Dependency and slicing

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Agenda

- Dependency and slicing
- Delta-debugging
- Program repair

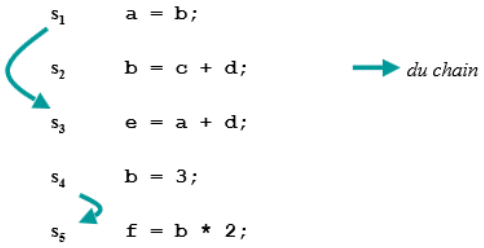
Dependency and slicing

- Dependencies: *control dependency* and *data dependency*
- *Dependency graphs*
- *Program slicing* (chopping, dicing, path slicing, thin slicing, executable slicing)
- *Taint analysis*

Data dependency

- Two statements are *data dependent*: the definition of a variable in a statement reaches the use of the same variable at another statement.
- Data dependency specifies the constraints on the order in which statement may be executed
- In software engineering field, we typically compute dependencies at source and IR (intermediate representation) level
- In compiler fields, the data dependencies are computed at IR and binary level

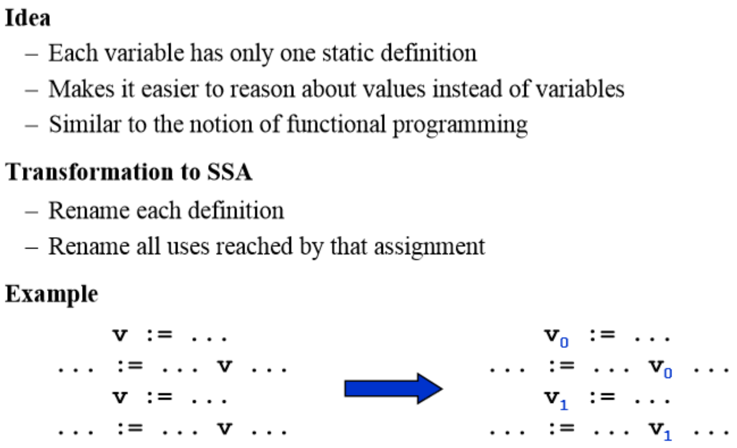
DU chains: def-use chains (link each def to uses)



```
s1    a = b;
s2    b = c + d;
s3    e = a + d;
s4    b = 3;
s5    f = b * 2;
```

- pro: fast to get data dependencies
- con: must be computed and updated, space overhead

SSA: static single assignment



Idea

- Each variable has only one static definition
- Makes it easier to reason about values instead of variables
- Similar to the notion of functional programming

Transformation to SSA

- Rename each definition
- Rename all uses reached by that assignment

Example

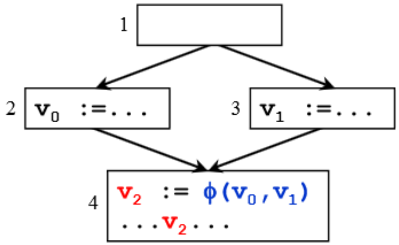
$$
\begin{array}{rcl}
v & := & \ldots \\
\ldots\ := & \ldots\ v\ \ldots & \\
v & := & \ldots \\
\ldots\ := & \ldots\ v\ \ldots &
\end{array}
\quad\Longrightarrow\quad
\begin{array}{rcl}
v_0 & := & \ldots \\
\ldots\ := & \ldots\ v_0\ \ldots & \\
v_1 & := & \ldots \\
\ldots\ := & \ldots\ v_1\ \ldots &
\end{array}
$$

SSA

Merging Definitions

– ϕ-functions merge multiple reaching definitions

Example



SSA

Transformation to SSA

- place ϕ function
- rename variables

- each value produced in the program is represented using a variable
- pro: allow analyses and transformations to be simpler and more efficient
- con: may not be executable (requires extra translations to and from); space and time overhead

Data Dependency Graphs

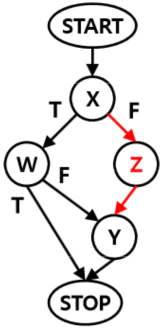
PDG: program dependency graphs (software engineering) – data dependency graphs [1987:ferrante]: node is the statement, edge is the data dependency relation

It is acyclic unless there is a loop in the program

Control Dependency

Let G be a control flow graph. Let X and Y be nodes in G. Y is control dependent on X iff

- There exists a directed path **P** from X to Y with any Z in P post-dominated by Y and
- X is not post-dominated by Y

