CMSC 631
Program Analysis and Understanding
Spring 2013

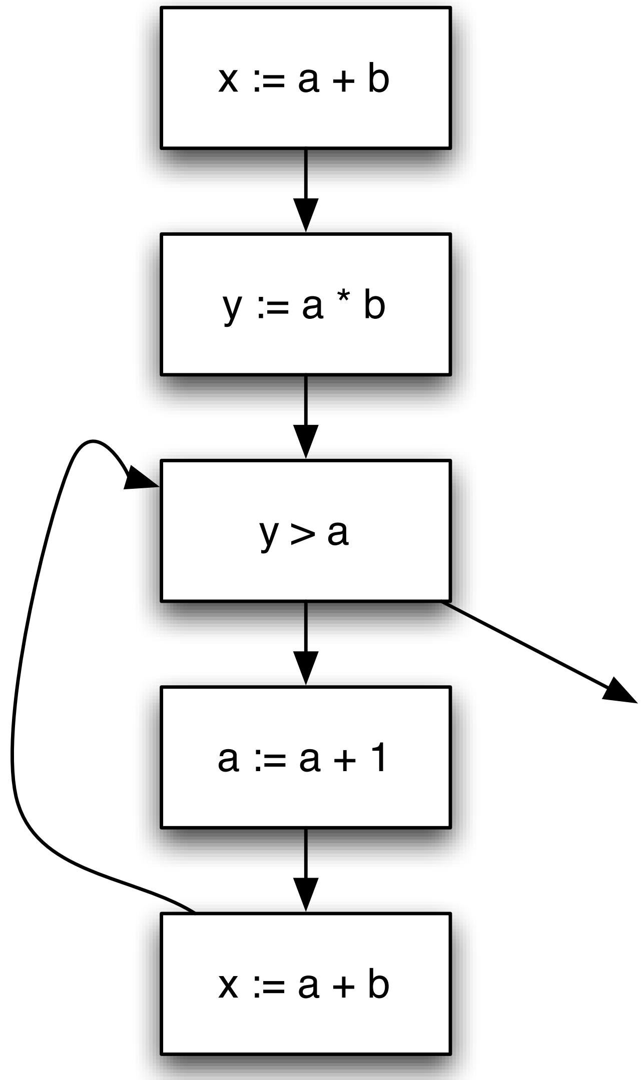
Data Flow Analysis

Data Flow Analysis

- A framework for proving facts about programs
- Reasons about lots of little facts
- Little or no interaction between facts
  - Works best on properties about *how* program computes
- Based on all paths through program
  - Including infeasible paths
- Operates on control-flow graphs, typically

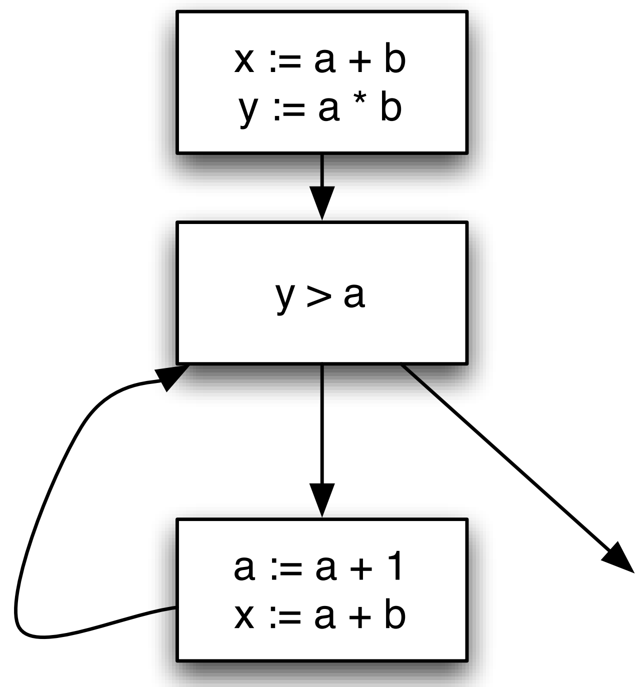
Control-Flow Graph Example

```
x := a + b;
y := a * b;
while (y > a) {
    a := a + 1;
    x := a + b
}
```



Control-Flow Graph w/Basic Blocks

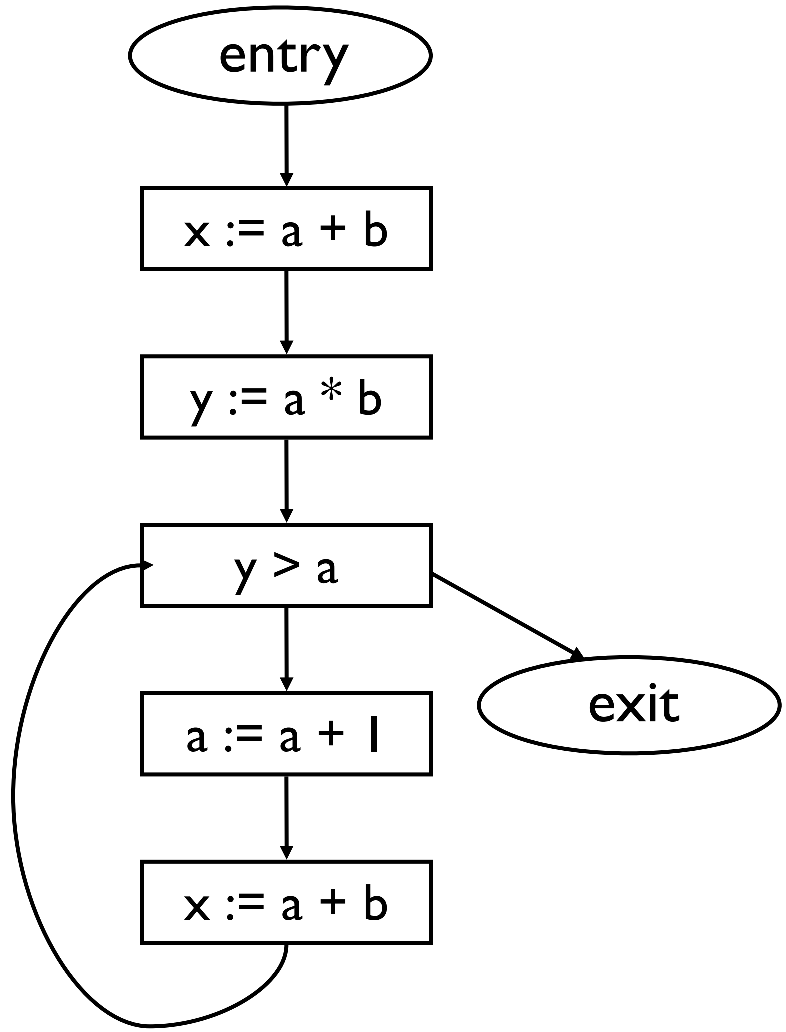
```
x := a + b;
y := a * b;
while (y > a + b) {
   a := a + 1;
   x := a + b
}
```



- Can lead to more efficient implementations
- But more complicated to explain, so...
  - We'll use single-statement blocks in lecture today

