Advanced Program Analyses for Object-oriented Systems

Dr. Barbara G. Ryder
Rutgers University
http://www.cs.rutgers.edu/~ryder
http://prolangs.rutgers.edu/
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PROLANGS

- Languages/Compilers and Software Engineering
  - Algorithm design and prototyping
- Mature research projects
  - Incremental dataflow analysis, TOPLAS 1988, POPL'88, POPL'90, TSE 1990, ICSE97, ICSE99
  - Pointer analysis of C programs, POPL'91, PLDI'92
  - Side effect analysis of C systems, PLDI'93, TOPLAS 2001
  - *Points-to* and *def-use* analysis of statically-typed object-oriented programs (C++/Java) - POPL'99, OOPSLA'01, ISSTA'02,Invited paper at CC'03, TOSEM 2005, ICSM 2005
  - Profiling by sampling in Java feedback directed optimization, LCPC'00, PLDI'01, OOPSLA'02
  - Analysis of program fragments (i.e., modules, libraries), FSE'99, CC'01, ICSE'03, IEEE-TSE 2004

PROLANGS

- Ongoing research projects
  - Change impact analysis for object-oriented systems PASTE'01, DCS-TR-533(9/03), OOPSLA'04, ICSM'05, FSE'06, IEEE-TSE 2007, ISSTA'07
  - Robustness testing of Java web server applications, DSN'01, ISSTA'04, IEEE-TSE 2005, Eclipse Wkshp OOPSLA'05, ICSE'07
  - Analyses to aid performance understanding of programs built with frameworks (e.g., Tomcat, Websphere) ISSTA'07
  - Using more precise static analyses information SE applications, SCAM'06, JSME'07, PASTE'07

Course Outline

- Lecture 1
  - Theoretical foundations of dataflow analysis
  - Issues in analyzing OO programs
    - Polymorphism
    - Dynamic class loading and reflection
    - Use of libraries and frameworks
  - What is reference analysis?

Course Outline

- Lecture 2
  - Type-based call graph construction
    - CHA, RTA
  - Dimensions of analysis precision
  - Context-insensitive reference analysis
    - Flow sensitivity, context sensitivity, field sensitivity
    - XTA, FieldSens
    - Client analyses: Side effects, devirtualization, thread/method-local objects

Course Outline

- Lecture 3
  - Context-sensitive reference analyses of OO programs
    - K-CFA versus object-sensitive analysis (ObjSens)
    - Client analyses: cast check removal, devirtualization
  - Dynamic analysis of OO programs
    - Finding 'hot methods' for JIT compilation through sampling

Course Outline

- Lecture 4
  - Experiences with dynamic sampling for FDO
  - Optimizations for OO programs
    - Method inlining w & w/o guards
      - Pre-existence
    - Control-flow path splitting
    - Method specialization
    - Object layout for better cache performance
    - JIKES RVM online FDO experiments

Course Outline

- Lecture 5
  - Analysis uses in testing and program understanding
  - Uses of analysis in software tools
    - Testing exception handling code
    - Interclass dependence analysis for class testing
    - Blended analysis for performance diagnosis

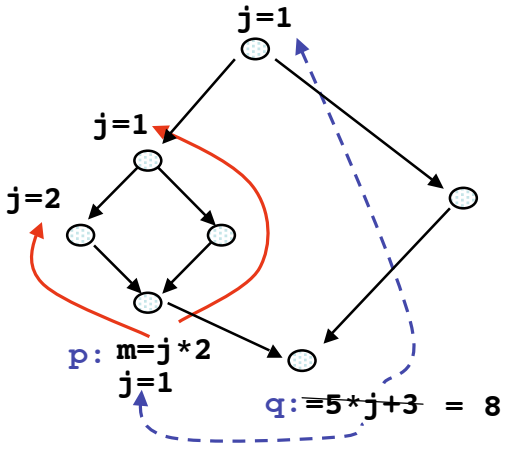
Lecture 1 - Outline

- Motivation
- Theoretical foundations of dataflow analysis
  - Lattices, monotone DF frameworks, fixed point theorem,
    - Convergence, complexity, precision, safety properties
- How analysis of OO programs is different from classical (Fortran) analysis
  - Polymorphism
  - Dynamic class loading and reflection
  - Use of libraries and frameworks
- Call graph construction - enabling technology

Example

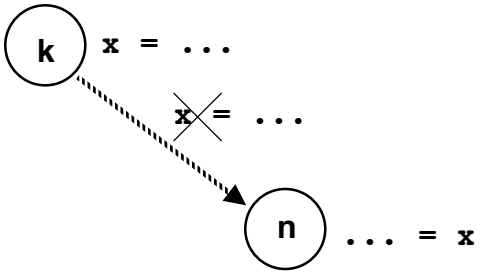
```
int f(){
   int j,k;
   j=1;
   if(…){j=1;
         if(…) j=2;
         k=j*2;
      p: m=j*2;
         j=1;}
   else {…}
q: k=5*j+3;
   return k;
}
```

Are any of these expressions at p and q, compile-time constants?



