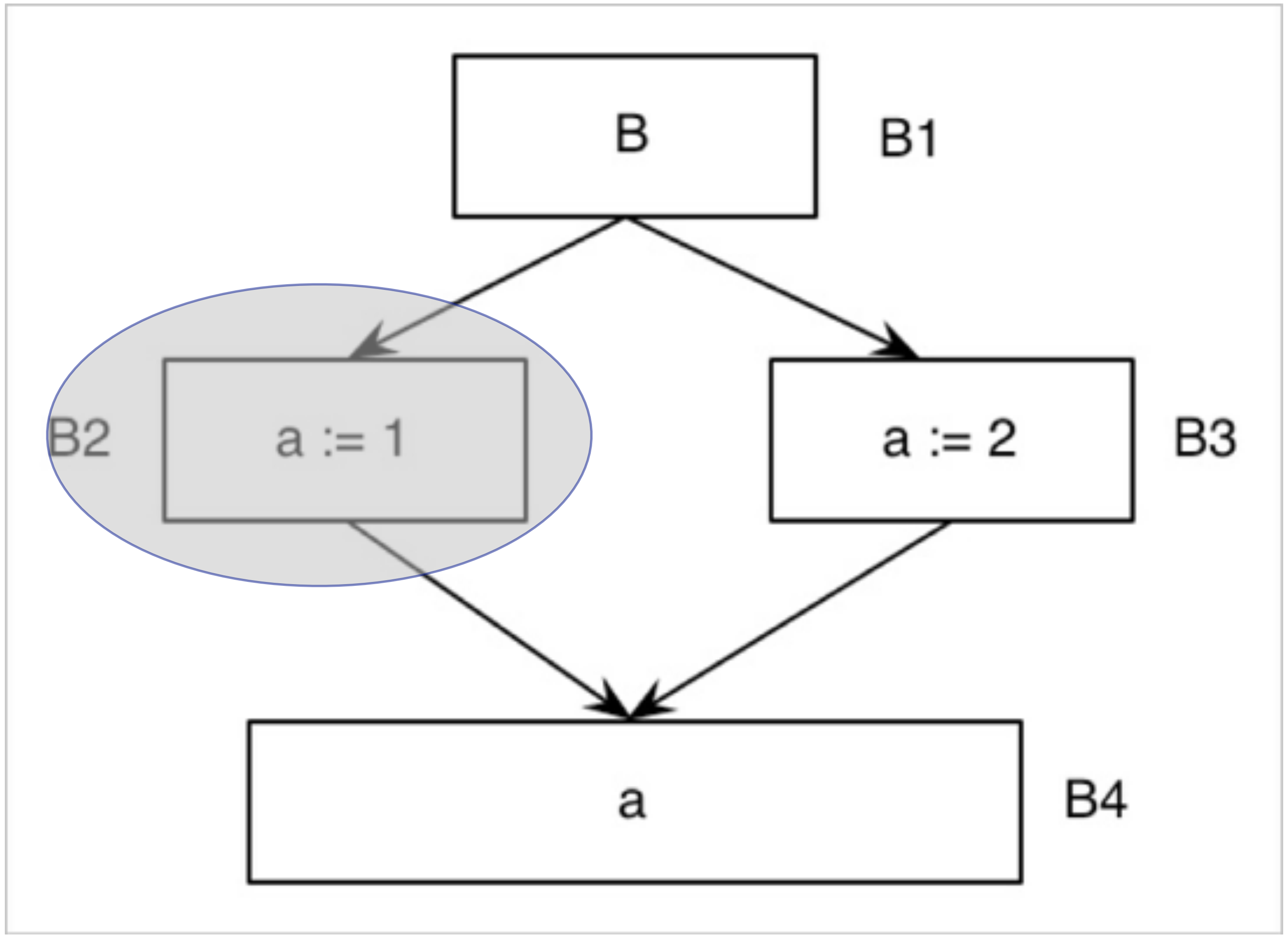
DF(B1)={?}
DF(B2)=
DF(B3)=
DF(B4)=

Simple Example



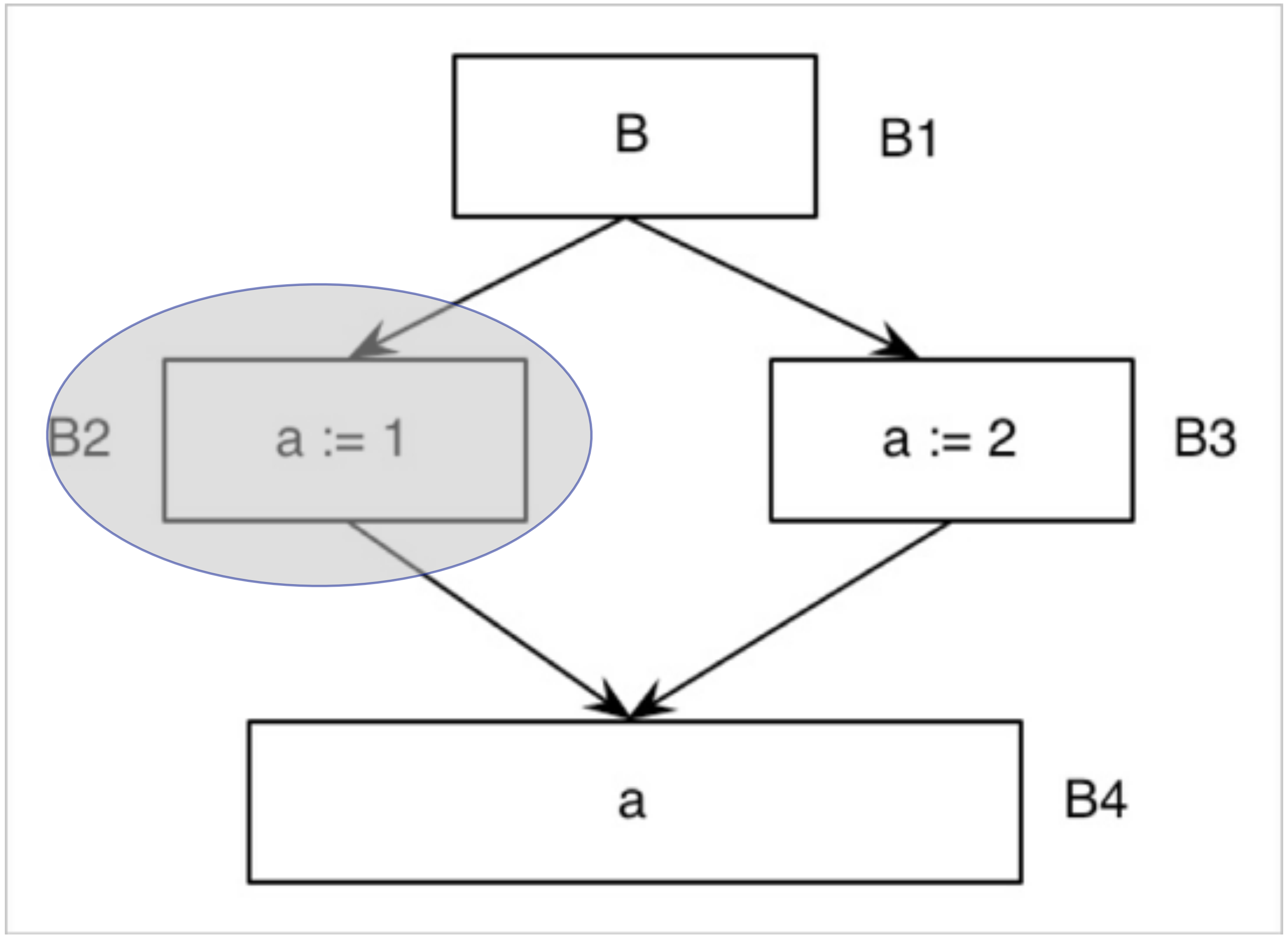
DF(B1)={}
DF(B2)=
