# SOAR: Smalltalk Without Bytecodes

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It is so difficult to find the *beginning*. Or, better, it is difficult to begin at the beginning. And not try to go further back.
– Ludwig Wittgenstein, *On Certainty*, §471.

**Abstract**

We have implemented Smalltalk-80 on an instruction-level simulator for a RISC microcomputer called SOAR. Measurements suggest that even a conventional computer can provide high performance for Smalltalk-80 by abandoning the 'Smalltalk Virtual Machine' in favor of compiling Smalltalk directly to SOAR machine code, linearizing the activation records on the machine stack, eliminating the object table, and replacing reference counting with a new technique called Generation Scavenging. In order to implement these techniques, we had to find new ways of hashing objects, accessing often-used objects, invoking blocks, referencing activation records, managing activation record stacks, and converting the virtual machine images.

## 1. Introduction

This paper focuses on software techniques to support Smalltalk[1] on conventional architectures. It reports on our experiences implementing Smalltalk on a reduced instruction set computer (RISC [13,8]) called SOAR (for Smalltalk On A RISC). Although SOAR has some hardware support for running Smalltalk, our experience has led us to the conclusion that efficient execution of Smalltalk requires less hardware support than we initially supposed. This survey of our implementation should provide a roadmap for those wanting to implement Smalltalk on conventional architectures. In the discussion that follows, we assume the reader is somewhat familiar with both ST-80 [6], and with RISCs.

The designers of ST-80 adopted the purist position that everything in the system would be an "object." This was not limited to the usual basic data types, but extended even to the state of the machine: activation records, instructions, and program counters all conformed to a specified format. For example, since the design did not countenance pointers into the middle of subroutines, the return address for every subroutine call and even the program counter had to be an integer offset, not an absolute address. Even the most frequently accessed of all data – instructions – were constrained by this design. The language was defined in terms of an interpreter for a virtual machine with a set of instructions called "bytecodes". This made ST-80 portable since interpreters for this virtual machine can be straightforward. ST-80 was developed on research machines (the latest of which is the Dorado [3,9]) that had writable control stores and could do the interpretation in firmware. So with the Dorado's 70ns micro-cycle time, they were able both to define a portable virtual machine for Smalltalk, and still achieve very acceptable performance interpreting bytecodes (although in some circles this is not called interpretation, but execution of native machine code.)

There are several reasons why Smalltalk programs have proven especially difficult to execute quickly.

- The language has been defined in terms of a bytecode interpreter. Interpreters are slow.
- The pure object-orientation of the language implies a huge number of procedure calls ("messages"), which are often time-consuming in conventional implementations.
- The definition of Smalltalk execution and the style of its customary use require the rapid creation and automatic reclamation of many objects. This puts a heavy demand on the memory management mechanism.

[1] Smalltalk-80 is a trademark of the Xerox Corporation. Whenever we are referring to the official Smalltalk-80 language and implementation [6], we will use the abbreviation ST-80. Whenever we refer to the *language* and its variants generically, apart from any implementation, we will simply say "Smalltalk."

Most of the early implementations of Smalltalk on "traditional" von Neumann architectures have been evaluated as slow to abysmal, as evidenced by Krasner's collection of Smalltalk implementation studies [7]. Efforts to speed up interpreters' execution have included Suzuki and Terada's predeclaration of object types [16] and Deutsch and Schiffman's caching of Smalltalk procedures in native machine code while otherwise preserving the bytecode orientation of the definition [4]. The SOAR project differs from Suzuki and Terada's effort in that we do not require pre-declaration of types for efficient execution. We differ from Deutsch and Schiffman in that we do not try to maintain the illusion of a virtual machine executing bytecodes. The semantics of SOAR Smalltalk differs from ST-80 in several ways:

- Our *compiled methods* contain integers (which are also SOAR machine instructions); ST-80's contain bytecodes.
- Our *method contexts* (ST-80's activation records) have fixed size, reside on the machine stack, and are moved into heap space only when necessary. ST-80's are allocated from the heap like all other objects.
- Our *block contexts* are different from their activation records; ST-80 blurs the distinction between a block and its activation record.

These differences have no effect on almost all Smalltalk programs, since most programs do not deal directly with this level of the system. Furthermore, these differences involve parts of the system at so low a level that they are invisible in almost all other programming languages. Few other portable languages provide explicit access to procedure stack frames and *guarantee* the results of manipulating them. Therefore, we believe that the differences we introduce are entirely reasonable, particularly since they allow us to achieve acceptable performance executing Smalltalk.

Our approach does create some performance problems with the primitive operation *become*, which we do support. Fortunately, this operation is rather rare, and we are tackling the performance problem with a straightforward re-implementation of the system routines to avoid using *become*. Eventually, we may simply cease to support it.