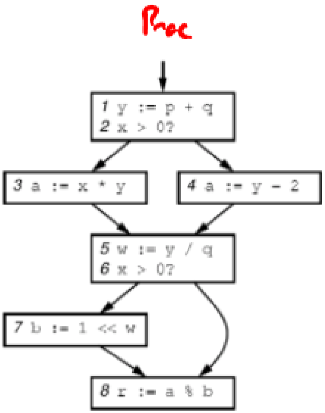


*If **Y** is control dependent on **X** then **X** must have **two exits**.*

Control Dependency

- the first statement is *control dependent* on the entry of the program
- from Condition 1: Y is not control dependent on any node(s) between X and Y; that is, X is the first node Y is control dependent on
- Intuitively, control dependency between two statements exists if one statement "controls" the execution of the other (e.g. through if- or while-statements).

Control Dependency: Example



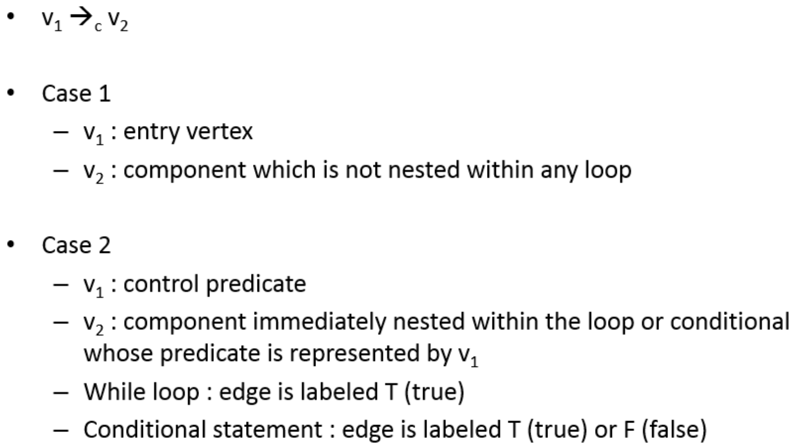
Control dependence relation

3	depends	on	2
4	"	"	2
7	"	"	6

$$\begin{tikzcd}
 & & \text{Proc} \arrow[dll, dash] \arrow[dl, dash] \arrow[d, dash] \arrow[dr, dash] \arrow[drr, dash] & & \\
1 & 2 \arrow[dl, dash, "F"'] \arrow[d, dash, "T"] & 5 & 6 \arrow[d, dash, "F"] & 8 \\
3 & 4 & & 7 &
\end{tikzcd}$$

Control Dependency Graph

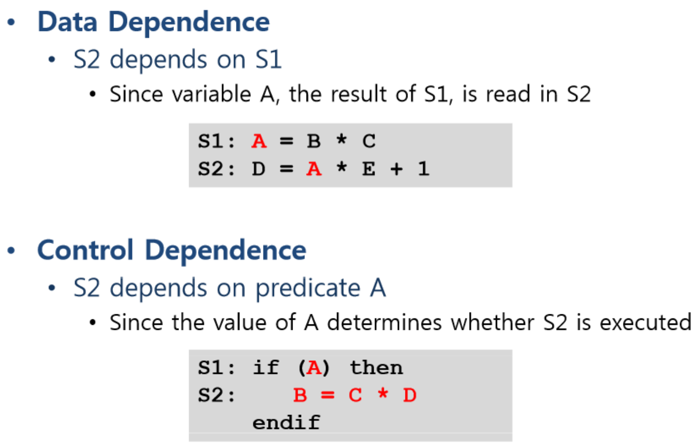
node is the statement, edge is the control dependency relation



- $v_1 \rightarrow_c v_2$
- Case 1
  - v_1 : entry vertex
  - v_2 : component which is not nested within any loop
- Case 2
  - v_1 : control predicate
  - v_2 : component immediately nested within the loop or conditional whose predicate is represented by v_1
  - While loop : edge is labeled T (true)
  - Conditional statement : edge is labeled T (true) or F (false)

Program Dependence Graphs (PDG)

Node: statements
Edge: control and data dependency edges
Data Dependency + Control Dependency [1987:Ferrante:TOPLAS]



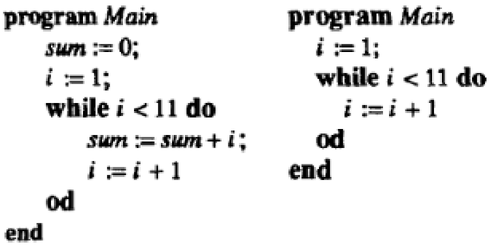
- **Data Dependence**
  - S2 depends on S1
    - Since variable A, the result of S1, is read in S2

```
S1: A = B * C
S2: D = A * E + 1
```

