

Implementing safe module unloading for the FPGA Oberon operating system

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In FPGA Oberon¹, there exist three possible types of references to a loaded module M²:

1. *Client references* exist when other loaded modules *import* module M.
2. *Type references* exist when type tags (addresses of type descriptors) in *dynamic* objects reachable by other loaded modules refer to descriptors of types *declared* in module M.
3. *Procedure variable references* exist when procedure variables in *static* or *dynamic* objects reachable by other loaded modules refer to procedures *declared* in module M.

In most Oberon implementations, only *client* references are checked prior to module unloading. *Type* and *procedure variable* references are usually not checked, although various approaches are typically employed to address the case where modules *with* such references are unloaded³.

In Experimental Oberon⁴, a revision of FPGA Oberon, *all* possible types of references to a loaded module or module group are checked as follows prior to module *unloading* (Figure 1):

- If clients exist, a module or module group is never unloaded.
- If no client, type or procedure variable references to a module or module group exist in the remaining modules or data structures, it is unloaded and its associated memory is released.
- If no clients, but type or procedure variable references exist, the module *unload* command takes no action by default and merely displays the names of the modules containing the references that caused the removal to fail. If, however, the *force* option */f* is specified⁵, the modules are initially removed (only) from the *list* of loaded modules, without releasing their associated memory. Such “hidden” modules are later physically removed from *memory*, as soon as there are no more references to them from anywhere in the system.

¹ <http://www.projectoberon.com>

² An Oberon module can be viewed as a container of types, variables and procedures, where variables can be procedure-typed. Types can be declared as *global* types (in which case they can be exported and referenced by name in clients) or as types *local* to a procedure (in which case they cannot be exported). Variables can be statically declared as *global* variables (allocated in the module area when a module is loaded) or as *local* variables (allocated on the stack when a procedure is called), or they can be dynamically allocated in the *heap* via the predefined procedure *NEW*. Procedures can be declared as global or local procedures. They can also be assigned to *global* procedure variables (of the same or a different module) or to procedure variable fields in *dynamic* objects – even if they are not exported. Thus, in general there can be type, variable, procedure and procedure variable references from both static and dynamic objects of other modules to static or dynamic objects of the modules to be unloaded. However, only *dynamic* type references and *static* and *dynamic* procedure variable references need to be checked during module unloading for the following reasons: First, *static* type, variable and procedure references from other loaded modules can only refer by *name* to types, variables or procedures *declared* in the modules to be unloaded. Such references are already handled via their import/export relationship during module unloading (if clients exist, a module or module group is never unloaded) and therefore don't need to be checked separately. Second, *dynamic* pointer variable references from global or dynamic *pointer* variables of other modules to *dynamic* objects reachable by the modules to be unloaded *should* not be checked, as such references *should* not prevent module unloading. In the Oberon system, such references will be handled by the garbage collector during a future garbage collection cycle, i.e. heap records reachable by the just unloaded modules *and* other still loaded modules will not be collected, whereas heap records that *were* reachable *only* by the just unloaded modules *will* be collected – as they should. Thus, the handling of dynamic pointer references is delegated to the garbage collector. Finally, *pointer* variable references to *static* objects declared as global variables are only possible by resorting to low-level facilities and should be avoided (and, in fact, be disallowed).

³ See <http://github.com/andreaspirklbauer/Oberon-experimental/blob/master/Documentation/Historical-notes-on-module-unloading-in-Oberon.pdf>

⁴ <http://www.github.com/andreaspirklbauer/Oberon-experimental>

⁵ The force option */f* must be specified at the *end* of the list of modules to be unloaded, e.g., *System.Free M1 M2 M3/f*