The SOAR project started with the basic RISC assumption that memory would be plentiful and should be traded in exchange for speed. There were two questions. First, how can Smalltalk be executed quickly on more traditional architectures? Second, what changes to the traditional architectural model would produce a fast execution vehicle? The SOAR project concentrated on both questions with approximately equal emphasis, and our solution took the form of a judicious split of functionality between innovative hardware and software support. This paper will primarily discuss the project's answers to the first question. We have discussed the second question in other papers [19,20,15], and Pendleton has described the implementation of the SOAR processor itself [14]. Currently, we are still executing on a simulator running on Sun workstations. We have completely booted the system; it paints the windows and we have run the standard macro-benchmarks. We are waiting for completely functional chips to plug into the board to run on Sun workstations. The migration path from the Xerox image to SOAR is outlined in Fig. 1. It is worth noting that we needed to use an existing Smalltalk system to modify the image. BS (Berkeley Smalltalk), a

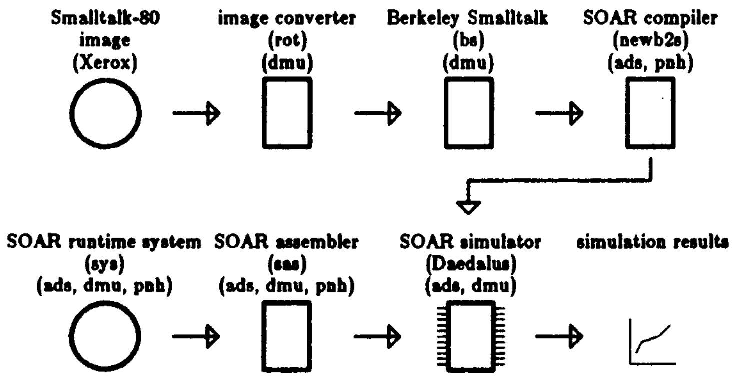

Smalltalk-80 image (Xerox)
image converter (rot) (dmu)
Berkeley Smalltalk (bs) (dmu)
SOAR compiler (newb2s) (ads, pnh)
SOAR runtime system (sys) (ads, dmu, pnh)
SOAR assembler (sas) (ads, dmu, pnh)
SOAR simulator (Daedalus) (ads, dmu)
simulation results

*Figure 1: Steps involved in a SOAR simulation.* First, *rot* removes the object table from the Xerox ST-80 image. We then use BS (Berkeley Smalltalk) to make any modifications necessary in the image (e.g. to eliminate some *becomes*). BS is a 68000 version of ST-80 which maintains the bytecode virtual machine as its lowest level: it was not a system noted for speed. Newb2s produces a Smalltalk image for SOAR by converting the BS objects to SOAR format and running Hilfinger's *Slapdash* compiler, which translates the bytecoded programs to SOAR instructions. We have also coded the Smalltalk primitive operations and storage management software in SOAR assembly language. After this is assembled, it is fed to our SOAR simulator along with the Smalltalk image. The initials below each system indicate its author: ads is Dain Samples, pnh is Paul Hilfinger, and dmu is David Ungar.

bytecode interpreter on Sun workstations that interprets bytecodes, provided that system.

The complete SOAR system is projected to run ten times faster than BS, about five times faster than the system that Deutsch and Schiffman describe, or about the speed of the implementation on the Dorado.

We will describe our software solutions in a bottom-up (inside-out) order. Thus, we start with general object management, including addressing and reclamation, and proceed to compiled subroutines, activation records (contexts), and processes. Table 2 summarizes this paper by listing problems we have considered and a brief outline of our solutions. The bytecode→SOAR compiler is outside the scope of this paper; see Bush's description for more details [2].

## 2. Direct Addressing – Eliminating the Object Table

ST-80 addresses objects by an integer index into an object table, not through a direct word or byte address. Few real machines have the ability to perform such segment-oriented addressing on 100,000 segments averaging 14 words in length. Those that can - such as the iAPX-432 - pay a large price in speed or cost or both. In Smalltalk, the cost of indirection is justified by the need for cheap memory compaction: when objects are moved, only the object table need be updated. However, we did not want to penalize every object access just to ease compaction, so we eliminated the object table by designing a reclamation algorithm that also compacts. BS and SOAR are the only Smalltalk systems without object tables (Figs 3 and 4).

The indirection through such a table is an indirect cost of other storage management strategies that is sometimes overlooked. It can be a bottleneck: we have determined that a typical ST-80 system accesses the object table 1.2 times per bytecode [17]. Assuming SOAR performs as fast as the Dorado (300K bytecode/sec), SOAR would access the object table 360,000 times per second. The absolute minimum table access would be a single load instruction, which takes two cycles. Assuming 400 ns per cycle, such an indirection would take 800 ns and, at 360,000 table accesses per second, that would be 0.29 seconds of indirection time for each second of processing time. Discussions with Deutsch suggest that further optimization possibly could halve this overhead. In other words, an object table would slow SOAR by 15% to 29%.