- **Control Dependence**
  - S2 depends on predicate A
    - Since the value of A determines whether S2 is executed

```
S1: if (A) then
S2:     B = C * D
    endif
```

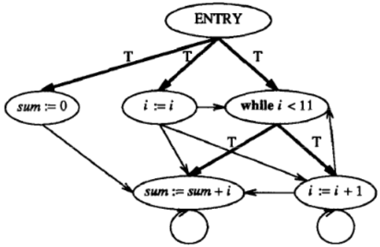
Program Dependence Graphs (PDG): Example

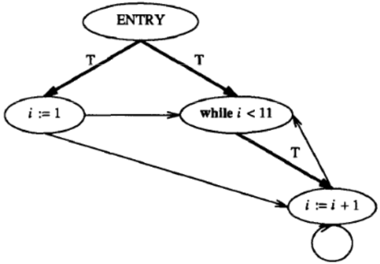


```
program Main
    sum := 0;
    i := 1;
    while i < 11 do
        sum := sum + i;
        i := i + 1
    od
end
```

```
program Main
    i := 1;
    while i < 11 do
        i := i + 1
    od
end
```

Program Dependence Graphs (PDG): Example





Construct PDG

General approaches

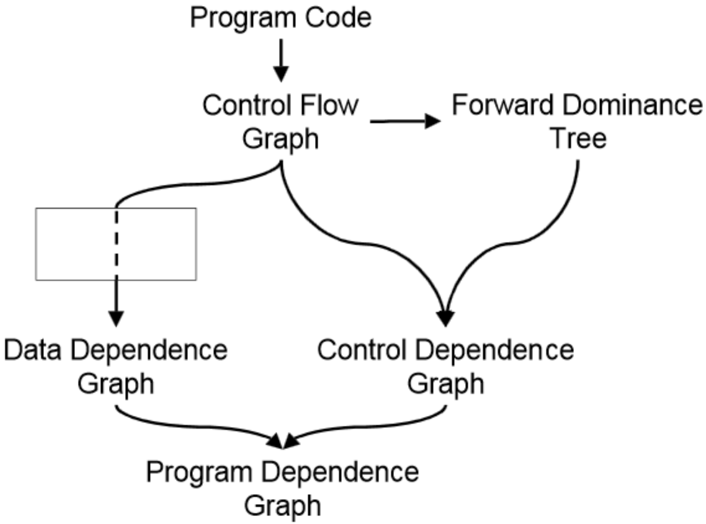
- Data dependence: def-use relations
- Control dependence: control flow graphs, post dominators

Tools: Frama-C (for C), Code Surfer (C/C++)

More algorithms:

- The program dependence graph and its use in optimization, 1987, TOPLAS
- Efficiently computing static single assignment form and the control dependence graph, 1991, TOPLAS
- Interprocedural slicing using dependence graphs, 1988, PLDI

Construct PDG

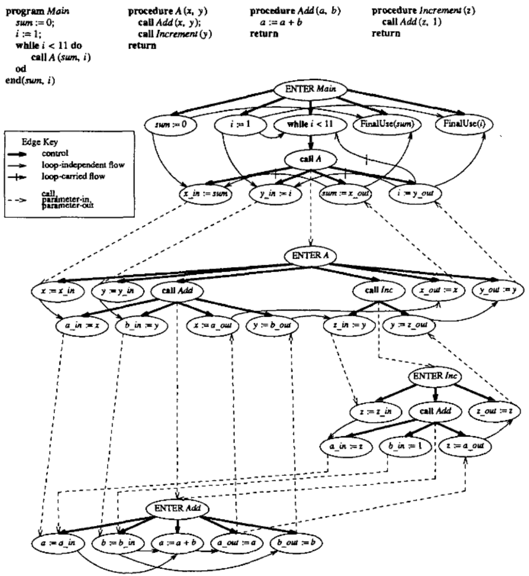


System Dependence Graphs (SDG)

SDG: an interprocedural dependence graph representation – a collection of method dependence graphs [1988:Horwitz, 1996:Larsen] (also used by Horwitz, Reps, Binkley)

- Program dependence graph: Represents the system's main program
- Procedure dependence graphs: Represent the system's auxiliary procedures
- Some additional edges
    - Edges that represent direct dependence between a call site and the called procedure
    - Edges that represent transitive dependence due to calls