Example with Entry and Exit

```
x := a + b;
y := a * b;
while (y > a) {
    a := a + 1;
    x := a + b
}
```



- All nodes without a (normal) predecessor should be pointed to by entry
- All nodes without a successor should point to exit

Notes on Entry and Exit

- Typically, we perform data flow analysis on a function body
- Functions usually have
  - A unique entry point
  - Multiple exit points
- So in practice, there can be multiple exit nodes in the CFG
  - For the rest of these slides, we'll assume there's only one
  - In practice, just treat all exit nodes the same way as if there's only one exit node

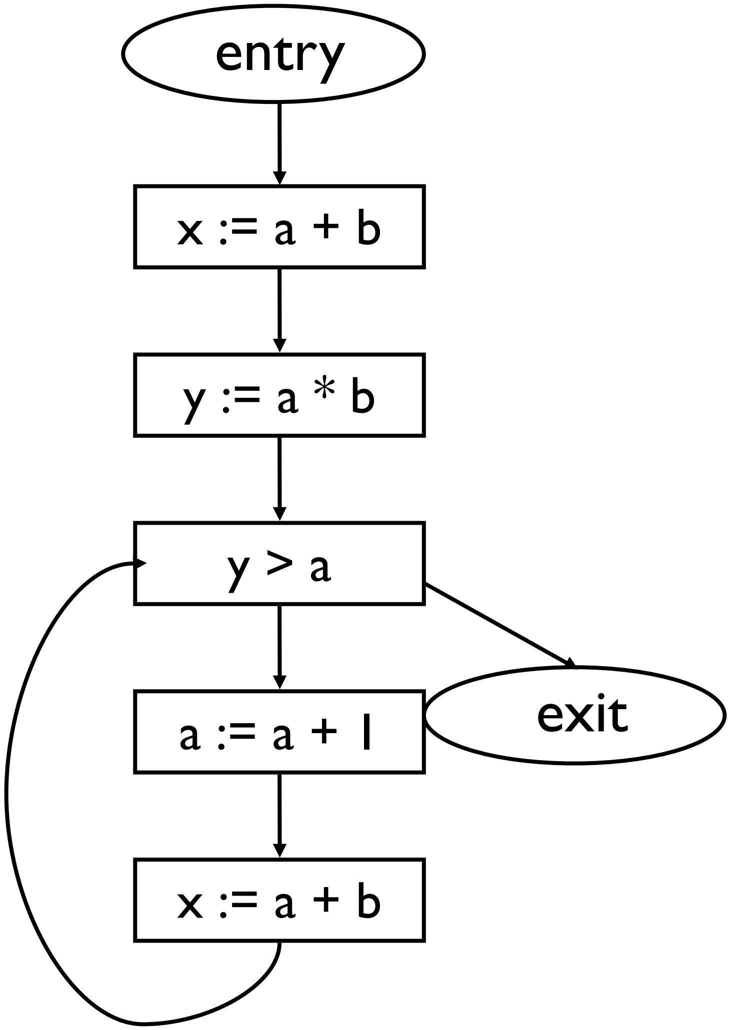
Available Expressions

- An expression e is available at program point p if
  - e is computed on every path to p, and
  - the value of e has not changed since the last time e was computed on the paths to p

- Optimization
  - If an expression is available, need not be recomputed
    - (At least, if it's still in a register somewhere)

Data Flow Facts

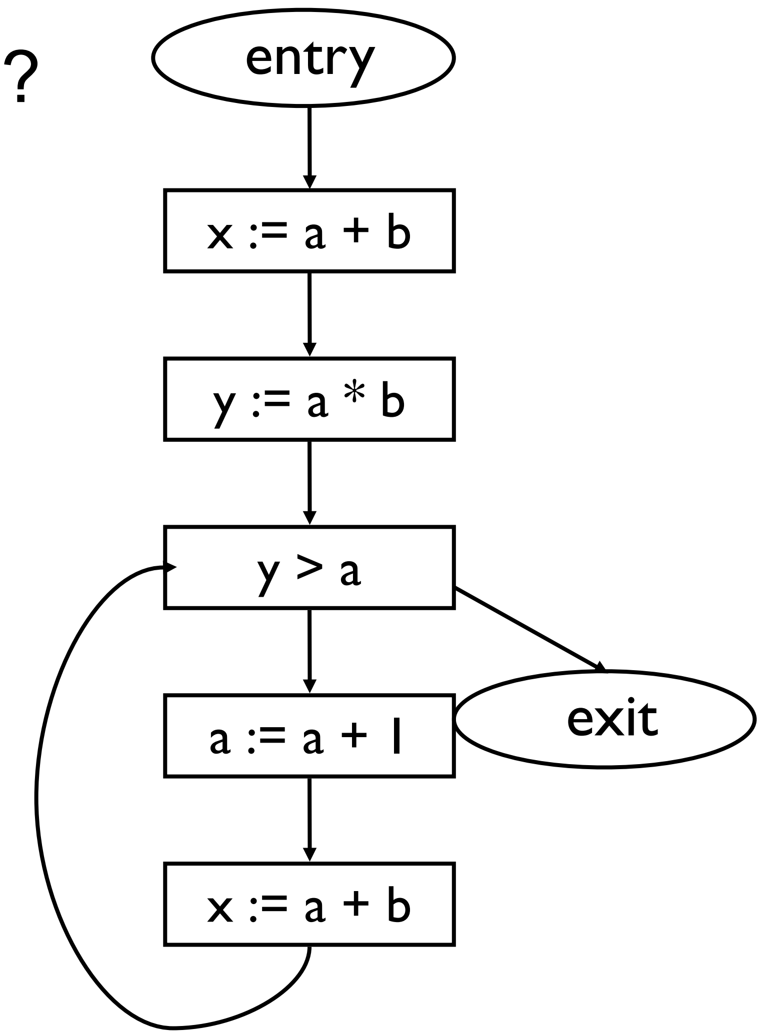
- Is expression e available?
- Facts:
  - a + b is available
  - a * b is available
  - a + 1 is available



