Representation Sharing for Prolog

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Abstract

Representation sharing can reduce the memory footprint of a program by sharing one representation between duplicate terms. The most common implementation of representation sharing in functional programming systems is known as hash-consing. In the context of Prolog, representation sharing has been given little attention. Some current techniques that deal with representation sharing are reviewed. The new contributions are: (1) an easy implementation of input sharing for findall/3; (2) a description of a sharer module that introduces representation sharing at runtime. Their realization is shown in the context of the WAM as implemented by hProlog. Both can be adapted to any WAM-like Prolog implementation. The sharer works independently of the garbage collector, but it can be made to cooperate with the garbage collector. Benchmark results show that the sharer has a cost comparable to the heap garbage collector, that its effectiveness is highly application dependent, and that its policy must be tuned to the collector.

KEYWORDS: Prolog, WAM, memory management

1 Introduction

Data structures with the same value during the rest of their common life can share the same representation. This is exploited in various contexts, e.g., by the intern method for Strings in Java, by hash-consing in functional languages (Goto 1974), and by data deduplication during backup. In programming language implementation, hash-consing is probably the best known representation sharing technique: hash-consing was invented by Ershov in (Ershov 1958) and used by Goto in (Goto 1974) in an implementation of Lisp. Originally, hash-consing was performed during all term creations so that no duplicate terms occurred during the execution of a program. (Appel and Gonçalves 1993) explores the idea of using hash-consing only during generational garbage collection: the new generation contains non-hash-consed terms, and on promotion to the older generation, they are hash-consed: for the first time, a representation sharing technique is cooperating with the garbage collector. Our approach is most closely related to (Appel and Gonçalves 1993), but also has some important differences.

Representation sharing has been given little explicit attention in the context of Prolog
implementation. However, the issue pops up from time to time. Here are some historical highlights:

- in 1989, in his Diplomarbeit, Ulrich Neumerkel (Neumerkel 1989) mentioned how by applying DFA-minimization to Prolog terms, certain programs can run in linear space (instead of quadratic); there was no implementation; in Section 8.1, his example program is used as a benchmark
- 1991: (Sahlin and Carlsson 1991) ends with the sentence: It still remains to be seen, however, what we meant by “folding identical structures”; the current paper offers a solution to this mysterious sentence
- in a 1995 comp.lang.prolog post, Edmund Grimley-Evans (Grimley-Evans 1995) asked for more sharing in `findall/3`, i.e., he wanted the solution list of a call to `findall/3` to share with the generator; input sharing (Mariën and Demoen 1993) does exactly that; Section 3 describes input sharing more precisely and how it can be implemented efficiently
- in 2001 Logic Programming Pearl (O’Keefe 2001), R. O’Keefe mentioned a `findall/3` query that could benefit from representation sharing in the answers; as for the previous bullet, Section 3 contains the solution
- in 2002, (Demoen 2002) gave a fresh view on garbage collection for Prolog; it detailed a number of desirable (optimal) properties of a garbage collector, one of which is the introduction of representation sharing (albeit naming it differently)
- in May 2009, Ulrich Neumerkel posted an excerpt of his Diplomarbeit in comp.lang.prolog and urged implementations to provide for more representation sharing, either during unification, or during garbage collection; he used the term factoring; we prefer representation sharing; the current paper is the result of exploring its implementation issues

The paper is organized as follows: Section 2 starts with describing what we mean by representation sharing. Section 2 lists a number of more or less popular forms of representation sharing in Prolog. Section 3 describes how to retain input sharing for `findall/3` and evaluates our implementation on a number of benchmarks.

Section 4 sets the scene for the focus of the rest of the paper: general sharing for Prolog. Section 5 forms the intuition on such sharing, while Section 6 introduces the notion of absorption: it shows when individual cells can share their representation and the approximation that works for us. It then lifts representation sharing from individual cells to compound terms and discusses some properties of our notion of representation sharing. Section 7 explains our implementation of representation sharing based on the earlier decisions. Section 8 discusses the benchmarks and the experimental results. Section 9 shows extensions of the basic implementation, variations and related issues. Section 10 discusses related work, and we conclude in Section 11.

We have used hProlog 3.1.* as the Prolog engine to experiment with, but it is clear that everything can be ported to other WAM-like systems as well: we make that more explicit later on. hProlog is a descendant of dProlog as described in (Demoen and Nguyen 2000). SICStus Prolog 4.1.1 serves as a yardstick to show that the hProlog time and space figures are close to a reliable state of the art system. All benchmarks were run on an Intel Core2 Duo Processor T8100 2.10 GHz.
We assume the reader to be familiar with the WAM (Aït-Kaci 1991; Warren 1983) and Prolog (Clocksin and Mellish 1984). We use the term heap when others use global stack, i.e., the place where compound terms are allocated. We use local stack and environment stack interchangeably and denote it by LS in pictures.

2 Representation Sharing versus Hash-Consing

Consider the predicates main1 and main2 defined as

\[
\text{main1} :- \\
\quad X = f(1,2,Z), \\
\quad Y = f(1,2,Z), \\
\quad \text{use}(X,Y).
\]

\[
\text{main2} :- \\
\quad X = f(1,2,Z), \\
\quad X = Y, \\
\quad \text{use}(X,Y).
\]

In a naive\(^1\) implementation, the execution of `?- main1.` just before the call to `use/2`, results in a memory situation as in the left of Figure 1. In this figure, the heap cell with Z is a self-reference in the WAM. Clearly, the terms X and Y are exactly the same ever after they have been created, and therefore they can share the same representation: that sharing can be seen in the right of Figure 1 and in the code for the predicate main2.

Hash-consing is usually associated with the technique that keeps a hash table of terms and during term creation checks whether a term is new or exists already in the hash table.

An implementation with hash-consing usually changes the representation of terms, and consequently the code that deals explicitly with this representation. For Prolog the affected code would be general unification and built-in predicates. That is too intrusive for our aims: we intend our implementation of representation sharing to be easy to integrate in other Prolog systems and there should be no global impact. So, we will keep the usual (WAM) term representation and do not touch any part of the implementation, except for the sharer module that introduces representation sharing. Given the complexity of current Prolog systems, this seems to us the only way to make representation sharing accepted by implementors.

\(^1\) I.e., an implementation without compile time common subexpression elimination; however, note the danger of such optimization in the presence of destructive assignment: see Section 9
Some Forms of Representation Sharing for Prolog

Prolog implementations already provide some specific representation sharing. Here are a few examples:

- in older implementations, the predicate `copy_term/2` copies ground terms; in newer implementations —starting probably with SICStus Prolog (Carlsson 1990)— `copy_term/2` avoids copying ground (sub)terms; this means that the second argument can have some representation sharing with the first argument; however, note that mutable ground terms must be copied by `copy_term/2`, because otherwise sharing would become observable at the program level; we discuss this issue further in Section 9
- some programs contain ground terms at the source level; a typical example is the second argument of a goal like `member(Assoc, [fx, fy, xf, yf, xf, yf])`; ECLiPSe (Wallace et al. 1997) pre-allocates such ground terms, and makes sure that any time such a fact or goal is called, the ground term is re-used; Mercury performs this compile-time optimization as well
- when two terms are unified, they can share a common representation in the forward execution; at various stages in its life, BinProlog (Tarau 1991) enforced such sharing by (in WAM speak) redirecting the S-tagged pointer of one of the two terms and (conditionally) trailing this change so that on backtracking it can be undone; if trailing is not needed, then the savings can be huge; otherwise, the locality of access can be improved, but memory and time savings can be negative; a similar technique was already used for strings only in the Logix implementation of Flat Concurrent Prolog (Hirsch et al. 1987)

In each of the above cases, the implementor of the Prolog system decided for more representation sharing than would be the case in a more straightforward implementation. Application programmers and library developers usually take care as well to let their run-time data structures share common parts.

In the above, `copy_term/2` and unification are built-in predicates that have a chance to increase representation sharing. In Section 3, `findall/3` is added to this shortlist.

3 Input Sharing for `findall/3`

In (Mariën and Demoen 1993), the notion of input sharing was introduced in the context of `findall/3`. Input sharing consists of a solution in the output from `findall/3` (its third argument) sharing with the input to `findall/3` (its second argument).