System Dependence Graphs (SDG)



```
program Main
   sum := 0;
   i := 1;
   while i < 11 do
       call A (sum, i)
   od
end(sum, i)
```

```
procedure A (x, y)
   call Add (x, y);
   call Increment (y)
return
```

```
procedure Add (a, b)
   a := a + b
return
```

```
procedure Increment (z)
   call Add (z, 1)
return
```

System Dependence Graphs (SDG)

Five new vertices for SDG

- Call-site vertex
- Actual-in:
  - Control dependent on call-site vertex
  - Copy values of actual parameters to call temporaries
- Actual-out:
  - Control dependent on call-site vertex
  - Copy from return temporaries
- Formal-in:
  - Control dependent on procedure's entry vertex
  - Copy value of formal parameters from call temporaries
- Formal-out:
  - Control dependent on procedure's entry vertex
  - Copy to return temporaries

System Dependence Graphs (SDG)

Three new edges for SDG

- Call edge
  - Call-site $\rightarrow$ Procedure-entry
  - From each call-site vertex to the corresponding procedure-entry vertex
- Parameter-in edge
  - Actual-in $\rightarrow$ Formal-in
  - From each actual-in vertex at a call site to the corresponding formal-in vertex in the called procedure
- Parameter-out edge
  - Formal-out $\rightarrow$ Actual-out
  - From each formal-out vertex in the called procedure to the corresponding actual-out vertex at the call site

Program Slicing

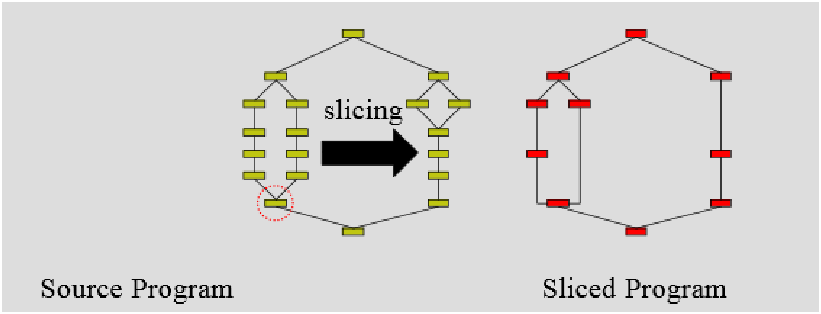
Origin of the Idea

Analysis technique introduced by Mark Weiser in his PHD thesis (1979)

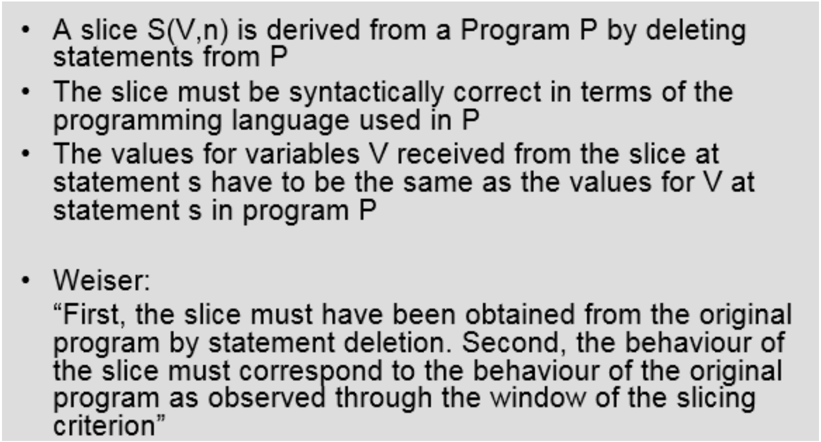
- Idea derived when he was observing experienced programmers debugging a program
- Result: Every experienced programmer uses slicing to debug a program

Program Slicing: Intuitive Understanding

Intuitively, the slice of a program with respect to program point p and variable x consists of all statements and predicates of the program that might affect the value of x at point p



