Program Slicing

The final project survey

- Quick logistics note
  - If you haven't filled the final projects group survey, and *especially if you want me to pair you with a team*, please fill the survey soon!
  - (This is for getting a snapshot of where we are now, not for immediately before the team formation deadline!)
  - Find link in the slack!

Reading reflection

- What did the two tools you saw in the demo videos have in common?
- When you figure out that a program you're debugging is producing a wrong output, what's your next step?

The key common feature: program slicing!

1981

PROGRAM SLICING*

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Abstract

Program slicing is a method used by experienced computer programmers for abstracting from programs. Starting from a subset of a program's behavior, slicing reduces that program to a minimal form which still produces that behavior. The reduced program, called a "slice", is an independent program guaranteed to faithfully represent the original program within the domain of the specified subset of behavior.

Finding a slice is in general unsolvable. A dataflow algorithm is presented for approximating slices when the behavior subset is specified as the values of a set of variables at a statement. Experimental evidence is presented that these slices are used by programmers during debugging. Experience with two automatic slicing tools is summarized. New measures of program complexity are suggested based on the organization of a program's slices.

KEYWORDS: debugging, program maintenance, software tools, program metrics, human factors, dataflow analysis

Introduction

A large computer program is more easily constructed, understood, and maintained when broken into smaller pieces. Several different methods

behavior is of interest. For instance, during debugging a subset of behavior is being corrected, and in program modification or maintenance a subset of behavior is being improved or replaced. In these cases, a programmer starts from the program behavior and proceeds to find and modify the corresponding portions of program code. Code not having to do with behavior of interest is ignored. Gould and Dronkowski (1974) report programmers behaving this way during debugging, and a further confirming experiment is presented below.

A programmer maintaining a large, unfamiliar program would almost have to use this behavior-first approach to the code. Understanding an entire system to change only a small piece would take too much time. Since most program maintenance is done by persons other than the program designers, and since 67 percent of programming effort goes into maintenance (Zelkowitz, Shaw, and Gannon 1979), decomposing programs by behavior must be a common occurence.

Automatic slicing requires that behavior be specified in a certain form. If the behavior of interest can be expressed as the values of some sets of variables at some set of statements, then this specification is said to be a slicing criterion. Dataflow analysis (Hecht 1977) can find all the program code which might have influenced the specified behavior, and this code is called a

Examples of Slices

The original program:

```
 1   BEGIN
 2   READ(X,Y)
 3   TOTAL := 0.0
 4   SUM := 0.0
 5   IF X <= 1
 6      THEN SUM := Y
 7      ELSE BEGIN
 8         READ(Z)
 9         TOTAL := X*Y
10         END
11   WRITE(TOTAL,SUM)
12   END.
```

Slice on the value of Z at statement 12.

```
BEGIN
READ(X,Y)
IF X <  1
   THEN
   ELSE READ(Z)
END.
```

Slice on the value of X at statement 9.

```
BEGIN
READ(X,Y)
END.
```

Slice on the value of TOTAL at statement 12.

```
BEGIN
READ(X,Y)
TOTAL := 0
IF X <= 1
   THEN
   ELSE TOTAL := X*Y
END.
```

```
sum = 0
prod = 1
i = 1
while ( i < 11)
{
  sum = sum + i
  prod = prod * i
  i = i + 1
}
```

prod

```
prod = 1
i = 1
while ( i < 11)
{

  prod = prod * i
  i = i + 1
}
```

The same example, but maybe a bit more familiar looking!

figure from Program Slicing, Keith Gallagher et al.

Original image from YouTuber Craftingeek EN

Ok, let's get a look at this AST thing

```python
sum_acc = 0
prod_acc = 1
i = 1
while (i < 11):
    sum_acc = sum_acc + i
    prod_acc = prod_acc * i
    i = i + 1
print("sum", sum_acc)
print("prod", prod_acc)
```

Our Python program (the one we're analyzing, not the one we're running)

```python
code = open(filename).read()
tree = ast.parse(code)
astpretty.pprint(tree)
```

