6. Intermediate Representation

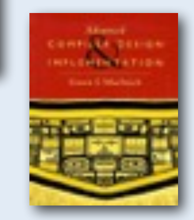
Oscar Nierstrasz

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.

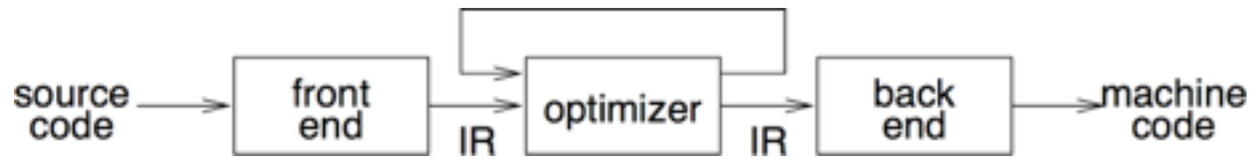
Roadmap

> **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

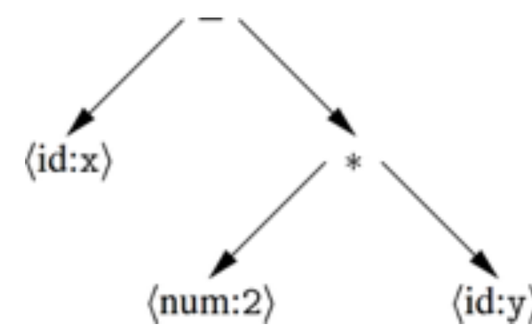
Subtle design decisions in the IR can have far-reaching effects on the speed and effectiveness of the compiler!

➔ *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!

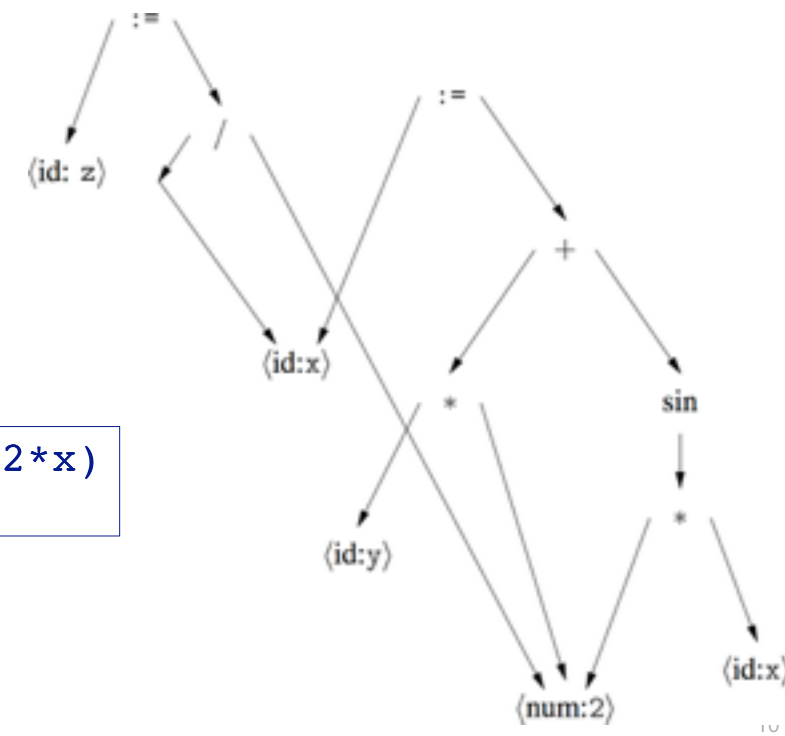


A linear operator form of this tree (postfix) would be:

```
x 2 y * -
```

Directed acyclic graph

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

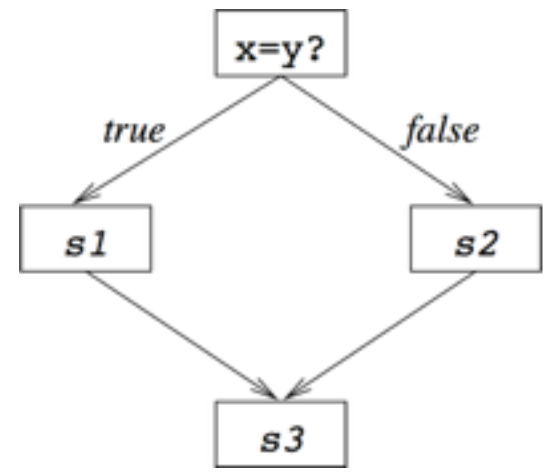



```
x := 2 * y + sin(2*x)
z := x / 2
```

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

Roadmap

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

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

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

SSA form makes clear that a2 is not the same as a1, so easier for analysis

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? …
```


is it a1 or is it a2?

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 …
```


is it a1 or is it a2?