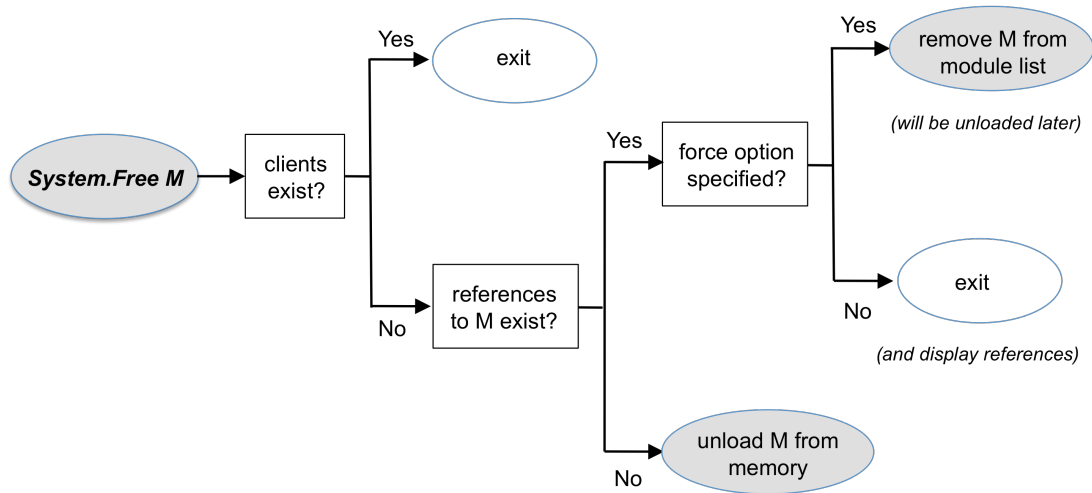


Figure 1: Safe module unloading in Experimental Oberon

Removing modules only from the *list* of loaded modules amounts to *renaming* them, allowing other modules with the same names to be reloaded again, without having to unload (from memory) earlier versions that are still referenced⁶. Removing a module from *memory* frees up the memory area previously occupied by the module block⁷.

To make the removal of no longer referenced hidden module data *automatic*, a new command *Modules.Collect* has been included in the Oberon background task handling garbage collection. It checks all possible combinations of k modules chosen from n hidden modules for clients and references, and removes those module subgroups from memory that are no longer referenced. The command *Modules.Collect* can also be manually activated at any time. Alternatively, the user can invoke *System.Collect*, which includes a call to *Modules.Collect*.

In sum, module unloading does not affect past references, as module data is kept in memory for exactly as long as necessary and removed from it as soon as possible.

For example, older versions of a module's code can still be executed if they are referenced by static or dynamic procedure variables in other modules, even if a newer version of the module has been reloaded in the meantime⁸. Type descriptors also remain accessible to other modules for exactly as long as needed. This covers the important case where a structure rooted in a variable of base type T declared in a base module M contains elements of an extension T' defined in a client module M' , which is unloaded⁹. Such elements typically contain both *type* references (type tags) and *procedure variable* references (handler procedures) referring to M' . This is common in the Oberon viewer system, for example, where M is module *Viewers*.

⁶ Modules removed only from the list of loaded modules, but not from memory, are marked with an asterisk in the output of the command *System.ShowModules*. Commands of such "hidden" modules can be accessed by either specifying their module number or their (modified) module name, both of which are displayed by the command *System.ShowModules*. In both cases, the corresponding command text must be enclosed in double quotes. If a module M carries module number 14, for instance, one can activate a command $M.P$ also by clicking on the text "14.P". Typical use cases include hidden modules that still have background tasks installed which can only be removed by activating a command of the hidden modules themselves, or hidden modules that still have open viewers. If the command to close a viewer is displayed in the viewer's menu bar, the user can manually edit the command text (by clicking within its bottom two pixel lines), replace the module name by its module number and enclose the modified command text in double quotes. Although this is somewhat clumsy, it at least enables the user to close the viewer. An alternative approach is to provide a "Close" command that also accepts the marked viewer as argument (using procedure *Oberon.MarkedViewer*).

⁷ In FPGA Oberon 2013 on RISC and in Experimental Oberon, the module block includes the module's type descriptors. In some other Oberon implementations, such as Oberon on Ceres, type descriptors are not stored in the module block, but are dynamically allocated in the heap at module load time, in order to persist them beyond the lifetime of their associated modules. In Experimental Oberon, no such special precaution is necessary, as module blocks are removed only from the list of loaded modules and not from memory, if they are still referenced by other modules. Thus, type descriptors can safely be stored in the (static) module blocks.

⁸ If an older version of a module's code accesses global variables (of itself or of other modules), it will automatically access the "right" version of such variables – as it should.

⁹ Note that for *type* references, it is actually possible to know at compile time, whether a module M may potentially lead to references from other modules at run time (but not whether it actually will): If M does not declare record types which are extensions T' of an imported type T , records declared in M cannot be inserted in a data structure rooted in a variable of an imported type T – precisely because they are not extensions of T (in the Oberon language, the assignment $p := p'$ is allowed only if the type of p' is the same as the type of p or an extension of it).

If a module *group* is to be unloaded and there exist clients or references *only* within this group, it is unloaded as a *whole*. This can be used to remove module groups with *cyclic* references¹⁰.