Later, in the Logic Programming Pearl (O’Keefe 2001) it is suggested that `findall/3` could avoid repeatedly copying the same terms over and over again: this would improve the space complexity of some queries that use `findall/3`, from $O(n^2)$ to $O(n)$. However, R. O’Keefe suggests that hash-consing should be used, with the consequence that the time complexity remains the same: our implementation of input sharing —which is exactly what is needed here— improves both the time and space complexity. The example used in (O’Keefe 2001) is rather complicated, so for now, we use as an illustration a piece of simple Prolog code that was posted in (Grimley-Evans 1995); we changed the names of the predicates and variables.
findall_tails(L,Tails) :- findall(Tail,is_tail(L,Tail),Tails).

is_tail(L,L).

is_tail([_|R],L) :- is_tail(R,L).

all_tails([],[]).

all_tails([|L|S]) :- L = [_[|R]], all_tails(R,S).

Clearly, goals of the form \(?-\) findall_tails(L,Tails). and \(?-\) all_tails(L,Tails). with a ground argument L succeed with the same answer Tails. E.g.,

\(?-\) findall_tails([1,2,3],Tails).
Tails = [[1,2,3],[2,3],[3],[]]

The usual implementation of \(\text{findall}/3\) copies over and over again parts of the input list L, and this results in quadratic behavior (in the length of L) for \(\text{findall_tails}/2\), while \(\text{all_tails}/2\) is linear, both in space and time! Clearly, with enough input sharing the \(\text{findall_tails}/2\) query could be linear.

In the following sections we show how a traditional \(\text{findall}/3\) implementation in the context of the WAM can be easily adapted to cater for input sharing. An alternative copy-once implementation of \(\text{findall}/3\) is also shown.

Before going into the details, it is worth pointing out the limitations of input sharing. Clearly, if L is a list with non-ground elements, the two queries

\(?-\) findall_tails(L,Tails). \(?-\) all_tails(L,Tails).

yield different answers. The first query makes fresh variants of the variables in each of the solutions in Tails, while the second query does not. As an example:

\(?-\) findall_tails([X,Y,Z],L),
\(\text{numbervars}(L,0,\_).\)
L = [[A,B,C],[D,E],[F],[]]
\(?-\) all_tails([X,Y,Z],L),
\(\text{numbervars}(L,0,\_).\)
L = [[A,B,C],[B,C],[C],[]]
\(X = A\ Y = B\ Z = C\)

This means we can use an input sharing version of \(\text{findall}/3\) when the arguments of the generator are either ground or free: the danger is only in terms containing variables.

\subsection{3.1 The Implementation of findall/3}
The hProlog implementation of \(\text{findall}/3\) follows the same pattern as in many systems:
findall(Template,Generator,SolList) :-
    findall_init(Handle),
    { call(Generator),
      findall_add(Template,Handle),
      fail
    ;
      findall_get_solutions(SolList,Handle) }
).

For simplicity, we have left out all error checking and error recovery code. The predicate findall_init/1 returns a handle, so that the particular invocation of findall/3 is identified: this is used for correct treatment of nested calls to findall/3. findall_add/2 uses that handle, and copies the Template to a temporary zone. findall_get_solutions/2 uses the handle as well: it retrieves the complete list of solutions from the temporary zone and unifies it with the third argument to findall/3.

The next section describes how to turn this code into code that shares the input.

3.2 The basic Idea of Input Sharing for findall/3

The predicate findall_add/2 in our implementation of findall/3 is just a version of copy_term/2: at the implementation level, they both use the same C function for the actual copying. The same is true for findall_get_solutions/2.

The first idea might be to use an implementation of copy_term/2 that avoids copying ground terms. However, in the context of findall/3, groundness is not enough: the ground term must also be old enough, so that backtracking (over the Generator) cannot alter it. To be more precise, anything ground that survives backtracking over the Generator need not be copied by findall_add/2. Or put still another way: anything ground before the call to findall(Template,Generator,SolList) need not be copied by findall_add/2.

Such terms can be recognized easily: their root resides in a heap segment that is not newer than the call to findall/3.

So we need to be able to identify the older heap part relevant to a particular call to findall/3. That is quite easy in the WAM: we just remember the relevant heap pointer!

3.3 findall/3 with Input Sharing: the Implementation

We use two new low-level built-in predicates:

- current_heap_top(-): unifies the argument with (an abstraction of) the current value of the heap pointer H
- set_copy_heap_barrier(+): sets a global (C-)implementation variable (named copy_heap_barrier) to the heap pointer value corresponding to its argument

The following code shows how the new built-ins are used:
An additional small change needs to be made to the implementation of findall\(_{\text{add}}/2\) (and findall\(_{\text{get_solutions}}/2\)) as well: when a term is about to be copied and it is older than copy\(_{\text{heapbarrier}}\), only the root pointer to this term is copied. It amounts to adding a statement like

```haskell
if (struct_addr < copy_heapbarrier) { *whereto = struct_addr; continue; }
```

at a few places in the C code of copy\(_{\text{term}}/2\): this piece of code just copies the top pointer of the structured term instead of copying it recursively. The C variable struct\(_{\text{addr}}\) holds the address of the structure about to be copied.

For explanatory reasons, we have shown the implementation of sharing\(_{\text{findall}}/3\) as a variant of the basic implementation of findall\(_{\text{3}}\) using two new built-ins. However, one can also fold the functionality of these new built-ins into adapted versions of findall\(_{\text{init}}, \text{add, get_solutions}}\): the top-of-heap at the moment of calling sharing\(_{\text{findall}}/3\) is then stored in the data structures belonging to that particular call. This top-of-heap at the moment of calling sharing\(_{\text{findall}}/3\) must also be appropriately treated by the garbage collector.

### 3.4 An Example

The heap and temporary findall zone are shown in Figure 2 for the very simple query

```prolog
?- findall(X, X=f(1,2,3), L).
```

The left part of the picture shows three snapshots during the execution of the query without input sharing. The right part shows the corresponding snapshots with input sharing. The snapshots are taken

- just before findall\(_{\text{add}}/2\) is executed: the temporary zone is still empty
- just after findall\(_{\text{add}}/2\) is executed: at the left, the temporary zone contains a copy of the term f(1,2,3); at the right, there is a pointer to the term on the heap
- just after findall\(_{\text{get_solutions}}/2\) is executed: the temporary zone can be discarded; at the left, the solution list contains a copy of f(1,2,3); at the right, there is just a pointer to the old term on the heap

The space savings are clear.
The usual implementation of \texttt{findall/3} copies the solutions twice. BinProlog was probably the first implementation copying the solution only once, by means of a technique named \textit{heap lifting} or more popularly a \textit{bubble in the heap} (Tarau 1992). Currently, the BinProlog implementation (Tarau and Majumdar 2009) relies on \textit{engines} for \texttt{findall/3}. Mercury also uses a copy-once \texttt{findall} (named \texttt{solutions/2}): as Mercury relies on the Boehm-collector (Boehm and Weiser 1988), there is no memory management hassle with a bubble in the heap.

It is rather easy to implement a copy-once \texttt{findall/3} in any Prolog system that has non-backtrackable destructive assignment (with \texttt{nb_setarg/3}) as in hProlog or SWI-Prolog (Wielemaker et al. 2008)

\begin{verbatim}
copy_once_findall(Template,Generator,SolList) :-
    Term = container([]),
    ( call(Generator),
      Term = container(PartialSolList),
      copy_term(Template,Y),
      nb_setarg(1,Term,[Y|PartialSolList]),
      fail ;
      Term = container(FinalSolList),
      reverse(FinalSolList,SolList) ).
\end{verbatim}

Note that SWI-Prolog uses \texttt{nb_linkarg/3} as the name for hProlog’s \texttt{nb_setarg/3}

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Fig. 2. Findall without and with Input Sharing
As before, this code can be enhanced with the newly introduced built-ins to yield a copy_once,sharing FINDALL. If copying the solutions dominates the execution, the copy-once findall/3 is about twice as fast as the regular findall/3. However, its main drawback is that it consumes (for the benchmarks below) about three times as much heap space. The reason is that nb_setarg/3 must freeze the heap if its third argument is a compound term. The heap-lifting technique (which we have not implemented in hProlog) does not have this drawback.

3.6 Experimental Evaluation

Input sharing improves (sometimes) the complexity (space and time), and the constant overhead is really very small, as can be judged from the changes needed to implement it. One could therefore argue that benchmarks are not needed. Even so, we present two benchmarks: one is the findall(Tails) example (see Section 3.7). We start with a findall/3 related query from (O’Keefe 2001): this pearl is about tree construction and traversal. It contains the following text:

Query $q^1$ requires at least $O(n^2)$ space to hold the result. If findall/3 copied terms using some kind of hash consing, the space cost could be reduced to $O(n)$, but not the time cost, because it would still be necessary to test whether a newly generated solution could share structure with existing ones.