Here's the one we're running…

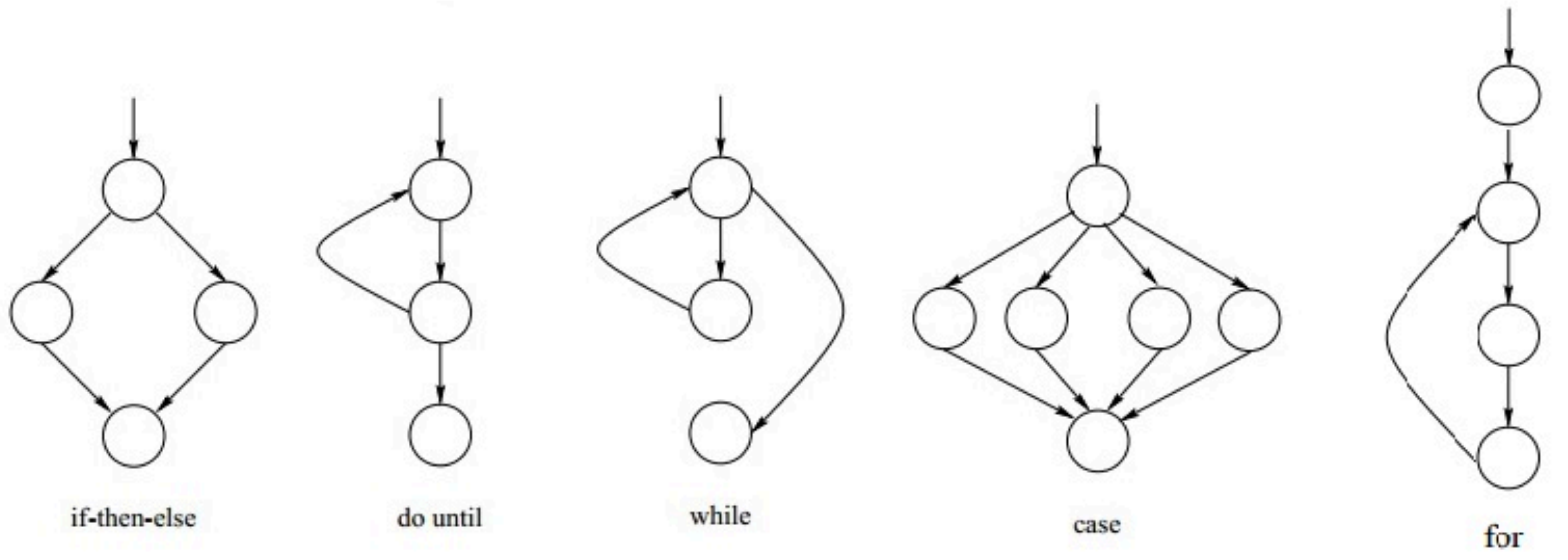
Look at that beautiful AST!

```
Module(
    body=[
        Assign(
            lineno=1,
            col_offset=0,
            end_lineno=1,
            end_col_offset=11,
            targets=[Name(lineno=1, col_offset=0, end_lineno=1, end_col_offset=7, id='sum_acc', ctx=Store()
            value=Constant(lineno=1, col_offset=10, end_lineno=1, end_col_offset=11, value=0, kind=None),
            type_comment=None,
        ),
        Assign(
            lineno=2,
            col_offset=0,
            end_lineno=2,
            end_col_offset=12,
            targets=[Name(lineno=2, col_offset=0, end_lineno=2, end_col_offset=8, id='prod_acc', ctx=Store(
            value=Constant(lineno=2, col_offset=11, end_lineno=2, end_col_offset=12, value=1, kind=None),
            type_comment=None,
        ),
        Assign(
            lineno=3,
            col_offset=0,
            end_lineno=3,
            end_col_offset=5,
            targets=[Name(lineno=3, col_offset=0, end_lineno=3, end_col_offset=1, id='i', ctx=Store())],
            value=Constant(lineno=3, col_offset=4, end_lineno=3, end_col_offset=5, value=1, kind=None),
            type_comment=None,
        ),
        While(
            lineno=4,
            col_offset=0,
            end_lineno=7,
            end_col_offset=10,
            test=Compare(
                lineno=4,
                col_offset=7,
```

Next, we need to know how control flows through the program

Enter…the control flow graph (CFG)

We'll build up a graph representing all the paths we could take through the program during execution