It is also possible to release *entire subsystems* of modules. The command *System.FreeImports* attempts to unload the specified modules and all their direct and indirect *imports*. It may be used for conventional module stacks with a single top module, for example a compiler. By contrast, the command *System.FreeClients* unloads the specified modules and all their direct and indirect *clients*. This variant may be used for module stacks written in the object-oriented programming style with their typically inverted module hierarchy, for example a graphics editor.

Note that these unloading strategies amount to *heuristics* and may tend to unload rather large parts of the system, which may not be desired. Thus, the recommended way to unload modules is to use the command *System.Free* with a *specific* set of modules provided as parameters.

For added convenience, the tool commands *System.ShowRefs* and *System.ShowExternalRefs* can be used to identify all modules containing references to a given module or module group.

Implementation aspects

To unload a module or module group, the module *unload* command first *selects* the modules to be unloaded using procedure *Modules.Select* and then invokes procedure *Modules.Check*. Clients are checked first. This is easily accomplished by simply verifying whether *unselected* modules import *selected* modules¹¹:

```
1  PROCEDURE FindClients*(proc: ModHandler; VAR res: INTEGER);
2  VAR mod, imp, prev, m: Module; p, q: INTEGER; continue: BOOLEAN;
3  BEGIN res := 0; mod := root; continue := proc # NIL; prev := NIL;
4  WHILE continue & (mod # NIL) DO
5    IF (mod.name[0] # 0X) & mod.selected & (mod.refcnt > 0) THEN m := root;
6    WHILE continue & (m # NIL) DO
7      IF (m.name[0] # 0X) & ~m.selected THEN p := m.imp; q := m.cmd;
8      WHILE p < q DO imp := Mem[p];
9      IF imp = mod THEN INC(res, proc(m, mod, prev, continue)); prev := mod; p := q ELSE INC(p, 4) END
10     END
11     END ;
12     m := m.next
13   END
14   END ;
15   mod := mod.next
16 END
17 END FindClients;
```

If clients exist, no further action is taken and the module unload command exits.

If no clients exist, references are checked next. As mentioned earlier, references that *need* to be checked prior to module unloading include *type tags* (addresses of type descriptors) in *dynamic* heap objects reachable by all other loaded modules pointing to descriptors of types declared in the modules to be unloaded, and *procedure variables* installed in *dynamic* or *static* objects of other modules referring to *static* procedures declared in the modules to be unloaded.

¹⁰ In Oberon, cyclic references can be created by pointers or procedure variables, whereas cyclic module imports are normally not allowed. However, through a tricky sequence of compilation and editing steps, it is in fact possible to *construct* cyclic module imports, which cannot be detected by the compiler. But even though they can be created, such modules are not allowed to be loaded, as the module loader of Experimental Oberon – adopting the approach chosen in Original Oberon and FPGA Oberon – would enter an endless recursion, eventually leading to a stack overflow or out-of-memory condition – a totally acceptable solution for such an artificially constructed case. But even if modules with cyclic module imports *were* allowed to be loaded, Experimental Oberon would handle them correctly upon unloading, i.e. if no external clients or references exist, such a module group would simply be unloaded as a whole – as it should.

¹¹ Mem stands for the entire memory and assignments involving Mem are expressed as SYSTEM.GET(a, x) for x := Mem[a] and SYSTEM.PUT(a, x) for Mem[a] := x.

References from *dynamic* objects are checked using a conventional *mark-scan* scheme:

```
1  PROCEDURE FindDynamicRefs*(type, proc: RefHandler; VAR resType, resProc: INTEGER; all: BOOLEAN);
2    VAR mod: Module;
3  BEGIN mod := root;
4    WHILE mod # NIL DO
5      IF (mod.name[0] # 0X) & ~mod.selected THEN Kernel.Mark(mod.ptr);
6        IF ~all THEN Kernel.Scan(type, proc, mod.name, resType, resProc) END
7      END ;
8      mod := mod.next
9    END ;
10   IF all THEN Kernel.Scan(type, proc, "", resType, resProc) END
11 END FindDynamicRefs;
```

During the *mark* phase, heap records reachable by all *named* global pointer variables of *all other* loaded modules are marked (line 5), thereby excluding records reachable *only* by the specified modules themselves. This automatically recognizes module groups and ensures that when a module *or module group* is referenced *only* by itself, it can still be unloaded. The *scan phase* (line 6 or 10), implemented as a separate procedure *Scan*¹² in module *Kernel*, scans the heap sequentially, unmarks all *marked* records and checks whether the *type tags* of the marked records point to descriptors of types in the *selected* modules and whether *procedure variables* declared in these heap records refer to procedures declared in those same modules.

