CSE503: Software Engineering

David Notkin
University of Washington
Computer Science & Engineering
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A classic tool: slicing

- Of interest by itself
- And for the underlying representations
  - Originally, data flow
  - Later, program dependence graphs

Slicing, dicing, chopping

- Program slicing is an approach to selecting semantically related statements from a program [Weiser]
- In particular, a slice of a program with respect to a program point is a projection of the program that includes only the parts of the program that might affect the values of the variables used at that point
  - The slice consists of a set of statements that are usually not contiguous

Basic ideas

- If you need to perform a software engineering task, selecting a slice will reduce the size of the code base that you need to consider
- Debugging was the first task considered
  - Weiser even performed some basic user studies
- Claims have been made about how slicing might aid program understanding, maintenance, testing, differencing, specialization, reuse and merging

Example

```
read(n)
i := 1;
sum := 0;
product := 1;
while i <= n do begin
    sum := sum + i;
    product :=
      product * i;
    i := i + 1;
end;
write(sum);
write(product);
```

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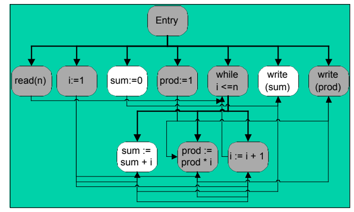
Weiser's approach

- For Weiser, a slice was a reduced, executable program obtained by removing statements from a program
  - The new program had to share parts of the behavior of the original
- Weiser computed slices using a dataflow algorithm, given a program point (criterion)
  - Using data flow and control dependences, iteratively add sets of relevant statements until a fixpoint is reached

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



- Thick lines are control dependences
- Thin lines are (data) flow dependences

Real PDGs are a bit more complicated

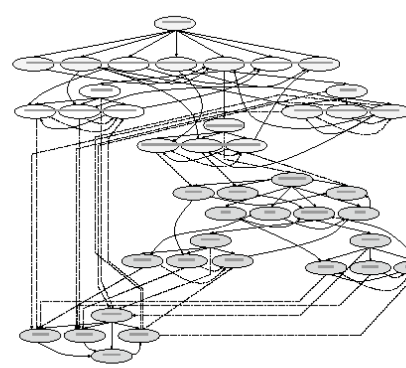
- Vertices in the graph represent (a) assignment states and (b) predicates in the program
- Edges represent control and data flow dependences
- Control dependences always start at a predicate (or the entry node)
  - They are labeled with a boolean
  - Intuitively, node w is control dependent on node v if the predicate of node v evaluates to the label on the edge from v to w – that is, what happens at w controls whether or not v executes
  - An assignment statement followed immediately by another assignment statement have no control dependence between them, since the second one always executes when the first one does
- Data dependences represent the possible flow of values through the program
  - (Roughly) there is a data dependence (edge) from node v to node w if v includes an assignment to some variable x, and then w includes a use of (that specific) x.
    - These can be separated into (at least) loop-independent and loop-carried dependences, which roughly distinguish whether the relationship is across iterations of a loop or not
- Def-order dependences can also be used; these aren't needed for all analyses, but ensure that only equivalent programs have isomorphic PDGs.

Procedures

- What happens when you have procedures and still want to slice?
- Weiser extended his dataflow algorithm to interprocedural slicing
- The PDG approach also extends to procedures
  - But interprocedural PDGs are a bit hairy (Horwitz, Reps, Binkley used SDGs)
  - Representing conventional parameter passing is not straightforward

The next slide...

- ..shows a fuzzy version of the SDG for a version of the product/sum program
  - Procedures `Add` and `Multiply` are defined
  - They are invoked to compute the `sum`, the `product` and to increment `i` in the loop



Context

- A big issue in interprocedural slicing is whether context is considered
- In Weiser's algorithm, every call to a procedure could be considered as returning to *any* call site
  - This in general significantly increases the size of a slice

Reps et al.

- Reps and colleagues have a number of results for handling contextual information for slices
- These algorithms generally work to respect the call-return structure of the original program
  - This information is usually captured as summary edges for call nodes
- www.cs.wisc.edu/~reps/talks/PLDI00.tutorial.ppt
  - General graph reachability for program analysis tutorial

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"

Technical issues

- How to slice in the face of unstructured control flow?
- Must slices be executable?
- What about slicing in the face of pointers?
- What about those pesky preprocessor statements?

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

Dynamic slicing

- Conventional program slicing assumes nothing about the inputs
- Dynamic slicing [Agrawal & Horgan 1990] [Korel & Laski 1990] is a variant that considers slicing with respect to a given test case (or suite) – increased precision for debugging is the intent

Lackwit (O'Callahan & Jackson)

- Code-oriented tool that exploits type inference
- Answers queries about C programs
  - e.g., "locate all potential assignments to this field"
  - Accounts for aliasing, calls through function pointers, type casts
- Efficient
  - e.g., answers queries about a Linux kernel (157KLOC) in under 10 minutes on a PC

Lackwit

- Semantic
- Scalable
- Real language (C)
- Static
- Can work on incomplete programs
  - Make assumptions about missing code, or supply stubs

- Sample queries
  - Which integer variables contain file handles?
  - Can pointer foo in function bar be passed to free()? If so, what paths in the call graph are involved?
  - Field f of variable v has an incorrect value; where in the source might it have changed?
  - Which functions modify the cur_veh field of map_manager_global?

