CSE211: Compiler Design

Oct. 27, 2021

- **Topic**: Optimizations using SSA

```
3:                                                    ; preds = %1
  %4 = tail call i32 @_Z14first_functionv(), !dbg !19
  call void @llvm.dbg.value(metadata i32 %4, metadata !14, metadata
  br label %7, !dbg !21

5:                                                    ; preds = %1
  %6 = tail call i32 @_Z15second_functionv(), !dbg !22
  call void @llvm.dbg.value(metadata i32 %6, metadata !14, metadata
  br label %7

7:                                                    ; preds = %5, %3
  %8 = phi i32 [ %4, %3 ], [ %6, %5 ], !dbg !24
  call void @llvm.dbg.value(metadata i32 %8, metadata !14, metadata
  ret i32 %8, !dbg !25
}
```

Announcements

- Homework 2:
  - Due Nov. 1
  - Great questions on slack!
  - Office hours tomorrow (sign up sheet)

- Midterm assigned after class!
  - 1 week to do the midterm
  - Do not ask questions on slack, instead message me directly! I will create a canvas discussion with FAQs. Only I can post!
  - Do not discuss with classmates until after the due date
  - Plan on about 2.5 hours (not including studying!)
    - Students have reported anywhere from 2 to 7 hours

CSE211: Compiler Design

Oct. 27, 2021

- **Topic**: Optimizations using SSA

```
3:                                                  ; preds = %1
  %4 = tail call i32 @_Z14first_functionv(), !dbg !19
  call void @llvm.dbg.value(metadata i32 %4, metadata !14, metadata
  br label %7, !dbg !21

5:                                                  ; preds = %1
  %6 = tail call i32 @_Z15second_functionv(), !dbg !22
  call void @llvm.dbg.value(metadata i32 %6, metadata !14, metadata
  br label %7

7:                                                  ; preds = %5, %3
  %8 = phi i32 [ %4, %3 ], [ %6, %5 ], !dbg !24
  call void @llvm.dbg.value(metadata i32 %8, metadata !14, metadata
  ret i32 %8, !dbg !25
}
```

Review: SSA

Static Single-Assignment Form (SSA)

- Every variable is defined and written to *once*
  - We have seen this in local value numbering!

- Control flow is captured using ϕ instructions

ϕ instructions

- Example: how to convert this code into SSA?

```
int x;

if (<some_condition>) {
  x = 5;
}

else {
  x = 7;
}

print(x)
```

ϕ instructions

- Example: how to convert this code into SSA?

```
int x;

if (<some_condition>) {
  x = 5;
}

else {
  x = 7;
}

print(x)
```

Start with numbering

ϕ instructions

- Example: how to convert this code into SSA?

```
int x;

if (<some_condition>) {
  x0 = 5;
}

else {
  x1 = 7;
}

print(x)
```

Start with numbering

ϕ instructions

- Example: how to convert this code into SSA?

```
int x;

if (<some_condition>) {
  x0 = 5;
}

else {
  x1 = 7;
}

print(x)
```

Start with numbering

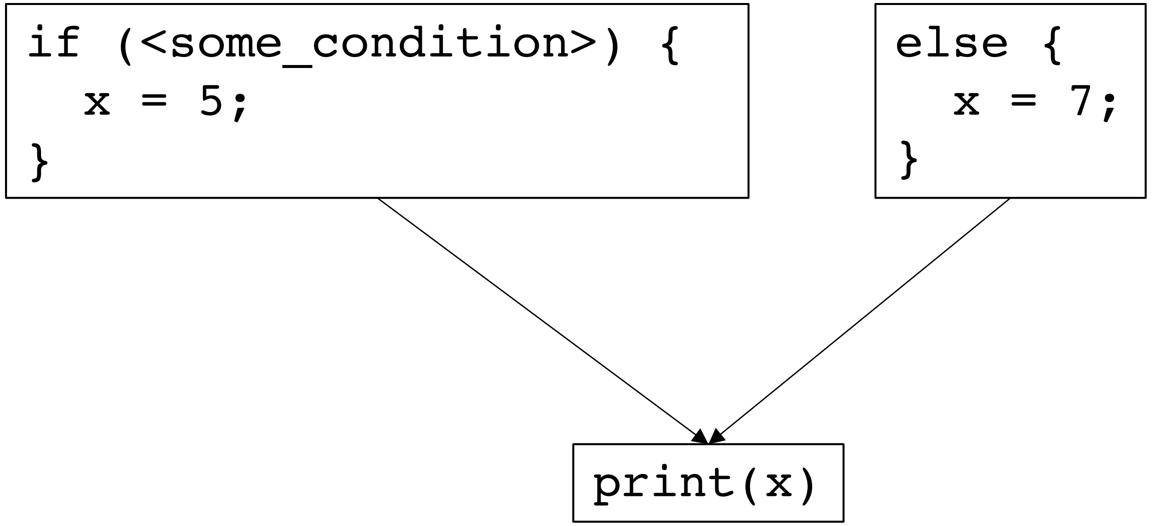
What here?

ϕ instructions

- Example: how to convert this code into SSA?

```
int x;

if (<some_condition>) {
  x = 5;
}

else {
  x = 7;
}

print(x)
```

let’s make a CFG

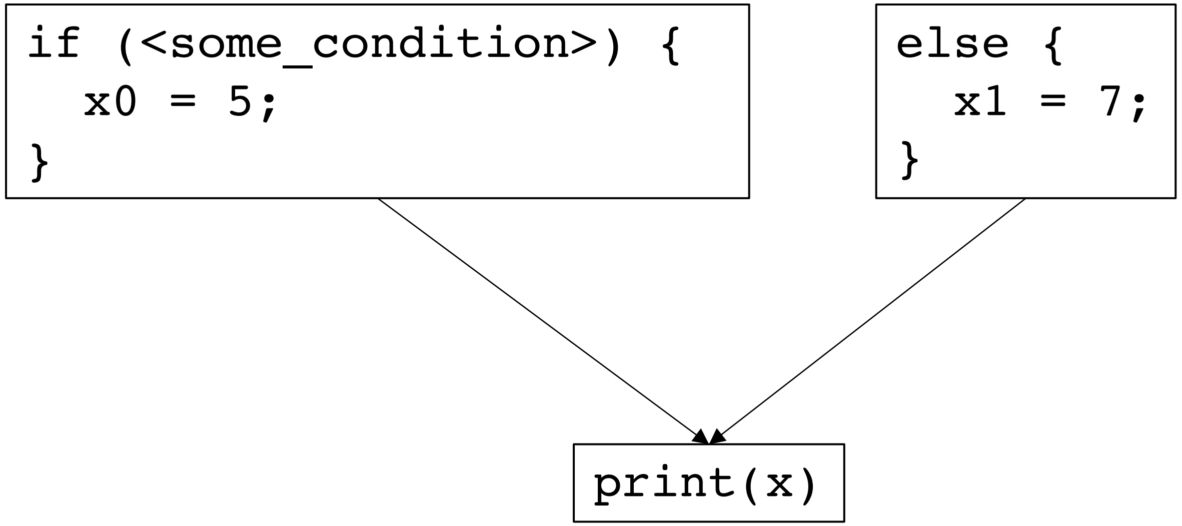


ϕ instructions

- Example: how to convert this code into SSA?

```
int x;

if (<some_condition>) {
  x0 = 5;
}

else {
  x1 = 7;
}

print(x)
```

number the variables



ϕ instructions

- Example: how to convert this code into SSA?

```
int x;

if (<some_condition>) {
  x0 = 5;
}

else {
  x1 = 7;
}

x2 = φ(x0, x1);
print(x2)
```

number the variables

```
if (<some_condition>) {
  x0 = 5;
}
```

```
else {
  x1 = 7;
}
```

selects the value for x depending on which CFG path was taken

```
x2 = φ(x0, x1,x3);
x3 = x2 + 1;
print(x2)
```

How to insert ϕ instructions

- 2 phases:
  - inserting phi instructions
  - numbering

Maximal SSA

Example

```
x = 1;
y = 2;

if (<condition>) {
  x = y;
}

else {
  x = 6;
  y = 100;
}

print(x)
```

Insert ϕ with argument placeholders

```
x = 1;
y = 2;

if (<condition>) {
  x = ϕ(...);
  y = ϕ(...);
  x = y;
}

else {
  x = ϕ(...);
  y = ϕ(...);
  x = 6;
  y = 100;
}

x = ϕ(...);
y = ϕ(...);
print(x)
```

Rename variables iterate through basic blocks with a global counter

```
x0 = 1;
y1 = 2;

if (<condition>) {
  x3 = ϕ(...);
  y4 = ϕ(...);
  x5 = y4;
}

else {
  x6 = ϕ(...);
  y7 = ϕ(...);
  x8 = 6;
  y9 = 100;
}

x10 = ϕ(...);
y11 = ϕ(...);
print(x10)
```

