An Applicable Family of Data Flow Testing Criteria

- Assumptions about the program
  - No
    - goto statements
    - with
    - variant records
    - Functions having 'var' parameters
      - By reference
    - Procedural or functional parameters
    - Conformant arrays
      - size of an array parameter is not known to the called function until run-time
  - Every Boolean expression that determines the flow of control has at least one occurrence of a variable or a call to the function 'eof' or 'eoln'

Program Structure

- Program consists of 'blocks'
- Block
  - Sequence of statements
    - Whenever the first statement is executed, the remaining statements in the block are executed in the given order
- Can be represented by a flow graph

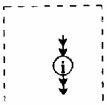
Classifying each variable occurrence

- Definition
  - Value is stored in a memory location
- Use
  - Value is fetched from a memory location
- Undefinition
  - Value and location becomes unbound
- C-use
  - Use in a computation or output statement
  - Associated with each node
- P-use
  - Use in a predicate
  - Associated with each edge

Simple Statements

Assignment statement: v:= *expr;*

Node i has c-uses of each variable in *expr* followed by a definition of v.



Simple Statements

Input/Output statements:

read(v1,...,vn);
readln(v1,...,vn);
read(f,v1,...,vn);
readln(f,v1,...,vn);

Node i has definitions of v1,...,vn.
If the file variable f is present then node i
also has a c-use followed by a definition of f↑.

write(e1,...,en);
writeln(e1,...,en);
write(f,e1,...,en);
writeln(f,e1,...,en);

Node i has c-uses of each variable occurring in e1,...,en.
If the file variable f is present then node i
also has a definition followed by a c-use of f↑.

Simple Statements

Procedure call: P(e1,...,en);

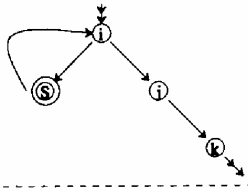
Node j has c-uses of each variable occuring in
the expressions e1,...,en.
These are followed by definitions of each actual
parameter which corresponds to a var formal parameter.

Nodes i and k are included to assure that
the procedure call has its own node.

Repetitive Statements

while statement: while B do S;

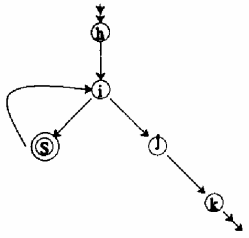
Let h be the entry node
to subgraph S.
Edges (i,h) and (i,j) have
p-uses of each variable in
the boolean expression B.



Repetitive Statements

for statement:
for v:=e1 to e2 do S;
for v:=e1 downto e2 do S;

Let tmp be a new variable.
Let f and g be the entry
and exit nodes, respectively,
of S. Node h has c-uses of
each variable in e1,
followed by a definition of v and
c-uses of each variable in e2
followed by a definition of tmp.
Edges (i,f) and (i,j) have
p-uses of v and tmp. Node g has
a c-use followed by a def of v.

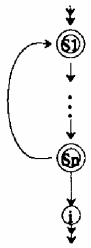


Repetitive Statements

repeat statement:

repeat S1;...;Sn until B;

Let j be the entry node of S1, and let k be the exit node of Sn.
Edges (k,j) and (k,i) have p-uses of each variable in the boolean expression B.

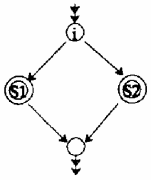


Conditional Statements

if-then-else statement

if B then S1;
if B then S1 else S2;

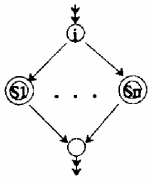
Let k and j be the entry nodes of S1 and S2, respectively.
Edges (i,j) and (i,k) have p-uses of each variable in the boolean expression B.
if there is no "else" part then subgraph S2 has a single node corresponding to an empty block.



Conditional Statements

case e1 of
label-list1 : S1;
⋮
label-listn : Sn
end;

Let j1,...,jn be the entry nodes of S1,...,Sn, respectively.
Edges (i,j1),...,(i,jn)
have p-uses of each variable in the expression e1.