We have also estimated the impact of indirection on code size. An Object Table would require an extra instruction to load or store a literal variable, and one indirection in the method prologue (for the receiver). We assume that many indirections will be optimized away as in Deutsch and Schiffman's system, that the Object Table can reference as many objects as a direct-pointer system can, and that all indirect addresses in ST-80 and direct addresses in SOAR occupy 32-bit words. Table 5 presents our analysis under these assumptions. The extra code for an object table would add 2% to the size of the system.

Table 2: Summary of problems and solutions

- **object addressing**: Use direct pointers, obviating the Object Table.
- **slow 'become' primitive *sans* Object Table**: Rewrite system classes to use explicit indirection.
- **consistent hashing *sans* Object Table**: Extend object headers with a hash value fixed upon object creation.
- **accessing well-known objects**: Use a registry of needed objects.
- **storage reclamation**: Use Generation Scavenging: stop and copy young survivors.
- **memory fragmentation**: Compact young objects during scavenging. Reorganize old objects offline. Page old objects.
- **efficient creation/deletion for activation records**: Use a stack of activation records for normal cases.
- **pointers to activation records**: Detect non-lifo activation records by checking stores and return values. Maintain a table of pointers to activation records in the stack. On return from a non-lifo context, copy it to the heap, update pointers by searching the table, and remove its entries from the table. Put object headers in the gaps between activation records so that an activation record on the stack looks like an object.
- **block context objects**: Separate block objects from their activation records. A block object is a real object; an activation record is just an activation record. Create block objects upon blockCopy (if necessary); create activation records upon evaluating the block.
- **freeing activation record stack**: The *suspend* primitive checks for calls from *terminate*, whereupon it rescues non-lifo contexts and reclaims the stack.
- **fast method lookup**: Use an in-line cache—patch method lookups to direct calls. A method's prologue checks that it is appropriate for the receiver's type. When methods are redefined, their code is modified to force invalidation of cached in-line calls to them.
- **converting context objects in image**: Throw them away—use the *genesis* method.
- **pointers into scavenged methods**: Methods must be old; they are only garbage collected offline.

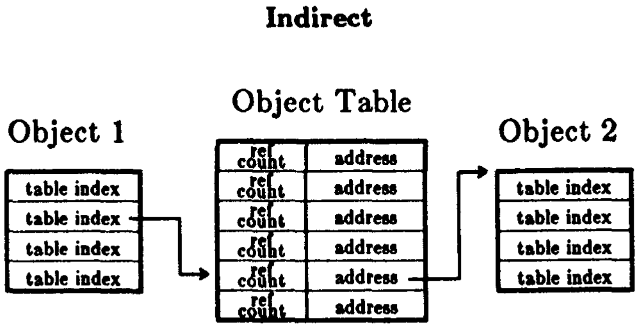


*Figure 3: Indirect addressing.* In traditional ST-80 systems, each pointer is really a table index. The table entry contains the target's reference count and memory address. This indirection required previous ST-80 systems to dedicate base registers to frequently accessed objects. The overhead to update these registers slowed each procedure call and return.

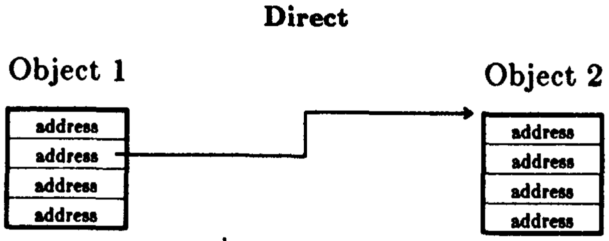


*Figure 4: Direct addressing.* A SOAR pointer contains the virtual address of the target object. This is the fastest way to follow pointers.

| **Table 5: Static cost of object indirection.** | |
|---|---|
| method prologues | 4654 |
| literal variable loads | 3532 |
| literal variable stores | 254 |
| total image size | 1,500 kB |
| relative cost of additional code | 2.25% |

**Becomes.** Although we eliminated the object table to improve performance, there is one ST-80 primitive operation that runs much slower without it. The *become* primitive exchanges the identities of two objects, so that all pointers to the first object are redirected to the second, and vice versa.

A ST-80 system with an object table can perform a *become* quickly by exchanging object table entries (Figure 6). A system without an object table (such as SOAR) must search objects and exchange pointers. Although we have devised strategies to limit the search, a worst case *become* still involves a search throughout virtual memory. The resulting long pause is generally unacceptable. We avoided this problem by rewriting the software for ST-80 data structures to avoid *becomes*. To establish the feasibility of this approach, we added new Collection classes that mimic old ones without resorting to *becomes* (Figure 7), and then modified the macro-benchmarks to take advantage of our *become*-less classes. Wallace discusses the details [21]. Table 8 presents an analysis of this change on system performance. Our efforts to eliminate *becomes* from programs that did use them were handsomely repaid with an 18% to 28% performance improvement.