Program Slicing: Intuitive Understanding

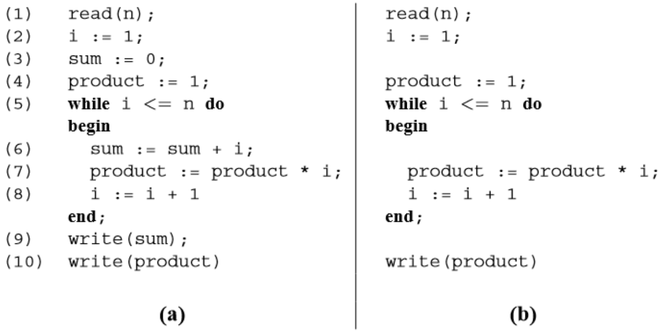


- A slice S(V,n) is derived from a Program P by deleting statements from P
- The slice must be syntactically correct in terms of the programming language used in P
- The values for variables V received from the slice at statement s have to be the same as the values for V at statement s in program P
- Weiser:
  "First, the slice must have been obtained from the original program by statement deletion. Second, the behaviour of the slice must correspond to the behaviour of the original program as observed through the window of the slicing criterion"

Program Slicing: Definition

[1981:Weiser:ICSE] [1995:Tip]

- *(Backward) slice* of v at S is the set of statements involved in computing v's value at S
- A *slicing criterion* of a program P is a tuple $\langle i, V \rangle$, where i is a statement in P and V is a subset of the variables in P



```
(1)    read(n);
(2)    i := 1;
(3)    sum := 0;
(4)    product := 1;
(5)    while i <= n do
       begin
(6)      sum := sum + i;
(7)      product := product * i;
(8)      i := i + 1
       end;
(9)    write(sum);
(10)   write(product)
```

(a)

```
read(n);
i := 1;

product := 1;
while i <= n do
begin

  product := product * i;
  i := i + 1
end;

write(product)
```

(b)

(a) An example program. **(b)** A slice of the program w.r.t. criterion (10, `product`).

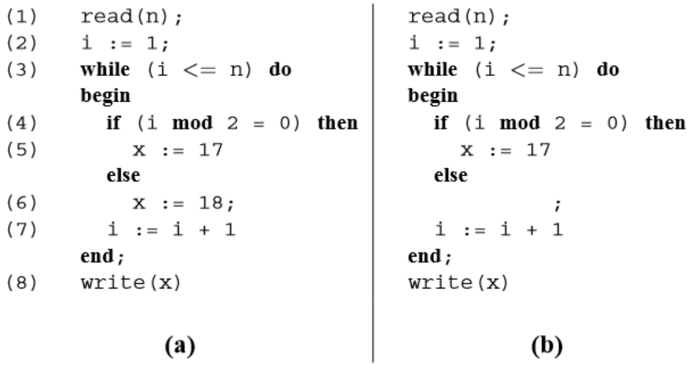
Program Slicing: Definition

static slice and *dynamic slice*:

- *static slice* is computed without making assumptions regarding a program's input (for all possible inputs and paths)
- the computation of *dynamic slice* relies on a specific test case

Program Slicing: Definition

What is the static slice for the program on the left?



```
(1)    read(n);
(2)    i := 1;
(3)    while (i <= n) do
       begin
(4)      if (i mod 2 = 0) then
(5)        x := 17
         else
(6)        x := 18;
(7)      i := i + 1
       end;
(8)    write(x)
```

(a)

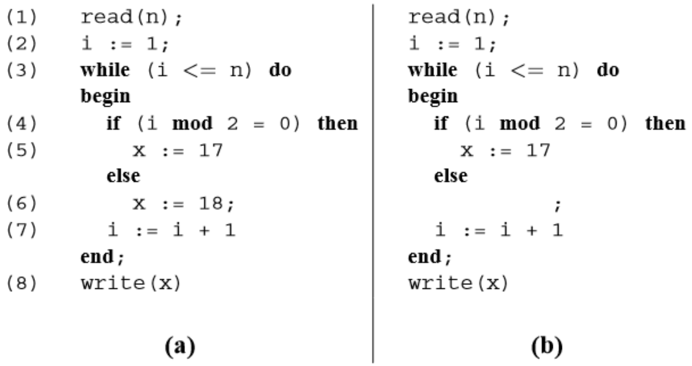
```
read(n);
i := 1;
while (i <= n) do
begin
  if (i mod 2 = 0) then
    x := 17
  else
            ;
  i := i + 1
end;
write(x)
```

(b)

(a) Another example program. **(b)** Dynamic slice w.r.t. criterion (n = 2, 8^1, x)

Program Slicing: Definition

What is the static slice for the program on the left?



```
(1)   read(n);
(2)   i := 1;
(3)   while (i <= n) do
      begin
(4)     if (i mod 2 = 0) then
(5)       x := 17
        else
(6)       x := 18;
(7)     i := i + 1
      end;
(8)   write(x)

              (a)
```

```
read(n);
i := 1;
while (i <= n) do
begin
  if (i mod 2 = 0) then
    x := 17
  else
              ;
  i := i + 1
end;
write(x)

        (b)
```