An additional boolean parameter *all* allows the caller to specify whether the *mark* phase should first mark the heap records reachable by *all* other loaded modules before initiating the *scan* phase *once* (used for module unloading), or whether the *scan* phase should be initiated *N* times after marking the heap records reachable by *each* of the other *N* loaded modules (this may, for instance, be used to enumerate the references to each module *individually*).

Finally, the check for procedure variable references is also performed for all *global* procedure variables, whose offsets in the module's data section are obtained from an array in the module's *meta* data section, headed by the link *mod.pvr* in the module descriptor (see below):

```
1  PROCEDURE FindStaticRefs*(proc: RefHandler; VAR res: INTEGER);
2    VAR mod: Module; pref, pvadr, r: LONGINT; continue: BOOLEAN;
3  BEGIN res := 0; mod := root; continue := proc # NIL;
4    WHILE continue & (mod # NIL) DO
5      IF (mod.name[0] # 0X) & ~mod.selected THEN
6        pref := mod.pvr; pvadr := Mem[pref];
7        WHILE continue & (pvadr # 0) DO r := Mem[pref]
8          INC(res, proc(r, mod.name, continue));
9          INC(pref, 4); pvadr := Mem[pref]
10       END
11     END ;
12     mod := mod.next
13   END
14 END FindStaticRefs;
```

Note that the procedures *FindClients*, *FindDynamicRefs* and *FindStaticRefs* are expressed as *generic* traversal schemes which accept *parametric* handler procedures that are called for each encountered object. This allows these procedures to be used for *other* purposes as well, for example to *count* the clients or references to a given module or module group.

¹² The original procedure *Kernel.Scan* (implementing the scan phase of the Oberon garbage collector) has been renamed to *Kernel.Collect*, in analogy to procedure *Modules.Collect*.

In order to omit in module *Kernel* any reference to the module list rooted in module *Modules*, procedure *Kernel.Scan* is also expressed as a *generic* heap scan scheme¹³:

```

1  PROCEDURE Scan*(type, proc: Handler; s: ARRAY OF CHAR; VAR resType, resProc: INTEGER);
2    VAR offadr, offset, p, r, mark, tag, size: LONGINT; continue: BOOLEAN;
3  BEGIN p := heapOrg; resType := 0; resProc := 0; continue := (type # NIL) OR (proc # NIL);
4    REPEAT mark := Mem[p+4];
5      IF mark < 0 THEN (*free*) size := Mem[p]
6    ELSE (*allocated*) tag := Mem[p]; size := Mem[tag];
7      IF mark > 0 THEN (*marked*) Mem[p+4] := 0;
8      IF continue THEN
9        IF type # NIL THEN INC(resType, type(tag, s, continue)) END ;
10       IF continue & (proc # NIL) THEN offadr := tag + 16; offset := Mem[offadr];
11       WHILE offset # -1 DO (*pointers*) INC(offadr, 4); offset := Mem[offadr] END ;
12       INC(offadr, 4); offset := Mem[offadr];
13       WHILE continue & (offset # -1) DO (*procedures*) r := Mem[p+8+offset];
14       INC(resProc, proc(r, s, continue));
15       INC(offadr, 4); offset := Mem[offadr]
16     END
17   END
18 END
19 END
20 END ;
21 INC(p, size)
22 UNTIL p >= heapLim
23 END Scan;
```

This scheme calls *parametric* handler procedures for individual elements of each *marked* heap record rather than *directly* checking whether these records contain *type* or *procedure variable* references to the modules to be unloaded. Procedure *type* is called with the *type tag* of the heap record as argument (line 9), while procedure *proc* is called for each procedure variable declared in the same record with (the address of) the *procedure* itself as argument (line 14). The results of the handler calls are *separately* added up for each handler and returned in the variable parameters *resType* and *resProc*.

An additional variable parameter *continue* allows the handler procedures to indicate to the caller that they are no longer to be called (lines 8, 10, 13). The scan process itself continues, but only to *unmark* the remaining marked records (line 7).

Procedure *Modules.Check* uses procedures *FindClients*, *FindDynamicRefs* and *FindStaticRefs* by passing its private handler procedures *HandleClient* and *HandleRef*. Procedure *HandleClient* sets the variable parameter *continue* to *false* in order to stop the search for external clients (during module unloading, one only needs to know *whether* clients exist, but not how many). Procedure *HandleRef* checks whether the argument supplied by procedures *Kernel.Scan* (either a type tag or a procedure variable within a heap record) and *FindStaticRefs* (a global procedure variable) references *any* of the selected modules to be unloaded.