fill in ϕ arguments by considering CFG

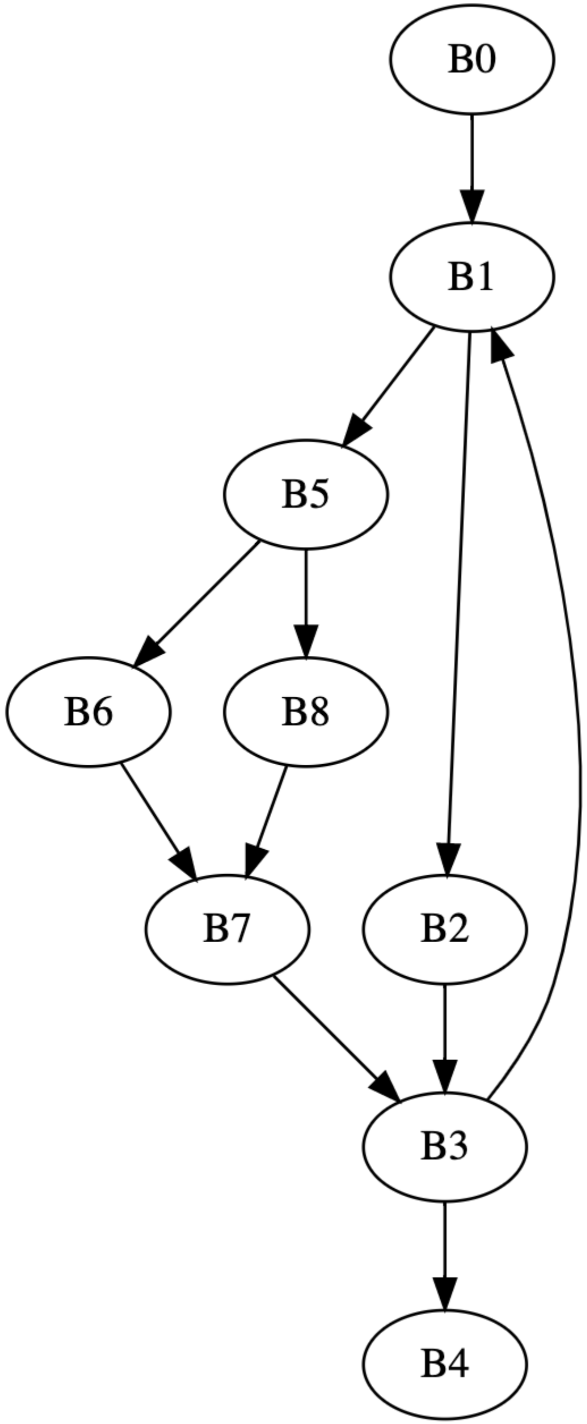
```
x0 = 1;
y1 = 2;

if (<condition>) {
  x3 = ϕ(x0);
  y4 = ϕ(y1);
  x5 = y4;
}

else {
  x6 = ϕ(x0);
  y7 = ϕ(y1);
  x8 = 6;
  y9 = 100;
}

x10 = ϕ(x5,x8);
y11 = ϕ(y4,y9);
print(x10)
```

Dominance frontier

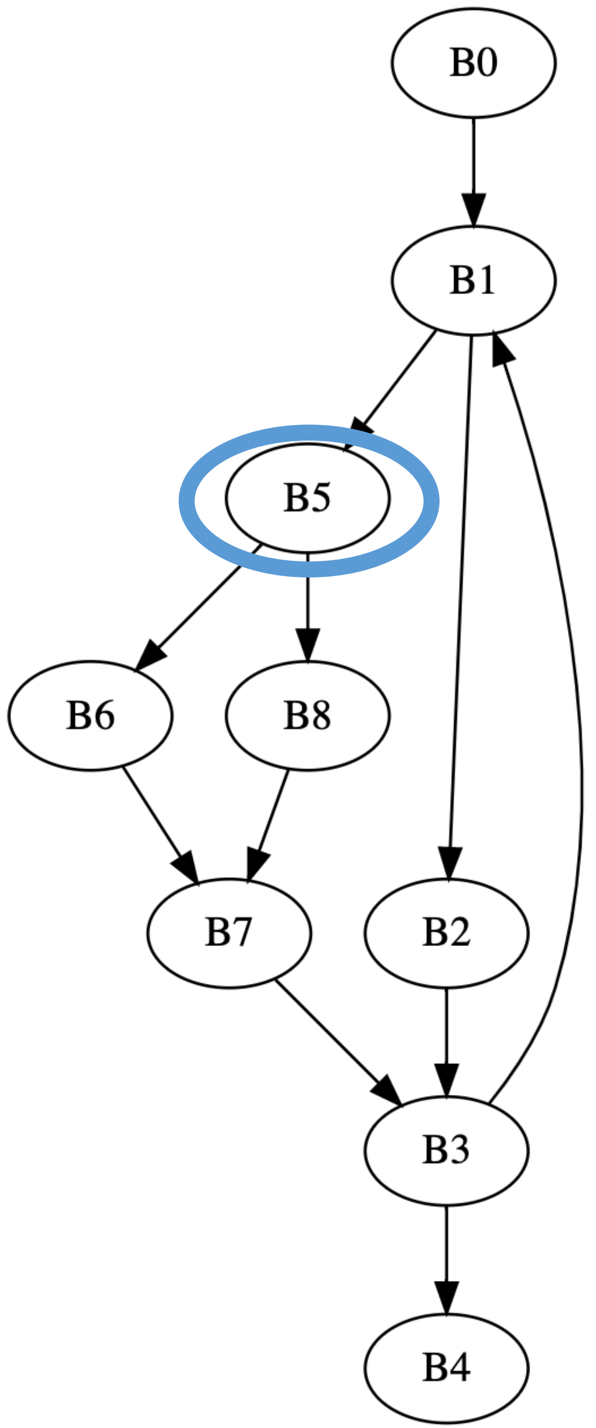
- a viz using coloring (thanks to Chris Liu!)
- Efficient algorithm for computing in EAC section 9.3.2 using a dominator tree. Please read when you get the chance!

Note that we are using strict dominance: nodes don't dominate themselves!

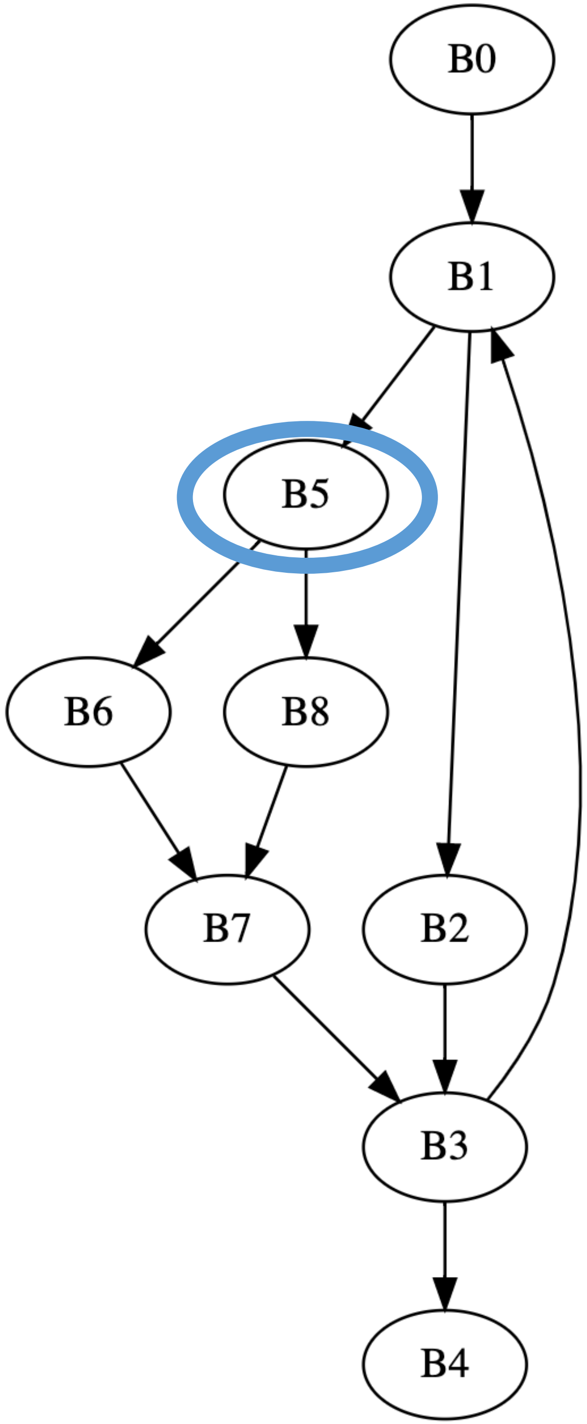
Node	Dominators
B0	
B1	B0,
B2	B0, B1,
B3	B0, B1,
B4	B0, B1, B3,
B5	B0, B1,
B6	B0, B1, B5,
B7	B0, B1, B5,
B8	B0, B1, B5,



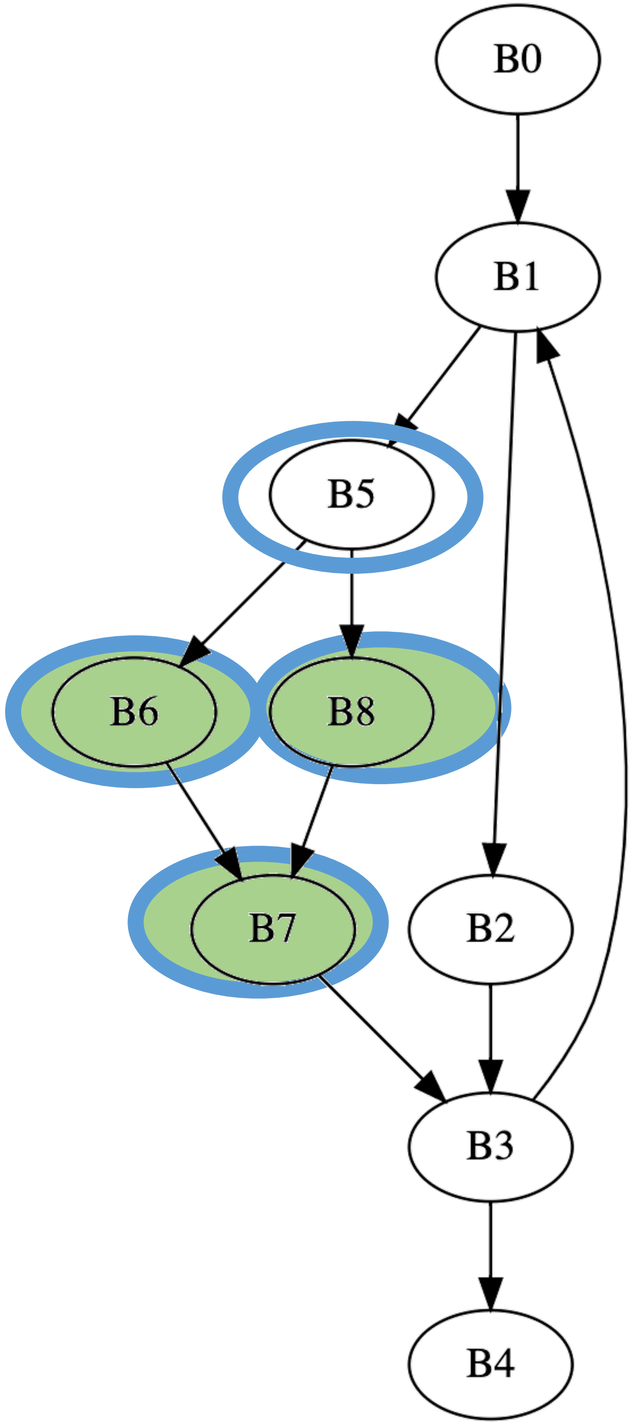
Node	Dominators
B0	
B1	B0,
B2	B0, B1,
B3	B0, B1,
B4	B0, B1, B3,
B5	B0, B1,
B6	B0, B1, B5,
B7	B0, B1, B5,
B8	B0, B1, B5,



