Intermodular Slicing of Object-Oriented Programs

Christoph Steindl

Department of Practical Computer Science (System Software)
Johannes Kepler University Linz, Austria
steindl@ssw.uni-linz.ac.at

Abstract. We describe a program slicing tool for object-oriented programs. Program slicing [Wei84] uses control flow and data flow information to visualise dependences and assist the programmer in debugging and in program understanding. Object-oriented programs exploit features like dynamic binding which complicate interprocedural alias analysis. Two distinctive features of our *Slicer* are the support for intermodular slicing and the usage of user-feedback during the computation of data flow information. To cope with the problem of alias analysis in the presence of function pointers (which is NP-hard [ZhR94]), we decided to first use a conservative approach leading to less precise data flow information, but then use the user's expertise to restrict the effects of dynamic binding at polymorphic call sites to get more precise solutions which should still be safe.

1 Overview

We implemented a program slicing tool for static forward slicing of object-oriented programs written in the programming language Oberon-2 [MöWi91] (for a technical description see [Ste97]). We did not restrict the language in any kind which means that we had to cope with structured types (records and arrays), global variables of any type, objects on the heap, side-effects of function calls, nested procedures, recursion, dynamic binding due to type-bound procedures (methods) and procedure variables (function pointers), and modules.

Program slicing has many applications such as debugging, code understanding, program testing, software metrics, and automatic parallelisation. Weiser [Wei84] originally defined a slice with respect to a program point p and a subset of the program variables V to consist of all statements in the program that may affect the values of the variables in V at point p. He presented algorithms which use data flow analysis on control flow graphs to compute intraprocedural and interprocedural slices.

The underlying data structures of our *Slicer* are the *abstract syntax tree (AST)* constructed by the front-end of the Oberon compiler [Cre90]. Additional information (such as control and data dependences) is added to the nodes of this syntax tree during the computation. We define a slice with respect to a node of the AST (starting node). The nodes of the AST represent the program at a fine granularity (see Fig. 1), i.e. one statement can consist of many nodes (function calls, operators, variable usages, variable definitions, etc.). The target and origin of control and data dependences are nodes of the AST, not whole statements. This allows for fine-grained slicing (cf. [Ern94]), therefore we call our slicing method *expression-oriented* in contrast

to *statement-oriented* slicing. Our slicing algorithm is based on the two-pass slicing algorithm of Horwitz et al. [HRB90] where slicing is seen as a graph-reachability problem (this algorithm uses summary information at call sites to account for the calling context of procedures) and on the algorithm of Livadas et al. [LivC94, LivJ95] for the computation of transitive dependences of parameters of procedures. In order to slice the program with respect to the starting node, the graph representation of the program is traversed backwards from the starting node along control and data dependence edges. All nodes that could be reached belong to the slice because they potentially affect the starting node.
We extended the notion of interprocedural slicing to intermodular slicing. Information that has been computed once is reused when slicing other modules that import previously sliced modules. Furthermore, we support object-oriented features such as inheritance, type extension, polymorphism, and dynamic binding. Since the construction of summary information at call sites is the most costly computation, it is worthwhile to cache this information in a repository and reuse as much information as possible from previous computations.
Zhang and Ryder showed that aliasing analysis in the presence of function pointers is NP-hard in most cases [ZhR94]. This justifies to use safe approximations since exact algorithms would be prohibitive for an interactive slicing tool where the maximum response time must be in the order of seconds. Our approach to reach satisfying results is to use feedback from the user during the computation of data flow information. The user can for example restrict the dynamic type of polymorphic variables and thereby disable specific destinations at polymorphic call sites.
Section 2 discusses intraprocedural and interprocedural control flow analysis that copes with dynamic binding. Section 3 shows how we compute data flow information and how type information can be used for simple but efficient alias analysis. Section 4 describes our support for interprocedural and intermodular slicing. Section 5 describes how we support object-oriented features. Section 6 gives examples of the user interface and user feedback. Finally, section 7 compares our Slicer with other slicing tools and classifies it according to the criteria used in Hoffner's comparison of program slicing tools [Hof95], whereas section 8 gives an outlook onto future work.

2 Control Flow Analysis

2.1 Intraprocedural Control Flow Analysis

In general, control dependences can be defined in terms of the control flow graph (consisting of so-called basic blocks) and dominators [Aho86] (for a definition of these terms see [FOW87] and [Aho86]). In Oberon-2, the computation of intraprocedural control flow information is - in most cases - very easy, since Oberon contains mainly constructs for structured control flow. These control dependences therefore simply reflect the program's nesting structure.