Although we have eliminated *becomes* invoked by the system classes, the SOAR programmer must either shy away from this primitive, or be prepared to pay a stiff performance penalty. However, we believe that the *become* primitive is so intrinsically expensive - requiring either a scan of virtual memory or a level of indirection that slows down many frequent operations - that alternatives should be sought. Eventually, all instances of *becomes* will be removed from the SOAR system, and the primitive no longer supported. The SWAMP project has reached the same conclusion [11].

**Frequently-used objects.** Although we have eliminated the object table, there remain a few objects, such as nil, true, false, Point, String etc that the runtime support routines must locate quickly. This is almost the same set of objects with permanently assigned object table indices in ST-80. Our solution to this problem is to create the *registry*, a static system data structure containing a table of pointers to often-used objects. It also contains other necessary system data. The registry and the "registered" objects (there are about 18 in our system) are locked down by assigning them to fixed locations in memory.

**Hashing.** Perhaps the subtlest problem with eliminating the object table arises from the semantics required of all Smalltalk objects to allow the fast implementation of the ubiquitous Smalltalk Dictionaries. For performance, Smalltalk requires that each object be capable of quickly returning a hash value that remains invariant over the

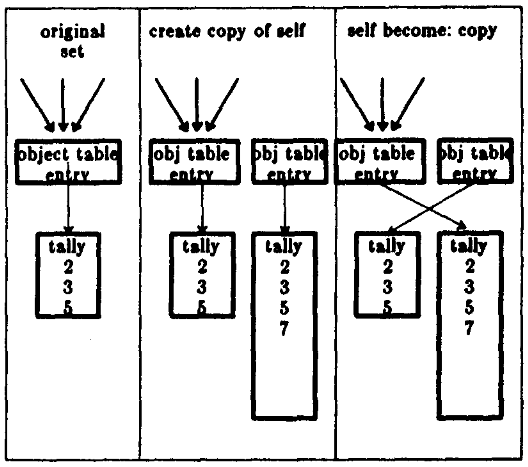


*Figure 6: Growing with* become. The sequence above illustrates how a set employs become to grow in a ST-80 system. Initially, the set is {2, 3, 5} and we attempt to add 7 to it. The set creates a larger copy of itself and uses become: to replace the original set with the larger version.

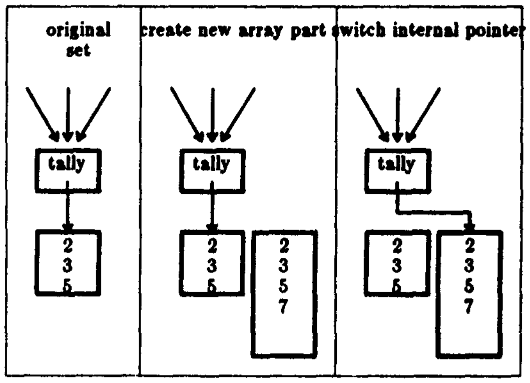


*Figure 7: Growing without* become.

The sequence above illustrates how our modified sets grow without resorting to *become*. The contents are stored in a separate array. To grow, the set allocates a larger array, initializes it, and redirects an internal pointer to the new array. We have replaced costly implicit indirection with explicit indirection.

**Table 8: Performance impact of eliminating becomes.**

| benchmark | # becomes | duration w/ becomes (cycles) | duration w/o becomes (cycles) | cycles saved |
|---|---|---|---|---|
| printDefinition | 0 | 75,475 | 75,317 | 0% |
| compiler | 7 | 1,383,201 | 1,127,658 | 18% |
| decompiler | 38 | 4,045,641 | 3,006,974 | 26% |
| printHierarchy | 3 | 165,997 | 119,574 | 28% |

object's lifetime. Since we assume that time is critical and space is plentiful, we chose to add a field to the header of each object, containing an integer assigned by the instantiation primitive (*new* and *new:*). The hash primitive simply returns this field.

## 3. Generation Scavenging

Early in the SOAR project, we realized that automatic storage allocation and reclamation could easily become a bottleneck. Our measurements as well as those of Deutsch and Schiffman, indicated that overhead for allocation and freeing in ST-80 systems ranged from 10-20%. Furthermore, we knew that some reclamation algorithms introduced annoying pauses; some required the programmer to explicitly free circular structures of objects; and most had been implemented in microcode. Since we wanted to attain good performance without microcode, we designed, implemented, and measured *Generation Scavenging*, a new garbage collection technique that limits pause times to a fraction of a second, meshes well with virtual memory, reclaims circular structures, and uses only 3% of the CPU time on SOAR [18]. This is less than a third of the time of deferred reference counting, the next best algorithm. The technique requires no hardware support—in particular, it requires no microcode. (Experience with SOAR has also made us realize that some of the other algorithms that are usually microcoded need not be.)