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 …)

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if x = y then
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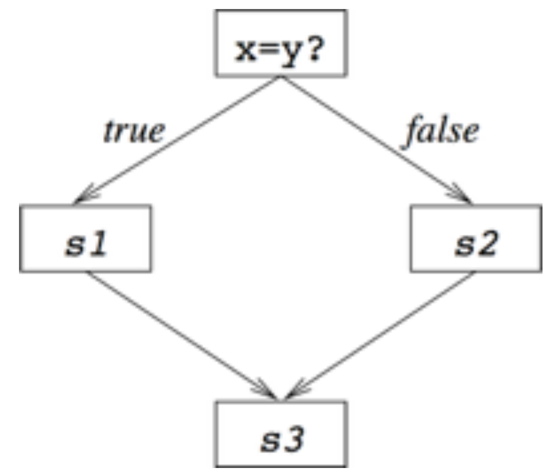
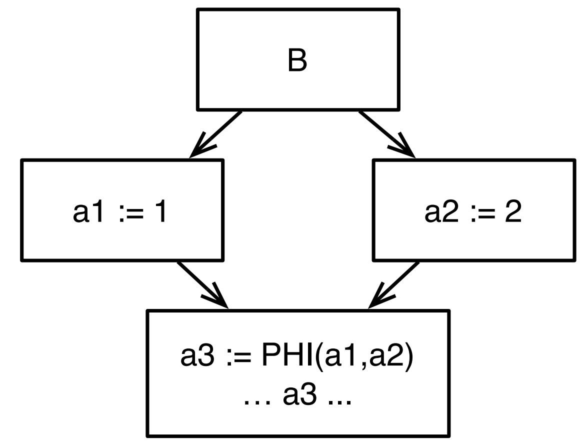
```



SSA: a Simple Example

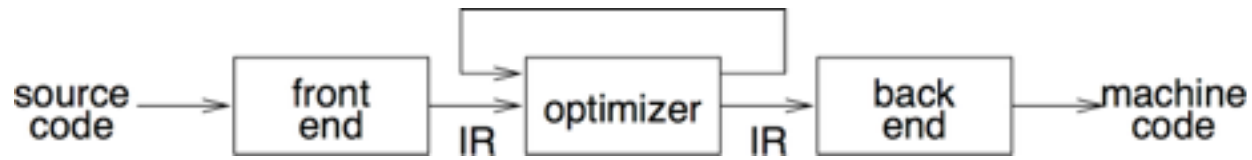
```
if B then
  a1 := 1
else
  a2 := 2
end
a3 := Φ(a1,a2)
  … a3 …
```



Roadmap

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

Recall: IR



- front end produces IR
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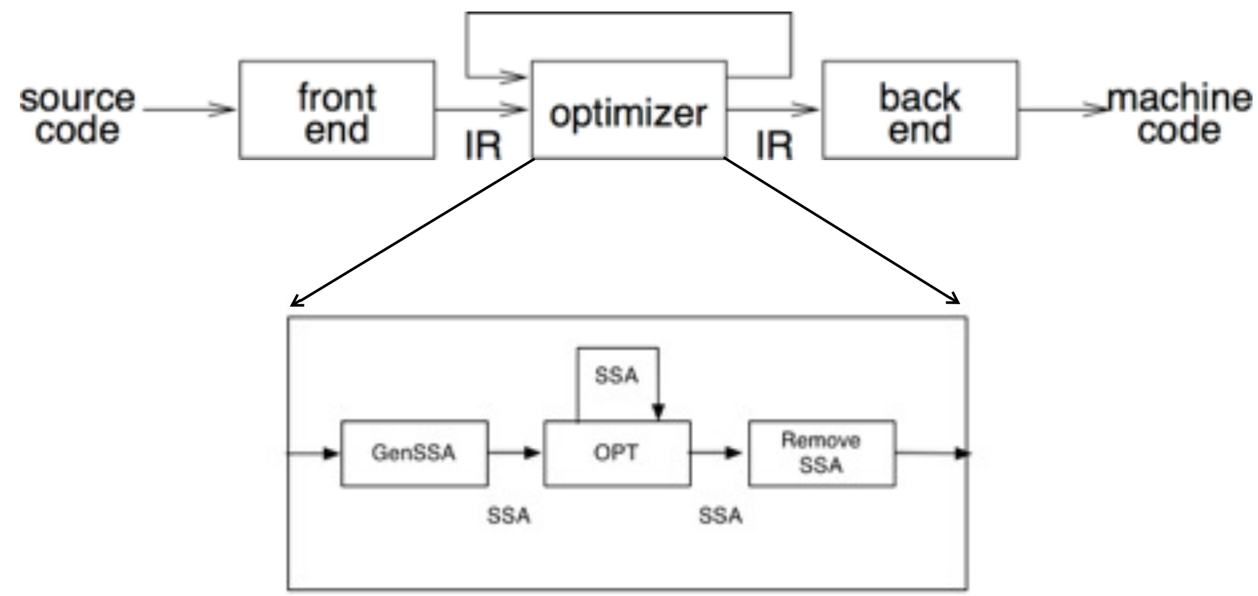
- back end transform IR to target code

SSA as IR



Current trend in compiler community is to use SSA as *the* IR for everything in back end.