2.2 Interprocedural Control Flow Analysis and the Handling of Dynamic Binding

For interprocedural slicing, we have to compute interprocedural control dependences due to procedure and function calls which represent transfers of control from the call site to the called procedure. For statically bound calls (ordinary procedure and function calls), the interprocedural control flow graph is built by simply linking the call sites (*call* nodes of the AST) with the destination of the calls (*enter* nodes). In addition to static binding, Oberon-2 offers two ways of dynamic binding: type-bound procedures (or methods) and procedure variables (or function pointers).

For dynamically bound calls we use the following approximation: In the first step we introduce links between the call sites and all possible destinations (this corresponds to the results obtained by Class Hierarchy Analysis [DGC94]). Then we present the results to the user and let the user decide if we overestimated the set of destinations. The user can enable and disable some of the links (see Section 6; this corresponds to truly dynamic information that can be obtained by profiling the program but that can not be deduced even by flow-sensitive type analysis [PaR93]). Then we perform data flow analysis on the enabled interprocedural links. Zhang and Ryder showed that aliasing analysis in the presence of function pointers is NP-hard in most cases [ZhR94]. It is therefore reasonable to use approximations during data flow analysis. We decided to use only safe approximations in the first place, and let the user opt for further optimisations (which may be unsafe in general but correct for the use case that the user has in mind - we are not using this information for improving the performance of the program but rather to assist the programmer during the interactive process of debugging and program understanding).

Above all we consider it important to minimise the number of dynamically bound procedures and the number of possible destinations per call site. In order to achieve this we use the following rules:

1. Super calls can be bound statically since it is known at compile time which is the overridden method in the super class.
2. Type-bound procedures (methods) can be bound statically if
   a) the actual receiver of the method is a monomorphic variable,
   b) the record type is not exported and there are no extensions of this record type (no overridden method possible), or
   c) the record type is not exported and the method is not overridden in any of the extensions within the same module.

The rules 2.b) and 2.c) describe the cases where the method is surely not overridden (this corresponds to an empty *Override* set of the method in the terms of [Bac97]).

For the cases of true dynamic binding we have to find all possible destinations of the calls. For type-bound procedures, these are simply the methods of the statically known class of the receiver and all subclasses (this is a conservative assumption and can be improved by fast techniques like Rapid Type Analysis [Bac97] or by other flow sensitive techniques [PaR93]). For procedure variables, we have to determine the set of possible destinations either by propagating the assigned procedures along all possible paths in the invocation graph [EGH94] or by using the following approximations:

1. A procedure must be assigned somewhere to a procedure variable. Otherwise it can never be the destination of a call.
2. The type of the procedure and the type of the procedure variable must match (this depends on the semantics of the programming language, in Oberon this means basically that the procedures have the same number of parameters where corresponding parameters have same types, see [MöWi91]).

In order to verify if these approximations yield reasonable results, we counted the call sites in various software packages and classified them:

Package	$stat_1$	$stat_2$	$stat_3$	$stat_4$	dyn_1	dyn_2	dyn_3
Slicer	4290	0	135	22	0	121	51
Compiler	3766	0	0	0	0	0	0
Kepler	899	40	0	0	0	456	14
Dialogs	1204	67	0	0	0	650	10
Oberon System	5555	0	58	1	0	268	109

Tab. 1. Statistics of statically and dynamically bound calls

$stat_1$: statically bound procedure/function calls
$stat_2$: statically bound super calls
$stat_3$: statically bound method call (receiver is monomorphic)
$stat_4$: statically bound method call (method not overridden)
dyn_1: dynamically bound method call (all possible methods known)
dyn_2: dynamically bound method call (unknown methods may be called)
dyn_3: dynamically bound procedure call via procedure variable

Even for truly object-oriented programs the percentage of dynamically bound calls to statically bound calls does not exceed 30%. This verifies our main assumption that - although dynamic binding cannot be ignored - the majority of calls can be bound statically.

3 Data Flow Analysis

The computation of data flow information is much more complicated than the computation of control flow information. As mentioned earlier, aliasing analysis in the presence of procedure variables is NP-hard for languages like Oberon-2 with arrays, pointers and reference parameters.