Briefly and simply, memory is divided into two regions: one containing 'old' objects, the other containing 'new' objects. All objects are allocated out of new space, and when this space is depleted, the live new objects are traversed and copied (see Fig. 9). The starting points of the traversal are the object pointers in the activation stack, together with all pointers from old to new objects. To find the latter, the system performs a *cross-generation* check of stores into objects, and updates a table for each store of a new into an old object. Since most Smalltalk objects die young, there are relatively few objects that survive; on the average, only 3% to 5% of new objects survive and have to be moved. The algorithm actually used is more sophisticated than that just described (for example, there are more than two regions), but nevertheless executes with less overhead than mark-and-sweep or reference counting algorithms (3% vs 9-20%).

Not only is the cost of the scavenging operation *per se* quite small, but the distributed overhead entailed by the cross-generation checks is also small. These checks require few instructions and no extra data references. One could perform them in software by checking the source and target pointers against the new/old dividing line. The SOAR store instruction does the checks in hardware using tag bits in the address field. It turns out that doing the check in software is so simple and infrequent (a 1% performance penalty) that it was a mistake to have put the check into the hardware. Furthermore, storing a young pointer into an old object is so rare (only 4% of all stores) that recording it adds only 0.05% overhead. Using a small number of generations permits a cheap software check, and contrasts with, for example, ZetaLisp's strategy, which requires extra hardware in the page map to keep track of many small generations and to check stores [12].

## 4. Activation record management

Everything in ST-80 is an object, including activation records. If ST-80 were implemented straightforwardly from its description (as were most of the early bytecode interpreters) then each procedure call (message send) would require the allocation and initialization of an activation record from the heap. Each return would leave a dead activation record for garbage collection to reclaim. Given the high percentage of procedure calls in

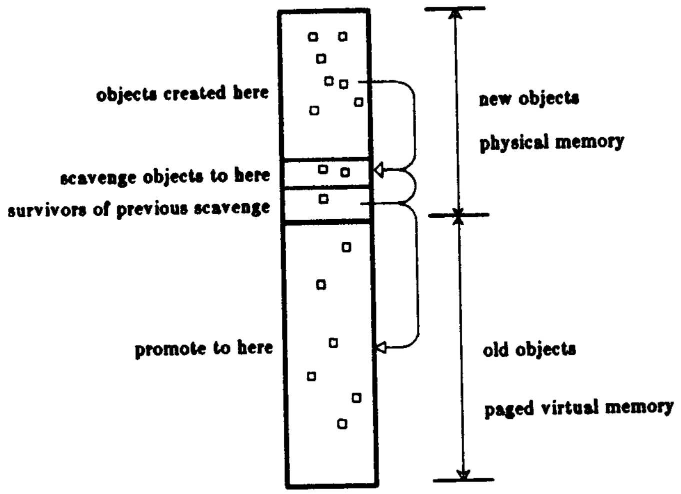


*Figure 9: Bird's eye view of Generation Scavenging.* After an object has survived enough scavenges, it is promoted to the old object area. New objects are locked down in physical memory; old objects reside in virtual memory and may be paged out.

Smalltalk programs activation record allocation and freeing can be a very large proportion of the running time. Falcone's measurements indicate that 83% of all objects allocated in ST-80 are activation records, and 28% of all bytecodes executed result in calls of one sort or another [5]. So, some sort of blending of Smalltalk's model of activation records (context objects) with an efficient stack implementation is indicated for smooth execution [22]. This mixture seems particularly inviting considering that, according to Deutsch and Schiffman, 85% of all Smalltalk activation records behave like traditional activation records during their lifetime. Most of them are created by a call, never used as data objects, and released as soon as the executing procedure (method) exits.

This problem has been attacked in other Smalltalk systems on conventional machines. Suzuki and Terada's system keeps a small memory area for the machine stack. When the stack becomes full, activation records are swapped out to heap space in first-in-first-out order (much like managing register windows on a RISC chip). If any context in the stack needs to be retained then *all* contexts in the stack are moved to heap space. Deutsch and Schiffman's system creates a context object either in heap space, or on the machine stack, depending on how and when the object is created. If a pointer is generated to a context on the machine stack, then it is marked specially to be popped into heap space instead of oblivion. We understand that the Tektronix system caches the current context in a convenient format, and eliminates the allocation and initialization for leaf activation records.