(NB: for compilers that generate machine code, not those that generate bytecode.)

Transforming to SSA

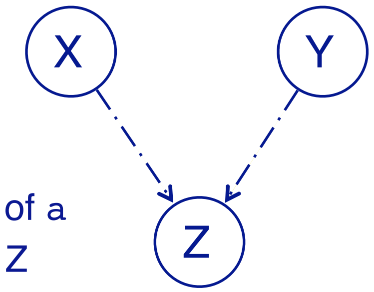
> ***Problem: Performance / Memory***
—Minimize number of inserted Φ-functions
—Do not spend too much time

> ***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*

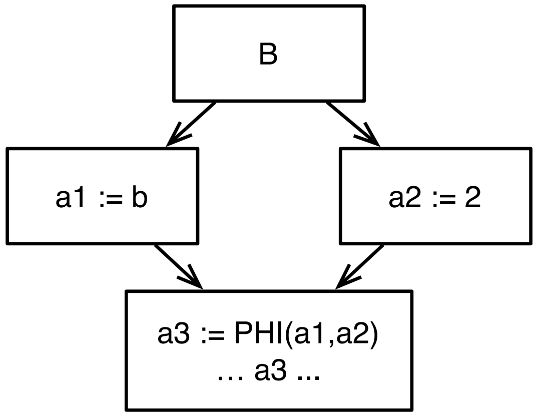
Iterated Path-Convergence

> 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 and SSA generation**
- > Applications of SSA
- > Φ-congruence and SSA removal

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 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"

NB: If x is used in a Φ-function in N, then there is another path to N, but not to its predecessors.

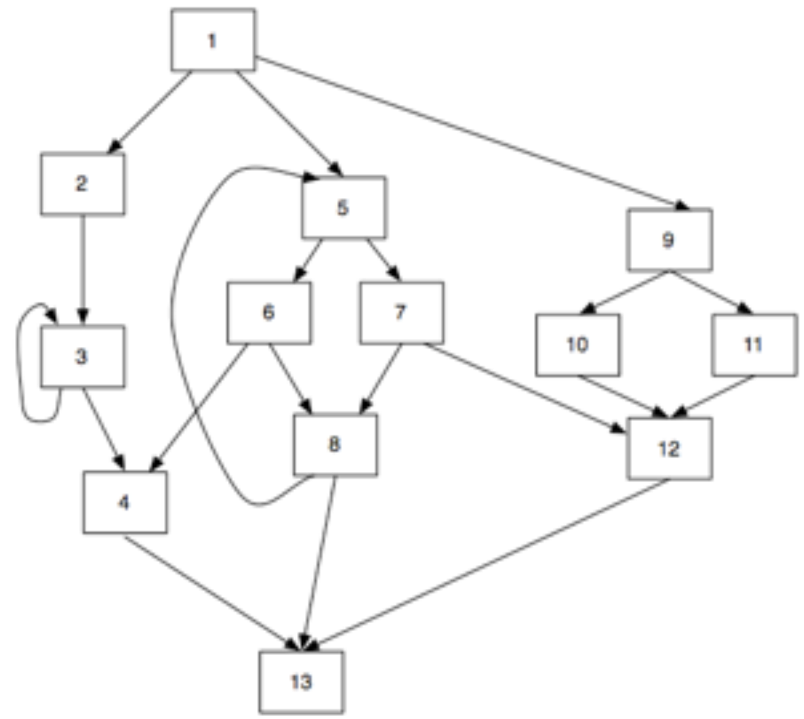