Lackwit analysis

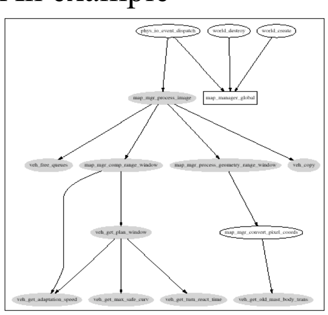
- Approximate (may return false positives)
- Conservative (may not return false negatives) under some conditions
  - C's type system has holes
  - Lackwit makes assumptions similar to those made by programmers (e.g., "no out-of-bounds memory accesses")
  - Lackwit is unsound only for programs that don't satisfy these assumptions

Query commonalities

- There are a huge number of names for storage locations
  - local and global variables; procedure parameters; for records, etc., the sub-components
- Values flow from location to location, which can be associated with many different names
- Archetypal query: Which other names identify locations to which a value could flow to or from a location with this given name?
  - Answers can be given textually or graphically

An example

- Query about the `cur_veh` field of `map_manager_global`
- Shaded ovals are functions extracting fields from the global
- Unshaded ovals pass pointers to the structure but don't manipulate it
- Edges between ovals are calls
- Rectangles are globals
- Edges to rectangles are variable accesses



Claim

- This graph shows which functions would have to be checked when changing the invariants of the current vehicle object
  - Requires semantics, since many of the relationships are induced by aliasing over pointers

Underlying technique

- Use type inference, allowing type information to be exploited to reduce information about values flowing to locations (and thus names)
- But what to do in programming languages without rich type systems?

Trivial example

- `DollarAmt getSalary(EmployeeNum e)`
- Relatively standard declaration
- Allows us to determine that there is no way for the value of `e` to flow to the result of the function
  - Because they have different types

- `int getSalary(int e)`
- Another, perhaps more common, way to declare the same function
- This doesn't allow the direct inference that `e`'s value doesn't flow to the function return
  - Because they have the same type
- Demands type inference mechanism for precision

Lackwit's type system

- Lackwit ignores the C type declarations
- Computes new types in a richer type system

- `char* strcpy(char* dest,char* source)`
- $(\mathtt{num}^{\alpha}\ \mathtt{ref}^{\beta}, \mathtt{num}^{\alpha}\ \mathtt{ref}^{\gamma}) \rightarrow^{\phi} \mathtt{num}^{\alpha}\ \mathtt{ref}^{\beta}$
- Implies
  - Result may be aliased with `dest` (flow between pointers)
  - Values may flow between the characters of the parameters
  - No flow between `source` and `dest` arguments (no aliasing)

Incomplete type information

- ```
  void* return1st(void* x,void* y)
  {
      return x; }
  ```
- $(a\ \mathbf{ref}^{\beta}, b) \rightarrow^{\phi} a\ \mathbf{ref}^{\beta}$

- The type variable a indicates that the type of the contents of the pointer `x` is unconstrained
  - But it must be the same as the type of the contents of pointer `y`
- Increases the set of queries that Lackwit can answer with precision

Polymorphism

- ```
  char* ptr1;
  struct timeval* ptr2;
  char** ptr3;
  …
  return1st(ptr1,ptr2); return1st(ptr2,ptr3)
  ```
- Both calls match the previous function declaration
- This is solved (basically) by giving `return1st` a richer type and instantiating it at every call site
  - $(c\ \mathbf{ref}^{\beta}, d) \rightarrow^{\delta} c\ \mathbf{ref}^{\beta}$
  - $(e\ \mathbf{ref}^{\alpha}, f) \rightarrow^{\chi} e\ \mathbf{ref}^{\alpha}$

Type stuff

- Modified form of Hindley-Milner algorithm "W"
- Efforts made to handle
  - Mutable types
  - Recursive types
  - Null pointers
  - Uninitialized data
  - Type casts
  - Declaration order

```
void copy(char * from, char * to) {
    *to = *from;
}
void copy5(char * fromarray, char * toarray) {
    int i;
    for (i = 0; i < 5; i++) {
        copy(from + i, to + i);
    }
}
void main(void) {
    char from1[5] = { 'h', 'e', 'l', 'l', 'o' };
    char to1[5];
    char from2[5] = { 'k', 'i', 't', 't', 'y' };
    char to2[5];
    copy5(from1, to1);
    copy5(from2, to2);
```

copy	$\forall\alpha.\forall\beta.\forall\phi.(\text{num}^{\alpha}\ \text{ref}^{\beta},\ \text{num}^{\alpha}\ \text{ref}^{\chi}) \to^{\phi} ()$
copy5	$\forall\delta.\forall\varphi.\forall\sigma.(\text{num}^{\delta}\ \text{ref}^{\varphi},\ \text{num}^{\delta}\ \text{ref}^{\kappa}) \to^{\sigma} ()$
main:from1	$\text{num}^{\theta}\ \text{ref}^{\rho}$
main:to1	$\text{num}^{\theta}\ \text{ref}^{\eta}$
main:from2	$\text{num}^{\mu}\ \text{ref}^{\zeta}$
main:to2	$\text{num}^{\mu}\ \text{ref}^{\gamma}$

- `*from1` is not compatible with either `*from2` or `*to2`
  - But it is with `copy:*from`, `copy:*to`, `copy5:*from` + `copy5:*to`

Morphin case study

- Robot control program of about 17KLOC
- Vehicle object contains two queue objects
  - Client was investigating combining these two queues into one
- Queried each queue object to discover operations performed and their contexts
- The two graphs each contained 171 nodes
  - But each graph had only five nodes highlighted as "accessor" nodes

Example

- These five matches helped identify code to be changed
- grep would have returned false matches and missed matches when parameters were passed to functions
- Context-sensitivity needed to distinguish the two queue onjects
  - Because both are passed as arguments to the same queue functions

Recap

- Helps find relationships among variables in a C program
  - Exploits type inference to understand values flowing to locations and thus names
- Approximate, although safe under many (most?) conditions
- Reasonably efficient