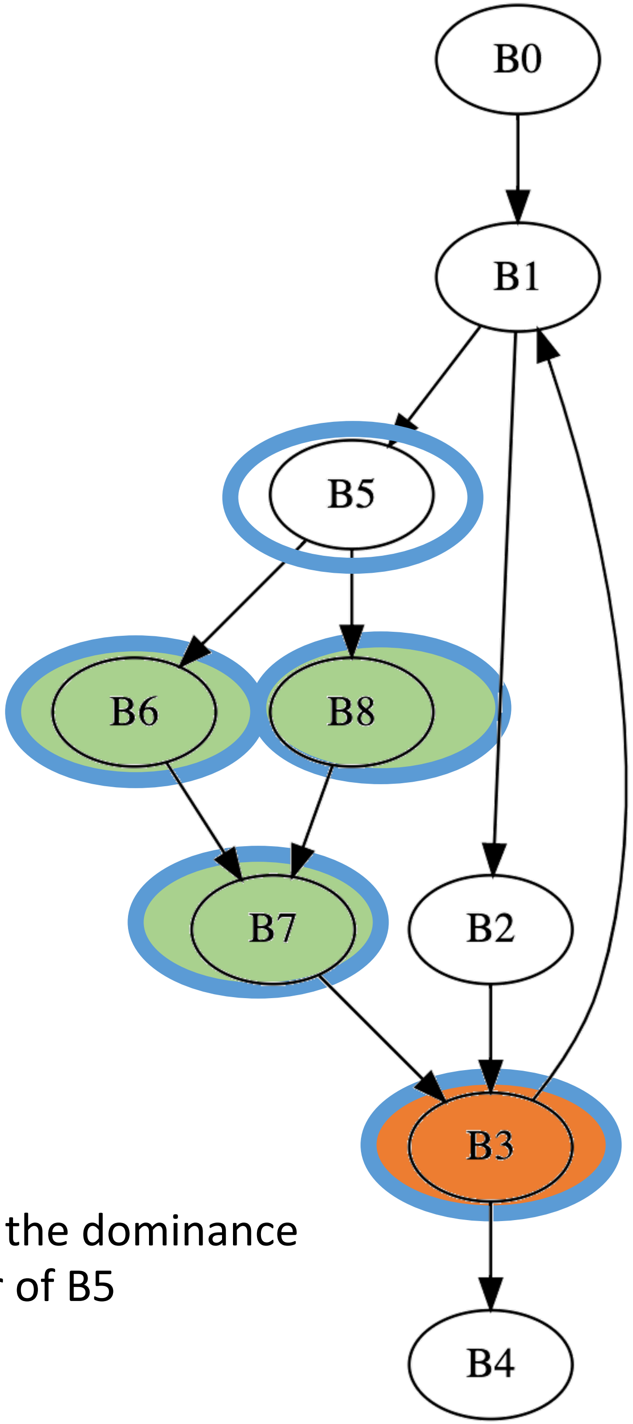
Node	Dominators
B0	
B1	B0,
B2	B0, B1,
B3	B0, B1,
B4	B0, B1, B3,
B5	B0, B1,
B6	B0, B1, B5,
B7	B0, B1, B5,
B8	B0, B1, B5,



Node	Dominators
B0	
B1	B0,
B2	B0, B1,
B3	B0, B1,
B4	B0, B1, B3,
B5	B0, B1,
B6	B0, B1, B5,
B7	B0, B1, B5,
B8	B0, B1, B5,

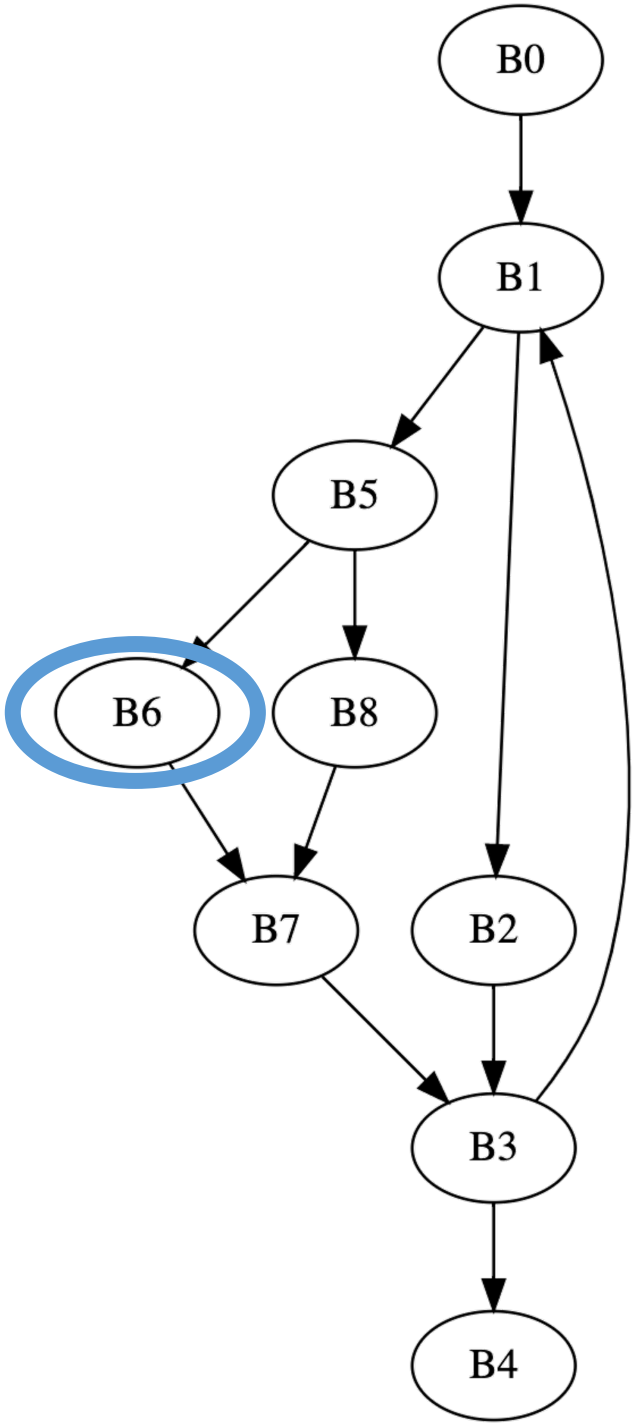


Node	Dominators
B0	
B1	B0,
B2	B0, B1,
B3	B0, B1,
B4	B0, B1, B3,
B5	B0, B1,
B6	B0, B1, B5,
B7	B0, B1, B5,
B8	B0, B1, B5,

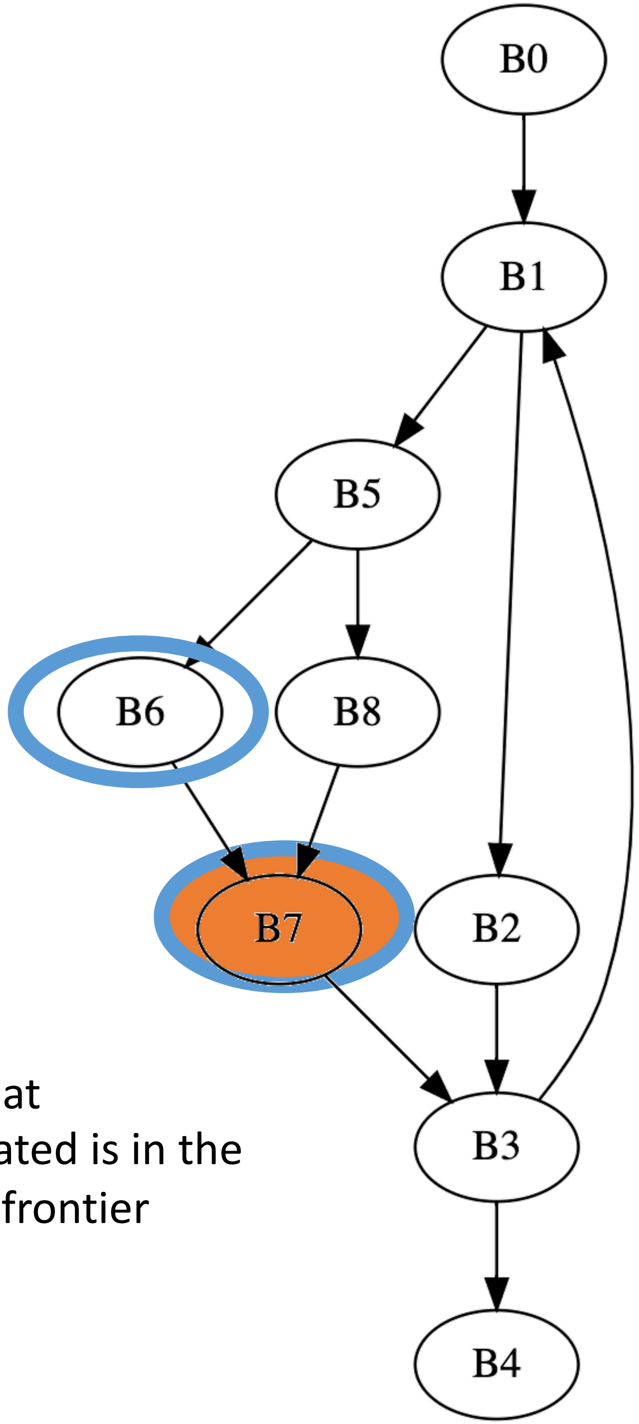


B3 is in the dominance frontier of B5

Node	Dominators
B0	
B1	B0,
B2	B0, B1,
B3	B0, B1,
B4	B0, B1, B3,
B5	B0, B1,
B6	B0, B1, B5,
B7	B0, B1, B5,
B8	B0, B1, B5,