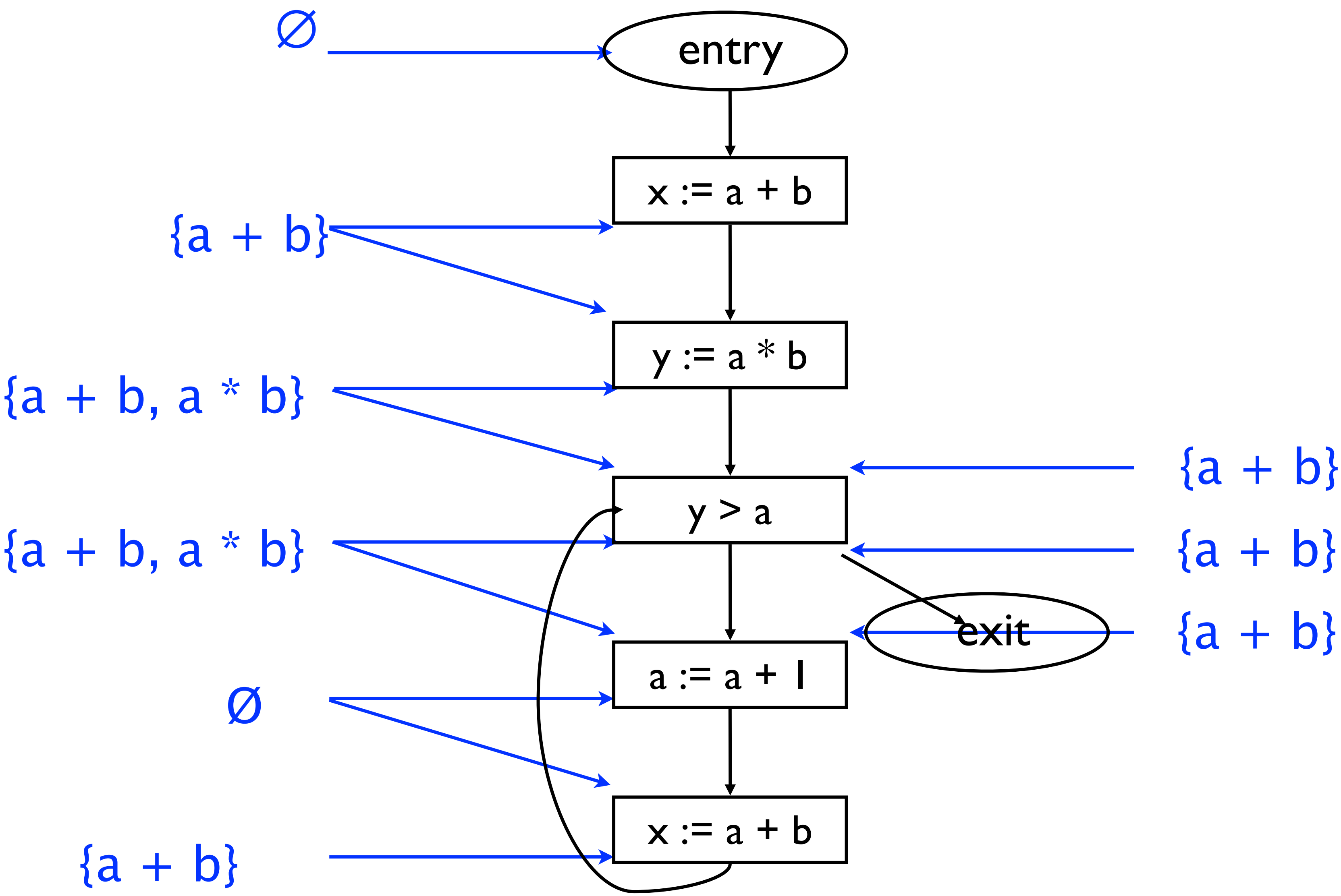
Gen and Kill

- What is the effect of each statement on the set of facts?

Stmt	Gen	Kill
x := a + b	a + b	
y := a * b	a * b	
a := a + 1		a + 1, a + b, a * b



Computing Available Expressions



Terminology

- A *joint point* is a program point where two branches meet

- Available expressions is a *forward must* problem
  - Forward = Data flow from in to out
  - Must = At join point, property must hold on all paths that are joined

Data Flow Equations

- Let s be a statement
  - succ(s) = { immediate successor statements of s }
  - pred(s) = { immediate predecessor statements of s}
  - in(s) = program point just before executing s
  - out(s) = program point just after executing s

- $\text{in}(s) = \bigcap_{s' \in \text{pred}(s)} \text{out}(s')$

- $\text{out}(s) = \text{gen}(s) \cup (\text{in}(s) - \text{kill}(s))$
  - Note: These are also called *transfer functions*

Liveness Analysis

- A variable v is *live* at program point p if
  - v will be used on some execution path originating from p...
  - before v is overwritten

- Optimization
  - If a variable is not live, no need to keep it in a register
  - If variable is dead at assignment, can eliminate assignment

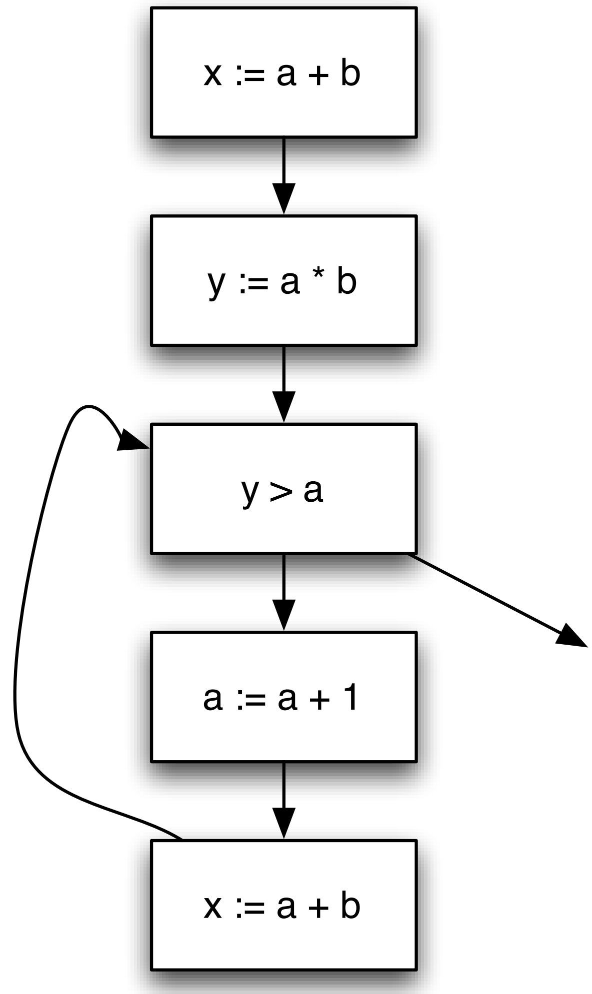
Data Flow Equations

- Available expressions is a forward must analysis
  - Data flow propagate in same dir as CFG edges
  - Expr is available only if available on all paths
- Liveness is a *backward may* problem
  - To know if variable live, need to look at future uses
  - Variable is live if used on some path
- $\text{out}(s) = \bigcup_{s' \in \text{succ}(s)} \text{in}(s')$
- $\text{in}(s) = \text{gen}(s) \cup (\text{out}(s) - \text{kill}(s))$