Our approach differs in two ways: we have a more selective algorithm for detecting those activation records that need to be moved to the heap, and we don't try very hard to mask the differences between ST-80 contexts and our activation records. Objects in heap space can point to contexts still on the stack. Figure 10 illustrates how registers are stored in the stack with 'gaps' between the activation records: the gaps contain the context object headers. The main difference between our implementation and ST-80 is that we support only one size of activation record: the SOAR stack frame is sixteen words. Once this change is promulgated throughout the system, it doesn't make any difference to objects manipulating activation records whether the AR's are on the stack or in heap space.

But now we have the problem of knowing when an activation record on the top of the machine stack must be discarded or moved into heap space. For example, a subroutine can obtain a pointer to its own activation record and place it in a global variable. After the subroutine returns, another routine can inspect the activation record via the global variable. In this case, it is necessary to have moved the activation from the machine stack into heap space. (See Fig. 11.) Extraordinary measures are required to preserve the correct objects. Our strategy is like that for generation scavenging: we monitor stores and returns. When a pointer to an activation record is either stored into an object or returned up the call stack, the referenced activation record is marked as *non-lifo:* that is, it may outlive its existence on the LIFO machine stack. When a non-lifo activation record is about to be destroyed (when a return instruction would pop it off the stack) it must be moved from the stack to the heap.

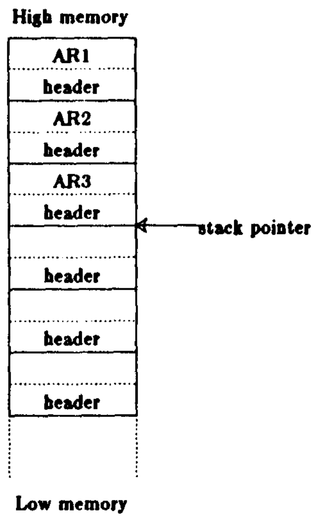
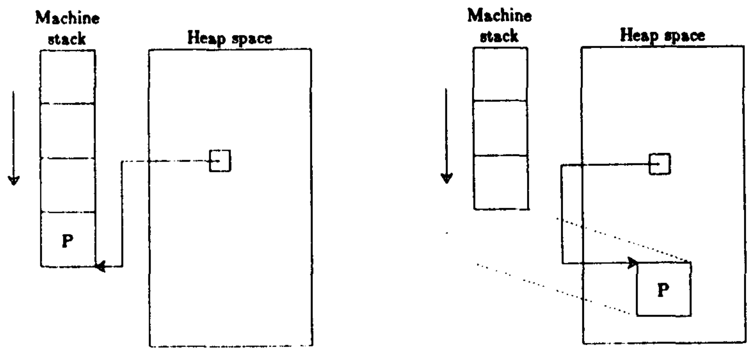


*Figure 10: SOAR Activation records.* showing the gaps in memory in which the object headers for the context objects are placed. The diagram shows three active contexts in the stack.



P stores a pointer to its activation record

When P returns, its activation must be moved to Heap space because of this pointer.

*Figure 11 Saving activation records*

**Dangling Pointers.** Any time a new activation record is allocated on the stack, all entries in that record must be initialized to nil to avoid dangling references (see Fig. 12). This is an unnecessary overhead if one is using fixed-length records that may not be completely utilized by all activations, as we are on SOAR. We avoid this overhead by keeping a record of the highest point reached on the stack with a ***highwater mark***. The SOAR register window handler keeps track of this mark. Generation scavenging scans the active portion of the stack, and nils all portions of the stack between the current activation record and the highwater mark. While objects may be scavenged needlessly, (again, see Fig. 12) they are guaranteed to exist. By initializing only those portions of the activation record that are used, and keeping track of the highwater mark between generation scavenges, we eliminate any possibility of dangling references, and obviate initializing entire activation records.

**Debugger.** One problem with our modification of the format and handling of activation records is that the ST-80 debugger that comes with the image from Xerox PARC can no longer be used. Debugging is only slightly more complicated for SOAR code than with bytecodes. It certainly is no worse than any other machine code debugger, and, because it will be embedded in a Smalltalk system, it will certainly be a 'symbolic' debugger: the user should never see have to SOAR machine code. While decompiling SOAR code to Smalltalk may be difficult, having the source code resident removes the difficulty. Because Smalltalk procedures are small, and compilation is fast, an error location in a sequence of SOAR instructions can be quickly mapped onto the appropriate location in the Smalltalk routine by simply recompiling the routine where the offense occurred. (The Turbo-Pascal system makes very effective use of this technique [1].) We have a debugger implemented for Smalltalk on SOAR, although it has not yet been incorporated into our system and itself debugged [10]. There are still open questions in this area, and work on the debugger remains in progress.