(a) Another example program. **(b)** Dynamic slice w.r.t. criterion (n = 2, 8^1, x)

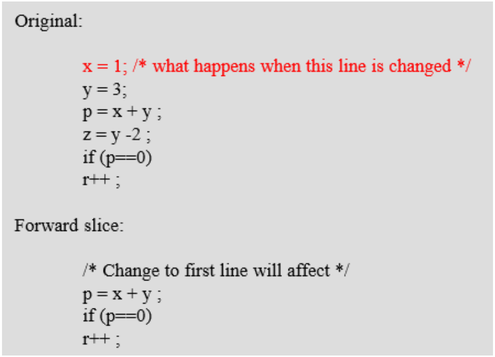
Here, the static slice is the entire program

Program Slicing: Definition

- A *data slice* is obtained by only taking data dependence into account; a *control slice* consists of the set of control predicates surrounding a language construct.
- The closure of all data and control slices w.r.t. an expression is the slice w.r.t. the set of variables used in the expression.

Program Slicing: Definition

Forward slice of a program with respect to a program point p and variable x consists of all statements and predicates of the program that might be affected by the value of x at point p



Original:

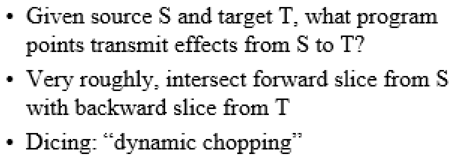
```
        x = 1; /* what happens when this line is changed */
        y = 3;
        p = x + y ;
        z = y -2 ;
        if (p==0)
        r++ ;
```

Forward slice:

```
        /* Change to first line will affect */
        p = x + y ;
        if (p==0)
        r++ ;
```

Chopping and dicing: Combining two slices

Program chopping



- Given source S and target T, what program points transmit effects from S to T?
- Very roughly, intersect forward slice from S with backward slice from T
- Dicing: “dynamic chopping”

Chopping and dicing: Combining two slices

- *Program dicing* [lyle:weiser:1987] [chen:1993] – used for fault localization
- a method for combining the information of different slices
- a program computes a correct value for variable x and an incorrect value for variable y, the bug is likely to be found in statements that are in the slice w.r.t. y, but not in the slice w.r.t. x.
- A static program dice is the set difference of the static slice of an incorrect variable and the static slice of a correct variable.

Program Slicing: Applications

Program understanding

- What is affected by what?

Program restructuring

- Isolate functionally distinct pieces of code

Program specialization and reuse

- Use slices to represent specialized pieces of code
- Only reuse relevant slices

Program differencing

- Compare slices to identify program changes

Program Slicing: Applications

Test coverage

- What new test cases would improve code coverage?
- What regression tests should be run after a change?

Model checking

- Reduce state space by removing irrelevant parts of the program

Automatic differentiation

- Activity analysis– what variables contribute to the derivative of a function?

Program Slicing: Applications

backward slicing [1990:Horwitz:PLDI]

- Debugging
- Understand complicated code
- Isolate individual computation threads within a program, automatic parallelization
- Automatically integrating program variants (merge commits) [1987:Horwitz:POPL]
- ...

Program Slicing: Applications

Forward slicing

- Show how a value computed is being used subsequently
- Inspect the parts of a program that may be affected by a proposed modification, to check that there are no unforeseen effects on the program's behavior [1995:Tip]
- Taint analysis
- ...

Taint Analysis

- information flows from object x to object y, denoted $x \to y$, whenever information stored in x is transferred to, object y. (forward slicing)

  - Identify **input dependent** variables at each program location
  - Two kinds of dependencies:

Data dependencies

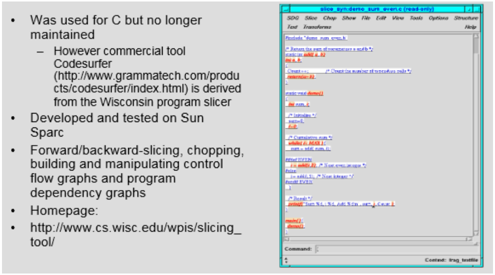
```
// x is tainted
   y = x ; z = y + 1 ; y = 3 ;
// z is tainted
```

Control dependencies

```
// x is tainted
   if (x > 0) y = 3 else y = 4 ;
// y is tainted
```