We emphasize that procedure *Modules.Check* is not only called when a module is unloaded by the *user*, but also by the Oberon *background* task that removes no longer referenced *hidden* module data from memory. Thus, it must be written such that it can correctly handle *both* visible *and* hidden modules in the module data structure rooted in module *Modules*.

¹³ A simplified version scanning only *record* blocks (allocated via *NEW(p)*, where *p* is a *POINTER TO RECORD*) is shown. The full implementation also covers *array* blocks in the heap.

Implementation prerequisites

In order to make the outlined validation pass possible, type descriptors of *dynamic* objects¹⁴ allocated in the *heap* as well as the descriptors of *global* module data located in *static* module blocks contain a list of *procedure variable offsets*, adopting an approach employed in one of the earlier implementations of the Original Oberon system (MacOberon)¹⁵. The resulting run-time representation of a *dynamic* record and its associated type descriptor is shown in Figure 2 (the *method table* used to implement Oberon-2 style *type-bound procedures* is not discussed here).

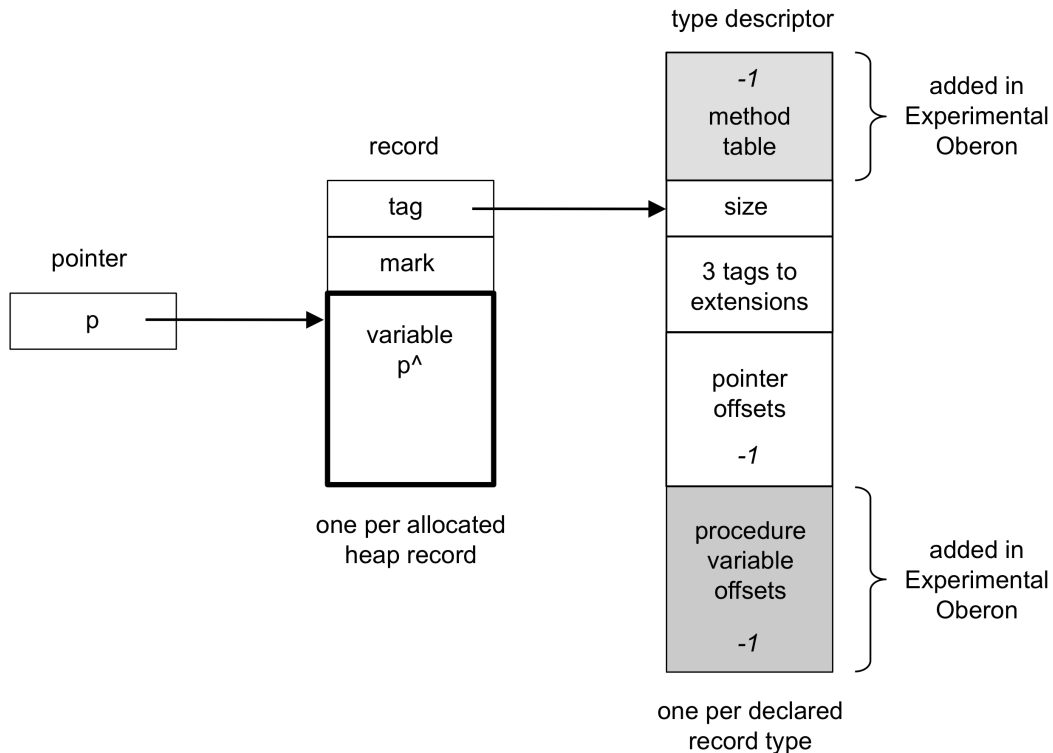


Figure 2: Run-time representation of a dynamic record and its type descriptor in Experimental Oberon

The descriptors also contain the offsets of *hidden* (not exported) procedure variables, enabling the module *unload* command to check *all* possible procedure variable locations in the entire system for possible procedure variable references to the modules to be unloaded.

To make the offsets of hidden *procedure variables* in exported record types available to client modules, symbol files also include them. An importing module may, for example, declare a global variable of an imported record type, which contains *hidden* procedure variables, or declare a record type that contains or extends an imported one. We recall that in Original Oberon, hidden *pointers*, although not exported and therefore invisible in client modules, are already included in symbol files because their offsets are needed for garbage collection¹⁶. Similarly, in Experimental Oberon, the locations of visible *and* hidden procedure variables are needed for reference checking during module unloading, as shown in the following example.