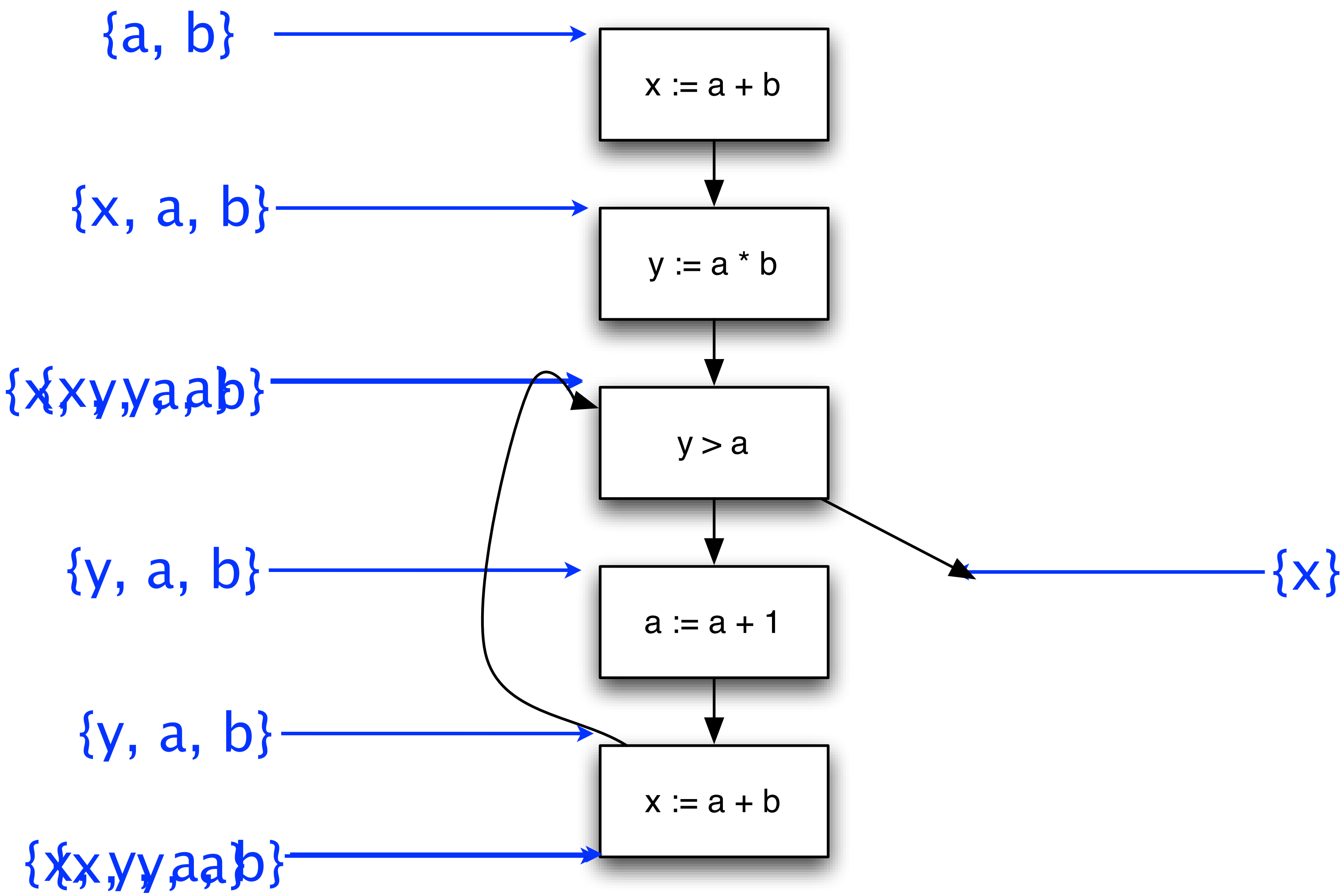
Gen and Kill

- What is the effect of each statement on the set of facts?

Stmt	Gen	Kill
x := a + b	a, b	x
y := a * b	a, b	y
y > a	a, y	
a := a + 1	a	a



Computing Live Variables



Very Busy Expressions

- An expression e is *very busy* at point p if
  - On every path from p, expression e is evaluated before the value of e is changed

- Optimization
  - Can hoist very busy expression computation

- What kind of problem?
  - Forward or backward? backward
  - May or must? must

Reaching Definitions

- A *definition* of a variable v is an assignment to v
- A definition of variable v reaches point p if
  - There is no intervening assignment to v

- Also called def-use information

- What kind of problem?
  - Forward or backward? forward
  - May or must? may

Space of Data Flow Analyses

	May	Must
Forward	Reaching definitions	Available expressions
Backward	Live variables	Very busy expressions

- Most data flow analyses can be classified this way
  - A few don't fit: bidirectional analysis
- Lots of literature on data flow analysis

Solving data flow equations

- Let's start with forward may analysis
  - Dataflow equations:
    - $in(s) = \bigcup_{s' \in pred(s)} out(s')$
    - $out(s) = gen(s) \cup (in(s) - kill(s))$
- Need algorithm to compute in and out at each stmt
- Key observation: out(s) is *monotonic* in in(s)
  - gen(s) and kill(s) are fixed for a given s
  - If, during our algorithm, in(s) grows, then out(s) grows
  - Furthermore, out(s) and in(s) have max size
- Same with in(s)
  - in terms of out(s') for precedessors s'

Solving data flow equations (cont'd)

- Idea: fixpoint algorithm
  - Set out(entry) to emptyset
    - E.g., we know no definitions reach the entry of the program
  - Initially, assume in(s), out(s) empty everywhere else, also
  - Pick a statement s
    - Compute in(s) from predecessors' out's
    - Compute new out(s) for s
  - Repeat until nothing changes
- Improvement: use a worklist
  - Add statements to worklist if their in(s) might change
  - Fixpoint reached when worklist is empty

Forward May Data Flow Algorithm

$out(entry) = \varnothing$
for all other statements s
  $out(s) = \varnothing$
W = *all statements*   *// worklist*
while W not empty
  take s from W
    $in(s) = \cup_{s' \in pred(s)} out(s')$
    $temp = gen(s) \cup (in(s) - kill(s))$
    if $temp \neq out(s)$ then
      $out(s) = temp$
      $W := W \cup succ(s)$
    end
end

Generalizing

	May	Must
Forward	$in(s) = \bigcup_{s' \in pred(s)} out(s')$ $out(s) = gen(s) \cup (in(s) - kill(s))$ $out(entry) = \varnothing$ initial out elsewhere = $\varnothing$	$in(s) = \bigcap_{s' \in pred(s)} out(s')$ $out(s) = gen(s) \cup (in(s) - kill(s))$ $out(entry) = \varnothing$ initial out elsewhere = {all facts}
Backward	$out(s) = \bigcup_{s' \in succ(s)} in(s')$ $in(s) = gen(s) \cup (out(s) - kill(s))$ $in(exit) = \varnothing$ initial in elsewhere = $\varnothing$	$out(s) = \bigcap_{s' \in succ(s)} in(s')$ $in(s) = gen(s) \cup (out(s) - kill(s))$ $in(exit) = \varnothing$ initial out elsewhere = {all facts}

Forward Analysis

```
out(entry) = ∅
for all other statements s
  out(s) = ∅
W = all statements      // worklist
while W not empty
  take s from W
    in(s) = ∪_{s′∈pred(s)} out(s′)
    temp = gen(s) ∪ (in(s) - kill(s))
    if temp ≠ out(s) then
      out(s) = temp
      W := W ∪ succ(s)
    end
end
```

