

CSC2/455 Software Analysis and Improvement

Foundations of Data Flow Analysis - II

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URCS

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Part I of Foundations

- Methods to solve dataflow analysis equations
 - IDEAL
 - Meet over paths (MOP)
 - Maximum Fixed Point (MFP)
 - IDEAL \subseteq MOP \subseteq MFP
- (Semi)lattice-based framework
 - (D, V, \wedge, F) , dataflow analysis
 - (V, \wedge) , meet semilattice
 - (V, \leq) , partial order, where $x \leq y$ iff $x \wedge y = x$
 - Monotone framework
- Greatest Lower Bound
 - $z \leq x$ and $z \leq y$, where $z = x \wedge y$

Monotone Framework

- A given (D, V, \wedge, F) is monotone if for all $x, y \in V$, and $f \in F$:
 - $x \leq y \rightarrow f(x) \leq f(y)$
 - equivalently, $x \leq y \rightarrow f(x \wedge y) \leq f(x) \wedge f(y)$
 - The proof of equivalence is in the textbook.
- In addition, the framework is *distributive* if:
 - $f(x \wedge y) = f(x) \wedge f(y)$
- Note that these properties do not necessarily arise automatically, F must be designed to have these properties
 - And proofs must be written to show that F does.
 - We'll see this for a complicated example today.

General Iterative Algorithm

```
forwards(IN, OUT, meet, top, v_entry, f_transfer)
    OUT[entry] = v_entry

    for each basic block B except ENTRY:
        OUT[B] = top

    do {
        for each basic block B except ENTRY:
            # this calculates the meet over predecessors, /\p OUT[p]
            IN[B] = reduce(meet, [OUT[p] for p in B.predecessors])
            OUT[B] = f_transfer(IN[B])

    } while(some OUT changes value)
```

- Does this calculate the solution to the dataflow problem?
- Does this algorithm terminate?
- Does this algorithm calculate the *maximum* fixed point – i.e. the most precise solution admissible?

This class

- Proofs that answer these three questions
- Relationships between IDEAL, MOP and MFP in terms of the framework
- Examples of:
 - a non-distributive framework (from Dragon 9.4, Constant Propagation)
 - lattices containing infinite values
 - possibly some proof writing exercises (from Dragon 9.3)

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Proof #1

```
do {
  for each basic block B except ENTRY:
    # this calculates the meet over predecessors, / \p OUT[p]
    IN[B] = reduce(meet, [OUT[p] for p in B.predecessors])
    OUT[B] = f_transfer(IN[B])
} while(some OUT changes value)
```

The iterative algorithm computes the solution to the dataflow problem.

- The iterative algorithm performs an unbounded number of iterations as long as IN and OUT change
- *When it terminates*, IN and OUT have not changed for an iteration
- The values of IN and OUT therefore satisfy the equations
 - Hence they are solutions of the dataflow problem

Proof #2

The iterative algorithm terminates (i.e. converges to a fix point).

- When we apply the \wedge operator, we obtain the glb
 - i.e. $z = x \wedge y$ and $z \leq x$ and $z \leq y$
- Since the framework is monotone:
 - $f(x) \leq f(y)$ if $x \leq y$
 - i.e. OUT values are no greater than the IN values
- At each step, these values decrease or remain the same
 - When they all remain the same, we terminate
- If values decrease, recall the lattice has finite height
 - Implies a finite number of steps before we reach \perp
 - $x \wedge \perp = \perp$ and $f(\perp) = \perp$ (i.e once a value becomes \perp , it no longer changes)
 - We terminate in this case as well

Proof #3

The fixed point solution computed by the iterative algorithm is the *maximum* fixed point.

Proof By induction, for forward analyses

(*BASIS*) After the first iteration, values of $IN[B]$ and $OUT[B]$ are \leq their initial values.

- At initialization, $OUT[B]$ is \top for all blocks B except ENTRY
- After the first iteration, in a monotone framework, all values will be \leq those at initialization by definitions of the \wedge and transfer functions

Proof #3: Inductive step

Assume that:

- $\text{IN}[B]^k \leq \text{IN}[B]^{k-1}$
- $\text{OUT}[B]^k \leq \text{OUT}[B]^{k-1}$

Show that:

- $\text{IN}[B]^{k+1} \leq \text{IN}[B]^k$
- $\text{OUT}[B]^{k+1} \leq \text{OUT}[B]^k$

Proof #3: Continued

- To obtain $\text{IN}[B]$ we must apply \wedge to all $\text{OUT}[P]$
 - P is a predecessor of B
 - This implies $\text{IN}[B] \leq \text{OUT}[P]$ (\wedge yields glb)
 - From our inductive hypothesis, $\text{OUT}[P]^k \leq \text{OUT}[P]^{k-1}$
 - applying \wedge on both sides over all P , $\text{IN}[B]^{k+1} \leq \text{IN}[B]^k$
- Now, $\text{OUT}[B] = f(\text{IN}[B])$
 - In the monotone framework, $f(x) \leq f(y)$ when $x \leq y$
 - We have shown $\text{IN}[B]^{k+1} \leq \text{IN}[B]^k$
 - Therefore, after applying f to both sides, by monotonicity, we have $\text{OUT}[B]^{k+1} \leq \text{OUT}[B]^k$

Properties of the IDEAL solution

- Any solution greater than IDEAL is incorrect (or unsafe)
- Any solution less than or equal to IDEAL is conservative¹, or safe.