Dominance is a property of basic blocks. (one Node dominates a set of nodes).

For the dominance property, "definition of x" thus means the basic block in which x is defined.

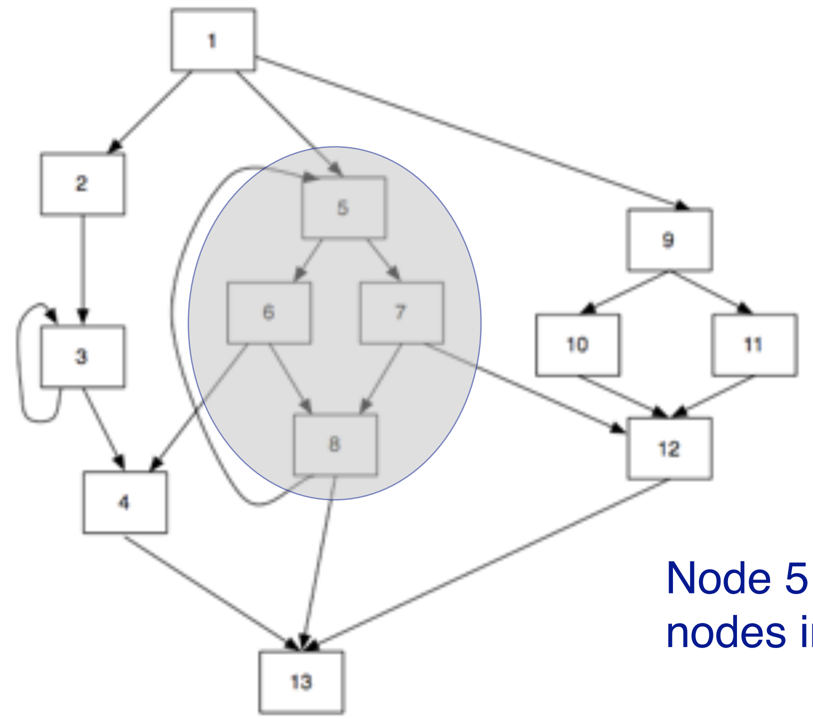
Dominance and SSA Creation

- 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



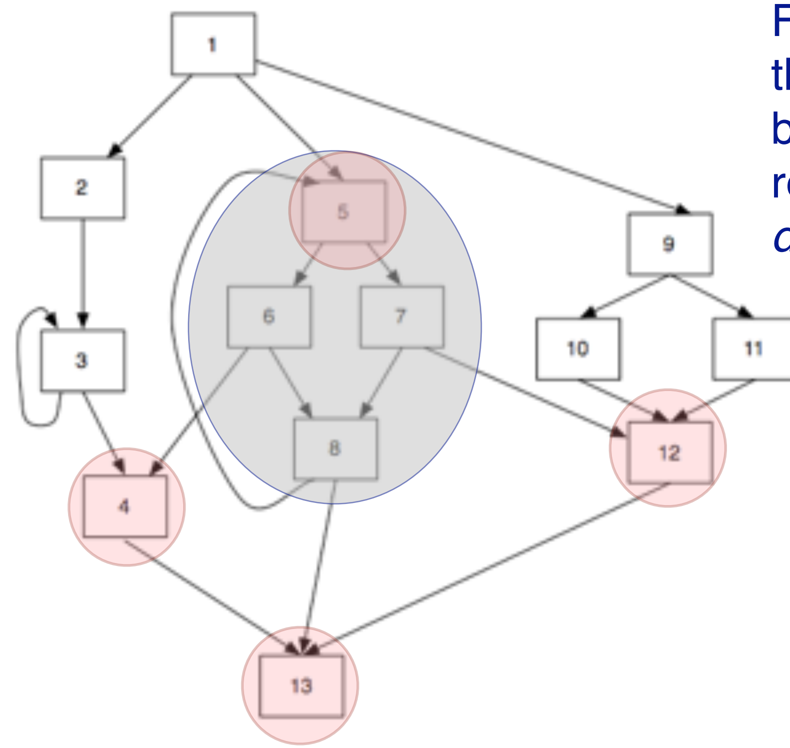
Dominance frontier



Node 5 dominates all nodes in the gray area

I.e., there is no path to any of these nodes except through node 5.

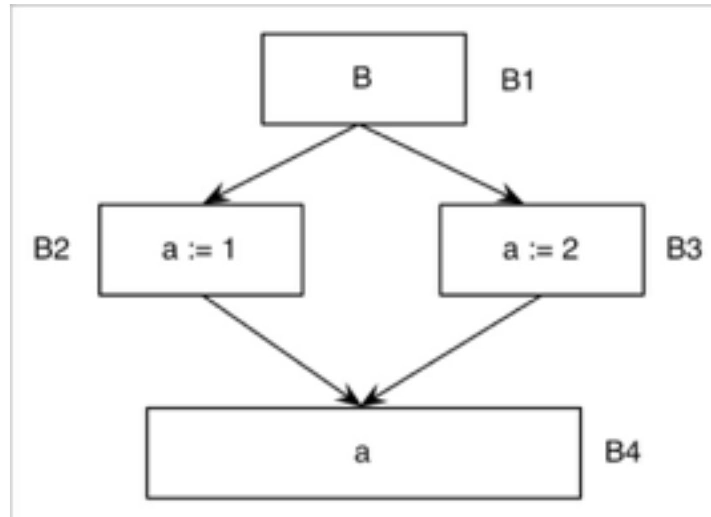
Dominance frontier



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

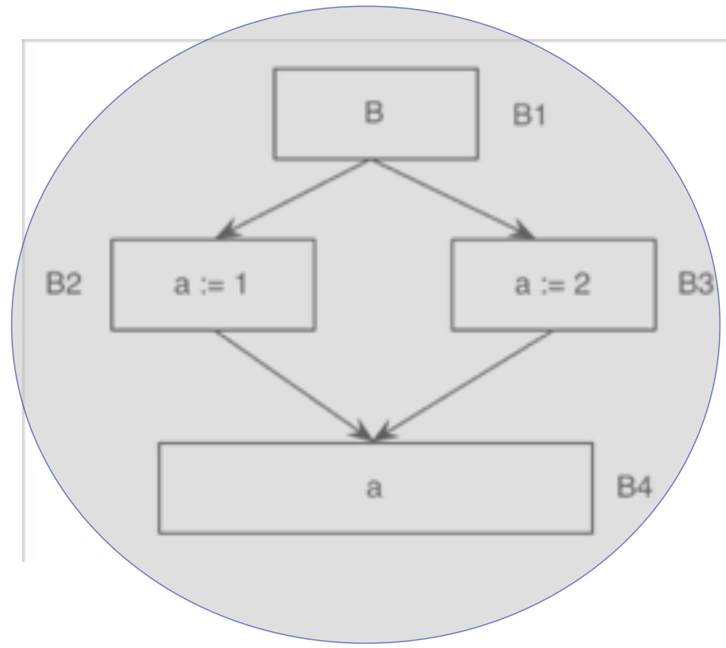
DF(5)= {4, 5, 12, 13}

Simple Example



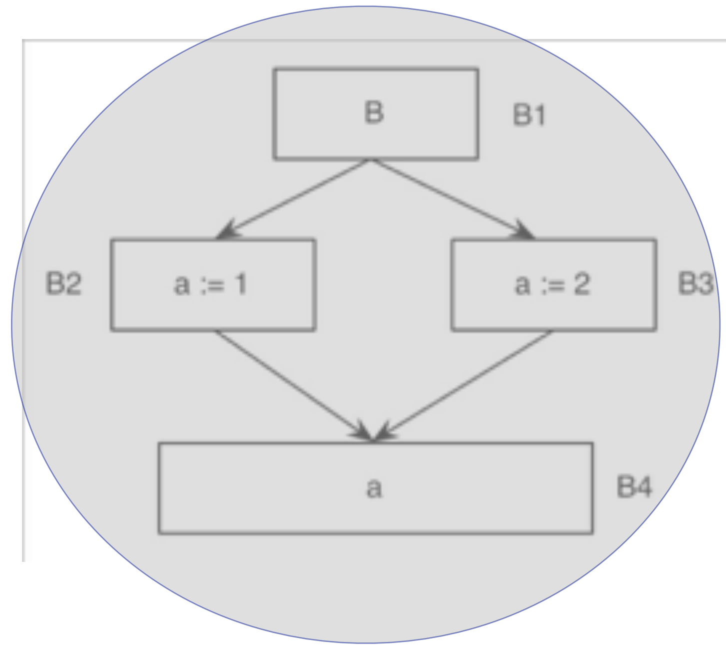
DF(B1)=
DF(B2)=
DF(B3)=