**Blocks.** Activation record management becomes much more complicated when Smalltalk blocks are implemented. ST-80 blocks implement control structures by allowing one routine to control execution in another's context. Frequently, a block is created, passed down the call chain to a subroutine that repeatedly invokes the block and then returns. For good performance, we do not mark an activation record as non-lifo if the only references to it are from blocks. Instead, the store and return checks treat the block as a surrogate for its home activation record. If a pointer to a block is stored, its home gets marked as non-lifo. In other words, although a block is an object that refers to a context, we do not mark that context as non-lifo until the block itself becomes non-lifo.

We differ from Deutsch and Schiffman in that, apparently, they create activation records for Smalltalk blocks automatically in heap space, while we treat them as stack allocated activation records. Without going into great detail, we would criticize the design of ST-80 on this point. While Smalltalk separates the notion of a procedure and its associated activation record(s), the separation between blocks and their activation records is muddled. In our implementation, we separate these inappropriately confused notions, and keep activation records for blocks on the machine stack along with activation records for procedures. Blocks are now objects in their own right. (Peter Deutsch put this bee in our bonnet.)

## 5. Process Management

In ST-80, processes are simply objects that point to the current activation record, which in turn points to the preceding activation. When the process object is no longer referenced, it is reclaimed and all activation records for that process are also reclaimed if not referenced elsewhere. Because SOAR handles activation records differently, it requires special measures to initialize processes and activation records, and to reclaim the memory they use when they are no longer active.

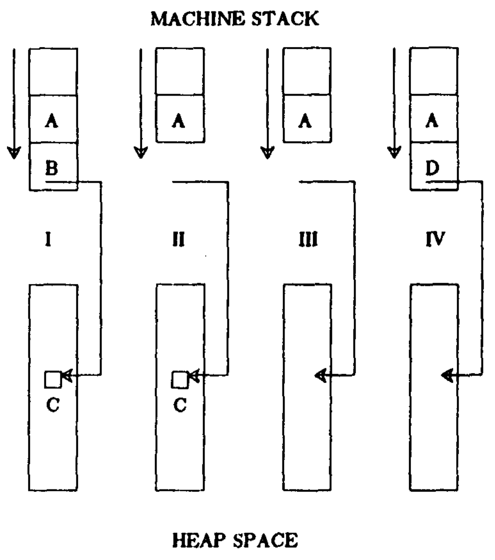


*Figure 12: Machine stacks and scavenging of nonexistent objects.* (I) Procedure A calls procedure B. Procedure B creates a pointer to object C in its activation record and (II) returns. At this point a garbage collection takes place and (III) reclaims the memory occupied by the now useless object C. (IV) Procedure A now calls procedure D, which does not reinitialize the register containing that old pointer to C. If another garbage collection were to occur at (IV), the activation record for D would contain a pointer to an object that no longer exists. If no garbage collection were done between (II) and (IV), then C would be retained by a garbage collection at (IV). The method described in the text using a ***highwater mark*** would have nilled the pointer to C during the garbage collection at (II).

On SOAR, each process is allocated a fixed size chunk of memory for its activation stack. When there are more activations in a process than can fit in this memory, it allocates a new chunk and links the new activation stack to the full one. Managing activation stacks works well on SOAR because of mechanisms that exist for RISC register windows. Whenever a call (or message send) would deplete the number of register windows available on the chip, the processor branches to a window handler. The handler spills the oldest window on the chip into the activation stack, and also checks for stack overflow. If the activation stack is also about to overflow, then the handler spills the register windows still on chip into the current activation stack, allocates and initializes a new activation stack, and begins execution in the new activation stack. When a return instruction is interrupted by a window underflow (when the appropriate activation record is not on chip). The handler performs the inverse operation.

**Images.** Changing instruction sets presents another problem related to processes. Smalltalk images are saved states of execution. There is no such thing as a bootstrap of Smalltalk because all images are frozen snapshots of executing systems, including any active processes. Sometime in the early 1980's one version of ST-80 was booted and initialized, and all versions since have been snapshots of that original boot. That is, Smalltalk systems are saved, but not born again.

Because we were throwing away bytecodes, linearizing activation records on a machine stack, and changing the garbage collection method (among other things), we determined that converting a running image was much more work than simply booting a compiled system. We then had to determine how to boot and initialize the system. When we asked Peter Deutsch about this possibility, he responded that it had been so long since anyone at Xerox had tried, he didn't know if the initialization code worked any longer. Fortunately for us, the code in the Smalltalk system for booting was correct. We wrote one procedure that would call and initialize all of the appropriate objects and begin spinning off the necessary background processes. The procedure, called ***genesis***, consists of less than a dozen lines of Smalltalk.