DF(B3)=
DF(B4)=

Simple Example



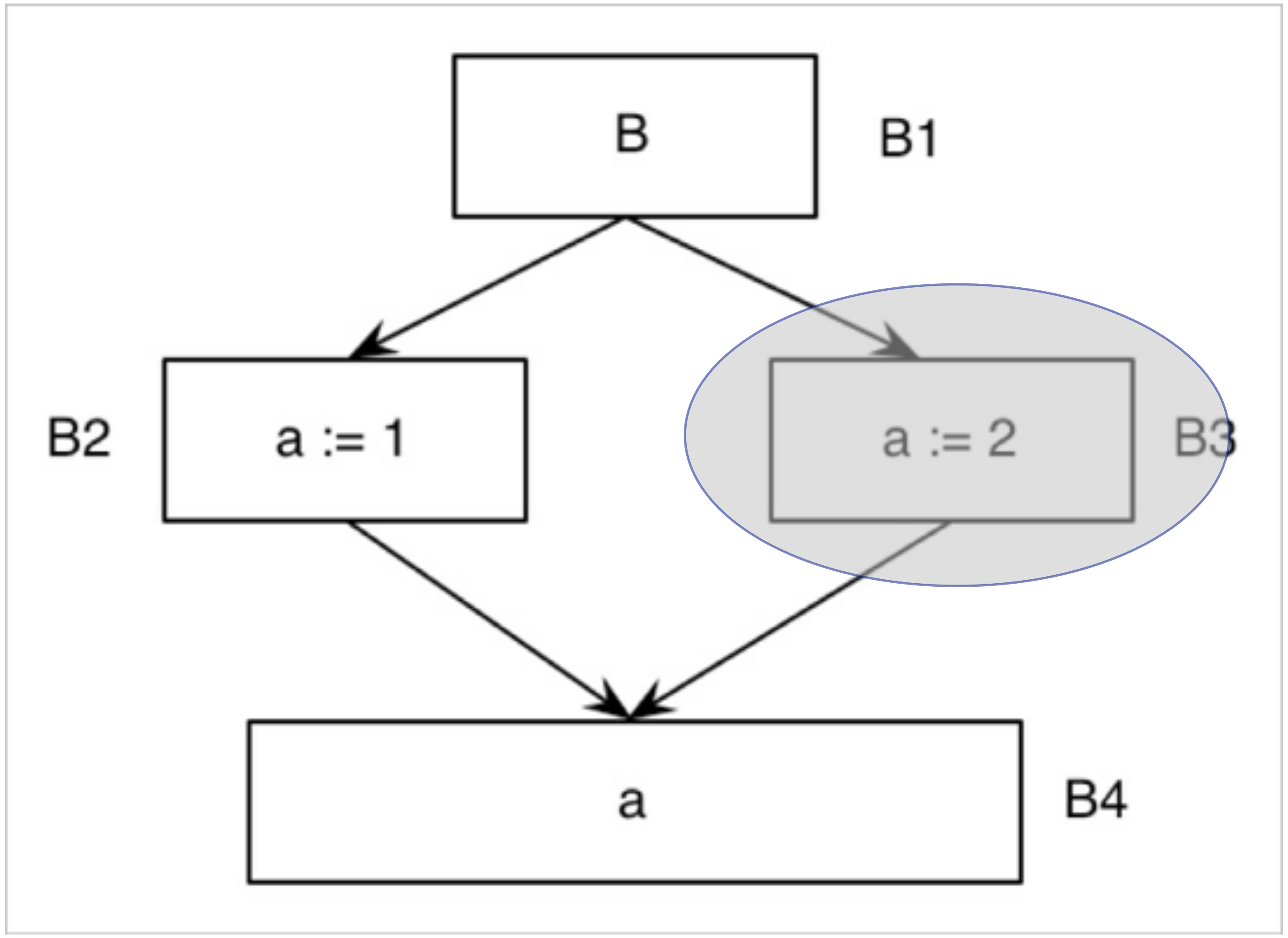
DF(B1)={}
DF(B2)={?}
DF(B3)=
DF(B4)=

Simple Example



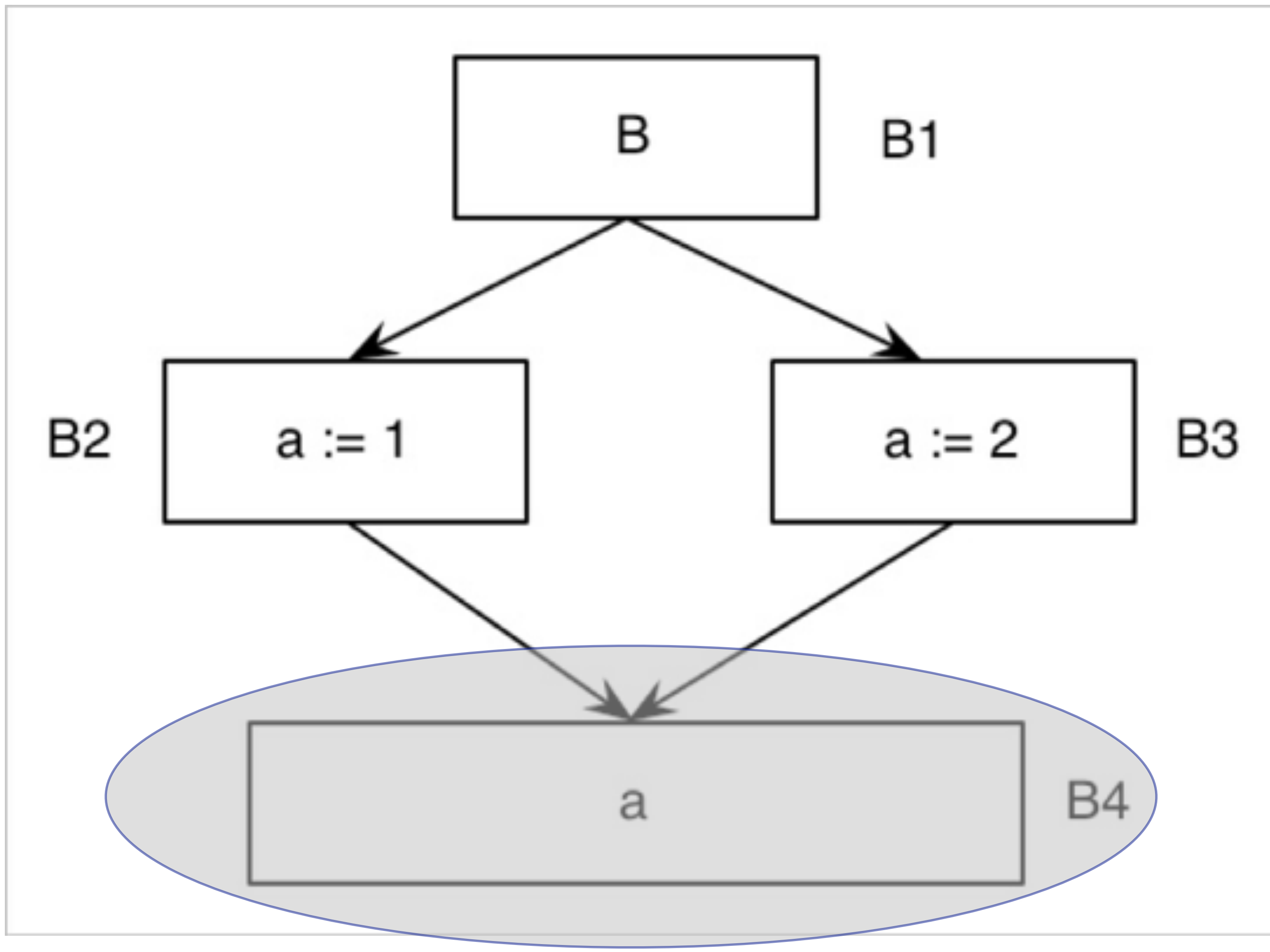