DF(B4)=

Simple Example



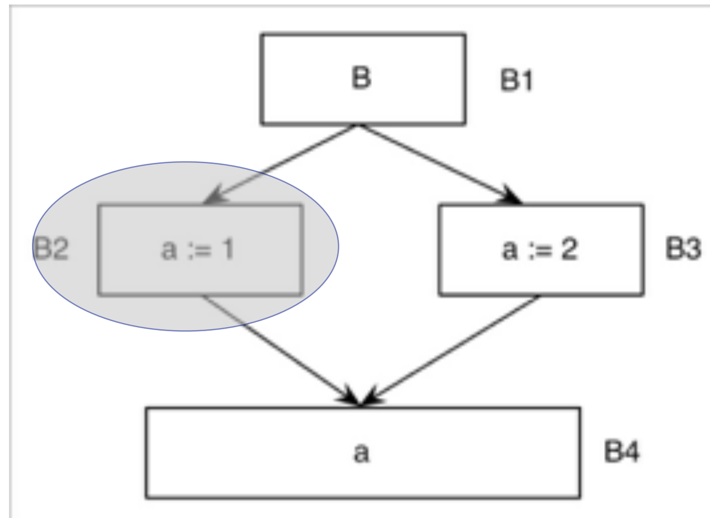
DF(B1)={?}
DF(B2)=
DF(B3)=
DF(B4)=

Simple Example



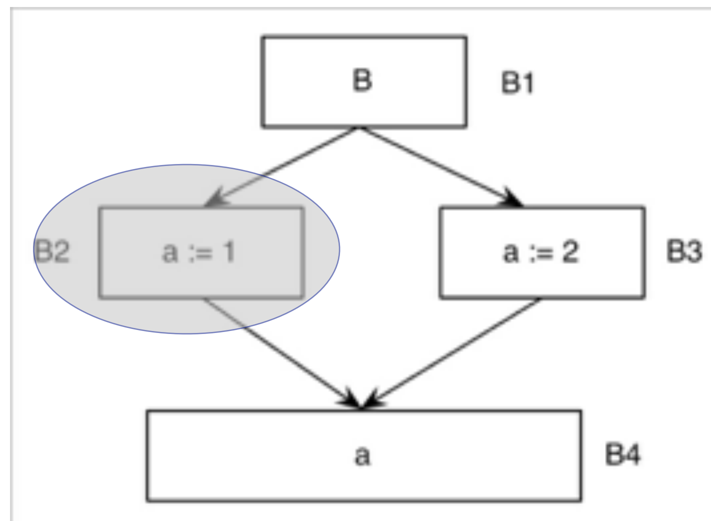
DF(B1)={}
DF(B2)=
DF(B3)=
DF(B4)=

Simple Example



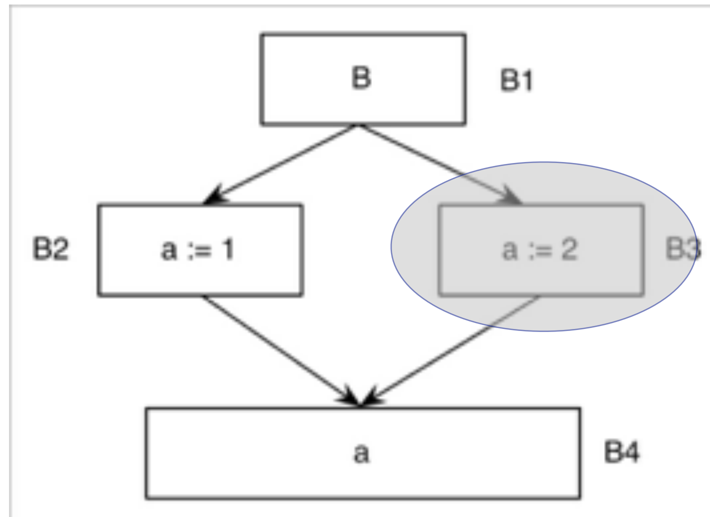
DF(B1)={}
DF(B2)={?}
DF(B3)=
DF(B4)=

Simple Example



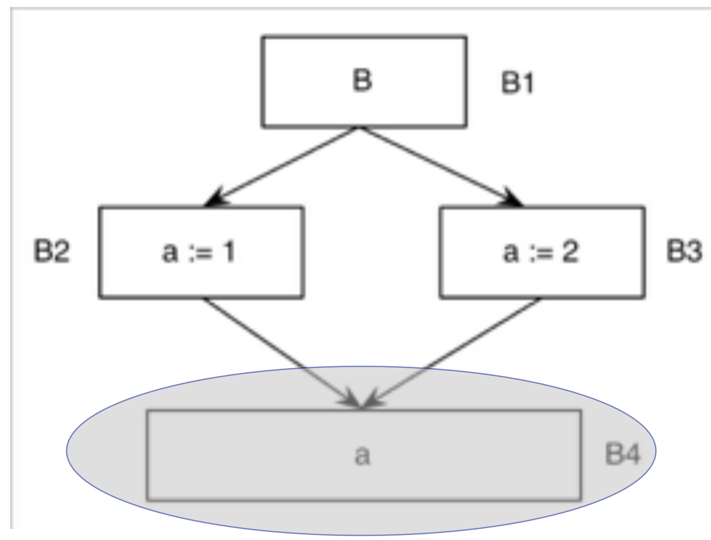
DF(B1)={}
DF(B2)={B4}
DF(B3)=
DF(B4)=

Simple Example



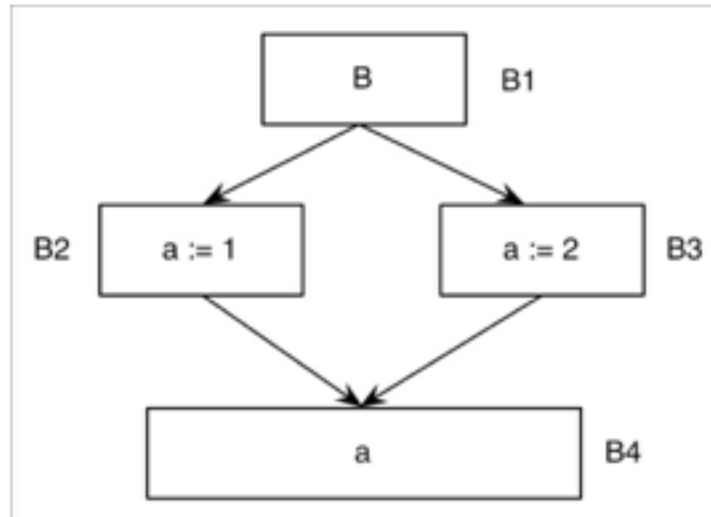
DF(B1)={}
DF(B2)={B4}
DF(B3)={B4}
DF(B4)=

Simple Example



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

Simple Example



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

Φ-Function needed in B4 (for a)

Roadmap

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