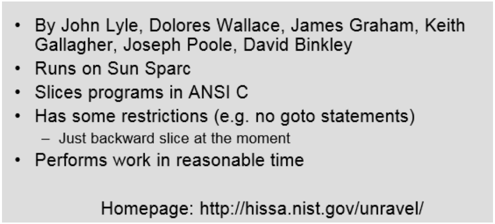
Compute Slice: Tools

- Code Surfer (academic license)



- Was used for C but no longer maintained
  - However commercial tool Codesurfer (http://www.grammatech.com/products/codesurfer/index.html) is derived from the Wisconsin program slicer
- Developed and tested on Sun Sparc
- Forward/backward-slicing, chopping, building and manipulating control flow graphs and program dependency graphs
- Homepage:
- http://www.cs.wisc.edu/wpis/slicing_tool/

- Unravel

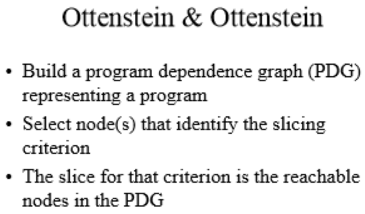


- By John Lyle, Dolores Wallace, James Graham, Keith Gallagher, Joseph Poole, David Binkley
- Runs on Sun Sparc
- Slices programs in ANSI C
- Has some restrictions (e.g. no goto statements)
  - Just backward slice at the moment
- Performs work in reasonable time

Homepage: http://hissa.nist.gov/unravel/

Compute Slice: Algorithms:

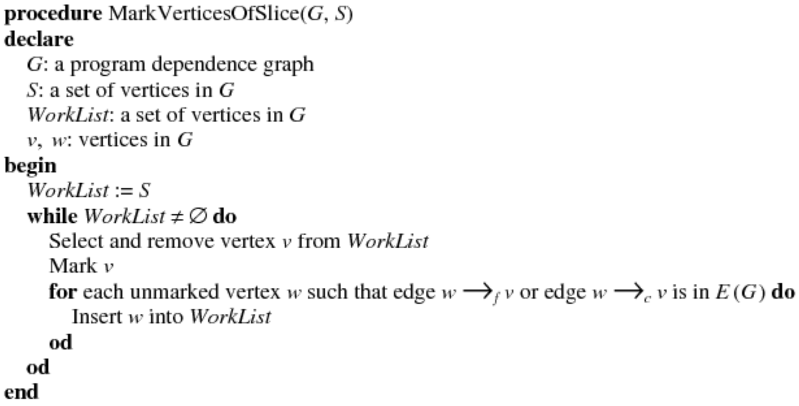
Reachability on PDG



Ottenstein & Ottenstein

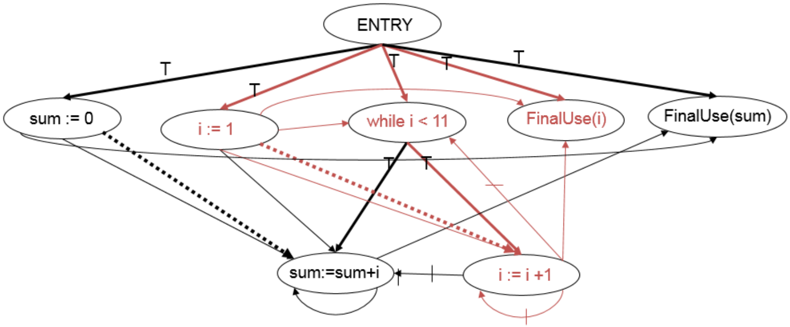
- Build a program dependence graph (PDG) representing a program
- Select node(s) that identify the slicing criterion
- The slice for that criterion is the reachable nodes in the PDG

Compute Slice: Algorithms



```
procedure MarkVerticesOfSlice($G$, $S$)
declare
   $G$: a program dependence graph
   $S$: a set of vertices in $G$
   $WorkList$: a set of vertices in $G$
   $v$, $w$: vertices in $G$
begin
   $WorkList := S$
   while $WorkList \neq \emptyset$ do
      Select and remove vertex $v$ from $WorkList$
      Mark $v$
      for each unmarked vertex $w$ such that edge $w \longrightarrow_f v$ or edge $w \longrightarrow_c v$ is in $E(G)$ do
         Insert $w$ into $WorkList$
      od
   od
end
```

Slicing on FinalUse(i)