**Dead processes.** There was another consequence of our decision to "stackify" the Smalltalk activation records: we could no longer depend on automatic storage management to reclaim dead processes. The problem occurs principally because the Xerox Smalltalk implementation simply suspends processes and depends on reference counting to reclaim the storage; hence, it does not provide a "terminate process" primitive. While generation scavenging reclaims the process objects themselves, the activation record stacks are *not* Smalltalk objects in heap space and must be treated differently. But the lack of a 'process terminate' means it is difficult to tell when activation record stacks can be reclaimed. We have solved this problem by having our version of the "suspend process" primitive check all process suspensions in the context of the call to determine if it really is a suspension or an effective process termination. For a termination, the process stack is reclaimed immediately.

## 6. Results

Anyone interested in implementing Smalltalk efficiently needs not only to understand the dynamics of ST-80 as defined, but also the potential consequences of modifying that definition. In Table 13 we present figures from our simulations of our system running the standard macrobenchmarks[2] to judge the execution efficiency of Smalltalk implementations.

One conclusion is apparent: the system primitives are important. For every second spent in compiled code, three seconds are spent in the runtime system.

Of all the features designed into the system, the software features turn out to be more important than the hardware features in their effect on the final performance figures. The speedups attributable to specific features of the hardware and software are summarized in Table 14. This table indicates how much longer a task would take if the indicated feature were removed from our system. For example if we removed the Deutsch and Schiffman in-line cache from our system, it would run 26% slower. If all the features indicated were removed, a task that currently takes 100 seconds would then take 263 seconds.

The SOAR project took the well-worn phrase "hardware prices are falling" at face value and assumed that users would rather spend money on memory chips than on complicated mechanisms. Compiling Smalltalk into SOAR increases the size of the Smalltalk image by about 0.5 Mb. Deutsch and Schiffman estimated that compiling all of the Smalltalk image into 68000 code would increase its size by one megabyte. Given that the original Smalltalk image is over 1.5 Mb, compiling to SOAR is a reasonable tradeoff.

Table 15 contains information on the amount of code that had to be written to implement Smalltalk on SOAR. The C code running on the Sun includes the interface routines with the SOAR board, interface routines with the Sun's graphics display device[3], floating point routines, and file system interface routines. It does not include the code for Bill Bush's Smalltalk→SOAR compiler written in Smalltalk, nor the code in *genesis*.

## 7. Conclusions

Our experience has confirmed that it is possible to compile Smalltalk to the native code of more traditional von Neumann architectures and achieve reasonable performance. In-line caching of method lookup, use of a conventional activation stack (with relatively inconsequential modifications to the semantics of blocks and activation contexts), use of direct object pointers, and use of generation scavenging for storage reclamation were of particular importance in achieving this performance. In considering features of RISC architectures for supporting

[2] As distinguished from the *microbenchmarks*, which check the efficiency of the more primitive facilities of the system (plus, array reference, string concatenation, for example).

[3] BitBlt is on the Sun side, but CharacterScanner is on the SOAR side.

**Table 13. Time in major activities for macrobenchmarks.**

| Benchmark | time in runtime library | time in cache check | total time in runtime system |
|---|---|---|---|
| classOrganizer | 59% | 14% | 73% |
| compilerBenchmark | 66% | 10% | 76% |
| decompiler | 68% | 10% | 78% |
| printDefinition | 62% | 11% | 73% |
| printHierarchy | 76% | 7% | 83% |
| average | 66% | 10% | 76% |

**Table 14. Software vs. Hardware improvements.**

| | |
|---|---|
| Software | 158% |
| compilation (estimated) | 100% |
| in-line cache | 26% |
| direct pointers + GS | 32% |
| Hardware | 105% |
| register windows | 46% |
| tagged integers | 33% |
| non-delayed jumps | 11% |
| single cycle nilling of activation record | 4% |
| software interrupt | 7% |
| trap instructions | 4% |

Table 15: Code for SOAR runtime system.

| files | lines | words | chars | function |
|---|---|---|---|---|
| 19 | 3365 | 12491 | 90094 | misc files |
| 16 | 3847 | 11799 | 95817 | prim files |
| 2 | 1126 | 4845 | 34141 | trap handler files |
| 3 | 364 | 1604 | 11063 | process files |
| 40 | 8702 | 30739 | 231115 | SOAR sub-total files |
| 22 | 3134 | 9909 | 73518 | Sun interface files (in C) |
| 66 | 11836 | 40648 | 304633 | grand totals |

Smalltalk, we found that register windows and very simple dynamic type checking for the common primitive arithmetic operations on integers provided almost 75% of the performance improvement we achieved through hardware.

A bytecode virtual machine is very effective for defining precisely the semantics of a language, and bytecode interpretation is an exceptionally fast way of obtaining a slow implementation of that language. The SOAR project has confirmed that memory can be traded for performance—that compiling directly to native code on a RISC architecture is a viable implementation route for a fast implementation. Smalltalk on 400ns SOAR will run as fast as the fastest known implementation, the Xerox Dorado.

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