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!

Constant propagation: substitute constants and evaluate constant expressions
Value numbering: number values & expressions to eliminate redundant computation
Invariant code motion and removal: move invariant code out of loops
Strength reduction: replace expensive operations by equivalent, cheaper ones (eg multiplication by addition)
Partial redundancy elimination: move common subexpressions to eliminate recomputation

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…*

Roadmap

- > Intermediate representations
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- > Applications of SSA
- > **Φ-congruence and SSA removal**

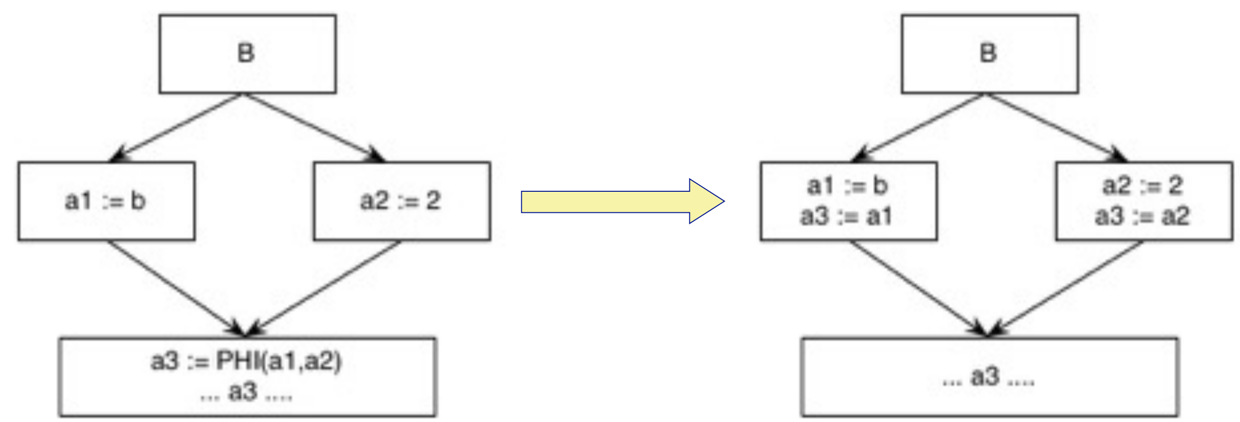