Reaching Definitions Dataflow Problem

- *Definition* A statement which may change the value of a variable
- A definition of a variable *x* at node *k* *reaches* node *n* if there is a definition-clear path from *k* to *n*.

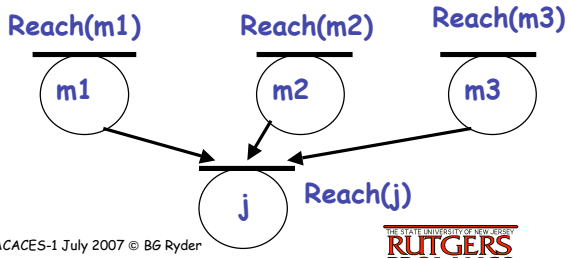


Reaching Definitions Equations

$$Reach(j) = \bigcup_{m \in Pred(j)} \{ Reach(m) \cap pres(m) \cup dgen(m) \}$$

where:

pres(m) is the set of defs preserved through node *m*
dgen(m) is the set of defs generated at node *m*
Pred(j) is the set of immediate predecessors of node *j*



Questions

- How do we solve these dataflow eqns?
  - How do we know that a solution exists?
  - How do we know how quickly a solution can be found?
- How do we formulate other dataflow problems that are useful for code optimization?
  - What do we need to define to formulate a dataflow analysis?
- How do we define dataflow problems that involve method calls (interprocedural)?

Answers

- Firm, mathematical foundations underlie dataflow analysis
  - Lattice theory, partially ordered sets
  - Functions with specific properties to ensure convergence
    - Fixed point theorem provides solution procedure
- Serves as underpinnings of all static analyses in compilation
  - But not necessary to explain all analyses using this formalism

Lattice Theory

- Partial ordering $\leq$
  - Relation between pairs of elements
  - Reflexive $x \leq x$
  - Anti-symmetric $x \leq y,\ y \leq x \Rightarrow x = y$
  - Transitive $x \leq y,\ y \leq z \Rightarrow x \leq z$
- Partially ordered set (Set S, $\leq$)
- 0 Element $0 \leq x,\ \forall x \in S$
- 1 Element $1 \geq \forall x \in S$

A partially ordered set need not have 0 or 1 element.

Lattice Theory

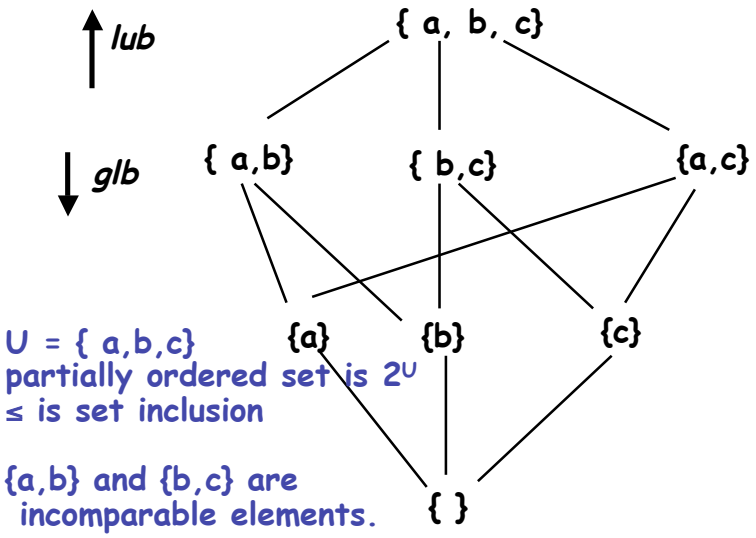
- Greatest lower bound (glb)
  a, b $\in$ partially ordered set S, c $\in$ S is glb(a, b)
  if c $\leq$ a and c $\leq$ b then
  for any z $\in$ S, z $\leq$ a, z $\leq$ b $\Rightarrow$ z $\leq$ c

if glb is unique it is called the meet (Λ) of a and b

- Least upper bound (lub)
  a, b $\in$ partially ordered set S, c $\in$ S is lub(a,b)
  if c $\geq$ a and c $\geq$ b then
  for any d $\in$ S, d $\geq$ a, d $\geq$ b $\Rightarrow$ c $\leq$ d.