We perform the computation of data flow information in two phases: First we compute the used and defined variables per node in the AST. Then we compute the reaching definitions in a syntax-directed manner.

3.1 Computation of Used and Defined Variables

In the first phase we compute the used and defined variables per node in the AST. In Oberon-2, the value of variables can only be changed by assignment statements or by passing the variable as a reference parameter to a procedure, provided that the called procedure actually defines the variable. Then the sets *gen* and *kill* (implemented as bit-vectors, see [Aho86]) are computed for each defining node:

gen(node) = {identification of node} where *node* defines the variable *a*

kill(node) = D_a - gen(node)   with D_a = set of all definitions of variable *a*

3.2 Computation of Reaching Definitions

In the second phase we compute the reaching definitions in a syntax-directed manner. The following data flow equations are used to the compute reaching definitions *in* for each node of the AST (cf. [Aho86]):

(1) Sequence S = S1 S2
gen(S) = gen(S2) U (gen(S1) - kill(S2))
kill(S) = kill(S2) U (kill(S1) - gen(S2))
out(S) = gen(S) U (in(S) - kill(S))

(2) Selection (IF, CASE)
gen(S) = union of gen of all branches
kill(S) = intersection of kill of all branches
in of each branch = in(S)
out(S) = union of out of all branches

(3) Iteration (LOOP, WHILE, REPEAT)
gen(S) = gen of nested statement sequence S1
kill(S) = kill(S1)
in(S1) = in(S) U gen(S1)
out(S) = out(S1)

In Fig. 1, we show the AST of the statement sequence in Example 1 with encircled definitions of variables and data dependences to the reaching definitions. The left-hand side of an assignment statement (i.e. the defined variable) is finally data dependent on all used variables of the right-hand side of the assignment. These variable nodes on the right-hand side are again data dependent on all reaching definitions. *if* nodes are data dependent on all variable usage nodes in the expression sub-tree.

Example 1:

```
Read(i);
IF i < 0 THEN i := -i END ;
j := i * 3;
```

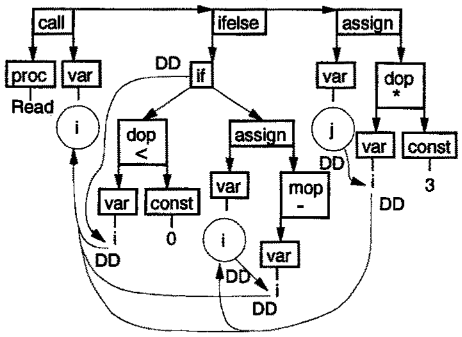


Fig. 1. AST of the statement sequence in Example 1 with definitions of variables, reaching definitions, and data dependences (DD)

3.3 Alias Analysis

In order to handle aliasing effects correctly, we generate for each definition of a variable non-killing definitions for each variable that may be an alias. This is a conservative approach that can be improved substantially by techniques like *Storage Shape Graphs* [Cha90, LivR94], but is surprisingly effective if we use type information in order to restrict the sets of variables that may be aliases. Two objects may only be aliases if they have the same type or if one could be a record field or an array element of the other.

The following table shows how one can further restrict the set of objects that may be aliases by using information about where the object is declared:

- Local objects are declared in a procedure. They are only accessible in the declaring procedure.
- Global objects are declared in a module and are accessible from anywhere within the module. Global objects can be exported from a module and imported (and used) by other modules. This export can be read/write (thereby granting full access to the object) or read-only.
- Intermediate objects are objects that are declared in a nesting procedure and can be accessed from nested procedures.

Table 2 shows whether two objects *o1* (row) and *o2* (column) can be aliases.

o1 \ o2	(1)	(2)	(3)	(4)	(5)	(6)
(1) local var	no	no	no	no	no	no
(2) intermediate var	no	no	yes*	no	no	no
(3) reference par	no	yes*	yes	yes	no	yes
(4) global var (this mod.)	no	no	yes	no	no	no
(5) global var (other mod.), read-only	no	no	no	no	no	no
(6) global var (other mod.), r/w	no	no	yes	no	no	no

Tab. 2. Possible Aliases

(1) Local variables (including value parameters) can never be aliases of other objects (in Oberon, pointers always reference objects on the heap and never local objects on the stack).
(2) Intermediate variables (including intermediate value parameters) can only be aliased by reference parameters with a further restriction (indicated by a "*" in the table) that the reference parameter must have a higher nesting level (par.level > var.level).
(3) Aliases are mainly introduced by reference parameters.
(4) Global variables of the same module can only be aliased by reference parameters.
(5) Global variables of another module that are exported read-only cannot be used as reference parameters (this would require write access). Because they can only be read or used as value parameters they cannot be aliases of other objects.
(6) Global variables of another module can only be aliased by reference parameters.