Vugranam C. Sreedhar, et al, *“Translating Out of Static Single Assignment Form”*, LNCS 1694, 1999, doi:10.1007/3-540-48294-6_13

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 …

Here we simply push the assignments to a3 up to each branch.

Sreedhar shows that the naive approach can be wrong if variables “interfere”.

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*

x and y are connected if they are used or defined in the same Φ instruction

Φ-Congruence Property

Φ-congruence property:

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

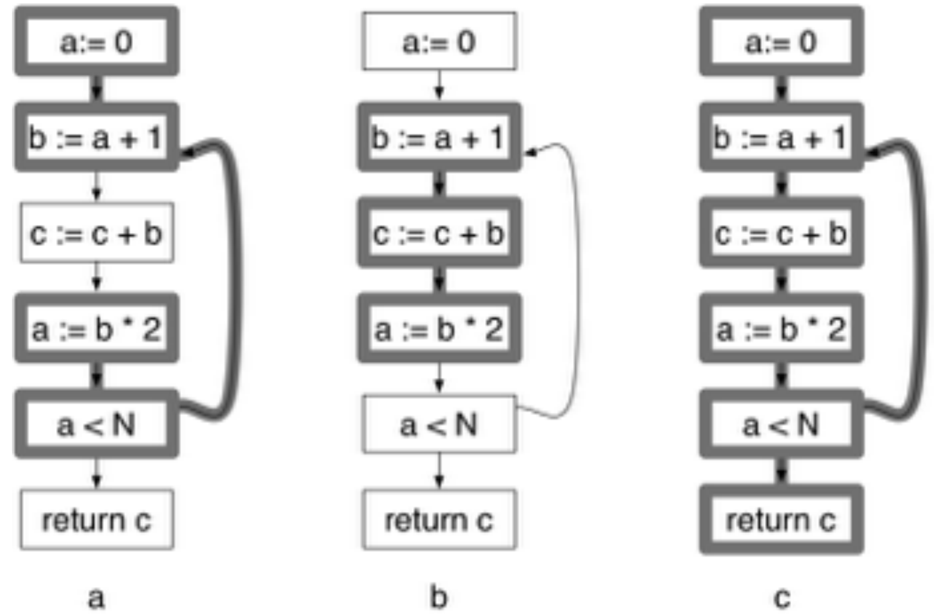
SSA without optimizations has Φ-congruence property

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

The property obviously holds before optimization, since all Φ-connected variables started out as the same variable.