Note that the $n$ above is the number of nodes in the tree, not the tree depth: the number of nodes is roughly $4^\text{depth}$ where depth is the depth of the tree.

We needed to make a slight change to the program from (O’Keefe 2001): in its original form it contains a mk_tree/2 predicate defined as

```prolog
mk_tree(D, node(D,C)) :-
    D > 0 ->
    D1 is D - 1,
    C = [T1,T2,T3,T4],
    mk_tree(D1, T1),
    mk_tree(D1, T2),
    mk_tree(D1, T3),
    mk_tree(D1, T4)
    ; C = []
).
```

Because of the conjunction $C = [T1,T2,T3,T4]$, mk_tree(D1, T), the heap representation of the constructed tree is linear in the first argument D, even though it has an exponential number of nodes: indeed, the constructed tree has a lot of internal sharing. Such internal sharing is retained by most reasonable implementations of copy_term/2 and by findall_add/2.\(^3\)

In order to test what (O’Keefe 2001) really meant, we have changed the particular conjunction to

```prolog
C = [T1,T2,T3,T4],
mk_tree(D1, T1),
mk_tree(D1, T2),
mk_tree(D1, T3),
mk_tree(D1, T4)
```

\(^3\) $f_1(N)$ in the Appendix

\(^4\) A notable exception is Yap.
so that the size of the representation of the tree is linear in the number of nodes in the
tree (and exponential in D). This code rewrite achieves the desired effect because Prolog
systems typically don’t perform the analysis needed to notice that T1, T2, T3 and T4 are
declaratively the same value, and neither is this detected at runtime. See the Appendix for
all code necessary to run the benchmark.

3.6.1 The modified Tree Benchmark: Results

Table 1 shows timings (when considered meaningful) and space consumption for queries
?- f1(Depth) with different values of Depth. Times are reported in milliseconds, space in
bytes. We have chosen SICStus Prolog for comparison with another system because the
SICStus Prolog implementation performed better and more reliably than the other systems
we tried. Moreover, the trend of the measurements with other systems was basically the
same.

The timings without sharing do not show anything interesting complexity-wise: neither
of the implementations without input sharing can deal with more than about 5000 nodes.
The input sharing implementation on the other hand can go easily up to one million nodes.
The heap consumption columns give a good picture of how the heap size grows: the non-
input-sharing implementations show a quadratic dependency of the heap consumption on
the number of nodes. Only hProlog input sharing shows a linear dependency.

<table>
<thead>
<tr>
<th>Depth</th>
<th>hProlog time</th>
<th>hProlog space</th>
<th>hProlog input sharing time</th>
<th>hProlog input sharing space</th>
<th>SICStus Prolog time</th>
<th>SICStus Prolog space</th>
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</table>

Table 1. Heap consumption in bytes and time in msecs for the tree benchmark

Table 1 shows clearly that our simple implementation to enforce input sharing is very
effective and performs actually better than hoped for in (O’Keefe 2001). Indeed, we achieve
linear space and time complexity for the f1(Depth) query. Hash-consing would not be able
to do that.

3.7 The tails Benchmark

Table 2 shows the space consumption for the tails benchmark. The timings are meaning-
lessly small for the variants with sharing, and therefore only shown for the regular findall
columns. The Length/1000 column indicates the length of the ground input list L to queries of the form ?- all\_tails(L, Tails) and ?- [sharing\_findall(Tail, is\_tail(L, Tail), Tails).

<table>
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<th>Length /1000</th>
<th>regular findall</th>
<th>findall with input sharing</th>
<th>all_tails</th>
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</table>

Table 2. Heap consumption in KiB and time in msecs - tails benchmark

findall/3 with input sharing clearly beats the findall/3 without input sharing. SICStus Prolog can do larger sizes with the ordinary findall/3 implementation than hProlog: the latter runs out of memory earlier because of its different memory allocation and heap garbage collection policy.

We have tried to measure the overhead of our method, but it is too small to show up meaningfully in any of our experiments.

### 3.8 Conclusion on Input Sharing for findall/3

Already in (Grimley-Evans 1995) there was a demand for sharing between the input to findall/3 and its output. Also (O’Keeffe 2001) points out that this would be beneficial to some programs. Optimal input sharing would attempt to share all (sub)terms that are ground just before the call to findall/3. Checking this at runtime can be involved and costly. Our implementation approximates that by just checking that the root of a term is old enough, and relying on the programmer (or some other means) to use sharing\_findall/3 only when this simple check implies that the whole term was ground at the moment of the call to sharing\_findall/3. This is in particular true in the common case that the generator of findall/3 (its second argument) is a goal of which every argument is ground or free: that was the case for our benchmark findall\_tails/2. That condition on the generator can be easily checked before calling sharing\_findall/3 and could also be derived by program analysis.

Our approach does not implement solution sharing: hash-consing, or maybe even better
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tries, could do the job. Sections 4 and later provide a more general and lightweight solution to representation sharing.

In (O’Keefe 2001), one can also read:

“One referee suggested that Mercury’s ‘solutions/2’ would be cleverer. A test in the 0.10 release showed that it is not yet clever enough.”

As Mercury (Somogyi et al. 1996) relies on the Boehm-allocator and -collector for its memory management, it is quite difficult to devise a simple dynamic test whether a (ground) term is old enough: on the whole, a Mercury implementation does indeed not benefit from keeping the address order of terms consistent with their age. On the other hand, in the WAM, such a test comes natural with the needs of a strict heap allocation discipline and conditional trailing.

As a conclusion, we think we have succeeded in providing input sharing for findall/3 with minimal change to the underlying Prolog execution engine: any Prolog implementation with a heap allocation strategy similar to the WAM can incorporate it easily. How to present the functionality in a safe way to the user is a language design issue and as such beyond the scope of this paper.

4 General Representation Sharing for Prolog

(Appel and Gonçalves 1993) adapts a copying collector to perform hash-consing for the data in the older generation. Since we would like our implementation of representation sharer to be a model for other Prolog implementations, we cannot just copy that idea. Indeed, hash-consing requires a serious adaptation of the term representation, and moreover Prolog systems typically have sliding collectors, the exceptions being hProlog and BinProlog. Therefore we want to investigate representation sharing in a way that does not require a change in term representation, and that is independent of the details of the garbage collector: this will make it easier for Prolog systems to implement their own sharing module based on our experience. (Appel and Gonçalves 1993) argues that garbage collection time is a good moment to perform hash-consing, but there is no inherent need to do it only then. Still, we agree basically with (Appel and Gonçalves 1993): it is better to avoid putting any effort in sharing with dead terms.

We use as Prolog goals in the examples share and gc: the former performs representation sharing, the latter just performs garbage collection. By keeping the two separated, the issues become clearer, i.e., we make no assumptions on the workings of the garbage collector.

(Baker 1992) shows that the combination of tabling and hash-consing is particularly powerful: since duplicate terms do not occur, equality of terms can be decided by a single pointer comparison instead of by traversing the whole terms. However, in that context and in its original form, hash-consing guarantees representation sharing all the time, while that is not our aim. Unfortunately, (Baker 1992) does not show experimental data for hash-consing without tabling.
5 Representation Sharing in Prolog: Examples

Two issues make representation sharing in Prolog-like languages different from other languages: the logical variable and backtracking. Subsequent subsections show by example how these affect the possibilities for representation sharing.

5.1 Sharing within the same Segment

The first example in Section 2 shows the simplest case of sharing: the two terms are identical, in the same heap segment (as delimited by the HB pointers in the choicepoints) and ground at creation time.

The next example shows that identical ground terms in the same segment cannot always share their representation:

```prolog
main3 :-
T1 = f(a),
T2 = f(X),
(X = a, share ;
write(T1 \== T2)).
```

While executing the query `?- main3`, just before the execution of `share`, the terms T1 and T2 are identical, ground, and they are completely within the same segment. However, it would be wrong to make them share their representation, since in the failure continuation, they are no longer identical. Loosely speaking, the occurrence of trailed variables in a term makes the term unsuitable for representation sharing.