Entry and exit nodes

- **Entry node**
  - **Has the definition of**
    - Each parameter
    - Each non-local variable that is used in the program
    - Input buffer input↑
- **Exit node has**
  - **An undefinition of each local variable**
  - **A c-use of each variable parameter**
  - **A c-use of each non-local variable**
  - **A c-use of the input buffer input↑**

Arrays

- It is impossible to determine the particular array element which is being used or defined in an occurrence of an array variable
  - A[2]
  - A[i+j]
- Definition of a[expr]
  - A c-use of each variable in expr
  - Followed by a definition of a
- Use of a[expr]
  - c-uses of all the variables in expr
  - Followed by a use of a

Pointers

- Impossible to determine statically the memory location to which a pointer points
- Syntactic treatment
- If p is a pointer variable
  - Definition of p^
    - C-use of p
    - Followed by a definition of p^
  - Use of p^
    - C-use of p
    - Followed by a c-use of p^
- Ignore definitions and uses of p^

Records & Files

- Records
  - Each field is treated as an individual variable
  - Any unqualified occurrence of a record is treated as an occurrence of each field
- File variables
  - Considering the effect on the file buffer

Simplifying Assumptions

- No interprocedural dataflow analysis
- Ignore pointers
- Array reference simplification
- No aliasing/side-effects
- Consequences
  - Perhaps “less than perfect” test data

Global Definition

- **Global c-use**
  - A c-use of x in node i is global if x has been assigned in some block other than i
- **Def-clear path wrt x "from node i to node j" and "from node i to edge (n_m, j)"**
  - A path (i, n_1, n_2, ..., n_m, j) containing no definitions or undefinitions of x in nodes n_1, n_2, ..., n_m
- **Global definition of x**
  - **A node i has a global definition of a variable x if**
    - it has a definition of x and
    - there is a def-clear path wrt x from node i to some node containing
      - a global c-use or
      - edge containing a p-use of x

Restricted Programs Class

- **Satisfying the following properties**
  - **NSUP**
    - No-syntactic-undefined-p-use Property
      - For every p-use of a variable x on an edge (i,j), in P, there is some path from the start node to edge (i,j), which contains a global definition of x
  - **NSL**
    - Non-straight-line property
      - P has at least one conditional or repetitive statement
        - » At least one node in P's flow-graph has more than one successor
        - » At least one variable has a p-use in P

Def-use graph

- **Obtained from the flow graph**
- **Associate with each node the sets**
  - **C-use(i)**
    - Variables which have global c-uses in block-i
  - **Def(I)**
    - Variables which have global definitions in block-i
- **Associate with each edge (i,j)**
  - **P-use(i,j)**
    - Variables which have p-uses on edge (i,j)
- **Define sets of nodes**
  - **dcu(x,i)**
    - Nodes j such that x ∈ c-use(j) and there is a def-clear paths with respect to x from i to j
  - **dpu(x,i)**
    - Edges (j,k) such that x ∈ p-use(j,k) and there is a def-clear path with respect to x from i to (j,k)

Definitions for def-use graph

V	=	the set of variables
N	=	the set of nodes
E	=	the set of edges
def(i)	=	{x ∈ V | x has a global definition in block i}
c-use(i)	=	{x ∈ V | x has a global c-use in block i}
p-use(i,j)	=	{x ∈ V | x has a p-use in edge (i,j) }
dcu(x,i)	=	{j ∈ N | x ∈ c-use(j) and there is a def-clear path wrt x from i to j}
dpu(x,i)	=	{(j,k) ∈ E | x ∈ p-use(j,k) and there is a def-clear path wrt x from i to (j,k) }

Explanation

- If $x \in def(i)$ and $j \in dcu(x,i)$, then
  - x has a global definition in node i and
  - A c-use in node j, and
  - There is a definition clear path with respect to x from node i to node j
- Hence
  - It may be possible for control to reach node j with the variable x having the value which was assigned to it in node i