To see why, consider IDEAL solution $x = p_1 \wedge p_2 \wedge \dots \wedge p_n$:

- How can we obtain a value $z = p_1 \wedge \dots$ *greater than* x ?
- How can we obtain a value $y = p_1 \wedge \dots$ *less than* x ?

(recall the relationship between the results of the meet operator and its operands)

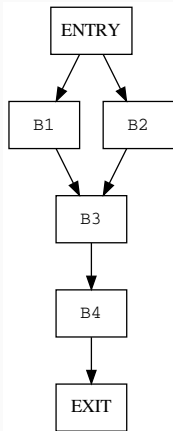
¹In the English sense

Relationship between IDEAL and MOP

- MOP considers a superset of all executable paths
 - MOP solution $y = p_1 \wedge p_2 \wedge \dots \wedge p_n \wedge p_{n+1} \dots$
- What is the relationship between MOP (y) and IDEAL (z)?

Relationship between MOP and MFP

- $MOP[B_4] = ((f_{B_3} \circ f_{B_1}) \wedge (f_{B_3} \circ f_{B_2}))(v_{entry})$
 - i.e., compose transfer functions over a path and then apply meet (e.g. $f_{B_3}(f_{B_1}(v_{entry}))$)
- $IN[B_4] = f_{B_3}(f_{B_1}(v_{entry}) \wedge f_{B_2}(v_{entry}))$
 - i.e. apply meet at join nodes



In a distributive framework, MOP = MFP

- $MOP[B_4] = ((f_{B_3} \circ f_{B_1}) \wedge (f_{B_3} \circ f_{B_2}))(v_{entry})$
- $IN[B_4] = f_{B_3}(f_{B_1}(v_{entry}) \wedge f_{B_2}(v_{entry}))$

If $f(x \wedge y) = f(x) \wedge f(y)$ (i.e. distributive):

- $IN[B_4] = f_{B_3}(f_{B_1}(v_{entry})) \wedge f_{B_3}(f_{B_2}(v_{entry}))$
- If the framework is distributive, then MOP solution = MFP solution
 - Otherwise by monotonicity $MFP \leq MOP$
- In either case,
 - $MFP \leq MOP \leq IDEAL$
 - So all methods produce “safe” solutions

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Analyses so far

- Live variable analysis
- Available Expressions
- Reaching Definitions
- These are all distributive (implies monotonicity)
- Their lattices contain a finite number of values
- Their lattices have finite height

Constant Propagation

- Does this variable have a constant value at this point in the program?
 - Used to perform constant folding (i.e. evaluate constant expressions at compile time)
- Data flow analysis framework
 - Direction?
 - Values?
 - Meet operator?
 - Transfer function?

Constant Propagation

- Direction: Forward
- Values:
 - UNDEF: variable is undefined so far
 - c : variable is constant value c
 - NAC: variable is not a constant
- Meet operators and transfer functions are slightly more complicated.

Meet for Constant Propagation

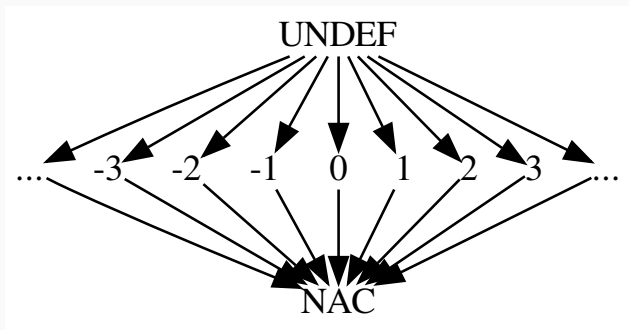
- $\text{UNDEF} \wedge v = ?$
- $\text{NAC} \wedge v = ?$
- $c \wedge c = ?$
- $c_1 \wedge c_2 = ? (c_1 \neq c_2)$

Meet for Constant Propagation

- $\text{UNDEF} \wedge v = v$
 - UNDEF is \top
- $\text{NAC} \wedge v = \text{NAC}$
 - NAC is \perp
- $c \wedge c = c$
- $c_1 \wedge c_2 = \text{NAC}$

What does the lattice for constant propagation look like?