if lub is unique is called the join (υ) of a and b

Partially Ordered Set Example



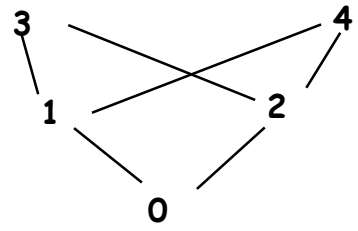
U = { a,b,c}
partially ordered set is 2^U
≤ is set inclusion

{a,b} and {b,c} are incomparable elements.

Definition of a Lattice (L, Λ, υ)

- L, a partially ordered set under ≤ such that every pair of elements has a unique glb (meet) and lub (join).
- A lattice need not contain an 0 or 1 element.
- A finite lattice must contain an 0 and 1 element.
- Not every partially ordered set is a lattice.
- If a ≤ x, ∀ x ∈ L, then a is 0 element of L
- If x ≤ a, ∀ x ∈ L, then a is 1 element of L

a partially ordered set, but not a lattice



There is no lub(3,4) in this partially ordered set so it is not a lattice.

Examples of Lattices

- H = (2^U , ∩, ∪) where U is a finite set
  - glb (s1, s2) is (s1 ∧ s2) which is s1 ∩ s2
  - lub (s1, s2) is (s1 ∨ s2) which is s1 ∪ s2
- J = (N_1 , gcd, lowest common multiple)
  - partial order relation is integer divide on N_1 n1 | n2 if division is even
  - lub (n1, n2) is n1 ∨ n2 = lowest common multiple(n1,n2)
  - glb (n1,n2) is n1 ∧ n2 = greatest common divisor (n1,n2)

Chain

- A partially ordered set C where, for every pair of elements

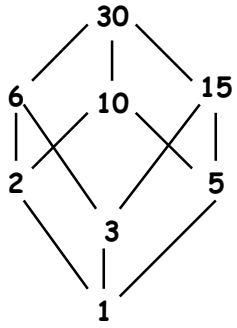
c1, c2 ∈ C, either c1 ≤ c2 or c2 ≤ c1.

e.g., { } ≤ {a} ≤ {a,b} ≤ {a,b,c}

and from the lattice as shown here,

1 ≤ 2 ≤ 6 ≤ 30

1 ≤ 3 ≤ 15 ≤ 30



Lattices are used in dataflow analysis to argue the existence of a solution obtainable through fixed-point iteration.

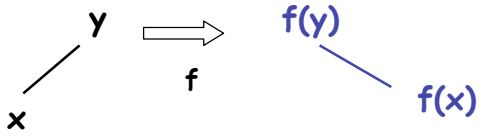
Finite length lattice: if every chain in lattice is finite

Functions on a Lattice

- (S,≤) partially ordered set, f: S --> S is monotonic iff

$$\forall x, y \in S,\ x \le y \Rightarrow f(x) \le f(y)$$

- Monotonic functions preserve domain ordering in their range values



- Distributive functions allow function application to distribute over the meet

$$\forall x, y \in S,\ f(x) \wedge f(y) = f(x \wedge y)$$

Fixed point theorem - Why it works?

Intutition:

Given a 0 in lattice and monotonic function f, $0 \leq f(0)$.

Apply f again and obtain

$0 \leq f(0) \leq f(f(0)) = f^2(0)$

Continuing,

$0 \leq f(0) \leq f^2(0) \leq f^3(0) \leq \ldots \leq f^k(0) = f^{k+1}(0)$ for a finite chain lattice.

This is tantamount to saying

$\lim_{k \Rightarrow \infty} f^k(0)$ exists and is called the *least fixed point* of f,

since $f(f^k(0)) = f^k(0)$ $\quad k \Rightarrow \infty$

Fixed Point Theorem

Thm: f: S --> S monotonic function on poset (S, ≤) with a 0 element and finite length. The *least fixed point* of f is $f^k(0)$ where

i. $f^0(x) = x$,

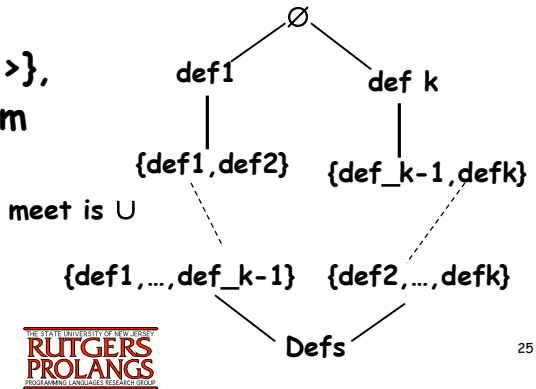
ii. $f^{i+1}(x) = f(f^i(x))$, $i \geq 0$,

iii. $f^k(0) = f(f^k(0))$ and this is the smallest k for which this is true.