More definitions

- Definition-c-use association
  - Triple (i,j,x) where i is a node containing a global definition of x and $j \in dcu(x,i)$
- Definition-p-use association
  - Triple (i,(j,k),x) where i is a node containing a global definition of x and $(j,k) \in dpu(x,i)$
- A path $(n_1,n_2, \ldots, n_j,n_k)$ is a du-path wrt x if n_1 has a global definition of x and either
  - n_k has a global c-use of x and $(n_1, \ldots,n_j, n_k)$ is a def-clear simple path wrt x, and
  - (n_j, n_k) has a p-use of x and $(n_1, .., n_j)$ is a def-clear loop-free path wrt x
- An association is a definition-c-use association, a definition-p-use association, or a du-path

Yet more definitions

- Complete path
  - Path from the entry node to the exit node
- Covering
  - A complete path π *covers* a definition-c-use association (i,j,x) if it has a definition clear subpath wrt x from i to j
  - A complete path π *covers* a definition-p-use association (i,(j,k),x) if it has a definition clear subpath wrt x from i to (j,k)
  - π covers a du-path π' if π' is a subpath of π
  - The set Π of paths covers an association if some element of the set does
  - A test set T covers an association if the elements of T cause the execution of the set of paths Π, and Π covers the association

Finally, the criteria

- Intuitively
  - The family of DF testing criteria is based on requiring that
    - the test data execute definition-clear paths from each node containing a global definition of a variable to specified nodes containing
      - global c-uses and
      - edges containing p-uses of that variable
  - For each variable definition, the criteria require that
    - All/some definition-clear paths wrt that variable from the node containing the definition to all/some of the uses/c-uses/p-uses reachable by some such paths be executed

All-defs criterion

- If variable x has a global definition in node i, the all-defs criterion requires the test data to exercise *some* path which goes from i to *some* node or edge at which the value assigned to x in node i is used

All-uses criterion

- If variable x has a global definition in node i, the all-uses criterion requires the test data to exercise *at least one* path which goes from i to *each* node and edge at which the value assigned to x in node i is used

All-DU-paths criterion

- If variable x has a global definition in node i, the all-DU-paths criterion requires the test data to exercise *all* paths which go from i to *each* node and edge at which the value assigned to x in node i is used

Other DF testing criteria

- All-p-uses
- All-c-uses
- All-p-uses/some-c-uses
- All-c-uses/some-p-uses

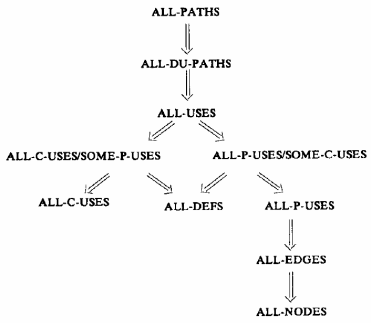
Definitions of DF criteria

CRITERION	ASSOCIATIONS REQUIRED
All-defs	Some (i,j,x) s.t. j∈ dcu(x,i) or some (i,(j,k),x) s.t. (j,k)∈ dpu(x,i).
All-c-uses	All (i,j,x) s.t. j∈ dcu(x,i).
All-p-uses	All (i,(j,k),x) s.t. (j,k)∈ dpu(x,i).
All-p-uses/some-c-uses	All (i,(j,k),x) s.t. (j,k)∈ dpu(x,i). In addition, if dpu(x,i)=ϕ then some (i,j,x) s.t. j∈ dcu(x,i). Note that since i has a *global* definition of x, dpu(x,i)=ϕ ⇒ dcu(x,i)≠ϕ.
All-c-uses/some-p-uses	All (i,j,x) s.t. j∈ dcu(x,i). In addition, if dcu(x,i)=ϕ then some (i,(j,k),x) s.t. (j,k)∈ dcu(x,i). Note that since i has a *global* definition of x, dcu(x,i)=ϕ ⇒ dpu(x,i)≠ϕ.
All-uses	All (i,j,x) s.t. j ∈ dcu(x,i) and all (i,(j,k),x) s.t. (j,k)∈ dpu(x,i).
All-du-paths	All du-paths from i to j with respect to x for each j∈ dcu(x,i) and all du-paths from i to (j,k) with respect to x for each (j,k)∈ dpu(x,i).