4 Expression-Oriented Program Slicing

We perform slicing on a "per node" basis which is also termed *expression-oriented* slicing (in contrast to *statement-oriented* slicing). The target and origin of control and data dependences are nodes of the AST, not whole statements. The units that are considered for inclusion into the slice are AST nodes. This allows for fine-grained slicing (cf. [Ern94]), i.e. the resulting slice is as precise as possible. E.g., only those variable definitions and declarations are highlighted to the user, whose variables are actually visited during slicing, in the import list only those modules are highlighted, that are actually needed somewhere in the slice, etc.

4.1 Interprocedural Program Slicing

We modelled our internal data structures for interprocedural slicing after the algorithm of Horwitz et al. [HRB90] and their *System Dependence Graph.* The following nodes and edges are used to facilitate interprocedural program slicing:

- *formal input parameter nodes* are added to the *enter* node of a procedure P for all parameters and for all used or defined variables, *formal output parameter nodes* for all parameters and for all defined variables (if the corresponding formal output parameter is defined on all control flow paths, the definition of the corresponding actual parameter is a killing definition, otherwise it is a non-killing definition), corresponding *actual parameter nodes* are added at the call sites calling P,
- *parameter-in edges* between *actual parameter nodes and formal input parameter nodes* (only if the formal parameter is at all used by the called procedure), *parameter-out edges* between *formal output parameter nodes and actual parameter nodes* (only if the formal parameter is at all defined by the called procedure), additionally for functions: *parameter-out edge* between the *procedure exit node* and the call site in order to account for the data flow of the return value,
- *call edges* linking the call sites with the destinations of the calls, and
- *transitive dependence edges* of formal output parameters (and for functions of the *procedure exit node*) on formal input parameters.

We use an adaptation of Livadas' algorithm [LivC94, LivJ95] for the computation of transitive dependences during data flow analysis by slicing the procedure intraprocedurally starting from the formal output parameters and inserting transitive dependences to all formal input parameters that have been marked during slicing. Fig. 2 shows the AST of Example 2. The formal input parameter node of *in* is marked during slicing for the formal output parameter node of *out*, therefore a transitive dependence edge is inserted from the formal output parameter node of *out* to the formal input parameter node of *in*. This transitive dependence edge is reflected onto all call sites. There is a data depencence edge incident to the formal input parameter node of *in* which means that the value of *in* is used. Therefore, a *parameter-in edge* is inserted from the actual parameter node to the formal parameter node. The formal input parameter node of *out* is not marked during slicing. This means that the definition of *out* at the formal input parameter node does not reach the formal output parameter node. In other words, *out* is defined on all control flow paths in procedure *Abs*. Thus, the definition of the second parameter is a killing definition at call sites of *Abs*. There is no data dependence edge incident to the formal input parameter node of *out*. This means that the value of *out* is never used. It is therefore not necessary to insert a *parameter-in edge* between the second parameter at the call sites of *Abs* and the formal input parameter of *out*, but a parameter-out edge is necessary, since *out* is defined in *Abs*.

Example 2:

```
PROCEDURE Abs (in: INTEGER; VAR out: INTEGER);
BEGIN
   IF in < 0 THEN out := - in
   ELSE out := in
   END
END Abs;
...
Abs(i, j)
```

After the computation of transitive dependences, interprocedural slices are computed by solving a graph reachability problem [HRB90]. To obtain precise slices, the computation of a slice must preserve the calling context of called procedures (especially if there are several call sites of the same procedure), and ensure that only paths corresponding to legal call/return sequences are considered.
The first pass of the interprocedural slicing algorithm [HRB90] determines all nodes that can be reached by a backwards traversal of control and data flow edges but without descending into called procedures. Transitive interprocedural dependence edges guarantee that calls can be side-stepped. In the second pass, the algorithm descends into all previously side-stepped calls and determines the remaining nodes in the slice. The slice is the union of the nodes visited during both passes.