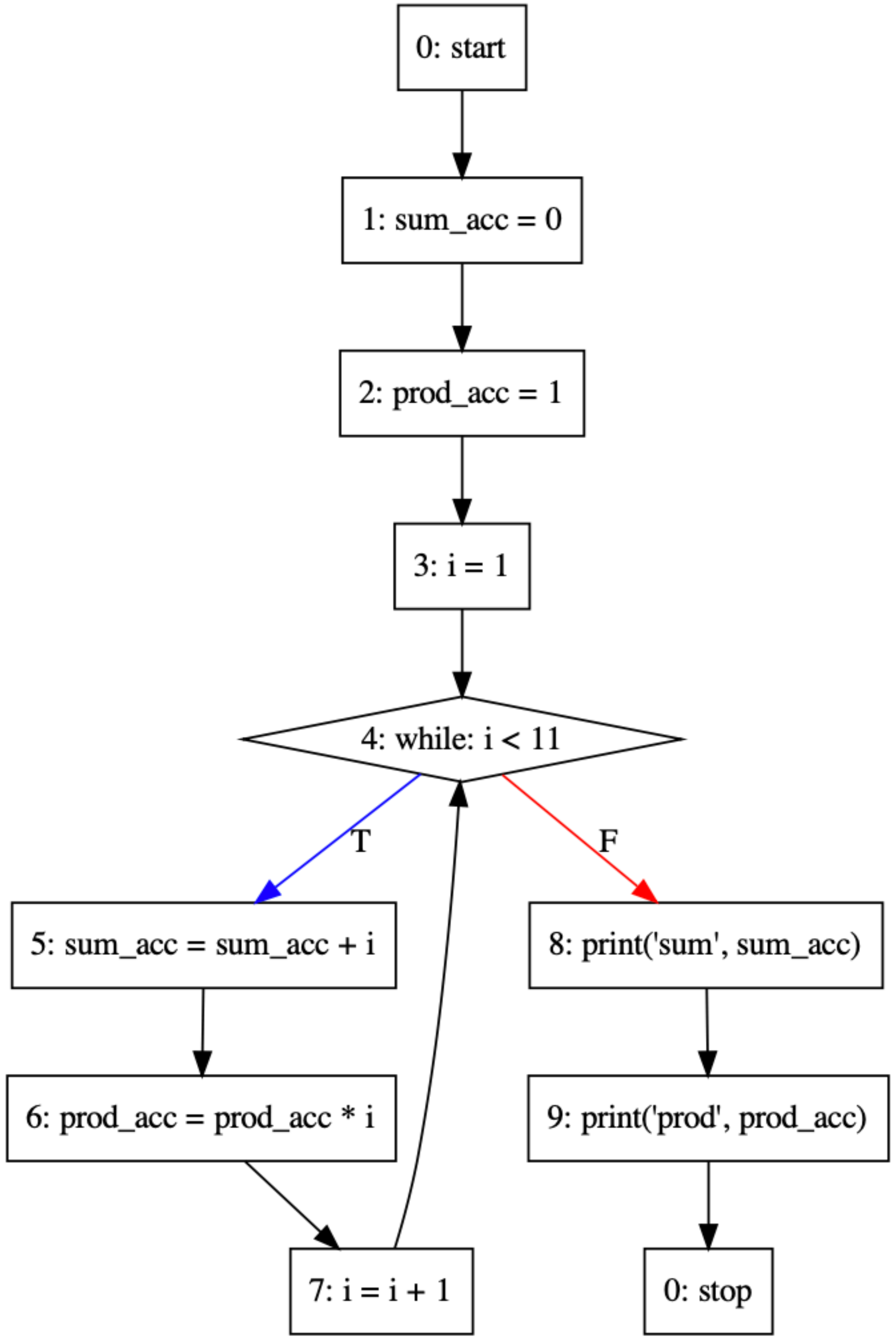


Another entry in our theme of 'there are so many ways to represent programs'!

CFGs

```python
sum_acc = 0
prod_acc = 1
i = 1
while (i < 11):
    sum_acc = sum_acc + i
    prod_acc = prod_acc * i
    i = i + 1
print("sum", sum_acc)
print("prod", prod_acc)
```

Program to analyze



The CFG!

But how do we get the slice from this thing?