5.2 Sharing between Segments

The previous examples dealt with representation sharing of terms that live in the same segment. The next example shows an issue with representation sharing of terms that live in different segments. Since we do not want to mix this issue with trailed heap locations, the example works with ground terms.

```prolog
main4 :-
T1 = f(a),
\{ 
T2 = f(a), share, use(T1,T2) ;
use(T1)
\}.
```

During the execution of the query `?- main4`, T1 and T2 live in two different segments. T1 lives in the oldest segment, as seen in the left of Figure 3$. Since T1 is used after

$^5$ The dashed line indicates the heap segment barrier
backtracking, the natural thing is to keep the representation of the oldest term, because it potentially lives longest. So the introduced sharing representation is as in the right of Figure 3. Alternatively, one could use as shared representation the one in the younger segment,

![Fig. 3. Representation Sharing of two Terms in different Segments](image)

but then the heap should be frozen, so that on backtracking the value of T1 does not get lost. We consider this a bad alternative, but a slight variation on the same example shows that the choice is not so clear cut:

```prolog
main5 :-
  T1 = f(a),
  use(T1),
  { T2 = f(a), share, gc, use(T2)
  ;
  dontuseT1
  }.

main6 :-
  T1 = f(a),
  use(T1),
  { T2 = f(a), gc, use(T2)
  ;
  dontuseT1
  }.
```

The code of main5 and main6 differs only in the call to `share` in main5.

- **with sharing in main5**: share keeps one representation of f(a) and puts it in the oldest segment; gc cannot reclaim that representation, because T2 is not dead; after backtracking to `dontuseT1`, the f(a) term is still on the heap
- **without sharing in main6**: at the point gc kicks in, T1 is unreachable and its representation disappears; this means that after backtracking to `dontuseT1`, the heap is empty

This example shows that representation sharing between terms in different segments can lead to a higher heap consumption, or more invocations of the garbage collection.

Finally, it is clear that mutable terms should not share their representation: it is in general impossible to know whether two mutable terms will be identical for the rest of their common lifetime. We deal with mutable terms in more detail in Section 9.

### 6 Sharable Terms and Absorption

The examples in the previous section give some intuition on what we mean by representation sharing, and also about its pitfalls. The examples also have indicated that we are working towards an implementation of a sharer that introduces sharing between two terms T1 and T2 by keeping the representation of one of them, say T1, and making T2 point to it. We coin this process **T1 absorbs T2**. This leads naturally to considering the notion T1 can absorb T2.
The most general definition of \( T1 \) can absorb \( T2 \) would be that the sequence of solutions to the running program does not change by letting \( T1 \) absorb \( T2 \). That condition is of course not decidable, so we need a workable approximation to it.

The next sections explore the notion can absorb further, first by focussing on representation sharing for individual heap cells and then by considering compound terms.

### 6.1 Representation Sharing for Individual Heap Cells

It pays off to study the most basic representation sharing of all: between two individual heap cells.

Clearly, when two cells, say \( c1 \) and \( c2 \), have different contents (and are live), neither of them can absorb the other. And when the two cells have identical addresses, they have absorbed each other already. So, we are left with the possibilities that

- \( c1 \) and \( c2 \) are in the same heap segment or not
- \( c1 \) and/or \( c2 \) is trailed or not

Without loss of generality, we assume that \( c1 \) is older than \( c2 \).

This results in the eight combinations shown in Figure 4: a trailed cell is shaded. The contents of the two cells at the moment of the snapshot is the same, but shaded cells will be set to free (a self-reference in the WAM) on backtracking to the appropriate choice-point. The horizontal dashed lines now indicate one or more heap segment separations. The vertical lines just separate the different cases.

**Fig. 4. The 8 combinations of two cells**

- **a**: \( c1 \) can absorb \( c2 \) and also vice versa, because the two cells have an identical contents, and that will remain so in the forward and in the backward computation
- **bcd**: in the forward computation, the two cells remain identical, but not after backtracking; so no representation sharing can take place, and neither can absorb the other
- **e**: on backtracking, \( c2 \) dies before the older cell \( c1 \), but for the duration of their common life, the two cells are identical, so representation sharing is allowed: \( c1 \) can absorb \( c2 \), but not the other way around
these cases are similar to cases b and c above: as soon as one of the trailed cells is untrailed by backtracking, the contents of c1 and c2 differ; therefore representation sharing is not allowed; neither can absorb the other.

h: there are two possibilities now:

(a) at the moment the older cell is untrailed, backtracking also recovers the segment in which the newer cell resides; this means that the newer cell dies, so the fact that the older cell is set to free does not prevent representation sharing; so c1 can absorb c2 (and not the other way around); this happens if c1 was trailed before the segment of c2 is final, or to put it differently: if the moment of trailing c1 is not after the segment of c2 is closed by a choicepoint; i.e., if c2 dies not later than c1 is untrailed, c1 can absorb c2

(b) otherwise, representation sharing is disallowed; neither cell can absorb the other.

Anticipating an implementation, we notice that it is important to be able to check quickly whether a cell is trailed. One bit—appropriately placed—is enough for that: that bit could be in the heap cells themselves, or it could be allocated in an array parallel to the heap. This would make cases a and e easy to identify.

To detect case h(a), however, we also need to retrieve quickly from a heap address, the heap segment number in which it was trailed. That requires more setup, and it would slow down the sharer. We think the expected gain in space too small to make this worthwhile. Instead, we went for disallowing sharing in case h(a), so that our notion of can absorb becomes quite simple and leads to a simple decision procedure. In the following piece of code, pcl and pc2 are pointers to heap cells c1 and c2:

```c
boolean can_absorb(cell *pcl, cell *pc2) {
    if (*pcl != *pc2) return(FALSE);
    if (trailed(pcl)) return(FALSE);
    if (trailed(pc2)) return(FALSE);
    return(pc1 < pc2);
}
```

If cell c1 can absorb cell c2, every (tagged) pointer to c2 can be changed into a (tagged) pointer to c1: this change does not affect the outcome of the execution. Note that it is immaterial whether the cell containing the (tagged) pointer to c2 is trailed or not.

Since trailing prevents a cell from being able to absorb, or being absorbed, it is in the interest of maximizing the chances for representation sharing to keep the trail tidy: this is in many Prolog systems done at the moment a cut (/\0) is executed. Also during garbage collection, the trail can be tidied.

### 6.2 Representation Sharing for Compound Terms

The representation of a compound term with principal functor foo/n in the WAM is an S-tagged pointer to an array of (n+1) contiguous heap cells, the first of which contains foo/n, and the next n cells contain one cell of the representation of one argument each. We name this array of (n+1) heap cells the body of the term.
The idea of one term absorbing the other is that after absorption, there is only one body instead of two, but there are still two cells with an S-tagged pointer pointing to it. See Figure 5.

Clearly a necessary condition for such representation sharing is that the two bodies have the same contents. Moreover, since a term body always belongs to a single segment, the condition worked out for absorption for two individual cells must hold for each pair of corresponding body elements. We arrive at the following

**Definition:** Term T1 can absorb term T2 if T1 is older than T2, T1 == T2 and neither T1 nor T2 contain trailed cells.

Figure 5 shows two bodies that fulfill the conditions.

![Figure 5](image)

Note that the example exhibits a situation we have not yet described: a variable chain. Dereferencing must be stopped when a trailed cell is found.

Note the similarity of the above analysis with the one for variable shunting in (Sahlin and Carlsson 1991).

An algorithm that given two terms decides whether one can absorb the other is now easily constructed. However, the naive use of this algorithm would be very inefficient.

### 6.3 Properties of our notion of can absorb

Before going to the implementation of representation sharing, it is good to understand some properties of the can absorb relation: the optimality (if any) of our algorithms depends crucially on those properties.

It is clear that can absorb is not symmetric: a newer term cannot absorb an older term in a different segment. Neither is can absorb anti-symmetric: case a in Section 6.1 shows that.

We denote by absorbed(x,y) the result of letting term x absorb term y, of course under the condition that x can absorb y.

An important part of our definition of can absorb is that the terms do not contain trailed cells: it implies that a candidate term for absorbing or being absorbed can be recognized without knowing the other term, i.e., one checks whether it contains trailed cells or not and by keeping information about visited terms, one can assure that this information about the terms can be gathered in time proportional to the heap.

From the definition, it also follows that can absorb is transitive:

\[(x \text{ can absorb } y) \land (y \text{ can absorb } z) \Rightarrow x \text{ can absorb } z\]
Finally, the absorption process is also associative, i.e.,

\[
\text{absorbed}(\text{absorbed}(x,y),z) \equiv \text{absorbed}(x,\text{absorbed}(y,z))
\]

(of course under the condition that \(x\) can absorb \(y\) and \(y\) can absorb \(z\)). This means that the order in which absorption takes place is immaterial: the end result is the same.