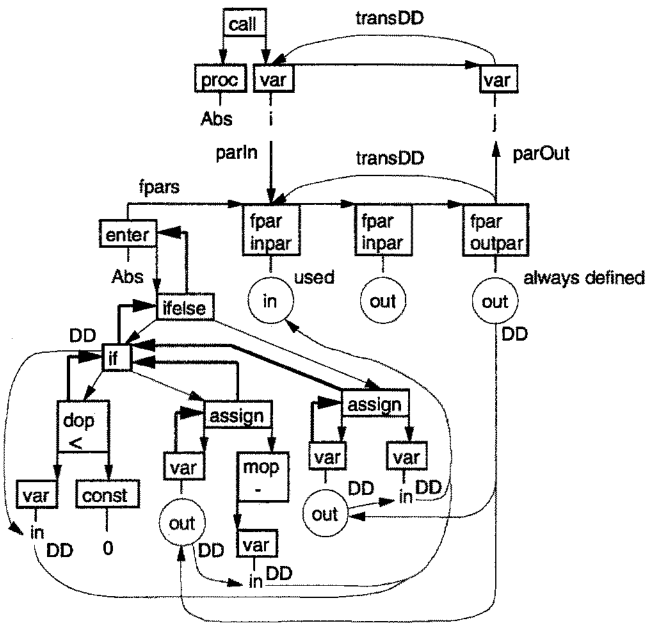


Fig. 2. Computation of transitive dependences (transDD)

4.2 Intermodular Program Slicing

In Oberon, large programs can be split up into several modules which may be compiled separately, each module defining its interface by exporting or not exporting items (variables, constants, types, procedures etc.). This interface is then stored in a so-called "symbol file". Other modules can import already existing modules, and the compiler uses the symbol files for type checking the imported items across module boundaries.

We extended this idea to provide for intermodular slicing in the following way: control flow and data flow information that is computed during slicing is stored in a repository and is reused when slicing dependent modules. The repository is therefore more or less an internalised directory of symbol files. Of course, one cannot keep all the information but has to omit unnecessary details. What is actually made persistent is the following:

- Every exported global procedure (function or method), the module body and every procedure that has been assigned to a procedure variable together with their lists of parameters. Furthermore, we keep the sets used and defined variables, the additional parameters of every procedure, the transitive dependences of the parameters and information about how the parameters are used by the procedure (parameter used as input parameter, as output parameter, used or defined at all, or defined on all control flow paths).
- Global types (since they may be used by parameters of global procedures, may be exported and extended and so on).

The repository for the core Oberon System (30 modules, 14000 lines, 11000 statements) [WiG88] occupies only about 800 kBytes of disk storage.

5 Support for Object-Oriented Features

The key concepts of object-oriented programming, like abstraction, information hiding, encapsulation of data and code, inheritance and type-extension, polymorphism and dynamic binding, are handled in a natural way. Since the underlying data structures of our *Slicer* are the abstract syntax tree and the symbol table (which is actually a general graph) generated by the front-end of the Oberon compiler, we do not have to build a Class Hierarchy Graph [Bac97] or similar data structures (cf. [LaH95a], [LaH95b], and [Kri94]) on our own, but reuse the information contained in the symbol table: For every class, the symbol table contains information about fields (including access rights) and the methods of the class, as well as the inheritance relationship between the classes. Information about inherited fields and methods can be accessed via a link to the superclass.
Polymorphism and type-extension must be accounted during alias analysis. When a field of an object of some class is changed, the conservative assumption would be that all objects of the same class are regarded as „possibly changed“. But since a polymorphic variable can also refer to an object of some extension of its static type, all objects of the same class and of extended classes must be regarded as „possibly changed“.
Encapsulation of code and data is not really a new feature of object-orientedness but can already be accomplished with modular programming languages like Modula-2. But in order to understand programs that exploit abstraction and information hiding, it is important to make visible to the user which (hidden) data is used during some calculation. If we slice for the last statement in *Client.Do* (the assignment to *z*) in Example 3, we have to include the first call of *R.Uniform* into the slice, since the last call of *R.Uniform* depends on the value of the invisible variable *R.state* which is assigned during the first call of *R.Uniform*. In order to make these effects of information hiding obvious to the user, we show all used and defined variables of procedures and functions that are not passed as parameters as additional parameters (cf. Section 4.1). In object-oriented programs, it seems to be even more essential to provide support for the understanding of control and data flow that is complicated by information hiding.