"includes"

- Criterion C_1 includes criterion C_2 iff
  - For every subprogram, any test set that satisfies C_1 also satisfies C_2
- C_1 strictly includes C_2, iff
  - denoted $C_1 \Rightarrow C_2$,
  - C_1 includes C_2 and for some subprogram P there is a test set that satisfies C_2 but does not satisfy C_1

Includes relationship



Applicability

- It may be the case that no test set for program P satisfies criterion C
  - Infeasible paths
- Tailor the DF criteria so that they are applicable
- Assumptions
  - All aliases are known
  - All side effects are known
  - No element of the test set causes the program to crash
    - Execution of entry node to exit node

Executable/Feasible Paths

- Recall
  - Complete path
    - Path from the entry node to the exit node
- Executable/feasible complete path
  - A complete path that is executed on some assignment of values to input variables
- Executable/feasible path
  - A subpath of an executable complete path

Recall Definition

- Definition-c-use association
  - Triple (i,j,x) where i is a node containing a global definition of x and $j \in dcu(x,i)$
- Definition-p-use association
  - Triple (i,(j,k),x) where i is a node containing a global definition of x and $(j,k) \in dpu(x,i)$
- A path $(n_1,n_2, \ldots, n_j,n_k)$ is a du-path wrt x if n_1 has a global definition of x and either
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- An association is a definition-c-use association, a definition-p-use association, or a du-path

Executable Associations

- Definition
  - An association is executable if there is some executable complete path that covers it; otherwise it is unexecutable
- $fdcu(x,i) \in dcu(x,i)$
  - Nodes j such that $x \in$ c-use(j) and there is an executable definition clear path wrt x from i to j
- $fdpu(x,i) \in dpu(x,i)$
  - Edges (j,k) such that $x \in$ p-use(j,k) and there is an executable definition clear path wrt x from i to (j,k)

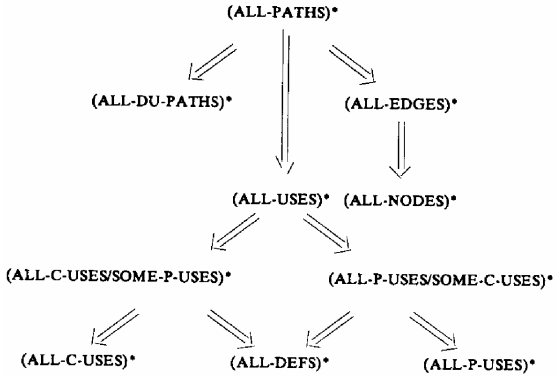
Equivalently

- $fdcu(x,i) =$
  - $\{j \in dcu(x,i) \mid$ the association (i,j,k) is executable$\}$
- $fdpu(x,i) =$
  - $\{(j,k) \in dpu(x,i) \mid$ the association (i,(j,k),x) is executable$\}$
- Intuitively
  - new criterion C* for each DF criterion C
  - By selecting the required associations from fdcu(x,i) and fdpu(x,i) instead of from dcu(x,i) and dpu(x,i)

Feasible Data-flow Criteria (FDF)