May

```
out(entry) = ∅
for all other statements s
  out(s) = all facts
W = all statements
while W not empty
  take s from W
    in(s) = ∩_{s′∈pred(s)} out(s′)
    temp = gen(s) ∪ (in(s) - kill(s))
    if temp ≠ out(s) then
      out(s) = temp
      W := W ∪ succ(s)
    end
end
```

Must

Backward Analysis

May	Must
in(exit) = ∅	in(exit) = ∅
for all other statements s	for all other statements s
in(s) = ∅	in(s) = *all facts*
W = *all statements*	W = *all statements*
while W not empty	while W not empty
take s from W	take s from W
out(s) = $\cup_{s' \in succ(s)}$ in(s′)	out(s) = $\cap_{s' \in succ(s)}$ in(s′)
temp = gen(s) ∪ (out(s) - kill(s))	temp = gen(s) ∪ (out(s) - kill(s))
if temp ≠ in(s) then	if temp ≠ in(s) then
in(s) = temp	in(s) = temp
W := W ∪ pred(s)	W := W ∪ pred(s)
end	end
end	end

Practical Implementation

- Represent set of facts as bit vector
  - $Fact_i$ represented by bit i
  - Intersection = bitwise and, union = bitwise or, etc

- “Only” a constant factor speedup
  - But very useful in practice

Generalizing Further

- Observe out(s) is a *function* of out(s') for preds s'

$$out(s) = gen(s) \cup ((\cup_{s' \in pred(s)} out(s')) - kill(s))$$

  - We can define other kinds of functions, to compute other kinds of information using dataflow analysis!
- Example: constant propagation
  - Facts — variable x has value n (at this program point)
  - Not quite gen/kill:

```
/* facts: a = 1, b = 2 */
x = a + b
/* facts: a = 1, b = 2, x = 3 */
```

    - Fact that x is 3 not determined syntactically by statement
    - So, how can we use data flow analysis to handle this case?

Partial Orders

- To generalize data flow analysis, need to introduce two mathematical structures:
  - Partial orders
  - Lattices

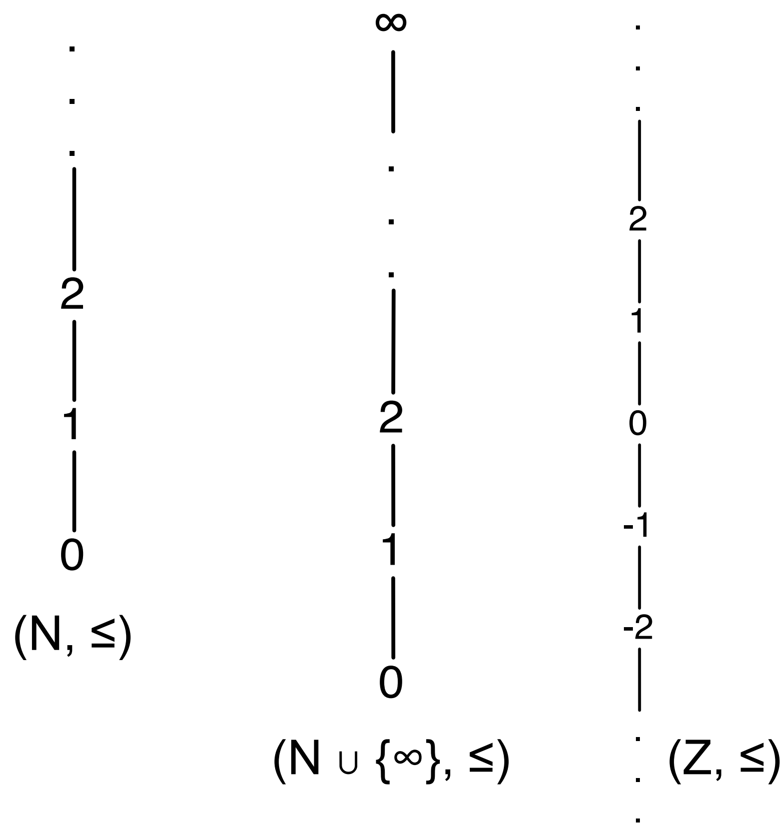
- A *partial order* (p.o.) is a pair $(P, \leq)$ such that
  - $\leq \subseteq P \times P$
  - $\leq$ is reflexive: $x \leq x$
  - $\leq$ is anti-symmetric: $x \leq y$ and $y \leq x \Rightarrow x = y$
  - $\leq$ is transitive: $x \leq y$ and $y \leq z \Rightarrow x \leq z$

Examples

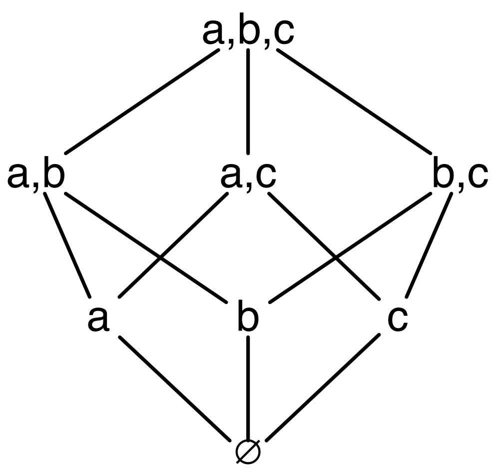
- $(N, \leq)$
  - Natural numbers with standard inequality
- $(N \cup \{\infty\}, \leq)$
  - Natural numbers plus infinity, with standard inequality
- $(Z, \leq)$
  - Integers with standard inequality
- For any set S, $(2^S, \subseteq)$
  - The *powerset partial order*
- For any set S, $(S, =)$
  - The *discrete partial order*
- A *2-crown* $(\{a,b,c,d\}, \{a<c, a<d, b<c, b<d\})$

Drawing Partial Orders

- We can write partial orders as graphs using the following conventions
  - Nodes are elements of the p.o.
  - Edge from element lower on page to high on page means lower element is strictly less than higher element

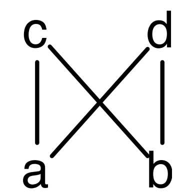


Drawing Partial Orders (cont'd)



({a,b,c}, ⊆)

({a,b,c}, =)



2-crown

Meet and Join Operations

- $\sqcap$ is the *meet* or *greatest lower bound* operation:
  - $x \sqcap y \leq x$ and $x \sqcap y \leq y$
  - if $z \leq x$ and $z \leq y$ then $z \leq x \sqcap y$
- $\sqcup$ is the *join* or *least upper bound* operation:
  - $x \leq x \sqcup y$ and $y \leq x \sqcup y$
  - if $x \leq z$ and $y \leq z$ then $x \sqcup y \leq z$

Examples

- $(\mathbb{N}, \leq)$, $(\mathbb{N} \cup \{\infty\}, \leq)$, $(\mathbb{Z}, \leq)$
  - $\sqcap = \min$, $\sqcup = \max$
- For any set S, $(2^S, \subseteq)$
  - $\sqcap = \cap$, $\sqcup = \cup$
- For any set S, $(S, =)$
  - $\sqcap$ and $\sqcup$ only defined when element is the same
- A *2-crown* $(\{a,b,c,d\}, \{a<c, a<d, b<c, b<d\})$
  - $a \sqcup b$ and $c \sqcap d$ undefined