Example 3:

```
MODULE Random;

VAR state: LONGINT;

PROCEDURE Uniform*(): LONGINT;
BEGIN ...
END Uniform;

END Random;
```

```
MODULE Client;
IMPORT R := Random;

PROCEDURE Do*;
BEGIN
   z := R.Uniform(   (*R.state*) );
   ...
   z := R.Uniform( (*R.state*) );
END Do;

END Client.
```

Dynamic binding is resolved by our interprocedural control flow analysis (see Section 2.2). *Polymorphic choice nodes* (see section 6.2) provide the user interface to restrict the effects of dynamic binding at polymorphic call sites.

6 User Interface and User Feedback

6.1 User Interface

The user interface of our Slicer is currently mainly textual with active elements [MöK96] for the following purposes:

- bi-directional hypertext links between the call sites and all procedures that may be called.
- reaching definitions - all reaching definitions are collected in a popup menu element. By selecting a definition from the popup element, this definition is shown in the code.
- polymorphic choice nodes - the user can enable and disable links to procedures at polymorphic call sites.
- parameter summary information - in the formal parameter lists of procedures parameter summary information is available via parameter info elements. The usage of the parameters is indicated by an arrow (↑ for definition without usage (OUT parameter), ↓ for usage without definition (IN parameter), ↕ for usage and definition (reference parameter), ↓! to indicate an anomaly for value parameters like "parameter is never used" or "assignment to value parameter", ↕! to indicate an anomaly for reference parameters like "possibly not set")). By clicking on these arrows of output parameters, the procedure is sliced intraprocedurally for this parameter.

By clicking on a statement, interprocedural slicing for the corresponding AST nodes is performed. All source code parts corresponding to AST nodes that have been reached during slicing are then emphasised by colouring them blue. When slicing for the last statement in Example 4, only the parts that are written in bold are actually in the slice. The slice is not executable, but shows all parts that can influence the last statement. The first assignment to *j* is in the slice because it generates a reaching definition for the parameter *j* in *SideEffect(j)*. This parameter is itself a killing definition for *j* because the formal parameter *i* of *SideEffect* is defined on all control flow paths. It is therefore also the only reaching definition of *j* at the last statement. If we were rather interested in an executable slice, everything of Example 4 would be in the slice. Most slicing tools perform *statement-oriented* slicing which would again include everything into the slice.

Example 4:

```
VAR i, j, k, l: INTEGER;

PROCEDURE SideEffect (VAR i: INTEGER): INTEGER;
BEGIN INC(i); RETURN i
```

```
END SideEffect;

...
BEGIN
    i := F0();
    j := F1();
    k := F2();
    l := i + SideEffect(j) * k;
    j := j
END
```

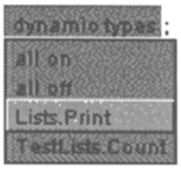
Furthermore the Slicer inserts annotations into the source code to indicate:

- control dependences and data dependences
- additional parameters for used and for defined objects that are not originally part of the formal parameter list
- parameter summary information (e.g.: parameter x is used; parameter y is defined; parameter z is used and always defined)
- dead code (e.g., procedures that are never called or code after a RETURN or EXIT statement)

Each of these active elements and annotations can be turned on and off to avoid getting lost in too much information.

6.2 User Feedback

As mentioned earlier, the user's expertise is used to restrict the effects of dynamic binding at polymorphic call sites. For type-bound procedures, the user may specify which of the possible dynamic types of the receiver shall be considered during data flow analysis. The notion of "dynamic type" of a polymorphic pointer variable which may point to objects of a given class (corresponding to the static type of the pointer variable) and subclasses thereof has therefore been extended in a natural way to procedure variables (function pointers): For procedure variables, the user may disable some of the possible destinations of the polymorphic call sites. The user can click on a polymorphic choice element and disable or enable all or some of the destinations of the call. On the right, there is the popped-up view of a polymorphic choice element. The user can disable the link to *Lists.Print* if she is not interested in the effects of *Lists.Print* on the polymorphic call site.



7 Comparison

Since the underlying data structure of our *Slicer* is the AST and the symbol table of the Oberon compiler, all object-oriented features like inheritance, type extension, and dynamic binding are already handled and we do not need to introduce additional kinds of edges and nodes like *class entry nodes, class member edges* [LaH95a, LaH95b] or *class header nodes, class membership edges, inheritance edges, polymorphic call edges,* and *inherited method edges* [Kri94].
The response times when using our slicing tools are always within 5 seconds for the

computation of control and data flow information and less than a second for slicing itself. Memory usage is in the order of some megabytes for large modules, it is approximately twice the memory used by the standard Oberon compiler to compile the module.