¹⁴ See chapter 8.2, page 109, of the book *Project Oberon 2013 Edition* for a detailed description of an Oberon type descriptor. A type descriptor contains certain information about dynamically allocated records that is shared by all allocated objects of the same record type (such as its size, information about type extensions and the offsets of pointer fields within the record).

¹⁵ <http://e-collection.library.ethz.ch/eserv/eth:3269/eth-3269-01.pdf> (The Implementation of MacOberon, 1990)

¹⁶ See chapter 12.6.2, page 41, of the book *Project Oberon 2013 Edition* for a description of why the offsets of hidden pointers are needed during garbage collection.

```

1  MODULE M0;
2    TYPE Proc* = PROCEDURE; Rec* = RECORD p*, q: Proc END ;  (*q is a hidden field*)
3    PROCEDURE Q*(r: Rec); BEGIN r.q END Q;
4    PROCEDURE Init*(VAR r: Rec; p, q: Proc); BEGIN r.p := p; r.q := q END Init;
5  END M0.
6
7  MODULE M1;
8    IMPORT M0;
9    VAR r: M0.Rec;
10   PROCEDURE Init*(p, q: M0.Proc); BEGIN M0.Init(r, p, q) END Init;
11 END M1.
12
13 MODULE M2;
14   IMPORT M1;
15   PROCEDURE Q; BEGIN END Q;
16   PROCEDURE Set1*; BEGIN M1.Init(NIL, NIL) END Set1;
17   PROCEDURE Set2*; BEGIN M1.Init(NIL, Q) END Set2;
18 END M2.
19
20 M2.Set1 System.Free M2 ~      ... can unload M2
21 M2.Set2 System.Free M2 ~      ... can't unload M2 (as M2.Q is referenced in global procedure variable M1.r.q)

```

Here the global record *r* declared in module *M1* contains a hidden field *M1.r.q* that is accessible only in the exporting module *M0*. If another module *M2* installs a procedure *M2.Q* in this hidden record field, for example by using an installation procedure *Init* provided by *M0* and called in *M1*, a procedure variable reference from *M1* to *M2* is created, with the (intended) effect that module *M2* can no longer be unloaded.

Hidden *pointers* are included in symbol files without their names, and their (imported) type in the symbol table is of the form *ORB.NilTyp*. Hidden *procedure variables* are also included without their names, and their symbol table type is of the form *ORB.NoTyp*¹⁷. For additional details, see procedures *ORB.FindHiddenFields*, *ORG.FindRefFlds*, *ORG.NoRefs* and *ORG.FindRefs*.

An obvious shortcoming of the reference checking scheme outlined above is that it requires *additional* run-time information to be present in *all* type descriptors of *all* modules *solely* for the purpose of reference checking, which in turn is *only* needed in the relatively infrequent case of module releases. In addition, modules now also contain an *additional* section in the module block containing the offsets of global procedure variables. However, since there exists only one type descriptor per declared record *type* rather than one per allocated heap *record*, and global procedure variables tend to be rare, the additional memory requirements are negligible¹⁸.

Although the operation of *reference checking* may appear expensive at first, in practice there is no performance issue. It is comparable in complexity to garbage collection and thus barely noticeable – at least on systems with small to medium sized dynamic spaces (heaps). This is in spite of the fact that for *each* heap record encountered in the *mark* phase *all* modules to be unloaded are checked for references during the *scan* phase. Note that reference checking *stops* when the *first* reference is detected, and module unloading is rare except, perhaps, during development, where however the *number* of references tends to be small.

¹⁷ This is acceptable because for record fields, the types *ORB.NilTyp* and *ORB.NoTyp* are not used otherwise.

¹⁸ Adding procedure variable offsets to type descriptors is, strictly speaking, not necessary, as the compiler could always rearrange the memory layout of a record such that all procedure variable fields are placed in a contiguous section at the beginning of it, making their offsets implicit. Thus, it is in principle possible to realize the reference checking scheme without additional fields in type descriptors. We refrained from implementing this refinement for two main reasons. First, it would increase the complexity of the compiler. At first glance, it might seem that in order to rearrange a record's field list, only a small change needs to be made to a single procedure in the compiler (*ORP.RecordType* in Oberon 2013). However, a complication arises because records may recursively contain other records, each again containing procedure variables at arbitrary offsets. While it is always possible to "flatten out" such recursive record structures, it would make other record operations more complex. For example, assignments to subrecords would become less natural, as their fields would no longer be placed in a contiguous section in memory. Second, the memory savings in type descriptors would be marginal, given that there exists only one type descriptor per declared record *type* rather than one per allocated heap *record*. Most applications are programmed in the conventional programming style, where installed procedures are rare. For example, in the Oberon operating system, the object-oriented programming style is restricted to the viewer system, which provides distributed control in the form of installed handlers – of which there is usually only one per *type* of viewer. In sum, the benefit obtained by saving a few fields in a relatively small number of type descriptors appears negligible, and the additional effort required to implement this refinement would be hard to justify.