Lattices

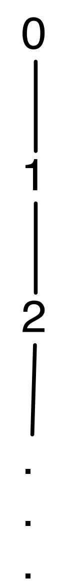
- A p.o. is a *lattice* if $\sqcap$ and $\sqcup$ are defined on any two elements
  - A partial order is a *complete lattice* if $\sqcap$ and $\sqcup$ are defined on any set
- A lattice has unique elements $\bot$ ("bottom") and $\top$ ("top") such that
  - $x \sqcap \bot = \bot$ $\quad$ $x \sqcup \bot = x$
  - $x \sqcap \top = x$ $\quad$ $x \sqcup \top = \top$
- In a lattice,
  - $x \leq y$ iff $x \sqcap y = x$
  - $x \leq y$ iff $x \sqcup y = y$

Examples

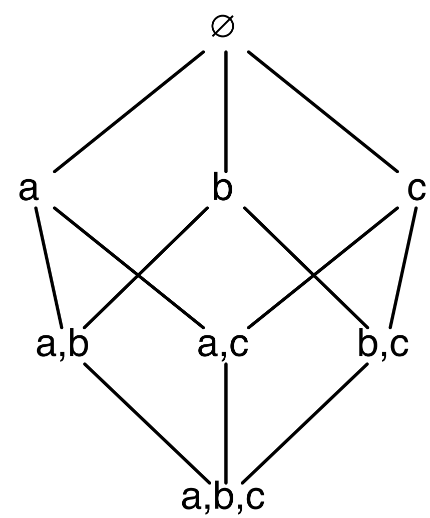
- $(N, \leq)$
  - $\perp = 0$, $\top$ undefined; is a lattice, but not a complete lattice
- $(N \cup \{\infty\}, \leq)$
  - $\perp = 0$, $\top = \infty$; is a complete lattice
- $(Z, \leq)$
  - $\perp$, $\top$ undefined; is a lattice, but not a complete lattice
- For any set S, $(2^S, \subseteq)$
  - $\perp = \varnothing$, $\top = S$, is a complete lattice
- For any set S, $(S, =)$
  - $\perp$, $\top$ undefined; not a lattice
- A *2-crown* $(\{a,b,c,d\}, \{a<c, a<d, b<c, b<d\})$
  - $\perp$, $\top$ undefined; not a lattice

Flipping a Lattice

- Lemma: If (P, ≤) is a lattice, then (P, λxy.y ≤ x) is also a lattice
  - I.e., if we flip the sense of ≤, we still have a lattice
- Examples:



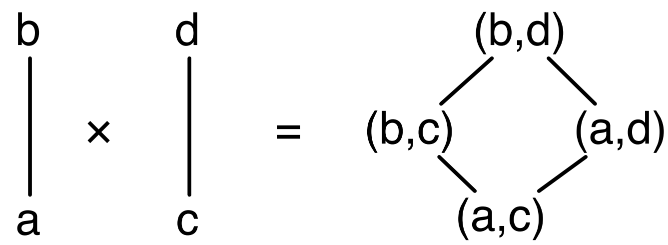
(N, ≥)

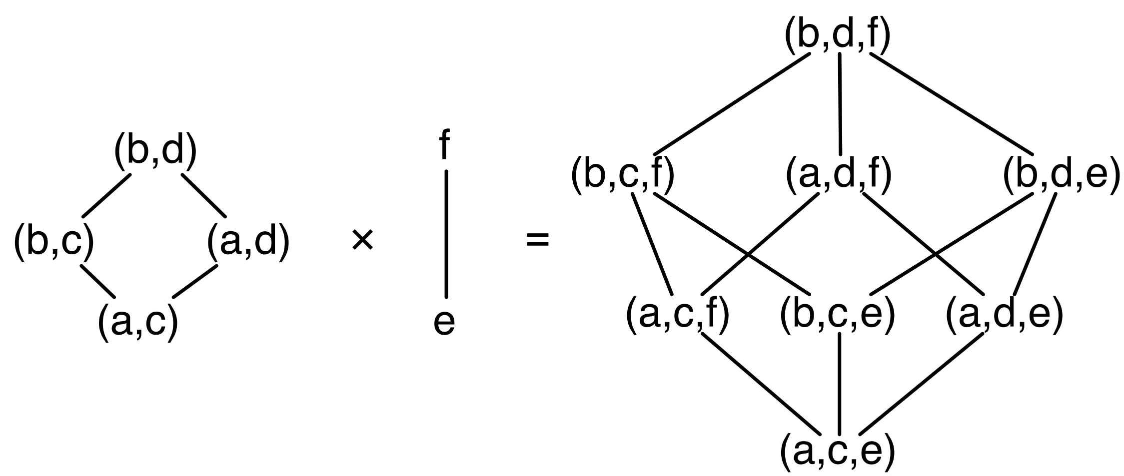


({a,b,c}, ⊇)

Cross-product lattice

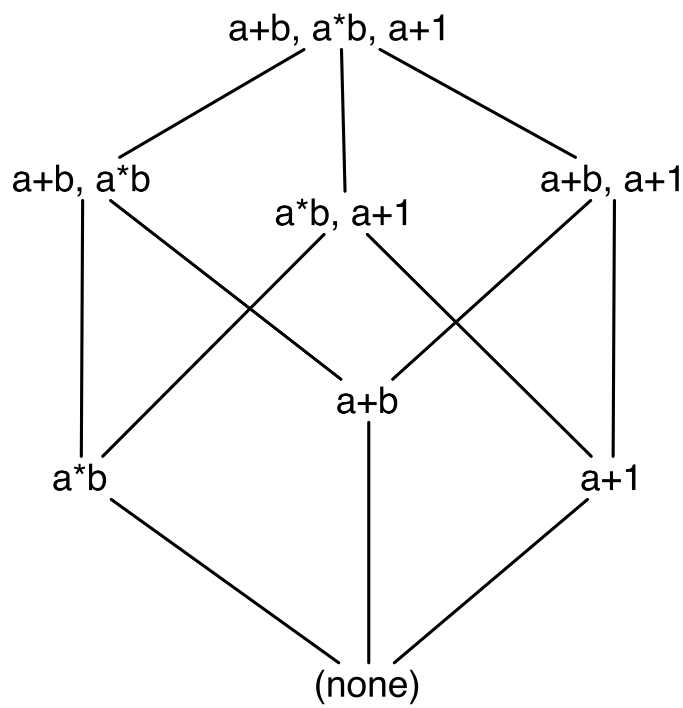
- Lemma: Suppose $(P, \leq_1)$ and $(Q, \leq_2)$ are lattices. Then $(P \times Q, \leq)$ is also a lattice, where
  - $(p,q) \leq (p', q')$ iff $p \leq_1 p'$ and $q \leq_2 q'$
  - (Can also take cross product of more than 2 lattices, in the natural way)
- Examples:





Data Flow Facts and Lattices

- Sets of dataflow facts form the powerset lattice
  - Example: Available expressions