According to Hoffner [Hof95], our *Slicer* can be classified as follows:

- *Slicing variables*: The slicing criterion cannot consist of an AST node and an arbitrary variable, rather must the variable be used or defined at the statement.
- *Type of result:* The AST nodes that are part of the slice are emphasised by colouring them.
- *Slicing point*: The slicing criterion is a specific node in the AST rather than a combination of a statement and a variable.
- *Scope of slice*: The scope of the slice is intermodular (not only interprocedural or even intraprocedural). Already computed slicing information is kept in a repository and reused when slicing dependent modules.
- *Slicing direction*: Although our discussion focused on backward slicing, our techniques are also applicable for the calculation of forward slices [HRB90]. No additional analysis information is required to calculate forward slices.
- *Abstraction level*: We use *expression-oriented* slicing which is finer-grained than *statement-oriented* or *procedure-oriented* slicing. The units that are considered for inclusion into the slice are AST nodes.
- *Type of information*: The kind of information is *semi-dynamic* as it combines static information (obtained from the source code) with dynamic information (obtained via user feedback).
- *Computing method*: We compute slices by a graph reachability algorithm on the enriched AST (in contrast to solving data flow equations).

Among other things, Hoffner compares three slicing tools: *Kamkar's slicing tool* [Kam93], *Spyder* [Agr91], and the *Wisconsin Program Integration System*. He reports time measurements between 25 seconds (Kamkar's tool) and 430 seconds (Spyder) for computing control and data flow information of a 300 lines program (Calculator for infix expressions) on a SPARC-station 10/20. The memory usage is estimated by the number of nodes and edges (ranging from about 600 to about 2300 nodes and up to 6000 edges) Our slicer takes approximately one second in order to compute control and data flow information on a 200 MHz Pentium, the time for slicing is not noticeable. During slicing we use approximately 700 kBytes of memory which may be comparable to the memory used by the other slicing tools. Therefore, we dare say that our slicing tool is really appropriate for interactive use.

8 Conclusion and Future Work

Our *Slicer* (available via http://www.ssw.uni-linz.ac.at/Staff/CS/Slicing.html) helps a lot during debugging and reverse engineering. To use Oberon-2 as a source and target language helped us on the one hand (because we already had a parser, a compiler and other tools for that language), but made it difficult on the other hand (e.g., due to reference parameters, dynamic binding, and modules). However, we could not have implemented a slicing tool with the same functionality for as big a language as C++. Therefore we are glad about the choice of the language.

The main contributions of our work are:
1. Intermodular slicing with caching of already computed information in a repository.
2. Efficient and natural support for object-oriented features.
3. Resolution of dynamic binding in the first place and usage of user feedback in order to restrict the effects of dynamic binding later on at polymorphic call sites.
4. Expression-oriented slicing yielding precise semi-dynamic slices.

Currently we are working on a port of our program slicer to Java. In the future, we will try to further decrease the effects of dynamic binding (cf. [CaG94], [PaR93]). Furthermore, we want to improve our alias analysis to reduce the number of possible aliases at definitions (thereby reducing the number of non-killing definitions).

9 Acknowledgements

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10 Bibliography

[Agr91] Hiralal Agrawal: Towards Automatic Debugging of Computer Programs. PhD thesis, Purdue University, West Lafayette, Indiana, 1991.

[Aho86] Alfred V. Aho, Ravi Sethi, Jeffrey D. Ullman: Compilers: Principles, Techniques, and Tools. Addison-Wesley, 1986.

[Bac97] David Bacon: Fast and Effective Optimization of Statically Typed Object-Oriented Languages. PhD thesis, University of California at Berkeley, http://http.cs.berkeley.edu/~dfb/papers/thesis.ps

[CaG94] Brad Calder, Dirk Grunwald: Reducing indirect function call overhead in C++ programs. 21st ACM Symposium on Principles of Programming Languages, 1994.

[Cha90] David R. Chase, Mark N. Wegman, F. Kenneth Zadeck: Analysis of Pointers and Structures, ACM Conference on Programming Language Design and Implementation, 1990.

[Cre90] Régis Crelier, OP2: A Portable Oberon Compiler. Technical report 125, ETH Zürich, February 1990.