Thus, the presented solution, which was mainly chosen for its simplicity, appears to be amply sufficient for most practical purposes.

Alternatives considered

Alternative #1:

As an alternative to the outlined conventional mark-scan scheme – where the *mark* phase first marks *all* heap objects reachable by *all other* loaded modules and the *scan* phase then checks for references from the *marked* records to the modules to be unloaded – one might be tempted to check for references directly *during* the *mark* phase and simply *stop* marking records as soon as the first reference is found. While this has the potential to be more efficient, it would lead to a number of complications.

First, we note that the pointer rotation scheme used during the *mark* phase temporarily modifies not only the *mark* field, but also the *pointer variable* fields of the encountered heap records (the Deutsch-Schorr-Waite graph marking algorithm¹⁹ is used, which essentially establishes a “return path” used during future visits of a node, effectively replacing the stack of procedure activations by a stack of marked nodes). As a consequence, one cannot simply exit the *mark* phase when a reference is found, but would also need to undo *all* pointer modifications made up to that point. The easiest way to achieve this is by letting the *mark* phase run to completion. But this would undo the performance gain initially hoped for. Second, if one wants to omit in module *Kernel* any reference to the data structure managed by module *Modules*, one would also need to express the *mark* phase as a *generic* heap traversal scheme accepting parametric handler procedures for reference checking, similar to the generic heap *scan* scheme outlined above. But such a generalization would open up the possibility for an erroneous handler procedure to prematurely end the *mark* phase, leaving the heap in a potentially irreparable state. In sum, one seems well advised not to meddle with the *mark* phase. Finally, one would still need a separate *scan* phase to *unmark* the already marked portion of the heap.

Alternative #2:

Another possible variant would be to treat *procedure variables* and *type tags* like *pointers*, and *procedures* and *type descriptors* referenced by them like *records* during the *mark* phase of reference checking. This could easily be achieved by making procedures and type descriptors *look like* records, which in turn could be accomplished by making them carry a *type tag* and a *mark field*. These additional fields would be inserted as a prefix to (the code section of) *each* declared procedure and (the type descriptor of) *each* declared record type in the module block. All static *procedures* would share a common “procedure descriptor” and all *type descriptors* a common “meta-type descriptor”. These descriptors would contain no tags to extensions and no pointer offsets. Consequently, they can be represented by one and the same shared global “meta descriptor”, which could be stored at a fixed location within the module area for example. The resulting run-time representation of *procedures* and *type descriptors* is shown in Figure 3.

¹⁹ Herbert Schorr and William M. Waite, “An efficient machine-independent procedure for garbage collection in various list structures”, CACM, 10(8):501-506, August 1967.