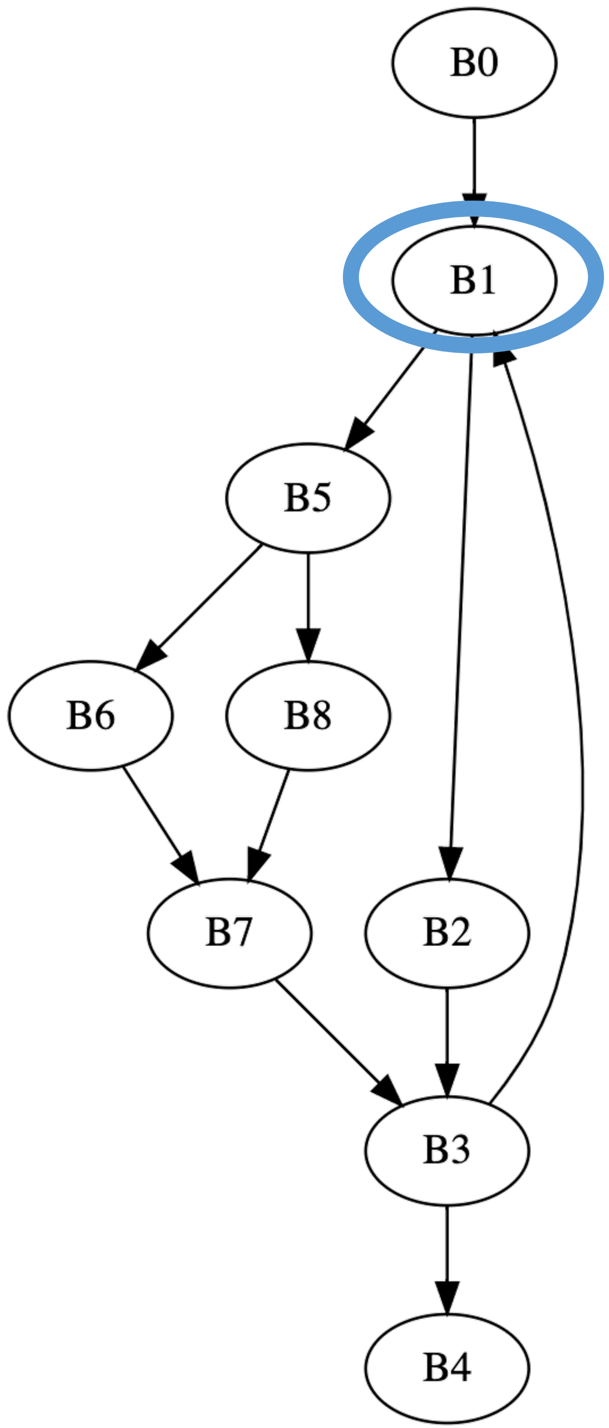


Node	Dominators
B0	
B1	B0,
B2	B0, B1,
B3	B0, B1,
B4	B0, B1, B3,
B5	B0, B1,
B6	B0, B1, B5,
B7	B0, B1, B5,
B8	B0, B1, B5,

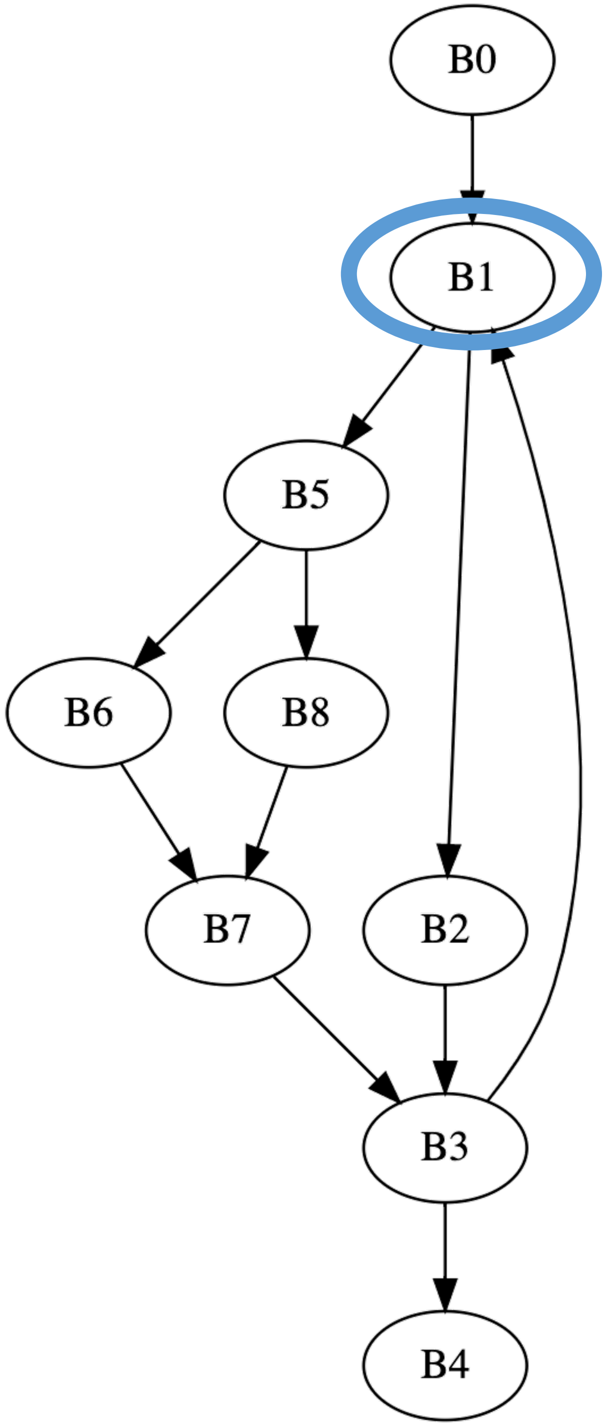


Any child that
isn't dominated is in the
dominance frontier

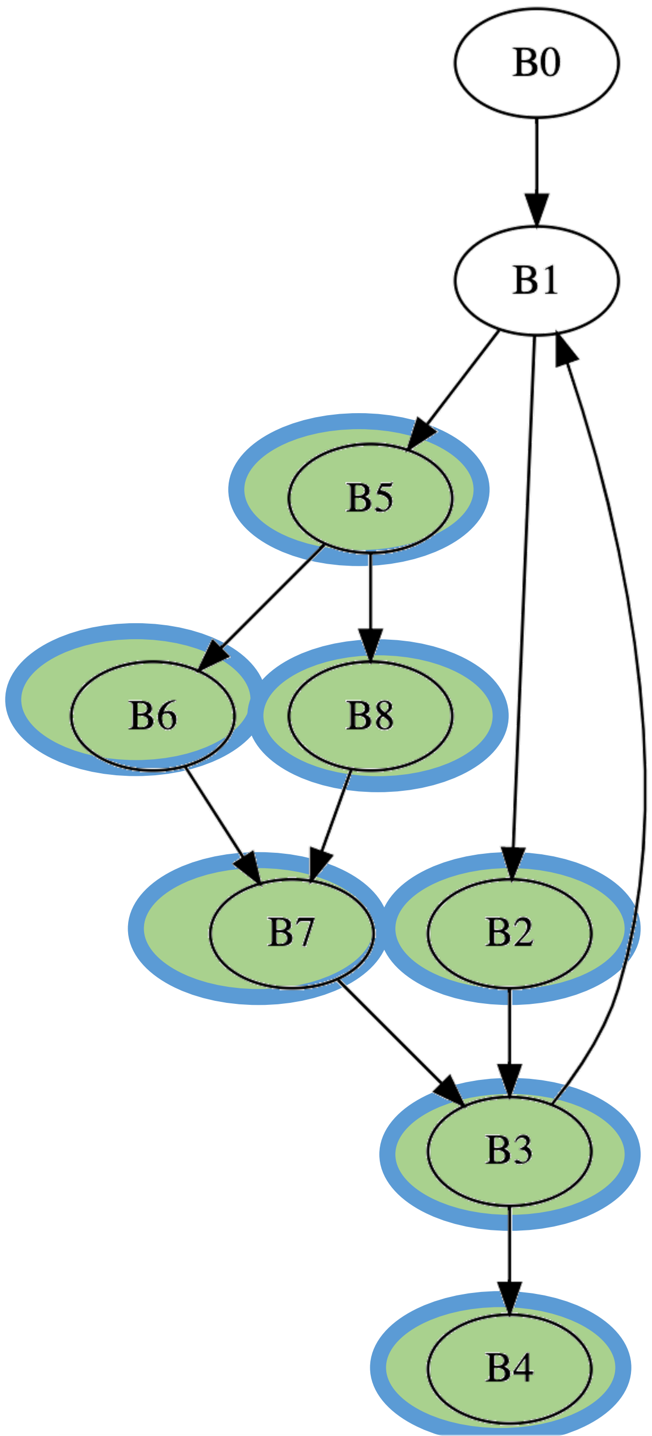
Node	Dominators
B0	
B1	B0,
B2	B0, B1,
B3	B0, B1,
B4	B0, B1, B3,
B5	B0, B1,
B6	B0, B1, B5,
B7	B0, B1, B5,
B8	B0, B1, B5,