Starting from a CFG, we'll compute data flow information about the set of relevant variables at each node

n	Statement	ref(n)	def(n)	relevant(n)

We'll use this ^ and this ^ to figure out this ^

Referenced at node n

Defined at node n

Program Slicing: Straight-Line Code

Slice for node ***n*** and variables ***V***

1. Initialize the relevant sets of all nodes to the empty set.
2. Insert all variables of ***V*** into **relevant(*n*)**.
3. For ***n***'s immediate predecessor ***m***, compute **relevant(*m*)** by:

    // first exclude all variables defined at ***m*** (because we're overwriting it)
    relevant(*m*) := **relevant(*n*)** - **def(*m*)**
    // if **m** defines a variable that's relevant at **n**
    if **def(*m*)** in **relevant(*n*)** then
        // include the variables that are referenced at **m**
        relevant(*m*) := **relevant(m)** ∪ **ref(*m*)**
        include ***m*** in the slice
    end

4. Repeat (3) for ***m***'s immediate predecessors, and work backwards in the CFG until we reach the start node or the relevant set is empty

Bolded n are included in the slice

n	Statement	ref(n)	def(n)	relevant(n)
1	b = 1		b	
2	c = 2		c	b
3	d = 3		d	b, c
4	a = d	d	a	b, c
5	d = b + d	b, d	d	b, c
6	b = b + 1	b	b	b, c
7	a = b + c	b, c	a	b, c
8	print a	a		a

slice for <8, {a}>

Step 2: relevant(8) = {a}
Step 3: relevant(7) = relevant(8) - def(7) = {a} - {a} = {}
relevant(7) = relevant(7) ∪ ref(7) = {} ∪ {b, c} = {b, c}
Since node 7 defines a variable relevant at node 8, it is included into the slice.
Step 3: relevant(6) = relevant(7) - def(6) = {b, c} - {b} = {c}
relevant(6) = relevant(6) ∪ ref(6) = {c} ∪ {b} = {b, c}
Since node 6 defines a variable relevant at node 7, it is included into the slice.
Step 3: relevant(5) = relevant(6) - def(5) = {b, c} - {d} = {b, c}
Step 3: relevant(4) = relevant(5) - def(4) = {b, c} - {a} = {b, c}
Step 3: relevant(3) = relevant(4) - def(3) = {b, c} - {d} = {b, c}
Step 3: relevant(2) = relevant(3) - def(2) = {b, c} - {c} = {b}
relevant(2) = relevant(2) ∪ ref(2) = {b} ∪ {} = {b}
Since node 2 defines a variable relevant at node 3, it is included into the slice.
Step 3: relevant(1) = relevant(2) - def(1) = {b} - {b} = {}
relevant(1) = relevant(1) ∪ ref(1) = {} ∪ {} = {}
Since node 1 defines a variable relevant at node 2, it is included into the slice.

What will happen if we add an if statement into our program?

- Any guesses?

Moving towards handling control flow…

- We have to extend our earlier approach to:
  - If we add a node ***m*** to our slice:
    - also add the *control set* of ***m*** to our slice
      - (the control set is the set of predicates that directly control its execution)
      - for each node ***c*** included based on being in the control set:
        - make a new slice! Starting at node ***c*** for variables **ref(*c*)**. The original slice (for <***n***, ***V***>) will now also include all nodes in the slice for <***c***, **ref(*c*)**>
  - Union the relevant sets (e.g., **relevant(m_1)** and **relevant(m_2)**) for cases where we have multiple descendants with a shared predecessor
    - (Remember that once we have control flow, we can have multiple descendants!)

n	Statement	ref(n)	def(n)	control(n)	relevant(n)
1	b = 1		b		
2	c = 2		c		b
3	d = 3		d		b, c
4	a = d	d	a		b, c, d
5	if a then	a			b, c, d
6	d = b + d	b, d	d	5	b, d
7	c = b + d	b, d	c	5	b, d
	else				
8	b = b + 1	b	b	5	b, c
9	d = b + 1	b	d	5	b, c
	endif				b, c
10	a = b + c	b, c	a		b, c
11	print a	a			a