Together, these properties allow for a basically linear sharing algorithm, on condition that term hashing is perfect. With a less than perfect hash function, the algorithm might need to traverse some terms more than once.

7 Implementation of Representation Sharing

We have taken hProlog as the platform for an implementation of representation sharing. hProlog is based on the WAM (Aït-Kaci 1991; Warren 1983) with a few differences:

- the choicepoint stack and environment stack are not interleaved as in the WAM, but separate stacks as in SICStus Prolog
- free variables only reside on the heap; i.e., there are no self-references in the environment stack, just as in Aquarius Prolog (Van Roy and Despain 1992)
- hProlog supports some more native types like char, string and bigint; it also has attributed variables

hProlog employs a mark-and-copy type of garbage collector, with its roots in (Bevenyr and Lindgren 1994), and it preserves segment order as described in (Vandeginste et al. 2002). Most other systems use a sliding collector based on (Appleby et al. 1988). hProlog does not implement variable shunting.

hProlog is a direct descendant of dProlog (Demoen and Nguyen 2000). Its purpose is to offer a platform for experiments in WAM-like Prolog implementation. Its high performance gives the experiments an extra dimension of credibility.

The implementation uses two data structures: they can be seen in Figure 6. We name them \texttt{cached}\_\texttt{hash} table and \texttt{hashed}\_\texttt{terms} table. Together they form the sharer tables.

- \texttt{cached}\_\texttt{hash}: this is an array the size of the WAM heap (or global stack) and can be though of as parallel to the heap; its entries contain information about the corresponding heap cells; the information is one of the following three:
  - \texttt{no-info}: the corresponding heap cell has not been \texttt{treated} yet
  - \texttt{impossible}: the corresponding heap cell cannot participate in representation sharing; see Section 7.3 for more on this
  - a pointer to the \texttt{hashed}\_\texttt{terms} table: the corresponding heap cell has been treated, and its sharing information can be found by following the pointer

- \texttt{hashed}\_\texttt{terms}: this data structure contains records with two fields: \texttt{hashvalue} and \texttt{term}; suppose a pointer in the \texttt{cached}\_\texttt{hash} points to a record in the \texttt{hashed}\_\texttt{terms}, and the corresponding heap cell A is the entry point of term \texttt{TermA}, then
  - the \texttt{hashvalue} field in the record is the hash value of term \texttt{TermA}
— the term field in the record is a pointer to a heap cell B that is the entry point of a term TermB that can absorb TermA (provided A and B are the not same cell); our implementation makes sure that the heap cell B is as old as possible, i.e., B is equal to A or older than A

Treating a heap cell consists in filling out the corresponding cell in the cached_hash table and possibly the hashed_terms table.

The implementation of the hashed_terms table is actually as a hash table: the hash-value of a term modulo the size of the hash table is used for determining the place in the hashed_terms, and a linked list of buckets is used to resolve collisions. Many other implementations of this hashed_terms table would be fine as well.

Our first description of the algorithm only tries to introduce sharing between structures (not lists). Therefore, for now, hashed_terms pointers can only appear in cached_hash cells corresponding to a heap cell containing a functor descriptor.

The main algorithm consists of two phases:

- **build**: it builds the cached_hash and hashed_terms tables; during this phase nothing is changed to the heap; this phase treats all heap cells
- **absorb**: it performs all absorption possible by using the cached_hash and hashed_terms tables

In the algorithms below, we use beginheap and endheap for the pointers to the first (oldest) cell in the heap and the last (newest). We assume no cell is trailed, and come back to this point later.

### 7.1 Phase I: building the cached_hash and hashed_terms tables

The build phase performs the action compute_hash for each cell in the heap: the corresponding cell in the cached_hash is set to either impossible or to a pointer to the hashed_terms. The function compute_hash is always called with a tagged term as argument.

In the code below, we use STRUCT as the tag of a pointer pointing to the functor cell of a compound term. In figures, this tag shows simply as S. The function call $tag(p,STRUCT)$ returns such a STRUCT tagged pointer; the function $untag$ has the opposite effect. A function call like $tag(term)$ returns the tag of its argument.

Note that the following code ignores certain issues like checking whether a cell is trailed, and LISTS. We deal with them in Section 7.3.
foreach p in [beginheap, endheap] && is_functor(*p)
    compute_hash(tag(p, STRUCT)); // ignore return value

int compute_hash(p)
{
    deref(p);
    switch tag(p)
    {
        case FREE:
        case ATOMIC:
            return(p);
        case STRUCT:
            p = untag(p, STRUCT);
            if (already_computed(p)) return(already_computed_hash(p));
            hashvalue = *p;
            foreach argument of structure p do
                hashvalue += compute_hash(argument);
            save_hash(hashvalue, p);
            return(hashvalue);
    }
}

The particular hash value computed above is not relevant for our discussion: in practice, there are better (more complicated) ways to compute hash values of terms.

The function call already_computed(p) checks whether the corresponding element in the cached_hash table points to the hashed_terms table. already_computed_hash(p) returns the hash value previously computed (for the term starting at p) from the hashed_terms entry corresponding to p: in this way, re-computation (and re-traversal of the same term) is avoided.

In the save_hash function that follows, we have left out collision handling: for the sake of the presentation, we assume perfect hashing.

save_hash(hashvalue, p)
{
    index = hashvalue % length(hashed_terms);
    cached_hash[p-beginheap] = hashed_terms + index;
    if (empty(hashed_terms[index]))
    {
        hashed_terms[index].term = p;
        hashed_terms[index].hashvalue = hashvalue;
        return;
    }

    // a non-empty entry might need to be adapted
    if newer(hashed_terms[index].term, p) hashed_terms[index].term = p;
The last line in save_hash makes sure that the term pointed at in an hashed_terms entry is as old as possible. The reason is that it is safe to let an older term absorb a younger one.

Figure 6 shows how three equal terms are treated by compute_hash and the effect thereof on the cached_hash and hashed_terms tables.

![Diagram](image)

(a) After treating middle f(a,b)  
(b) After treating younger f(a,b)  
(c) After treating older f(a,b)

Fig. 6. Three identical terms are treated during the build phase

### 7.2 Phase II: Absorbing

The absorb phase performs the actual representation sharing: an S-tagged pointer is redirected to the oldest term body that can absorb it. The code is very simple:

```plaintext
foreach cell c in the heap  
  in the local stack  
  in the choicepoint stack  
  in the argument registers do  
  let p be the contents of c;  
  if (tag(p) == STRUCT)  
  {  
    q = untag(p,STRUCT);  
    if (cached_hash[q-beginheap] points to hashed_terms)  
      replace c by tag(cached_hash[q-beginheap]->term,STRUCT);  
  }
```

Figure 7 shows how the older term absorbs the two identical younger terms.

### 7.3 Comments on the Code

The code in Section 7.1 ignores certain issues:

- **checking whether a heap cell is trailed**: during the initialization of the build phase, the cached_hash table entries corresponding to trailed heap entries are initialized to impossible; this requires traversing the trail once and it makes checking whether a cell is trailed constant time; the checks whether a heap cell is trailed are required during the dereferencing loop; when a trailed cell is encountered, the computation of the hash value is stopped and the corresponding cached_hash table entries of the term containing the trailed cell are also set to impossible.
other datatypes: the code takes into account only non-list structured terms, atoms and variables; it is easy to extend it to other types that occupy a single cell; for other atomic types (real, string, bigint) we have followed the same principle as for non-list structured terms: those types are implemented roughly like such terms, i.e., with a tagged pointer to a header on the heap which is followed by the actual value that can span several heap cells; for lists, we have a different solution: see Section 7.4

foreach: our implementation uses a linear scan for the foreach constructs: this is possible for all the stacks in hProlog; if this is not the case, one can traverse the live data starting from the root set as the garbage collector does (e.g., during its marking phase)

The code implementing the above is less than 700 lines of plain C that reuses very little previously existing code.

Note that in the context of our copying collector, the extra space needed for representation sharing is just the hashed_terms table: the cached_hash table has exactly the same size as the collector needs for performing its collector duties.

7.4 Representation Sharing of Lists

In the WAM, lists have no header like other compound terms. A list is represented by an L-tagged pointer to two consecutive heap cells containing the first element of the list and its tail respectively. Clearly, we cannot deal with lists as in the previous algorithm. The change is however small: we keep the hashed_terms pointer in the cell corresponding to the list-pointer. Figure 8 shows an example with just lists.