[DGC94] Jeffrey Dean, David Grove, Craig Chambers: Optimization of Object-Oriented Programs Using Static Class Hierarchy Analysis. In Proceedings of the Ninth European Conference on Object-Oriented Programming - ECOOP'95 (Aarhus, Denmark), Springer-Verlag, August 1995.

[EGH94] Maryam Emami, Rakesh Ghiya, Laurie J. Hendren: Context-Sensitive Interprocedural Points-to Analysis in the Presence of Function Pointers. ACM Conference on Programming Language Design and Implementation, 1994.

[Ern94] Michael D. Ernst: Practical fine-grained static slicing of optimized code. Technical report MSR-TR-94-14, Microsoft Research.

[FOW87] Jeanne Ferrante, Karl J. Ottenstein, Joe D. Warren: The Program Dependence Graph and Its Use in Optimization. ACM TOPLAS vol. 9, no. 3, July 1987.

[Hof95] Tommy Hoffner: Evaluation and comparison of program slicing tools. Technical report LiTH-IDA-R-95-01, Department of Computer and Information Science, Linköping University, Sweden, 1995.

[HRB90] Susan Horwitz, Thomas Reps, David Binkley: Interprocedural Slicing Using Dependence Graphs. ACM TOPLAS vol. 12, no. 1, Jan. 1990.

[Kam93] Mariam Kamkar: Interprocedural Dynamic Slicing with Applications to Debugging and Testing. PhD thesis, Linköping University, Sweden, April 1993.

[Kri94] Anand Krishnaswamy: Program Slicing: An Application of Object-oriented Program Dependency Graphs. Technical report, Department of Computer Science, Clemson University, ftp://ftp.cs.clemson.edu/techreports/94-109.ps.Z

[LaH95a] Loren D. Larsen, Mary Jean Harrold: Slicing Object-Oriented Software. Techical report, Department of Computer Science, Clemson University, ftp://ftp.cs.clemson.edu/techreports/95-103.ps.Z

[LaH95b] Loren D. Larsen, Mary Jean Harrold: Slicing Object-Oriented Software. Techical report, Department of Computer Science, Clemson University, ftp://ftp.cs.clemson.edu/techreports/95-114.ps.Z

[LivC94] Panos E. Livadas, Stephen Croll: A New Algorithm for the Calculation of Transitive Dependences. Technical report, Computer and Information Sciences Department, University of Florida, 1994, ftp://ftp.cis.ufl.edu/pub/faculty/pel/tech_reports/recursions.ps.gz

[LivJ95] Panos E. Livadas, Theodore Johnson: An Optimal Algorithm for the Construction of the System Dependence Graph. Technical report, Computer and Information Sciences Department, University of Florida, 1995, ftp://ftp.cis.ufl.edu/cis/tech-reports/tr95/tr95-011.ps.Z

[LivR94] Panos E. Livadas, Adam Rosenstein: Slicing in the Presence of Pointer Variables. Technical report, Computer and Information Sciences Department, University of Florida, 1994, ftp://ftp.cis.ufl.edu/pub/faculty/pel/tech_reports/pointers.ps.gz

[MöK96] Hanspeter Mössenböck, Kai Koskimies: Active Text for Structuring and Understanding Source Code. SOFTWARE - Practice and Experience, 26(7), 1996.

[MöWi91] Hanspeter Mössenböck, Niklaus Wirth: The Programming Language Oberon-2, Structured Programming, vol. 12, no. 4, 1991.

[PaR93] Hemant D. Pande, Barbara G. Ryder: Static type determination for C++. Technical report, LCSR-TR-197, Rutgers University, February 1993.

[Ste97] Christoph Steindl: Program Slicing for Oberon. Technical report 11, Institut für Praktische Informatik, JKU Linz, 1997.

[Wei84] Mark Weiser: Program Slicing. IEEE Trans. Software Engineering, vol. SE-10, no. 4, July 1984.

[WiG88] Niklaus Wirth, Jürg Gutknecht: The Oberon System. Technical report 88, Departement Informatik, ETH Zürich, 1988. An up-to-date version of the Oberon System can be obtained via ftp://ftp.ssw.uni-linz.ac.at/pub/Oberon

[ZhR94] Sean Zhang, Barbara G. Ryder: Complexity of Single Level Function Pointer Aliasing Analysis. ftp://athos.rutgers.edu/pub/technical-reports/lcsr-tr-233.ps.Z