

CS443: Compiler Construction

Lecture 16: Static Single Assignment

Stefan Muller

Based on material by Steve Zdancewic

Static Single Assignment: Local variables assigned only once

- Every variable name associated with one static value
 - Like FP with no shadowing!
- Great for optimizations!

For straight-line code, just number different instances of variables

```
int x = 3;  
int y = 0;  
x = x + 1;  
y = x + 2;
```

```
int x1 = 3;  
int y1 = 0;  
x2 = x1 + 1;  
y2 = x2 + 2;
```

```
%x1 = add i64 3, 0  
%y1 = add i64 0, 0  
%x2 = add i64 %x1, 1  
%y2 = add i64 %x2, 2
```

Need to keep track of
what “version” of each var
we’re accessing

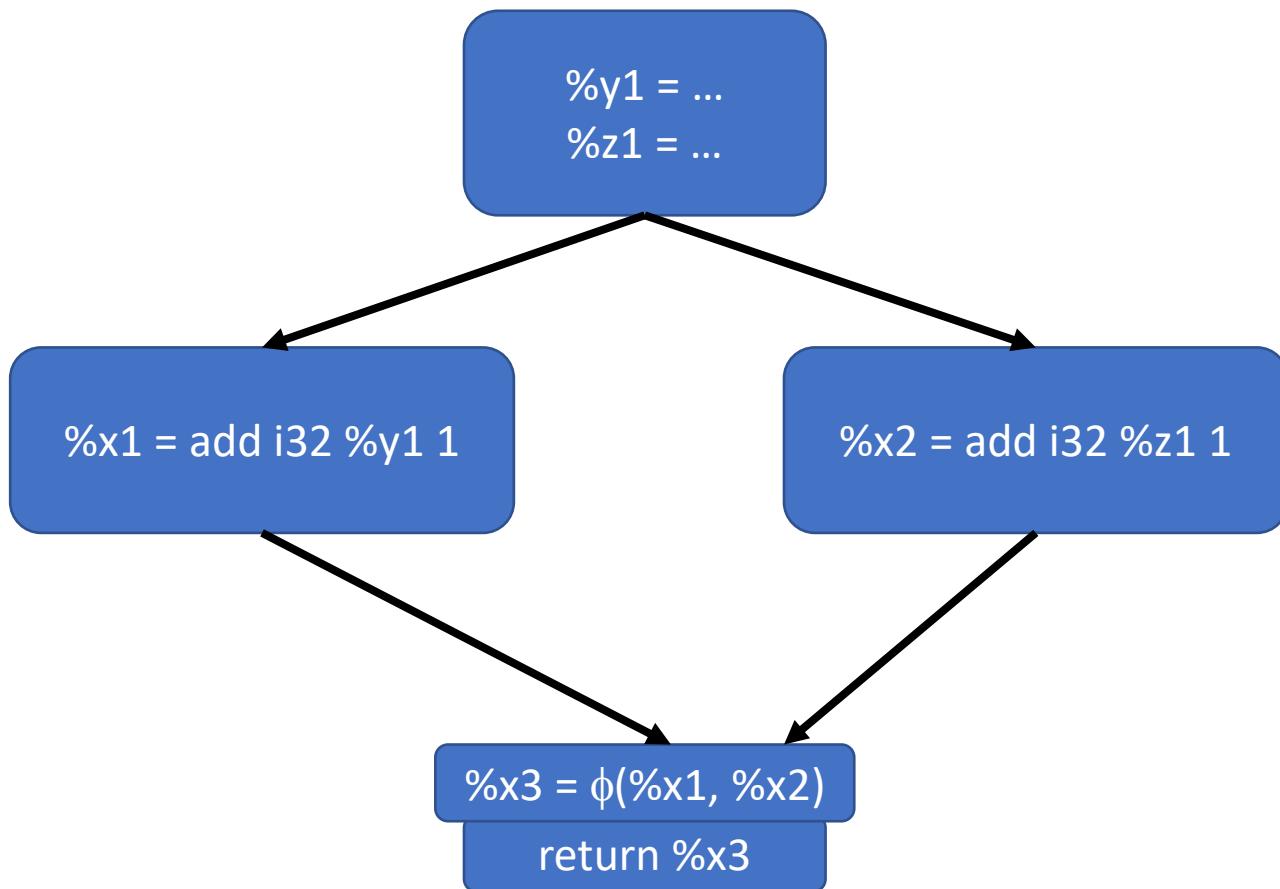
Branching causes a problem

```
int y = ...
int x = ...
int z = ...
if (p) {
    x = y + 1;
} else {
    x = y * 2;
}
z = x + 3;
```



```
entry:
    %y1 = ...
    %x1 = ...
    %z1 = ...
    %p = icmp ...
    br i1 %p, label %then, label %else
then:
    %x2 = add i64 %y1, 1
    br label %merge
else:
    %x3 = mul i64 %y1, 2
    br label %merge
merge:
    %z2 = %add i64 ???, 3
```

Phi (ϕ) functions “choose” which version of a variable based on where we came from