DF(B1)={}
DF(B2)={B4}
DF(B3)=
DF(B4)=

Simple Example



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

Simple Example



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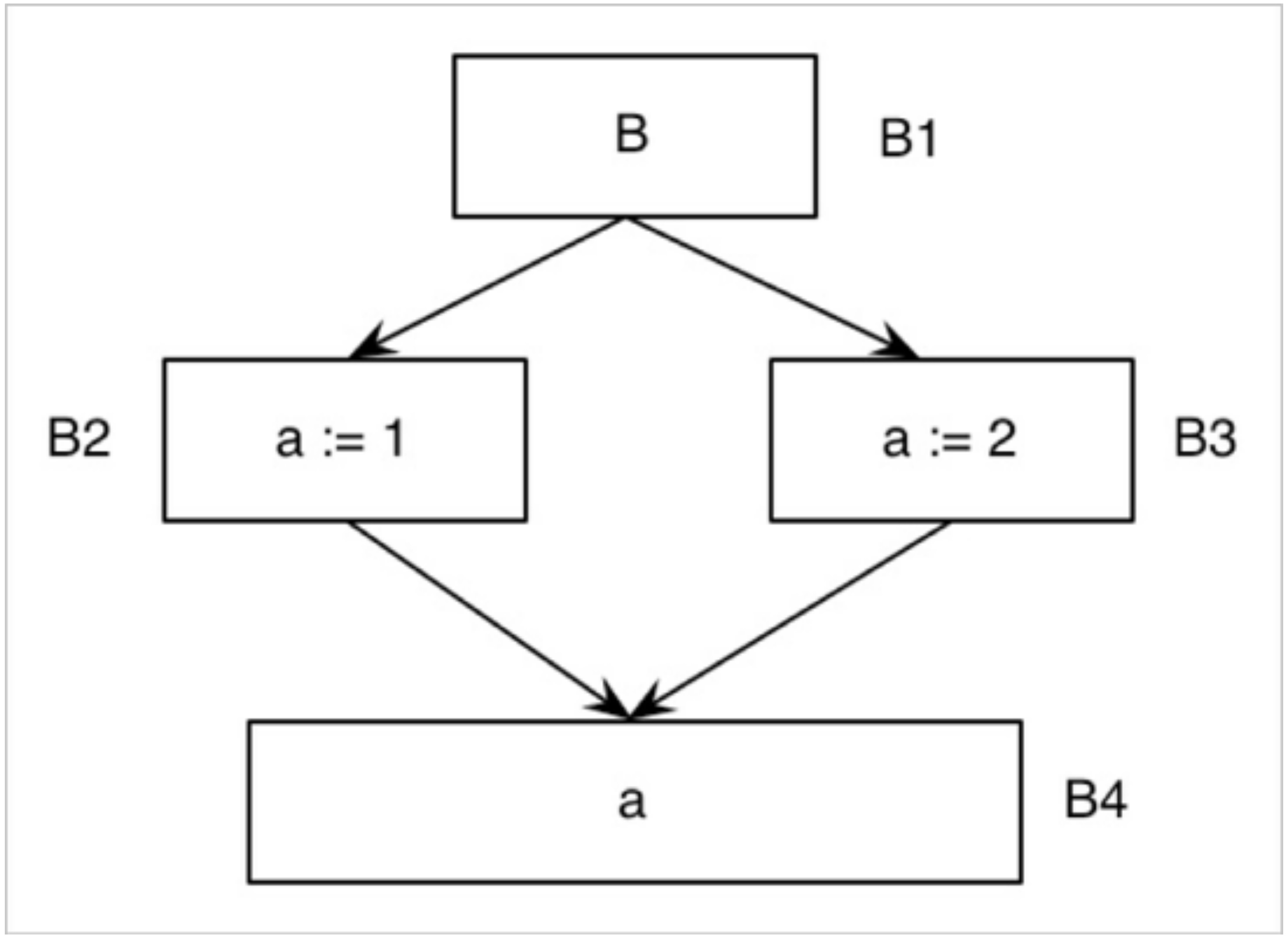
DF(B4)={}

Simple Example



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

Φ-Function needed in B4 (for a)

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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 lecture!