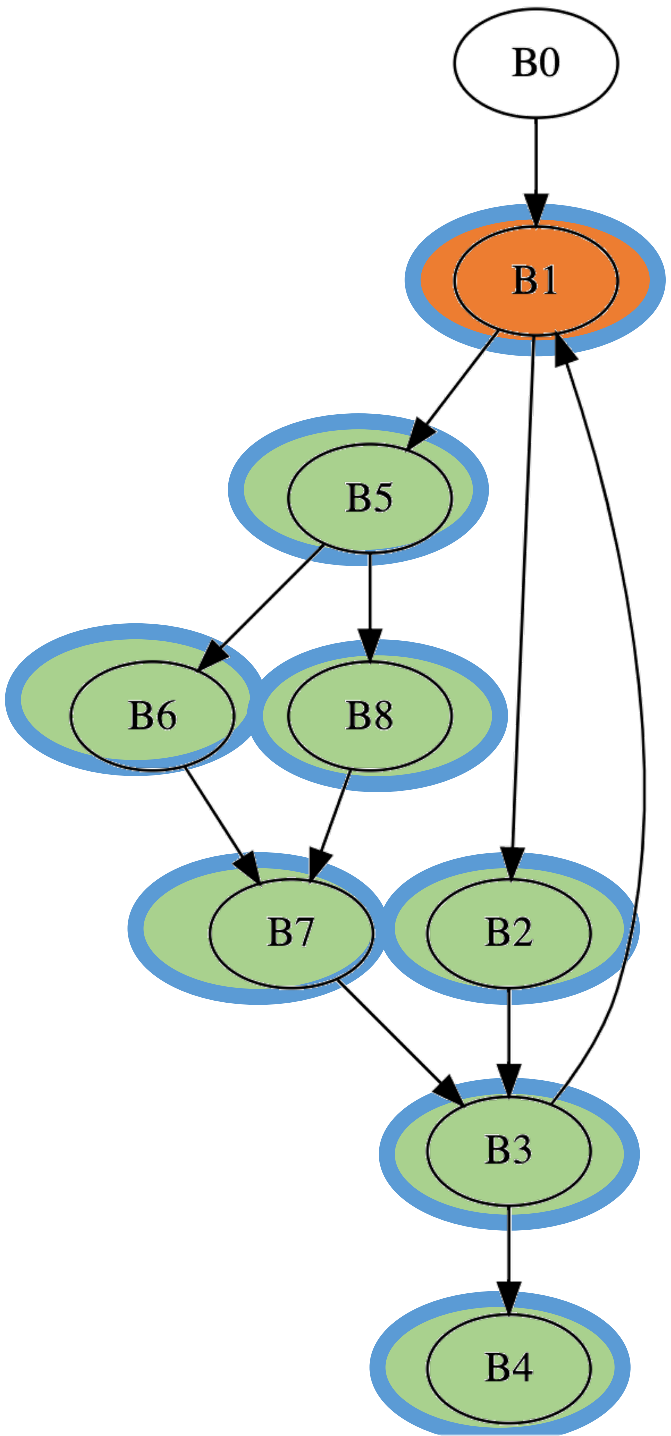
Node	Dominators
B0	
B1	B0,
B2	B0, B1,
B3	B0, B1,
B4	B0, B1, B3,
B5	B0, B1,
B6	B0, B1, B5,
B7	B0, B1, B5,
B8	B0, B1, B5,



Node	Dominators
B0	
B1	B0,
B2	B0, B1,
B3	B0, B1,
B4	B0, B1, B3,
B5	B0, B1,
B6	B0, B1, B5,
B7	B0, B1, B5,
B8	B0, B1, B5,

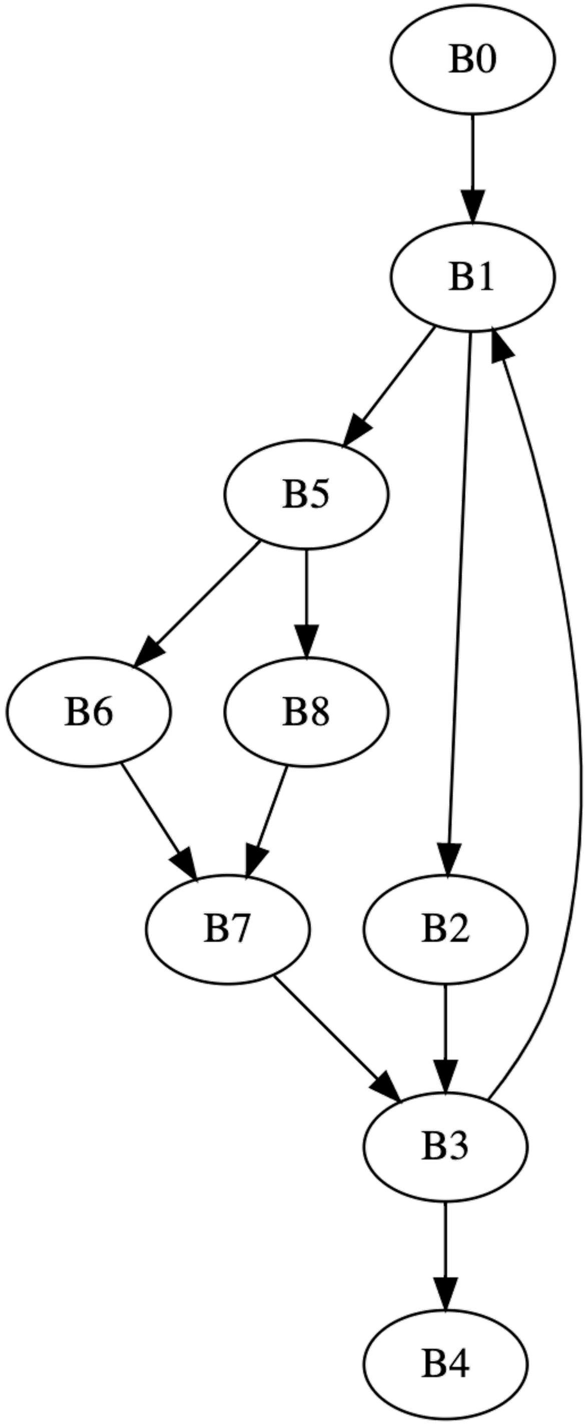


Node	Dominators
B0	
B1	B0,
B2	B0, B1,
B3	B0, B1,
B4	B0, B1, B3,
B5	B0, B1,
B6	B0, B1, B5,
B7	B0, B1, B5,
B8	B0, B1, B5,



How to use the dominator frontier?

Node	Dominator Frontier
B0	{}
B1	B1
B2	B3
B3	B1
B4	{}
B5	B3
B6	B7
B7	B3
B8	B7



A variable assigned to in B2 may need a phi node in which node?

Optimizations using SSA

Constant Propagation

- Perform certain operations at compile time if the values are known

- Flow the information of known values throughout the program

Constant Folding

If values are constant:

```
x = 128 * 2 * 5;
```

Constant Folding

If values are constant:

```
x = 128 * 2 * 5;
```

```
x = 1280;
```

Constant Folding

If values are constant:

```
x = 128 * 2 * 5;
```

```
x = 1280;
```

Using identities

```
x = z * 0;
```

Constant Folding

If values are constant:

```
x = 128 * 2 * 5;
```

```
x = 1280;
```

Using identities

```
x = z * 0;
```

```
x = 0;
```

Constant Folding

If values are constant:

```
x = 128 * 2 * 5;
```

```
x = 1280;
```

Using identities

```
x = z * 0;
```

```
x = 0;
```

Operations on other data structures

```
x = “CSE” + “211”;
```

Constant Folding

If values are constant:

```
x = 128 * 2 * 5;
```

```
x = 1280;
```

Using identities

```
x = z * 0;
```

```
x = 0;
```

Operations on other data structures

```
x = “CSE” + “211”;
```

```
x = “CSE211”;
```

local to expressions!

Constant Propagation

multiple expressions:

```
x = 42;
y = x + 5;
```

Constant Propagation

multiple expressions:

```
x = 42;
y = x + 5;
```

```
y = 47;
```

Constant Propagation

multiple expressions:

```
x = 42;
y = x + 5;
```

```
y = 47;
```

Within a basic block, you can use local value numbering

Constant Propagation

multiple expressions:

```
x = 42;
y = x + 5;
```

```
y = 47;
```

What about across basic blocks?

```
x = 42;
z = 5;
if (<some condition> {
   y = 5;
}
else {
   y = z;
}
w = y;
```

To do this, we’re going to use a lattice

- An object in abstract algebra
- Unique to each analysis you want to implement
  - Kind of like the flow function

A simple lattice

- A set of symbols: $\{c_1, c_2, c_3 \ldots\}$
- Special symbols:
  - Top : T
  - Bottom : $\perp$

- Meet operator: $\wedge$

A simple lattice

- A set of symbols: $\{c_1, c_2, c_3 \ldots\}$
- Special symbols:
  - Top : $\top$
  - Bottom : $\bot$
- Meet operator: $\wedge$

Lattices are an abstract algebra construct, with a few properties:

$\bot \wedge x = \bot$
$\top \wedge x = x$
Where x is any symbol

A simple lattice

- A set of symbols: $\{c_1, c_2, c_3 \ldots\}$
- Special symbols:
  - Top : T
  - Bottom : ⊥
- Meet operator: $\wedge$

Lattices are an abstract algebra construct, with a few properties:

$\perp \wedge x = \perp$
$\top \wedge x = x$
Where x is any symbol

For each analysis, we get to define symbols and the meet operation over them.