Phi in LLVM

```
%dest = phi <ty> [<val>, <label>]+
```

```
int y = ...
int x = ...
int z = ...
if (p) {
    x = y + 1;
} else {
    x = y * 2;
}
z = x + 3;
```



```
%y1 = ...
%x1 = ...
%z1 = ...
%p = icmp ...
br i1 %p, label %then, label %else
then:
    %x2 = add i64 %y1, 1
    br label %merge
else:
    %x3 = mul i64 %y1, 2
    br label %merge
merge:
    %x4 = phi i64 [%x2, %then], [%x3, %else]
    %z2 = %add i64 %x4, 3
```

Converting to inefficient SSA is pretty simple in theory

- Rerun all definitions of each variable
 - Update uses of variables with correct number
 - Insert phi nodes at join points
-
- This inserts way more phi functions than you need. The algorithm for doing better is complex and based on dominators

Phi functions are fictitious

- Q: How do we implement phi?
- A: Usually don't
 - If we're lucky/smart, %x2, %x3, and %x4 will all be in same reg anyway
 - Can also convert out of SSA before compiling to assembly
 - If all else fails, can implement it as a `mov` instruction before the jump

“If all else fails, can implement it as a mov instruction before the jump”

then:

```
%x2 = add i64 %y1, 1
```

```
br label %merge
```

else:

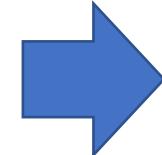
```
%x3 = mul i64 %y1, 2
```

```
br label %merge
```

merge:

```
%x4 = phi i64 [%x2, then], [%x3, %else]
```

```
%z2 = %add i64 %x4, 3
```



then:

```
addi a2, a1, 1
```

```
mv a4, a2
```

```
jal zero, merge
```

else:

```
addi t0, zero, 2
```

```
mul a3, a1, t0
```

```
mv a4, a3
```

merge:

```
addi a5, a4, 3
```

“If we’re lucky/smart, %x2, %x3, and %x4 will all be in same reg anyway”

then:

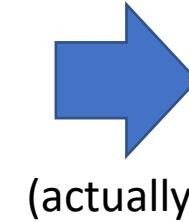
```
%x2 = add i64 %y1, 1  
br label %merge
```

else:

```
%x3 = mul i64 %y1, 2  
br label %merge
```

merge:

```
%x4 = phi i64 [%x2, then], [%x3, else]  
%z2 = %add i64 %x4, 3
```



then:

```
addi a2, a1, 1  
jal zero, merge
```

else:

```
addi t0, zero, 2  
mul a2, a1, t0
```

merge:

```
addi a5, a2, 3
```

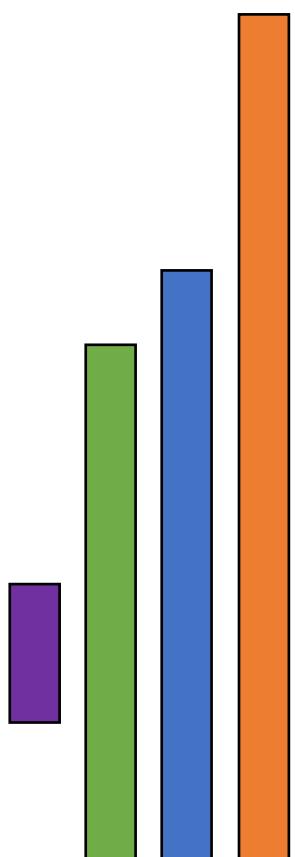
“Arguments” to phi functions may be defined “later”

```
int x = 0;  
while (x < 10)  
    x++;
```



```
entry:  
    %x1 = add i32 0 0  
    br label %test  
  
test:  
    %x2 = phi i32 [%x1, %entry], [%x3, body]  
    %p = icmp lt i32 %x2 10  
    br i1 %p, label %body, label %end  
  
body:  
    %x3 = add i32 %x2 1  
    br label %test  
  
end: ...
```

Aside: How is scope handled in LLVM?



```
entry:
  %x1 = add i32 0 0
  br label %test

test:
  %x2 = phi i32 [%x1, %entry], [%x3, body]
  %p = icmp lt i32 %x2 10
  br i1 %p, label %body, label %end

body:
  %x3 = add i32 %x2 1
  br label %test

end: ...
```

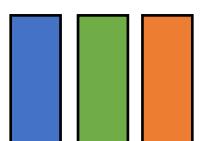
What if I show it this way?

```
entry:  
    %x1 = add i32 0 0  
    br label %test
```

```
test:  
    %x2 = phi i32 [%x1, %entry], [%x3, body]  
    %p = icmp lt i32 %x2 10  
    br i1 %p, label %body, label %end
```

```
body:  
    %x3 = add i32 %x2 1  
    br label %test
```

```
end: ...
```