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…*

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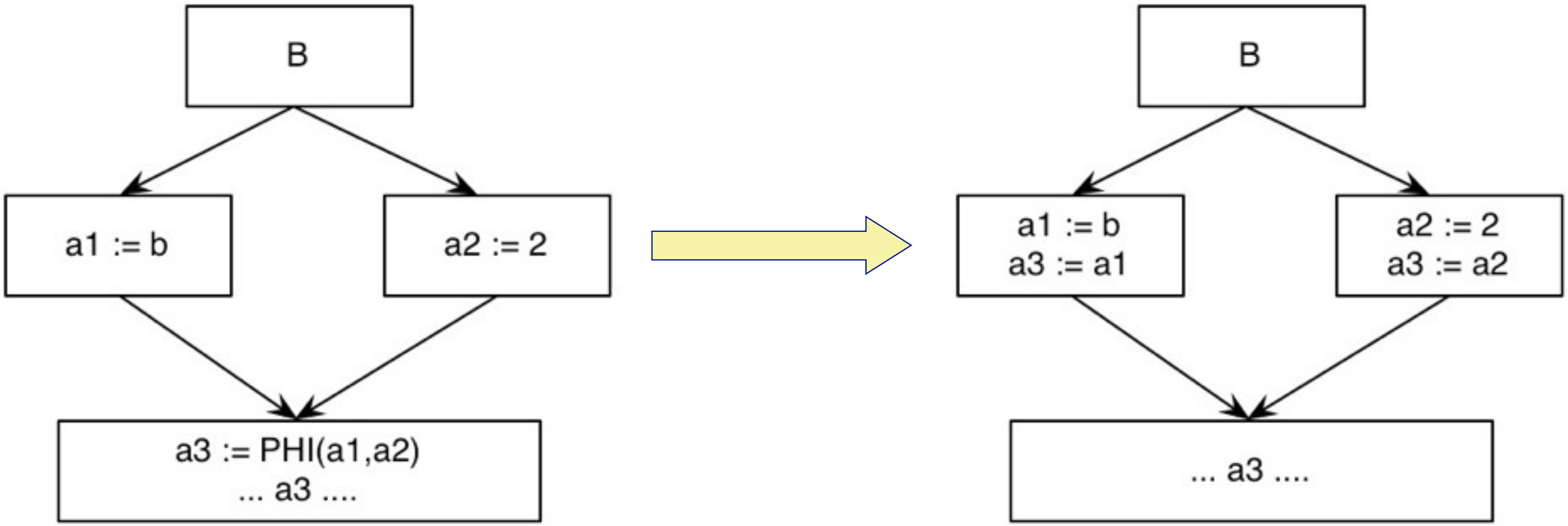
Vugranam C. Sreedhar, et al, *“Translating Out of Static Single Assignment Form”*, LNCS 1694, 1999, doi:10.1007/3-540-48294-6_13

Transforming out-of SSA

- Processor cannot execute Φ-Function

- How do we remove it?

Simple Copy Placement



Naive copy placement may produce incorrect results after optimization …

Φ-Congruence

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

a1 = Φ(a1,a1) ⇨ a1 = a1

- Insert Copies
- Rename Variables

Φ-Congruence: Definitions

Φ-connected(x):

a3 = Φ(a1, a2)
a5 = Φ(a3, a4)

a1, a2, a3 are Φ-*connected*
a3, a4, a5 are Φ-*connected*

Φ-congruence-class:

Transitive closure of Φ-connected(x).

a1-a5 are Φ-*congruent*

Φ-Congruence Property

Φ-congruence property:

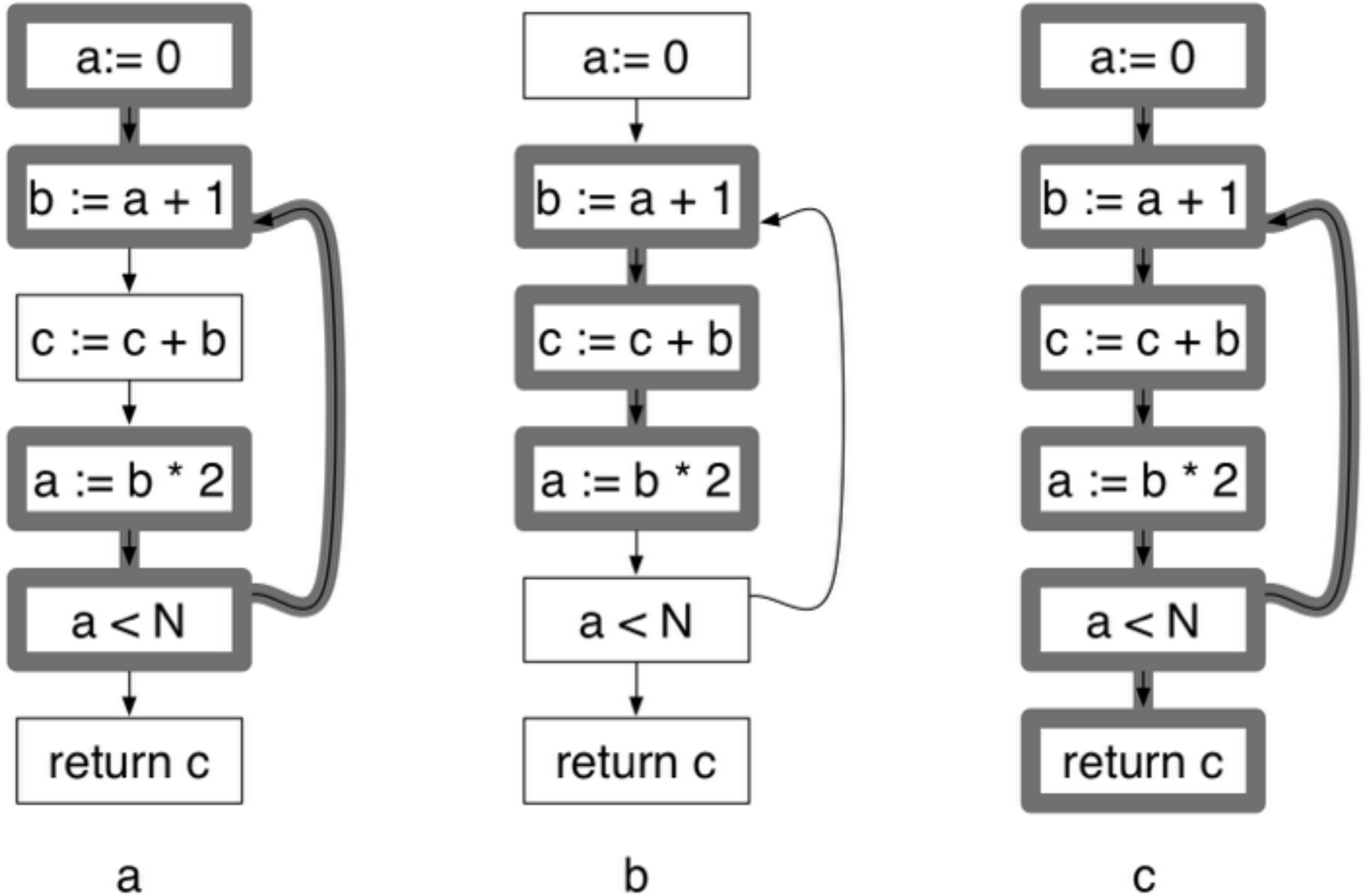
All variables of the same congruence class can be replaced by one representative variable without changing the semantics.