- For any p such that f(p)=p, $f^k(0) \leq p$.
- Theorem justifies the iterative algorithm for global data flow analysis for lattices & functions with right properties
- Dual theorem exists for 1 element and *maximal fixed point* for k such that $f^k(1) = f^{k+1}(1)$.

Reaching Definitions

- REACH meet operation is set union with partial order is ⊇ superset inclusion
  - Why? recall that the 0 element a is such that $a \leq x = a, \forall x$ which means a is a superset of x!
- Defs = {<node,var>}, all defs in program
- 0 element Defs
- 1 element is ∅



How to solve? Worklist Algm

$$\text{Reach}(j) = \bigcup_{m \in \text{Pred}(j)} \{ \text{Reach}(m) \cap \text{pres}(m) \cup \text{dgen}(m) \}$$

Initialize all CFG nodes to ∅.
Put all nodes on the worklist W.
Loop: Do until W is empty{
    remove a node from the worklist W;
    calculate righthandside of above eqn;
    compare result with Reach(j)
      if result is different, {update Reach(j) and
        put descendent nodes of j on worklist W}
    }
//when terminates have correct reaching definitions solution at each node

Monotone Dataflow Frameworks

- Formalism for expressing and categorizing data flow problems (Kildall, POPL'73) <G, L, F, M>
  - G, flowgraph <N, E, ρ>
  - L, (semi-)lattice with meet Λ
    - usually assume L has a 0 and 1 element
    - finite chains
  - F, function space, $\forall f \in F$, f: L --> L
    - Contains identity function
    - Closed under composition $\forall f, g \in F, f \circ g \in F$
    - Closed under pointwise meet, if $h(x) = f(x) \Lambda g(x)$ then $h \in F$
  - M : E --> F, maps an edge to a corresponding transfer function that describes data flow effect of traversing that edge

Function Properties that Guarantee a Solution

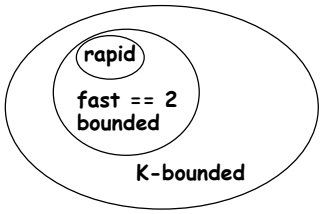
- *Montonicity*
  - Defined as $x \leq y \Rightarrow f(x) \leq f(y)$.
  - Equivalent formulation of definition
    $f(x \Lambda y) \leq f(x) \Lambda f(y)$
- *Distributivity*
  - If $f(x \Lambda y) = f(x) \Lambda f(y)$ then f *distributive*
  - Distributivity implies monotonicity
  - Four classical bitvector problems are distributive

Function Properties - Convergence

K-bounded: all contributions to MFP solution occur prior to Kth iteration

Fast: 1 pass around a cycle is enough to summarize its contribution to the dataflow solution (e.g., reflexive transitive closure is fast but not rapid)

Rapid: contribution of a cycle is independent of value at entry node; 1 pass around the cycle is enough. All classical bitvector problems are rapid



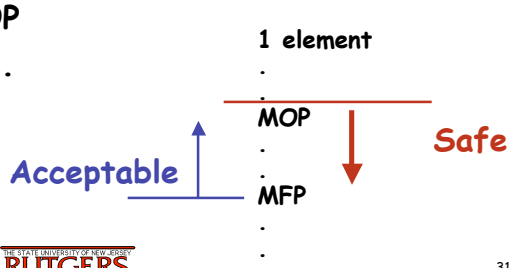
MOP vs MFP

- If *distributive* functions define the dataflow problem, to obtain dataflow solution at node n, can gather information on paths (e.g., P1, P2) simultaneously without loss of precision.
  - e.g., $f_{P1}(0)$, $f_{P2}(0)$ needn't be calculated explicitly
- However, Kam and Ullman showed that this is not true for all *monotone* functions; Kam, Ullman, 1976,1977
- Therefore, MFP only approximates MOP for general monotone functions that are not distributive.