Note that functor cells can only appear on the heap, while list pointers can occur also in environments, choicepoints, and the argument registers. As a result, with just a hashed_terms pointer array parallel to the heap, some representation sharing in the other stacks can get lost for lists. A similar hashed_terms pointer array parallel to the other stacks can solve this problem: our implementation does not do that. Another solution consists in using the cell of the first element of a list for keeping the corresponding hashed_terms information. We have not explored that alternative.
7.5 When to run the Sharer

It seems obvious that the sharer must be run either during GC, or just after GC. Our sharer can be adapted to run during GC most easily when the GC starts with a marking phase: the build phase of the sharer can indeed be integrated in the marking phase of the collector. The absorb phase can be run before the next GC phase, or be integrated with it. That would lead to a (mark+build)&(copy+absorb) collector for hProlog. In a sliding GC context, this would become (mark+build)&(compact+absorb).

Still, we choose from the beginning to run the sharer as an independent module that could actually be run at any time. Just after GC seems the best, because at that moment, the heap has minimal size. We name that policy after GC.

There is one snag in this: the space freed by the sharer cannot be used immediately, and the beneficial effect of the sharer can be seen only after the next GC. Therefore, it feels like immediately after the sharer, another GC should be done. We name that policy between GC.

We have therefore added an option to hProlog:

- -r0: no sharing
- -r1: sharer with policy after GC
- -r2: sharer with policy between GC

Note that the absorb phase could estimate the amount of space it has freed, and the decision to switch from one policy to the other could be based on that.

8 The Benchmarks and the Results

Since (Appel and Gonçalves 1993) is closest to our representation sharing, we are inclined to use the same benchmarks. However, (Appel and Gonçalves 1993) shows overall very little impact of hash-consing and unfortunately, the benchmarks were not analyzed so as to explain why hash-consing is not effective on them. On the other hand, one cannot a priori assume that our sharer will show the same behavior, because of the differences between our respective implementations, and even the language:

- hProlog only performs major collections, while SML/NJ has a generational collector (with two generations)
our sharer does not alter the representation of terms, while (Appel and Gonçalves 1993) performs hash-consing (which entails a representation change) on the old generation only

SML/NJ is a deterministic language and a boolean SML/NJ function is like a semi-det predicate in Prolog: however, in a typical Prolog implementation, the data it creates is (on failure) backtracked over in Prolog and the WAM recovers its space: this can have a huge impact on some benchmarks (the mandelbrot benchmark is an example)

in (Appel and Gonçalves 1993) hash-consing was inseparably tied to the (generational) collector; in contrast, we have explicitly aimed at keeping the collector and the sharer separated (we argue why in Section 4); this has an impact on the efficiency of the sharing process

So it seems worthwhile to redo some of the benchmarks of (Appel and Gonçalves 1993). The following section describes those benchmarks as well as some others not appearing in (Appel and Gonçalves 1993).

8.1 The Benchmarks

8.1.1 Boyer

Boyer is a famous benchmark initially conceived by R. Gabriel for Lisp, and later used in other functional and logic contexts. Essentially, it rewrites a term to a canonical form. Boyer has been the subject of many studies, and in particular for proving that it is not a good benchmark: see for instance (Baker 1992). Anyway, in (Appel and Gonçalves 1993), this benchmark shows the best results for hash-consing. The inherent reason is that terms are rewritten to a canonical form and thus many initially different terms end up the same. We measured that the final result of the rewriting process needs 39 834 heap cells without representation sharing, and only about 200 with representation sharing.

This makes boyer close to an optimal benchmark for showing the effectiveness of representation sharing.

Note that the boyer benchmark also benefits a lot from tabling (Chen and Warren 1996). This means that repeated computations are going on, which explains also the high amount of representation sharing. However, while tabling does avoid the repetition of duplicate computations, as usually implemented, it does not avoid the creation of duplicate terms on the heap. It is possible to add to the tries enough info so that ground terms need be copied only once to the heap as long as this copy is not backtracked over.

8.1.2 Life

(Appel and Gonçalves 1993) also uses the well known Game of Life as a benchmark. We have written a version in Prolog following the ideas of Chris Reade (Reade 1989), just as (Appel and Gonçalves 1993) did. A (live) cell is represented as a tuple in coordinate form
(X,Y). A generation is a list of live cells. The program keeps a list of the first 1000 generations, starting from the The Weekender\(^6\) which is a glider, i.e., a pattern that repeats itself after a few generations (7 in this case) translated a few cells (2 in this case). If just the most recent generation is kept alive, one expects little from running the sharer immediately after a major collection, as the just rewritten generation is garbage. Our benchmark still shows some 50% memory improvement, because it keeps all computed generations in a list, so that the existing overlap between generations is shared.

(Appel and Gonçalves 1993) shows little gain from hash consing for this benchmark, but we could not retrieve the initial generation(s) on which the benchmark was run.

8.1.3 Mandelbrot

This benchmark was also used in (Appel and Gonçalves 1993): it computes (actually outputs) a bitmap of a Mandelbrot set of a given dimension. Since the output does not play a role in the heap usage, we have removed the code for the output. We took the version from the Computer Language Benchmarks Game (http://shootout.alioth.debian.org/) written for Mercury and based on a version by Glendon Holst. Mandelbrot uses quite a bit of heap and as such appears a good memory benchmark. However, one can see quickly that literally all memory used by mandelbrot is by floating point numbers: computed floating point numbers have the tendency to be different and therefore representation sharing might not have much effect. We have indeed checked that half of the generated floating point numbers are unique during the benchmark.

Almost all the floating point numbers are generated during a ground call to mandel/5, a semidet predicate called as the condition in an if-then-else as follows:

\[
\begin{align*}
\text{mandel(Height, Width, Y, X, 50) } & \rightarrow \\
\text{ByteOut1 is (ByteOut0 << 1)} \\
; \\
\text{ByteOut1 is (ByteOut0 << 1) } & \mathord{\text{// 0x1}} \\
\end{align*}
\]

In the setting of (Appel and Gonçalves 1993) (generational collection + hash-consing) the Mandelbrot benchmark has the following characteristic: if the garbage collector runs during the test (mandel/5) then a few floats are copied to the older generation, otherwise, no float from the new generation survives the collection. So, not even all computed floats end up in the zone subject to hash-consing.

In our setting (only major collections + representation sharing), at each collection, only some floats in the test are alive. Exactly at that moment, the chance for duplicates is very small.

\(^6\) See http://fano.ics.uci.edu/ca/rules/b3s23/g10.html
The effect of hash-consing or representation sharing is expected to be very small for the mandelbrot benchmark.

Our test runs of the mandelbrot benchmark indeed show zero gain from representation sharing.

8.1.4 One more classical Prolog benchmark: tsp

We were unable to retrieve more benchmarks from (Appel and Gonçalves 1993), so we tried different benchmarks from the established general Prolog benchmark suite. None showed any benefit from representation sharing. We report only on tsp; just like mandelbrot and the other benchmarks showing no benefit, it is mainly good for showing the overhead of the useless sharer.

8.1.5 blid/1

The next program was altered slightly from what Ulrich Neumeier posted in comp.lang.prolog; it appears also in his Diplomarbeit (Neumerkel 1989).

```
blid(N) :- blam([]).
blam([]). length(L, N), blam([L|L]) :- blam(L).
blam([L|L]), id(L,K), use(K).
use(_).

id([]), []).

id([L1|R1], [L2|R2]) :- id(L1,L2), % L1 = L2
use(_).

id([L1|R1], [L2|R2]), % R1 = R2
```

His question was Are there systems, that execute a goal blid(N) in space proportional to N? Say blid(24). At first we expected that with our representation sharing, space would be indeed linear in N. However, the expansion policy and order in which events (garbage collection and representation sharing) take place is also crucial.

- with the after GC policy, the following happens:
  a1: the first GC finds that 99% (or more) of the data is live, and decides to expand the heap
  a2: the sharer shares most data
  a3: the next triggered GC finds that about half of the heap is live, so does not expand
  a4: the following sharer shares most of the data
  a5: points a3 and a4 are repeated

- with the between GC policy, the following happens:
  b1: the first GC finds that 99% (or more) of the data is live, and decides to expand the heap
  b2: the sharer shares most data
  b3: the second GC collects almost all data
  b4: points b1, b2 and b3 are repeated
The first GC in a1 and b1 is triggered by lack of space, the second GC (in b3) is there by policy. A GC can decide to expand the heap (in hProlog when the occupancy is more than 75%; this is known after marking). So one sees that in the case of the between GC policy, the heap is repeatedly expanded, even though the program could run in constant space (with the aid of the sharer). With the after GC, we do not get into this repeated expansion.