SSA without optimizations has Φ-congruence property

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

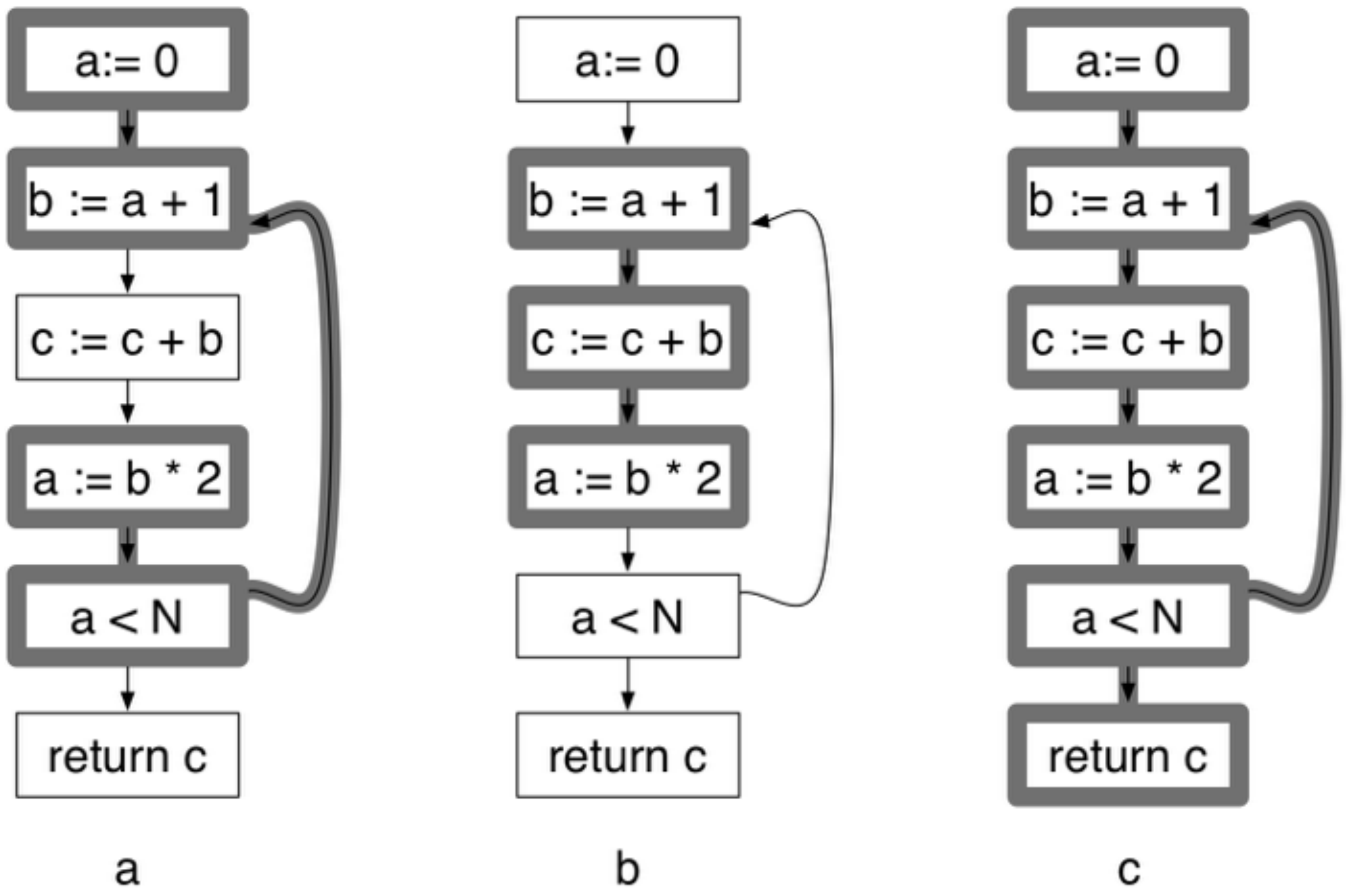
Liveness

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



a and b are never live on the same edges, so two registers suffice to hold a, b and c

Interference



a and c are 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

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!

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 Φ-function.
- ✎ When do we place Φ-functions
- ✎ How to remove Φ-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-address code and CFG for SSA?*