Transfer Functions

- Recall this step from *forward must* analysis:

$$in(s) := \cap_{s' \in pred(s)} out(s')$$

$$temp := gen(s) \cup (in(s) - kill(s))$$

- Let's recast this in terms of powerset lattice
  - $\cap$ is $\sqcap$ in the lattice
  - gen(s), kill(s) are fixed
    - So temp is a function of in(s)
  - Putting this together:

$$in(s) := \sqcap_{s' \in pred(s)} out(s')$$

$$temp := f_s(in(s))$$

$$\text{where } f_s(x) = gen(s) \cup (x - kill(s))$$

f_s is a *transfer function*

Forward May Analysis

- What about forward may analysis?

$$in(s) := \cup_{s' \in pred(s)} out(s')$$

$$temp := gen(s) \cup (in(s) - kill(s))$$

  - We can just use the flipped powerset lattice
    - $\cup$ is $\sqcap$ is that lattice
  - So we get the same equations

$$in(s) := \sqcap_{s' \in pred(s)} out(s')$$

$$temp := f_s(in(s))$$

$$\text{where } f_s(x) = gen(s) \cup in(s) - kill(s)$$

- Same idea for must/may backward analysis
  - But still separate from forward analysis

Initial Facts

- Recall also from *forward must* analysis:

  out(entry) = ∅

  initial out elsewhere = {all facts}

- Values of these in lattice terms depends on analysis
  - Available expressions
    - out(entry) is the same as $\bot$
    - initial out elsewhere is the same as $\top$
  - Reaching definitions (with $\leq$ as $\supseteq$)
    - out(entry) is ∅ which is $\top$ in this lattice (flipped powerset)
    - initial out elsewhere is also $\top$

Data Flow Analysis, over Lattices

```
out(entry) = (as given)
for all other statements s
  out(s) = ⊤
W = all statements      // worklist
while W not empty
  take s from W
    in(s) = ⊓s′∈pred(s) out(s′)
    temp = fs(in(s))
    if temp ≠ out(s) then
      out(s) = temp
      W := W ∪ succ(s)
    end
end
```

Forward

```
in(exit) = (as given)
for all other statements s
  in(s) = ⊤
W = all statements
while W not empty
  take s from W
    out(s) = ⊓s′∈succ(s) in(s′)
    temp = fs(out(s))
    if temp ≠ in(s) then
      in(s) = temp
      W := W ∪ pred(s)
    end
end
```

Backward

(Red = varies by analysis)

DFA over Lattices, cont'd

- A dataflow analysis is defined by 4 things:
  - Forward or backward
  - The lattice
    - Data flow facts
    - $\sqcap$ operation
      - In terms of gen/kill dfa, this specifies may or must
    - $\top$ value
      - In terms of gen/kill dfa, this specifies the initial facts assumed at each statement
  - Transfer functions
    - In terms of gen/kill dfa, this defines gen and kill
  - Facts at entry (for forward) or exit (for backward)
    - In terms of gen/kill dfa, this defines set of facts for entry or exit node

Four Analyses as Lattices (P, $\leq$)

- Available expressions
  - Forward analysis
  - P = sets of expressions
  - $S1 \sqcap S2 = S1 \cap S2$
  - Top = set of all expressions
  - Entry facts = $\emptyset$ = no expressions available at entry
- Reaching Definitions
  - Forward analysis
  - P = set of definitions (assignment statements)
  - $S1 \sqcap S2 = S1 \cup S2$
  - Top = empty set
  - Entry facts = $\emptyset$ = no definitions reach entry

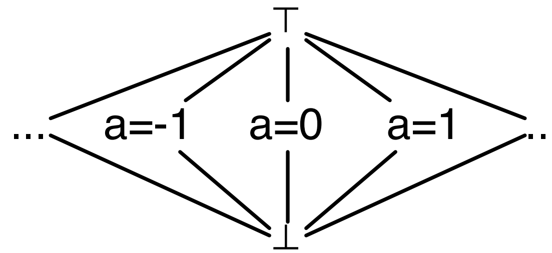
Four Analyses as Lattices (P, ≤)

- Very busy expressions
  - Backward analysis
  - P = sets of expressions
  - S1 ⊓ S2 = S1 ∩ S2
  - Top = set of all expressions
  - Exit facts = ∅ = no expressions busy at exit
- Live variables
  - Backward analysis
  - P = set of variables
  - S1 ⊓ S2 = S1 ∪ S2
  - Top = empty set
  - Exit facts = ∅ = no variables live at exit

Constant Propagation

- Idea: maintain possible value of each variable

L_a =



  - ⊤ = initial value = haven't seen assignment to a yet
  - ⊥= multiple different possible values for a

- DFA definition:
  - Forward analysis
  - Lattice = $L_a \times L_b \times \ldots$ (for all variables in program)
    - I.e., maintain one possible value of each variable
  - Initial facts (at entry) = ⊤ (variables all unassigned)

Monotonicity and Desc. Chain

- A function f on a partial order is *monotonic* (or *order preserving*) if

$$x \leq y \Rightarrow f(x) \leq f(y)$$

  - Examples
    - $\lambda x.x+1$ on partial order $(Z, \leq)$ is monotonic
    - $\lambda x.-x$ on partial order $(Z, \leq)$ is not monotonic
- Transfer functions in gen/kill DFA are monotonic
  - temp = gen(s) ∪ (in(s) - kill(s))
    - Holds because gen(s) and kill(s) are fixed
    - Thus, if we shrink in(s), temp can only shrink
- A *descending chain* in a lattice is a sequence
  - $x0 \sqsupset x1 \sqsupset x2 \sqsupset \ldots$
  - *Height* of lattice = length of longest descending chain

Monotonicity and Transfer Fns

- If f_s is monotonic, how often can we apply this step?

$$in(s) = \sqcap_{s' \in pred(s)} out(s')$$
$$temp = f_s(in(s))$$

  - Claim: $out(s)$ only shrinks
    - Proof: $out(s)$ starts out as $\top$
    - Assume $out(s')$ shrinks for all predecessors s' of s
    - Then $\sqcap_{s' \in pred(s)} out(s')$ shrinks
    - Since f_s monotonic, $f_s(\sqcap_{s' \in pred(s)} out(s'))$ shrinks

Termination

- Suppose we have a DFA with
  - Finite height lattice
  - Monotonic transfer functions

  Both hold for gen/kill probs and constant prop
- Then, at every step in DFA we
  - Remove a statement from the worklist, and/or
  - Strictly decrease some dataflow fact at a program point
    - (By monotonicity)
    - Only add new statements to worklist after strict decrease
  - ⇒ termination! (by finite height)
- Moreover, must terminate in O(nk) time
  - n = # of statements in program
  - k = height of lattice
  - (assumes meet operation takes O(1) time)

Fixpoints

- We always start with $\top$
  - E.g., every expr is available, no defns reach this point
  - Most optimistic assumption
  - Strongest possible hypothesis
    - = true of fewest number of states
- Revise as we encounter contradictions
  - Always move down in the lattice (with meet)
- Result: A *greatest fixpoint* solution of the data flow equations

Least vs. Greatest Fixpoints

- Dataflow tradition: Start with $\top$, use $\sqcap$
  - Computes a greatest fixpoint
  - Technically, rather than a lattice, we only need a
    - *finite height meet semilattice with top*
    - (*meet semilattice* = $a \sqcap b$ defined on any a,b but $a \sqcup b$ may not be defined)

- Denotational semantics trad.: Start with $\bot$, use $\sqcup$
  - Computes least fixpoint

- So, direction of DFA may depend on community author comes from...