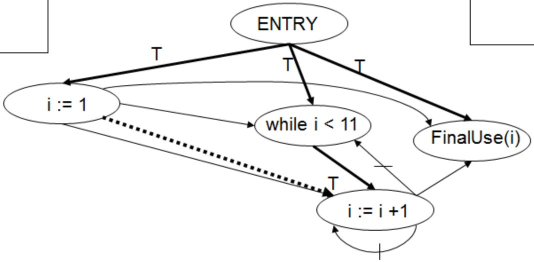


Slicing on FinalUse(i)

```
program Main
  sum := 0;
  i := 1;
  while i < 11 do
    sum := sum +i;
    i := i+1
  od
End(sum,i)
```

Slice on *FinalUse(i)*

```
program Main
  i := 1;
  while i < 11 do
     i := i+1;
  od
End(i)
```



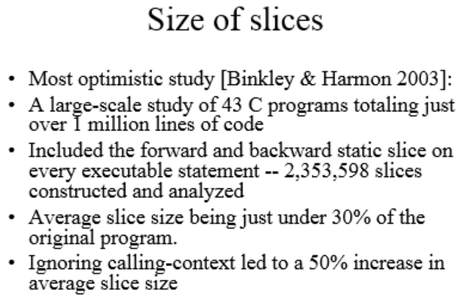
Compute Data and Control Slice

- Data slice: nodes that v transitively data dependent on – finding transitive data dependence on the data dependence graph
- Control slice: nodes that v transitive control dependent on – finding transitive control dependence on the control dependence graph

Dynamic Slicing

See Xiangyu Zhang's Slides

Advanced Concepts: *Thin Slicing*



Size of slices

- Most optimistic study [Binkley & Harmon 2003]:
- A large-scale study of 43 C programs totaling just over 1 million lines of code
- Included the forward and backward static slice on every executable statement -- 2,353,598 slices constructed and analyzed
- Average slice size being just under 30% of the original program.
- Ignoring calling-context led to a 50% increase in average slice size

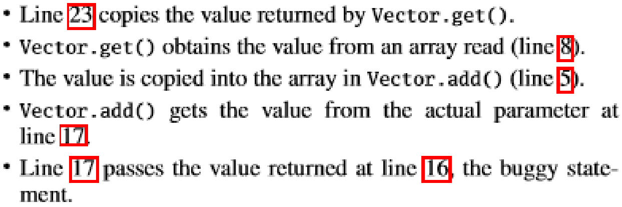
Advanced Concepts: *Thin Slicing*

[2007:PLDI:Sridharan:Bodik]

- A thin slice is a subset of statements upon which s is transitively *flow dependent* (also known as data dependent), obtained by ignoring uses of base pointers in dereference s
- A statement s is flow dependent on statement t if:
  1. s can read from some storage location l
  2. t can write to l
  3. There exists a control-flow path from t to s on which l is not re-defined
- for a seed that reads a value from a container object, a thin slice includes statements that store the value into the container, but excludes statements that manipulate pointers to the container itself.
- 3.3 times fewer statements for debugging, 9.4 times fewer statements for program understanding

```
class Vector {
  Object[] elems; int count;
  Vector() { elems = new Object[10]; }
  void add(Object p) {
    this.elems[count++] = p;
  }
  Object get(int ind) {
    return this.elems[ind];
  } ...
}
Vector readNames(InputStream input) {
  Vector firstNames = new Vector();
  while (!eof(input)) {
    String fullName = readFullName(input);
    int spaceInd = fullName.indexOf(' ');
    String firstName =
      fullName.substring(0,spaceInd-1);
    names.add(firstName);
  }
  return firstNames;
}
void printNames(Vector firstNames) {
  for (int i = 0; i < firstNames.size(); i++) {
    String firstName = (String)firstNames.get(i);
    print("FIRST NAME: " + firstName);
  }
}
void main(String[] args) {
  Vector firstNames =
    readNames(new InputStream(args[0]));
  SessionState s = getState();
  s.setNames(firstNames);
  ...;
  SessionState t = getState();
  printNames(t.getNames());
}
```

Advanced Concepts: *Thin Slicing*



- Line 23 copies the value returned by `Vector.get()`.
- `Vector.get()` obtains the value from an array read (line 8).
- The value is copied into the array in `Vector.add()` (line 5).
- `Vector.add()` gets the value from the actual parameter at line 17.
- Line 17 passes the value returned at line 16, the buggy statement.

References and Further Reading

- Path slicing
- Thin slicing
- All You Ever Wanted to Know About Dynamic Taint Analysis and Forward Symbolic Execution (but might have been afraid to ask)
- Certification of programs for secure information flow