slice for <11, {a}>

Step 2: relevant(11) = {a}
Step 3: relevant(10) = relevant(11) - def(10) = {a} - {a} = {}
relevant(10) = relevant(10) ∪ ref(10) = {} ∪ {b, c} = {b, c}
Since node 10 defines a variable relevant at node 11, it is included into the slice.
Step 3: relevant(9) = relevant(10) - def(9) = {b, c} - {d} = {b, c}
Step 3: relevant(8) = relevant(9) - def(8) = {b, c} - {b} = {c}
relevant(8) = relevant(8) ∪ ref(8) = {c} ∪ {b} = {b, c}
Since node 8 defines a variable relevant at node 9, it is included into the slice.
Since control(8) = 5, node 5 is included into the slice.
The slice for node 5 with respect to ref(5) is computed below.
Step 3: relevant(7) = relevant(10) - def(7) = {b, c} - {c} = {b}
relevant(7) = relevant(7) ∪ ref(7) = {b} ∪ {b, d} = {b, d}
Since node 7 defines a variable relevant at node 10, it is included into the slice.
Since control(7) = 5, node 5 is included into the slice.
The slice for node 5 with respect to ref(5) is computed below.
Step 3: relevant(6) = relevant(7) - def(6) = {b, d} - {d} = {b}
relevant(6) = relevant(6) ∪ ref(6) = {b} ∪ {b, d} = {b, d}
Since node 6 defines a variable relevant at node 7, it is included into the slice.
Step 3: relevant(5) = relevant(6) ∪ relevant(8) = {b, d} ∪ {b, c} = {b, c, d}
Step 3: relevant(4) = relevant(5) - def(4) = {b, c, d} - {a} = {b, c, d}
Step 3: relevant(3) = relevant(4) - def(3) = {b, c, d} - {d} = {b, c}
relevant(3) = relevant(3) ∪ ref(3) = {b, c} ∪ {} = {b, c}
Since node 3 defines a variable relevant at node 4, it is included into the slice.
Step 3: relevant(2) = relevant(3) - def(2) = {b, c} - {c} = {b}
relevant(2) = relevant(2) ∪ ref(2) = {b} ∪ {} = {b}
Since node 2 defines a variable relevant at node 3, it is included into the slice.
Step 3: relevant(1) = relevant(2) - def(1) = {b} - {b} = {}
relevant(1) = relevant(1) ∪ ref(1) = {} ∪ {} = {}
Since node 1 defines a variable relevant at node 2, it is included into the slice.

slice currently contains: 10, 8, 7, 6, 5, 3, 2, 1

We're not done yet! Remember slice for node 5 w.r.t. ref(5)!

Let's take care of that subslice

n	Statement	ref(n)	def(n)	control(n)	relevant(n)
1	b = 1		b		
2	c = 2		c		
3	d = 3		d		{}
4	a = d	d	a		{d}
5	if a then	a			{a}
6	d = b + d	b, d	d	5	
7	c = b + d	b, d	c	5	
	else				
8	b = b + 1	b	b	5	
9	d = b + 1	b	d	5	
	endif				
10	a = b + c	b, c	a		
11	print a	a			

slice for <5, {a}>

Step 2: relevant(5) = {a}
Step 3: relevant(4) = relevant(5) - def(4) = {a} - {a} = {}
Since node 4 defines a variable relevant at node 5, it is included into the slice.
relevant(4) = relevant(4) ∪ ref(4) = {} ∪ {d} = {d}
Step 3: relevant(3) = relevant(4) - def(3) = {d} - {d} = {}
Since node 3 defines a variable relevant at node 4, it is included into the slice.
relevant(3) = relevant(3) ∪ ref(3) = {} ∪ {} = {}
Since the relevant set is empty, no more nodes will be included into the slice.

final slice contains: 10, 8, 7, 6, 5, 4, 3, 2, 1

More reading

- The nice worked examples in these slides come from:
  - Program Slicing for Object-Oriented Programming Languages, Christoph Steindl (dissertation)
- If you want to dig in on these specific worked examples, take a look at Chapter 3 of the dissertation:
  - http://www.ssw.uni-linz.ac.at/General/Staff/CS/Research/Publications/Ste99a.html
- A more comprehensive resource:
  - Cooper and Torczon's Engineering a Compiler textbook
  - http://www.r-5.org/files/books/computers/compilers/writing/Keith_Cooper_Linda_Torczon-Engineering_a_Compiler-EN.pdf

What about loops?

- If we have loops, we have to keep iterating over the CFG until our slice and our relevant sets stabilize
- You won't be required to handle loops for your homework, but it's pretty fun if you're interested :)

Let’s do this!

- Fire up your 

- This is going to be our last programming assignment of the semester, so get ready to do some language hacking :)