A simple lattice

- A set of symbols: $\{c_1, c_2, c_3 \ldots\}$
- Special symbols:
  - Top : T
  - Bottom : ⊥
- Meet operator: ∧

Lattices are an abstract algebra construct, with a few properties:

$\perp \wedge x = \perp$
$\top \wedge x = x$
Where x is any symbol

For constant propagation:

take the symbols to be integers

Simple meet operations for integers:
if c_i != c_j :
  $c_i \wedge c_j = \perp$

else:
$c_i \wedge c_j = c_j$

Constant propagation

- Map each SSA variable x to a lattice value:
  - Value(x) = $\top$ if the analysis has not made a judgment
  - Value(x) = $\mathbf{c_i}$ if the analysis found that variable x holds value c_i
  - Value(x) = $\perp$ if the analysis has found that the value cannot be known

Constant propagation algorithm

Initially:

Assign each SSA variable a value c based on its expression:

- a constant c_i if the value can be known
- $\perp$ if the value comes from an argument or input
- $\top$ otherwise, e.g. if the value comes from a ϕ node

Then, create a “uses” map

This can be done in a single pass

Example:

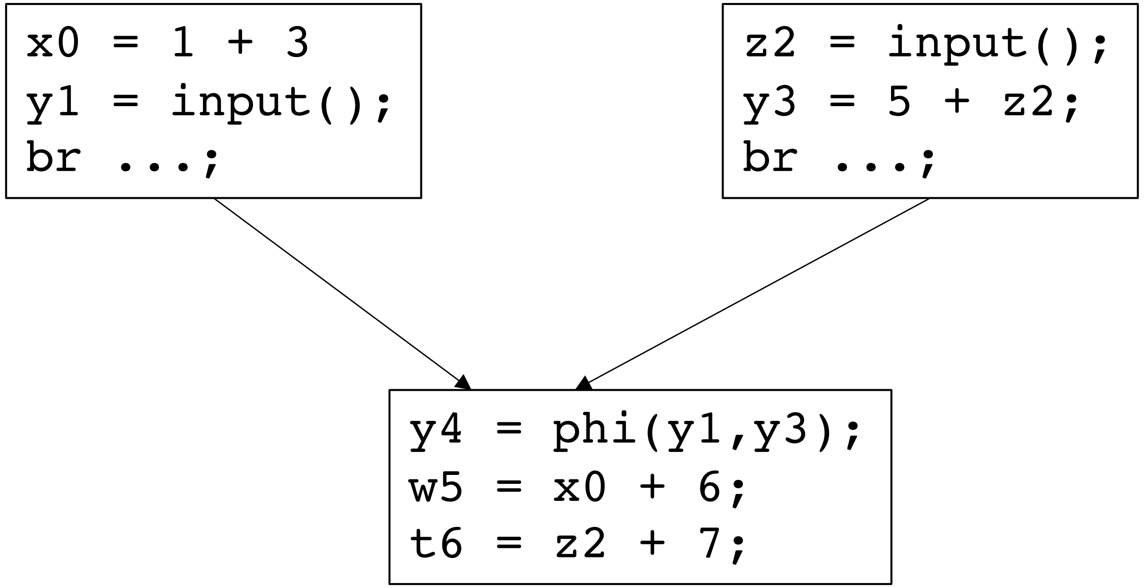
```
Value {
  x0 : 4
  y1 : B
  z2 : B
  y3 : T
  y4 : T
  w5 : T
  t6 : T
}
```

```
x0 = 1 + 3
y1 = input();
br ...;
```

```
z2 = input();
y3 = 5 + z2;
br ...;
```

```
y4 = phi(y1,y3);
w5 = x0 + 6;
t6 = z2 + 7;
```

Example:




```
Value {
  x0 : 4
  y1 : B
  z2 : B
  y3 : T
  y4 : T
  w5 : T
  t6 : T
}
```

```
Uses {
  x0 : [w5]
  y1 : [y4]
  z2 : [y3, t6]
  y3 : [y4]
  y4 : []
  w5 : []
  t6 : []
}
```

Constant propagation algorithm

worklist based algorithm:

All variables **NOT** assigned to T get put on a worklist

iterate through the worklist:

For every item *n* in the worklist, we can look up the uses of *n*

evaluate each use *m* over the lattice

Example:

```
x0 = 1 + 3
y1 = input();
br ...;
```

```
z2 = input();
y3 = 5 + 1;
br ...;
```

```
y4 = phi(y1,y3);
w5 = x0 + 6;
t6 = z2 + 7;
```

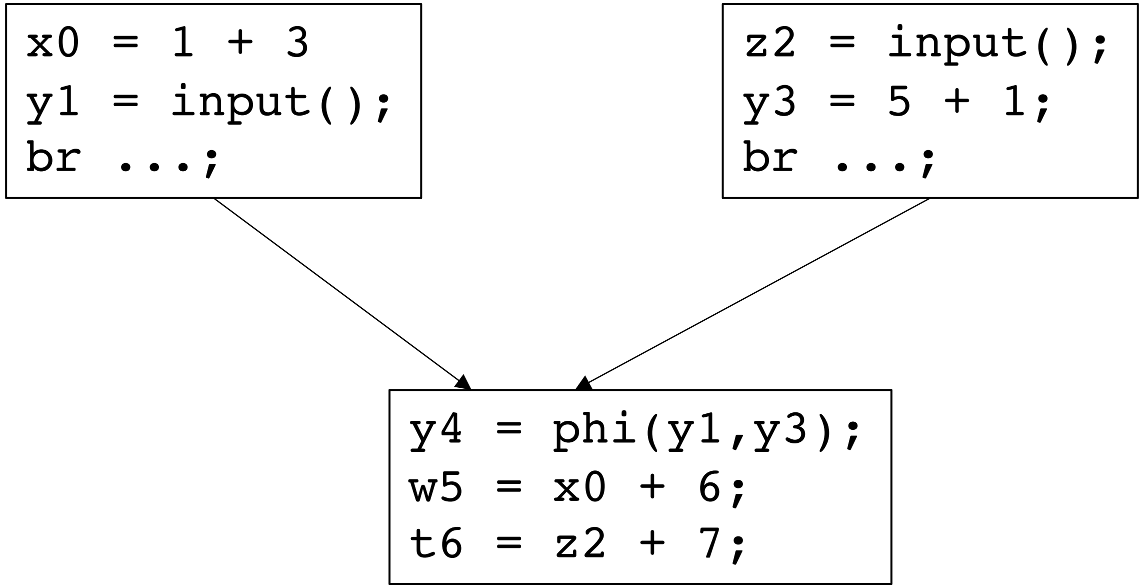
Worklist: `[x0, y1, z2, y3]`

```
Value {
  x0 : 4
  y1 : B
  z2 : B
  y3 : 6
  y4 : T
  w5 : T
  t6 : T
}
```

```
Uses {
  x0 : [w5]
  y1 : [y4]
  z2 : [t6]
  y3 : [y4]
  y4 : []
  w5 : []
  t6 : []
}
```

Example:

```
Value {
  x0 : 4
  y1 : B
  z2 : B
  y3 : 6
  y4 : T
  w5 : T
  t6 : T
}
```




```
Uses {
  x0 : [w5]
  y1 : [y4]
  z2 : [t6]
  y3 : [y4]
  y4 : []
  w5 : []
  t6 : []
}
```

Worklist: `[x0,y1,z2,y3]`

Constant propagation algorithm

for each item in the worklist, evaluate all of it’s uses *m* over the lattice (unique to each optimization)

Example: *m = n*x*

if (Value(n) is ⊥ or Value(x) is ⊥)

  Value(m) = ⊥**;**
  Add m to the worklist if Value(m) has changed;
  break;

Example:

```
x0 = 1 + 3
y1 = input();
br ...;
```

```
z2 = input();
y3 = 5 + 1;
br ...;
```

```
y4 = phi(y1,y3);
w5 = x0 + 6;
t6 = z2 + 7;
```

Worklist: `[x0,y1,z2,y3]`

```
Value {
  x0 : 4
  y1 : B
  z2 : B
  y3 : 6
  y4 : T
  w5 : T
  t6 : T
}
```

```
Uses {
  x0 : [w5]
  y1 : [y4]
  z2 : [t6]
  y3 : [y4]
  y4 : []
  w5 : []
  t6 : []
}
```

Example:

```
x0 = 1 + 3
y1 = input();
br ...;
```

```
z2 = input();
y3 = 5 + 1;
br ...;
```

```
y4 = phi(y1,y3);
w5 = x0 + 6;
t6 = z2 + 7;
```

Worklist: `[x0,y1,z2,y3,t6]`

```
Value {
  x0 : 4
  y1 : B
  z2 : B
  y3 : 6
  y4 : T
  w5 : T
  t6 : B
}
```

```
Uses {
  x0 : [w5]
  y1 : [y4]
  z2 : [t6]
  y3 : [y4]
  y4 : []
  w5 : []
  t6 : []
}
```

Constant propagation algorithm

evaluate m over the lattice (unique to each optimization)

Example: *m = n*x*

if (Value(n) is $\perp$ or Value(x) is $\perp$)

Value(m) = $\perp$**;**
Add m to the worklist if Value(m) has changed;
break;

Can we optimize this for special cases?

Example:

```
x0 = 1 + 3
y1 = input();
br ...;
```

```
z2 = input();
y3 = 5 + 1;
br ...;
```

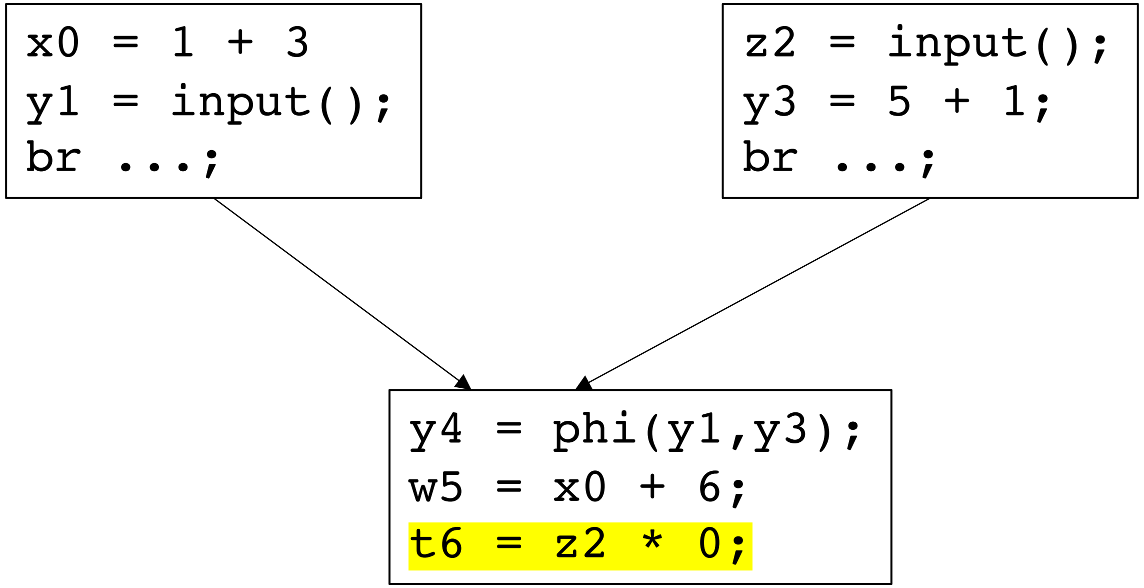
```
y4 = phi(y1,y3);
w5 = x0 + 6;
t6 = z2 * 0;
```