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*

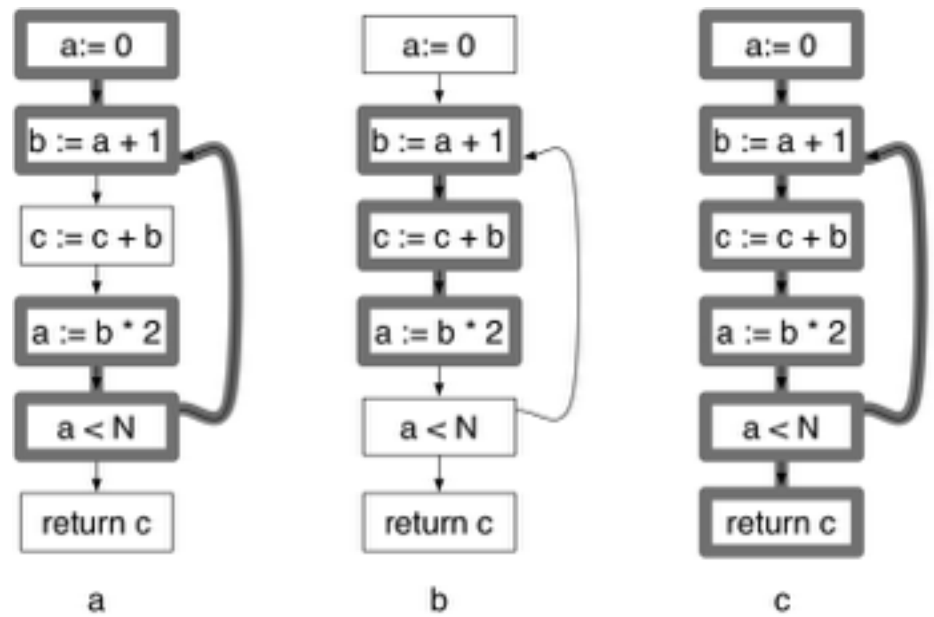


a and b are never live on the same edges, so two registers suffice to hold a, b and c

I.e., follow paths from assignments to last use before a new assignment.

NB: c is implicitly assigned when it is defined, so is live from the start to its first use.

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

CSSA = Conventional SSA
TSSA = Transformed SSA

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!

So, don't remove Φ functions before register allocation! Keep them till end.

(Many reasons to keep SSA as IR for various phases in the back end.)

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?*