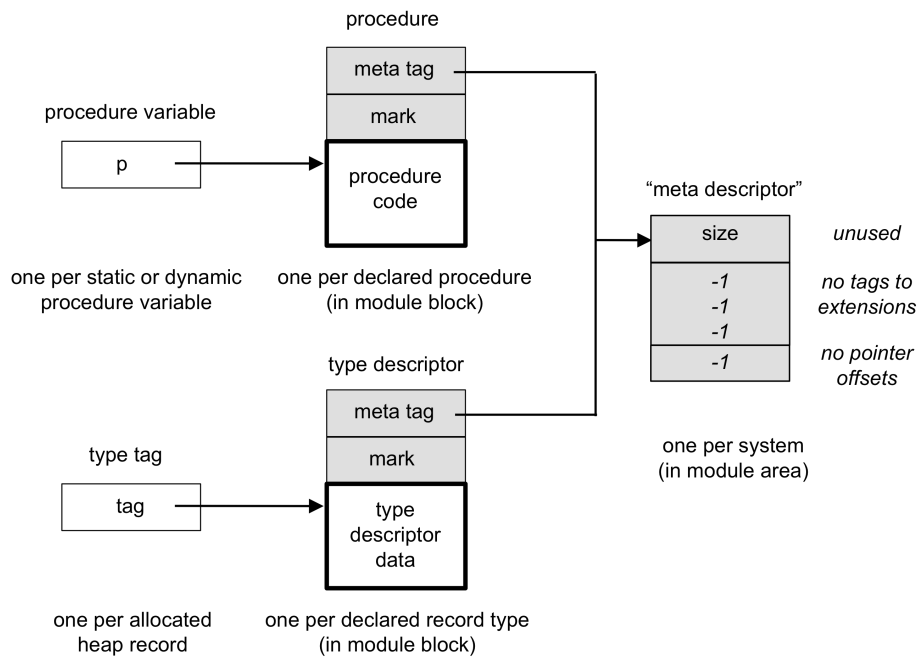


Figure 3: Procedure variable and type tag interpreted as *pointer*, and procedure and type descriptor interpreted as *record*

Alternative #3:

A simpler variant would be to treat procedure variables and type tags as *special cases* during the *mark* phase, eliminating the need for a *meta* tag field as well as the shared *meta* descriptor. The resulting run-time representation of *procedures* and *type descriptors* is shown in Figure 4.

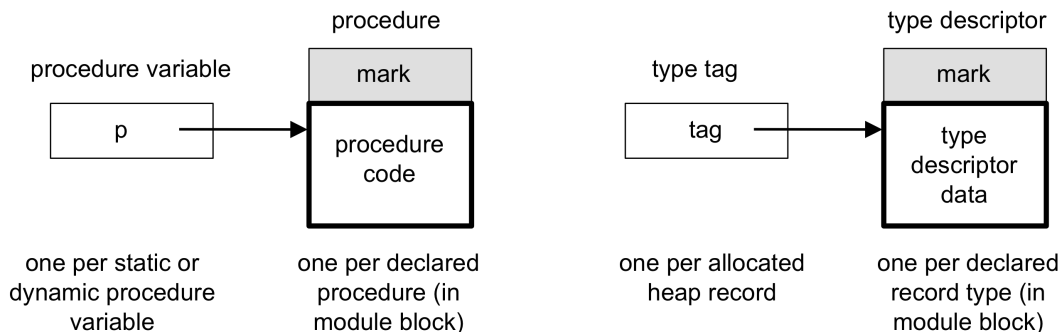


Figure 4: Procedures and type descriptors with an additional *mark* field

With these preparations, the *mark* phase of reference checking could be suitably *extended* to also include *procedure variables* in the list of “pointers” to be traversed. In sum, the mark phase not only “touches” all reachable objects in the *heap*, but also those in the static *module blocks*.

While this technique appears appealing at first glance, a few points are worth mentioning. First, the *extended* mark phase requires an extra *mark* field to be inserted as a prefix to *each* procedure and *each* type descriptor in the module block. Given that most procedures and type descriptors are never referenced, this appears to be overkill. One could therefore decide to add the *mark* field only to *module descriptors* rather than individual *procedures* or *type descriptors* during the *mark* phase. While this would make the check whether any of the selected modules is referenced a trivial task, it would render the *mark* phase more complex, as it would now need to *locate* the module descriptor belonging to a given procedure or type descriptor (on systems

where additional meta-information is present in the run-time representation of loaded modules, such as the locations of procedures and type descriptors in module blocks or *back pointers* from each object of a module to its module descriptor, the mark phase would be simpler; however, neither Original Oberon 2013 nor Experimental Oberon offer such *metaprogramming* facilities). Second, one would still need to mark *all* objects, for the same reason as outlined above, i.e. one cannot simply exit in the middle of the *mark* phase without additional action. Third, one would also still need an extra *scan* phase to unmark the marked objects.

Finally, a comparison of the code required to implement the various alternatives showed that our solution is *by far* the simplest: the combined implementation cost of *all* modifications to the runtime representation of type descriptors and descriptors of global module data, the object and symbol file formats and the module loader, is only about 15 source lines of code²⁰, while the *reference checking* phase itself amounts to less than 75 lines (the *total* implementation cost to realize *safe module unloading*, including the ability to unload module *groups* and the automatic collection of no longer referenced hidden modules, amounts to about 250 source lines of code).

* * *

²⁰ See procedures *ORB.InType* (+ 1 line), *ORB.FindHiddenFields* (+ 1 line), *ORG.BuildTD* (+ 1 line), *ORG.Close* (+ 7 lines) and *Modules.Load* (+ 4 lines).