The lattice for constant propagation



The Transfer Function

- $\text{OUT}[s] = f(\text{IN}[s])$ for a statement s
 - Slightly easier to understand if we use statements instead of basic blocks
- Observe that non-assignment statements do not change values
 - f is simply the identity function $f(x) = x$ for such statements
- What about assignment statements?
 - $x = c$, where x is a variable, and c is a constant
 - $x = y + z$, where $+$ is any binary operator
 - $x = *y$ or $x = f(\dots)$, where f is a function call

The Transfer Function - II

- Note that IN (and OUT) are maps (i.e. dictionaries)
 - From variables to their current dataflow values (UNDEF, c , or NAC)
 - Let's call this map m , so that $m(x)$ returns the dataflow value for variable x
- $x = c$, changes $m(x) \leftarrow c$
- $x = y + z$, where $+$ is any binary operator (not just addition)
 - $m(x) \leftarrow m(y) + m(z)$ if $m(y)$ and $m(z)$ are constants
 - $m(x) \leftarrow \text{NAC}$ if either $m(y)$ or $m(z)$ is NAC
 - $m(x) \leftarrow \text{UNDEF}$ otherwise
- $x = *y$ or $x = f(\dots)$, $m(x) \leftarrow \text{NAC}$ (conservatively)
- Note that $m(v) \leftarrow m(v)$ for all $v \neq x$
 - I.e. the other values of the map remain unchanged

Note that I use slightly different notation than the textbook, which uses m' on the LHS

Is this monotonic?

Is $\text{OUT}[s] \leq \text{IN}[s]$ for every s ?

- For the two cases below, it is “surely ... monotone”:
 - $m(x) \leftarrow c$
 - $m(x) \leftarrow \text{NAC}$
- What about $x = y + z$?
 - Need to show that $m(x)$ does not get greater as $m(y)$ (and/or) $m(z)$ get smaller
 - Show by case analysis and symmetry

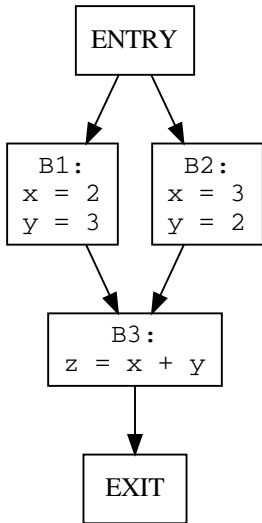
$x = y + z$ as $m(z)$ gets smaller

$m(y)$	$m(z)$	output $m(x)$
UNDEF	UNDEF c_2 NAC	UNDEF
c_1	UNDEF c_2 NAC	
NAC	UNDEF c_2 NAC	NAC

$x = y + z$ as $m(z)$ gets smaller (answers)

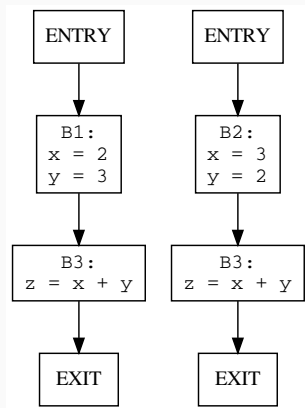
$m(y)$	$m(z)$	output $m(x)$
UNDEF	UNDEF c_2 NAC	UNDEF UNDEF NAC
c_1	UNDEF c_2 NAC	UNDEF $c_1 + c_2$ NAC
NAC	UNDEF c_2 NAC	NAC NAC NAC

Is it distributive?



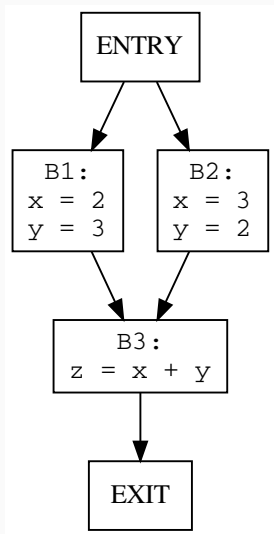
MOP solution

- Path 1 ($x = 2; y = 3; z = x + y$)
 - $m(z) = 5$, so z is a constant
- Path 2 ($x = 3; y = 2; z = x + y$)
 - $m(z) = 5$, so z is a constant
- Meet over Path 1 and Path 2
 - $m(z) = 5 \wedge 5$, so z is a constant



MFP solution

- At end of block B_1
 - $m(x) = 2$ and $m(y) = 3$
- At end of block B_2
 - $m(x) = 3$ and $m(y) = 2$
- Meet before block B_3
 - $m(x) = 2 \wedge 3$ (i.e. case $c_1 \wedge c_2$)
 - $m(y) = 3 \wedge 2$
- Conclusion?



Constant Propagation is not distributive

- For constant propagation, in most non-trivial programs
 - $MFP < MOP$

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References

- Chapter 9 of the Dragon book
 - Section 9.3, 9.4