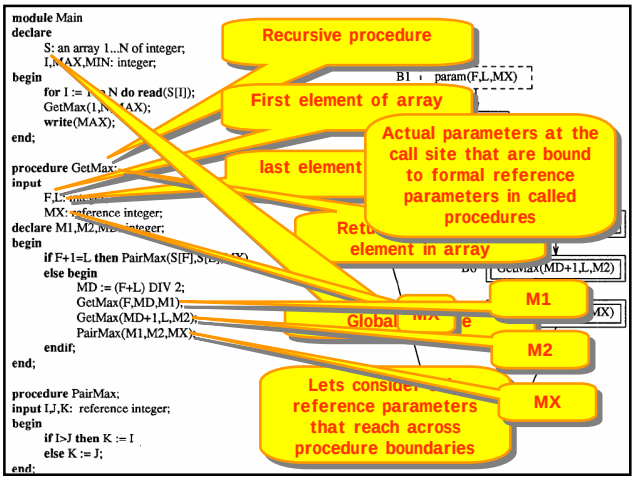
CRITERION	REQUIRED ASSOCIATIONS
(all-defs)*	if fdcu(x,i) ∪ fdpu(x,i) ≠ ϕ then some (i,j,x) s.t j∈ fdcu(x,i) or some (i,(j,k),x) s.t. (j,k)∈ fdpu(x,i).
(all-c-uses)*	all (i,j,x) s.t. j∈ fdcu(x,i).
(all-p-uses)*	all (i,(j,k),x) s.t. (j,k)∈ fdpu(x,i).
(all-p-uses/some-c-uses)*	all (i,(j,k),x) s.t. (j,k)∈ fdpu(x,i). In addition, if fdpu(x,i) = ϕ and fdcu(x,i) ≠ ϕ then some (i,j,x) s.t. j∈ fdcu(x,i).
(all-c-uses/some-p-uses)*	all (i,j,x) s.t. j∈ fdcu(x,i). In addition, if fdcu(x,i) = ϕ and fdpu(x,i) ≠ ϕ then some (i,(j,k),x) s.t. (j,k)∈ fdpu(x,i).
(all-uses)*	all (i,j,x) s.t. j ∈ fdcu(x,i) and all (i,(j,k),x) s.t. (j,k) ∈ fdpu(x,i).
(all-du-paths)*	all executable du-paths with respect to x from i to j s.t. j∈ dcu(x,i) and all executable du-paths with respect to x from i to (j,k) for each (j,k) ∈ dpu(x,i).

Includes Relationships

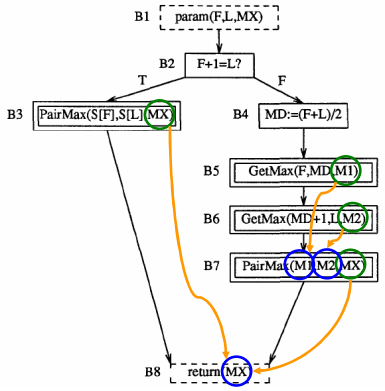


Interprocedural DF Testing

- Most DF testing methodologies deal with dependencies that exist within a procedure (i.e., *intra*procedural)
- Data dependencies also exist among procedures
- Requires analysis of the flow of data across procedure boundaries
- Calls and Returns
- Direct dependencies (single call/return)
- Indirect dependencies (multiple calls/returns)



The Def-uses

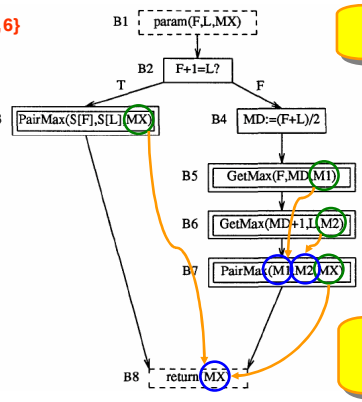


A test case

S = {3,5,1,6}

F = 1

L = 4



Execute and check

All def-use pairs are covered

Any missed def-uses?

```
module Main
declare
        S: an array 1..N of integer;
        I,MAX,MIN: integer;
begin
        for I := 1 to N do read(S[I]);
        GetMax(1,N,MAX);
        write(MAX);
end;

procedure GetMax;
input
        F,L: integer;
        MX: reference integer;
declare M1,M2,MD: integer;
begin
        if F+1=L then PairMax(S[F],S[L],MX)
        else begin
                MD := (F+L) DIV 2;
                GetMax(F,MD,M1);
                GetMax(MD+1,L,M2);
                PairMax(M1,M2,MX);
        endif;
end;

procedure PairMax;
input I,J,K: reference integer;
begin
        if I>J then K := I
        else K := J;
end;
```