Worklist: `[x0,y1,z2,y3]`

```
Value {
  x0 : 4
  y1 : B
  z2 : B
  y3 : 6
  y4 : T
  w5 : T
  t6 : 0
}
```

```
Uses {
  x0 : [w5]
  y1 : [y4]
  z2 : [t6]
  y3 : [y4]
  y4 : []
  w5 : []
  t6 : []
}
```

Example:



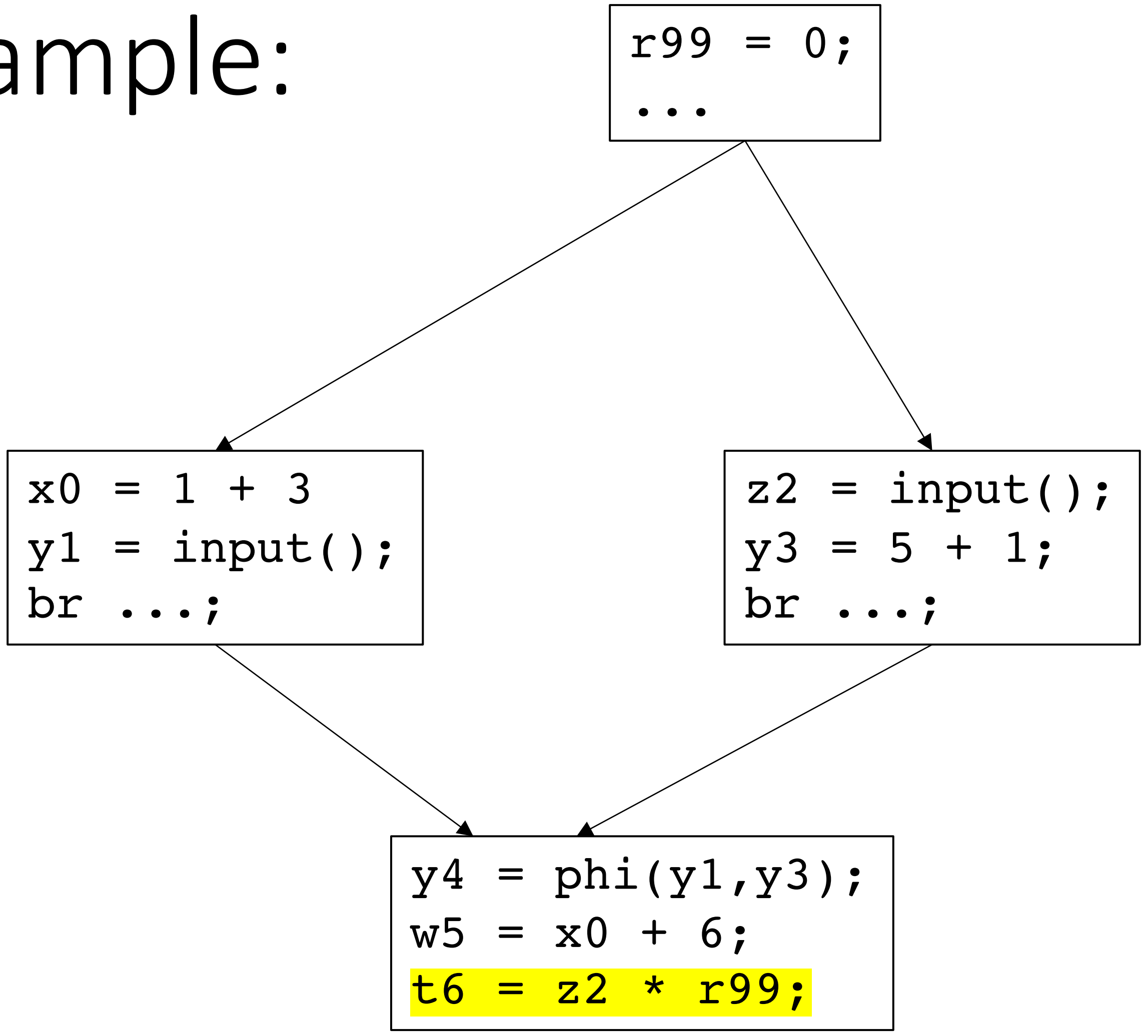

```
Value {
  x0 : 4
  y1 : B
  z2 : B
  y3 : 6
  y4 : T
  w5 : T
  t6 : T
}
```

```
Uses {
  x0 : [w5]
  y1 : [y4]
  z2 : [t6]
  y3 : [y4]
  y4 : []
  w5 : []
  t6 : []
}
```

Worklist: `[x0,y1,z2,y3]`

Can't this be done
at the expression level?

Example:




```
Value {
   x0  :  4
   y1  :  B
   z2  :  B
   y3  :  6
   y4  :  T
   w5  :  T
   t6  :  T
   r99  :  0
}

Uses {
   x0  :  [w5]
   y1  :  [y4]
   z2  :  [t6]
   y3  :  [y4]
   y4  :  []
   w5  :  []
   t6  :  []
}
```

Worklist: [x0,y1,z2,y3]

Can’t this be done
at the expression level?

Example:

```
x0 = 1 + 3
y1 = input();
br ...;
```

```
z2 = input();
y3 = 5 + 1;
br ...;
```

```
y4 = phi(y1,y3);
w5 = x0 + 6;
t6 = z2 + 7;
```

Worklist: `[x0,y1,z2,y3]`

```
Value {
  x0 : 4
  y1 : B
  z2 : B
  y3 : 6
  y4 : T
  w5 : T
  t6 : T
}
```

```
Uses {
  x0 : [w5]
  y1 : [y4]
  z2 : [t6]
  y3 : [y4]
  y4 : []
  w5 : []
  t6 : []
}
```

Constant propagation algorithm

evaluate m over the lattice (unique to each optimization)

Example: *m = n*x*

// continued from previous slide

if (Value(n) has a value and Value(x) has a value)

  Value(m) = **evaluate**(Value(n), Value(x))**;**
  Add m to the worklist if Value(m) has changed;
  break;

Example:

```
x0 = 1 + 3
y1 = input();
br ...;
```

```
z2 = input();
y3 = 5 + 1;
br ...;
```

```
y4 = phi(y1,y3);
w5 = x0 + 6;
t6 = z2 + 7;
```

Worklist: `[x0,y1,y3,w5]`

```
Value {
  x0 : 4
  y1 : B
  z2 : B
  y3 : 6
  y4 : T
  w5 : 10
  t6 : T
}
```

```
Uses {
  x0 : [w5]
  y1 : [y4]
  z2 : [t6]
  y3 : [y4]
  y4 : []
  w5 : []
  t6 : []
}
```

Example:

```
x0 = 1 + 3
y1 = input();
br ...;
```

```
z2 = input();
y3 = 5 + 1;
br ...;
```

```
y4 = phi(y1,y3);
w5 = x0 + 6;
t6 = z2 + 7;
```

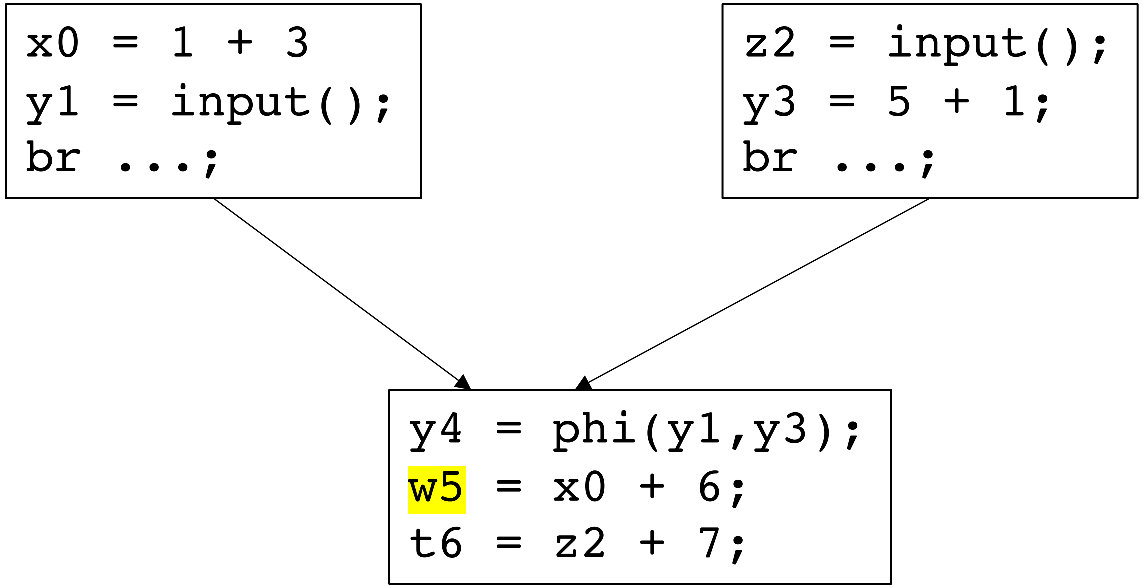
Worklist: [x0,y1,y3]

```
Value {
  x0 : 4
  y1 : B
  z2 : B
  y3 : 6
  y4 : T
  w5 : T
  t6 : T
}
```

```
Uses {
  x0 : [w5]
  y1 : [y4]
  z2 : [t6]
  y3 : [y4]
  y4 : []
  w5 : []
  t6 : []
}
```