Distributive Dataflow Problems

- A monotonic transfer function f also satisfies

$$f(x \sqcap y) \le f(x) \sqcap f(y)$$

  - Proof: By monotonicity, $f(x \sqcap y) \le f(x)$ and $f(x \sqcap y) \le f(y)$, i.e., $f(x \sqcap y)$ is a lower bound of $f(x)$ and $f(y)$. But then since $\sqcap$ is the greatest lower bound, $f(x \sqcap y) \le f(x) \sqcap f(y)$.

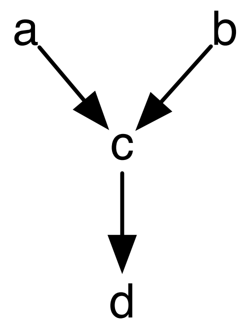
- A transfer function f is *distributive* if it satisfies

$$f(x \sqcap y) = f(x) \sqcap f(y)$$

  - Notice this is stronger than monotonicity

Benefit of Distributivity

- Suppose we have the following CFG with four statements, a,b,c,d, with transfer fns f_a, f_b, f_c, f_d



- Then joins lose no information!
  - out(a) = fa(in(a))
  - out(b) = fb(in(b))
  - out(c) = fc(out(a) ⊓ out(b)) = fc(fa(in(a)) ⊓ fb(in(b)) = fc(fa(in(a))) ⊓ fc(fb(in(b)))
  - out(d) = fd(out(c)) = fd(fc(fa(in(a))) ⊓ fc(fb(in(b))) = fd(fc(fa(in(a)))) ⊓ fd(fc(fb(in(b))))

Accuracy of Data Flow Analysis

- Ideally, we would like to compute the *meet over all paths* (MOP) solution:
  - If p is a path through the CFG, let f_p be the composition of transfer functions for the statements along p
  - Let $path(s)$ be the set of paths from the entry to s
  - Define

$$MOP(s) = \sqcap_{p \in path(s)} f_p(\top)$$

    - I.e., $MOP(s)$ is the set of dataflow facts if we separately apply the transfer functions along every path (assuming $\top$ is the initial value at the entry) and then apply $\sqcap$ to the result
    - This is the best we could possibly do if we want one data flow fact per program point and we ignore conditional tests along the path
- If a data flow problem is distributive, then solving the data flow equations in the standard way yields the MOP solution!

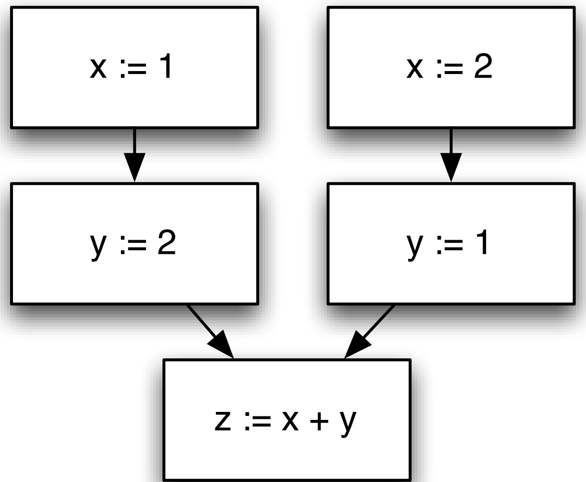
What Problems are Distributive?

- Analyses of *how* the program computes
  - Live variables
  - Available expressions
  - Reaching definitions
  - Very busy expressions

- All gen/kill problems are distributive

A Non-Distributive Example

- Constant propagation



  - {x=1,y=2} ⊓ {x=2,y=1} = {x=⊥, y=⊥}
  - The join at in(z:=x+y) loses information
  - But in fact, z=3 every time we run this program
- In general, analysis of *what* the program computes in not distributive

Basic Blocks

- Recall a *basic block* is a sequence of statements s.t.
  - No statement except the last in a branch
  - There are no branches to any statement in the block except the first

- In some data flow implementations,
  - Compute gen/kill for each basic block as a whole
    - Compose transfer functions
  - Store only in/out for each basic block
  - Typical basic block ~5 statements
    - At least, this used to be the case...

Order Matters

- Assume forward data flow problem
  - Let $G = (V, E)$ be the CFG
  - Let k be the height of the lattice
- If G acyclic, visit in topological order
  - Visit head before tail of edge
- Running time $O(|E|)$
  - No matter what size the lattice

Order Matters — Cycles

- If G has cycles, visit in reverse postorder
  - Order from depth-first search
  - (Reverse for backward analysis)
- Let Q = max # back edges on cycle-free path
  - Nesting depth
  - Back edge is from node to ancestor in DFS tree
- If $\forall x.f(x) \leq x$ (sufficient, but not necessary), then running time is $O((Q+1)|E|)$
  - Proportional to structure of CFG rather than lattice

Flow-Sensitivity

- Data flow analysis is *flow-sensitive*
  - The order of statements is taken into account
  - I.e., we keep track of facts per program point

- Alternative: *Flow-insensitive* analysis
  - Analysis the same regardless of statement order
  - Standard example: types
    - /* x : int */ x := ... /* x : int */

Data Flow Analysis and Functions

- What happens at a function call?
  - Lots of proposed solutions in data flow analysis literature
- In practice, only analyze one procedure at a time
- Consequences
  - Call to function kills all data flow facts
  - May be able to improve depending on language, e.g., function call may not affect locals

More Terminology

- An analysis that models only a single function at a time is *intraprocedural*
- An analysis that takes multiple functions into account is *interprocedural*
- An analysis that takes the whole program into account is *whole program*

- Note: *global* analysis means "more than one basic block," but still within a function
  - Old terminology from when computers were slow...

Data Flow Analysis and The Heap

- Data Flow is good at analyzing local variables
  - But what about values stored in the heap?
  - Not modeled in traditional data flow
- In practice: *x := e
  - Assume all data flow facts killed (!)
  - Or, assume write through x may affect any variable whose address has been taken
- In general, hard to analyze pointers

Proebsting's Law

- Moore's Law: Hardware advances double computing power every 18 months.

- Proebsting's Law: Compiler advances double computing power every 18 *years*.

  - Not so much bang for the buck!

DFA and Defect Detection

- LCLint - Evans et al. (UVa)
- METAL - Engler et al. (Stanford, now Coverity)
- ESP - Das et al. (MSR)
- FindBugs - Hovemeyer, Pugh (Maryland)
  - For Java. The first three are for C.

- Many other one-shot projects
  - Memory leak detection
  - Security vulnerability checking (tainting, info. leaks)