If hProlog also had a heap shrinking policy, the between GC policy would after its second collection shrink the heap, and this would amount to almost the same effect as the after GC policy.

This shows that the combination of a reasonable heap expansion policy and a reasonable sharer policy can result in an overall bad policy. More work could be done on this.

Note that in its original form, \texttt{id/2} also contains the two commented out unifications, and that with unification factoring these would also introduce the sharing needed to run in \(O(N)\) heap (always with the aid of GC of course).

8.1.6 Four Applications

The next four benchmarks provide some insight in what to expect from the sharer in a some typical applications of Prolog: there is little impact on memory and performance.

Tree Learner. This realistic benchmark consists of a best-first relational regression tree learner written by Bernd Gutmann (Gutmann and Kersting 2006). The program is about 900 LOC. It works on a data set of 350K facts.

Emul. Emul is a BAM emulator (Van Roy and Despain 1992) written by Peter Van Roy in Prolog. The benchmark consists in executing the BAM code for the famous SEND+MORE=MONEY problem. It is about 1K LOC.

An XSB compiler. xsbcomp is an old version of the XSB compiler (Sagonas et al. 1994) and a run of the benchmark consists in compiling itself. The XSB compiler is about 5K LOC and also uses the hProlog or SICStus Prolog reader which are also in Prolog.

The hProlog compiler. In this benchmark, the hProlog compiler compiles itself. It uses \texttt{setarg/3} heavily, so we need a \texttt{mutable/1} (see Section 9) declaration for 7 functors. This benchmark cannot be run by SICStus. The hProlog compiler (which is a version of the hipP compiler (Blockeel et al. 2000) written by Henk Vandecasteele) plus all other code it needs (reader, optimizer ...) totals more than 10K LOC.

8.1.7 Worst and best Case

It is not clear what the best and worst case for our sharer is: if the heap were just one huge flat term (say of the form \(f(1,2,3,\ldots)\)) then only one hash value would have to be saved in the hashed terms table, and in some sense that is both best and worst, because the least time is lost in collisions etc, but also no sharing can be performed. So we choose the following as best-versus-worst case: a large complete binary tree in which every node is of the form \texttt{node(tree,tree,number)}. In what we consider the best case, the number is always the same
(and thus resembles a bit the blid data structure in Section 8.1.5). This leads to a very sparse hashed terms table, and a large amount of sharing. In the worst case, the number is different in all nodes: as a result, the hashed terms becomes quite full, and no sharing is possible at all. The main reason for this benchmark is to find out how the build and the absorb phase contribute to the total time of the sharer.

### 8.2 The Benchmark Results for Representation Sharing

The results are shown in Table 3. Time is in milliseconds. Space is in Mib or Kib as indicated in the table.

The first two columns denote the benchmark and system used (with the sharing option for hProlog). Then follow the total time taken by heap garbage collection (including the stack shifter), the total time taken by the sharing module, the total execution time and the number of garbage collections. Then follow four columns related to space: the initial heap size, the final heap size and the amount of space collected by the garbage collections are given in megabytes. Finally, there is the heap high water mark at the end of the benchmark given in KiB instead of Mib because the figures vary widely. It measures the size of the result computed by the benchmark and it includes a small system specific overhead from the toplevel: for mandelbrot, the figure is just that overhead.

Table 3 shows sometimes a large difference between the memory consumption of SICStus Prolog and hProlog. Also the time spent in garbage collection, and the number of collections can be very different. The reason is that although both systems are based on the WAM, they differ in a number of other design decision. In particular, their heap expansion policy differs, their garbage collectors differ (the SICStus Prolog one is generational and compacting, while the hProlog one is non-generational and copying), they have a different approach to floating point arithmetic, and hProlog does not allocate free variables in the local stack.

In addition to the results in Table 3, we can also mention that the build phase takes between 8.3 (for blid) and 2.6 (for worst) times as long as the absorb phase: the absorb phase is indeed much simpler.

### 8.3 Conclusions from the Benchmarks

By and large our results confirm the findings of (Appel and Gonçalves 1993): most benchmarks hardly benefit from representation sharing, and sometimes the space and time performance becomes worse. Apart from the artificial benchmark blid/1, only for boyer do we find a much larger—huge in fact—benefit from representation sharing than in (Appel and Gonçalves 1993). We have not been able to pinpoint why: the benchmarks used in (Appel and Gonçalves 1993) are not even available anymore, let alone the queries. The fact that generational collection retains terms longer than an only-major-collections strategy might play a role. Still, our result is in line with the (confluent) rewriting character of boyer.

The time taken by our implementation of representation sharing is reasonable: the algorithm is linear in the size of the heap, localstack, choicepointstack and trail, so complexity wise not worse than an actual garbage collection. The traversal of the stacks is however less complicated, since one does not need to take into account the liveness of the locations
### Table 3. The Sharer and the Collector

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anymore and less copying is going on. In our application benchmarks, the sharer always
takes less time than the garbage collection. It is clear that a better policy, and improvements
to our implementation code, can make the sharer even more efficient. Our sharer does not
depend on the efficiency of the underlying Prolog system, neither its garbage collector,
so we feel it is safe to say that our sharer can be implemented with the same (or better)
performance in other WAM-like systems.

9 Variations, Extensions and related Issues

Unusual Sharing. In (Demoen 2002), the rather unusual representation sharings depicted
in Figure 10 are described.

![Figure 10. Unusual representation sharing](image)

Our current representation sharing implementation does not achieve the above sharings.
Still, all ingredients are present and while the expected gains are small, it is nice that the
above unusual sharing can be achieved in time linear in the size of the heap (assuming
perfect hashing).

Cyclic Terms. (Appel and Gonçalves 1993) deals with cyclic terms by excluding them
from hash-consing. It is easy to do the same in our implementation as follows:

1. besides the special values no-info and impossible, cached_hash entry can also have
   the value busy
2. when a functor cell is visited for the first time, that corresponding cached_hash entry
   is set to busy
3. when a functor cell is visited recursively, a check on the corresponding cached_hash
   entry detects that there is a cycle: the field is set to impossible
4. as usual, when a term is visited completely, its corresponding field is set to an ap-
   propriate value, i.e., impossible or a pointer to the hashed_terms table

However, one can do better: a variation of point 3 above yields a procedure that can
perform representation sharing also for cyclic terms.

3’. when a functor cell is visited recursively, a check on the corresponding cached_hash
   entry detects that there is a cycle: a fixed value (say 17) is returned as the hash value
   of this term; the corresponding cached_hash entry is not updated at this time: this
   happens when the visit has returned to the point where the entry was set to busy
The procedure for testing equality of terms must also be adapted to deal correctly with cycles: this is common practice now in most Prolog systems.

Note that it does not matter which value is chosen in (3’) above. What matters is only that the hash value of terms that can share their representation is the same. Still, our procedure can attach a different hash value to cyclic terms that are equal (in the sense of ==/2) and could share their representation. This results in no representation sharing for those cyclic terms. As an example:

```
  test :- X = f(1,f(1,X)), share, use(X).
```

does not result in the same heap representation as

```
  test :- X = f(1,X), use(X).
```

The procedure based on minimization of finite automata described in (Neumerkel 1989) does.

**Mutable Terms.** Prolog systems supporting destructive update —through `setarg/3`, mutable terms or for attributed variables— often do this using a trail in which each entry keeps the old value: clearly, these old values can point to sharable terms and they can be updated accordingly in the final absorb phase.

However, just as a ground mutable term must be copied by `copy_term/2`, a mutable term itself is not allowed to absorb or be absorbed. This means that mutable terms should be recognizable during the build phase. In SICStus Prolog this is the case ($mutable/2$ is reserved for this), but not so in other systems (e.g., SWI Prolog, Yap, hProlog ...). In hProlog we have resolved that problem by introducing a declaration: `:- mutable foo/3`. declares that the arguments of any `foo/3` term can be destructively updated, and effectively prevents sharing of `foo/3` terms. We use one bit in the functor table and the overhead during the build phase is unnoticeable. Note that the `:- mutable` declaration does not readily work across modules.

**Cooperation between Collector and Sharing.** We have implemented the representation sharing module independent of the garbage collector module. The advantage is less dependency and a higher potential that the sharer can be integrated in other systems. The disadvantage is that some information that the garbage collector has computed, needs to be recomputed by the sharing module. For instance, the collector might leave behind information on which cells are trailed, and which cells contain sharable information. This would speed up the sharer and in particular the build phase.