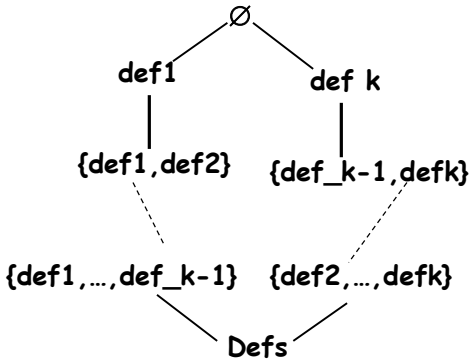
Safety of Dataflow Solution

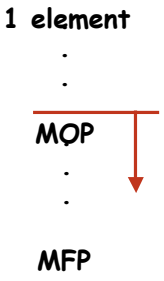
- Safe solution underestimates the actual dataflow solution; $x \leq MOP$ is an approximate solution
- Acceptable solution is one that contains a fixed point of the function, $y \geq z$ where z is any fixed point.
- If they exist, MOP is largest safe solution and MFP is smallest acceptable solution.
- Between MFP and MOP

are interesting solutions.



Reaching Definitions





Safe solutions contain the MOP

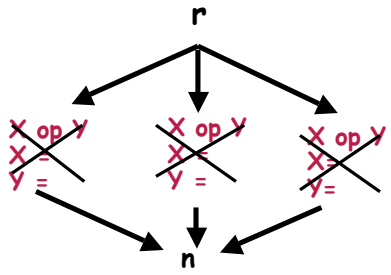
Safe Solutions

- REACH: it is safe to err by saying a definition reaches when it DOES NOT REACH.
  - This may inhibit dead code elimination transformations
  - Since REACH functions are distributive, MOP=MFP here

Available Expressions

- An expression X op Y is *available* at program point *n* if EVERY path from program entry to *n* evaluates X op Y, and after every evaluation prior to reaching *n*, there are NO subsequent assignments to X or Y.

Used to enable common subexpression elimination



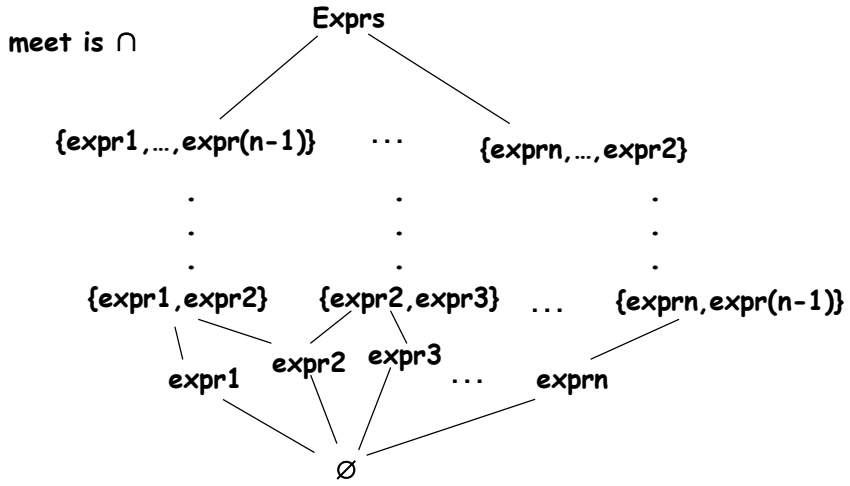
Available Expressions Equations

$$Avail(j) = \bigcap_{m \in Pred(j)} \{ Avail(m) \cap epres(m) \cup egen(m) \}$$

where:

- epres(m) is the set of expressions preserved through node *m*
- egen(m) is the set of (downwards exposed) expressions generated at node *m*
- pred(j) is the set of immediate predecessors of node *j*

Available Expressions



Safe Solutions

- AVAIL: it is safe to err by saying an expression is NOT AVAILABLE when it might be.
  - This may inhibit *common subexpression elimination* transformations
  - Since AVAIL functions are distributive, MOP=MFP here

How is analysis of OOPLs different?

- Domain: Java, C++, C# like languages

Fortran:	OOPLs:
Fixed call structure	Dynamic dispatch
Limited polymorphism of primitive types	Polymorphism (i.e., subtyping)
	Use of libraries and frameworks
Whole program analysis easy because all libraries necessary for compilation	Dynamic statements affecting execution (e.g., reflective calls, dynamic class loading)

Reference Analysis

- *Determines information about the set of objects to which a reference variable or field may point during program execution*
- An enabling analysis for OOPLs
  - Its precision affects precision of subsequent analysis clients (e.g., side effects)
  - Need to find the right cost/benefit tradeoff for particular problem

Reference Analysis

- OOPLs need type information about objects to which reference variables can point to resolve dynamic dispatch
- Often data accesses are indirect to object fields through a reference, so that the set of objects that might be accessed depends on which object that reference can refer at execution time
- Need to pose this as a compile-time program analysis with representations for reference variables/fields, objects and classes.