Example:

```
Value {
   x0 : 4
   y1 : B
   z2 : B
   y3 : 6
   y4 : T
   w5 : T
   t6 : T
}
```




```
Uses {
   x0 : [w5]
   y1 : [y4]
   z2 : [t6]
   y3 : [y4]
   y4 : []
   w5 : []
   t6 : []
}
```

Worklist: [x0,y1,y3]

The elephant in the room

…

Example:

```
x0 = 1 + 3
y1 = input();
br ...;
```

```
z2 = input();
y3 = 5 + 1;
br ...;
```

```
y4 = phi(y1,y3);
w5 = x0 + 6;
t6 = z2 + 7;
```

Worklist: `[x0,y1,y3]`

```
Value {
  x0 : 4
  y1 : B
  z2 : B
  y3 : 6
  y4 : T
  w5 : T
  t6 : T
}
```

```
Uses {
  x0 : [w5]
  y1 : [y4]
  z2 : [t6]
  y3 : [y4]
  y4 : []
  w5 : []
  t6 : []
}
```

Constant propagation algorithm

evaluate m over the lattice:

Example: $m = \phi(x_1 , x_2)$

Value(m) = $x_1 \wedge x_2$

if Value(m) is not T and Value(m) has changed, then add m to the worklist

Example:

```
x0 = 1 + 3
y1 = input();
br ...;
```

```
z2 = input();
y3 = 5 + 1;
br ...;
```

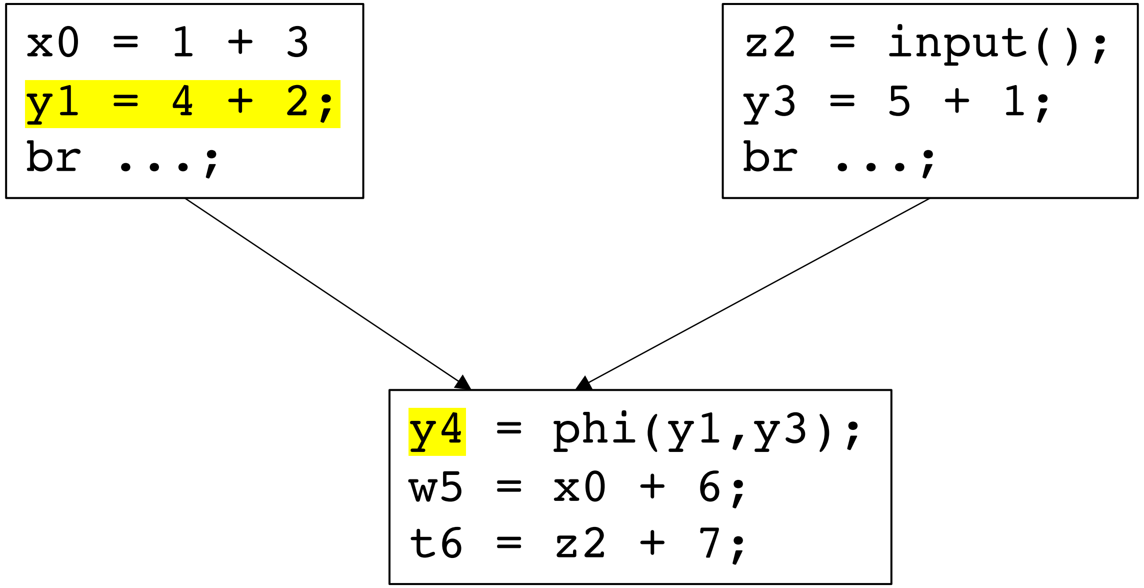
```
y4 = phi(y1,y3);
w5 = x0 + 6;
t6 = z2 + 7;
```

Worklist: `[x0,y1,y3]`

```
Value {
  x0 : 4
  y1 : B
  z2 : B
  y3 : 6
  y4 : B
  w5 : T
  t6 : T
}
```

```
Uses {
  x0 : [w5]
  y1 : [y4]
  z2 : [t6]
  y3 : [y4]
  y4 : []
  w5 : []
  t6 : []
}
```

Example:



Worklist: [x0,y1,y3]

```
Value {
  x0 : 4
  y1 : B
  z2 : B
  y3 : 6
  y4 : T
  w5 : T
  t6 : T
}
```

```
Uses {
  x0 : [w5]
  y1 : [y4]
  z2 : [t6]
  y3 : [y4]
  y4 : []
  w5 : []
  t6 : []
}
```

Constant propagation algorithm

evaluate m over the lattice:

Example: $m = \phi(x_1 , x_2)$

Value(m) = $x_1 \wedge x_2$

if Value(m) is not T and Value(m) has changed, then add m to the worklist

Constant propagation algorithm

evaluate m over the lattice:

Issue here: potentially assigning a value that might not hold

Example: $m = \phi(x_1, x_2)$

Value(m) = $x_1 \wedge x_2$

if Value(m) is not T and Value(m) has changed, then add m to the worklist

Example loop:

```
y3 = 1;
x0 = 17;
br ...;
```

```
x1 = phi(x0,x2);
x2 = x1 + y3;
```

x1:17

Example loop:

```
y3 = 0;
x0 = 17;
br ...;
```

```
x1 = phi(x0,x2);
x2 = x1 + y3;
```

optimistic analysis: Assume unknowns will be the target value for the optimization. Correct later

pessimistic analysis: Assume unknowns will NOT be the target value for the optimization.

Pros/cons?

A simple lattice

- A set of symbols: $\{c_1, c_2, c_3 \ldots\}$
- Special symbols:
  - Top : T
  - Bottom : ⊥
- Meet operator: ∧

Lattices are an abstract algebra construct, with a few properties:

$\perp \wedge x = \perp$
$T \wedge x = x$
Where x is any symbol

For Loop unrolling

take the symbols to be integers

Simple meet operations for integers:
if c_i != c_j :
$c_i \wedge c_j = \perp$

else:
$c_i \wedge c_j = c_j$

A simple lattice

- A set of symbols: $\{c_1, c_2, c_3 \ldots\}$
- Special symbols:
  - Top : T
  - Bottom : ⊥
- Meet operator: $\wedge$

Lattices are an abstract algebra construct, with a few properties:

$\perp \wedge x = \perp$
$T \wedge x = x$
Where x is any symbol

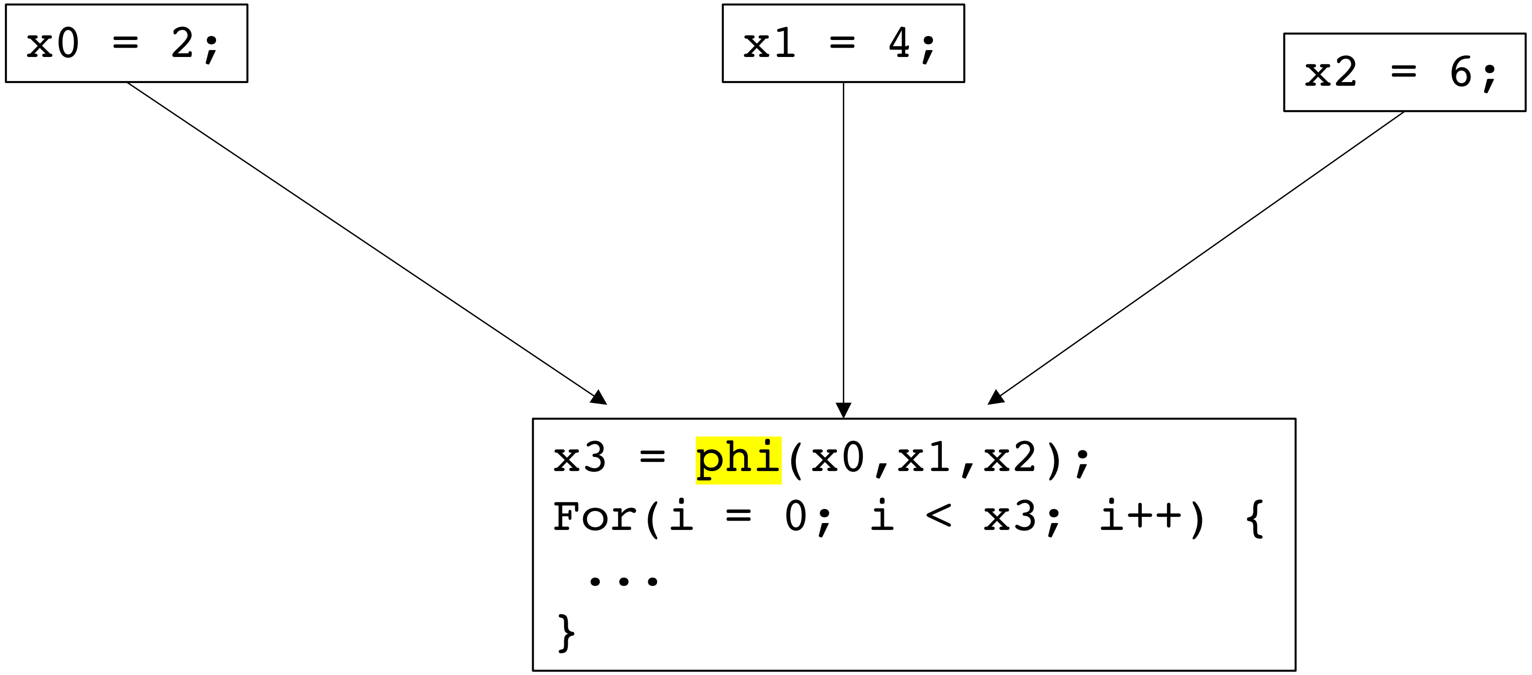
For Loop unrolling

take the symbols to be integers representing the GCD

$c_i \wedge c_j = GCD(c_i, c_j)$

Another lattice

- Given loop code:
  - Is it possible to unroll the loop N times?



Another lattice

- Value ranges

Track if `i,j,k` *are guaranteed to be between 0 and 1024.*

Meet operator takes a union of possible ranges.

```
int * x = int[1024];
x[i] = x[j] + x[k];
```

See you on Friday!

- We will move on to module 3: parallelization
- I will post midterm before midnight tonight
- Office hours tomorrow (2-3pm)