**What if Representation Sharing does not work.** The benchmark programs show that representation sharing is not always effective: it depends indeed highly on the type of program. When representation sharing does not work, this can be noticed during a run of the representation sharing module by observing the hashed terms. If it keeps growing, it means that lots of different terms are found. This in turn gives an indication that representation sharing is not effective. An important advantage of our implementation is that the representation sharing process can be abandoned at any time since no changes to the WAM run-time data structures are made until the absorb phase in which structure (or list ...) pointers are
updated, and even the absorb phase can be stopped before finishing. Also, if representation sharing is run from time to time only—as suggested by Ulrich Neumerkel—then the frequency of running it can take into account the effectiveness of representation sharing up to that moment. Such tuning could depend also on the relative performance of the garbage collector and the representation sharing module.

**Parallelization.** During the scanning phase, the stacks (heap, local stack ...) are read-only, while the cached_hash and the hashed_terms can be read and written by different workers. During the absorb phase, the cached_hash and hashed_terms are read-only, and only the stacks are written to.

By giving different workers a different part of the heap to start working on, duplicate work might be avoided and synchronization slowdown kept low in the scanning phase. During the absorb phase, giving different workers different parts of the stacks makes their actions completely independent.

**Variable Chains.** We have not treated variable chains in much detail, as we were mostly interested in sharing between the bodies of compound data. However, a slight extension of the code for the build phase can also call save_hash for all reference cells. That results in a similar effect as variable shunting as described in (Sahlin and Carlsson 1991), but is not as complete as the method described there. Figure 11 shows an example of how a chain of references is transformed.

![Fig. 11. Absorption for chains of references in action](image)

**Backtrackable Representation Sharing.** Backtrackable representation sharing would follow the principle that when two terms are identical (as for ==/2) then one can absorb the other, regardless of whether they have trailed cells or not. The change made (to a LIST or STRUCT-tagged pointer) by the absorb phase is now conditionally (and value) trailed. This costs extra trail space of course. On cut, the trail can be tidied, so in case the computation becomes eventually deterministic, the amount of sharing can be arbitrarily larger than without this form of backtrackable representation sharing. However, suppose that all sharing were trailed, then it is possible that an immediately following GC would not be able to recover anything. And if the computation becomes deterministic eventually, running...
the sharer will do the same job as was done in the case of the backtrackable representation sharing, only later -- which might be even better, because the earlier sharing could have been unnecessary because backtracking has destroyed it. All in all, our feeling is that backtrackable representation sharing is not worth its while.

Partial Sharing. Partial sharing refers to running the sharer in an incomplete way, i.e., it achieves part of its potential effect, but maybe not all.

Partial sharing can result for instance from restricting the part of the heap in which duplicate terms are identified, i.e., restricting the scan phase to part of the heap. Another possibility is to restrict sharing to certain terms, e.g., just for lists, or to certain parts of the other stacks. It is one of the strengths of our implementation approach that all such variations can be incorporated rather easily.

Incremental Sharing. The notion of incremental sharing refers to the possibility to perform a partial sharer pass, e.g., on part of the heap, and continue that pass later on, eventually obtaining the same effect as running the sharer completely. The ability to perform partial sharing is certainly needed, but there is more: information must be passed from one partial run to the other, and the user program and the sharer must be able to run in an interleaved way. This raises immediately question of the completeness, but also efficiency is at stake.

The issues with incremental sharing are similar to the ones with generational sharing in the next paragraph and we do not discuss further incremental sharing separately.

Generational Sharing. The notion of generational sharing refers to the possibility to avoid performing sharing on a part of the heap on which it was performed earlier. In analogy with generational garbage collection, there is a rationale for performing generational sharing: for generational garbage collection, the rationale is that new objects tend to die quickly. For generational sharing the rationale is that redoing sharing on old data (on which sharing was performed earlier) does not pay off.

Our strategy to non-generational sharing is to recompute the cached_hash and hashed_terms tables from scratch every time after a new garbage collection. With generational sharing, one would like to reuse the part of the tables corresponding to the older generation.

We reason about forward computation first: The information on terms in the older generation that were ground at the previous run of the sharer and eligible for sharing at that moment is still valid. The same is generally not true for a non-ground term: it can now contain cells that are trailed, and in that case the information about the term is to be discarded from the table, or at least not used. Since it is not straightforward to keep track of which information in the tables is no longer valid because of this reason, it might be best to restrict a generational sharer to ground terms only.

Now suppose that backtracking has taken place between two activations of the sharer: generally, this invalidates entries in the sharer tables because terms have disappeared. It is easy to adapt the cached_hash table (it shrinks with the heap on backtracking), but the hashed_terms table also needs to be adapted. By keeping high and low water marks of the
top of heap pointer, this can also be achieved. The cost of adapting the tables might be larger than the cost of rebuilding them however.

10 Related Work

(Appel and Gonçalves 1993) describes how hash-consing can be performed during garbage collection in an implementation of Standard ML (SML/NJ). The collector is generational, and the data structures in the old generation are hash-consed. In this way, the operation of hash-consing is restricted to data structures that are expected to live long. The reported performance and space gains are disappointing; half of the benchmarks lose performance (up to 25%) and the gain is maximally 10% (for boyer). The space improvement is even smaller: on most benchmarks less than 1%. Also for space, boyer is the exception with about 15%. Note however, that these space figures are about the amount of data copied to the older generation, i.e., the data that is hash-consed, and which is collected infrequently. As such, these numbers do not give full insight in the potential of hash-consing. Still, (Appel and Gonçalves 1993) is most closely related to our implementation of representation sharing for Prolog: our strategy is to perform representation sharing after a (major) garbage collection, so we introduce sharing only for data that just survived a collection.

Mercury (Somogyi et al. 1996) is basically a functional language, and the issue of trailing does not enter. In the developers' mailing list in August 1999, the issue of hash consing was raised with a proposal for an implementation as well as how to present it to the user. It is interesting that at some point, the opposite of our :: mutable declaration was proposed. As an example :: pragma hash_cons(foo/3) tells the compiler to hash-cons the constructors of type foo/3. As far as we know, the proposals were not implemented.

Last but not least, (Neumerkel 1989) provides the example blid/1, and gives a high-level outline of an algorithm for minimization of heap terms seen as DFAs. Our implementation can be seen as a concrete version of that algorithm. However, our minimization shows mostly similarities with (Ershov 1958) in which Ershov uses (for the first time in the published history of computer science) hashing to detect common subtrees in a given tree.

11 Conclusion

Without the questions by Ulrich Neumerkel on comp.lang.prolog, we would not have worked on this topic and we are grateful for his insistence that Prolog systems should have a sharer. We have provided a practical and efficient implementation of representation sharing, that can be incorporated without problems in most WAM based systems. Our implementation has the advantage that it does not rely on a particular garbage collection strategy or implementation. On the other hand, a tighter integration of the garbage collector with the representation sharing module can make the latter more efficient. Still, representation sharing is not effective for all programs, so it must not be applied indiscriminately, i.e., it needs its own policy. We have also shown that input sharing for findall/3 is easy to implement.
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References


Appendix: the relevant Part from the Program in (O’Keefe 2001)

```prolog
representation_sharing_for_prolog

tree_children(node(_,Children), Children).

up_down(P, ptr(T,L,R,A)) :-
    var(P) ->
        A = ptr(_,_,_), \ not_no_ptr, that is.
        P = A
    ;
        A = P,
    P = ptr(Tree,_,_,_),
    tree_children(Tree, Children),
    up_down_star(P, D).

up_down_star(P, D) :-
    var(A) ->
        up_down_plus(A, D)
    ;
        A = D
    ;
        up_down_plus[A, D]
        

up_down_plus[A, D] :-
    ( var(A) ->
        up_down(X, D),
        up_down_star(A, X)
    ;
        up_down(X, D)
    )
.

split_children([], L, T, R).
split_children([T|R], L, L, T, R) :-
    split_children([X|S], L0, L, T, R).

mk_tree(D, node(D,C)) :-
    ( D > 0 ->
        D1 is D - 1,
        C = [T1,T2,T3,T4],
        mk_tree(D1, T1),
        mk_tree(D1, T2),
        mk_tree(D1, T3),
        mk_tree(D1, T4)
    ;
        C = []
    )
.

f1(N) :- mk_tree(N,T),
    top_pointer(T,P),
    findall(Q, up_down_star(P, Q), _L).
```