Reference Analysis enables…

- Construction of possible calling structure of program - call graph
  - Dynamic dispatch of methods based on runtime type of receiver `x.f();`
- Understanding of possible dataflow in program
  - Indirect side effects through reference variables and fields `r.g=`
- Uses of call graph
  - e.g., Program slicing, obtaining method coverage metrics for testing, heap optimization, etc

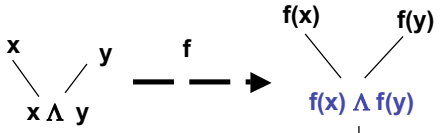
Uses of Reference Analysis Information in Software Tools

- Program understanding tools
  - Semantic browsers
  - Program slicers
- Software maintenance tools
  - Change impact analysis tools
- Testing tools
  - Coverage metrics

Analyses to be Discussed

- Lecture 2:
  - Type hierarchy-based reference analyses
    - CHA, RTA
  - Incorporating flow
    - FieldSens (Andersen-based points-to)
- Lecture 3:
  - Incorporating flow and calling context
    - 1-CFA
    - ObjSens (object-sensitive)

Monotonicity



f: L --> L
x Λ y ≤ x
x Λ y ≤ y
by defn of meet of x, y; and

f(x) Λ f(y) ≤ f(x)
f(x) Λ f(y) ≤ f(y)
by defn of meet of f(x), f(y).

f(x Λ y) ≤ f(x)
f(x Λ y) ≤ f(y)
by monotonicity of f

f(x Λ y) ≤ f(x) Λ f(y)
by defn meet of f(x), f(y)

Therefore, x ≤ y ⇒ f(x) ≤ f(y) (1)
implies
f(x Λ y) ≤ f(x) Λ f(y) (2).

Monotonicity, cont.

Show f(x Λ y) ≤ f(x) Λ f(y) (2) implies x ≤ y ⇒ f(x) ≤ f(y) (1)
Then we know these two definitions of monotonicity are equivalent.

Assume x ≤ y. Then x Λ y = x by defn of meet.

f(x Λ y) = f(x) ≤ f(x) Λ f(y) which is given.

Then f(x) Λ (f(x) Λ f(y)) = f(x) by defn of meet.

But (f(x) Λ f(x)) Λ f(y) = f(x) Λ f(y) = f(x) by associativity of meet

Therefore, f(x) ≤ f(y) by defn of meet.

So (2) implies (1).

Therefore, these definitions of monotonicity are equivalent.

Available Expressions

- lattice is 2^{Exprs} where Exprs is set of all binary expressions in program
- Partial order is $\subseteq$ (subset inclusion) so meet is $\cap$
- < Exprs,Exprs,...,Exprs> is 1 element
- < $\emptyset, \emptyset, ..., \emptyset$) is 0 element
- From the data flow equations for AVAIL, we know that if a set of dataflow facts X is true on entry to a flowgraph node n, then f(X) is true on each exit edge of n where

$$f(X) = epres(n) \cap X \cup egen(n)$$

f is called the *transfer function* for AVAIL

Available Expresions

- Cross product lattice is
  - (2^{Exprs} , 2^{Exprs} ,..., 2^{Exprs}) with n components where n is number of nodes in the cfg and $\leq'$ is $\leq$ component-wise
- Since Avail equation at a node can be expressed thusly,

$$Avail(j) = \bigcap_{m \in Pred(j)} \{ Avail(m) \cap epres(m) \cup egen(m) \}$$

  - AVAIL (j) is the solution at entry of node j and f(AVAIL(j)) is solution at exit of node j,

$g_j = \cap f(g_m)$, $m \in Pred(j)$

Available Expressions

- Can you show g_i monotone?
  $g_i : (2^{Exprs}, 2^{Exprs}, \ldots, 2^{Exprs}) \dashrightarrow 2^{Exprs}$
- Then this induces the monotonicity of F,
  $F = (g_1, \ldots, g_n)$
- Application of dual of fixed point theorem here to find the maximal fixed point. Iterate down from the 1 element.
  - Initialize ρ to $\varnothing$, all other cfg nodes to Exprs.