Scope is based on *dominance*

entry:

```
%x1 = add i32 0 0  
br label %test
```

“Definition must dominate all uses”

test:

```
%x2 = phi i32 [%x1, %entry], [%x3, body]  
%p = icmp lt i32 %x2 10  
br i1 %p, label %body, label %end
```

body:

```
%x3 = add i32 %x2 1  
br label %test
```

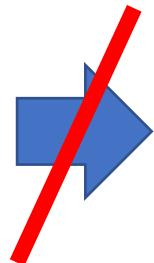
end: ...



x2, body in scope at end
CS 443 - Fall 2024 - Lecture 16

Aside #2: Why does LLVM not have a move instruction?

```
int sqrt(int n) {  
    int i = n;  
    while (i * i > n)  
        i--;  
    return i;  
}
```

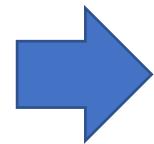


```
define @sqrt(i32 %n) {  
    %i1 = mov i32 %n  
    br label %test  
  
test:  
    %i2 = phi i32 [%i1, %entry], [%i3, %body]  
    %sq = mul i32 %i2 %i2  
    %p = icmp i32 gt %sq %n  
    br i1 %p, label %body, label %end  
  
body:  
    %i3 = sub i32 %i2 1  
    br label %test  
  
end:  
    ret i32 %i2
```

*Declares %i1 to be %n.
What's the point?*

Aside #2: Why does LLVM not have a move instruction?

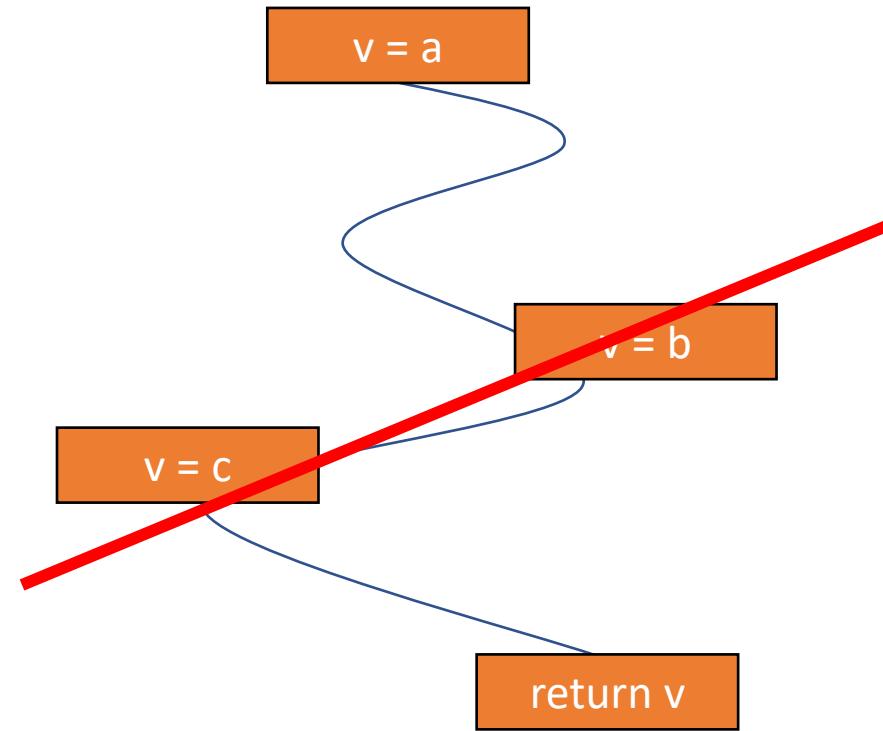
```
int sqrt(int n) {  
    int i = n;  
    while (i * i > n)  
        i--;  
    return i;  
}
```



(Related to copy propagation optimization—next class)

```
define @sqrt(i32 %n) {  
    br label %test  
test:  
    %i2 = phi i32 [%n, %entry], [%i3, %body]  
    %sq = mul i32 %i2 %i2  
    %p = icmp i32 gt %sq %n  
    br i1 %p, label %body, label %end  
body:  
    %i3 = sub i32 %i2 1  
    br label %test  
end:  
    ret i32 %i2
```

Liveness, revisited: just propagate back from uses to (the only) def



Liveness no longer needs iterative dataflow!

- Appel, LLVM compiler: propagate from uses of each var back to def
- This paper: like a dataflow analysis, but just 2 passes!

Computing Liveness Sets for SSA-Form Programs

Florian Brandner*, Benoit Boissinot*, Alain Darte*,
Benoît Dupont de Dinechin†, Fabrice Rastello*

Domaine : Algorithmique, programmation, logiciels et architectures
Équipe-Projet COMPSYS

* Compsys, LIP, UMR 5668 CNRS, INRIA, ENS-Lyon, UCB-Lyon

† Kalray

d'ensembles comme dans l'analyse de flot de données standard. Une telle stratégie d'exploration des chemins a été proposée par Appel dans son “Tiger book” et est également utilisée dans le compilateur LLVM. Notre seconde contribu-

Reaching definitions is essentially irrelevant!

- Is $\%x4$ in scope? Then the (one) definition of $\%x4$ reaches here
- (Not surprising, as you can think of converting to SSA as based on reaching definitions)